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Advancing Highway Traffic Monitoring Through Strategic Research

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Advancing Highway Traffic Monitoring Through Strategic Research

Standing Committee on Highway Traffic Monitoring

December 2017

Transportation Research Board 500 Fifth Street, NW Washington, DC 20001 www.TRB.org

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Standing Committee on Highway Traffic Monitoring

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Foreword

LAWRENCE A. KLEIN

Traffic monitoring to characterize the population of vehicles on our nation's roadways involves the measuring and recording of traffic characteristics such as vehicle volume, classification (by axle number or vehicle length), speed, weight, lane occupancy, or a combination of these characteristics. Traffic monitoring programs within transportation agencies have evolved relatively slowly over time, even though traffic monitoring is a critical need within state and municipal departments of transportation. Responsibility for overall traffic monitoring program management typically resides within the planning division or planning office of a state department of transportation or other regional transportation agency. Program management responsibilities include oversight of data collection, processing, analysis, and reporting processes.

Data acquisition methods through the decades have progressed from manual counts of vehicles and vehicle type to automated systems that gather vehicle data through the Global Positioning System and cellular devices. Along with the vehicle industry's electronic revolution, we have witnessed an evolution in our ability to collect vast quantities of different types of data. The issue now is how to manage those data and extract from them the required information to meet state and federal reporting requirements and the other myriad of uses of traffic monitoring data in an expeditious manner.

Transportation planners traditionally have dealt with long-range travel needs and goals, and funding constraints with little consideration of short-term operational issues. Transportation agencies, metropolitan planning organizations, and other interested parties increasingly are recognizing the value of coordination and collaboration among all stakeholders and the operators of the nation's road network.

This E-Circular represents a timely capture of the state of the practice and state of the art in highway traffic monitoring, encompassing the known universe of data acquisition, analysis and reporting tools, quality assurance and quality control techniques, and trends in emerging technologies. It will aid traffic management agencies, transportation planners, and designers in understanding how accurate highway traffic data are acquired and used, and will provide the entire transportation community with an excellent explanation of current practices and gaps in knowledge from which to move forward. The document provides guidance to those involved with highway data acquisition, reporting, and its applications, and will assist them in meeting present day and future requirements. Furthermore, each section presents suggested research that is needed to close the gaps in current knowledge and practices.

ACKNOWLEDGMENTS

This E-Circular was developed over the past year with the leadership and assistance of the Highway Traffic Monitoring Committee members and its friends. The dedicated efforts, unselfish time commitments, insights, and inspiration of these volunteers made this circular possible.

The Transportation Research Board (TRB) Highway Traffic Monitoring Committee cochairs, Liz Stotz and Jonathan Regehr, with the assistance of Lawrence Klein, provided overall leadership, guidance, and encouragement to the authors of the chapters. The timely publication of this document could not have occurred without the support and direction of Tom Palmerlee who kept us informed of TRB's publication procedures and time constraints.

Many other individuals contributed to the development of the E-Circular. These include Lei Bu, Alan Chachich, Thomas Chase, Mike Fontaine, Kim Hajek, Tingting Huang, Steven Jessberger, Anne-Marie McDonnell, Olga Selezneva, Ioannis Tsapakis, Anita Vandervalk, Chris Vaughan, Billy M. Williams, and M. Anil Yazici.

PUBLISHER'S NOTE

The views expressed in this publication are those of the committee and do not necessarily reflect the views of the TRB or the National Academies of Science, Engineering, and Medicine. This publication has not been subjected to the formal TRB peer-review process.

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Introduction

As an integral part of the surface transportation network, our nation's roadways play an essential role in providing safe and efficient transportation services for commuting, commercial enterprises, and the recreational pursuits of the general public. The roadway infrastructure also facilitates government transportation needs and services (e.g., emergency service providers, first responders, military, and security) and enables quick responses to weather-related natural disasters and human-caused emergencies.

With the advent of intelligent transportation systems (ITS) and enhanced measuring devices, agencies responsible for collecting and reporting traffic flow and vehicle classification data are able to gather a greater variety and quantity of data as compared to what was common decades ago. In addition, advanced detection, surveillance, data acquisition, information analysis and dissemination, and telecommunications have increased the accuracy and hopefully the reliability of such data and the information derived from them.

The mission of the Highway Traffic Monitoring Committee is to provide resources, support, and guidance to enhance, enable, and advance the state of the practice of highway traffic monitoring and data collection technologies, methods, and management techniques. Thus, the Highway Traffic Monitoring Committee is concerned with all aspects of research in the field of highway traffic monitoring, such as detection, counting, and classification of motorized and nonmotorized transportation vehicles and pedestrians. Its scope encompasses the full range of monitoring activities, including the specification and installation of sensors (including those installed below or on the payement surface and above it either to the side or over the traffic lanes), installation materials and techniques, signal processing algorithms, data analysis and reporting methods, comprehensive monitoring programs, and in-motion weighing of vehicles. The committee is also involved with the development of highway monitoring standards to ensure that applicable high-quality traffic data are acquired for diverse applications including federal data reporting, planning, and highway design and maintenance. Accordingly, its scope is aligned with the overarching objective of highway traffic monitoring programs, namely to improve the safety of the traveling public, the quality of the highway network, and ensure that accurate traffic count data are available for freight planning, railroad crossing, pavement management, and other applications.

To address the need to develop monitoring practices for bicycles and pedestrians, particularly in urban environments, the Highway Traffic Monitoring Committee established the Joint Bicycle and Pedestrian Data Subcommittee even though bicycle and pedestrian travel are not currently reflected in the committee's mission. The subcommittee developed *Transportation Research Circular E-C183: Monitoring Bicyclist and Pedestrian Travel and Behavior: Current Research and Practice* in 2014. Therefore, this document does not discuss issues concerned with the monitoring of these travel modes.

PURPOSE

The purpose of this E-Circular is to

• Leverage previous and ongoing research efforts related to highway traffic monitoring;

• 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 Highway Traffic Monitoring Committee;

• Identify potential areas of research for each strategic focus area for the Highway Traffic Monitoring Committee to consider advancing as projects within the National Cooperative Highway Research Program (NCHRP); and

• Consider research that could be useful for other agencies [e.g., Federal Highway Administration (FHWA) and state departments of transportation (DOTs)], organizations [e.g., American Association of State Highway and Transportation Officials (AASHTO) and the Institute of Transportation Engineers (ITE)], research interests [e.g., Long-Term Pavement Performance (LTPP) program and *Mechanistic–Empirical Pavement Design Guide* (MEPDG) Pooled-Fund Study], and academia.

ORGANIZATION

The Highway Traffic Monitoring Committee has identified five 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 last area— Traffic Monitoring Statistics, Data Quality, Usage, and Integration—contains seven subareas as indicated below. The strategic focus areas and subareas include the following:

- Traffic Monitoring Program Management;
- Continuous Traffic Count Programs;
- Short-Duration Traffic Count Programs;
- Weigh-in-Motion;
- Traffic Monitoring Statistics, Data Quality, Usage, and Integration:
 - Managing Large Traffic Datasets;
 - Performance Measures;
 - Pavement Engineering Applications;
 - Data Quality and Equipment Calibration;
 - Integrating Traffic Counts with Connected Vehicle Data;
 - Travel Time, Speed, and Reliability Data; and
 - Potential Research Topics.

While these focus areas are distinct, there is often overlap in strategies and needs between one or more focus area, such as between Managing Large Traffic Datasets and Integrating Traffic Counts with Connected Vehicle Data or between Performance Measures and Travel Time, Speed, and Reliability Data. Table 1 lists the volunteers who led and facilitated the development of the chapters that support each focus area. Without their leadership, this E-Circular could not have been possible. In addition, Lawrence Klein served an invaluable role as technical editor of the overall document, while Maggie Cusack-Steciuk, PBS Engineering and Associates P.C., was instrumental in steering the document through the TRB publication process.

Focus Area	Leads
Traffic Monitoring Program Management	Anita Vandervalk,Kim Hajek
Continuous Traffic Count Programs	Liz Stolz
Short-Duration Traffic Count Programs	Ioannis Tsapakis
Weigh-in-Motion	Anne-Marie McDonnell, Olga Selezneva
Traffic Monitoring Statistics, Data Quality, Usage, and Integration:	
Managing Large Traffic Datasets	Steven Jessberger
Traffic Monitoring and Performance Measures	Anita Vandervalk
Pavement Engineering Applications	Olga Selezneva
Data Quality and Equipment Calibration	Steven Jessberger
Integrating Traffic Counts with Connected Vehicle Data	Alan Chachich, Chris Vaughan, Thomas Chase
Travel Time, Speed, and Reliability Data	Mike Fontaine, Billy M. Williams, M. Anil Yazici, Tingting Huang, Lei Bu
Potential Research Topics	Committee

 TABLE 1 Volunteer Leads by Focus Area

Traffic Monitoring Program Management

Anita Vandervalk Kim Hajek

STATE OF THE PRACTICE

Traffic monitoring programs within transportation agencies have evolved relatively slowly over the past few years. However, despite increasing availability of private-sector data sources (such as probe speed data), traffic monitoring remains a critical need within state and municipal department of transportations (DOTs). Responsibility for overall traffic monitoring program management typically resides within the planning division or planning office of a state DOT or other regional transportation agency. Program management responsibilities include oversight of data collection, processing, analysis, and reporting processes. Traffic monitoring programs measure and record traffic characteristics such as vehicle volume, classification (by axle or length), speed, weight, lane occupancy, or a combination of these characteristics. Since each DOT has its own unique organizational structure there is a wide degree of latitude in how DOTs utilize staff and contractors to collect and process traffic data in accordance with federal guidance outlined in the Traffic Monitoring Guide (TMG). While the TMG provides guidance and best practice examples of what to collect and how to report it, AASHTO Guidelines for Traffic Data Programs (AASHTO Guide) includes guidance tailored to states needs and uses of traffic data, giving advice for all facets of traffic monitoring from equipment selection for data collection to generation and submission of required reports. Figure 1 illustrates an approach used by the West Virginia DOT to organize the management of its traffic monitoring program.



FIGURE 1 Overview of West Virginia DOT's traffic monitoring program.

The figure depicts typical traffic monitoring program functions that are implemented at all state DOTs, including management and training of staff within the section or unit assigned to collect and process traffic data. These functions incorporate coordination with other sections that may use traffic data to support planning and other engineering functions of the DOT involving design, construction, and maintenance of the state's transportation system. The traffic monitoring program must also provide easy access to traffic data for external stakeholders such as metropolitan planning organizations (MPOs), consultants, researchers, law enforcement (weight data), and the general public to meet their business needs.

STATE OF THE ART

Unique and common approaches are used by states to manage their traffic monitoring programs. The unique approaches are featured in this section as examples of state-of-the-art practices, which include but are not limited to the following:

1. Development of customized guides and manuals for traffic monitoring programs;

2. Use of data business plans to improve management of traffic monitoring programs including use of self-assessment tools; and

3. Integration of traffic data programs to leverage operations and ITS data collection programs or local data collection.

Each of these practices is described in more detail in the following paragraphs.

Development of Guides and Manuals Customized for the DOT to Supplement Guidance in the TMG

Several state DOTs either have or are in the process of developing customized handbooks or manuals that explain the policies, organization structure, business processes, and technology tools (including traffic databases) that support and manage their traffic monitoring programs. These manuals follow TMG guidance while supporting the DOT's management of traffic monitoring within the existing organizational structure and in accordance with DOT policies and procedures regarding collection, storage, and use of data. An example from West Virginia illustrates how development of their *Traffic Data Collection Handbook* supports their traffic monitoring program. Its creation allowed West Virginia DOT to incorporate the latest guidance from the Federal Highway Administration (FHWA) TMG (revised in 2013) into a customized handbook for West Virginia DOT. The West Virginia DOT *Traffic Data Collection Handbook* contains the following elements:

• Documents collection, analysis, reporting processes, and field and office components of the traffic monitoring program;

- Documents federal requirements for traffic data;
- Defines offices, roles, and responsibilities for the traffic monitoring program; and
- Incorporates specific instructions on equipment calibration and use of software to

store, perform QA–quality control (QC), analyze, and produce data sets and reports for FHWA and other traffic data users.

Many other states have traffic monitoring program manuals including Florida, Texas, Illinois, Ohio, Tennessee, and New Jersey. States needing to develop similar manuals or update existing manuals may benefit from reviews of these recently developed and updated manuals.

Use of Data Business Plans to Support Traffic Monitoring Programs

Data business plans designed specifically for traffic monitoring programs improve data management in this business area, although typically an agency may develop a data business plan that incorporates many business areas, one of which is the traffic monitoring program. The data business plan for the FHWA Office of Operations states: "a data business plan is a document that guides an agency in data management practices throughout the organization, in accordance with standards, policies, and procedures that specifically focus on data systems, databases, and business processes. It should be a living document that describes an agency's vision, goals, objectives, and actions related to improving data management in the agency. If successful, a data business plan will create an implementable coordination process that results in time and cost savings, as well as improved efficiency in business operations and work."

A traffic data business plan is designed to

- Support federal and state DOT needs for traffic and speed data;
- Formalize documentation of traffic monitoring program business processes;
- Establish visioning for traffic data programs to meet future needs;
- Identify gaps and needs related to traffic data programs; and
- Develop a roadmap (or implementation plan) to address gaps.

The following examples from West Virginia and Vermont illustrate how data business planning is applied to support traffic data program management at their respective DOTs, while the Colorado example illustrates the benefits of traffic program self-assessment.

West Virginia

In addition to its traffic monitoring program, the West Virginia DOT developed a traffic data business plan that:

- Defines roles and responsibilities for management of traffic data.
- Defines the vision and mission for the traffic monitoring program as follows:

- Vision: all West Virginia DOT business decisions regarding use of traffic data are supported by reliable data from the traffic monitoring program.

- Mission: to provide reliable, timely, and accurate traffic data and information that is easily accessed and shared for analysis and use by West Virginia DOT divisions, districts, and offices and by external users, including federal, state, and local agencies, and the general public.

• Documents new and improved business processes to support the traffic monitoring program.

- Documents gaps, issues, and challenges.
- Makes recommendations to address gaps, issues, and challenges.
- Provides next steps in the form of an implementation plan.

Vermont

The Vermont Agency of Transportation (VTrans) used a four-step approach to develop a data business plan to improve data management practices in the Transportation Systems Maintenance and Operations Section of the Planning Division. The four steps below follow the traditional tenets of a traffic data business plan.

- 1. Plan for mobility data management and governance;
- 2. Assess the current state of mobility data programs;
- 3. Conduct gap assessment; and
- 4. Develop an improvement plan.

VTrans defined their data business plan as "an actionable plan that prioritizes action items, specifies respective responsibilities, and identifies necessary resources for improving the data management practices."

The intended outcomes for VTrans' Traffic Data Program Business Plan include the following:

1. Mobility data at VTrans will be well organized and managed.

• Collection and update efforts will be carried out according to the needs of both the internal and external users.

2. Internal staff can use the data to perform comprehensive diagnostics of the transportation system or planning of resource allocation.

3. External stakeholders can have easy access to appropriate datasets and apply them to meet their own business needs including:

• Ensuring mobility data are available to analyze impacts and better manage seasonal events and construction zones.

• Supporting improved mobility by enabling improved traffic signal timing.

Application of data management program self-assessment tools is another technique to improve overall management of traffic monitoring programs. *NCHRP Report 814: Data to Support Transportation Agency Business Needs: A Self-Assessment Guide* provides a guidebook for agencies to implement the self-inspection process, including self-assessment case studies of data management programs at Michigan DOT and Utah DOT for specific business areas such as mobility and congestion, facilities management, maintenance, project scoping, and design. The guidebook can be useful for evaluating and improving the value of data for decision-making and data-management practices" (*NCHRP Synthesis 508: Data Management and Governance Practices*, 2017).

The following example from the Colorado DOT illustrates how it applied a selfassessment evaluation process to their traffic monitoring program when a new manager took over responsibility for that program and was able to successfully streamline it and improve efficiencies in collection, processing, and reporting of traffic data.

Colorado

Traffic Monitoring Program Self-Assessment Colorado DOT utilized consultant services to assist and guide their traffic monitoring program in an evaluation and assessment using self-assessment tools to indicate levels of maturity in data management practices. The assessment included evaluating existing business processes, databases, and technology used to support the program. The analysis revealed that there were opportunities to replace existing manual processes with automated processes, eliminate processes that were no longer needed, and integrate multiple processes into new processes to streamline delivery of traffic data in a more efficient manner. New technology tools were also developed with assistance from the consultant to facilitate delivery of timely, accurate, high-quality traffic data to the community of traffic data users. Other state DOTs with limited staff resources may consider a similar approach for evaluating management of existing traffic monitoring programs and implementing improvements to their programs.

Integration of Traffic Data Programs to Leverage Operations and ITS Data Collection Programs or Local Data Collection

Many states are taking advantage of other data programs to combine data or resources to collect the data. For example, Virginia has well over 600 sites collecting both traffic data for the traffic monitoring staff and speed data for the ITS staff.

Georgia DOT created an innovative program to collect data from regional agencies around the state. Each year, Georgia DOT allocates \$1 million through the University of Georgia to the agencies for the collection of traffic data on all public roads. This Moving Ahead for Progress in the 21st Century Act (MAP-21) Data Monitoring Program is designed to meet the upcoming needs for annual average daily traffic (AADT) on all public roads in the state.

EMERGING TRENDS OR DRIVERS OF CHANGE

Emerging Trends

Emerging trends at state DOTs promise improved overall management of traffic monitoring programs. Several of these trends are discussed in the following paragraphs.

Complete or Partial Privatization of Traffic Monitoring Programs

Georgia and Virginia have privatized at least portions of their traffic monitoring equipment installation and maintenance. Privatization of a traffic monitoring program may include implementing what is referred to as a pay for data management model that includes transitioning the ownership, procurement, operation, and maintenance of traffic-counting equipment and modems to a contractor. This model allows DOTs to convert their in-house staff into traffic count contract administrators and field inspectors. Under this model, it is presumed that the DOT staff would continue specialized training throughout the year in use of the latest technology including any new equipment and software needed to support traffic monitoring programs. This training may be in the form of attendance and participation at national monitoring program conferences such as the North American Travel Monitoring Exposition and Conference, customized training provided by traffic equipment vendors at DOT offices or elsewhere, participation in peer exchanges with other DOTs, or at university, professional organization, and other private or government-sponsored update courses and seminars. Continued participation in these training opportunities will ensure that the DOT staffs maintain the needed competencies levels to oversee contractors responsible for maintenance of equipment and collection of traffic data.

The pay for data model allows DOTs to be flexible when technology changes occur by limiting DOT investment in equipment, and enables the use of the latest traffic-counting techniques and procedures by exploiting the experience gained from using a nationwide contractor. This has the potential to improve the quality and quantity of traffic data collected. Implementing a pay for data model requires DOTs to develop a detailed procurement document and to establish a contract with a vendor where the DOT only pays the vendor for high-quality data that passes the highest quality standards. Georgia DOT is an example of a state that issued a request for proposals in March, 2017 to solicit contractors for a "Pay for Data" model.

Coordination with Asset Management and ITS Programs Regarding Maintenance of Traffic Monitoring Program Equipment

Coordination between traffic monitoring and asset management or ITS and transportation system management and operations programs may provide opportunities to streamline processes for maintenance of equipment, thereby reducing maintenance costs. This approach may require cross-training of maintenance staff in supporting multiple types of equipment, such as that used to collect continuous-count data and equipment used to collect ITS data. Some providers of customized state DOT traffic monitoring program databases have indicated that their systems can retrieve specific types of traffic data (e.g., volume) from ITS equipment and subsequently store the data in the master traffic database that supports traffic monitoring. The standard QA-QC procedures can then be performed on the data collected by ITS equipment. Using equipment for dual purposes not only saves the governmental agency money, but it provides quick access to data and allows for multiple groups within the agency to perform quality checks of the data.

Drivers of Change

Drivers of change may come from both internal and external sources. These drivers include:

- Internal staff turnover due to organizational changes or retirements, etc.;
- New policies and guidance issued at federal level (e.g., traffic data needed for performance measures);
- Centralization of IT services external to DOT agency, presenting new challenges to the management of the traffic monitoring program (e.g., access to and implementation of upgraded software that supports the program); and
- Changing needs for traffic data identified by the community of interest (COI) or stakeholders that utilize traffic data as illustrated in Figure 2 for West Virginia.

A state's traffic monitoring program managers must be able to respond to these changes in an expeditious manner to ensure that all stakeholders have access to traffic data when needed.



FIGURE 2 West Virginia DOT traffic COI.

Additional research may be needed to further investigate the source and types of "drivers" and to categorize and prioritize the "drivers of change" to assist the traffic monitoring program managers make informed decisions on which drivers need immediate action or responses.

GAPS IN PRACTICE OR KNOWLEDGE

Some state DOTs may still struggle with managing their traffic monitoring programs due to the following issues:

• Traffic monitoring programs must respond in a timely manner to changes in federal guidance or mandates [e.g., via TMG, Highway Performance Monitoring System (HPMS) Field Manual or MAP-21 performance measures] that may impose new data collection or reporting requirements on the traffic monitoring program. For example, MAP-21–Fixing America's Surface Transportation (FAST) Act requires states to collect or estimate AADTs on all public roads to support safety measures. Traffic volumes are already collected under the HPMS for federal aid roadway segments and ramps. However, states are concerned about their ability to collect and maintain traffic data on local roads. FHWA is currently commissioning two relevant projects to assist with this challenge: *Collection and Estimation of AADT on Lower-Volume Roads* (active) from the FHWA Office of Safety and *Improved Vehicle Miles Traveled (VMT) Estimation on Non-Federal Aid System Roadways* (anticipated) from the FHWA Office of Highway Policy Information:

• Business practices deeply embedded in the culture of the agency (i.e., continued use of manual processes, "that's the way it's always been done") inhibit growth and progress in improving management of the program.

• The presence of business area silos inhibits sharing of traffic data and information across or between business units (e.g., ITS data and traffic monitoring data).

• Agency organizational structure may impact current management practices of the traffic monitoring program. This can include but not be limited to use of staff resources needed to maintain data collection field equipment and coordination with ITS staff for maintenance of both ITS and continuous-count station (CCS) equipment.

• While several states may have general data business plans, they do not have traffic monitoring program data business plans (or updated traffic monitoring program manuals or handbooks) to support the traffic monitoring program specifically.

• Retirements and integration of new staff presents challenges in knowledge transfer and training of new staff in time to ensure continued efficient management of the traffic monitoring program.

• Lack of formal protocols for sharing of data between the state DOT and local government agencies regarding traffic data may impede progress in utilizing available external data sources. Correcting this deficiency can reduce data collection costs and free internal state DOT staff to focus on other aspects of the traffic monitoring program (e.g., oversight of data collection contractors).

• Additional research is required to identify the advantages and challenges related to full or partial privatization of traffic monitoring programs.

CURRENT AND PROPOSED NATIONAL RESEARCH AND INITIATIVES

Proposed National Research

1. Explore which state DOTs have successfully implemented specific data business planning tools to support their traffic monitoring programs and how the use of data business plans helped to improve management of these programs.

2. Investigate and document how privatization of traffic data collection impacts management of staff and resources (internal and external) to complete the timely delivery of quality traffic data products (e.g., AADT, VMT, etc.) previously produced by the state DOT using their in-house resources.

3. Examine the management challenges and lessons learned from partial or fullprivatization of traffic monitoring programs (e.g., impacts of realignment of traffic monitoring program staff, what new QA/QC processes may need to be implemented to validate data collected through privatization, etc.).

4. Conduct research to develop roadmap, guidebook, or tutorial publications that describe best practices for management of traffic monitoring program equipment, ITS equipment, and other agency assets used to support the data needs of the traffic monitoring program.

5. Examine the impacts of drivers of change on the successful management of traffic monitoring programs. Who or what are the drivers? How do their needs compare and rank with needs identified by other drivers?

RESOURCES

- Assessment of Insourcing/Outsourcing Practices for Traffic Monitoring Data Collection, April 2016 (FHWA Publication No. PL-16-024), provides a comprehensive examination of the current state of privatization practices at state DOTs for traffic data collection.
- *NCHRP Synthesis 508: Data Management and Governance Practices*, 2017, offers guidance and best practice examples of states and other government agencies that utilize data governance and data business planning practices to improve management of their data programs.

