PAVEMENT CONDITION MONITORING WITH CONNECTED VEHICLE DATA

Michigan Department of Transportation

CENTER FOR AUTOMOTIVE RESEARCH

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TABLE OF CONTENTS

LISTS OF FIGURES AND TABLES

EXECUTIVE SUMMARY

The U.S. DOT Connected Vehicle Program is actively developing connected vehicle applications to improve the safety, mobility, and environmental impact of transportation. While connected vehicle applications to transportation asset management (TAM) are not a primary focus of the national program, such applications are of special interest to state and local agencies responsible for management of the transportation infrastructure. Asset management is an important component of state and local transportation agencies charged with maintaining the transportation infrastructure with limited resources.

Considering the possibility for safer and more efficient data collection, the Michigan Department of Transportation (MDOT) asked researchers at the Center for Automotive Research (CAR) to investigate the potential for connected vehicle data to contribute to pavement condition and performance data for the department's transportation asset management (TAM) programs.

CAR's investigation involved the analysis and synthesis of several research reports and pilot projects to determine feasible methods of implementation of connected-vehicle data, also known as vehicle-to-X (V2X) data, into real-world TAM programs. To date, the United States is home to few examples of the use of connected vehicle technology within asset management programs. Nonetheless, available evidence offers useful lessons for the transportation asset management community.

One important element of cost-effective application of V2X data to pavement condition monitoring is that data may be collected by sensors already installed on typical vehicles. Sensor systems aboard modern vehicles (e.g., gyroscopes, accelerometers, suspension travel detectors) have the potential to provide valuable data that can be used to assess pavement condition. This potential also faces some challenges, one of which is that vehicles are generally not factory-equipped with the capability of accessing raw sensor data without a proprietary parameter ID (PID) code from the vehicle manufacturer. Future vehicles may make such data available without requiring manufacturer consent. However, valuable data may also be captured by exploiting the capacity of consumer-grade smart mobile devices (e.g., smartphones). The sensing and processing capacity of modern smart phones can be used to capture pavement condition data, with or without integration with built-in vehicle systems.

The technology to allow for data capture from mobile devices is already established, but V2X data may be fundamentally different in form and function from traditional pavement condition data. Using such data in existing TAM programs may require novel methods of data processing and management on the part of transportation agencies. So far, methods of integrating V2X data into TAM programs have not been standardized or thoroughly developed. First-adopter agencies will have to innovate.

CAR's findings reveal that use of V2X data for asset management is possible but will require novel and proactive techniques of data management built on enterprise database architecture. The initial cost of using V2X data will be primarily in modifying existing databases and associated decision-management software to accommodate the unique nature of V2X data. Nonetheless, the potential of V2X data is such that successful implementation could negate the need for expensive methods of manual pavement condition data collection as currently performed by most transportation agencies. The research team recommends that transportation agencies begin modifying TAM programs as soon as practical to allow for the inclusion of V2X data.

INTRODUCTION

With the advent of the U.S. DOT Connected Vehicle Program and the strong growth of the commercial telematics and mobile device sectors in recent years, connected vehicle technology receives considerable attention within the automotive and transportation infrastructure industries, as well as in the media. One common claim is that connected vehicle data can be used to monitor the condition of the transportation infrastructure. Such statements have attracted the attention of public transportation agencies as they look for increasingly safe, efficient, and cost-effective ways to improve their transportation asset management (TAM) programs.

The Michigan Department of Transportation (MDOT) stands as a recognized leader in both asset management practices and connected vehicle technology. Thus, MDOT has a strong interest in studying the intersection of these two domains. Therefore, MDOT asked the Center for Automotive Research (CAR) to investigate the potential for using connected vehicles to monitor the physical condition of transportation system assets—in particular, the condition of roadway *pavement*. This report presents the findings from CAR's research, along with recommendations for implementing connected vehicle systems within asset management programs.

At the most basic level, the term *connected vehicle* implies the ability of the vehicle to transmit or receive (or both) information via wireless communication. Interpreted broadly, it could describe most every vehicle on the road. This already expansive definition is further blurred if we consider the ability for vehicle operators and passengers to transmit and/or receive information while in the vehicle with carried-in mobile devices (e.g., smartphones), and for aftermarket data acquisition systems to provide data beyond the ability of consumer-grade equipment.

Establishing a universal definition for a connected vehicle would be an extensive and complicated task. Fortunately, this is not necessary for the purposes of this investigation. For this work, we are specifically interested in connected vehicles that can collect or create data that can be used in TAM programs. We can further specify that because we are interested primarily in the *data*, as opposed to the vehicle, we also will consider data from carried-in mobile devices within vehicles. Thus, for the purposes of this study, *connected vehicle data* (V2X data) consist of any data collected or created by sensors embedded in a typical light vehicle or present in consumer-grade mobile device brought into a vehicle. With an established definition of connected vehicle data, we can now define a specific research question: *"How can connected vehicle data be applied to pavement condition monitoring?"*

This report provides an overview of TAM, followed by examination of typical pavement condition/performance monitoring practices, investigation of transportation asset condition monitoring applications of connected vehicle data and discussions of data integration and retention. It concludes with a summary of the findings of this study and general recommendations for transportation agencies interested in using connected vehicle data in TAM programs.

OVERVIEW OF TRANSPORTATION ASSET MANAGEMENT

Transportation asset condition monitoring is an essential component of the broader process of transportation asset management (TAM). In general, TAM refers to a strategic long-term approach to managing and investing in the transportation infrastructure (AASHTO, 2002). This section provides a general overview of TAM principles and practices.

ASSET MANAGEMENT PRINCIPLES

Transportation organizations have expended considerable effort in determining efficient and effective TAM practices based on general core principles. According to foundational work completed by the American Association of State Highway and Transportation Officials (AASHTO), three fundamental principles are embedded in any effective TAM framework (AASHTO, 2002). These are:

- **Strategic Approach:** A strategic approach to TAM focuses on long-term goal-oriented action and considers the entire existing and future transportation system to the extent practicable.
- **Encompassing Multiple Business Processes:** Asset management includes processes related to planning, program development and recommendation, engineering of projects and services, and program delivery. Decisions on allocating resources are policy-driven and performance-based, consider a range of alternatives, have clear criteria for decision- making, and investigate the most cost-effective solutions through analyses of tradeoffs.
- **Reliant on Good Information and Analytic Capabilities:** Quality data and information is important at all stages of asset management. Information technology is a practical necessity in supporting asset management, although there are many ways in which automated techniques can be beneficially applied.

Similarly, according to a recent report published by the Transportation Research Board (TRB), there are five widely understood principles of asset management (TRB, 2009):

- **Policy-driven**: Resource allocation decisions are based on a well-defined set of policy goals and objectives.
- **Performance-based**: Policy objectives are translated into system performance measures that are used for both day-to-day and strategic management.
- **Analysis of Options and Tradeoffs**: Decisions on how to allocate funds within and across different types of investments (e.g., preventive maintenance versus rehabilitation, pavements versus bridges) are based on an analysis of how different allocations will impact achievement of relevant policy objectives.
- **Decisions Based on Quality Information**: The merits of different options with respect to an agency's policy goals are evaluated using credible and current data.
- **Monitoring Provides Clear Accountability and Feedback:** Performance results are monitored and reported for both impacts and effectiveness.

Transportation asset management is an iterative and data-driven process whereby clear performance measures are used to continually reassess and revise goals, strategic planning, and tactical approaches. The goal is a decision-support system that is perpetually gathering data and applying it to achieve further system efficiencies (see Figure 1).

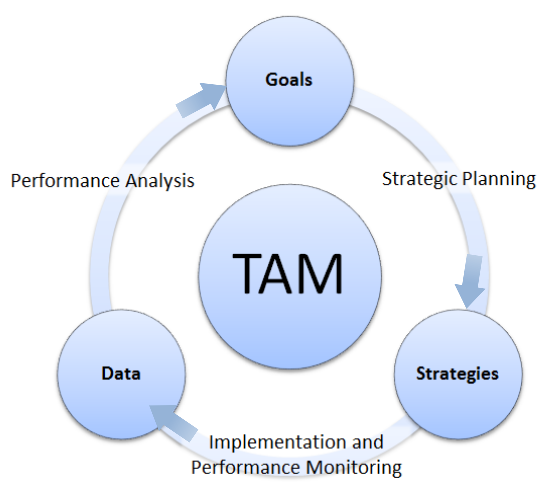

Figure 1: Basic TAM Cycle

According to TRB:

> "The asset management principles and process described apply to all types of investments in transportation infrastructure assets. Conceptually asset management is not limited to a preservation focus, but considers the full range of potential investments, as well as factors related to safety, operations, environmental management, corridor management, and project/program delivery" (TRB, 2009).

While the scope of data relevant to TAM is extensive, monitoring of the physical condition of transportation assets is central. Table 1 outlines an example of core TAM asset data for a sufficient asset management program. The core physical asset data described in Table 1 is designed to allow a robust decision-support software package to provide accurate information to TAM program managers.

Table 1: Example of Core Asset Data for TAM (Adapted from TRB, 2009)

Physical Asset Type	Example Data Types
Pavement	Structural adequacy, Distress, Serviceability, Friction, Design details, Construction history, Maintenance history
Bridges	Structural adequacy (NBI Rating), Design details, Construction history, Maintenance. history
Signage	Condition, Reflectivity, Installation and maintenance history
Electronic Signals	Condition, Efficacy, Installation and maintenance history, Energy use
Pavement Markings/ Delineators	Condition, Installation and maintenance history
Guardrails	Condition, Installation and maintenance history
Drainage	Condition, Efficacy, Design Details, Environmental impact, Construction and maintenance history
Lighting	Condition, Efficacy, Energy usage, Environmental impact, Installation and maintenance history
ITS Roadside Equip. and Communications	Condition, Efficacy, Installation and maintenance history

TRANSPORTATION ASSET MANAGEMENT LEGAL DEFINITIONS AND REQUIREMENTS

In U.S. Federal law, the term *asset management* means:

> "... a strategic and systematic process of operating, maintaining, and improving physical assets, with a focus on both engineering and economic analysis based upon quality information, to identify a structured sequence of maintenance, preservation, repair, rehabilitation, and replacement actions that will achieve and sustain a desired state of good repair over the lifecycle of the assets at minimum practicable cost" (23 USC S101, MAP-21).

