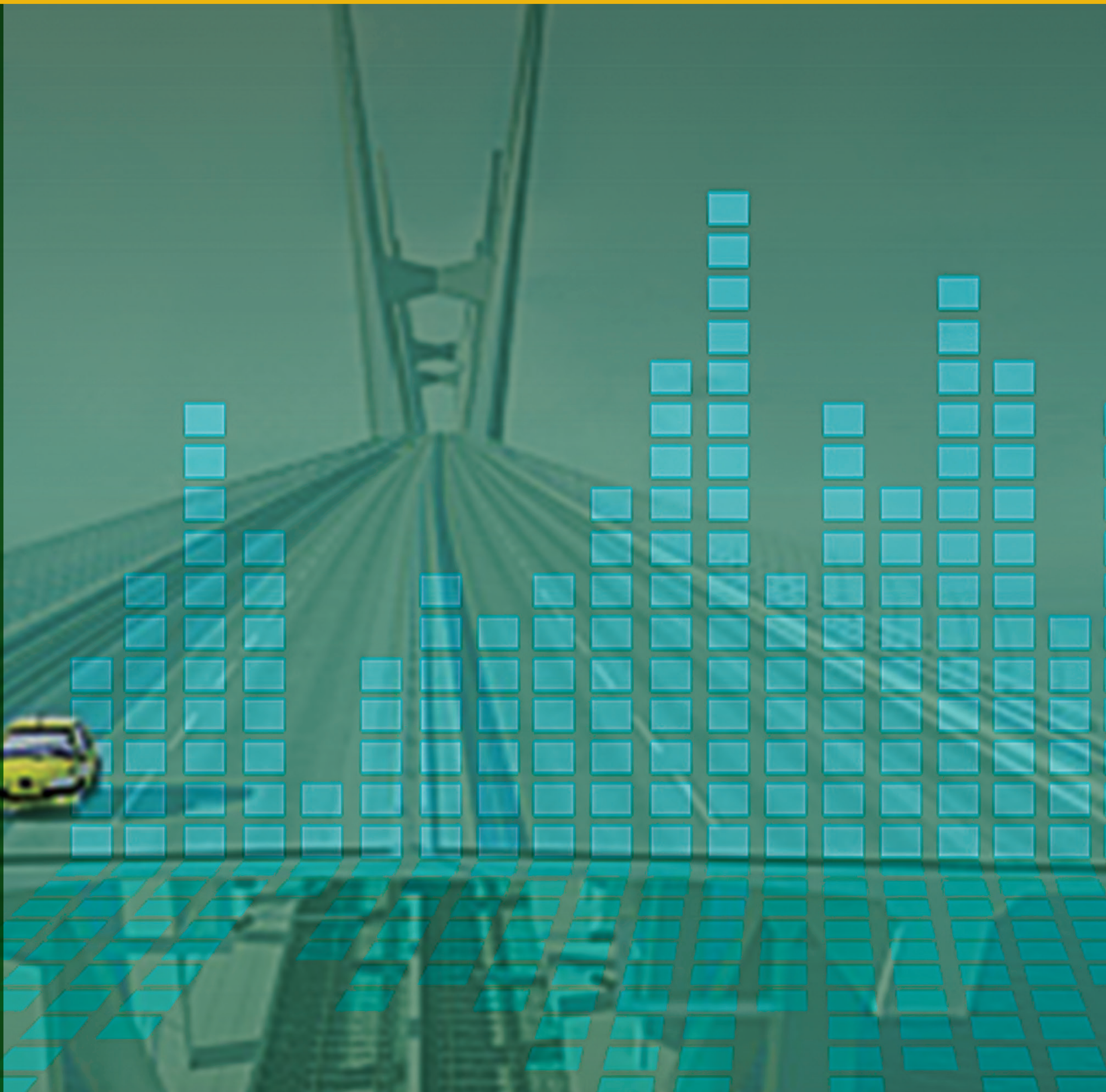
The Exploratory Advanced Research Program