Other publications of interest include:

- *Traffic Monitoring Guide*. Federal Highway Administration, U.S. Department of Transportation, October, 2016. https://www.fhwa.dot.gov/policyinformation/tmguide/.
- FHWA Office of Safety. *Collection of MIRE FDE on Non-State–Owned Public Roads*. Federal Highway Administration, U.S. Department of Transportation.
- FHWA Office of Safety. *Roadway Data Extraction Technical Program* (anticipated). Federal Highway Administration, U.S. Department of Transportation.
- Oregon Department of Transportation. A Method to Estimate Annual Average Daily Traffic for Minor Facilities for MAP-21 Reporting and Statewide Safety Analysis.
- Louisiana Department of Transportation and Development. Evaluating Cell Phone Data for AADT Estimation.
- Transportation Association of Canada. *Traffic Monitoring Practices Guide for Canadian Provinces and Municipalities*, 2017. http://www.tac-atc.ca/en/publications/ptm-tmpg-e. Accessed October 2, 2017.

Continuous-Count Traffic Programs

LIZ STOLZ

STATE OF THE PRACTICE

Within the context of highway traffic monitoring, continuous counting is defined as collecting vehicle volume, vehicle class, and vehicle weight information for the nation's roadways continually with an often hourly or smaller time increment over a period of more than one week. Short-duration counting is typically performed for one to seven days at any given time and location and can include 15-min, hourly, or daily accumulations of traffic-counting data. Governmental agencies instrument roadways with technology capable of providing continuous-counting traffic data that are delivered to the FHWA on a monthly basis. The monthly traffic count data from the state DOTs are compiled and published in a monthly traffic volume trends report (1).

Traffic data supports capital investment programs, budgets, and effective design and maintenance programs. Reference guidance for continuous counting can be found in the AASHTO Guidelines for Traffic Data Programs (2). The AASHTO guide is intended for state and local transportation agencies and others involved in traffic data programs. Professional traffic monitoring personnel can use this document to establish traffic monitoring practices that reflect current practice and advances made in the past several years.

Although each state DOT collects continuous-count traffic data for their specific needs, there are several similarities across the nation's traffic monitoring programs. Every continuous-counting traffic monitoring program manager must be familiar with the various monitoring technologies available to count roadway traffic. The other critical aspect that traffic monitoring program managers must understand is data integration and usage once the count data are collected. All traffic monitoring programs utilize some type of software and store their data within a database. The traffic data management software can be as basic as a spreadsheet, or as complex as a sophisticated and customized software management product.

STATE OF THE ART

Traffic monitoring programs are conducted by in-house or contracted staff or both to install continuous traffic-counting equipment. State-of-the-art programs deploy a variety of technologies such as radar, in-pavement loop detection, and video detection systems. Differences across traffic monitoring technologies are described in the 2016 TMG (*3*), *Traffic Detector Handbook* (*4*), and *ITS Sensors and Architectures for Traffic Management and Connected Vehicles* (*5*). Many DOTs, such as the Florida DOT, dedicate a section of roadway for testing multiple continuous-counting traffic monitoring technologies. These test sections allow an agency to evaluate and compare the accuracies and types of data output by multiple types of technology.

State-of-the-art programs manage and test the use of continuous-counting equipment to identify temporal traffic patterns, which drive the factoring process applied to convert shortduration counts into AADT estimates. The continuous classification equipment is used to identify classification distributions and temporal traffic patterns by vehicle class. One challenge many traffic program managers face is where to place continuous-count devices so that they produce the factors needed for the short-duration count program at the desired level of accuracy.

EMERGING TRENDS OR DRIVERS OF CHANGE

In addition to program guidance documentation found in the *Guidelines for Traffic Data Programs* and the TMG, there are a number of emerging trends that continue to assist continuous-counting traffic monitoring programs advance. For example, transportation data users are continually asked to incorporate visualization into their data analyzes. TRB's peer-reviewed publication *Statistical Methods and Visualization* provides guidance on data analysis in general, including statistical method evaluations and comparisons and representations of data, such as line and bar charts (6). These practices also apply to continuous traffic-counting data. The TMG contains information concerning continuous and short-duration counting and methods for factoring. It also includes guidance for volume, speed, classification, weight, and per-vehicle data collection, and provides information on utilizing nontraditional sources such as operations and ITS data.

Collecting traffic data once and using the data for many uses and often many times is a trend that many data collection agencies, including the FHWA, have been supporting for many years. Several examples of using weigh-in-motion (WIM) data as inputs to create load spectra for site-specific axle loads needed for pavement management purposes are found in *Transportation Research Record: Journal of the Transportation Research Board, No. 2443, Vol. 2* (7). State DOT continuous-counting WIM data are also provided to the FHWA on an annual basis.

Furthermore, traffic data collection programs play a significant role in providing information to an agency's overall asset management system. Many reports describe the incorporation of data systems into the asset management function. An example is *Data Systems and Asset Management (8)*, where a number of references illustrate how critical collecting continuous traffic-counting data is to the overall agency's mission.

Another traffic data program driver of change is customer expectations in terms of timeliness of data availability (i.e., moving toward real time) and data quality.

GAPS IN PRACTICE OR KNOWLEDGE

Traffic monitoring program staffs continue to integrate multiple equipment and data sources into their programs. However, traffic monitoring program data quality requirements prevent some interagency departments from sharing traffic monitoring sites, installation, equipment, and data. The gap in knowledge and practice that many DOTs have yet to overcome causes data integration challenges because of the use of different technologies and differences in cultural and institutional coordination practices.

A specific example is integrating ITS data with traffic monitoring program data. Within DOT agencies, the traffic monitoring division is managed by a different group of staff and is often located in a different building than the ITS program division. Most issues with the ITS data result from the lack of complete data from ITS sites. On any given day, a small amount of data may be missing, but that missing data keeps DOTs from utilizing this nontraditional permanent source. This is the motivation for the FHWA development of a new AADT formula that, unlike

the AASHTO method, reduces bias and permits smaller than daily time increments in AADTs. The new AADT method is detailed in the TMG (3). The method allows many ITS locations to be converted into continuous-counting sites if data from each time increment for each day of the week are present for each month of the year. Many agencies have explored the idea of integrating traffic monitoring and ITS data, but very few have successfully integrated these datasets. Many agencies have not coordinated operations across the ITS and traffic monitoring divisions, such as collocating monitoring equipment, and agencies may not be aware of the equipment configurations, installations, and data management practices needed to successfully integrate ITS and traffic monitoring data. One successful example, as noted in the TMG, is the Virginia DOT which integrates ITS and traffic monitoring datasets and uses data collecting equipment and other field assets for two different operational and business purposes.

CURRENT AND PROPOSED NATIONAL RESEARCH AND INITIATIVES

There are many current and proposed national research initiatives related to collecting continuous-counting data that address the gaps in practice or knowledge discussed above. As mentioned in the Emerging Trends section, several agencies are exploring data visualization and integration of data with that from other internal and external partners. TRB's Highway Traffic Monitoring Committee created a Research Subcommittee in 2016 to emphasize the need for future research and to develop Research Needs Statements (RNS) and research proposals.

Lists of funded research studies pertinent to the Highway Traffic Monitoring Committee's mission were compiled by the Research Subcommittee and are found in the references below:

• Improving Motorcycle Detection and Count Data. Final Report: http://onlinepubs.trb .org /onlinepubs/nchrp/nchrp_rpt_760.pdf.

• Loop and Length-Based Vehicle Classification. There are many studies of this topic with the latest being a FHWA Pooled-Fund Program executed by the Minnesota DOT. Final Report: http://lrrb.org/media/reports/201233.pdf. Accessed Sep. 20, 2017.

• Assessment of Insourcing and Outsourcing: Practices for Traffic Monitoring Data Collection. https://www.fhwa.dot.gov/policyinformation/travel_monitoring/pubs/pl16024/.

Other research activities directly related to continuous counting include:

• FHWA Local AADT (in process). Contacts are Stuart Thompson or Steven Jessberger.

• FHWA U.S. Vehicle Inventory (in process). Contact is Daniel Jenkins.

• FHWA SBIR on Re-Identification of Heavy Vehicle Utilizing Inductive Signatures. Phase II (in process). Contact is Steven Jessberger.

• Quantitative understanding of data quality (precision and accuracy) associated with different AADT methods and the influence traffic monitoring duration and frequency on factoring portable counts to AADTs (9).

Traffic Data Collection Insourcing and Outsourcing Best Practices

At past meetings, members of the Highway Traffic Monitoring Committee expressed interest in gathering information about best practices within the traffic data community. State and local agency practitioners, industry contacts, and academicians were encouraged to participate in the annual committee meeting to provide input and feedback on the research needs topic area of documenting best practices for outsourcing traffic data. During the 2013 TRB Annual Highway Traffic Monitoring Committee Meeting, this topic was discussed and the FHWA decided to fund this research topic. A study was conducted in 2015 and published in April 2016 (*10*). The results appear in the form of RNS and a number of continuous-counting reference documents.

Other ongoing research topics such as visualizing traffic data continue to gain momentum and are looking to be funded in the future, including traffic signal systems traffic data collection and integration.

Traffic Signal Systems Traffic Counting

The traffic monitoring community has expressed interest in obtaining continuous counts from traffic signal systems. Several research projects have provided information related to leveraging existing traffic signal systems to obtain continuous counts, such as the study conducted by the Georgia DOT (11). Its conclusion was that in certain situations, such as in corridors, it could be advantageous to require the signal controllers to detect vehicles from the setback or system loops, but overall it was too cumbersome to try to apply on a statewide basis. Furthermore, to improve the usability of intersection signal detector data for traffic monitoring, the report recommends that for future installations and maintenance of existing detectors, detection zones be moved further upstream beyond the maximum queue length of a typical peak-hour queue and beyond the beginning of the turn lanes. Notwithstanding this effort, the intersection signal detector data do not usually provide the FHWA 13-class vehicle classification information. An exception to this finding occurs when inductive loop detector electronics modules such as the I-Loop Duo Card are used (5).

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Short-Duration Traffic Count Programs

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STATE OF THE PRACTICE

Short-duration count programs are concerned with the management aspects of noncontinuous data collection programs. Unlike CCSs that have high installation, operating, and maintenance costs, short-duration counts are significantly less expensive to conduct, providing the spatial, i.e., geographic, diversity and coverage needed to obtain volume, class, and weight information representative of vehicles using the transportation system. The primary objective is to obtain counts at a sufficient number of locations on a roadway, so that the traffic volume estimate available for a given highway segment accurately portrays the actual traffic volume on that segment. To develop AADT estimates, many agencies typically factor (i.e., multiply) the ADT of a short-duration count using one or multiple adjustment factors (e.g., seasonal, day of week, time of day, axle, and growth factors).

Highway agencies perform short-duration counts for a variety of purposes including meeting federal reporting requirements (e.g., HPMS), supplying information for individual projects (e.g., corridor studies, pavement design, maintenance, repair, rehabilitation, reconstruction, traffic control studies), developing lane closure policies, and providing broad knowledge of roadway use.

Short-duration count programs are typically divided into coverage count and special needs count subsets. The coverage count subset encompasses the roadway system on a periodic basis to meet both point-specific and area needs, including the HPMS reporting requirements. The special needs subset comprises additional counts necessary to meet specific needs of other users (1). Special needs counts can contribute to coverage requirements if properly collected, stored, and factored.

The location and frequency of short-duration counts is a function of each agency's policies, funding levels, geographic areas of responsibility, and needs. As used here, "duration," widely known as "term," can be a period of a few hours up to several days (e.g., 1 week). The ways in which agencies balance the benefits and costs of addressing their objectives against their limited traffic-counting budgets have led to different data collection programs nationwide. Some agencies consider a weeklong count conducted every 7 years with data recorded for every hour of each day to be adequate. Others consider a 48-h count every 3 years with only daily counts recorded to be adequate. The spacing between short-duration counts along a roadway is also subject to agency discretion.

Short-duration counts are collected with equipment that typically includes portable traffic recorders (PTRs) (or counters) and automatic traffic recorders (ATRs). PTRs are mobile traffic vehicle counters or classifiers easily moved to different locations. PTRs are not permanently installed in the infrastructure. The most commonly used PTRs are pneumatic tubes that are stretched across the monitored lanes (2). ATRs are data collection stations permanently installed at specific locations to record the distribution and variation of traffic flow by hour of day, day of week, and month of year. An ATR typically collects data continuously, but some agencies only operate them periodically to collect short-duration counts. In some cases, the sensors are permanently installed in the pavement along with a portable counting device, located in the

roadside cabinet, to collect the short-duration counts. Agencies sometimes refer to these count stations as portable.

Short-duration count stations may record different types of data depending on the type of sensor used. These data include number of axles, axle spacing, traffic volume, volume by vehicle classification, speed, bumper-to-bumper length, gap, and headway (3). The data may either be aggregated over a time period or on a per-vehicle basis. Table 1 presents the sensor technologies that are commonly used for short-duration counts.

STATE OF THE ART

Short-duration traffic monitoring technology has evolved over the past 20 years due to a combination of factors such as:

- Need for more timely and accurate information;
- Ability to share information (traffic counts, project needs, etc.) across agencies;
- Advancements in low-cost computing and communications technology;
- Limited resources devoted to the collection of short-duration data;

• Safety and performance issues caused during the installation and maintenance of intrusive sensors;

• High cost associated with providing traffic control or closing lanes during the installation and maintenance of intrusive sensors;

- Poor quality, short lifetime, and high maintenance cost of traffic equipment;
- New data reporting requirements; and
- Increased traffic volumes.

Many agencies have started to test and use nonintrusive sensors—i.e., those located above or to the side of the roadway—to obtain short-duration counts. These can be installed and maintained often without personnel having to enter the travel lane. Although side-mounted sensors have the advantages of easy installation, access, and maintenance, vehicles in lanes farthest from the sensor can be obscured by long and tall vehicles traveling in the lanes closer to the sensor (5).

In addition, data processing and QA/QC procedures have been automated to a large extent. In the past, QA/QC was primarily done manually by engineers, however, the majority of the most recent data processing software is provided by equipment manufacturers. Only a few agencies still use in-house or third-party software for QC. The equipment software typically provides several tools that allow users to create graphs and traffic reports, calibrate equipment and traffic parameters, edit information about the study, analyze data, set up groups of automated tests to check analysis results for certain conditions, export results in commonly used formats (e.g., Excel), e-mail results, customize settings for time formatting and units of measurement, and so forth.

Software compatibility across manufacturers has started to expand by increasing reporting flexibility. Manufacturers have also started to integrate geographic information systems (GIS) into their software and hardware by improving data management practices. Some

Technology	Number of Sensors Needed for Speed Data Collection	Vehicle Class Data Collected	Number of Lanes of Data Collected by Each Sensor	Environmental Issues and Concerns	Other Issues and Concerns	
Road tubes, traditional	2 (1 lane only)	Axle based (FHWA 13+)	1 per pair of sensors (only lanes adjacent to shoulders)Not suited to snowy conditions		Accuracy limitations under very heavy traffic volumes or stop-and-go conditions	
Road tubes, multilane design	2 per lane	Axle based (FHWA 13+)	1 per pair of sensors	Not suited to snowy conditions	Accuracy limitations under very heavy traffic volumes or stop-and-go conditions	
Tape switches	2 per lane	Axle based (FHWA 13+)	1 per pair of sensors	Placement difficulties in wet conditions	Need protection of lead wires if placed on lanes not adjacent to shoulders	
Magnetometers	2 per lane	Length based (for most sensor designs)	1 per pair of sensors (2 sensors per lane if speed or vehicle length is needed)	Most magnetic technology sensors require a short lane closure for sensor placement	Some sensors are placed in the pavement, others on the pavement, and others under the pavement	
Video detection systems	1 camera	Length based	Multiple	Possible performance degradation in snow, fog, smoke, dust storms, sun glint, or glare; night operation may require street lights; other effects: shadows (false or missed calls), reflections from wet pavement (false calls), vehicle occlusion in distant lanes when camera is side mounted, projection of tall vehicles into adjacent lanes (false calls) and headlights past the stop bar (dropped calls)	Camera is mounted on an extensible pole on a trailer pulled to the site; generally slow to set up	

TABLE 1 Sensors for Collection of Short-DurationCounts of Motorized Vehicles (4, 5)

Continued on next page.

Technology	Number of Sensors Needed for Speed Data Collection	Vehicle Class Data Collected	Number of Lanes of Data Collected by Each Sensor	Environmental Issues and Concerns	Other Issues and Concerns
Piezo sensors	2 per lane	Axle-based (FHWA 13+)	1 per pair of sensors	Very cold weather may affect performance	Need protection of lead wires if placed on lanes not adjacent to shoulders
Lidar	1	Axle-based (FHWA 13+)	Usually 1 (multiple lanes with some models)	Fog and heavy snow can degrade performance and large crown in road will block beams; occlusion	No in-road installation required
Microwave presence- detecting radar	1 per direction (side- mounted), 1 per lane (overhead) although some overhead models monitor multiple lanes	Length based	Multiple	Side-mounted radars may have occlusion issues in lanes furthest from sensor with heavy or stop- and-go traffic in a multiple lane scenario	Sensor is mounted on an extensible pole on a trailer pulled to the site
Acoustic	1 sensor	None	Multiple	Background sounds may interfere	Sensor is mounted on an extensible pole on a trailer; sensor mounting height is a function of number of lanes monitored and distance from nearest lane

TABLE 1 (continued) Sensors for Collection of Short-DurationCounts of Motorized Vehicles (4, 5)

equipment can be accessed remotely (e.g., over the Internet) allowing users to monitor and transfer real-time data by minimizing the need to manually extract the data from the equipment.

Other advancements in traffic count technology support an overall increase in the maximum duration of a short-duration count to as long a period as several weeks. The main reasons are increased data storage capacity, improved battery life, and increased exploitation of solar panels.

Overall, short-duration count programs become more efficient if various data collection efforts are coordinated so that one counting program meets multiple needs. Examples of coordination include: sharing data collection activities, equipment, and schedules with local agencies; using technologies that include access to software encouraging integration, dissemination, conversion of schedules and data collected from state and local agencies; and establishing data governance committees with members from national, state, and local agencies. State DOT leaders in sharing data across state and local agencies can be found across the country, including a few highlighted states such as New York State DOT, Colorado DOT, and Ohio DOT.

GAPS IN PRACTICE OR KNOWLEDGE

This section presents issues, challenges, undiscovered areas, and other gaps pertaining to the collection and analysis of short-duration traffic data.

Assignment of Short-Duration Counts to Seasonal Adjustment Factor Groupings

The *Traffic Monitoring Guide* (1) recommends the use of cluster analysis in conjunction with traditional methods for the creation of factor groups. However, there is lack of specified and definable characteristics for assigning short-duration counts to groups \hat{u} seasonal adjustment factors (SAF). The majority of research studies that dealt with the improvement of AADT accuracy from short-duration counts focus mainly on lowering the errors associated with the creation of adjustment factor groupings. Prior research has shown that the assignment step is the most critical element in the AADT estimation process. Potential ineffective allocation of short-term counts to SAF groups may triple the prediction error (6). In the absence of relevant guidelines and recommendations, further research is needed to fill this gap (7).

Data Collection on Non-Federal-Aid System Roads

A major aspect of the Highway Safety Improvement Program rule-making is the requirement that states must collect and use a subset of Model Inventory of Roadway Elements (MIRE) fundamental data elements (FDE) for all public roadways, including NFAS roads, which are typically rural minor collectors and both rural and urban local roads. States were supposed to define anticipated improvements to collect MIRE FDE in their traffic records strategic plan by July 1, 2017, and by September 30, 2026 data must be accessible for all public roads. Traffic volumes (AADT) are already collected under the HPMS for federal aid roadway segments and ramps. States are concerned about their ability to collect data on local roads and also to maintain the data. New ideas for how to affordably collect or estimate this data will be needed.

Lack of Interagency Coordination

Many state agencies do not have any agreements with local agencies to coordinate data collection activities. Lack of coordination among agencies often leads to duplication of efforts and an inability to share resources toward making traffic-counting programs more efficient.

Impact of Construction Activity and Incidents

Construction and incidents may have a significant impact on alternative routes that carry the rerouted traffic, resulting in increased traffic volumes captured by the traffic equipment. Likewise, the route that traffic is being diverted from will experience decreased traffic volumes. Unless determined and clearly specified by data collection personnel, the final data user has no way of knowing the underlying reasons for abnormality in the data.

Data Quality and Assurance

The ability to efficiently process and assess the quality of data from different data collection equipment is a challenging task for many agencies. Not all traffic equipment has its own data processing software and not all vendors produce equipment of the same quality. Some equipment has been heavily tested and operates more reliably than other. Different vendor's equipment can produce different results for any given detection technology because the electronics and the vendor's software may perform differently.

Accuracy of Classification Data Collected in Saturated Traffic Conditions

High traffic volumes or congestion may not be accurately captured by vehicle classification equipment. For example, under saturated traffic conditions, traffic detectors may fail to determine whether four counted axles represent two cars or one truck. Further, traffic detectors that work on vehicle presence detection often produce erroneous data under stop-and-go traffic conditions (δ).

Securing Road Tubes on the Pavement

Inability to properly secure road tubes on the pavement surface throughout the duration of a count affects the amount and quality of data collected. This issue is more profound on routes with significant truck traffic and high-volume roads.

Equipment Failures

Equipment malfunctions, communication problems, and other technical failures affect the amount and quality of data collected. Some equipment failures are caused by external factors such as inclement weather conditions, vandalism, utility operations, pavement repair and maintenance.

Safety of Traffic Personnel

Safety of staff that installs or maintains short-duration traffic equipment is a major concern, particularly on high-volume routes. The need to safeguard data collection staff without having to apply traffic control is the main reason that many efforts have focused on advancing nonintrusive detection technologies.

In addition, several documents—such as FHWA's *Traffic Detector Handbook* (3rd Edition) (9), A Summary of Vehicle Detection and Surveillance Technologies Used in Intelligent Transportation Systems (10), Sensor Technologies and Data Requirements for ITS (11), and ITS Sensors and Architectures for Traffic Management and Connected Vehicles (5)—provide strengths and limitations of various sensor technologies and applications.

CURRENT AND PROPOSED NATIONAL RESEARCH AND INITIATIVES

This section provides ongoing and anticipated projects, as well as proposed research topics that aim to address undiscovered areas and support trends with innovating technologies:

• FHWA Office of Safety: *Collection and Estimation of AADT on Lower-Volume Roads* (active);

• FHWA Office of Highway Policy Information: *Improved VMT Estimation on Non-Federal Aid System Roadways* (anticipated);

• FHWA Office of Safety: *Collection of MIRE FDE on Non-State-Owned Public Roads* (anticipated);

• FHWA Office of Safety: Roadway Data Extraction Technical Program (anticipated);

• Oregon DOT: A Method to Estimate Annual Average Daily Traffic for Minor Facilities for MAP-21 Reporting and Statewide Safety Analysis (active); and

• Louisiana Department of Transportation and Development: Evaluating Cell Phone Data for AADT Estimation (active).

There is a need to validate the performance of various statistical and nonstatistical methods (e.g., discriminant analysis, support vector regression, decision trees) that have been used in the past to assign short-duration counts to factor groups. The validation needs to be based on Travel Monitoring Analysis System and HPMS data from various states that exhibit different traffic patterns, roadway and socioeconomic characteristics. The study needs to determine the most-effective attributes that can be used to develop assignment models. Examples of such attributes are hourly traffic volumes, hourly adjustment factors, ADT, ADTT, time of day, day of week, month, season, roadway functional class, spatial proximity of short-duration counts to factor groups, and so forth.

Another potential research topic is detection of short-duration data abnormalities and unusual trends caused by construction activity, incidents, or other planned and unplanned events that have not been reported by data collection personnel. The research would validate the performance of various detection methods and approaches that may include, but will not be limited to, network analysis, data integration with other crash records and ITS systems, comparison of current versus historical traffic data, and so forth. The research would identify the best performing detection method(s) and for each method will describe the main elements needed for successful implementation such as data inputs, data flow process, software and hardware requirements, necessary actions, applicability, limitations, anticipated accuracy, level of effort, and implementation cost.