The U.S. Department of Transportation (U.S. DOT) does not currently place specific requirements on a State's TAM program. However, State TAM programs are influenced by various requirements attached to current Federal transportation funding, as discussed below.

U.S. DOT HIGHWAY PERFORMANCE MONITORING SYSTEM

The Federal Highway Administration (FHWA) of U.S. DOT is responsible for assuring adequate nationwide asset management of the federal aid highway system. In order to consistently track and manage pavement conditions of the nation's highways, the FHWA requires each State to report specific pavement data attributes via the Highway Performance Monitoring System (HPMS). Required data include objective performance metrics such as roughness, faulting, rutting, and cracking (FHWA, 2013).

NATIONAL BRIDGE INSPECTION SYSTEM

The National Bridge Inspection System (NBIS), established by FHWA, sets the national standards for the proper safety inspection and evaluation of all highway bridges. NBIS regulations apply to all publicly-owned highway bridges longer than twenty feet located on public roads (TRB, 2009). The Federally required NBIS reporting procedures consist of manual inspection and reporting of specific bridge elements (MDOT, 2009).

MAP-21 (USC TITLE 23)

The relationship between Federal regulations and State TAM programs is currently in flux. The current Federal highways funding bill, *Moving Ahead for Progress in the 21st Century* (MAP-21), requires the design and implementation of a *National Highway System Performance Program* to supplement or supplant the current HPMS. The National Highway System (NHS) Performance Program will include specific requirements placed on a State's TAM program, at least as it pertains to the NHS.

The *National Highway System* refers to the Federal-aid-eligible highway system, including the Interstate Highway System, designated connector highways, and a strategic highway network as determined by the U.S. DOT. MAP-21 legislation expanded the NHS (effective fiscal year 2012)—adding principle arterial routes that were not previously included. The specifics of the NHS Performance Program and related requirements have not yet been announced. However, there are some general requirements embedded in MAP-21 that policymakers will have to consider.

- **Risk-based:** States will be required to develop a "risk-based asset management plan" for the NHS assets within the State (MAP-21). Risk-based asset management is generally considered to cover both internal programmatic risks, and external non-programmatic risks (TRB, 2009).
- **Performance driven:** MAP-21 legislation requires that States "shall include strategies leading to a program of projects" that supports specific goals and associated metrics (MAP-21).
- **Comprehensive:** The NHS Performance Program will "encourage States to include all infrastructure assets within the right-of-way" of an NHS corridor (MAP-21).

The specifics of the national NHS Performance Program are scheduled to be established by April 1, 2014. States will be required to develop and implement a State asset management plan for the NHS for fiscal year 2016 (MAP-21, 23 USC 119 (e)(5)).

STATE LONG-RANGE PLAN

The State Long Range Plan, as required by Federal regulations, is a broad plan with at least a 20-year outlook. States use this document to establish a long-term vision to guide strategic planning (MDOT, 2009).

STATE TRANSPORTATION IMPROVEMENT PROGRAM

The State Transportation Improvement Program (STIP) is a federally mandated planning document that lists surface transportation projects that the State intends to fund under the Federal-aid transportation program. The STIP provides information on the programs and projects to which State and local transportation agencies have committed to over the next four years, and verifies that resources are available to meet the State portion of financial obligations. For a project to be listed in the STIP, it must have identified funding within the four-year period covered by the document. Metropolitan Planning Organizations (MPOs) are required to submit their own TIPs to receive Federal funding of local projects within designated urbanized areas. Ideally, project selection for both State and MPO TIPs is supported by robust TAM programs utilizing mechanistic-empirical decision support software.

TRANSPORTATION ASSET MANAGEMENT IN MICHIGAN

This section links general concepts of transportation asset management to specific approaches taken in the State of Michigan.

In Michigan State law, asset management means:

> "... an ongoing process of maintaining, upgrading, and operating physical assets cost-effectively, based on a continuous physical inventory and condition assessment" (MCL 247.659a).

MDOT takes an Asset Management approach to managing highway investments. Michigan asset management is a strategic approach to linking data, goals, investment strategies, programs and projects into a systemic process to ensure achievement of a desired result.

The steps in the MDOT asset management process include the following:

- Goals and objectives are established in the State Long Range Transportation Plan (SLRP). The SLRP provides the policy guidelines, implementation strategies and measures of efficiencies necessary for program development
- System inventory and condition data is collected
- Condition data is analyzed, and rates of deterioration are computed
- Performance measures and standards are set or reaffirmed
- Investment strategies are developed using forecasting tools
- Investment strategies guide the development of programs and the selection of projects
- The program of projects is monitored and any necessary adjustments are implemented

MDOT Transportation Management System

MDOT was one of the first transportation agencies to develop a comprehensive architecture for an agency-wide enterprise database to support a state-of-the-art TAM program. This architecture, the MDOT Transportation Management System (TMS), includes six component databases (Figure 2), each geo-referenced to a single statewide linear referencing system; the Michigan Geographic Framework (MGF). The MDOT TMS is envisioned as a single "integrated management system ... using one logical relational database," allowing decisions to be "based on an integrated, consistent set of information that ensures philosophical and operational alignment of the efforts in all areas of MDOT" (MDOT, a).

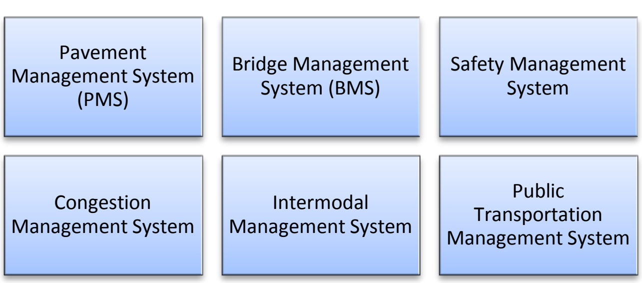

Figure 2: MDOT's Transportation Management System Component Subsystems

MDOT Five Year Transportation Program

MDOT manages the State-owned rights-of-way on designated state trunklines (i.e., I, M, and US routes). MDOT project planning for the trunkline system is performed through a rolling five-year highway transportation investment program. The program is developed by MDOT through its regional planning agencies (RPAs). The MDOT five-year Transportation Program is an integrated multi-modal program that implements the goals and policies outlined by the State Transportation Commission (STC). The Program includes public transit, rail, aviation, marine, and non-motorized transportation, in addition to bridges and highways.

For decision support in prioritization of trunkline projects, MDOT uses individual pavement and bridge management system databases (PMS and Pontis) to feed into software tools called the *Road Quality Forecasting System* (RQFS) and *Bridge Condition Forecasting System* (BCFS). Final program decisions incorporate participation and cooperation from affected counties, MPOs, municipalities, and the general public.

MDOT Call for Projects

MDOT's jurisdictional control is generally limited to the state trunklines that comprise eight percent of the linear miles in Michigan’s road network (MDOT, 2012a). Michigan's remaining statewide surface transportation assets are managed by local (county and municipal) governments. All federally funded highway projects must be included in the STIP. MDOT coordinates statewide project planning with an annual *call for projects*; soliciting local transportation agencies to submit applications for local projects to be included in the STIP.

Michigan Transportation Asset Management Council

The Michigan Transportation Asset Management Council (TAMC) was formed within the State Transportation Commission in 2002. TAMC was created primarily to develop a coordinated, unified asset management process to be followed by the various roadway agencies within the State, and to advise the State Transportation Commission on a statewide asset management strategy (TAMC, 2012, MCL 247.651g).

Because MDOT does not have direct jurisdictional control over 92 percent of the mileage of Michigan's road network, TAMC provides a link between MDOT, regional, county, and local TAM strategies. TAMC works with all parties to assess and coordinate asset management of transportation infrastructure statewide. Local transportation improvement programs are encouraged to utilize accepted asset management practices, but they do not need to have TAM programs approved by MDOT or the TAMC (MCL 247.659a). Nonetheless, MDOT approval of local TAM systems *is* required for municipalities to be allowed increased flexibility in state funding of their local systems (MCL 247.663).

OVERVIEW OF PAVEMENT CONDITION AND PERFORMANCE ASSESSMENT

MDOT depends on the pavement management system (PMS) database for pavement asset condition monitoring. Pavement condition and performance can generally be described by four basic data categories (National Highway Institute, 2002):

- Structural Adequacy/Deflection
- Surface Distress
- Serviceability/Ride-Quality
- Surface Friction

These basic metrics can be used in combination to estimate a pavement's *remaining service life* (RSL); the time after which a pavement is no longer able to function as designed. This framework can be used to organize available metrics as outlined below. This section concludes with a discussion of specific aspects of pavement condition monitoring as practiced in Michigan.

STRUCTURAL ADEQUACY/DEFLECTION

Structural adequacy refers to the "ability of the pavement to carry loads without resulting in undue distress" (National Highway Institute, 2002). Determination of structural adequacy involves evaluation of deflection data within a context of pavement properties and performance demand. Deflection data collection requires specialized measurement equipment called a *deflectometer*. Pavement deflection is not a required dataset for federal HPMS reporting, and MDOT does not typically collect pavement deflection data at this time for the asset management program (with the exception of bridge scoping).

SURFACE DISTRESS

Surface distress is traditionally assessed via visual survey of the pavement surface. This is performed by engineers walking a representative portion of the pavement and recording the type, severity, and extent of defects. MDOT distress data is generally collected by a video recorder fitted to a data collection vehicle, such as that shown in Figure 4. The video is subsequently analyzed by engineers who record the type, severity, and approximate location of pavement distresses (Michigan Auditor General, 2012).

Various transportation agencies have developed and implemented alternative metrics for distress. Often, distress data is combined with roughness data and/or other variables when used for asset management or reporting purposes (Wu, Groeger, Simpson, & Hicks, 2010). Primary distresses required for federal reporting include rutting, faulting, and cracking (FHWA, 2013).