EXPLORATORY ADVANCED RESEARCH

Use of Vehicle Noise for Roadways, Bridge, and Infrastructure Health Monitoring

WORKSHOP SUMMARY REPORT • AUGUST 20-21, 2013



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16. Abstract On August 20–21, 2013, at the Turner–Fairbank Highway Research Center in McLean, VA, the Federal Highway Administration's Exploratory Advanced Research Program convened a 2-day workshop entitled, "Use of Vehicle Noise for Roadways, Bridge, and Infrastructure Health Monitoring." The objectives of the workshop were to discuss the possibilities of using vehicle noise for roadways, bridge, and infrastructure health monitoring and to use a noise-based data collection system that could assess infrastructure for proactive and efficient infrastructure maintenance and operations, higher infrastructure safety, and less traffic congestion.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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List of Acronyms and Abbreviations

General Terms

3D	three-dimensional
4D	four-dimensional
AASHTO	American Association of State Highway and Transportation Officials
ABS	anti-lock braking system
DAS	data acquisition system
DOT	Department of Transportation
DSS	decision support system
DTPS	dynamic tire pressure sensor
DUAP	data uses analysis and processing
EAR	Exploratory Advanced Research
ESRI	Economic and Social Research Institute
FHWA	Federal Highway Administration
GIS	geographic information system
GPR	ground penetrating radar
GPS	Global Positioning System
HPMS	Highway Performance Monitoring System
IR	infrared
IRI	international roughness index
LIDAR	light detection and ranging
LTBP	Long-Term Bridge Performance
MASS	mobile acoustic subsurface sensing
MDOT	Michigan Department of Transportation
MTD	mean texture depth
MWR	millimeter-wave radar
NBI	National Bridge Inventory
NDE	nondestructive evaluation
NHS	National Highway System
NVH	noise, vibration, and harshness

PAVEMON	pavement monitoring
PCA	principal component analysis
PCI	pavement condition index
RABIT™	Robot-Assisted Bridge Inspection Tool™
R&D	research and development
RD&T	research, development, and technology
TFHRC	Turner–Fairbank Highway Research Center
VIDAS	vehicle-based information and data acquisition system
VOO	vehicles of opportunity
VOTERS	versatile onboard traffic-embedded roaming sensors

Introduction

On August 20–21, 2013, at the Turner–Fairbank Highway Research Center (TFHRC) in McLean, VA, the Federal Highway Administration's (FHWA) Exploratory Advanced Research (EAR) Program convened a 2-day workshop entitled, "Use of Vehicle Noise for Roadways, Bridge, and Infrastructure Health Monitoring." The objectives of the workshop were to discuss the possibilities of using vehicle noise for roadways, bridge, and infrastructure health monitoring and to use a noise-based data collection system that could assess infrastructure for proactive and efficient infrastructure maintenance and operations, higher infrastructure safety, and less traffic congestion.

Michael Trentacoste, Associate Administrator for Research, Development, and Technology (RD&T) and Director of TFHRC, welcomed workshop participants. Trentacoste introduced the subject of the workshop and encouraged participants to think beyond the technology that is currently available for the transportation industry. He also asked participants to consider several themes during the workshop, including how to collect data in a cost-effective manner, how the data would be integrated for analysis, and if there are any technologies that are being applied in other fields that might be applicable for this discussion.

Joe Peters, Director of the Office of Operations Research and Development (R&D), then highlighted some of the current issues facing the industry. These issues include congestion, safety, and the inspiration for the workshop, reactive maintenance. Peters also emphasized the need for a delivery system to send informational messages from damaged infrastructure and encouraged participants to think beyond technologies that are available today.

Next, Cheryl Richter, Assistant Director for Pavements Research and Development of the Office of Infrastructure R&D, described her vision of a future in which the need for infrastructure damage alert systems would be eliminated by performing preventative maintenance at the appropriate time. This type of system would include technologies that assess infrastructure so that aging infrastructure could be addressed appropriately.

David Kuehn, EAR Program Manager, provided an overview of the EAR Program and described the focus areas for this discussion. Topics included connected highway vehicle systems, technology for assessing performance, and information sciences.

Mohammed Yousuf, who is with FHWA's Office of Operations R&D, offered participants some perspective on how far technology has come in the past 100 years, specifically within the automotive industry. He also provided an overview of how much data are available today and explained the importance of asset management. Yousuf proposed using noise, vibration, and harshness (NVH) as a metric to study roadways, bridges, and infrastructure by creating infrastructure-aware vehicles that act as mobile sensors and by leveraging emerging technologies and existing vehicle systems. Yousuf also noted that advanced data-processing methods need to be developed to interpret the data. He went on to provide several examples of using embedded microphones in vehicle systems, which included tire-pressure monitoring, wheel sensors, and infotainment systems. Yousuf explained that, after the noise data collection, using a series of sophisticated processing techniques could provide alerts for specified criteria for a given scenario or condition. In summary, Yousuf noted that potential impact of creating such a system could lead to new methods of asset-based data collection. In addition, with new forms of data available, gathered by using passenger vehicles as probe sensors, further discoveries could lead to other tools that would benefit the field, and supervisory site visits for asset management could be eliminated.