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Weigh-in-Motion

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STATE OF THE PRACTICE

Description of Weigh-in-Motion

WIM is a traffic monitoring technology designed to capture and record axle weights and gross vehicle weights, as vehicles drive over measurement sensors at or near posted highway speeds. In addition to weight, other vehicle characteristics are being collected such as axle spacing, bumper-to-bumper length, vehicle classification, vehicle count, and speed. While a number of technologies can measure length and axle spacing, measurement of weight has been much more challenging for the industry. Measurement of weight while a vehicle is in motion is the primary focus of this section of the circular.

WIM systems that are capable of reporting the weight of vehicles traveling at normal highway speeds make the weighing process more efficient and less disruptive as compared to pull-out permanent or portable static weigh stations that require the vehicle to be stopped. WIM systems typically use in-road or under-the-bridge sensors to measure the dynamic forces applied by the tires as a vehicle passes over the sensor. The sensor output is converted to an estimate of the static weight of the vehicle.

Several technologies exist to capture or predict the applied forces, including in-pavement sensors that use strain or hydraulic pressure gauges, in-pavement sensors that use piezoelectric properties of different materials, and sensors that use structural response of bridge structural members. In-pavement sensors are the most widely used technology in the United States as compared to bridge sensors. Sensor costs align with data quality measures such as accuracy, repeatability, and reliability. When selecting a sensor, the data quality sought should align with the needs of the applications.

WIM Data Applications

WIM data address the need to accurately and reliably characterize trucks and loading for a wide range of applications. WIM systems produce more accurate vehicle classification data than traditional vehicle classification technology due to the use of axle weight data. Traditionally state highway agencies in the United States have primarily collected WIM data for the purpose of submittal to the FHWA. Many highway planning and engineering applications have traditionally relied upon assumed axle weights and estimated percent of trucks in the vehicle mix. Researchers have relied upon WIM data for many essential applications including advancements in bridge and pavement design methods. WIM data are used by leading practitioners for highway planning, pavement and bridge design, pavement and bridge management, load rating, freight planning and analyzes, safety, legislative and regulatory studies, and motor vehicle enforcement, where heavy truck axle load data are utilized to plan enforcement activities and to identify specific vehicles that violate federal and state size and weight laws during real-time onsite monitoring. Additionally, WIM data are used to support network analyzes to improve operational

efficiencies and enable data-driven transportation asset management decisions and the moreefficient use of funding.

WIM System Components

The major components of a WIM system include the following:

1. Sensors embedded in the roadway surface, or placed on the surface, or on or under bridge decks to detect, weigh, and classify vehicles;

2. Electronics to control the WIM system collection, processing and storage of sensor measurements;

3. WIM infrastructure, including conduit, cabinet, and junction boxes;

4. Support devices, such as alternating current or solar power equipment to power the WIM electronics, and communication devices to transmit the collected data to a remote server;

5. Firmware installed in the WIM electronics to process sensor measurements and analyze, format, and temporarily store collected data; and

6. Pavement for in-pavement systems meeting smoothness requirements for 300 ft total, 250 ft prior to, and 50 ft after the WIM system (1); bridge structure for bridge WIM systems (single-span bridges or culverts with specific criteria regarding type, length, and skew).

An example of in-pavement WIM system design is shown in Figure 1. Variations in system layouts include inductive loop, WIM sensor, WIM sensor, and inductive loop; some systems use staggered half-lane sensors. The appropriate distance between sensors typically range between 12 to 16 ft and should be calculated based on the operating speeds of the site and expected vehicle dynamics (2).



FIGURE 1 In-pavement WIM system design for full-lane piezo-quartz WIM sensors.

WIM Standards and Performance Requirements

Several WIM standards are available for use. In the United States, the American Society for Testing and Materials (ASTM) *Standard Specification for Highway Weigh-In-Motion Systems with User Requirements and Test Methods* (3) is the primary accepted WIM standard. This document categorizes sensors by their performance characteristics and intended applications. Sensor accuracy is defined by the error tolerances, where errors are computed as percent difference from the static weight. The 95% compliance defined in ASTM E1318-09 specifies the minimum percentage of measurements that should be within the specified tolerances to satisfy the performance requirements.

Enhanced performance requirements were developed by the FHWA LTPP in an effort to collect research-quality WIM data (1). LTPP tolerances are the same as the ASTM E1318-09, but instead of 95% compliance, it uses statistically computed 95% confidence interval to verify if the tolerances listed in Table 1 have been satisfied. The confidence interval is computed using the errors in individual weight and spacing measurements [gross vehicle weight (GVW), axle weight, axle group weight, axle spacing, and wheelbase expressed as percent difference from the static weight and spacing measurements]. The mean error (measurement bias) is also computed and added to the left and right boundary of the 95% confidence interval to obtain the range of errors that is then tested against the ASTM tolerances. The LTPP performance requirements include provisions for testing over a 30-degree temperature range and three speed bins.

Other recognized WIM standards are the Cooperation in Science and Technology (COST) 323 Standard and NMi International WIM Standard (2016) that were created in Europe (4, 5).

Best Practices

In the United States, WIM data collection is primarily performed by the state transportation agency. Best practices for WIM data collection include the following:

• Judicious site selection that follows ASTM E1318-09 requirements or smoothness

requirements specified in the AASHTO M331-13 Standard Specification, Smoothness of Pavement in WIM systems (6), or Optimum WIM Locator Software (OWL) (7, 8);

• In-road sensors permanently installed in smooth structurally sound pavements;

• Use of WIM sensors that are not sensitive to changes in the environment or changes in pavement stiffness;

	Tolerance for 95% Compliance [®]					
				Туре IV		
Function	Type 1	Type II	Type III	Value \geq lb (kg) ^b	±lb (kg)	
Wheel load	±25%		±20%	5,000 (2,300)	300 (100)	
Axle load	±20%	±30%	±15%	12,000 (5,400)	500 (200)	
Axle-group load	±15%	±20%	±10%	25,000 (11.30)	1,200 (500)	
Gross vehicle weight	±10%	±15%	±6%	60,000 (27,200)	2,500 (1,100)	
Speed	$\pm 1 \text{ mph} (2 \text{ km/h})$					
Axle spacing and wheelbase	± 0.6 ft (0.15 m)					

 TABLE 1 Functional Performance Requirements for WIM Systems (3)

^a 95% of the respective data items produced by the WIM system must be within tolerance.

^b Lower values are not usually a concern in enforcement.
• Continuous collection of per-vehicle data that enables monitoring data quality, fast identification of data quality issues, and evaluation of seasonal variations in truck weights;

• Routine data quality checks in the office, typically using weights of Class 9 vehicles (GVW, single and tandem axle weights, and tandem axle spacing);

• Routine field validation and calibration using heavy trucks of known weight to establish ground truth. This is documented in NCHRP Synthesis 386 and LTPP Field Operations Guide for Specific Pavement Study (SPS) WIM Sites (1, 9);

• Routine field observations, at the time of calibration or independently, to visually check reasonableness of the system output for capturing the range of vehicle types in the traffic stream (vehicle classification checks);

• Routine preventive maintenance per WIM sensor manufacturers' recommended schedule; and

• Proper documentation of installation, maintenance, calibration, repair, and replacement activities.

Challenges

In general, WIM sensor measurement accuracy is dependent on three factors: the geometry and smoothness of the roadway leading up to and around the sensors, the vehicle's dynamic response to the pavement, and the accuracy of the sensor itself. Other factors that contribute to the reduced accuracy or usability of the WIM data arise from the following activities:

• Vehicles changing lanes near the sensor location, accelerating or braking over sensors, and shifting cargo;

• Lack of proper maintenance and calibration that minimize data quality degradation;

• Lack of field validations or calibration by many states because of the high expense of using heavy trucks of known weight for calibration;

• Lane closures needed for routine maintenance of bending plate and load cell systems, adding to the expense and reduced frequency of periodic maintenance;

• Differences in the sensitivity of WIM sensors to variations in temperature and to pavement structural response under load; and

• Difficulties in sharing WIM data collected by different vendors' systems because each WIM vendor uses its own raw data format, although the FHWA W-card or per-vehicle format are considered the common format for WIM data sharing in the United States (7).

STATE OF THE ART

This section highlights recently completed research studies that are ready for implementation by highway agencies and utilization or further advancement by academic and research institutions.

Advances in WIM Sensor Technology

WIM Systems with Add-On Capabilities

Recent advances include WIM systems with add-on capabilities, such as:

• Systems that include images of the vehicles linked to the measurement data for visual verification of vehicle characteristics;

• Systems that include license plate and vehicle registration information readers;

• Systems linked to variable messaging signs allowing rerouting of vehicles for inspection or infrastructure protection;

• Sensors that measure traffic wander (i.e., drifting within the lane); and

• Advancements in data storage, power requirements, and data communications have enabled the deployment at more remote locations, near real-time data monitoring, and retaining of all vehicle records (versus a filtered set in the past, due to storage capabilities).

Nonintrusive Bridge WIM Sensors

Other technological advances are related to the use of bridge WIM systems that typically provide GVW rather than axle weights. They calculate truck weight data from instrumentation mounted under a bridge that respond to bridge structural movements. The systems are generally considered nonintrusive, as often there is usually nothing mounted in the pavement. The presence of multiple vehicles on the bridge can present a challenge. Applicability of the system is dependent upon the bridge characteristics. The layout and success of the technique is bridge-specific. This technology provides the potential for a portable WIM system application. Internationally, large culverts have also been instrumented instead of bridges. In the United States, several installations (e.g., New Jersey and Alabama) have collected data for evaluation of weights and for analyzes of bridge health and response to loadings.

Vehicle Reidentification for WIM Calibration

Vehicle signatures obtained from inductive loops can be used to re-identify vehicles at downstream locations based on an assumed travel time window. State-of-the-art inductive loop cards that scan the vehicles passing over the loops at a sampling rate up to 5000 Hz can be installed at WIM stations to re-identify the vehicle (10). Comparison of the WIM measurements for the same vehicle at two or more locations facilitates a quick comparison of sensor performance to detect decreased accuracy sooner. In addition, use of WIM systems that include license plate and vehicle registration information readers could be used for the same re-identification purpose.

LTPP WIM-Based Vehicle Classification Rules

The LTPP program developed and deployed a set of rules that classify vehicles using WIM system vehicle axle spacing and weight data. These vehicle classification rules are applied across the country at the test sites included in the LTPP SPS Traffic Data Collection Pooled-Fund Study TPF-5(004). WIM data collected based on these rules were used by LTPP to develop axle loading default values for the AASHTO *Mechanistic–Empirical Pavement Design Guide* (MEPDG) (11).

Advances in WIM Data Usage

WIM Data Use for Freight Planning

The freight community is seeking WIM data to improve characterization and modeling of truck movement and demands. These data can be coupled with other data sources to provide robust analyzes and better understanding and decisions to enable improved movement of goods. The pooled-fund study TPF-5(280) produced web-based traffic data visualization and analysis tools that offer data quality review and control functions, data visualization capabilities and analysis, and data output controls to meet pavement design, freight analysis, and truck weight and load trend analysis. The accompanying report contains information on how state agencies can use the tool to better understand the "cargo" component of WIM data (*12*).

WIM and Freight Data Use for MEPDG

Georgia, Michigan, and Pennsylvania DOTs completed research studies to develop methodology for traffic loading characterization applicable to all the roads in the states based on available WIM installations, truck volume, road inventory, and freight road network information (*13–15*). The results were applied to develop traffic loading defaults and methods for selecting loading defaults for pavement design using the MEPDG method. Georgia DOT and Pennsylvania DOT utilized the results of the FHWA–LTPP TPF5(004) study and the LTPP–Pavement Loading User Guide (PLUG) tool [16] to develop or test the local axle loading defaults.

LTPP-PLUG

The FHWA LTPP program developed PLUG and the accompanying LTPP–PLUG software to assist agencies in acquiring axle loading inputs and defaults based on WIM data (16). LTPP–PLUG assists in selecting the default values for MEPDG and in developing input files for AASHTOWare Pavement Mechanistic–Empirical (ME) Design software. The defaults can be used for pavement sites where WIM data are limited or do not exist. Using LTPP–PLUG, agencies can compare their own data to the LTPP axle loading defaults and decide which is better to use. Users also have the option of being guided through the selection process. Also built into the LTPP–PLUG software is a mechanism for grouping axle loading distributions supplied independently by state highway agencies and then computing state-specific axle loading defaults.

Effect of WIM Accuracy on Pavement Design (LTPP Findings)

LTPP-conducted sensitivity studies of the effect of WIM precision and bias on pavement design outcomes using the MEPDG method. The research findings recommend specifying ASTM 1318-09 Type 1 WIM systems as the means to collect WIM data for pavement design. Furthermore, the measurement bias should be kept as close to zero as possible through regular calibration. The FHWA–LTPP TPF5(004) study shows that bias under 2% could be consistently achieved through regular WIM calibration for piezo-quartz, bending plate, and load cell WIM sensors. The results of sensitivity analyzes also found that the same increase in error due to bias is far more critical than the error increase due to more poor precision. Bias over 5% should be avoided in WIM data collected for pavement design purposes (*17*).

LTPP Pavement Loading Defaults Based on Research-Quality WIM Data

The new MEPDG requires detailed axle loading information in the form of normalized axle load spectra, number of axles per truck class and axle group types, and axle spacing inputs as part of traffic loading inputs. These data are obtained from WIM sites. Research-quality WIM data from the LTPP SPS produced a method to compute the default axle loading values needed for MEPDG applications. The research report describes WIM data selection criteria that include data reliability assessment, presents findings from the LTPP SPS Traffic Data Collection Pooled-Fund Study WIM data review, describes the new traffic loading defaults and the methods to generate them, and gives recommendations for their use (*17*).

Advances in WIM Program Management and Operations

Pavement Smoothness and WIM Smoothness Index

Pavement smoothness is critical to achieving acceptable system performance and considered to be part of the WIM system design, installation, and maintenance process. Recognizing the importance of pavement smoothness for WIM applications, FHWA–LTPP conducted the research investigation that led to the development of the AASHTO M331-13 Standard Specification, Smoothness of Pavement in WIM systems. This specification contains requirements and procedures for evaluating pavement smoothness at candidate WIM sensor installation locations. The pavement smoothness analysis is accomplished using the profile data (collected with a high-speed profiler) and the Optimal WIM Locator, developed as part of the FHWA–LTPP ProVal data analysis software (7, 8, 18). The WIM smoothness index values computed using OWL can be used to identify the optimal placement of sensor locations based on pavement profile and vehicle dynamics (U.S. Class 9 vehicles) to maximize WIM performance. Additional field evaluation of the values provided by the software is being investigated as part of the LTPP WIM Field Validation and Calibration Studies.

LTPP Method for WIM Validation and Calibration

The FHWA–LTPP program developed a WIM validation and calibration method to assure research-quality WIM data collection. Using the LTPP procedure, measurement accuracy is determined by computing the 95% confidence interval of measurement errors and comparing the interval with the tolerances provided in Table 1. To meet the LTPP performance requirements for a given sensor type, the sums of the upper and lower bounds of the confidence interval with the mean measurement error should be within the tolerance range specified in Table 1. In addition, any systematic bias (mean measurement error) should be kept under 2%. The LTPP method for WIM validation and calibration also incorporates the requirements for temperature, speed, and pavement smoothness. Several states are testing or implementing the LTPP method or some variation of the method in their WIM validation and calibration (Virginia, Maryland, Wisconsin, and Arizona).

WIM Data Integration

Efforts are under way to develop business processes at state highway agencies allowing WIM data sharing between multiple users (planning, design, freight, safety, clean air). Examples include:

• Maryland and Arizona share WIM data between law enforcement and pavement design offices.

• New Mexico and Arizona integrate WIM data in pavement warranties and related disputes.

• Montana and Arizona use WIM data to assess roadway network needs and loadings for many applications.

• Many states are developing enterprise data plans that will assist in further integration of WIM data in vital DOT functions, including asset management, design, environmental studies, planning, research, safety, and weight enforcement.

WIM Operation Management Tools

Arizona DOT has developed a suite of WIM program management and operation tools to aid in activities such as WIM site selection, WIM site design, QA of WIM installation, WIM maintenance, WIM calibration, WIM data quality review, and tracking the history of the activities performed at each WIM site. These tools are based on the findings from the survey of the best WIM practices in selected state highway agencies, in-depth analysis of the procedures developed and implemented by the FHWA–LTPP TPF 5(004) study, and the requirements set forth in ASTM E1318-09.

Use of WIM as sorters at weigh station facilities has advanced the ability to collect data and to validate system performance. This was documented in the Virginia Tech study (19). A tentative code for the use of WIM for screening and sorter applications was developed and is included in the NIST (National Institute of Standards and Technology) *Handbook 44* (20).

EMERGING TRENDS OR DRIVERS OF CHANGE

The recognition of the value of WIM data continues to grow in the transportation field. We live in the world of data analytics, data mining and data visualization, and instant data access from any location. These historical changes will have an effect on how WIM data are collected and exploited.

Historically, when site-specific traffic loading data were unavailable, assumptions were made about the load magnitudes and load distributions. Now, it is recognized that many of these assumptions, still in use today, are not accurate or not applicable. Use of actual WIM data provides the specificity needed to optimize highway and bridge planning and design decisions.

In the United States, the ongoing implementation of the data-driven performance measures in transportation asset management is creating a renewed interest in WIM data and serves as a driver of change. The management initiatives that will be improved with the use of traffic loading and vehicle classification data collected by WIM include the following:

• Pavement design and management;

- Bridge design, management, and load rating;
- Commercial vehicle operations (enforcement);
- Safety and systems analyzes;
- Freight planning and operations;
- Commerce; and
- Air quality and noise quality analyses.

The paradigm shift in U.S. pavement design practice from the empirical to ME methods serves as a driver for improvements in WIM programs within state highway agencies as they calibrate the MEPDG method to their traffic loading environment. That has driven interest in better defining WIM data coverage requirements for measurements that enable agencies to acquire the data they need without over or under representing the network, and created a higher emphasis on WIM data quality.

Effectiveness and sustainability of the WIM programs ("do more with less") could be further improved by the following:

- Use of contractors with specialized WIM knowledge;
- Utilization of performance-based WIM data collection contracts;

• Development and preservation of the institutional knowledge through development of operation manuals, guides, and instructional and training materials;

• Improved efficiency of WIM operations by exploiting robust tools based on current standards and best practices;

• Improved ability to collect and share data across institutional departments;

• Improved definition of coverage requirements (a minimum number of locations to meet the greatest number of needs); and

• High-level management understanding of the need and support for WIM programs.

GAPS IN PRACTICE OR KNOWLEDGE

Gaps that exist in current state of WIM practice include the following.

• In the United States, many state highway agencies collect WIM data for submittal to FHWA. However, there is limited application of these data for improvement of other functions at the state level, such as pavement and bridge design, load rating, freight studies, congestion, safety analyzes, and agency-level transportation management decisions.

• New design methods, such as MEPDG (13, 21) and new bridge design methods provide fresh opportunities to use site-specific WIM data. However, many states are slow to take advantage of the available WIM data or lack the funding needed to establish modern or expand existing WIM programs. The result is the application of default data in design and uncertainty in the magnitude of over or under design stemming from variability in traffic data estimates.

• Despite considerable interest, Bridge WIM (BWIM) capabilities are not being fully utilized or pursued in the United States. Further initiatives are needed to advance BWIM successfully beyond research and limited applications.

• WIM data collection requires considerable technical skills and knowledge. Advanced awareness and understanding of WIM systems and WIM system performance are needed to evaluate data quality, identify performance issues, and troubleshoot sources of error. There is a need for robust tools to assist WIM personnel in the technically challenging tasks.

• Despite being identified as priority technology by AASHTO over a decade ago, few agencies have allocated support to build and sustain effective WIM programs. Sufficient management support and priority are necessary to obtain the needed staffing, skills, and resources to make WIM a standard production tool.

• Vehicle weights and dimensions are changing. Hence, awareness of current and potential future alterations to the fleet are important, as is the awareness of if and how those changes are adequately captured in the WIM data records.

• Linking and sharing WIM data with commercial vehicle operations is currently lacking, including access for WIM data analysts to information regarding vehicles with special permits. This access is needed to assess validity of WIM data or retrieve truck transponder data.

• Limited availability of automated programs to check data quality and reduce the dependence on staffing and institutional knowledge.

• Lack of documented institutional knowledge that could be used for training of new personnel.

• Limited data sharing between collectors and users (including saving data from enforcement in-line sorter systems for other applications such as design and management of infrastructure).

• Data quality degrades significantly without proper maintenance and calibration. However, regular calibration and validation using heavy trucks of known weight is cost prohibitive to some agencies. In practice, many states do not perform field validations due to high expense.

CURRENT RESEARCH INITIATIVES

Emerging WIM Sensor Technology

Nano Concrete WIM Sensor Technology

The Hawaii DOT conducted research on the installation of Oceanit's nano concrete–based WIM sensors and conducted field testing as part of FHWA's Highway's for Life Program in 2016. This system adds Oceanit's proprietary nanomaterial admixture to concrete to function as a sensor that detects the presence and weight of vehicles. Because it is composed of concrete material, it can be installed as a pavement or bridge surface. Initial prototypes were developed and deployed at a weigh station in Honolulu. The prototype demonstrated the ability to measure axle loads from five-axle trailers in motion through the weigh station. Additional pilot studies are proposed for deployment on a state highway.

Strain Gauge Strip Sensor

The Oregon DOT and its Motor Carrier Transportation Division installed a strain gauge strip technology (by Intercomp) in Lagrande, Oregon, for evaluation. This technology was sought as a

lower-maintenance, lower-cost alternative to full-scale load cell technology. Based on passing acceptance tests and meeting performance requirements, Oregon has incorporated this technology at all WIM sites statewide.

Bridge WIM Pilot Implementations

BWIM continues to be used on a limited scale. Routinely deployed internationally, a commercial product (SiWIM from Cestel) in Europe was installed at three locations in the United States (Alabama, New Jersey, and Mississippi). Bridge instrumentation for the calculations of loads from bridge responses were deployed in Canada, Connecticut, and Illinois.

Advances in WIM Data Usage

WIM and Freight Data Use for MEPDG

Michigan DOT is conducting follow-up research to develop an enhanced methodology for traffic loading characterization for U.S. roads based on available WIM installations, road inventory, and freight data. The results will be used to develop improved traffic loading defaults and a robust procedure of default selection for pavement design using MEPDG method.

LTPP WIM Data Use for Pavement Research and MEPDG Applications

More than 20 years of WIM data have been collected and stored in the FHWA–LTPP research database from over 800 WIM sites located in 50 states and nine Canadian provinces. These data were collected by the state highway agencies and LTPP contractors using evolving WIM technology and were not always accompanied by the data accuracy information or equipment calibration records. The LTPP program is conducting an investigation to rate WIM data usability for pavement applications based on data quality, quantity, and data reasonableness with the goal to increase WIM data usage and improve confidence in WIM data by LTPP users. To further facilitate use of WIM data available through LTPP program, LTPP is developing analysis-ready traffic parameters for all LTPP sites and traffic inputs that could be used as a direct input in the AASHTOWare Pavement ME Design software and a Guide to LTPP Traffic Data.

Research in WIM Program Management and Operations

WIM Sensor Testing Facilities

Currently, at least two state highway agencies have active WIM testing facilities. Florida DOT has a unique WIM testing facility that provides means for side-by-side comparison of the performance of different WIM sensors, different WIM controllers, power and communication devices, and different installation practices. Data collected at this facility are instrumental in the evaluation of advantages and limitations associated with WIM equipment cost, accuracy, and efficiency of installation practices. This is an ongoing research effort.

Minnesota maintains the MnROAD testing facility that includes WIM testing (22). The long-term goal of this research is to evaluate the change in performance of the sensors and system over time, and the life-cycle cost of the different systems. Currently, three different test

sensor configurations are being tested: (1) Kistler sensors with IRD controller, (2) Intercomp sensors and Intercomp controller, and (3) Kistler sensors and Kistler controller. Initial study results were scheduled for publication in summer 2017. In the future, Minnesota DOT personnel will generate an annual report updating the performance of the systems.

Visualization Tools for Innovative WIM Data Quality Control

A data visualization analysis tool assures quality traffic data for transportation program and project development. The pooled-fund TPF-5(280) tool meets freight transportation needs, infrastructure (pavement and bridge) preservation needs, and weight enforcement needs by incorporating data QC functions and data visualization capabilities (*12*). It is a user-friendly, web-based application that processes truck WIM and other traffic characterization data to generate quality data summaries needed for pavement design inputs, freight analysis, truck weight load trend analysis, bridge load trend analysis, and other applications.