Figure 3: Long-Term Pavement Performance (LTPP) Program Pavement Distress Raters Participating in a 2010 Workshop (Photo credit: FHWA)

RUTTING

Rutting is a measurement of depression in the surface of an asphalt pavement, usually caused by plastic deformation of the pavement or base layer (MDOT, 2009). Severe rutting can create unsafe driving conditions, and often correlates to specific failure mechanisms at work in the underlying pavement base layers.

FAULTING

Faulting is a measurement of vertical movement in a slab of Portland Cement Concrete (PCC) adjacent to a joint or crack (MDOT, 2009). Severe faulting can damage vehicles, and often correlates to specific failure mechanisms at work in the underlying pavement base layers.

CRACKING

Pavement *cracking* is a primary consideration in pavement distress surveys. Technicians record the extent and severity of cracking, and often also note the type of cracking. Federal HPMS reporting requires values for cracking length, and cracking percent (FHWA, 2013). A robust TAM database would ideally provide detail on the type of cracking observed. For example, in flexible (Hot Mix Asphalt (HMA) pavements, distresses such as *fatigue cracking*, *longitudinal cracking*, and *transverse cracking* likely indicate different modes of pavement failure and underlying causes (Ram & Peshkin, 2013).

DISTRESS INDEX

A *distress index* (DI) is a composite index computed from measurements of raw distress data including cracking, raveling, flushing, spalling, faulting, etc. The MDOT standard DI reflects the total accumulated distress point value for a given pavement section normalized to a 0.1-mile length (MDOT, 2009). In MDOT's TAM program, DI is the primary data component used to estimate RSL on State trunklines (MDOT, n.d.-b; Michigan Auditor General, 2012).

Figure 4: Data Collection Vehicle Contracted by MDOT

SERVICEABILITY/RIDE-QUALITY

Serviceability is essentially an evaluation of the pavement interaction with a typical highway vehicle (National Highway Institute, 2002). Similarly, *ride-quality* reflects the experience of human users within such vehicles. Serviceability/ride-quality measures are traditionally approximated by a pavement profile or some type of standardized roughness index.

INTERNATIONAL ROUGHNESS INDEX

The *International Roughness Index* (IRI) is a standard and objective measure of pavement surface roughness, and is a reporting requirement for HPMS (FHWA, 2013). IRI is the ratio of the accumulated suspension motion to the distance traveled obtained from a mathematical model of a standard vehicle traversing a measured profile at a speed of 80 km/h (50 mph). Expressed in units of meters per kilometer (inches per mile), the IRI represents the longitudinal surface profile in the wheelpath (National Highway Institute, 2002).

At the present time, IRI is the most widely used pavement condition measure, and often the only objective metric used to determine overall condition. However, a recent FHWA report has expressed concern that overreliance on IRI is not desirable:

> "A potential problem with this approach is that over time and underneath the smooth surface, the structural capacity of the pavement could be deteriorating" (Guerre et al., 2012).

SURFACE FRICTION

Surface friction relates to the skid-resistance of the pavement. Reduced surface friction of a pavement is a safety issue, as vehicles may have longer stopping distances or increased likeliness of loss of control. Values for friction are complicated by macro-texture (texture that allows drainage, in order to prevent hydroplaning), micro-texture (the actual texture of the stone aggregate particles), changes in micro-texture due to aggregate polishing, the tire type (including its rubber composition), and tread pattern. Surface friction is *not* a required dataset for Federal HPMS reporting (FHWA, 2013).

MDOT conducts surface friction tests on the entire trunkline system on a three-year cycle. The Pavement Operations group within the Construction Field Services Division of the Bureau of Field Services conducts the testing using a *Dynatest* 1295 locked wheel pavement friction tester, shown if Figure 5. The friction testing unit meets the requirements of ASTM E-274 (Hynes, 2013). Findings of unacceptably low frictional coefficients (μ) may result in reactive maintenance measures such as chip sealing or grinding. Frictional coefficient measurements do not generally factor into the formal Michigan transportation asset management program (i.e., the Five-year Transportation Program).

Figure 5: MDOT Friction Testing Unit

REMAINING SERVICE LIFE

Pavement condition and performance data, as described above, provides only a non-temporal (snapshot) assessment of the pavement condition. Effective TAM programs must be capable of accurately predicting pavement performance and condition into the future. Such a process requires estimation of a pavement's *remaining service life* (RSL).

A traditional approach to estimating RSL is based on the structural and functional condition of the pavement. The RSL represents "the period of time under specified site conditions during which a pavement's structural or functional condition is expected to remain within stated limits, provided that appropriate routine and preventative maintenance are carried out (Titus-Glover, Fang, Alam, O'Toole, & Michael I, 2010). Examples of specified site conditions may include:

- Traffic data and forecasting
- Climate data
- Planned maintenance activities
- Stated/assumed end condition level of the pavement

A typical RSL graph (pavement condition vs. time) is shown in Figure 6. Note that RSL could vary significantly based on the effect site conditions has on pavement deterioration. RSL can also change by adjusting the assumed end-life condition(s).

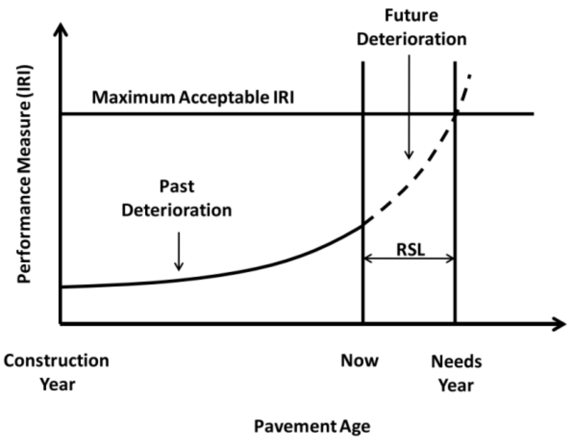

Figure 6: Example of Pavement RSL Graph (Titus-Glover et al., 2010)

The preferred approach to estimating RSL involves forecasting multiple pavement condition and performance measures, rather than a single metric. This should consider at least one minimum acceptable value for both a structural condition (i.e., distress), and a functional condition (i.e., roughness). The effective RSL could then be calculated based on either the minimum RSL for any of the individual components, or a weighted average (Titus-Glover et al., 2010).

AASHTO and the FHWA Office of Asset Management recommend a *mechanistic-empirical* method to determine RSL (Titus-Glover et al., 2010). The core performance measures for such an approach are shown in Table 2.

Table 2: Core Performance Measures for RSL Estimation (Titus-Glover et al., 2010)

Pavement Type	Distress Type	Units
Jointed Plain Concrete Pavement	Transverse "slab" cracking	Percent of slabs cracked
	Mean transverse joint faulting	Inches
	Transverse joint spalling	Percent of joints spalled
	Smoothness (IRI)	Inches per mile
Hot-mix Asphalt Pavement	Alligator Cracking	Percent of lane area
	Rutting	Inches
	Transverse cracking	Feet per mile
	Smoothness (IRI)	Inches per mile
Asphalt over Concrete Overlay	Reflection cracking	Percent of lanes cracked

Table 2 includes only the core pavement performance measures thought necessary for a state-of-the-art approach to TAM. Ideally, these metrics would be contextualized by additional metrics and data available from an enterprise database.

MICHIGAN PAVEMENT CONDITION MONITORING APPROACHES

For decision-support regarding highway pavement projects, MDOT concentrates on an estimate of RSL based on the MDOT distress index. MDOT also employs two additional rating scales; *Sufficiency*, and the *Pavement Surface Evaluation and Rating (PASER)* scale for intra-state reporting purposes. Both ratings are collected via "windshield surveys," essentially agency staff driving the road at normal speed and applying a numerical rating based on experience and trained subjective judgment.

MDOT SUFFICIENCY RATING

According to the FY 2011 Michigan State Financial Report, "the state's primary method to measure and monitor pavement conditions" of State trunk lines is the *sufficiency rating*. MDOT has been collecting sufficiency rating data since 1961 via "a visual analysis conducted by an engineer" (State of Michigan, 2011). This rating is used by MDOT for long-term pavement quality tracking, and to support RQFS results. MDOT sufficiency is reported on a 5-point scale, as shown in Table 6

PASER RATING

The PASER scale is a 1-10 rating system assessed on the basis of a windshield survey. The TAMC has designated the PASER rating system to collect statewide pavement condition data. The PASER system was chosen because, "the data is easy to collect, it is of sufficient detail for statewide network-level analysis, and it is the method currently used by most road agencies in Michigan" (TAMC, 2012).

According to an advisory document provided by TAMC, "due to the subjectivity of [PASER], representatives from multiple agencies are required which in turn builds collaboration between agencies and can be noted as a positive aspect." PASER data is collected from, "a vehicle containing one representative each from MDOT, the Metropolitan Planning Organization (MPO), or Regional Planning Organization (RPO), and local City/Village or County" (TAMC, 2011). The raters receive training and certification to encourage accuracy and consistency between rating teams. According to TAMC, numerical PASER ratings are translatable to condition categories and prescribed treatment options, as shown Table 3, below.

Table 3: PASER Ratings and Treatment Options

Quality	Rating	Treatment (Asphalt)	Treatment (PCC)
Excellent	9,10	No maintenance required	No maintenance required
Good	7,8	Crack sealing and minor patching	Routine maintenance
Fair	5,6	Preservative treatments (non-structural)	Surface repairs, partial-depth patching.
Poor	3,4	Structural renewal (overlay)	Extensive slab or joint rehabilitation
Failed	1,2	Reconstruction	Reconstruction

TAMC also uses PASER ratings to determine a value for RSL (TAMC, 2011). A template document provided to transportation agencies states that:

> "PASER rating of 10 or 9 having more than 10 years of remaining service life, a rating of 8 or 7 having an RSL of 5 to 10 years, and a rating of 6 or below equating to less than 5 years RSL" (Michigan Transportation Asset Management Council, 2011).

MDOT REMAINING SERVICE LIFE

MDOT defines *RSL* as, "the estimated remaining time in years until a pavement's most cost-effective treatment requires either reconstruction or rehabilitation" (MDOT, 2012b). RSL is a central component of MDOT's transportation asset management program.