Shane Boone at the Office of Infrastructure R&D provided key background information on FHWA's nondestructive evaluation (NDE) activities and the Long-Term Bridge Performance (LTBP) program. He said a reliable NDE method that bridge owners have been using for the last 40 years to evaluate bridge delamination and debonding is *chain drag*.[1] Boone explained that, although chain drag is inexpensive, it cannot be performed at highway speed; thus a lane must be closed, which causes congestion. Boone encouraged participants to consider how this type of measurement could be performed at highway speeds, what frequencies would be required, what properties of the materials could be evaluated, and how this process could be automated in the future.

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[1] For more information on chain drag, visit http://onlinepubs.trb.org/onlinepubs/shrp2/SHRP2_S2-R06A-RR-1.pdf

Panel Discussion

Topic: Asset Management Current Practices, Key Issues, and Near-Term Advances

Panelists
Shane Boone, *Office of Infrastructure Research and Development*
Dr. John Popovics*, University of Illinois*
Jack Stickel, *Alaska Department of Transportation*

Goals

Panel members began by discussing goals for using vehicle noise as a measure of infrastructure health. The following considerations were agreed upon:

- **Detecting defects.** The ultimate goal is to detect defects, such as potholes, before they become issues.
- **Evaluating at speed.** Researchers need to evaluate materials at highway speed, which may preclude physical contact with the materials.
- **Calibrating messages and alerts.** Collecting both acoustic and location data from many passenger vehicles in real time allows for calibration of location messages and degradation alerts.
- **Specifying a threshold.** Data should be collected all the time but only reported at a specified threshold.
- **Understanding degradation and deterioration.** Continual data collection will allow for trending over time and a better understanding of degradation and deterioration.

The panel then discussed the needs for the facilitation of these goals as outlined in the following sections.

Integration

The panelists highlighted that interaction between research and practice can result more quickly in infrastructure managers who can manage maintenance with minimal interruption.

Data Management

To process the large quantities of data collected by these systems, the panelists suggested first identifying how to sort through the data so that the information will be most useful. They also noted that the main purpose of collecting the data is to predict when materials need to be replaced.

Technology Needs

Current Technology

The panel members initially highlighted the the Robot-Assisted Bridge Inspection Tool™ (RABIT™), an FHWA LTBP robot that integrates real-time acoustic, optical, radar, and other sensors to gather information about the condition of bridges while it travels along them. This tool provides near real-time information about the condition of a concrete bridge deck, and the precise location and nature of the damage.[2] This was noted by the panelists as a step in the right direction.

Panel members then discussed current features on vehicles with the potential to be used for these goals. For example, active suspension is one feature that could indicate the density of the materials by evaluating the damping properties of the material.

Other sensors that could be used in conjunction with acoustic sensors include optical sensors to visually confirm anomalies identified in data, depending on the quality and price point of cameras. During discussion, the panel members noted that infrared (IR) cameras can remove shadow from the images. According to the panelists, Illinois Department of Transportation uses a van with optical cameras to document pavement status. The panelists also highlighted that the use of ground penetrating radar (GPR) frequencies required for appropriate data collection may not be available for private or commercial fleet vehicles because of interference with other entities.

In summary, panelists discussed tracking the location of vehicles. They highlighted that, although commercial or maintenance vehicles could use differential Global Positioning Systems (GPS) so that their position in lanes are known, passenger vehicles would be more likely to use GPS found on mobile phones. This is because the cost of differential GPS to determine position, which cannot currently meet the required level of accuracy.