Vehicle volume, classification, WIM, and speed traffic data can be visualized with the tool. It accommodates traffic data needs for the TMG data formats, HPMS traffic data attributes, and global traffic data loading formats. The resulting product offers: (1) data quality review and control functions; (2) GIS data visualization capabilities and analysis; and (3) GIS data output controls to meet pavement design, freight analysis, and truck weight and load trend analysis, bridge load trend analysis, and related truck travel data analysis.

The project investigated proven technologies and systems, e.g., Travel Monitoring Analysis System (TMAS), Vehicle Travel Information System Environmental Systems Research Institute Mapping, HPMS, Google map, and SAS (originally Statistical Analysis System), to design and develop specific requirements that process and generate quantitative analytical reports using easily assessable visualization output tools.

FHWA WIM Pocket Guide

FHWA is conducting research to develop a WIM Pocket Guide based on the best practices in WIM programs implemented by different state highway agencies. The guide will include practical guidelines for WIM sensor selection, WIM site design, installation, maintenance, calibration, and data collection and instructional videos for WIM sensor installations. Guide completion is planned for spring 2018.

FUTURE NATIONAL RESEARCH NEEDS

Accuracy Improvement Through Multisensor WIM

Research indicates that multisensor WIM can improve the accuracy of WIM (*3*). However, further research is needed to determine the realistic accuracy levels that could be achieved under different field conditions with various sensor types. The cost effectiveness of multisensor WIM systems needs to be evaluated from the cost–quality relationship point of view.

WIM Sensor Calibration Using Connected Vehicles

Exploratory research is necessary in the area of road infrastructure or WIM controller-to-vehicle connection to explore the possibility of communication between a WIM controller and onboard vehicle sensors or onboard WIM communication device to facilitate remote calibration. This approach has the potential to eliminate the requirement for a WIM technician to be onsite to perform the calibration. The technique sends a signal from a calibration truck to trigger the WIM controller to flag the vehicle record corresponding to the passage of a calibration truck (or a truck of known or onboard measured weight from free-flow traffic, if feasible) over the sensor. The WIM technician can then identify and review flagged records (from a remote location, say a traffic operations center) and make a decision about whether to change WIM compensation factors. This technology could reduce the cost of calibration, reduce the time a WIM technician spends in calibration activities, and improve safety of field personnel. Research conducted in Australia on the use of onboard vehicle weighing systems and WIM systems supports the benefits of using both types of devices (23).

WIM Data to Improve Transportation Systems

Knowledge of the types of vehicles, and specifically vehicular loads, are critical inputs for design and management of transportation structures and systems. The advent of automated means to collect WIM data has provided for site-specific, per-vehicle data in lieu of presumptions and, hence, the opportunity for more-effective designs and management of transportation systems. New pavement design (e.g., MEPDG) and bridge design [e.g., Load and Resistance Factor Design (24)] methods include provisions for using actual data that are effective in improving the designs. Other applications including issuing load restrictions for roads or bridges, improved commercial vehicle weight enforcement, traffic management, work zone management, freight planning and logistics, bridge rehabilitation, and highway design and safety also require load data. However, the extent and efficiency of using the actual load data for improved practices at transportation agencies varies among transportation agencies and, in many cases, is limited.

A survey of transportation agencies is indispensable in determining how and where WIM data are utilized, needed skills and tools for a variety of data applications, quality of data for various purposes, and how existing data collection practices are and can be more efficiently integrated to improve decision-making and transportation network management, mobility, and safety. Since collecting WIM data is expensive, it is necessary to quantify the real value of the data in order to justify the investments. Most agencies can quantify the cost of collecting WIM data, but they cannot quantify the cost of not collecting WIM data. The value in using these data should be quantified and the collected data should be used for the maximum benefit. The proposed synthesis research project would shed light on how WIM data are utilized by agencies, and more importantly, how and why it is not being used.

Impacts of Classification and Weight Data on Pavement Design

More state highway agencies move to implementation of MEPDG method in their pavement designs each year. The new MEPDG method provides users with the requirement to directly input vehicle classification and axle weight data. This design approach forces consideration of whether site-specific data are necessary or some level of defaults could provide similar accuracy

in pavement design outcomes. Therefore, research is required to investigate the impacts of classification and weight data on pavement design outcomes using the MEPDG method, including trade-offs from using simplified vehicle classification, WIM data obtained from portable WIM, and data from short-term vehicle classification sampling. The research findings will aid highway agencies in determining the extent for vehicle classification and WIM data coverage needed to satisfy pavement design requirements.

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Managing Large Datasets

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STATE OF THE PRACTICE

Local, cities and towns, MPOs, and state DOTs collect traffic monitoring data for sections of roadway that represent travel patterns on their surface transportation network. Data from continuous and short-duration counts can be part of this large dataset. Continuous counting involves collecting traffic data continually within an hourly or more frequent time interval over a period of more than 1 week in any given location and can include 365 days per year of hourly (or 15 min, daily, etc.) vehicle count data. Continuous traffic data (volume, classification, speed, and weight) represent the temporal data needed for developing factors to annualize short-term counts. Short-duration traffic data counts are normally taken between 1 to 7 days and represent the spatial data sets for an agency's roadways. Accordingly, traffic data stored in large databases represent the temporal and spatial information from the continuous and short-duration counts, station information, volume, speed, classification, weight, and even per-vehicle records and other attributes such as meta data. The 2016 FHWA *TMG* contains example formats for storage of these data (*1*). The TMG is intended to assist state and local transportation agencies, and others involved in traffic data acquisition and reporting programs.

Although each agency often collects both continuous and short-duration counting traffic data per their specific needs, there are several similarities across the nation's traffic monitoring programs. Every traffic-counting program must store their data for reporting purposes and access by their customers. Traffic monitoring programs must be familiar with the various protocols and needs of the agencies they interact with to ensure the best data are utilized for decision-making. Traffic data are often managed through software developed to process and analyze big data. Data management can be as simple as using a spreadsheet or as sophisticated as a customized software management system. The traffic dataset is also considered big data because there are millions of volume data records stored for each contributing traffic vehicle.

A large travel database can lead to better consistency and data integrity, which means that it can avoid duplication and ensure data accuracy through its design and a series of constraints. Therefore, the more data that are collected at a greater frequency, the more accurate the dataset becomes. The tables in a relational database are linked through a key that functions as an identifier in each table to uniquely pinpoint a row. Each table has one or more primary key columns, and other tables that need to link to the first table contain a foreign key column whose value matches the first table's primary key. Providing these integrated aspects of the large dataset to those who utilize them to perform other tasks is important. The traffic dataset becomes even larger when not aggregating datasets and also when data are used to calculate other parameters such as traffic volume factors used to adjust short-duration traffic counts that represent an AADT statistic. If some data within the large database are dependent on external sources or other internal sources, then the limitation and rights to such data use must be contained in the documentation for the large dataset. This is required to create, document, and make the large dataset available to those managing and utilizing it. Large traffic datasets support capital investment programs and budgets, and effective design and maintenance programs. Guidance is available from the AASHTO, for example, in the *Guidelines for Traffic Data Programs* that contains recommended counting procedures and national traffic monitoring techniques that reflect current practice (2). Differences in traffic monitoring technologies and advances made in the past several years in data collection methods are described in the TMG (1). Many agencies document methods for providing QA, QC, and database structures that ensure the collected data are beneficial and relevant to those who utilize it. The AASHTO Guidelines and TMG recommend periodic review of procedures implemented in the traffic monitoring program, which include manipulation of data and their storage in large databases.

STATE OF THE ART

Traffic monitoring programs maintain their traffic data and related meta data for use by in-house staff, contractors, and public agencies. State-of-the-art programs deploy systems to manage the data and perform the numerous functions needed for success of the traffic monitoring program. Those functions include obtaining the counts from the devices, initial QC checks to determine completeness of the data, advanced QC checks to confirm the data meets acceptable ranges, and established methods to both store and report the traffic data. Once the quality review is complete, the data are made available in large databases for reporting, uploading to other sites for use in other systems, or placed on public viewable websites for public consumption and reporting. Timeliness, quality, completeness, and transparency concerning the methods employed and the data calculation results and reviews are necessary for customers to have access to accurate datasets.

The *Highway Performance Monitoring System Field Manual* (3) details spatial and roadway attributes for proper geospatial reporting of data to FHWA and other depositories such as the MIRE (4). Spatial representation and integration of large traffic datasets is becoming increasing important as new advanced methods to visualize the data are now available with added new methods to spatially QC the data. What once were link (or line) based data now tell a story in the spatial representation of the data as traffic professionals consider safety implications, corridor studies, state-to-state travel patterns, and other applications.

Characteristics of Big Data

When dealing with large data sets, a question that arises is when does a traffic database become big data? For some people 100 GB might seem big, but for others 1 TB might be big, for still others 10 TB might appear big, and something else for other clients. The term big data is qualitative and is difficult to quantify. Hence, we identify big data by a few specific characteristics popularly known as the four Vs of big data: volume, velocity, variety, and veracity as depicted in Figure 1. These characteristics of large datasets provide an impetus to those utilizing data for travel monitoring to consider their importance when structuring an application, e.g., the time increments needed and reported, the structure of the databases, the quantity of data available, the control features within the databases that enable full management and exploitation of the large datasets, and the uncertainty of the data. Volume, velocity, variety, and veracity are discussed further below.



FIGURE 1 Four Vs of big data: volume, velocity, variety, and veracity.

Volume

Volume refers to the size of the dataset. Availability and the scale of data are growing rapidly. For example, technology advances make possible the TMG per-vehicle formatted (PVF) data that contains speed and class information in individual vehicle records. These data are spread across different databases often in diverse locations, in various formats, in large volumes ranging from megabytes to gigabytes or even larger. Today, data are most often not only generated by humans (manual counts), but by data recorders in large amounts.

Velocity

Velocity characterizes the speed at which the data are generated. Different applications have different latency requirements and in today's competitive world, decision makers want the necessary data and information in the least amount of time as possible (many ITS locations process data in 1-min increments), often in what is considered near real time or real time in certain scenarios. In different fields and different areas of technology, we see data acquisition generated at different speeds.

Variety

Variety signifies the different forms of data and the formats in which they are stored. In today's world, there are large volumes of unstructured data being generated apart from the structured data generated in enterprises. Advancements in big data technologies have triggered industries to develop powerful and reliable tools to read and analyze the voluminous unstructured data common today. Current traffic monitoring applications require organizations to not only rely on the structured data generated outside of the enterprise such as intersection loop data, crowdsourced data, and Bluetooth and automatic license plate reader data to stay competitive. Another aspect of traffic data that place them in the large dataset category is the assortment of traffic programs that over 450,000 statistics are published annually. Apart from the traditional flat files, spreadsheets, and relational databases, there are large quantities of unstructured data stored in the form of images, video traffic counting files, traffic site maintenance web logs, portable sensor data files, and individual vehicle records.

Veracity

Amassing a lot of data does not mean the data become clean and accurate. Data concerning traffic counts must remain consolidated, cleansed, consistent, and current to make the correct decisions. Furthermore, not all data are good. In fact, unfiltered data or data that are not quality checked are more likely to be bad than good. Although data quality and usability depends largely on the source, you can never rule out junk. This unreliability of data may make agency personnel reluctant to rely on information analysis. However, that's the wrong approach. No business tool is failure proof. Instead of discarding the unmatched potential of big data, public agencies and companies should work harder on implementing the right technology and people for its management (5, 6).

Data Storage

Data storage in the form of databases can occur in flat files or spreadsheets, hierarchical data, or relational data as indicated in Table 1. A spreadsheet or flat file is a simple method for storing data. Individual records have different data in each field with some fields serving as a key (header) to locate a particular record. For example, traffic station ID number may be one of the key fields in a record for a site's classification data and so on. For some traffic data records, there could be hundreds of fields associated with the record. When the number of fields becomes lengthy, a flat file is cumbersome to search and use manually. Also, the key field is usually determined by the programmer and searching by other determinants may be difficult for the user. Although this type of database is simple in its structure, expanding the number of fields usually entails reprogramming. Additionally, adding new records is time consuming, particularly when there are numerous fields. Other methods offer more flexibility and responsiveness in GIS.

Hierarchical files store data in more than one type of record, usually described as a "parent–child or one-to-many" relationship. One field is key to all records, but data in one record

Traffic Database Type	Advantages	Limitations
Flat files or spreadsheets	Simple methods and easy to use Fast data extraction and use	Larger datasets more difficult to process Adding new fields is more difficult Must know primary key(s)
Hierarchical data	Multiple associations to other datasets Fast data retrieval Adding or removing data fields is easy	Each association requires repetitive data Pointers require large data storage space Pointer path restricts access
Relational data	Flexibility and easy to use with new queries Physical data storage can change Easy access with only minimal training Can add or remove relationships and data	Adding new relations can require reprocessing Sequential access is rather slow Easy to make logic mistakes with queries Disc storage affects process time

TABLE 1 Attributes of Traffic Database File Types

do not have to be repeated in another. This system allows records with similar attributes to be associated together. The records are linked to each other by a set of key fields in a hierarchy of files. Each record, except for the master record, has a higher-level record file linked by a key field pointer. This allows one record to lead to another and so on in a descending pattern. An advantage is that when the relationship is clearly defined and queries follow a standard routine, a very efficient data structure results. The database is arranged per its use and customer requirements. Access to different records is readily available, or easy to deny to a user by not furnishing that unique file of the database. One of the disadvantages is the need to access the master record with the key fields determinant in order to link downward to other records.

Relational files connect different files or tables (relations) without using internal pointers or keys. Instead, a common data link is used to join or associate records together. The link is not hierarchical. A "matrix of tables" is used to store the traffic information. If the tables have a common link, they may be combined by the user to form new inquires and data output. This is the most flexible system and is particularly suited to structured query language (SQL). SQL is the most common relational database language in use today. Queries are not limited by a hierarchy of files, but instead are based on relationships from one type of record to another that the user establishes. Because of its flexibility, this relational file system is the most popular database model for GIS.

EMERGING TRENDS OR DRIVERS OF CHANGE

Agencies are collecting more travel monitoring data and merging data from unique and new sources. Collected data encompass speed data, nonmotorized vehicle data, PVF data, crowdsourced data, and real-time data. As agencies merge data from different sources and collect more detailed data, the fundamental aspects of the data sources and their key fields become

critical to exploiting the databases. One example is the AADT process first developed by AASHTO in the 1980s that relies on daily volumes to compute AADTs. With the new FHWA AADT calculation method, data of any time increment (1 min, 5 min, 15 min, or hourly) can be utilized (1). The new method strives to take advantage of the improved accuracy and utilization of datasets, mainly from ITS or traffic management center data that may have gaps. The result is larger more integrated traffic datasets and more comprehensive calculations.

The TMG provides agencies with volume, speed, classification, weight, nonmotorized, and PVF data collection formatting guidance for continuous and short-duration counting. It also contains information on utilizing nontraditional sources such as operations and ITS data sources. PVF data are now being considered by 14 state DOTs. Many DOTs collect PVF or event type data from their portable devices. Weight data have been per vehicle for years and it is only since the advent of cheaper data storage, improved processing abilities, and the greatly reduced cost of data transmission that PVF data can now be cost-effectively collected, processed, and stored. FHWA recommends that agencies move to PVF data recording and storage because of the ability to improve data utilization, add QC methods, and provide more detailed information to the traffic data users.

Additionally, most agencies are actively geolocating their traffic counts and providing the ability to visualize the data on maps and with other data on GIS layers to make informed decisions. Geolocation data are important to the datasets in that they are larger, can be quality analyzed and integrated with other datasets in new ways, and allow for a greater utilization when merged with other large datasets (i.e., safety, roadway management, or operations). Spatially represented data align with the concept of collect the data once correctly and use it many times.

If the large database is relational, which most databases are, it can cross-reference records in different tables and create relationships between the tables. For instance, if volume and speed count are linked, one could establish what time frame and location were represented. This is a frequent occurrence when the massive HERE and INRIX speed datasets are merged with traffic data volumes. HERE is a private company that provides maps for in-vehicle infotainment (pretrip first and last-mile guidance and route guidance), connected vehicle and highly automated vehicle navigation, traffic congestion, venue locations, and road roughness (7). INRIX is also a private company that provides data for traffic flow optimization and city planning (8).

Continuous-counting traffic monitoring program guidance captures several emerging trends, including new data analytical software tools for large datasets. Data displays can now be visualized much quicker and applied to larger datasets. For example, transportation data users are continually asked to incorporate visualization into their data analyzes to perform tasks such as identifying anomalies in the large dataset. Statistical Methods and Visualization provides guidance on how to analyze and present traffic-counting data (9). The paper describes statistical analytical methods, comparison methods, and representations of data in line and bar charts. Large spatial datasets can be structured as raster based (by grid cells) or vector based (by points and lines).

Collecting traffic data once and using the data for many applications many times is a trend that data collection agencies, including the FHWA, have been supporting for many years. One example is the assessment by Hajek et al. of the overall quality of traffic data from 890 LTPP traffic sites and the projection of axle loads for LTPP sites with adequate traffic data (10). The data are truck volumes collected using continuously operating automatic vehicle classifiers and truck axle weights collected using WIM scales or other scales operating during specified time periods.

Users of data need to be aware that adding a new traffic monitoring dataset has the potential to quadruple motorized traffic volume and will require big data management skills and resources to adequately exploit the rich dataset. A SQL relational database is becoming the trend for management of large databases.

Traffic data collection programs are also key in providing traffic data resources to an agency's overall asset management system. Several publications describe data systems as part of the asset management function, such as *Data Systems and Asset Management (11)*, where several references to traffic volume data illustrate the critical nature of collecting continuous traffic count data to the overall agency's mission and to the management of large databases and other assets.

GAPS IN PRACTICE OR KNOWLEDGE

Traffic monitoring systems continue to integrate multiple equipment and data sources into their programs, potentially creating large datasets. As ITS data and traffic monitoring data become integrated into searchable databases, agencies will be required to improve their ability to manage these large datasets.

Structured and unstructured data are available from traffic monitoring stations. When referring to traffic monitoring data, one thinks of a well-structured data set as being one that conforms to existing national, state, or local procedures. Often local counts and counts conducted to support individualized research or another individualized need may not contain the structured aspects that support utilization in a large database. Individualized data collection and counting for a specific project occurs frequently. The manual counts performed at rest areas, ramps, private industry for local needs, or agencies to support new construction or corridor improvements are often not utilized or inserted into larger systems or datasets. These data also lack the ability to be fully utilized for annualization applications, but can serve as a QC dataset to the larger annualization datasets.

Documentation of the methods used, key fields, database relationships, and availability of the data is lacking to fully utilize the rich and large traffic datasets available today. With proper documentation, large datasets can be more fully utilized and can be managed more easily. Public agencies are beginning to release vast amounts of data. The combining of spatial data having different attributes and structures may well be the next hurdle to overcome.

CURRENT AND PROPOSED NATIONAL RESEARCH AND INITIATIVES

Several governmental agencies are currently developing data visualization tools and engaging in programs that integrate data with interagency and external agency partners.

The FHWA Pooled-Fund TPF-5(280) project on Web-Based Traffic Data Visualization and Analysis Tools (12) developed methods to display WIM data and spatially represent the data on maps. This comprehensive tool enables one to view classification and weight data in new ways.

FHWA also has been conducting research into large dataset integration through the Integrated Transportation Information Platform (ITIP) (13), Datapalooza (14), Data Portal, Data Governance (15), and other projects focused on integration, display, and better utilization of large traffic and other federally managed datasets.

An area for research is data integration. Its immaturity appears to inhibit data sharing. Lack of robust data integration tools also constrains "collect it once correctly and use it many times" initiatives.

Another area for research is definition of the characteristics of large data sets, although some work in this area was performed through the TRB ADUS research (16).

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Traffic Monitoring and Performance Measures

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STATE OF THE PRACTICE

The concepts of performance measurement and traffic monitoring (statistics, data quality, usage, and integration) are closely related and highly dependent on each other. Traffic monitoring is a long-standing program within state DOTs. They play vital roles in gathering information in support of current and past performance of the transportation system and in predicting future performance. This capability is especially important to sustain the transportation planning responsibilities of the state DOT. Despite the proliferation of new private-sector probe data sources, monitoring of traffic volumes and its characteristics will continue to be a critical need for state DOTs and other transportation agencies.

This chapter addresses two key aspects that consider best practices in the area of performance measures related to traffic monitoring. The first is how agencies are using traffic data to support performance measures to describe system functioning including reporting, visualization, and ultimately making decisions related to efficient planning and operation of the transportation system. The second is how the concept of performance measures is applied to a traffic program to ensure optimal outcome of the traffic data in terms of quality, coverage, timeliness, and accuracy.

What Are Performance Measures?

According to NCHRP Report 706: Uses of Risk Management and Data Management to Support Target Setting for Performance-Based Resource Allocation by Transportation Agencies (1), performance measures are a set of metrics used by organizations to monitor progress toward achieving a goal or objective. The criteria for selecting measures often include feasibility, policy sensitivity, ease of understanding, and usefulness in actual decision-making. Performance management is a business process that links organization goals and objectives to resources and results. Performance measures, used along with well-defined and well-communicated targets, provide transparency and clarity to the resource allocation decision-making process. Performance-based resource allocation in any organization relies on the availability of timely, accurate, high-quality data which is easily accessible through a framework known as a data program. Such a program usually includes the functions of data collection, analysis, and reporting. In the case of a DOT, some examples include traffic, roadway inventory, safety, and pavement data programs.

Why Are Performance Measures and Traffic Data So Important and Related?

The FHWA TMG (2) states that traffic counts are fundamental to almost every task a highway agency performs and critical to a comprehensive performance measurement system. The timely delivery of high-quality data can serve as a critical framework for effective decision-making. The

ability to describe traffic volumes and vehicle types using a road reflects positively on the agency's ability to effectively perform its responsibilities and manage its budget. Per the TMG "The measurement of traffic volumes and its composition (class, weight, speed) is one of the most basic functions of highway planning and management. Traffic volume counts are the most common measure of roadway use and count data are needed as input to nearly all traffic engineering analyzes."

FHWA defines Transportation Performance Management (TPM) as a strategic approach that uses system information to make investment and policy decisions to achieve national performance goals (*3*). State DOTs are mostly concerned with performance in the areas of safety, mobility, preservation, and economic competitiveness. Traffic data and its associated performance measures including AADT and VMT form a cornerstone of mobility measures.

Florida DOT defines mobility performance measures in four dimensions: quantity, quality, accessibility, and utilization. Quantity is defined as how many vehicles, people, and trucks travel within the transportation system. The second important component of mobility measures is speed, which supports measures such as delay and travel time reliability. This chapter focuses on traffic volumes.

The Moving Ahead for Progress in the 21st Century (MAP-21) Act and FAST Act legislation introduced performance management into the Federal Highway Program through the establishment of goals. These require state DOTs and MPOs to report on and make progress toward targets they will set against a number of national performance measures. The objective of this new aspect of the federal program is to focus federal funds on the achievement of national goals, increasing accountability and transparency, and improving investment decision-making through performance-based planning and programming. The MAP-21 Act and FAST Act performance areas include safety, infrastructure condition, system reliability, freight movement and economic vitality, congestion reduction, and environmental sustainability. The implementation of the long-awaited legislation promises to change the way state DOTs and MPOs conduct transportation planning. Resource allocation decisions will be based on outcomebased measures, and TPM will be realized. The MAP-21 and FAST Act are clear in their intent to require a performance management approach to the federal investment in the nation's highways. Although performance management has gained momentum among state and local transportation agencies for several years, and many of them have implemented exemplary programs, the rule-making has accelerated the process significantly.

There are four main categories of measures defined in the FAST Act: safety, pavement, bridge mobility, and air quality. Traffic data (volumes) are required to support two of these categories. The safety measures to be reported by states and MPOs include: number of fatalities on all public roads, rate of fatalities per 100 million VMT on all public roads, number of serious injuries on all public roads, and rate of serious injuries per 100 million VMT on all public roads. The key data items are total VMT on all roads and annual number of fatalities in crashes involving a motor vehicle. All states are currently assessing how they will meet the need to obtain traffic volumes and VMT on all public roads.