MDOT's State PMS for trunklines calculates RSL based on a standard DI; a composite metric obtained from visual measurements of distress data

(MDOT, 2009). After DI is converted into a value for RSL, MDOT regional managers utilize the Road Quality Forecasting System (RQFS) software tool to explore cost/benefit analyses of alternative programming scenarios based on RSL (HUG, 2013). MDOT has developed a good/fair/poor designation based on RSL, as shown in Table 4, below.

Table 4: MDOT RQFS RSL Scale and Treatment Options

Quality	RSL (years)	Project Options
Good	8+	Reactive Maintenance
Fair	3-7	Capital Preventative Maintenance (CPM)
Poor	0-2	Rehabilitation or Reconstruction (R&R)

The variety of pavement condition metrics used in Michigan is the result of past efforts to improve pavement monitoring. MDOT is currently committed to further improving pavement condition monitoring by working with TAMC to improve quality control, quality assurance and duplications of efforts (Michigan Auditor General, 2012). Demonstrating how pavement condition monitoring in Michigan can be difficult to understand, a web-based reporting tool, the *Michigan Dashboard*, reports four unique pavement condition measurements (Sufficiency, IRI, PASER, RSL), as shown in Table 5. It is notable that the differing metrics may show distinct assessments and trends.

Table 5: Michigan Dashboard (MIScorecard) Performance Summary

Metric	Reported Measurement	Goal	2010	2011	2012	2013 (Nov)
Sufficiency	Percentage of trunk line pavements in fair or better condition	90%	83%	81%	79%	81%
IRI	Percentage of trunk line in fair (IRI<170) or better condition	90%	93%	94%	95%	94%
RSL	Percentage of trunk line pavements with RSL > 3 years.	90%	91%	89%	87%	89%
PASER	Percentage of paved Federal aid roads (trunk line and local) in fair or better condition	Improve year-over-year	65.2%	64.9%	66.4%	64.9%

Source: http://www.michigan.gov/documents/mdot/MDOT_Scorecard11-14-11_01-19-12_374118_7.pdf

Table 6: MDOT Sufficiency Rating

Quality	Rating	Description (Asphalt)	Description (PCC)
Excellent	1	Pavement shows no visible deterioration. Distresses are non-existent.	Pavement shows no visible deterioration. Distresses are non-existent.
Good	2	Some indication of initial deterioration, but not yet requiring appreciable amounts of maintenance. Distress items include the start of small transverse and/or longitudinal cracks. Slight rutting may be apparent in the wheel path.	Some indication of initial deterioration, but not yet requiring appreciable amounts of maintenance. Distress items may include the start of small transverse and/or longitudinal cracks, or slight seam and joint separation. Joints may show very small amounts of deterioration.
Fair	3	Average deterioration requiring occasional routine maintenance. Distresses may include minor transverse and longitudinal cracking becoming continuous throughout the segment. Severe cracking is patched effectively. Rutting may be a little more severe and hold small amounts of water.	Average deterioration requiring occasional routine maintenance. Distresses may include minor transverse and longitudinal cracking becoming continuous throughout the segment. Severe cracking is patched effectively. Through-lanes and shoulders may begin to show separation from failing tie bars.
Poor	4	Excessive deterioration requiring frequent maintenance and warrants resurfacing soon. Distress may be evident in wide transverse and longitudinal cracks. Severe “shallow cracking” could be evident if the pavement is composite. If the segment has been patched, the cracks may be showing through. Rutting is severe and may affect driving.	Excessive deterioration requiring frequent maintenance and warrants resurfacing soon. Distress may be evident in wide transverse and longitudinal cracks. If the segment has been patched, cracks may be showing through. Joint repairs could begin to fail. Shoulder and/or throughlane separation may be apparent. Popouts or spalling could also be present in the section.
Very Poor/ Failed	5	Extreme deterioration requiring continuous maintenance and warrants resurfacing or total cross-section replacement. Distress items may include severe transverse and longitudinal cracking or severe alligator cracking. Shadow cracking in composite pavement is wider than one inch. Rutting in wheel path may be severe and patching is no longer beneficial to pavement condition.	Extreme deterioration requiring continuous maintenance and warrants resurfacing or total cross-section replacement. Distress items may include severe transverse and longitudinal cracking, joints failing, and the patching is no longer beneficial to pavement condition. Spalling and edge cracking could also be severe.

CONNECTED VEHICLE DATA FOR PAVEMENT CONDITION MONITORING

Previous chapters of this report have provided overviews of TAM and pavement condition monitoring. This chapter describes how connected vehicle data (V2X data) may be utilized for pavement condition monitoring.

ASSET CONDITION MONITORING IN NATIONAL ITS ARCHITECTURE

Federal policy mandates that intelligent transportation systems (ITS) projects, including connected vehicle projects, be consistent with the *National ITS Architecture* (23 CFR 940). Considered broadly, *ITS systems* include any application of electronics and information technology to any component of the transportation system. ITS research is coordinated nationally through the Intelligent Transportation Systems Joint Program Office (ITS JPO) within U.S. DOT's Research and Innovative Technology Administration (RITA). The ITS JPO is currently operating under a five-year strategic research plan (2010-2014), with a focus on connected vehicle ITS systems. The ITS JPO research agenda has three applications focus areas: *safety*, *mobility*, and *environment/efficiency*. While ITS for TAM is not a stated research priority, the data generated by connected vehicle ITS systems could potentially be utilized in asset management.

A detailed summary of the National ITS Architecture is beyond the scope of this report. However, it should be noted that the National ITS Architecture should be consulted in the planning of any regional or local ITS deployment. Not only is conformity to the National ITS Architecture mandated by federal law, but ITS JPO resources can be very helpful in ITS deployment strategy and project planning.

The National ITS Architecture can be divided into a series of *objective categories*; the category most relevant to TAM is, "*Preserve Existing Infrastructure"* (RITA). Each objective category is divided into a series of individual objectives with associated metrics. A *service package* refers to, "slices of the Physical Architecture that address specific services ... A service package collects together several different subsystems, equipment packages, terminators, and architecture flows that provide the desired service" (RITA). The ITS service package *MC12–Infrastructure Monitoring*, shown in Figure 7, appears to be the only formal service package directly related to the pavement and bridge management components of TAM.

The Infrastructure Monitoring service package:

> "monitors the condition of pavement, bridges, tunnels, associated hardware, and other transportation-related infrastructure (e.g., culverts) using both fixed and vehicle-based infrastructure monitoring sensors. Fixed sensors monitor vibration, stress, temperature, continuity, and other parameters and mobile sensors and data logging devices collect information on current infrastructure condition. This service package also monitors vehicle probes for vertical acceleration data and other probe data that may be used to determine current pavement condition" (RITA).

Smith and Sauerwein (2011) reviewed the potential of using methods as envisioned by the U.S. DOT's Connected Vehicle Program to collect pavement condition data. The method of data collection utilized vehicle-embedded accelerometers, sensor hardware, and standardized DSRC-based on-board-equipment. A thoughtful analysis of this approach revealed several limitations and technical difficulties, including the following:

- OEM accelerometers are not standard across vehicles, and require individual assessment and calibration for the make and model of each vehicle.
- Accelerometer data from CAN bus can only be accessed with cooperation from the vehicle manufacturer.
- The standard SAE J2735 restricts the ability of vehicles to capture vertical acceleration data at a sufficiently high sample rate to produce usable roughness data for traditional metrics such as IRI.
- Transmission of roughness data using DSRC is

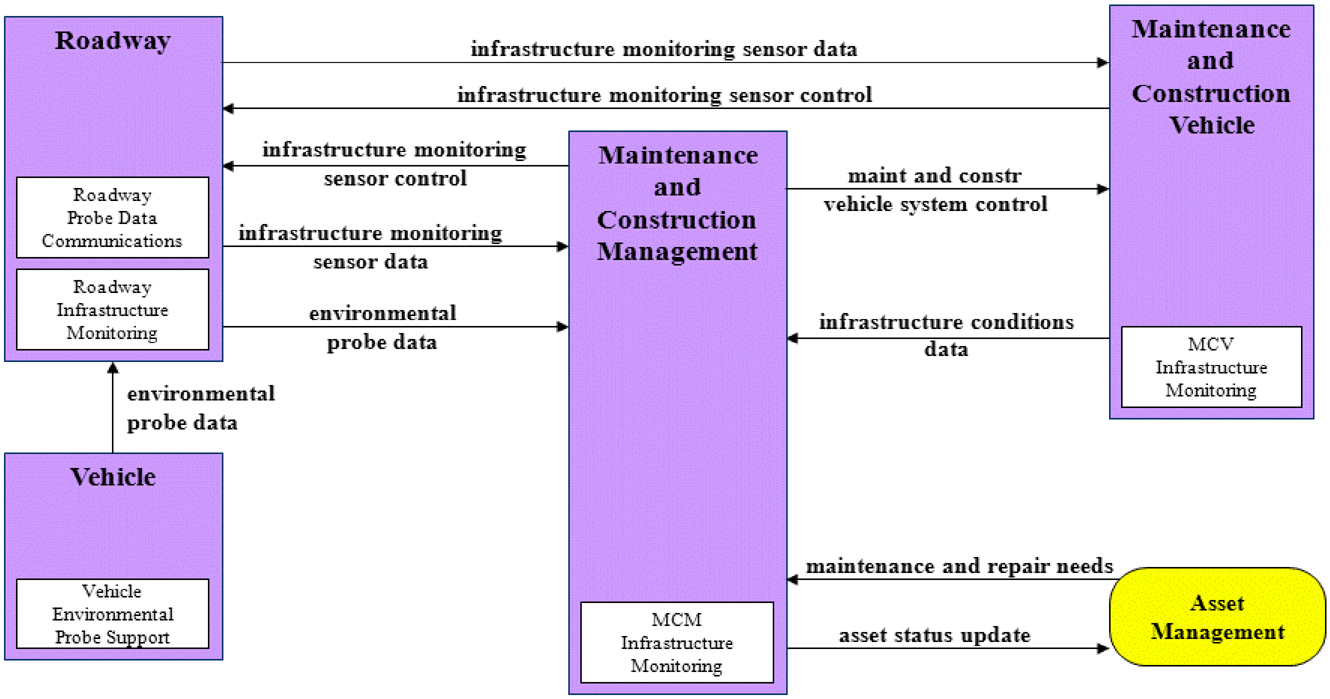

Figure 7: National ITS Architecture Infrastructure Monitoring Service Package. Source: RITA.

difficult due to large file sizes and unreliable transmission fidelity.