New Technologies

According to the panelists, the Alaska Department of Transportation and Public Facilities is exploring several new technologies, as follows:

- Light detection and ranging (LIDAR) and digital imaging and how to integrate with other operations.
- Road weather and traffic cameras.
- Maintenance decision support system (DSS).
- Side-fire radar for traffic volume.
- Quasi-real-time crash data.
- Geographic information system (GIS) capabilities.
    - The Economic and Social Research Institute (ESRI) is developing a new roads-and-highway application for linear referencing.
- Expanded collaboration and data sharing using ESRI's ArcGIS tool online.
    - The American Association of State Highway and Transportation Officials' (AASHTO) technology implementation group collaborated with the University of Connecticut to develop a program called "*UPlan*" (visit http://tig.transportation.org/Pages/UPlan.aspx for more information).
    - Remote data collection and remote power sources.
    - Remote power supplies.
        - Looking at fuel cell technology.

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[2] For more information, visit http://www.fhwa.dot.gov/research/tfhrc/programs/infrastructure/structures/ltbp/ltbpresearch/rabit/index.cfm

        - A brand new system by Q Technology that uses natural gas or propane.
    - FHWA's Road Weather Management Program.
        - Weather-responsive traffic management.
        - Strategies for road weather changes.

Asset Management

Known Efforts

Each State is required to develop a risk-based asset management plan for the National Highway System (NHS) to improve or preserve the condition of the assets and performance of the system (23 U.S.C. 119(e)(1), MAP-21 § 1106). The asset management plan for the NHS includes data collection, maintenance, preservation, and integration. Additional subtasks include developing a base map of all public roads with a linear referencing system that will be integrated with the Transportation for the Nation dataset.

Recommended Resources

Panelists recommended the following additional resources:

- Transportation Research Board. (2013). *AASHTO Transportation Asset Management Guide: A Focus on Implementation* (FHWA Publication No. FHWA-HIF-10-023). Washington, DC.
- Transportation Research Board. (2010). *National Cooperative Highway Research Program Report 666: Target-Setting Methods and Data Management to Support Performance-Based Resource Allocation by Transportation Agencies.* Washington, DC.

Gaps and Research Areas

Panelists suggested that integrating and linking all different asset classes and transportation information—by creating an enterprise road network with a linear referencing system—would be one approach to further research. One area noted for improvement is developing a governance framework within agencies. Other critical issues that require attention include data silos, integration, and establishing common definitions. Panelists suggested that a useful strategy would be to "collect once, use many times."

Current Research

Transportation Research Board research topics regarding asset management include the following:

- Expansion of capability maturity model.
- Roadway safety data partnership.
- Real-time system operation.

Day 1
Presentations

Presentation 1: What Can We Learn From Vehicle Noise and Vibration?

J. Gregory McDaniel
Boston University

J. Gregory McDaniel's presentation focused on *versatile onboard traffic-embedded roaming sensors* (VOTERS) that use *vehicles of opportunity* (VOO) as inspection data platforms. The research project that McDaniel described in the presentation has been ongoing for 5 years at Northeastern University.

McDaniel explained how the VOTERS project uses a test van that monitors road materials in real time. As shown in figure 1, the van is equipped with the following: GPS, camera, directional microphone behind the left rear tire, laser height sensor, dynamic tire pressure sensor (DTPS), rear-axle accelerometer, a five-sensor surface millimeter-wave radar array, and a power supply. The van also features a portable real-time monitoring system, control station, and data acquisition and processing station.

McDaniel provided an overview of how the VOTERS test van measures the surface waves in the road that carry information