Table 1 describes the MAP-21 mobility measures and associated data sources. VMT are based on number of vehicles. Although VMT data are essential for MAP-21 reporting, traffic data have been and continues to be a key data element to support mobility performance measures for prioritizing and selecting projects within state DOTs.

	Performance			
Parameter	Measure	Applicability	Data Items	Data Sources
Performance of the National Highway	Percent of the person- miles traveled on the Interstate that are reliable	The Interstate system	Level of travel time reliability VMT Occupancy factors	All vehicle data in National Performance Monitoring Research Data Set (NPMRDS) or
System (NHS)	Percent of the person- miles traveled on the non-Interstate NHS that are reliable	The non-Interstate NHS		equivalent VMT from HPMS Occupancy factors published by FHWA
Freight Movement	Truck travel time reliability index	The Interstate system	Truck travel time reliability index metric	Truck data in NPMRDS or equivalent
Congestion Mitigation and Air Quality Improvement (CMAQ) traffic congestion	Annual hours of peak- hour excessive delay per capita	The NHS in urbanized areas with a population over 1 million for the first performance period and in urbanized areas with a population over 200,000 for the second and all other performance periods that are also in nonattainment or maintenance areas for any of the criteria pollutants under the CMAQ Program	Total peak-hour excessive delay (person-hours) Total population	All vehicles data in NPMRDS or equivalent Bus, car, and truck volumes in HPMS Occupancy factors published by FHWA
	Percent of nonsingle occupancy vehicle (SOV) travel	NHS roads in urbanized areas with populations over 1 million that are, all or in part, designated as nonattainment or maintenance areas for any of the criteria pollutants under the CMAQ program	Applicable areas Percent of nonSOV travel	Method A: American Community Survey Method B: Local survey Method C: System use measurement
CMAQ On- Road Mobile Source Emissions	Total emissions reduction	All projects financed with funds from the 23 U.S.C. 149 CMAQ program apportioned to state DOTs in areas designated as nonattainment or maintenance for any of the criteria pollutants under the CMAQ program	Applicable projects Daily kilograms of emission reductions	CMAQ Public Access System

 TABLE 1 MAP-21 Mobility Measures and Associated Data Sources

STATE OF THE ART

Mobility Performance Measures

Traffic statistics are a crucial component of mobility measures and can be visualized in a variety of ways. Many states have developed dashboards to display their measures. A comprehensive resource for details on the rule-making, requirements, and state noteworthy practices is FHWA's TPM website (4, 5).

The TPM Digest (6) includes the latest information concerning online state dashboards, performance reports, mobility, performance-based planning, safety, events, workshops, webinars, research, and innovation. Noteworthy practices are included for the following topics: getting started, data collection and management, target setting, project prioritization and decision-making, reporting, and collaboration. External links are also provided to TPM dashboards for Alaska, Colorado, Delaware, Idaho, Iowa, Kansas, Michigan, New Hampshire, North Carolina, Ohio, Oregon, South Carolina, Virginia, Washington state, West Virginia, and Wisconsin and also the cities of Seattle, Washington, and San Francisco, California.

Exemplary mobility performance measures programs around the county include those in Florida (7, 8), Washington State (9), and Washington, D.C. Washington State DOT maintains a list of 51 state, commonwealth, and federal district transportation authorities and their online performance measurement and strategic planning mechanisms (10).

Use of Measures in Traffic Data Programs

The TMG (2) asserts that data business planning is an important component of any state DOT traffic monitoring program because it ensures that customer needs are met and the most efficient methods are deployed. Data business plans and state traffic monitoring guidelines are used by many states to define data collection, analysis and reporting measures related to data timeliness, accuracy, and completeness. Table 2 shows the performance measures Alaska Department of Transportation and Public Facilities (DOT&PF) developed to support system traffic data collection and analysis (11).

Some states are also developing "pay for data" models with specific measures related to privatizing and paying for traffic data. These include Virginia and, most recently, Georgia.

GAPS IN PRACTICE OR KNOWLEDGE

The art of using traffic data to support performance measurement and management within state DOTs is well developed. However, a few gaps are emerging within the industry.

Mobility Performance Measures

An extensive survey of all state DOTs was recently conducted for NCHRP Project 20-05-Synthesis Topic 48-14: Analyzing Data for Measuring Transportation Performance by State DOTs and MPOs (*12*). The survey asked for feedback regarding state DOT activities, gaps, and research needs related to collection and analysis of data to support the MAP-21 FAST Act

Requirements Identifier	Performance Measure Requirement	Performance Measure and Definition	Goal	Objective	Target	Data Needed	Timeframe Reported	Source (Existing or New, Manual, or Automatic)	Comments
TD-001	The system shall track the number of days past Jan. 1 it takes to perform final AADT calculation (by region)	Number of days past Jan. 1 to produce AADT factor	Reduce number of days	Reduce number of days to 90 days past Jan. 1	Reduce number of days to 90 days past Jan. 1—to occur no later than 2010	Date AADT calculation performed	Annually	Existing, manual— when e-mail sent to headquarters	Not applicable
TD-002	The system shall track the number of days past the end of the month it takes for the regions to submit their permanent traffic counts	Number of days past end of month	Reduce number of days past end of month	Reduce number of days past end of month to 7	Reduce number of days past end of month to 7	Date (in e-mail from region)	Monthly	Existing, manual	This is for PTR data
TD-003	The system shall track the number of permanent sites judged to be good per day (PTR, classification)	Number of good sites per day (i.e., those that provide volume and class)	Maximize number of good sites	Ensure 95% of all sites are good	Ensure 95% of all sites are good within 3 years (long term might be different set of requirements)	Total number of detectors operating daily Total number of good detectors Good = 24 h of delivering indented data (may be only volume or both volume and classification)	Daily, monthly	Existing, manual The districts send a "PTR letter" each month detailing what is broken and what isn't	An entire site is marked as down instead of per lane
TD-004	The system shall track the number of WIM station lanes working per day	Number of WIM station lanes working per day	Increase number of working stations	Ensure all stations are operational daily— allow 10% not working	Not available	Report data 24 h to be good	Daily	Automated data collection (can write scripts to do this)	There are detectors per lane with the WIM data

TABLE 2 Alaska DOT&PF Traffic Data Collection and Analysis Performance Measures (11)

performance measure requirements. Some of these gaps related to traffic data are discussed below.

States are challenged with providing traffic data or VMTs on all roads to support the safety measures. Many states have well developed traffic monitoring programs, but they often only cover state-owned facilities. Some states assume they will estimate the VMTs and others are developing partnerships and programs to obtain traffic volumes from partner agencies. For example, Georgia DOT is allocating funding to its regional partners to collect the traffic volume data for them. Georgia DOT will then take the lead in integrating the data at a statewide level.

States are interested in combining traffic volume with speed data as provided by private data probe vendors or by FHWA through the NPMRDS. This task is often challenging due to the different segments that exist for each of type of data. For example, probe data are reported on traffic message channels, which is a technology for delivering traffic and travel information to motor vehicle drivers by private information vendors. They use different traffic message channel networks that are tied to different mapping platforms. Traffic volumes are available within state DOTs at HPMS segment level (and other predefined segments).

Unfortunately, these segments do not match each other and are supported by different linear base maps, making the matching and integration effort very challenging and time consuming. Fortunately, this will not be an issue for MAP-21 FAST Act reporting given that states will report metrics into HPMS and FHWA will address this conflation of the data and networks. However, many states and transportation agencies are interested in combining speed and volume data sources to report on congestion, delay, and travel time reliability and they are still encountering these challenges.

Tools to integrate, analyze, and visualize traffic volume data with other sources such as speed, incidents, and weather is becoming more prevalent within the transportation industry. Still, the tools are expensive and are not always supported to the degree necessary for ad hoc performance management at the public agency level.

Use of Measures in Traffic Data Programs

A possible gap in this area is the lack of knowledge sharing across states with respect to how they are applying performance measures to manage their traffic data systems.

CURRENT AND PROPOSED NATIONAL RESEARCH AND INITIATIVES

Mobility Performance Measures

Two studies currently are under way through FHWA to explore and develop methods for collecting and estimating VMT on all roads:

• FHWA Office of Safety—Data Collection and AADT Estimation for Non-Federal Aid System Roads.

• FHWA Office of Policy Information—Improved VMT Estimation on Non-Federal Aid System Roadways.

Proposed future research includes:

• Investigate how probe data (such as INRIX and HERE) could be used to estimate traffic volumes.

• Explore how traffic and speed data can better support the developing mobility targets to meet MAP-21 FAST Act requirements.

Use of Measures in Traffic Data Programs

The FHWA Office of Operations recently completed a Data Business Plan Guide to assist state DOTs and transportation agencies with better managing and governing traffic data programs including speed and volume (13). The guide could be a useful tool for developing and applying programmatic performance measures related to traffic monitoring.

Future areas of research could include a synthesis project examining how state DOTs are using performance measures to manage and optimize their traffic data programs.

Setting Performance Targets

Even states and regions that are well along with performance measurement may have spent little time setting actual performance standards or targets outside of the traditional goal areas of asset management and safety. Implementation of MAP-21 and the FAST Act will generate a flurry of activity in target setting, requiring greater coordination and cooperation between agencies as they deal with technically challenging material. In addition, coordination of targets between state DOTs and MPOs is a relatively unprecedented activity that requires guidance.

Mobility

Templates

State DOTs would like to see FHWA developed templates.

Technical Issues – Conflation and Segmentation

A study that addresses and resolve all state issues pertaining to segmentation and conflation would be helpful, as would consideration of a standardized approach. It is possible that the new release of NPMRDS will address some of the issues. However, a comprehensive study may still be needed.

Tools

- Research and development of additional tools to support congestion management processes.
 - Research to develop better tools for forecasting heavy vehicle traffic.

Training

Research and development of skill sets, including educational programs related to data analytics.

Nonmotorized Data Collection

• Research, synthesis, and development of capabilities for nonmotorized data collection and estimation (such as bicycle and pedestrian) and

• Research related to nonmotorized level-of-service measures.

Vehicle Occupancy (Number of People in a Vehicle)

Research and methods regarding vehicle occupancy measures and estimates.

Forecasting

Research into "What are the variables that are most important for forecasting," such as mobility in general, passenger versus freight, trucks versus commodities.

New Data Sources

Vast amounts of traffic operations data are available through sources such as INRIX and Waze. Research to provide better understanding of this information, along with that from other data sources, will enhance a state's ability to forecast future values for mobility measures.

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TRAFFIC MONITORING STATISTICS, DATA QUALITY, USAGE, AND INTEGRATION

Pavement Engineering Applications

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STATE OF THE PRACTICE

Overview

Pavement engineering utilizes traffic parameters and traffic-counting data for pavement analysis, design, and management in the following ways:

• Traffic data and parameters enable detailed characterization or study of traffic loading effects on pavement structure, e.g., pavement analysis, research, and forensic studies.

• Summary traffic parameters support high-level analyzes (empirical pavement design, pavement performance or pavement maintenance modeling, or pavement management applications) (1).

• Other parameters find use in specialized pavement analysis and design software such as the *Mechanistic–Empirical Pavement Design Guide* (MEPDG) (1, 2).

Parameters that provide detailed characterization of traffic loading are used for mechanistic and mechanistic-empirical pavement response and performance modeling. Analysis and modeling of pavement response require information about wheel and axle load magnitude, load position and configuration (i.e., axle configuration and position of wheels on the pavement) as indicated in Figure 1, area of load application or tire footprint, load duration, and time history of load application (i.e., changes in load magnitude over time). Pavement performance modeling requires traffic loading history for the entire analysis period (i.e., the number and magnitudes of loads reported for specified time increments used in the analysis). This information is typically collected by the traffic data collection staff within a DOT. Traffic loading is one of many uses of traffic data making it challenging, but achievable, for the data collection staff to meet all of the traffic monitoring needs for pavement engineering applications.



FIGURE 1 Truck wheel and axle configuration and position are required for pavement response and performance modeling.

Summary traffic parameters find use in empirical pavement response and performance analysis and modeling, empirical pavement design procedures, and high-level analyzes supporting pavement management models and decision support tools. For these analyzes, a single traffic summary statistic is desired, such as the equivalent single-axle load (ESAL), average annual daily truck traffic (AADTT), cumulative truck volume, or total load. These summary statistics are also used to identify and group sites in categories that represent different levels of traffic.

Another set of traffic parameters is utilized as a direct input to specialized pavement analysis or design software, such as the traditional AASHTO 1993 and the newer MEPDG pavement software, AASHTOWare Pavement ME Design Software (1, 2).

Traffic Parameters Used in Empirical Pavement Analysis, Design, and Pavement Management Applications

The current state of practice in pavement engineering relies on empirically derived relationship between traffic summary statistics and pavement performance. Many studies of pavement response and performance use empirical methods or statistical models to correlate pavement performance parameters (for example, road roughness) monitored over time with traffic and environmental loads, site conditions, material properties, and construction practices. These studies frequently use a single traffic summary parameter to describe traffic. These analyzes may require a complete history of changes in the selected traffic summary parameter (computed annually for the duration of analysis period), a single cumulative value aggregated over the analysis period, or one representative traffic summary value. Most frequently used traffic summary parameters are AADTT and ESAL (2).

ESAL as a Traditional Summary Traffic Loading Statistic

ESAL has been used as a summary traffic loading statistic for pavement design and analysis applications since 1960s (*3*). ESAL is a concept developed from data collected at the American Association of State Highway Officials (AASHO) Road Test to establish a damage relationship for comparing the effects of axles carrying different loads. In ESAL computation, the load equivalency factors (LEFs) are used to convert a mixed stream of traffic consisting of different axle loads and axle configurations predicted over a design or analysis period into an equivalent number of 18,000-lb single-axle load applications summed over that period. Thus, ESAL is a cumulative traffic loading summary statistic. Although general understanding and consensus exist in the pavement engineering community that ESALs or LEFs do not precisely describe the relationship between axle load and specific pavement distresses like rutting or cracking, ESAL continues to be a convenient statistic for sizing and quantifying traffic loading levels for empirical pavement analysis and design.

When using this statistic, it should be understood that in addition to traffic, the ESAL value depends on pavement type, pavement thickness, and a compound measure of road condition expressed through a subjective pavement serviceability index. For example, ESAL values representing the same traffic stream can change simply because the pavement type changes or the pavement is rehabilitated and pavement thickness or roughness changes.

Generic ESAL

The generic ESAL (GESAL) is a parameter computed similarly to ESAL using LEF values for flexible pavements with the structural number equal to 5 and the terminal serviceability index equal to 2.5 (4). Because LEF values are set to a constant, GESALs are independent of pavement type and thickness, and level and type of pavement distress. Therefore, any changes in GESAL values can be attributed directly to changes in traffic loads. This makes GESAL a more-desired summary traffic loading statistic for comparison of loads or effects of loads on pavement performance between different sites. GESAL is more sensitive to the importance of heavy loads on pavement performance, compared to average load or total load summary statistics. However, use of constant LEF parameters makes GESAL not applicable as a direct input to pavement design.

Traffic and Truck Volume Summary Parameters

For pavement analyzes that are focused on characterizing traffic or truck volumes at a given location, the most widely used traffic volume parameters are AADT and AADTT. The AADTT parameter is more relevant for pavement analysis and management applications compared to AADT because trucks have much higher contribution to pavement damage compared to the lighter vehicles that make up most of AADT number.

Other traffic volume statistics that are used in pavement analyzes are total annual truck volume, annual truck volume by vehicle class, cumulative volume of class 9 vehicles and cumulative volume of heavy trucks (vehicles in FHWA classes 4 and 6 to 13).

STATE OF THE ART

MEPDG Traffic Parameters

The pavement engineering world is undergoing a paradigm shift from the empirical to ME design methods, with a goal to eventually develop mechanistic methods for pavement design. In contrast with the empirical pavement design method that for over 50 years included one traffic summary parameter (i.e., ESAL), the new ME method requires extensive use of traffic data.

Many of ME pavement performance analyzes are performed using the MEPDG method and software products such as AASHTOWare Pavement ME Design. This software utilizes a defined set of traffic input parameters in a specific format. Table 1 describes the traffic parameters required for analyzes and design based on the MEPDG method.

Traffic Loading Defaults for MEPDG

Recognizing the emerging state of WIM technology and the need for research-quality WIM data to support LTPP research, the LTPP program installed and maintained WIM equipment at SPS WIM sites in 22 states. This effort proved that collection of consistent high-quality WIM data [satisfying ASTM E1318 WIM Type I performance requirements (5)] over long periods of time

TABLE 1	Traffic Input Parameters Required by the
AASHT	OWare Pavement ME Design Software

MEPDG Input Parameter	Parameter Description
Axle load distribution factors (ALDF)	ALDF represents a percentile axle load distribution for a typical day for each calendar month for a typical design–analysis year. One set of ALDF is provided for each vehicle class (classes 4-13), axle group type (single, tandem, tridem, quad), and calendar month (January–December). ALDF remains constant between the analysis years.
Vehicle class volume distribution	One representative percentile distribution of vehicles in classes 4–13 is provided to represent an average vehicle class distribution for the base design or analysis year.
Monthly adjustment factors	One representative set of 12 monthly coefficients is provided for each vehicle class 4–13 to represent differences in truck volume between different calendar months for the base design or analysis year.
Hourly distribution factors	One representative set of 24 hourly factors showing the percentage of total truck traffic for each hour. Values are the same for all truck classes and only apply to truck volume. This input parameter only applies to portland cement concrete (PCC) pavements.
Number of axles per truck	One representative set of values showing the average number of single, tandem, tridem, and quad axles for each truck class (classes 4–13).
Base (first) year AADTT for design lane	One value representing average annual daily volume of vehicles in classes $4-13$ for the base design-analysis year. If this input parameter is used in MEPDG software in place of two-way AADTT, enter the following values also: percent trucks in design direction = 100% and percent trucks in design lane = 100%. Alternative input: MEPDG base (first) year two-way AADTT.
Base (first) year two- way AADTT	Two-way AADTT computed for the base design or analysis year.
Percent of trucks in design direction (%)	Percent of trucks in design direction (direction of LTPP lane) for the base design or analysis year.
Percent of trucks in design lane (%)	Percent of trucks in design lane (LTPP lane) for the base design or analysis year.
vehicle class annual volume growth rate by vehicle class (%)	Growth rate (%) for each truck class (classes 4–13). Applied together with the growth function (linear or compound) to estimate truck volume over analysis or design period from the base design or analysis year AADTT values.
Vehicle class growth function	Type of truck volume growth function: linear or compound, by vehicle class 4–13. Applied together with the growth rate to estimate truck volume over analysis–design period from the base design or analysis year AADTT values.
Operational speed (mph)	Value defined as posted speed limit or the average speed of the heavier trucks through the project limits.

Continued on next page.

MEPDG Input Parameter	Parameter Description
Axle spacing for tandem, tridem, and quad axles (in.)	Average representative axle spacing for tandem, tridem, and quad axles.
Average wheelbase length and corresponding percentage of trucks	The average wheelbase length and the corresponding percentages of trucks with wheelbases that fall in the following three categories: short (\leq 12 ft), medium (> 12 and \leq 15 ft), and long (> 15 and \leq 20 ft). For multi-unit and combination trucks, only wheelbase of the truck power unit (i.e., first unit) is considered. Used for top-down jointed plain concrete pavement cracking model only.
Average axle width	The distance in feet between two outside edges of an axle. Constant between all truck classes. Only needed for rigid pavement designs.
Mean wheel location	The mean distance in inches from the outer edge of the wheel to the pavement marking. This parameter is constant between all truck classes and does not change with time.
Truck wander standard deviation	Standard deviation from the mean wheel location, computed in inches based on measurements from the lane marking.
Dual tire spacing	This parameter is constant between all truck classes and does not change with time.

TABLE 1 (continued)Traffic input parameters required by the
AASHTOWare Pavement ME Design software

(10+ years) is possible with proper maintenance and calibration (6). The data from the LTPP SPS WIM sites have been used to develop the new generation of traffic loading defaults for use with the MEPDG method (7). These defaults were included in AASHTOWare Pavement ME Design software for use nationally and internationally. A guide for selection and use of these defaults was published by FHWA (8). LTPP is expanding its WIM program to cover more sites across the United States as part of the warm-mix asphalt pavement experiment. Several states are also working on or completed the development of their own MEPDG traffic loading defaults.

Traffic Parameters for Mechanistic–Empirical Pavement Performance Prediction

Research concerning ME pavement performance analysis and modeling focuses on analyzing and predicting pavement distress that develops over time. Most of the pavement distress (cracking, rutting, faulting, etc.) develops from incremental or cumulative changes in pavement structure due to material aging, environmental impacts, and traffic loading. Therefore, for traffic loading characterization, not only must information about individual traffic loads be known, but also the sequence and the cumulative total number of traffic load applications that lead to pavement deterioration over time.

Axle Loading Characterization

Traffic loads are summarized in the form of an axle load spectrum in order to track and summarize traffic load applications over time (7). The axle load spectrum represents a frequency distribution of axle loads, where counts of axle load applications, observed during a specified period of time, are summed and reported using predefined load bins. Recognizing the importance of load configuration, separate axle load spectra are used to summarize axle load counts for typical axle load groups: single, tandem, tridem, and quad. Depending on the intended application, load spectra could be created for an individual truck class or for all truck classes combined. In summary, axle load spectrum input provides information about the axle load magnitudes, number of axle load applications over a specified period of time, and load configuration (i.e., the number of axles in each axle load group). In some pavement applications, the axle load spectrum is called the axle load distribution.

Such detailed characterization of traffic loading allows modeling of pavement responses and performance using methods where each axle load application on the pavement, expected or observed during the analysis period, is modeled and its effect on pavement response and performance is predicted.

In addition to the axle load spectrum, information about the relative position of axle loads on the pavement is also important, especially for jointed rigid pavements. If no site-specific axle vehicle weight data are available to compute axle load spectrum, default axle weights could be selected for each vehicle class based on the primary road use.

Relative Pavement Performance Impact Factor

Traffic loading summary statistics include two new parameters, relative pavement performance impact factor (RPPIF) and annual total truck load (ATL). The RPPIF statistic is computed similarly to ESAL (7), but instead of the LEF factors based on the data from the AASHO Road Test, it utilizes W-factors determined through MEPDG analysis, based on the globally calibrated distress prediction models included in the NCHRP 1-37A MEPDG report and software (9). The analysis leading to W-factor development considered both jointed concrete and flexible AC pavements located in four different climatic regions (wet-freeze, wet-no freeze, dry-freeze, and dry-no freeze). Axle loadings of different magnitudes (using the same load levels as MEPDG ALDF) and configuration (single, tandem, tridem, and quad axle groups) were simulated using MEPDG software. Different types of predicted pavement distresses caused by loading were observed [rutting, fatigue cracking of AC and PCC, faulting, and international roughness index (IRI)]. All predictions were theoretical. From each MEPDG simulation, a load-pavement distress relationship that showed the highest sensitivity to a given axle loading magnitude was extracted and used in the development of the regression equation that related axle load with the observed maximum distress. All distresses were combined to produce one regression curve. This curve was used to compute W-factors. The goal of this exercise was to develop a single-value summary loading statistic—RPPIF—that could aid highway agencies determine the number of default axle load distributions necessary to support MEPDG pavement design implementation. Differences in RPPIF of 10% or more may lead to differences in pavement design thickness of the top structural layer of 0.5 in. or more and, thus, justify the need for multiple axle loading defaults. However, because different distresses were combined in the development of a single set of W-factors,

W-factors should not be used to relate axle loading to any specific distress and RPPIF difference should not be used for pavement thickness prediction.

The primary purpose or use of the RPPIF statistic is to compare axle loading distributions between different sites. As MEPDG models evolve, W-factors used for RPPIF computation may need to be updated or distress-specific W-factors and the RPPIF statistic may be desired for a particular pavement performance modeling task. As with GESAL, RPPIF values are independent of pavement type and thickness, and pavement distress. This statistic could also be used to identify and group the sites with similar traffic loading levels.

Annual Total Load

The ATL statistic is a simple estimate or summary of all traffic loads accumulated over a year. The main advantage of the ATL statistic is that it is independent of any empirically derived relationships that relate load to damage. However, this statistic cannot be used to infer whether trucks are empty or loaded and whether ATL value is affected by the number of trucks or by the weight of trucks (i.e., small number of heavy trucks and large number of light trucks may produce the same ATL value). This makes ATL less desirable for analyzes of pavement responses or performance that have a nonlinear relationship with the load magnitude.