In addition to these difficulties, the NHTSA has not yet issued a notice of intent to require DSRC in future vehicles. At this time, the timeline for DSRC-enabled vehicles and build-out of supporting infrastructure is unknown. For these reasons, further discussions of connected vehicle data sources will focus on technologies that do *not* necessarily require DRSC-enabled vehicles. While the U.S. DOT connected vehicle program emphasizes DSRC technology, the National ITS Architecture does allow for alternative methods of data transmission (e.g., cellular).

CONNECTED VEHICLE DATA SOURCES

For the purposes of this report, connected vehicle data, or *V2X data*, refers to any data originating from built-in vehicle systems or carried-in consumer devices aboard vehicles. While it is currently standard practice to purchase data from third-party providers who use connected probe vehicles to obtain network vehicle speed data, there are no known providers who use such vehicles to assess pavement condition. Outside of the future possibility of purchasing data from third-party providers, there are at least two distinct sources of V2X data that could be used to support asset condition monitoring:

- Agency operated fleet vehicles
- Privately owned vehicles operated by general public

The difference between V2X data from agency-owned vehicles versus private vehicles is most relevant to how data is obtained. Collecting V2X data from privately-owned vehicles (the travelling public) requires driver opt-in. There is currently no method of collecting sensor data from vehicle onboard systems or mobile consumer devices without the participation of the owner of the vehicle or mobile smart device.

For fleet vehicles capable of collecting data of interest, moving that data from the vehicle into a database may be relatively simple. This should be true whether the vehicle is in a transportation agency-operated fleet or a private fleet that provides third-party data. Some of the vehicle system (Controller Area Network (CAN) bus) data can be relayed through an on-board-diagnosis (OBD) wireless connector to a smart device, and then transmitted for processing or storage via a digital cellular connection or other means. Agency employees can be made responsible for activating such a system in the course of their normal operations. Unfortunately, the relatively small number of fleet vehicles available to collect V2X data may or may not create enough data to be useful for many TAM applications. An additional barrier is that vehicles generally do not allow raw sensor data (e.g., accelerometer, gyroscopes, suspension deflection) or relevant vehicle systems data (e.g., ABS, traction control) to be accessed by the OBD connection (Dawkins, Bishop, Powell, & Bevly, 2011). However, such data may be accessible through agreements with vehicle manufacturers to obtain proprietary PIN codes.

Several research programs are using aftermarket data acquisition systems to collect road-roughness data. For example, MDOT's Vehicle-based Information and Data Acquisition System (VIDAS) program, in combination with Data Use, Analysis and Processing (DUAP) efforts, focuses on such an approach. Smith and Sauerwein (2011) reviewed a variety of such approaches and found that "usable" roughness data can be captured using an aftermarket accelerometer, an on-board laptop computer, and a wireless cellular connection. With regards to pavement condition data, notable drawbacks to this approach include the cost of each data collection system (approximately $7,000) and the limited number of active probe vehicles that would be collecting data.

Research studies that have been conducted using such an approach generally involve rigorous calibration and control of the driving situation of the vehicles. It is somewhat likely that a vehicle fitted with an aftermarket data acquisition system could collect usable data if it is operated specifically for data collection. However, if the intent is to allow field operations vehicles to collect this data in the course of normal operation, this possibility is diminished. Even when the acquisition system is carefully calibrated, data readings are subject to vehicle speed, placement within the lane, and horizontal acceleration (e.g., lane changes, braking, etc.).

Additionally, while data collected with this method can be correlated rather closely to IRI, such a method may not fulfill Federal reporting requirements, and thus could not replace existing IRI data collection for such a purpose without a change in federal policy. Given these limitations and others, it is unlikely that aftermarket data-acquisition devices installed on normally-operating fleet vehicles is likely to provide a cost-effective method of pavement condition assessment in the near future.

Fortunately, the proliferation of carried-in mobile devices (e.g., smartphones) in vehicles presents an opportunity to "crowdsource" data from users of the road network, both from fleet vehicles and the motoring public. If a significant percentage of road system users were to participate in collecting such data, crowdsourced pavement serviceability data could supplement or even partially replace costly and less efficient pavement survey methods.

Given the aforementioned complications regarding retrieving vehicle data from the OBD port, and the limitations of aftermarket accelerometers the most likely near-term scenario for accessing usable V2X data would be to utilize the sensors, processors, and connectivity in carried-in mobile smart device (e.g. smartphones). The mobile device can perform data screening, fusion, and transmission for further data processing, analysis, or storage. The technology required to implement crowdsourced pavement condition monitoring smartphones is already established (R. Robinson, 2012), and the concept has been proven as workable (Ndoye, 2010).

As will be discussed in the next subsection, data collected by this method will not likely be a substitute for traditional metrics such as IRI or PASER in the near-term. A model similar to today's practice, where one vehicle is capable of capturing a specific metric in a single pass down a road, is not likely to be workable with smartphone-derived crowdsourced data. It is more likely that a multitude of data sources (probe vehicles) will need to participate in data collection to render a usable metric. Thus, in the near term, the primary barrier to V2X data collection is likely designing a program that would encourage a significant number of road users to participate (Dion & Robinson, 2010). One study has estimated that at least 1% of the national fleet would be necessary to provide adequate pavement condition monitoring (Dawkins et al., 2011), though some benefit may be observed at lower levels of fleet penetration.

CONNECTED VEHICLE DATA APPLICATIONS TO PAVEMENT CONDITION MONITORING

In the near-term, any V2X data applications for physical transportation infrastructure monitoring are most likely to apply to pavement conditions. A transition to V2X data sources will not be seamless for TAM program managers. However, it is possible that V2X data-based metrics may supplement or even supplant traditional metrics in coming decades.

OBJECTIVE AND SUBJECTIVE PAVEMENT CONDITION METRICS

The near-term potential for using connected vehicle data to obtain any of these traditional pavement condition metrics is very limited. Explaining the limitations of connected vehicle data in providing traditional measures must consider separately the *objective* and *subjective* metrics.

As previously discussed, there are four basic categories of objective pavement condition data:

- Structural adequacy (deflection under load)
- Surface distress (rutting, faulting, cracking, etc.)
- Serviceability (IRI)
- Surface friction (μ)

Generally speaking, the reason it is difficult to directly replace traditional *objective* metrics with V2X data is that collection of traditional objective pavement metrics requires specialized and calibrated equipment. Standard objective measurements are designed to be universal, precise, and repeatable. Any V2X dataset is very unlikely to meet these conditions in the foreseeable future, as discussed below for the four types of pavement condition data.

Structural Adequacy
Collecting deflection data to determine structural adequacy requires a very specific load pattern, and a very accurate measuring device. Standard vehicle-based sensors are not expected to meet this capability in the foreseeable future.

Distress
Surface distress data (rutting, faulting, cracking, etc.) is traditionally collected via visual surveys of representative sections of the pavement. Many transportation agencies and consulting firms now collect such data via mobile sensor systems. However, this data requires cameras (and possibly additional sensors) specifically calibrated to capture pavement distress data. Standard vehicle-based sensors are not expected to be capable of providing such data in the foreseeable future.

Serviceability/Ride Quality
Given the current emphasis on International Roughness Index (IRI) for pavement condition assessment, several studies have attempted to correlate connected vehicle data (accelerometer data) to IRI. Researchers have attempted to collect this data using V2X data from the CAN Bus (Dawkins et al., 2011), aftermarket accelerometers (Mixon, Garret, & Krueger, 2012), and with accelerometer data from smartphones mounted in vehicles (R. Robinson, 2012). Results indicate that vehicle-sensor correlations to IRI included noteworthy margins of error. In other words, a vehicle can provide *some* measure of roughness (Dawkins et. al., 2011 referred to this as a vehicle's "pseudo IRI").

The imperfect correlation between data obtained via onboard accelerometers with IRI may be an inherent difficulty in obtaining a standardized measurement with a tool (i.e., a stock consumer automobile) that was designed for other purposes. The tires and suspension systems on consumer vehicles are designed specifically to counteract the effects of pavement roughness; this is especially true of high-frequency low amplitude pavement roughness conditions (Flintsch, Valeri, Katicha, de Leon Izeppi, & Medina-Flintsch, 2012; R. Robinson, 2012). Additionally, achieving even loose correlation to IRI requires time-consuming calibration of each individual vehicle collecting data. Variables like device mounting angle and vehicle speed create additional sources of error (Mixon et al., 2012; R. Robinson, 2012).

However, just because embedded and mobile onboard sensors cannot provide IRI data does not mean that such data is not valuable. Applying V2X data usefully will likely require novel methods designed to utilize such crowdsourced data, as described later in this chapter.

Friction

Providing an appropriate measure of surface friction is difficult to begin with, as the measurement is affected by multiple variables (e.g., temperature, moisture, parameters of object in contact with pavement, etc.). MDOT's traditional method of assessing surface friction uses ASTM standardized and calibrated equipment under controlled conditions. V2X data may provide a general sense of pavement surface friction, but cannot provide a comparable measurement.

Subjective Metrics

The barrier to using V2X data to collect traditional *subjective* metrics of pavement condition data (e.g., PASER, sufficiency) is essentially the opposite of the issues with objective metrics. Recall that for the *objective* metrics, onboard vehicle sensors may not be capable of collecting data that is accurate, precise, and repeatable enough to significantly correlate to traditional scientific measurements. On the other hand, the same sensor data is basically *too* specialized and accurate to be correlated to human-subjective (windshield survey) rating systems.