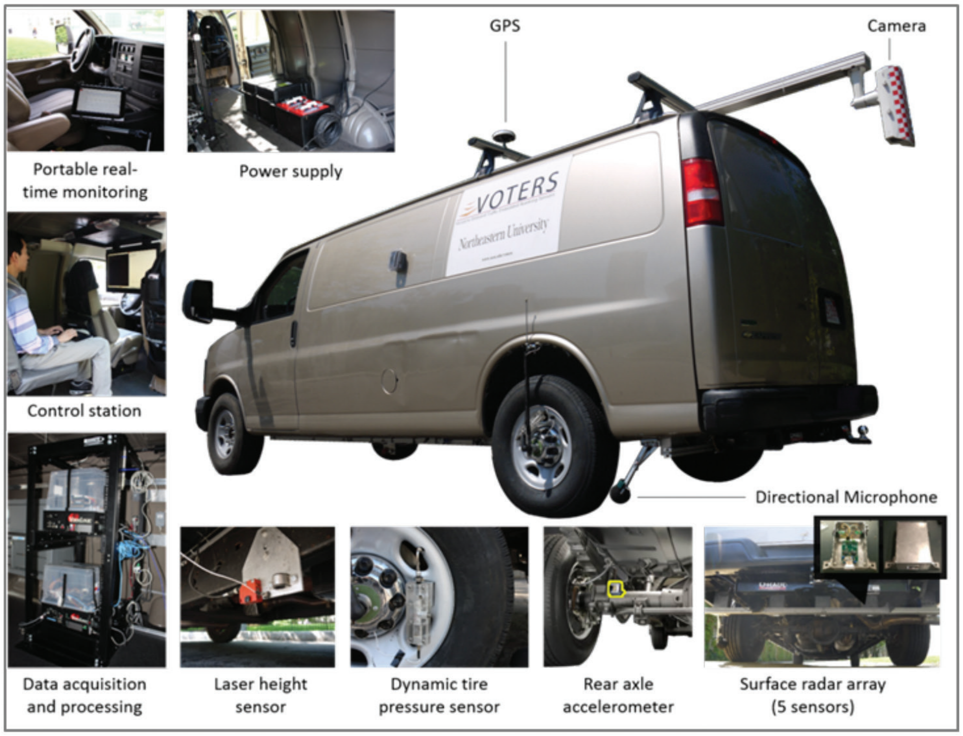

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Figure 1. The versatile onboard traffic-embedded roaming sensors (VOTERS) test van.

about subsurface conditions. Waves in the tire wall carry information about the road surface from road and tire interaction. A key point that McDaniel noted during the presentation was that the surface waves in the road have very large wavelengths that reach the width of the entire road. It is therefore not necessary to measure exactly over an area with a subsurface issue to detect the issue.

Specific challenges noted for these measurements include wind, vehicle vibration, and acoustic resonances. Key resonances to consider include the following:

- Engine rotation: 100s of Hz (100s of s^{-1}).
- Vehicle bounce against springs and suspension: 1–2 Hz (1–2 s^{-1}).
- Standing waves between the road and bottom of the car when integers of one-half wavelengths are present: 100s of Hz (100s of s^{-1}).
- Air in tire will resonate acoustically.

Principal Component Analysis

McDaniel explained to workshop participants how mounting the directional microphone behind the rear tire eliminates wind noise. Processing data by using the principal component analysis (PCA), developed for this purpose, filters out the remaining noise. The vehicle speed must be known to complete the PCA analysis to output the mean texture depth (MTD). This method has been validated, and calibration can be performed by driving on a road with a known MTD. An exterior microphone can also be used to find the MTD at three different vehicle speeds with this system.

Dynamic Tire Pressure

During the presentation, McDaniel noted that the DTPS concept measures the change in internal air pressure through a sensor mounted on the valve stem. This sensor can be added to any tire, powers itself, wirelessly transmits data, and will sample at 40 kHz. If the car is not moving, the sensor measures zero. He also noted the DTPS has been validated against an accelerometer on the ground.

McDaniel put forward to workshop participants several advantages to using DTPS, as follows:

- Ambient noise is no longer an issue, because the tire provides a barrier and approximately a 90-percent reduction in noise.
- Acoustic resonances involving the air in the tire act as a natural amplifier of ground motion.
- Interior pressure is a highly coupled to ground vibration through the adiabatic gas law.
- Measurements can be made at typical roadway traffic speed.

As shown in figure 2, if the DTPS is paired with an axel accelerometer, the impedance of the road can be measured to detect subsurface damage. This can also be performed at typical traffic speed, and the difference between the body of the car moving up and down and bumps in the road can be differentiated. McDaniel noted that this method can provide reliable correlations to a longitudinal road profile, pavement condition index, and international roughness index.