UNFULFILLED DATA NEEDS OR DRIVERS OF CHANGE

Traffic Parameters for Pavement Response Prediction Based on Mechanistic Models

As pavement engineering evolves from the empirical to ME, and then to the fully mechanistic methods, the demand for more accurate and more detailed traffic loading characterization continues to rise. The emerging mechanistic pavement response analysis and modeling studies focus on stresses, strains, and deflections that pavements experience under each traffic load application. Pavement responses could be predicted using static or dynamic mechanistic modeling methods.

Pavement responses predicted by static models (elastic, viscoelastic, and elastoplastic) depend on the following traffic loading parameters:

• Load magnitude;

• Load configuration (i.e., location and number of wheel loads simultaneously applied on the pavement surface);

- Sequence of loads;
- Time and date of load application;
- Area of load application and shape of load distribution under each wheel (i.e., over the tire footprint); and
 - Position of the wheels and axles relative to the pavement edge or concrete slab edges.

Pavement responses predicted by dynamic models consider the dynamic effect of the applied loads. In addition to the parameters listed above for static modeling, the dynamic models require the following additional inputs:
- Load duration,
- Rate of load application (number of load application per time unit measure), and

• Time-history of load application (change in load magnitude or pressure under tire footprint over time, as each wheel passes over the specific pavement location).

Existing traffic monitoring technology, especially WIM, can provide most but not all of the above parameters. New advancements are required to take WIM measurement ability beyond the estimation of the static equivalent of axle or truck load weight, to accurate recording of the full time history of load application, including accurate measurement of the dynamic forces applied by the tire to the pavement and quantification of the exact area of load application (load or tire footprint) and position of each tire footprint for each truck, relative to the pavement edge.

Accuracy of Weight Data

The emerging mechanistic and MEPDG methods currently being implemented demand an accurate measurement of traffic loads. To provide accurate prediction of stresses, strains, and deflections in pavement structure, weight measurements should be as accurate as those used for weight enforcement. For MEPDG methods, accuracy of WIM data should satisfy performance requirements of ASTM E1318 Type 1 WIM systems (*10*).

ONGOING RESEARCH TO FILL DATA GAPS OR IMPROVE DATA USE AND QUALITY

Study to Facilitate Use of LTPP Traffic Data in Pavement Applications

The FHWA–LTPP program is completing research that reviews nationwide traffic volume, classification, and WIM data available through the LTPP database. These data will be used to develop traffic parameters suitable for pavement research, design, and analysis applications, and rank these parameters for use by pavement researchers and practitioners. LTPP traffic volume, vehicle classification, and WIM data evaluations consider data availability, accuracy, and applicability for different pavement applications. New database tables with analysis-ready traffic parameters, along with the pavement analysts' *Guide to LTPP Traffic Data* are being developed. The guide will help LTPP users to quickly select the most appropriate LTPP traffic statistics for the pavement analyzes they are performing. In addition, LTPP is developing traffic inputs for all its traffic sites in the format compatible with the AASHTOWare Pavement ME Design software to facilitate LTPP traffic data use in MEPDG applications. This project will improve the LTPP database, both by improving the traffic load data and by making it easier for pavement researchers and practitioners to select the traffic data needed for their specific applications. The study's completion date is December 2017 (FHWA Contract DTFH6114C00018).

LTPP Study to Estimate Traffic Inputs for Network Level Pavement Applications

The FHWA–LTPP Program has recently completed a study using LTPP monitored traffic and a variety of spatial information covering location and demographic characteristics to generate models that estimate some of the traffic inputs for pavement applications. The set of models

developed allows a user with nothing more than traffic volume data and information derived from geospatial datasets to estimate truck volumes, truck growth rates for HPMS truck groups, truck distributions across FHWA TMG truck classes, and axle load distributions by axle group and vehicle classification. Additional information, for example monitored vehicle classification versus traffic volume data, or ESAL estimates versus no loading information or limited axle monitoring data versus ESALs alone, gives a more representative estimation for the network location. The models for selecting normalized axle load distributions in the absence of any monitored axle distribution data are being used for LTPP sections with no loading information or no loading information beyond ESAL estimates (FHWA Contract DTFH6114C00023).

WIM and Freight Data Use for MEPDG

About half of state highway agencies are in various stages of implementing the MEPDG method for pavement design and conducting traffic data studies to ready their state for MEPDG implementation. Two representative studies are being conducted in Michigan and Pennsylvania.

Michigan DOT is performing research to develop methodology for traffic loading characterization for all the roads in the state based on available WIM, road inventory, and freight data. The results will be used to develop traffic loading defaults and methodology of selecting these defaults for pavement design using MEPDG method.

The Pennsylvania DOT has begun the process of implementing the MEPDG into its routine pavement design practice through the characterization of traffic and material inputs, and verification–calibration of MEPDG transfer functions. A recent research study resulted in the development of a traffic inputs library for use in AASHTOWare Pavement ME Design software. To fill the gaps in traffic data, traffic default values were developed based on analysis of traffic data from Pennsylvania DOT's WIM and continuous automated vehicle classification traffic monitoring sites. However, for several truck traffic database. For these parameters, the defaults based on the research-quality WIM data collected by LTPP SPS WIM TPF5 (004) study were found applicable for Pennsylvania DOT designs. The traffic default values were included in the Pennsylvania DOT Pavement ME Design data library. The Pennsylvania DOT-specific traffic inputs will be used in the regional verification and calibration of transfer functions for Pennsylvania. They are required for predicting distresses in both flexible and rigid pavements

PROPOSED RESEARCH TO FILL DATA GAPS OR IMPROVE DATA USE AND QUALITY

Enabling Detailed Traffic Loading Data Collection

Research and development is needed for sensors capable of capturing the detailed and accurate traffic loading history, and information about the location and size of the loading area (tire footprint and load distribution) to enable mechanistic pavement response and performance modeling. The results of these research studies will aid in the development of the new generation of mechanistic pavement analysis, design, and management methods and tools.

Improving Accuracy of WIM Data

To be used in MEPDG pavement design and analysis models, WIM data accuracy should be at least that specified by ASTM E1318 Type 1 WIM system performance requirements. Measurements of heavy axle loads, in particular, need to be accurate and free of bias. The research is needed to provide a new generation of WIM tools to help monitor and maintain the desired accuracy of heavy axle load measurements.

Advanced Methods for Project-Level Traffic Loading Estimation

While site-specific axle loading information is ideal for pavement design, it is impractical to have a WIM site at every pavement design location due to the high cost of WIM data collection. Therefore, new methods are required to: (1) accurately estimate site-specific axle loading from the limited number of WIM sites maintained by state highway agencies, (2) obtain information about freight carried by trucks on specific highway roads, (3) gather data from connected vehicles (e.g., onboard truck sensors capable of transmitting truck or axle weight data), and (4) acquire other readily available data. In addition, research is needed to explore the feasibility of using inexpensive portable WIM data collection equipment and methods to aid in estimation of traffic loads for pavement design in combination with other data sources. Georgia DOT has found portable WIM data to be a viable source of general traffic loading information that could be used as an aid in selecting default values for high significance pavement designs that lack site-specific axle loading distribution data (10).

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Data Quality and Equipment Calibration

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STATE OF THE PRACTICE

Local cities and towns, MPOs and state DOTs collect highway traffic monitoring data (i.e., vehicle volume, class, and weight) for sections of roadway that represent travel on their surface transportation network. Continuous and short-duration counts of vehicles in the 13 FHWA classes are collected. Continuous counting involves collecting data continually in hourly or more frequent time increments. Continuous counting is similar to short-duration counting, but extends over an interval of more than one week in any given location and often includes 365 days per year of hourly (or 15 min, daily, etc.) traffic-counting data. Short-duration traffic data are normally acquired over one to seven days and represent the spatial data sets for the agency's roadways. Traffic data collection devices can be portable or permanently installed. Both require reliable and timely calibration and the ability to provide accurate data in support of roadway network decision processes. Equipment calibration can be simple when performed for volume counting vs. complex when utilized to calibrate WIM sites. QC and QA methods are most often contained throughout the process from field data collection to office processing and eventual production of the final data products. Accurate reporting of vehicle classification is important as class data are utilized in numerous ways from pavement design, to studying the environmental impacts of highways, and to supporting the mobility of goods movement in the United States.

Field calibration of traffic equipment must be performed at a minimum of every year as detailed in the FHWA TMG (1). The TMG provides guidance for state, local, and other transportation agencies involved in traffic data collection programs. For example, its recommended methods for volume calibration are by lane with a set minimum number of vehicles or time period by requiring the number observed by a ground truth device to match that from the counter within a given tolerance. Ground truth recommendations include manual counts performed by human observers, video recording with post processing counts by human observers, or comparison with a gold standard counter used only for calibration of volume counting devices. Equipment used to obtain field counts typically has accuracy within 5% to 10% of the true count. Standard forms should be used for recording the field counts and calibration results over multiple years.

Parameters calibrated at vehicle classification sites include speed; calibration is best performed utilizing a laser speed gun. Ensuring the site's speed data are accurate will also ensure the accuracy of the bumper-to-bumper or axle spacing measurements made at the site. The latter are needed for vehicle classification. Typically speed verification tolerance is within 1 to 2 mph. This is usually performed over a few-minutes interval by measuring the speed of different vehicle classes (by length or axle spacing) in each of the lanes. If the speed of the vehicle is accurate (within 1 to 2 mph), most often the counting and axle spacing are accurate, leading to proper vehicle classification. A second method for verifying the accuracy of classification sites involves having a vehicle of known bumper-to-bumper length or axle spacing travel across the sensor array in each lane. The final method for verification of vehicle class involves calibration by lane using manual class counts or video data to compare with the classification device under calibration. This method is among the best for checking the accuracy and should be done on a per-vehicle basis, checking each vehicle against the visual vehicle classification.

For WIM sites, calibration often requires utilization of vehicles of known weight, length, and spacing of each axle. The FHWA LTPP and long-term bridge performance studies of calibration of WIM sites recommend utilizing two different types of vehicles (one smaller vehicle and one fully loaded five-axle semi-truck). WIM calibration methods are specified in ASTM Standard E1318-09 (2) and elsewhere (3, 4). WIM site calibration is critical because spacing and weights from the sensors can vary over time and thus affect the accuracy of the measurements. There are various methods used to monitor the calibration of WIM sites including: (1) front axle weights of specific vehicle classes, e.g., five-axle semi-trucks (FHWA class 9), (2) tandem axle group weight distributions, and (3) GVW over time for a given time period or specific day of the week such as Wednesday.

Although each agency often collects both continuous and short-duration counting traffic data for their specific needs, there are several similarities across the nation's traffic monitoring programs in regard to calibration and QC. Documentation of procedures, standards, and specifications is normally performed by the state DOTs. Every traffic-counting program must provide their data to their customers and the goal of every count is that it represents what actually took place on the roadway for the reported period of time.

STATE OF THE ART

State-of-the-art programs utilize automated systems to manage the data quality (i.e., reliability and accuracy) and provide near real-time information resulting from the effective deployment of resources and corrective actions. Automated systems provide counts, initial QC checks to ensure the completeness and initial quality assurance of data, advanced QC checks to ensure the data meet nationally acceptable ranges and methods to store and report traffic data. Transparency concerning the methods employed and the results from the data calculations and reviews often occurs through documentation of practices.

Reference guidance for counting developed by the AASHTO is found in the *Guidelines for Traffic Data Programs*, 2nd edition (5). This document establishes recommended national traffic monitoring practices that reflect current practice. Differences across traffic monitoring technologies and advances made in the past several years in data collection methods are described in the 2016 TMG. Many state DOTs and other agencies are finding more-detailed collection and reporting of traffic data is required by the HPMS (6) and are trending toward collecting per-vehicle data at more locations. The detailed data supports improved methods to check data quality and correct issues as they are found. Per-vehicle data also supports advanced QC methods when post processing the data, along with the added value of a rich data set that provides speed by vehicle class, weight from WIM sites, and travel by vehicle type that is more detailed (when utilizing vehicle signatures) than the 13 vehicle classes specified by FHWA.

Many agencies have documented methods for QA, QC, and database structures. These include by lane automated feedback, e-mail of daily downloads, completeness, quality issues, and status of each day's data. *Seven Deadly Misconceptions About Information Quality* (7) is a document that assists in understanding data issues, what parts of data affect data quality, and how to best account for issues as they are detected. This information is helpful for repair,

troubleshooting, and identifying those sites that may warrant further scrutiny. The AASHTO traffic monitoring guidelines and FHWA TMG recommend periodic review of procedures utilized by traffic monitoring programs in the areas of QA, QC, calibration, and daily reviews of the traffic data no matter what their source.

There are also NIST methods and documents that describe calibration of data collection systems. New NIST standards on the use of WIM data are being investigated. In addition, the FHWA LTPP pooled-fund (8) and other studies contain data quality checks for both classification and weight data collection.

The TMG lists numerous issues that affect calibration of traffic-counting sites including QC methods employed in the FHWA TMAS. These are found in TMG Appendix J and the other references that describe data quality issues that agencies experience, such as applying best practices to check volume, classification, and weight data. Additional information concerning WIM data collection sites and the associated quality and calibration aspects of collecting WIM data are reported in Iowa State University's Center for Transportation Research and Education *Weigh-in-Motion Handbook (9)* and other sources found in Chapter 5, in the WIM article in this E-Circular.

EMERGING TRENDS OR DRIVERS OF CHANGE

Agencies are trending toward collecting more travel monitoring data. Whereas they used to collect only classes 4–13 for WIM data, many agencies now collect data for all vehicle types at WIM sites. There are now over 10 state DOTs collecting all per-vehicle weight data. Data collection includes collection of speed data, nonmotorized data, PVF data, crowdsourced data, or sometimes real-time data. In the past, data used to be by site; now data are collected and stored by travel direction or by lane. In addition, data are now usually summarized by 15- or 5-min intervals or per vehicle rather than by the hour. Many state DOTs and portable device vendors are moving toward collecting PVF data. In dealing with funding issues and reduced numbers of staff to complete quality data reviews, agencies are leaning toward more automated systems to obtain, review, store, analyze, and report the data. This has led to a number of companies providing QC services for agencies in the United States. Additionally, there are agencies that now pay for data that are both complete and of good quality instead of having the in-house staff perform such work. The 2016 TMG recommends that agencies shift to PVF data recording and storage because of the ability to improve data utilization, added QC methods, and the ability to provide more-detailed information to traffic data users.

One reason for the transition to new data collection methods and sources is that 10 years ago limitations were present in the cost of field data storage, transmission rates, and device central processing unit (CPU) speeds have been overcome or reduced to acceptable levels. With increased data resolution and availability has come a significant improvement in automated processing. Whether purchased from a software company or gathered by agency staff, traffic data are reviewed and processed faster than ever before. Many agencies are being pressed to provide data online and such public review and feedback have led to improved information in support of better decision-making.

Another driver of change is the shift from the AADT process developed by AASHTO in the 1980s (which used daily volumes to compute AADTs) to the improved FHWA AADT calculation method, which utilizes data of any time increment (1 min, 5 min, 15 min, or hourly) (1). The newer AADT method improves upon accuracy and exploitation of datasets from

nontraditional sources (primarily ITS), even those that contain gaps. This leads to larger and more-integrated traffic datasets, additional comprehensive calculations, improved AADT quality, and an increase in detailed information for reporting purposes.

Collecting traffic data once and using the data for many uses many times is a trend that numerous data collection agencies, including the FHWA, have been in support of for many years. For example, WIM data have been utilized to create spectra for site-specific axle loads used in pavement management applications (10). State DOT agency continuous-count WIM data are also provided to the FHWA through TMAS, which incorporated nonmotorized processing and data storage at a national level in TMAS version 2.8 in 2017.

Most agencies are pursuing geolocating their traffic counts and providing the ability to visualize the data on maps and with other data on GIS layers to make informed decisions. Geolocation data are important in that they are larger, can be quality analyzed and integrated with other datasets in new ways, and allow for a greater utilization of the data when merged with other large datasets (i.e., safety, roadway management, or operations). The spatially represented data are in alignment with processes that collect the data once correctly and use it many times. A recent FHWA pooled-fund study examined advanced methods to visualize data and review the information spatially and temporally (11). These techniques allow improved analysis and utilization of the rich set of class and weight data that traffic monitoring sites provide.

Traffic data collection programs are also key in providing information to an agency's overall asset management system. Several publications describe data collection systems as part of the asset management function, for example, *Data Systems and Asset Management (12)*.

GAPS IN PRACTICE OR KNOWLEDGE

Traffic monitoring program staffs continue to integrate multiple equipment and data sources into their programs. However, traffic monitoring program data quality requirements hinder some interagency departments from sharing traffic monitoring sites, installation, equipment, and data. This is a gap in both knowledge and practice, as many DOTs have yet to overcome data integration challenges due to technology configuration, cultural, and institutional coordination. By integrating datasets, the quality and calibration of the data from traffic sites can be independently verified as with FHWA data from HPMS, TMAS, and NHTS. These sets of volume data afford many opportunities to check data using nontraditional sources to insure trends and reported values represent the vehicle mix actually traveling on the roadway network.

Most issues with utilizing ITS data for traffic monitoring result from the absence of complete datasets due to a lack of technical knowledge about how to install and configure a site for both traffic monitoring and ITS operational purposes. With the development of FHWA's new AADT calculation method, many ITS locations can be used as continuous-counting sites if data from each time increment for each day of the week are present for each month of the year.

Manual data analysis becomes more complex as additional data from traffic sites are collected. Automated methods to verify the quality of the data is therefore needed. The old way of reviewing gaps in counts from counters, to reviewing pages of hourly counts from permanent counters, to now receiving reports and summaries of travel trends over various times has led to significant improvements for some agencies. This is beneficial for agencies that have modernized, but not all agencies have done so. Thus, there is cause for concern with inconsistent QA/QC methods employed by state, MPO, city, and local agencies.

Documentation of the methods used, key fields, database relationships, and availability of the data is lacking to fully utilize the rich and large traffic datasets available today. With proper documentation, large datasets can be more fully utilized and can be managed more easily. Public agencies are just now starting to release vast amounts of data and the combining of the spatial data, different attributes, and structures appears to be the next set of hurdles to overcome. Nonmotorized calibration, accuracy, and QA/QC methods need to be established to assist in establishing consistent data programs that support multimodal analysis.

Most data acquisition and reporting programs specify a tolerance that expresses the acceptable variability in the data. However, the accuracy or tolerance is often not related to a confidence interval or level. Thus, if a technician installs a road tube to obtain a needed count and it reports 9,250 axle hits that are then divided by 2, the agency reports a traffic count of 4,625 and may even designate it as the count representing a typical day. In reality, it is far from the truth without proper axle correction factors, hour of day, day of week, and month of year factors to ensure its accuracy. Establishing standard methods for obtaining counts and the associated accuracy of the different methods would contribute to informed decision-making based on good quality data versus data that may be questionable. Therefore, it should be the goal of the traffic-counting industry and the Highway Traffic Monitoring Committee to work toward establishing methods for obtaining the required accuracies and associated confidence intervals for volume, speed, classification, weight, and nonmotorized counts.

CURRENT NATIONAL RESEARCH AND INITIATIVES

Several agencies are exploring data visualization and integrating data with internal and external partners. The FHWA Pooled-Fund TPF-5(195) on Web-Based Traffic Data Visualization and Analysis Tools (11) developed methods to display and spatially represent WIM data on maps to view classification and weight data and other data quality issues in new ways.

A Small Business Innovation Research initiative that explored inductive loop detector signatures for vehicle classification concluded in the fall of 2017 (Phase II). This work improved the quality of classification counts and provided speed and detailed class of up to 200 unique vehicles from single-loop data. By using more detailed class and possibly reidentification of vehicles in the traffic stream, one may be able to gather additional information about the vehicle classes in the traffic stream and improve the quality of the data and calibration between traffic-counting sites.

FHWA started a project in 2017 to review all traffic terms appearing in HPMS, TMG, MIRE, *Highway Capacity Manual*, Institute of Transportation Engineers, etc., ensure that methods utilized to calculate a given traffic item are complete and correct, and reconcile any variances between documents.

FHWA also has initiated research projects to support MIRE for local AADT data collection and HPMS on local VMT calculations. Both of these are ongoing and are being led by offices within FHWA.

Nonmotorized research is currently being conducted by FHWA concerning collection methods and consistent reporting of nonmotorized counts for the United States. It is FHWA's goal to establish a national bicycle network compatible with the GIS HPMS roadway system.

Numerous state DOTs are enhancing their GIS networks to include bidirectional travel, more-detailed data integration within the state, better QCs, and more accurate data for the annual HPMS data submissions and items that support the FHWA TPM 1, 2, and 3 initiatives.

PROPOSED NATIONAL RESEARCH AND INITIATIVES

1. Study to determine the accuracy of traffic counts (volume, class, speed, weight, and identification of nonmotorized travel) needed for different applications of traffic data. Outcomes include accuracy and other attributes of research grade data, accuracy of WIM sensors for highway design, and accuracy of classification data for environmental and freight management applications. For example, is 10% accuracy good enough for vehicle classification data? Should the concept of a confidence interval be incorporated into ASTM Standard E1318 and if so, how? How many sites does one need in a state or metropolitan planning district to get a sufficient number of vehicle classification data samples? Should the number of sites be based on the type and funding resources of the agency providing the data, its service area, or the variability of the roadways?

2. What new methods can be employed to help automate site calibration? Is there a way of using cell phone or roadside readers that collect transponder, GPS, and Bluetooth information to verify classification site accuracy?

3. Can data be identified to fill in missing counts and, if so, how much data are needed and how should one tag the data or should it not be tagged at all?

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Integrating Traffic Counts with Connected Vehicle Data

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STATE OF THE PRACTICE

Connected vehicles communicate with each other through vehicle-to-vehicle (V2V) and with the infrastructure through vehicle-to-infrastructure (V2I) wireless communications. There are several commercial radio links to the vehicle mostly for entertainment and navigation that are sometimes referred to as "connected car," but the connected vehicle system described in the National Highway Traffic Safety Administration (NHTSA) Notice of Proposed Rule-Making of January 2017 is focused on safety and based on prior pilot programs and research that use dedicated short-range communications (DSRC) (1). DSRC radios function by using the IEEE 802.11-2012 wireless protocols that also specify Wi-Fi communications, and operate in the 5.875 to 5.925 GHz frequency band. NHTSA also released a policy document on automated vehicles (2). This chapter defines connected vehicles by the state of the practice just described, V2V communications via DSRC.

The first commercially available connected vehicles in the United States were introduced in March 2017 (*3*, *4*). Therefore, the state of the practice is defined by the Safety Pilot Model Deployment (SPMD) that tested over 2,700 connected vehicles in Ann Arbor, Michigan, from October 2012 to April 2013 and several other recent pilot studies that were conducted or are currently ongoing (*5*). These include Southeast Michigan and several analysis, modeling, and simulation testbeds that are evaluating the active transportation and demand management (ATDM) applications shown in Table 1. Although not indicated in the table, an additional testbed in San Diego, California, is analyzing potential ATDM applications that include queue warning, speed harmonization, intelligent signal control, dynamic lane use control, dynamic speed limits, dynamic merge control, predictive traveler information, managed lanes, and dynamic routing.

In most of the previous or current test programs, the primary data are conveyed by the broadcast of a basic safety message (BSM) by each vehicle several times a second (6). The standards prescribe a message transmission rate of 10 Hz, but that can be reduced during congestion. The BSM includes the GPS coordinates of the transmitting vehicle. Other nearby vehicles use this information to avoid accidents. The most common V2I messages sent by infrastructure transmitters are signal phase and timing (SPaT), which broadcasts information for a traffic signal, and MAP, which provide the geographic description of the intersection. Applications in the vehicles use the information to improve safety, fuel efficiency, and reduce emissions, among other things.