Subjective rating systems, such as PASER and similar sufficiency ratings, are heuristic (shortcut) approaches to pavement condition assessment that indirectly account for a wide range of condition factors. These ratings can be influenced by a number of variables that affect human judgment but cannot be measured by traditional onboard sensors. A rater's assessment of pavement condition could be influenced by such factors as the condition of the shoulders or curbs, the width of the lane, or even the color of the pavement (which is reflective of pavement age). Such broad considerations are justified when creating a comprehensive generalized rating of road condition, but cannot be disaggregated into data that reflects a single pavement condition metric. This explains why subjective rating systems such as PASER have been shown not to correlate well to objective measures such as IRI (Gerst, 2009; Sauerwein & Smith, 2011).

Conceptually, it can be expected to be very difficult to use objective sensor data to re-create subjective ratings; they are fundamentally distinct types of metrics. Robinson, 2012 investigated correlation between smart-device accelerometer data (using a software tool developed at the University of Michigan Transportation Research Institute called *DataProbe*) and PASER rating. The study found "reasonable correlation," with the caveat that there were exceptions to the correlation for which "no explanation can be found," except perhaps "the rather coarse resolution used in the [PASER] methodology" (R. Robinson, 2012). An additional possibility is likely that PASER raters consider factors other than pavement roughness in determining ratings.

It is theoretically possible to simulate human-subjective ratings with sensor data. Given enough information, a sufficiently robust algorithm could approximate human subjectivity. However, from an engineering perspective (and for similar reasons from an empirical-mechanistic TAM perspective), any coarse rating derived from relatively precise sensors would be less-valuable than the original data. It may be beneficial, however, if the method would allow road agencies to extrapolate trends from historic data sets using new data. The PASER rating system is valuable tool to TAMC and local road agencies throughout Michigan. Existing statewide practices in transportation asset management rely heavily on road condition rating derived using PASER methodology. Given this, any automated system that could provide a cost-effective alternative to manual PASER rating collection would be a valuable tool as a gap measure until TAM managers become accustomed to using V@X data more directly.

CROWDSOURCED PAVEMENT CONDITION AND PERFORMANCE METRICS

As discussed in the previous section, technical barriers may prevent V2X data from providing any metric that significantly correlates with any traditional measurement of pavement condition.

As a result, deriving value from V2X data may require recognizing differences between these novel data and traditional metrics.

One significant way that V2X data differ from traditional pavement condition data is V2X data do not directly refer to pavement condition. Generally, the source sensors of V2X data monitor the performance of the vehicle in response to pavement conditions. This is true for accelerometers and inertial sensors, whether embedded in the vehicle system, or in a mobile device (e.g., smartphone) within the vehicle. Thus, any assessment of pavement condition must be inferred from data regarding interactions between the vehicle, the driver, and the pavement. This dynamic creates important limitations on the repeatability and accuracy of V2X data collection. It can be expected that sensor data will vary with vehicle attributes and driving behavior. The data collected from one vehicle may provide a drastically different model of pavement condition than a second vehicle. Differences in vehicle dynamics, condition, and sensor configuration can create drastically different readings. Even with a single vehicle, different drivers, or even multiple passes from the same driver, can create significantly different assessments of pavement condition. Even if it can be shown that one vehicle can repeatedly collect similar datasets for multiple passes on a segment of road, this shows only the ability to provide an accurate model of that vehicle's interaction with the pavement. An assessment of pavement condition may then be inferred, but a different vehicle, equipped with a different suspension, may provide a different model of interaction with the pavement, creating a contradictory assessment of pavement condition.

The problem is *not* that connected vehicle data is inaccurate; it can be assumed that sensor data is precise enough to provide repeatable measurements given repeatable measurement procedures. The problem is that connected vehicle data is predictive only to the extent that it models the interaction with a single vehicle to a specific set of pavement and driving conditions. This limitation in generalizability is a serious weakness in using connected vehicle data for pavement asset condition monitoring.

Counteracting such a weakness, the primary strength of connected vehicle data is that it can be *crowdsourced*. The power of crowdsourced data is that large data sets collected from multiple sources negates limitations in generalizability from a single data source. While multiple vehicles may provide conflicting data relating to pavement condition, the sum total of the data should provide a reasonably accurate model of the roadway system in relation to how an average user experiences the system.

While V2X data cannot provide a direct replacement for any current metric, such a crowdsourced metric could be more valuable for a customer-service approach to TAM than any traditional measure. Essential to TAM is creating the optimum experience for users/customers of the transportation system with minimum cost. Current objective measures relating to the ride-quality/serviceability of pavement, such as IRI, generally create a model of the pavement from which the ride quality is inferred. Subjective measures, on the other hand, use human judgment to assess serviceability/ride-quality, but provide little value to a mechanistic-empirical approach to TAM. V2X data could provide the best attributes of both data types; measuring serviceability in an aggregated, but direct, objective metric.

An important consideration for obtaining pavement condition information from V2X data is the potentially massive volume of data that may be obtained from connected vehicles. Even with the cost of data storage and processing decreasing drastically, the cost of data transmission could be notable (R. Robinson, 2012). Additionally, the complexity of dealing with this data volume could be a barrier to effective use in any TAM program.

Fortunately, it is not necessary to integrate an entire trip-log worth of V2X data to obtain valuable information about the serviceability of the pavement. From a customer service perspective, and even from an engineering perspective, if the ride quality of the pavement is "good," most data relating to the pavement roughness is superfluous. We can probably assume that if the ride is relatively good, the pavement is relatively flat and smooth. What *is* valuable to know is where and how a vehicle experiences events associated with pavement distress (e.g., a "bump" or a "rough ride"). Such events can be detected algorithmically, allowing valuable data to be parsed from raw data streams (R. Robinson, 2012). One study estimated that the cost of transmitting such event-based data would be about $5 per vehicle per year (Dawkins et al., 2011). Under scenarios that utilize bundled data plans, the cost of data transmission would be essentially zero ($0), assuming that the marginal amount of data submitted by a user does not increase their marginal cost of a data plan. In this scenario, implementation costs to begin data collection would be limited to database modification, software design, and marketing efforts to recruit participants.

By comparing the available data from vehicle systems and smartphones with pavement condition attributes valuable in a TAM program, this study identifies three pavement conditions most likely to be assessed by V2X data. These are:

- Ride-Quality/Serviceability
- Potholes and Acute Distress
- Tire Slip Events

Ride Quality/Serviceability

Pavement roughness, usually in the form of IRI, is one of the most valuable and widely used pavement condition metrics applicable to TAM. Assessing pavement roughness can be valuable, but the reason it is widely used is because it is used to generalize the user experience of drivers and passengers in actual vehicles; the serviceability/ride-quality. With V2X data, we can bypass the need to make assumptions about serviceability based on pavement condition. We can directly measure effects of the pavement conditions on the vehicle performance.

Accelerometer data from smart phones is probably the type of connected vehicle data most likely to be successfully integrated into near-term TAM programs. The most basic way that connected vehicle data could be usefully applied to TAM is to create and log a geocoded "event" at points where the accelerometer data indicates that the car has experienced sudden acceleration; a "jarring," or a "bump." A number of vehicles collecting such data could be used to highlight rough pavement and potholes.

A TAM database containing such events could be used to define a new metric reflective of pavement serviceability. For example, discrete ranges of events could be converted into a numerical (1-10, 1-5, etc.) scale or a good/fair/poor rating enjoyed by policymakers. Such a scale would not directly correlate to any existing metric, but may actually provide more value to TAM than many existing measures. A V2X data-derived scale (e.g., "bumps per mile per day") would directly reflect user experience via objective data collection. Many TAM program managers may consider this preferable to subjective windshield surveys. Populating a database with crowdsourced event points from a number of connected vehicles could allow engineers and TAM program managers to identify where relatively more vehicles are experiencing the roughest ride. Additionally, such data would likely correlate closely with user costs of poor pavement; a valuable measure of transportation system performance.

Potholes and Acute Distresses

The next level of complexity to a measurement of pavement condition based on accelerometer sensor data may involve discerning potholes and acute distress types from generally rough pavement. These acute distresses would likely create distinct and recognizable sensor readings (R. Robinson, 2012). V2X pothole detection could be useful for reactive maintenance as well as strategic pavement management.

One significant advantage of connected vehicle data tracking of acute distresses is the potential to capture seasonal variations in pavement condition. Freeze/Thaw cycles in colder months interact with pavement in multiple ways. Data that reflect the seasonal development of acute distress points could result in increased accuracy in results from mechanistic-empirically based decision-support software.

Tire Slip Events

Modern vehicles include automated systems that detect and react to tire slippage. A smart device alone would not likely be able to identify low-friction pavement areas, and no V2X data would likely provide a direct measurement of friction (μ). However, it may be possible to create a data point (an *event*) associated with tire slippage, such as activation of vehicle ABS or traction control system. Unfortunately, this data is not generally available through the OBD connection, unless the manufacturer provides a proprietary PID code (R. L. Robinson, n.d.). It may also be possible to detect slip events by comparing speed data from the CAN bus (which is available via the OBD port in most vehicles) to GPS-derived speed.

While many of these "slip" events may be associated with environmental conditions or driving performance rather than pavement conditions, a large number of localized events could reflect low-friction pavement. Alternately, agglomerations of slip events could indicate problems with weather conditions, roadway geometry, signage, or signal management. Any data that would provide such information would be valuable to a mechanistic empirical TAM program that incorporates safety and traffic operations.

LONG-TERM POTENTIAL

Vehicles have had embedded sensors and OBD connections for several years. Yet, only within the last few years has it seemed feasible to use sensors in vehicles and mobile consumer devices to obtain data about transportation assets. Vehicles in the foreseeable future may include new types of sensors and available data that allow for more accurate assessment of pavement condition, and possibly information regarding other assets. Information that may be possible to collect via V2X data in the future may include the following:

- Specific Pavement Distress Data
- Pavement Roughness
- Structural Adequacy
- Pavement Markings and Roadside Assets

Specific Pavement Distress Data (Rutting, Cracking, Faulting, etc.)

With technology currently embedded in vehicle and mobile devices, it is already possible to recognize data that indicate problem areas of pavement. As V2X data is accrued and studied, analysts may be able to identify patterns in sensor readings that can be correlated to specific distresses and severities. For example, a specific frequency and wavelength, or combination thereof, of sensor readings may be found to correlate to a certain severity of raveling. A different pattern may be found to correlate with map cracking, and another with faulting. Further research may identify such correlations, but will likely require significantly more research on V2X data. Additional sensors available on future vehicles may also be utilized to detect pavement distress. Possibilities include cameras and various machine-vision sensors as may be used for active safety or automated driving, and sonic sensors as may be used for noise cancelling in the cabin.

Pavement Roughness

In previous discussions regarding V2X data, we use primarily accelerometer and vehicle system operations data to gauge the interaction of the vehicle with the pavement. Obtaining a standard roughness metric, such as IRI, generally requires advanced measurement equipment (e.g., laser range sensors) (Mixon et al., 2012). While today's vehicles are not fitted with such equipment, vehicles of the future may be. In fact, the 2014 Mercedes-Benz S-Class uses a Light-Detection-and-Ranging (lidar) scanner to measure pavement roughness as a component of an active suspension system (Lavrinc, 2013).

At this time, there has been no investigation towards using such a system to measure pavement roughness. It is unknown how or if the vehicle's LIDAR data may be used or transmitted by the vehicle, if it would be available through the OBD port, or if it would even be useful in creating a pavement roughness measure. Even with a best-case scenario, such a measurement would still not be as precise as a standard like IRI, but may be shown to correlate to IRI much better than current V2X datasets.

Structural Adequacy

Assessing structural adequacy requires precision measurement of deflection data, generally requiring laser ranging. As mentioned in the previous subsection, future vehicles may be equipped with

LIDAR sensors for real-time pavement condition assessment and reaction. It does not appear likely at this time that such sensors would be precise enough to measure deflection. However, future TAM managers should be mindful of this possibility. The ability to assess pavement strain in real time could lead to dynamic weight restriction policies, rather than rough seasonal policies now in place. This could greatly benefit both pavement preservation and the freight industry.

Pavement Markings and Roadside Assets

In the near term, V2X data for TAM is most likely to be used to assess pavement condition. Eventually, such practices may be expanded to collect data on other transportation system assets. Future vehicles may incorporate a variety of cameras and sensors that could be utilized in assessing conditions of the pavement as well as roadside assets. Automated driving systems that collect information regarding how and where the vehicle should drive may be capable of assessing if assets like pavement markings and signs are damaged, faded, or missing. Similarly, automated driving systems may scan the environment around the vehicle, including curbs, shoulders, and possibly sidewalks. Such data would not likely be 100% reliable or repeatable; different vehicles, using different software or in different conditions, may provide conflicting data. But, as with simple ride quality assessments, the crowdsourcing of multiple vehicles may provide TAM managers an accurate picture of where problem areas exist. This would also be valuable for reactive maintenance to issues like icy pavement, malfunctioning signals, or damaged signs.

SUMMARY

The potential for V2X data to be applied to asset condition monitoring is summarized in Table 7. The timeline has been divided into four categories:

- **3-5 years:** This category generally represents the metrics that could potentially be obtained with existing technology and infrastructure. The three year minimum reflects typical engineering practices that usually require at least three years of a new type of data to be collected before a baseline can be established and subsequent trends can be used as actionable information.
- **5-10 years:** This category reflects metrics that could potentially be obtained with existing technologies, but would involve extensive data collection and calibration of models to develop useful metrics.
- **10+ years:** This category reflects metrics that could potentially be obtained using equipment that could be installed on future consumer vehicles, or metrics that could be obtained using existing systems with very extensive data collection and calibration of models.
- **Unlikely:** This category reflects metrics that are unlikely to be obtained using embedded consumer-grade vehicle equipment, either because the metric is to precise to be obtained without specialized and calibrated sensor systems, or because the metric is subjective and not likely to allow correlation by algorithm.

An important caveat to this estimated timeline is that specialized aftermarket data acquisition systems are not within the scope of this paper. Such systems could be designed to capture asset condition data more efficiently and precisely as compared to using sensors embedded in consumer vehicle and smartphones.

Table 7: Potential for V2X Data Application to Asset Condition and Performance Monitoring

Data Category	Metric	Timeline
Pavement Structural Adequacy	Deflection Under Known (Non-Standard) Load	10+ years
	Deflectometer Data (Deflection/Strain Under Standard Load/Stress)	Unlikely
Pavement Surface Distress	Acute Distress *Events* (e.g., Potholes)	**3-5 years**
	Faulting	5-10 years
	Rutting	10+ years
	Cracking	10+ years
	Distress Index (DI)	10+ years
Pavement Ride Quality/ Serviceability	Rough Ride *Events*	**3-5 years**
	Event-Based Ride Quality Index	5-10 years
	Estimated International Roughness Index (Pseudo IRI) (by calibration to vehicle data)	5-10 years*
	Estimated International Roughness Index (IRI) (by correlation to crowdsourced data)	10+ years*
Pavement Surface Friction	Slippery Pavement *Events*	**3-5 years***
	Frictional Force (μ)	Unlikely
Subjective Pavement Ratings	PASER Rating (by correlation)	Unlikely**
	Sufficiency Rating (by correlation)	Unlikely**
Pavement Markings and Roadside Assets	Various	10+ Years

***May require partnerships with manufacturers for access to CAN bus data.**
****Barrier is inherent in correlating objective sensor data to a human-subjective rating scale.**

CONNECTED VEHICLE DATA MANAGEMENT AND INTEGRATION

The management of crowdsourced data is likely to be fundamentally different than traditional practices in TAM data management. Data will not be formally created within the agency or by consultants, but submitted continually from a distributed network of probe vehicles. This chapter highlights some of the unique implications and challenges that transportation agencies may face when trying to incorporate V2X data into TAM programs.

CONNECTED VEHICLE DATA COLLECTION

As previously discussed, perhaps the most likely near-term method of collecting V2X data for use in TAM databases would be to utilize a carried-in mobile smart device to monitor vehicle and/or device sensors for data events that correlate to pavement distress. Any data that is not used to create an event point can be discarded immediately, and does not need to be uploaded. The useful data (geocoded event points) can be uploaded in real time, at the conclusion of a trip, or another established period. Historical event data would be stored on external servers, but would not need to be stored on the device.

This type of event-based data is fundamentally different than traditional asset condition data currently used by pavement management databases. Storing and manipulating such data will likely require novel database designs and specifications. However, a V2X database could be referenced to established pavement management databases, allowing state-of-the-art TAM programs to find relationships between V2X data and established measures of pavement performance. As TAM program managers become familiar with such novel types of data, it is possible that V2X data could negate the need for existing methods of pavement condition monitoring.

The design of pre-processing (event-finding) logarithms could take several forms. For example, one method would be to establish a profile for each vehicle relating to "normal" sensor data in the course of a trip. Once a baseline of behavior for a vehicle is established, the program can selectively log only the data with a set variance from that baseline. A data monitoring program would identify the data points that meet whatever attributes are chosen, and create a geocoded "event" for this behavior. The attribute data logged in association with the event may vary based on the sensor data. For example, a sensor reading greater than two standard deviations from the mean may be tagged "pothole," and sent with only the single data point that triggered the event (Dawkins et al., 2011). On the other hand, if the sensors record a series of readings beyond one standard deviation, the program may create a "rough pavement" event, and log that series of data points. Establishing standards and practices for determining pavement condition events from raw sensor data will require some trial and error correlation to "ground truth" data.

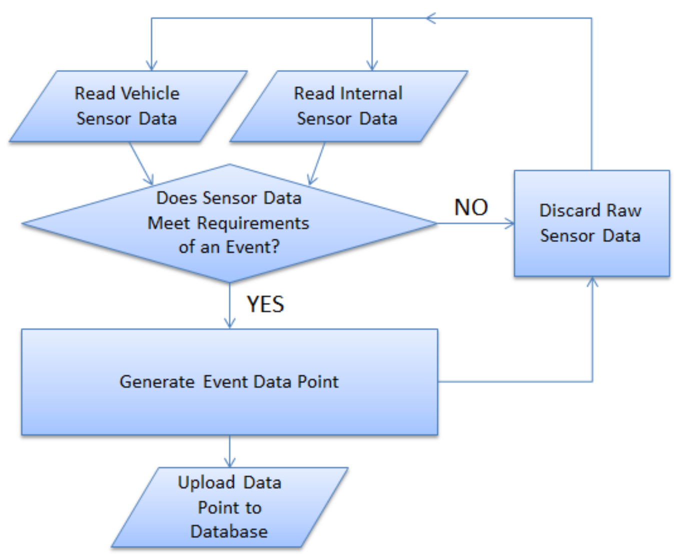

Figure 8: General Event Data Point Creation Flow Chart

It is important to keep in mind that even though event-finding applications may be developed through correlation to more traditional metrics, the V2X data is fundamentally different than existing metrics. Individual data points cannot be expected to have much objective value. The value is in the collection of a multiplicity of data points. Mass aggregation (crowdsourcing) of such event points creates an integrated quality assurance mechanism. If a location on a highway creates a single event point, this could be an outlier; For example somebody dropping a phone, or hitting a deer. If that same point creates a couple dozen events, there might be an issue worth investigating, though it might not be an emergent problem; For example, maybe a small percentage of drivers hug the shoulder and run over a drainage structure. However, if an event is created at the same point by multiple vehicles over a period of time, we can be pretty sure there is a real issue at that point impacting ride quality for a large percentage of road users.

DATA STORAGE

Because there have not yet been established methods of creating and processing V2X data for pavement condition monitoring, it currently cannot be known what data storage requirements will be necessary. Properly selected event-based V2X data should not impose significant concerns regarding data storage, *per se*. Recent studies in V2X data have not identified file size or data storage as barriers. For example, one study logged over 30,000 miles of relatively detailed V2X data, resulting in a database size of about 13 GB. Event-based data monitoring should be significantly less demanding of digital storage space.

However, managing V2X databases may be more labor-intensive. New data may be constantly streaming in. Database managers may have to develop novel routines for processing data in order to assure that only relevant data is used in application-based queries. MDOT's DUAP II program is currently designing a system by which ITS data will be accessible to the department's asset management databases.