The BSM can contain as few as a dozen or over a hundred data elements (7). The most useful data elements for infrastructure applications such as counting and traffic management would be the GPS coordinates, heading, and speed of vehicles contained in Part I of the BSM. An extended BSM can also include descriptive data describing vehicle dimensions, vehicle class, and trailer data. All identifiers in messages from a DSRC radio are changed frequently to

		San		Dallas		
ATDM Strategy	Application	Mateo	Phoenix	(ICM^{a})	Pasadena	Chicago
Active traffic management	Dynamic shoulder	—	—			
	lanes	—	—	_		
	Dynamic lane use	—	—	—	\checkmark	\checkmark
	control	—	—	_	\checkmark	
	Dynamic speed limits	—	\checkmark		\checkmark	
	Queue warning	_	_		\checkmark	
	Adaptive ramp	_	\checkmark		\checkmark	\checkmark
	metering					
	Dynamic junction					
	control					
	Adaptive traffic signal					
	control					
Active demand management	Predictive traveler		\checkmark			\checkmark
	information	_	\checkmark		\checkmark	\checkmark
	Dynamic routing					
Active parking	Dynamic priced		_			
management	parking					
Dynamic mobility	DMA^b program			_		
	evaluation					

TABLE 1 ATDM Testbed Applications

^{*a*} Integrated corridor management.

^b Dynamic mobility Intelligent Network Flow Optimization (INFLO) application consisting of queue warning, speed harmonization, and cooperative adaptive cruise control, and the Multimodal Intelligent Traffic Signal Systems application.

prevent tracking and protect the anonymity of drivers. But this also impedes the use of BSMs to measure travel time and origin-destination flows.

Therefore, in addition to the BSM, the SAE J2735 standard defines probe vehicle data (PVD) and a probe data management messages with the purpose of sending snapshots of data for use by infrastructure applications. Besides weather-related status flags, vehicle position, and vehicle class, these data include an optional vehicle identifier for selected types of vehicles.

The BSM is designed for safety applications, and hence transmits over a short range with low latency and small size. Short range requires many infrastructure receivers in order to use them for traffic data collection and management. Because the PVD message was designed for mobility rather than safety applications, it collects the snapshots and stores and transmits them later when in proximity of a V2I receiver making it a better choice for traffic data collection in a wider range of environments.

The U.S. DOT has made data from some connected vehicle pilot programs available to researchers via the Research Data Exchange (RDE). Data currently available include those data collected in the SPMD. This information was uploaded in December 2016 and includes the entire dataset captured and a sample dataset collected on April 11, 2013. Other SPMD data from April 5–7, 2013 was scheduled to be uploaded in December 2016, but has not yet been included in the RDE. This dataset is called the Enhanced Operational Data Environment (E-ODE) and includes vehicle responses to emulated road weather warnings, incident zone warnings and other unique circumstances.

Other connected vehicle (CV) data available on the RDE include simulation results from Phoenix and Dallas testbeds, among other locations. BSM data are also included in the RDE from a number of studies, including the SPMD. Likewise, data captured by Roadside Equipment (RSE) during pilot studies are available on the RDE.

One of the biggest benefits of the RDE is its influence on data formats and language. This is because each dataset imported into the RDE has to meet specific standards in order to avoid compatibility issues between datasets. This results in the standardization of language across datasets originating from various entities and agencies across the country (8), which will ensure interoperability and communication in the future between CV infrastructures as connected vehicles begin to infiltrate the market at a higher rate.

The U.S. DOT plans to migrate the data in the RDE to a new Open Portal that should supersede the RDE by the end of 2017. Open Portal is described later in this chapter under Current and Proposed National Research and Initiatives.

STATE OF THE ART

The U.S. DOT ITS Joint Program Office sponsored research to develop a basic mobility message (BMM) and dynamic interrogative data capture (DIDC) to better support mobility applications. The BSM is transmitted at short range at a fixed rate, typically 10 times per second (10 Hz) via DSRC to support safety applications. The PVD message has a more variable content and sends a single snapshot from multiple sources also via DSRC. The PVD can be sent periodically, when triggered, or when certain start and stop conditions occur, dependent on time, distance, and receiver availability.

The BMM is similar with the following improvements. It supports additional nonstandard data elements and may contain multiple snapshots from multiple sources. It can also be sent periodically, triggered, or conditionally, but the actual transmit times are stochastically varied to reduce reidentification risk. The other fundamental difference is that it is designed to use multiple communications media such as cellular, Wi-Fi, and DSRC.

When there are millions of CVs on the road, the huge quantity of data, much of it redundant for traffic data uses, will be a significant burden on communication systems. The DIDC uses a controller and control messages to optimize transmission and capture of vehicle-based data. Preliminary simulations indicate that BMM with DIDC can reduce the communications load by 99%. This is important for CVs to be able to support applications beyond safety.

The U.S. DOT awarded funds to deployment projects in three locations: New York City; Tampa, Florida; and Wyoming. These projects, which are currently being implemented, will be the first to use equipment that may be the first generation of deployable commercial equipment rather than prototype or developmental equipment. They will be the first to use the scalable version of the security credential management system (SCMS) called the proof-of-concept (POC) SCMS to provide cybersecurity and anonymity for the vehicles. These projects will also be the first to use equipment that has gone through the nascent certification process being developed to insure interoperability and security. The sites will use CV data for traffic operations and could include counts for other reporting.

EMERGING TRENDS OR DRIVERS OF CHANGE

Privacy continues to be one of the biggest concerns among the public with regards to automated vehicles and CVs, and drivers are right to have a reasonable expectation of privacy (9). Specifically, people don't want to be tracked and don't want their destinations to be discoverable to private or public entities. There has therefore been a strong push to anonymize captured data. This has been successfully accomplished in the industry, but it creates a problem for those wishing to collect travel data on these vehicles, particularly travel times. As a result, many have undertaken to find a solution to this issue. These solutions come in many forms, either through promise of maintained privacy to the public or by allowing the public to compromise on this issue by ensuring faster travel times as a reward for sharing their information.

A number of methods for capturing travel data have been proposed by researchers across the United States and Europe. One such method suggests piecing together fragmented travel segments from vehicles that have changing IDs, which will provide a reasonably accurate estimation of travel time along a corridor (10). Along a different vein, methods of compensation have been suggested that would encourage drivers to share information about their travel and driving behavior. Some insurance companies now offer drivers the option of installing a device in their vehicle that tracks their driving for the purpose of gauging driver safety. Thus far, this information has been used primarily by the insurance companies to determine driving styles, but the information captured could be provided to transportation agencies in order to capture travel information along routes maintained by that agency. Researchers in Albany, New York, have proposed a method to maintain driver privacy while still capturing driving styles for insurance companies (11). Likewise, methods like the "Highway Voting System" have been proposed to entice drivers to loosen their grip on their privacy in order to provide valuable traffic data to traffic management centers, which would result in quicker service time along their travel path (12).

The growing cyber threat is another critical trend highlighted by attention to hacking vehicles and traffic signals at DEF CON and Black Hat (the largest hacker conferences) in 2016 and 2017. In addition to the cybersecurity issues faced by traditional ITS, the distributed communications network and equipment ownership of connected and autonomous vehicles opens additional attack vectors. Potential attacks from the vehicle side include sending incorrect data, impersonating another vehicle, or even creating false data to impact safety and operational CV applications. Validation and network security issues in CV applications closely mirror issues described in other IoT applications. CV implementations could benefit greatly from incorporating lessons learned in existing IoT systems. A distributed denial of service attack is possible where a multitude of falsified messages are sent to flood the server to prevent real messages from being received. Vehicles can be similarly overwhelmed by too many false broadcast messages.

Other topic areas that are influencing the CV–AV industry are equity, data ownership and management, and funding. Regarding equity, a fear among some is that CVs and AVs will only be available or beneficial to the wealthy driving public, because retrofitting older vehicles is likely out of the question (due to cost of adding the required hardware and software capabilities) and not everyone can or will utilize these vehicles. The FHWA is aware of this issue and is attempting to get out in front of it before CVs are mass developed for the driving public. In fact, the Accessible Transportation Technologies Research Initiative is already researching ways in which CV and AV can assist disabled individuals or those whose travel is typically

nonmotorized (13) by providing information about vehicles in close proximity to pedestrians or bicyclists, which could greatly reduce the stress sometimes involved in nonmotorized travel.

Data ownership and management has been a persistent issue among transportation agencies even without consideration of CVs, as many agencies (local, county level, or statewide) have been unwilling to share and coordinate data with neighboring agencies (14). Additionally, these transportation agencies struggle with modification of their data management systems, state and agency policies on freedom of information, and how to utilize the potentially enormous amount of data in a timely manner while dealing with limited resources for program expansion. There are also continuing concerns over data ownership, an unwillingness to reformat existing data, or simply a fear of being judged by their peers regarding current practices. These hurdles have to be crossed if CV technology is to be successful, and this will likely start with education of transportation and safety agencies on the benefits of data sharing (safety improvements, congestion mitigation, cost savings, etc.). Fortunately, researchers have already begun informing agencies of the value of interagency data coordination and sharing, mainly through presentation of benefits of such coordination directly to a number of state and local agencies (15).

The development of wireless connectivity other than DSRC, such as 5G, is another trend to observe. It is possible that DSRC will become part of a heterogeneous 5G network that sets the rules between 5850–5925 MHz, or that it could be displaced by other technologies under development (16).

Another driver of change is the need for a self-sustaining business model or funding source to pay for the infrastructure portion of the CV system. Related questions are: will this involve infrastructure funding for other types of data acquisition such as traffic counting? Can counting programs use CV data as planned, or do they need to ask for specific information to be included in the CV data transmissions?

GAPS IN PRACTICE OR KNOWLEDGE

To date, CV communications are based on periodic messages, which may not be timely enough to support applications that must respond to irregular or unplanned events. The network communications and computing needs of CV applications depend on the urgency and scope of actions to be taken ranging from immediate safety needs to system monitoring. Those focused on safety rely on communication, algorithm execution, and decision-making to occur as quickly as possible. DSRC is capable of transmitting BSMs at a 10-Hz repetition rate, which allows vehicles to detect threats in time to avoid them. This must be done by broadcast (V2V or I2V) because the latency of a centralized or cloud processing system is too large for a safety application to prevent accidents.

The small latency requirement highlights the need for computing at the edge, meaning that computing and decision-making are performed in the vehicle to minimize the time for the system to warn drivers of safety issues, instead of this computation being performed in the infrastructure and only afterwards transmitted to the vehicle. On the other end of the spectrum of communication and computation needs, systemwide monitoring depends on aggregating the petabytes of data collected in a scenario where all vehicles are connected. The aggregation allows for more centralized processing and requires connectivity between RSEs collecting and aggregating messages and the server performing the network algorithms.

Other significant gaps include the following:

• The security of the SCMS has not yet been fully tested and proven. The POC SCMS is still under development with initial functionality due late in 2017.

• The trade-offs between onboard computing speed, computing bandwidth, and channel congestion are still not fully understood. This affects what computing can be done at the edge and what needs to be done in the infrastructure.

• Traffic agencies must still develop procedures for handling CV data that mitigates privacy concerns on the part of the public.

• Agencies responsible for traffic counts still don't know enough about CV data to understand how best to use it and what possibilities it might allow them.

• The impact of big data is poorly understood at present. New big data analytics have the potential to break the privacy of data that has been "anonymized," complicating efforts to avoid privacy concerns when collecting and using CV data.

CURRENT AND PROPOSED NATIONAL RESEARCH AND INITIATIVES

The U.S. DOT Intelligent Transportation Systems Joint Program Office (ITS JPO) is considering undertaking research leading to Event Driven Configurable Messaging that would provide the needed responsivity for sudden events and the flexibility to adapt to unforeseen future requirements of CV communications. How this might be beneficial for traffic data collection has yet to be determined. Other relevant projects recently completed or currently under way are listed below.

• Open Data Portal (under way). A public data sandbox to ingest large data sources that may be streaming and provide an interface for public use and sending primary data samples to data.transportation.gov (U.S. DOT's repository for primary data, e.g., from sensors). The project is in Beta testing through the summer and fall of 2017. Dataset areas that can be browsed include: CV Message, Application Message, Trajectories, Field Test, Sensor Data, Research Results, Connected Equipment, and Weather. Early featured data sets include a BSM point map of all the BSMs collected in the Advanced Messaging Concept Development (AMCD) field testing, all the BMCM's generated during AMCD field testing, and analyzes of the projects proposed by the seven finalists in U.S. DOT's Smart City Challenge (https://www.its.gov/data/accessed August 15, 2017). The public can track the progress of this work at https://github.com/usdot-its-jpo-data-portal/ (accessed August 17, 2017).

• Connected Data Systems (CDS) Program Integrating Emerging Data into Operational Practice Study (under way). The CDS Program seeks to operationalize scalable data management and delivery methods, exploiting the potential of high-volume multisource data to enhance current operational practices and transform future surface transportation systems management. This next-generation cross-cutting data research program is the natural successor program and builds on the success of the data capture and management program. The CDS Program recognizes that data-related research is needed across all programs, including CV pilots, connected automation, and smart connected cities, among others.

• ITS JPO CV Dynamic Mobility Applications (DMA) Program, particularly INFLO. The INFLO application from the ITS JPO CV DMA Program focuses on increasing throughput and reducing crashes by disseminating data gathered from CVs and infrastructure to roadway travelers. This can come in the form of the INFLO queue warning system, which provides drivers with information regarding downstream queues in order to avoid secondary collisions, the dynamic speed harmonization system, or the cooperative adaptive cruise control system— both of which serve the purpose of coordinating speeds among vehicles along a corridor or in a platoon in order to maximize throughput in given circumstances.

• ITS JPO CV Pilots Deployment Program. Three CV pilots are under way in the CV Pilot Deployment Program: New York City, Wyoming, and Tampa, Florida. The program is a national effort to deploy, test, and operationalize cutting-edge mobile and roadside technologies and enable multiple CV applications. These innovative technologies and applications have the potential for immediate beneficial impacts. The New York City pilot is focused on the safety of travelers and pedestrians in the city through the deployment of V2V and V2I CV technologies. The Wyoming pilot site focuses on the needs of the commercial vehicle operator in the state of Wyoming and will develop applications that use V2I and V2V connectivity to support a flexible range of services from advisories including roadside alerts, parking and inclement weather notifications, and dynamic travel guidance. The Tampa pilot site will deploy a variety of V2V and V2I applications to relieve congestion, reduce collisions, and prevent wrong-way entry on reversible express lanes (http://www.its.dot.gov/pilots/index.htm; accessed August 17, 2017).

• AASHTO SPaT Challenge. The AASHTO CV SPaT Deployment Challenge is being led by the V2I Deployment Coalition through AASHTO, ITE, and ITS America, with support from the AASHTO CV Working Group. The challenge was issued to deploy DSRC infrastructure with SPaT broadcasts in at least one corridor or network (approximately 20 signalized intersections) in each of the 50 states by January 2020. The SPaT message includes the current signal state for each approach lane at a signalized intersection as well as any active pre-emption or priority (https://www.transportationops.org/spatchallenge; accessed August 18, 2017).

• AASHTO/ITS JPO National CV Field Infrastructure Footprint Analysis Final Report, 2014 (http://ntl.bts.gov/lib/52000/52600/52602/FHWA-JPO-14-125_v2.pdf; accessed August 17, 2017).

• AASHTO/ITS JPO Near-Term V2I Transition and Phasing Analysis CV Application Prioritization Tool (under way). As part of a suite of tools, AASHTO and ITS JPO are developing a life-cycle cost model for V2I applications that will detail all cost components associated with deployment of V2I applications over a 20-year period. The model has researched costs included, but also has the flexibility for users to change costs. It is anticipated the cost model will provide users with insight and detailed estimates for installing, maintaining, customizing, and operating all needed elements of V2I applications.

• FHWA Office of Operations Advanced Traveler Information System (ATIS) 2.0 (under way). As a result of the rapid evolution of technologies and tools available, FHWA has initiated new technical initiatives to investigate, plan, develop, design and implement Next Generation or ATIS 2.0 solutions. This includes the investigation and design of new systems suitable for the collection and aggregation of traveler intent data for the use by system managers. The concept of operations or ConOps (October 2016) is available at https://ntl.bts.gov/lib/61000 /61100/61164/FHWA-JPO-17-481.pdf (accessed August 28, 2017). The ConOps provides an operational overview of the ATIS 2.0 Precursor System to be demonstrated in conjunction with TranStar in Houston, Texas. The new ATIS 2.0 Precursor System will advance the state of the practice for ATIS by incorporating traveler intent data in order to provide congestion prediction systems for use by system managers.

• FHWA Office of Policy CV Impacts on Transportation Planning (https://ntl.bts.gov /lib/59000/59200/59249/FHWA-JPO-16-412.pdf; accessed August 17, 2017). This report

established a roadmap for the state of the practice prior to 2016 and the potential next steps with regard to research and development of CV and AV systems. It detailed the capabilities of the existing technology and suggested potential necessary improvements, mainly pertaining to simulation models, as the modeling tools available up to that point had some inadequacies in correctly forecasting traffic with the introduction and influx and CVs and AVs.

• 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; accessed August 17, 2017). This research cataloged open issues that need to be resolved to enable successful deployment of CV–AV. The issues that will affect agencies and the public were organized into four areas: institutional, legal, policy, and operational. The researchers then narrowed the catalog to critical issues suitable for near-term research. Last, they were consolidated into research projects that are needed to address the highest priority issues and described in a roadmap that estimates the time and resources required for each. The projects are grouped into four general subject clusters: institutional and policy, infrastructure design and operations, transportation planning and, modal applications.

SUGGESTED RESEARCH PRIORITIES

Research concerning the following topics is most likely to have the greatest impact on the potential for counting and traffic management programs to exploit CV data. Early AVs are likely to use standardized CV data because AV data needs are less well-defined, more proprietary, and lack standards. Any potential benefit to sharing explicit AV data won't become obvious until AV development is more mature.

1. What interface should be used for counting programs and traffic operations to exploit CV data? How can local and state traffic authorities be cleared to connect?

2. Will the planned messaging for CVs meet the needs of traffic operations and counting programs? If not, what requirements should be input to advanced messaging research?

3. How can traffic authorities maximize the benefit of access to CV data? What potential does it unlock? What skill set changes are required?

4. How can unintended privacy issues be avoided in applications that involve the use and storing of CV data?

5. What is the impact of big data development analytics on extracting value from connected data and the risk of compromising privacy?

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TRAFFIC MONITORING STATISTICS, DATA QUALITY, USAGE, AND INTEGRATION

Travel Time, Speed, and Reliability Data

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STATE OF THE PRACTICE

Travel time, speed, and reliability data are commonly used by transportation agencies and researchers to quantify the quality of flow on the transportation network. Transportation agencies are increasingly focused on developing system performance measures to monitor overall network congestion, so these data sources have gained importance in recent years. Sources for travel time, speed, and reliability data have undergone rapid expansion in recent years, with a number of new data streams gaining widespread use in the last decade.

Data sources for speed, travel time, and reliability analysis can generally be categorized as probe-based systems, point detector systems, or systems that fuse both sources. Probe-based systems use data from a subset of vehicles to estimate overall traffic conditions on a network. These systems often track vehicles over space as they travel. Point detectors typically collect detailed information on vehicle speeds at a discrete point on a road. Table 1 lists the data sources currently in common use by agencies.

When one or more sources of data are available, travel time reliability measures could be derived if a long time-series of data is available. There are four reliability measures recommended by the FHWA: 90th or 95th percentile travel time, buffer index (BI), planning time index (PTI), and frequency that congestion exceeds some expected threshold (1). These measures are used in applications at national and state level. Additional measures of reliability are also included in the MAP-21 rule-making scheduled to go into effect in mid-2017. Some DOTs calculate reliability or congestion measures through their own data sources, and provide that information to the public (2, 3). There are also some DOTs who conduct studies on reliability measures as a part of their performance measure projects (4-6). While the MAP-21 rule-making will provide national level consistency in reporting on congestion and reliability, there currently exists a great deal of variation in the degree to which transportation agencies assess overall system congestion and reliability. Some DOTs also use travel time reliability data as a QC dataset to perform quality assurance examinations of their collected and calculated traffic data statistics, such as the AADT volumes and traffic classification data (passenger car, truck, multitrailer, etc.).

STATE OF THE ART

Although state DOTs and FHWA place increasing emphasis on quantifying system performance in terms of network speeds, travel times, and reliability, there remains a great deal of variation in the

System Type	Data Source	Characteristics
Probe-based systems	Bluetooth and Wi-Fi reidentification	These detect media access control (MAC) addresses broadcast by wireless phones, computers, and other devices located in vehicles. MAC addresses are matched at multiple locations to determine segment travel times. Since these systems are low cost and easily installed, a number of agencies have deployed these systems (7).
	Automatic vehicle location (AVL) devices	These utilize GPS data from a subset of vehicles in the traffic stream, typically transit vehicles, taxis, or trucking fleets. The data can be used to determine travel times, although additional screening may be required if vehicles are not representative of overall traffic characteristics. An example is AVL data from taxis in New York City (8).
	Automatic vehicle identification and toll tag devices	These schemes access the elapsed time between entry and exit points of vehicles equipped with electronic toll collection tags or other identification devices at toll collection gantries. The technique is effective on routes with a high penetration of equipped vehicles, but may not provide coverage further away from the tolled route (9).
	Automatic license plate readers (ALPRs)	ALPRs function similarly to MAC address and toll tag readers. ALPRs typically capture a larger sample of the traffic than MAC address and toll tag readers, but may be more expensive.
	NPMRDS	This set of probe data is provided by FHWA to public agencies to assist in performance measurement on the NHS. Only raw data from a private sector company is included with no imputation (10).
Point detector systems	Inductive loop detectors	Inductive loop detectors are commonly used to detect vehicle presence and measure traffic flow speeds. They can provide a measurement of the true population speed of vehicles, but they are often only densely installed on urban freeways. Extrapolation of the data away from the sensor location must be done with care.
	Microwave presence- detecting radar	Side-mounted microwave radar sensors capable of multi-lane detection are increasingly used by DOTs as a supplement to loop detectors since they do not disrupt traffic flow for installation or repair and are not subject to deterioration from road repair and heavy loads passing over them. Occlusion due to large vehicles can result in missing or inaccurate information in lanes furthest from the mounting location. Multi-lane microwave radar sensors are also available for mounting in a forward-looking configuration. This approach may avoid some of the occlusion effects experienced in side mounting, but may still be subject to occlusion when a large vehicle is stopped in front of a smaller one.
	Video detection system	Video detection systems are another sensor frequently encountered along highways and surface streets for collecting count, speed, occupancy, and other types of data such as lane change information. Users should be aware of possible limitations during night operation that may require street lights; heavy rain and snow, fog, haze, dust, smoke, sun glint, and glare; shadows (false or missed calls); reflections from wet pavement (false calls); vehicle occlusion in distant lanes when camera is side mounted; and projection of tall vehicles into adjacent lanes (false calls) and headlights past the stop bar (dropped calls).
Fused systems	Private-sector data	Private-sector sources provide fused data from AVL devices on commercial fleets, GPS smartphones, and available DOT sensors to estimate speeds and travel times using proprietary algorithms. These companies often afford broad spatial coverage at a lower per-mile cost than physical sensors. Travel time estimates are well validated on freeways, but arterial data quality varies by route. Examples of frequently used providers are HERE (<i>11</i>), INRIX (<i>12</i>), and TomTom (<i>13</i>).

 TABLE 1 Commonly Used Sources for Travel Time, Speed, and Reliability Data

degree to which agencies monitor their network. The second Strategic Highway Research Program (SHRP2) attempted to address this issue by establishing a reliability focus area and embarking on a program of projects between 2006 and 2015 that tackle concerns related to congestion and travel time reliability (14). The ultimate goal of this program was to develop methods and tools agencies could use to more formally and consistently assess travel time reliability across many projects.

Topics include the following (SHRP2 project numbers are shown in parentheses):

- Establishing monitoring programs for mobility and travel time reliability (L02);
- Methods to model the effect of projects on reliability (L03, L04, L08, L11); and
- Implementation guidance and assistance for implementing research products (L38, L55).

Over the past decade, a number of private-sector companies have begun selling travel time data derived from a combination of probe data and available agency-provided data. The University of Maryland has been conducting an ongoing vehicle probe project for the I-95 Corridor Coalition since 2008 to assess the data quality of various new and emerging probe data sources [15]. The project continues to assess these systems as they evolve, and has recently begun exploring options to estimate volume data from the probe data, which has historically been a limitation of private sector probe data streams. The methods are evolving, but involve the fusion of historic estimates, nearby real-time counts, and adjustments based on models relating real-time speed estimates with those from other volume sources.