It is important that data is stored as efficiently and consistently as possible. However, there is no benefit in destroying historical data, regardless of extended retention times. A review of literature has not discovered any experimental results indicating storage requirements of event-based pavement condition measurement. However, there are no indications that data storage for such a scheme would impose a relevant issue with regards to storage space or cost. It may be desirable to discard non-aggregated data after a certain period of time for reasons relating to privacy.

If storage of the multitude of events does become a concern, individual events can be converted to summary files that reflect key attributes of the set of events for a given time period. These summary files should be retained as long as possible. As V2X databases accumulate historical data, they will become increasingly powerful sources of information for mechanistic-empirical decision-support software used by state-of-the-art TAM programs.

DATA INTEGRATION

As V2X data may be fundamentally different in collection procedures and structure, TAM program managers may have to employ novel methods of data integration in order to translate V2X data into useful information. In the context of transportation asset management, data integration is:

> "the method by which multiple data sets from a variety of sources can be combined or linked to provide a more unified picture of what the data mean and how they can be applied to solve problems and make informed decisions that relate to the stewardship of transportation infrastructure assets" (FHWA, 2010).

A state-of-the-art TAM program is extensive and comprehensive. At the heart of an effective TAM program is a comprehensive enterprise database available to state-of-the-art decision-support software. Decision-support output should use a mechanistic-empirical iterative approach utilizing all available data, including traffic history and forecast model data, safety data, environmental and climate data, maintenance history, construction details, risk factors, demographic forecasts, and more. The system would incorporate known or assumed mechanistic-empirical correlations, but should also be capable of integrated *machine-learning*; i.e., discovering new correlations so as to more accurately predict the costs and benefits of potential transportation system asset management and investment decisions. A generic representation of a data integration process is given in Figure 9. The use of a robust enterprise database is a foundational assumption in discussing applications of V2X data to TAM. As most agencies do not currently utilize any kind of crowdsourced data, updates to TAM databases will have to account for these new forms of crowdsourced V2X data.

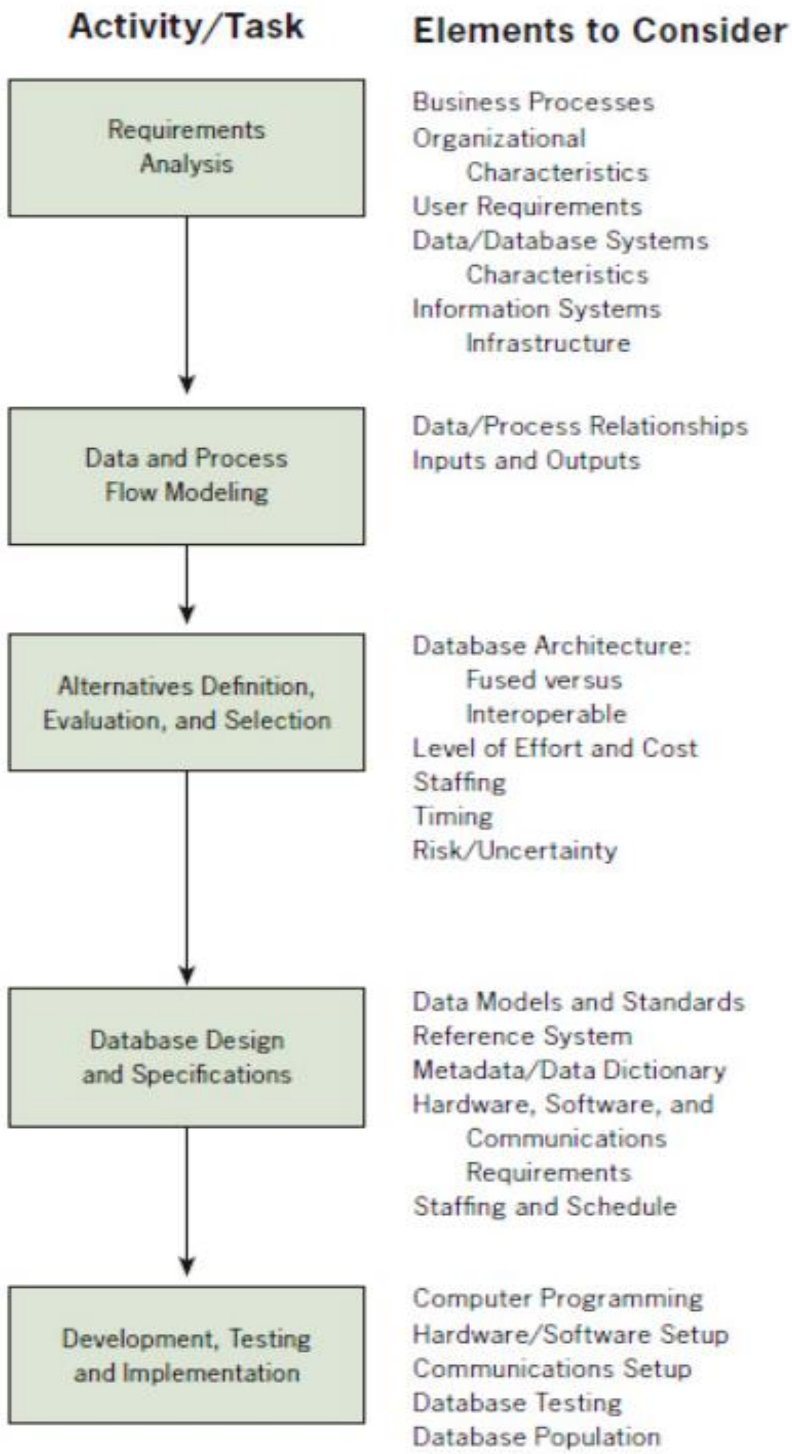

Figure 9: The Data Integration Process. Source: FHWA

CONCLUSIONS AND RECOMMENDATIONS

CAR's investigation of connected vehicle approaches for transportation asset management has revealed remaining challenges and recommendations for action.

SUMMARY OF FINDINGS

- Transportation agencies can improve the condition and operation of the transportation system by implementing state-of-the-art transportation asset management (TAM) programs that utilize data-based decision-support software.
- Connected vehicle data (V2X data) may be a valuable addition to enterprise TAM databases.
- The popularity of smart mobile devices in vehicles provides an opportunity to efficiently preprocess and collect V2X data.
- Near-term applications of V2X data are likely to include pavement condition monitoring.
- V2X-based data regarding pavement condition is not likely to directly provide traditional measures like IRI and PASER, but new metrics may supplement and eventually supplant traditional metrics.

CHALLENGES

- Many valuable V2X datasets (e.g., vehicle accelerometers, ABS status, traction control status, etc.) are not usually accessible outside the vehicle CAN bus. For the foreseeable future, accessing this data will require partnerships with manufacturers, a barrier to implementation.
- Standard methods of using V2X data in TAM do not yet exist. First-adopter agencies will have to innovate.
- V2X data must likely be collected for about three years before data can be fully implemented in decision-support systems. This is generally considered the minimum time required for asset managers and engineers to establish a baseline by which to compare future datasets.
- Using V2X data likely will require active data management and a state-of-the-art enterprise database or set of interlinked databases. Data screening, fusion, and integration may be challenging.

NEXT STEPS/FUTURE RESEARCH

There are not any substantial technological barriers to immediate use of connected vehicle data for pavement condition monitoring. The concept has been proven in several research studies. Yet, because the specific attributes of the V2X datasets are unfamiliar to transportation agencies, there is no clear path to implementation. First-adopter agencies will have to innovate.

At least three years of historical data are required to establish trends on which to base transportation planning and asset management decisions. Thus, for agencies to use V2X data for TAM in the future, agencies must start collecting the data now and begin integrating V2X databases into an enterprise database scheme. As databases become populated with V2X data, decision-support software may be used to identify correlations between V2X data and other proven/accepted measures of pavement performance. Eventually, legacy metrics may be completely supplanted by V2X data, resulting in substantial cost-savings for pavement condition monitoring. Additionally, MDOT's maintenance division may experiment with using the V2X data for reactive maintenance to potholes.

Many possibilities exist for creating and integrating V2X data into a TAM program. While several research projects have investigated algorithmic approaches to data integration, no obvious candidates for setting universal standards have emerged. This is not a reason to delay action. MDOT has many advantages that would allow the agency to become an early adopter in utilizing V2X data for pavement condition monitoring and TAM. Notably, MDOT has already developed the architecture for an enterprise TAM data scheme, the TMS. With some modification, the TMS could be expanded to include V2X data. Another distinct advantage is that MDOT is already collecting such data; ongoing research in the MDOT Data, Use, Analysis and Processing (DUAP) Project has involved collecting large V2X datasets relevant to pavement condition monitoring.

The gap between the MDOT (TMS) and V2X

data is that DUAP has been using project-specific databases, with no current link to MDOT agency databases. However, the DUAP V2X data scheme has been designed and data is now being collected. The next crucial step for MDOT is to bring the two together.

The Data Modernization Assurance & Governance (DMAG) is a new initiative taking place inside MDOT that could provide V2X with the exposure and momentum to carry DUAP II's knowledgebase into mainstream MDOT programs. DMAG is a multi-year program which will establish a Data Governance model with the responsibility of rationalizing data at the enterprise level. Data Governance will improve the value of data across the department.

DMAG, combined with V2X goals and data streams, can provide MDOT with greater return on its technology investment, including:

- Business benefits
    - Accurate and dependable data for better business decisions
    - Data integrated from multiple systems presented as a single best, master record
    - Improved data quality
    - Timely analysis and resolution of data issues due to ownership, and methods in place to remedy data issues
- Defined ownership of data; each identified data domain is assigned a single, vigilant owner who has responsibility for data quality and other aspects of managing the data
- Governance of data is rooted in business requirements through stated policies, standards and practices
- Consistent management of data issues across all areas of the business permits uniform administration and oversight despite the type of data
- Enhanced business and IT cooperation over all aspects of managing data, ensuring better Business visibility into data matters and better IT visibility into data demands

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