Examination of travel time reliability and congestion remains an active research area nationally. Space limitations prohibit a full discussion of all active projects. One example is a project being performed by the Institute for Multimodal Transportation at Jackson State University, which is attempting to develop effective baseline models and algorithms to evaluate the networkwide performance using a simulation tool based on the travel time reliability determined using GPS probe data collected from the Mississippi DOT. This project will measure freeway performance in terms of travel time reliability and locate congestion "hot spots" based on GPS probe data in Mississippi following the techniques specified by the MAP-21 System Performance rule-making.

GAPS IN PRACTICE OR KNOWLEDGE

A number of gaps in practice have been identified as probe data systems have become more commonplace. These are discussed briefly below.

Lack of Standard Definitions of Travel Time Reliability

Travel Time Reliability Definition and Metrics

Reliability is commonly defined with respect to a failure. For most engineering systems or processes (i.e., mechanical systems or power infrastructure networks), a failure is a well-defined state—e.g., a power line is broken and results in a black out. In transportation, there are no such clear failure states. In transit systems, failure can be defined based on the on-time performance with respect to the trip schedules. However, the highways keep on somewhat functioning even under heaviest congestion

levels, and the failure can be defined from different but not necessarily objective perspectives. Elefteriadou and Cui summarize the existing definitions into two main categories: (1) reliability with respect to a failure threshold set with respect to speed limit and (2) with respect to user perception and how travelers budget their trip time (16). Accordingly, researchers define reliability measures and metrics such as 90th or 95th percentile travel times, BI, PTI, coefficient of variation, and misery index (1, 16). Some of the suggested measures can be expressed in terms of one another under certain assumptions (17). However, due to ambiguity of the failure states and subjectivity of user perceptions, the reliability measures and metrics may not give consistent reliability levels for the same travel time distributions. The lack of standard definitions and metrics presents an important challenge to the formulation of robust travel time measures.

Network Aggregation

Available travel time reliability metrics are generally defined and valid for individual links, segments, and routes. Once those measures are utilized for a network with multiple links, they lose their statistical significance and applicability. These issues can be avoided either by suggesting meaningful and scalable aggregation of link-based definitions and metrics, or by formulating network-specific definitions and metrics. Systems and networkwide thinking is lacking for formulating travel time reliability concepts. This is a critical need as agencies seek to develop regional reliability indices.

Lack of Comprehensive High-Quality Data Across all Facilities

Due to region-, location-, and facility-specific travel time patterns, research on travel time reliability is heavily data driven. New technological advances and tools (ranging from smartphone apps to CVs) help collect travel time data from sensors and other sources that were not previously available. Besides the nature of the data source, there is also a lack of comprehensive geographical and facility coverage. Probe systems have historically had more difficulty estimating average conditions on arterial routes than freeway systems. Travel time distributions are much more variable on arterials, particularly in locations where traffic control signals may create multimodal travel time distributions, or locations where there are numerous access points. Probe systems that rely on MAC addresses may have to screen out data from nonvehicular traffic such as bicycles and pedestrians in order to estimate average performance. The density of fleet data used by AVL and private-sector data streams may also be lower on arterial roads than freeways. High-resolution data from traffic signal controllers have also been used to try to improve the quality of data on these roads. The 2016 North American Traffic Monitoring Exhibition and Conference held a workshop that discussed many of the ongoing issues related to arterial data (*18*). Improved travel time data on arterial roads remains a need.

Accessibility of Probe Data Sets

Many data sets, particularly those from private-sector providers, are not publicly available or involve using data that was processed using proprietary algorithms. This creates a situation where probe data is not broadly available, which can limit research and use of these data. For technical and legal reasons, merging the information obtained from different sources into a comprehensive dataset can be challenging. However, there is no comprehensive travel time data

repository to which researchers and practitioners have access. The lack of data access prohibits interested parties to pursue improvements in travel time reliability research and implementations. **Need for Big Data Analytics Tools**

The increasing number of data sources and their level of information detail introduce the challenge of developing tools to analyze the available data. For instance, several probe data providers are offering detailed vehicle trajectory data for sale. These data sets include vehicle positions up to every second. This is potentially a very rich data set that could be used for traffic monitoring, but data sets are large and typical agency tools are insufficient to process and analyze these data sets. Similarly, as connected and automated vehicles enter the vehicle fleet, there is the potential for a tremendous expansion in the amount of speed and trajectory data that will become available. However, methods to collect, process, and archive this data as the market share for these vehicles increase are lacking. Moreover, there are no clear guidelines regarding what the researchers and the practitioners expect and need from data analysis tools.

Data Fusion

Fusion of data from multiple sources reduces the uncertainty from individual sources, and also enhances the information quality. However, there is no consensus on the methodologies for efficient data fusion. Best practices for fusion of probe and point detector data are needed. In particular, the following actions should be taken to close the aforementioned gap.

The first step of the data fusion process is to develop understanding of the data. Research is needed to develop a comparative overview of the characteristics of various travel time and speed data sources in terms of coverage, quality, granularity, data lag, usability, accessibility, spatial referencing, and license conditions (where applicable). It is also important to understand the variables (such as location, time of day, day of week, weather, vehicle density, availability of road mileage markers or other types of mileage delineators, number of lanes, presence of hills and curves) that can affect the above characteristics. These considerations should help define the strength and weakness of each dataset in meeting the travel time, speed, and reliability needs.

Literature on data fusion algorithms is fairly broad. These data fusion algorithms include artificial neural networks, fuzzy logic, Dempster-Shafer evidence theory, Bayesian inference, and Kalman filtering. "How to select a model" is a basic question that needs to be addressed. The answer to this requires development of appropriate criteria for model selection. The selection criteria should focus on the effectiveness, simplicity, operational constraints, and requisites for a priori information (19).

CURRENT AND PROPOSED NATIONAL RESEARCH AND INITIATIVES

This section is organized by the research gap areas presented above. Under each category, currently active and recently completed research projects are listed, followed by open research questions that should be considered for development into NCHRP RNS.

Lack of Standard Definitions of Travel Time Reliability Concepts

Current Research

• SHRP 2 L02: Establishing Monitoring Programs for Mobility and Travel Time Reliability.

• SHRP 2 L08: Incorporation of Travel Time Reliability into the *Highway Capacity Manual.*

- SHRP 2 L14: Traveler Information and Travel Time Reliability.
- SHRP 2 L38: Pilot Testing of SHRP 2 Reliability Analytical Products (various projects in several states).

Proposed Research

• Develop consensus based standard definitions of key travel time concepts. Issues to be investigated include:

- Identification of inconsistencies, ambiguities, and errors in our current understandings and definitions of

• Travel time as a fundamental observable phenomenon and

• Travel time distributions for discrete time intervals and system routes estimated from the various, available data sources.

- How should we define travel time failure states in the context of travel time reliability?

- Should travel time failure state definitions be defined to account for the varying perspectives of the system manager, operator, and system user, and if so, how?

- How can we develop meaningful and consistent travel time performance measures that are robust relative to data sources?

Network Aggregation

Current Research

• None known

Proposed Research

• Develop meaningful and consistent travel time reliability performance measures at a network level. This research would include methods and considerations for different spatial granularities encompassing route level, city level, and state-level metrics.

Lack of Comprehensive High-Quality Data Across All Facilities

Current Research

• SHRP 2 L13: Archive for Reliability and Related Data.

• SHRP 2 L16: Assistance to Contractors to Archive Their Data for Reliability and Related Projects.

• I-95 Corridor Coalition Vehicle Probe Project, Phase II.

Proposed Research

• Determine how regional and statewide travel time reliability data systems should be designed to achieve the goals of providing broad access while maintaining quality, consistency, and security.

• Investigate methods to address the challenges that remain in developing high-quality travel time reliability data for nonfreeway arterials.

Accessibility of Probe Data Sets

Current Research

• While data archives are available on a case by case basis, they are not widely available across agencies and data often has limited accessibility outside individual agencies.

Proposed Research

• Determine best practices to facilitate data sharing between agencies and the research community, while respecting the needs of private-sector data providers and the public. This will include developing model policies, frameworks, and data-use agreements that provide public agencies and the research community effective access to private-sector data, while preserving private company profit potential and preserving individual traveler privacy.

Need for Big Data Analytics Tools

Current Research

• Several big data analysis tools have been developed to handle probe data from specific geographic areas. Examples include the following:

– University of Maryland Center for Advanced Transportation Technology Regional Integrated Transportation Information System (www.ritis.org) and

– Iowa State Center for Transportation Research and Education Real-Time Analytics of Transportation Data (REACTOR) (https://reactor.ctre.iastate.edu/).

Proposed Research

• Open-source tools are needed to process large volumes of speed and travel time data that are becoming available. Specific questions to be answered in this research include:

- What functional requirements should be satisfied by big data analytics tools in the contexts of transportation systems in general and travel time reliability in particular?

- What types of accurate analytical data can be derived from the already burgeoning data resources that are set to expand exponentially as the proportion of CV grows?

Data Fusion

Current Research

While a number of different sources have cataloged individual data set characteristics, no known comprehensive summary has been produced from the perspective of data fusion for travel time reliability and monitoring. Likewise, there is a large volume of research available on data fusion models, but guidance on model selection for speed and travel time data are not widely known, although some information is available (20-22). Furthermore, there is a need to investigate methods to combine existing volume data with probe data to estimate volumes on a broader spatial basis.

Proposed Research

• What are the characteristics are needed in the various data sources that support travel time reliability monitoring and traveler information?

• What are the relative strengths and weaknesses of the various data sources?

• Given the characteristics and assessment of the various data sources, what data fusion models and algorithms should be used to achieve the goal of maximizing the quality of derived information in the context of operational constraints and the potentially competing goals of simplicity and robust effectiveness? How can existing probe data streams be used to create more comprehensive estimates of traffic volumes on a broader spatial network?

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TRAFFIC MONITORING STATISTICS, DATA QUALITY, USAGE, AND INTEGRATION

Potential Research Topics

SUMMARY OF POTENTIAL RESEARCH AREAS

At the TRB Annual Meeting in January 2017, Highway Traffic Monitoring Committee members discussed several proposed and national research projects. The ranking of the topics in Figure 1 was produced by a vote of the committee members attending the meeting.

DRAFT RESEARCH NEEDS STATEMENTS

The following Draft RNS were developed by the Highway Traffic Monitoring Committee for use by the Research Subcommittee in a future workshop or committee breakout meeting. The intent of the draft statements is to assist in the development of full research proposals or synthesis proposals that will lead to funding of these projects.



FIGURE 1 Highway Traffic Monitoring Committee ranking of topics.

Leveraging Existing Traffic Signal Assets to Obtain Quality Traffic Counts: A Study Using Existing Traffic Devices Across the Country

In this challenging economic environment, state and local agency practitioners, industry contacts, and academicians are being asked to do more with fewer resources. This topic will focus on developing a guidance document that assists in documenting several exemplary traffic signal operations that have already or are beginning to leverage resources for multiple data needs and purposes.

A research needs statement to support this topic was drafted in May 2016 as shown below (1).

Research Problem Statement

There are many existing traffic devices installed throughout the nation for operational traffic management purposes. While these devices serve a need for traffic operations, many potential nontraffic operations customers of traffic count data such as traffic engineers, statisticians, traffic monitoring staff, and other transportation professionals are in need of obtaining traffic counts for historical and other nonoperational purposes. This research needs statement aims to conduct a study of existing and new methods for obtaining traffic counts from existing traffic signal assets including but not limited to signalized intersections, cross walk signals, and other traffic devices.

The suitability of traffic count data from installed and existing traffic devices needs to be assessed during this study to determine if the existing data can be collected, stored, and disseminated for purposes other than traffic operations. The research should evaluate available currently installed traffic devices and provide a traffic count suitability database for nonoperational traffic data usage.

Research Objectives

Research questions that will be addressed include the following:

1. Is it possible to obtain accurate traffic count data from existing traffic signal assets? If yes, the method of obtaining traffic counts should be documented. If not, the reason why traffic count data cannot be obtained should be documented.

2. What is the quality of traffic count data that can be obtained from existing traffic signal assets?

3. What is the appropriate usage of traffic count data obtained from existing traffic signal assets? Are the traffic signal data limited to operation usage only, why or why not?

4. What methods of data handling, storage, and QA/QC need to be implemented to obtain traffic counts from existing traffic signal assets?

5. What challenges exist to obtaining traffic count data from existing traffic signal devices?

6. What agencies are currently collecting traffic count data from existing traffic signal devices?

An existing literature review will be conducted and summarized in a best practice, lessons learned, and current state of the practice evaluation document.

The researcher assigned to complete this study will gather agency support and active participation across the nation that includes all jurisdictional levels such as city, county, state, and federal agency as well as private entity partners.

A final guidance report documenting results from this study will be prepared as a "best practice for obtaining traffic counts from existing traffic devices" guide.

Estimate of Funding and Research Period

- Estimate of project cost: \$200,000.
- Expected research duration: 18 months.

Traffic Data Monitoring Partnerships With ITS Operations

The objective of this study is to learn how the integration of new technology into traffic monitoring has removed barriers and how the partnerships created address data quality concerns.

A research needs statement to support his topic was prepared in April 2016 and is shown below (2).

Research Problem Statement

State DOT highway travel monitoring programs are continually seeking consistent traffic data sources that can be integrated into their business model. There have been many new advances and a rapid deployment of ITS systems that monitor and maintain a safe and operationally efficient transportation network.

Travel monitoring programs are seeking to expand their use of the data collected by ITS operations while sharing their systems data with ITS operations. The FHWA's 2016 TMG contains recommendations for implementing coordination between traffic monitoring programs and traffic operations programs. In Chapter 5 of the TMG, it suggests coordination mechanisms and provides five case studies documenting existing or previous partnerships. The chapter highlights four areas where coordination opportunities exist. They are "At the Traffic Sensor," "At the Roadside Cabinet," "After the Transportation Management Centers," and just "Coordinated Equipment Location Only." While the TMG has made a start in promoting data sharing, challenges still remain.

Research Objectives

The objective of this study is to learn how the integration of technology has removed barriers and how the partnerships have addressed data quality concerns. The study will provide the monitoring community a better understanding of how the partnerships are providing improved coordination and creating resource efficiencies while reducing the extent of individual agency programs.

The study will address the following questions:

1. When designing combination ITS–Traffic Monitoring (TM) sites for dual purposes (traffic operations and TM or historical reporting), can transportation agencies improve efficiency and lower costs?

2. How do ITS–TM sites vary with respect to site selection, installation, maintenance, and operations and how do these variances affect the reliability, shelf-life, and availability (up time) of a site?

3. How does collocating and cofunding a site leverage a transportation agency's resources?

4. What aspects of asset and performance management relate to installing ITS–TM sites and how does this impact a transportation agency's operations, maintenance, and traffic data reporting activities?

5. Are there any financial, staff resources, and site quality implications to installing ITS–TMS sites?

6. What is the current state of practice for installing ITS–TM sites across transportation agencies?

7. How is data quality managed and quantified?

8. What resources within a transportation organization determine how sites are qualified for dual purposes and how is it determined when there are dual purpose uses?

Estimate of Funding and Research Period

- Estimate of project cost: \$150,000.
- Expected research duration: 18 months.

Summary of Practice and Enhancements to Performance Criteria and Test Methods for Calibration of WIM Systems

The objective of this study is to assess performance criteria and test methods for WIM calibration based on the available standards and identify benefits and limitations of the different approaches. Further, this project will use available detailed WIM calibration data to simulate evaluation of WIM performance using the techniques outlined in different standards. The research is expected to produce recommendations that will improve the accuracy and efficiency of the WIM calibration process in a cost-efficient manner.

This research needs statement was formulated in conjunction with the preparation of the WIM chapter in this E-Circular.

Research Problem Statement

Accurate information about traffic loading is critical to many vital functions performed by state highway agencies, including law enforcement, tolls on paid roads, pavement and bridge design, and freight planning. Traffic loading data are typically collected by WIM systems equipped with in-road or under-the-bridge sensors that are triggered by the load applied through the wheels of the vehicle passing over the sensor. The performance or accuracy of the sensors is evaluated and calibrated though semiannual, annual or biannual field validation and calibration using test truck runs. WIM calibration and validation could be a costly and time-consuming process that requires specialized skills and knowledge. Several methods exist on how to perform field WIM system validation and calibration, including ASTM (3), LTPP (4), COST (5), NMi (6), and other standards. No comprehensive review and comparison of different methods have been done to date. It is expected that such review and evaluation would help practitioners to understand the

differences and benefits of different criteria and approaches used for WIM calibration. It is also expected that the study will result in recommendations for enhancements of the existing ASTM E1318 standard, which is the leading U.S. standard for WIM calibration and validation.

Research Objectives

The objective of this study is to review the performance criteria and test methods for WIM calibration based on the available standards and identify benefits and limitations of the different approaches. Further, this project will use the available detailed WIM calibration data documented over the past 10 years by the LTPP SPS WIM TPF-5(004) study and calibration data available from the state highway agencies to simulate evaluation of WIM performance using the techniques outlined in different standards. Findings on how well different techniques work will be analyzed and summarized, including accuracy and ease of use of the different techniques.

The research is expected to produce recommendations that will improve the accuracy and efficiency of the WIM calibration process in a cost-efficient manner. This effort would prepare the groundwork for future changes and updates to the ASTM E1318-09 performance criteria, including an updated ASTM test method for WIM calibration and improvement to the interpretation and evaluation of the WIM validation and calibration results.

The study could potentially include the creation of a tool to automate calibration data processing and decision-making in the field. Tool development would occur if the recommended updated and enhanced process includes more advanced statistical procedures than the current ASTM method. This item would add the need for additional funding and may not be appropriate for this problem statement, if the primary goal is ASTM E1318 update.

This research study is likely to include the following tasks.

1. Review and synthesize WIM performance criteria, calibration practices, and data accuracy evaluation methods in the U.S. and around the world (Europe, Australia).

2. Evaluate weight measurement accuracy based on calibration test truck runs data using different methods included in Task 1. LTPP has collected and developed documentation containing a detailed record of each calibration truck run at TPF-5(004) sites. These real data are available for over 10 years, over 20 different sites, and three sensor types. States have additional data for sensors not covered in LTPP study. These data could be used as an input for the analysis of different methods for determining WIM measurement accuracy.

3. Draw conclusions on the efficiency and limitations of different calibration methods used to evaluate WIM data accuracy.

4. Evaluate the relation between the successful WIM calibration results and the actual WIM site performance over time (3, 6, 12, and 18 months after calibration) for different sensor types. Draw conclusions on the efficiency and role of WIM calibration in maintaining WIM data accuracy over time and recommended frequency of calibration for different sensor types.

5. Develop recommendations regarding performance criteria (i.e., error tolerances), calibration procedures, methods to evaluate calibration results, and calibration frequency to assure consistency in data accuracy over time.

6. Prepare a letter of recommendations to ASTM on recommended changes and enhancements for ASTM E1318-09.

7. Optionally, develop a tool to automate computations and decision-making during WIM calibration process to make the new or enhanced calibration process and performance

criteria easily implementable by the highway agencies, similar to an AASHTO-approved tool for evaluating WIM smoothness index.

Estimate of Funding and Research Period

- Estimate of project cost: \$80,000–100,000K without Task 7, \$180,000 with Task 7.
- Expected research duration: 6 to 12 months without Task 7, 18 months with Task 7.

Roadmap for State and Local Traffic Authorities to Use CV Data for Counting Programs and Operations

The objective of this study is to determine the best approach for exploiting CV data and the types and scope of the efforts needed and by whom. The project will develop a roadmap of the steps to be taken and the research gaps to be filled for a state to assess how it might approach potential use of CV data.

This research needs statement was written in conjunction with the preparation the Integrating Traffic Counts with CV Data chapter in this E-Circular.

Research Problem Statement

CVs enhance safety, as defined under NHTSA's recent Notice of Proposed Rule-Making (NPR) (1), by continuously broadcasting their locations, path histories, vehicle type, and other information. Commercial deployment of CVs began in 2017 and will be an exponentially increasing source of rich traffic data. These data have the potential for revolutionary impacts for counting programs and traffic operations due to its ultimately high temporal and space resolution and widespread coverage.

SAE and IEEE standards define these data quite well in order to achieve interoperability. Even so, access to this data source will require that a number of issues be resolved in order to unlock this potential to state and local jurisdictions. What is the best path to be able to exploit these data and what kind of effort will be needed and by whom are still unknown. A roadmap is needed of the steps to be taken and the research gaps that need to be filled for a state to assess how it might want to approach potential use of the CV data.

Research Objectives

1. Identify unfulfilled needs that can be met and other benefits of state and local access to CV data.

2. Identify the issues, barriers, and risks that need to be resolved before state or local transportation authorities can access and use CV data.

3. Determine what research is required to fill essential gaps that stand in the way.

4. Identify legislative, regulatory, or institutional measures that might be needed

5. Create a roadmap of the tasks that need to be undertaken by states that want to use CV data for traffic counting or traffic operations. Because states vary so widely in capability and experience, the roadmap may need to define more than one path.

Research questions that will be addressed include the following:

- 1. What are states currently doing to use or prepare for CV data?
- 2. What new potentials could be unlocked with access to CV data?
- 3. What options are there for collecting CV data?
- 4. What interfaces can be used or must be developed?

5. Are the data defined by SAE 2735, SAE 2945, and IEEE 1609 sufficient or should states engage with federal research programs concerning CV data to have additional requirements met so the data better suit local needs?

6. How can the CV data be integrated with existing data sources to complement or replace them? This includes the impact on data quality.

7. What steps must a state take to be certified to collect, store, and process CV data securely and to mitigate privacy concerns?

8. What time frames are realistic to prepare for CV data?

9. What nontechnical issues must be resolved (e.g., staffing, regulation, and organization)?

Research Method

The researcher(s) will gather information from all jurisdictional levels such as city, county, state, and federal agencies as well as private entity partners to explore the technical and nontechnical issues involved. This may involve travel. They will solicit feedback on the draft roadmap from the same or a similar body of participants before crafting the proposed roadmap for their final report. The report will describe how they conducted their research, the information they gathered, findings made during their analysis, and the roadmap and discussion of its implications.

Estimate of Funding and Research Period

- Estimate of project cost: \$275,000.
- Expected research duration: 12–18 months.

References

 Federal Motor Vehicle Standards. V2V Communications. 49 CFR Part 571, Notice of Proposed Rule-Making, Docket No. NHTSA-2016-0126, RIN 2127-AL55. *Federal Register*, Vol. 82, No. 8, January 12, 2017, Proposed Rules, Document no. 2016-31059, beginning page 3854. http://www.safercar.gov/v2v/pdf/V2V%20NPRM_Web_Version.pdf.

NEXT STEPS

Although relatively few research topics are highlighted above through RNS, many more research areas were identified in each chapter to address the identified gaps in gathering and applying traffic count data. The actions described below are recommended for the Research Subcommittee of the Highway Traffic Monitoring Committee and the full committee.

1. The research subcommittee should compile lists of all research topics by chapter on large sheets of paper.
2. A ranking exercise should be performed, either at the 2018 Annual TRB Meeting or at the midyear meeting of the committee, where the lists are posted on the walls of the committee meeting room, and each attendee given some number of "dots" (perhaps five) to place next to the topics they consider most important to the mission of the committee. Those voting can place more than one dot next to a topic.

3. The research subcommittee tallies the votes and ranks the topics by the number of votes they receive.

4. The research subcommittee seeks to identify volunteers to prepare research proposals for the top ranked topics. These are reviewed by the full committee and other interested parties.

5. Endorsers and sponsors are identified for each proposal, e.g., the Highway Traffic Monitoring Committee and other TRB committees, FHWA, and state DOTs, particularly those with members on the AASHTO Standing Committee on Research and its Research Advisory Committee.

6. Completed research proposals are then submitted to NCHRP for project selection and funding.

An analogous procedure is used for synthesis topics that are funded by FHWA.

RESOURCES

- Research Needs Statement—Leveraging Existing Traffic Signal Assets to Obtain Quality Traffic Counts: A Study Using Existing Traffic Devices Across the Country, TRB Highway Traffic Monitoring Committee, May 2016.
- Research Needs Statement—Traffic Data Monitoring Partnerships with ITS Operations, TRB Highway Traffic Monitoring Committee, April 25, 2016.
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