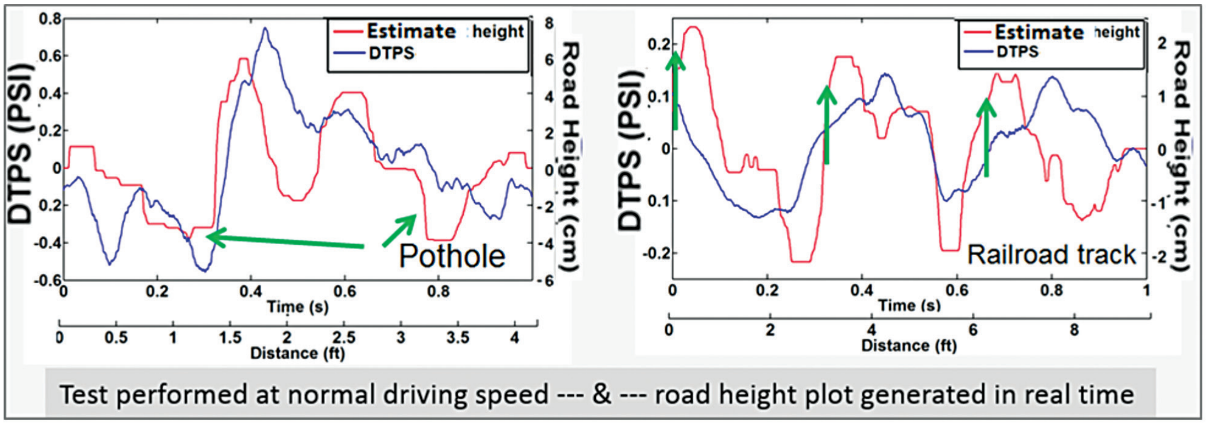

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Figure 2. Longitudinal road profile.

Sensing Surface Waves

For an acoustic-sensing method for detecting surface waves, McDaniel told workshop participants that it is recommended to put the microphones as close to the ground as possible (without touching the ground). This method includes the use of a mechanical excitation cart to create the waves. Because the signal-to-noise ratio is very poor when using this method, an iterative wave-fitting method algorithm is currently in development. This algorithm estimates the complex number of the wave, and an important output of this algorithm is the decay rate. McDaniel also explained that the decay rate contains information on the properties of the material and whether there could be subsurface damage.

Conclusion

In summary, McDaniel explained that all the methods presented are based on physics. He also highlighted that exploiting physics can provide significant advantages in noisy environments.

Questions

Following the presentation, McDaniel responded to the following question from a workshop participant:

- ***Are temperature changes accounted for in the tire?***

McDaniel confirmed that this is not the case because the time window during which the DTPS is used is very small, and the calculation assumes no transfer of heat energy.

Presentation 2: Seeing Below the Surface Using Acoustic-Based Sensing and Imaging

John S. Popovics
University of Illinois

John S. Popovics' presentation focused on cost-effective and accurate inspection of concrete transportation infrastructure. Popovics presented specific methodology to workshop participants, including scanning impact-echo for delamination detection and air-coupled ultrasonic surface wave characterization of defects.

Scanning Impact-Echo for Delamination Detection

Popovics began with an explanation of the impact-echo technique, a test based on impact resonance. The material is interrogated with a hammer, or ball drop, and the material responds by "ringing" in different stretch or flexural resonance modes, or a combination of modes. This allows for the identification of defects.

Popovics explained that flexural modes are easy to detect acoustically, and stretch modes are difficult to detect. In accordance, this method works well for near-surface delamination because it is characterized by flexural modes; however, a problem with the current methodology is that it requires detailed interrogation of the material and cannot be performed at highway speeds.

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Figure 3. The contactless impact-echo scanning system.

Popovics proceeded to describe the development of a contactless echo-scanning system that uses a microphone array. This is an inexpensive method that uses a rugged test setup. As shown in figure 3, a hand-driven impact produces the needed excitation. Popovics also provided experimental results from a static system and a platform that moves at walking speed. Modal analysis of the results produces detailed images for fixed-testing systems; however, this type of analysis is not practical for bridge decks, because the goal is to collect data with a moving platform.

To analyze data from a moving platform, the system collects individual spectral signals that are stacked and mapped. A four-dimensional (4D) plot can provide a view of a thickness-stretch mode, as shown in figure 4. Popovics suggested that the use of transparency simplifies the interpretation and clearly indicates where defects occur. For example, low-amplitude data are transparent (indicating no defect) and high-amplitude data are opaque (indicating a defect). This is considered a very effective way of filtering data to view defects, and when validated against other more personnel- and time-intensive methods, the 4D image produces the same end result.

Popovics also provided an overview of testing the nonmoving platform on an active bridge. The project research team collected data on the bridge deck in 90 minutes with a 100-percent hit rate. This meant that everywhere the analysis indicated there was a delamination, one was found. The presence of delamination at a subset of locations was determined from extracted core samples. Popovics noted that this method did not require filtering of signals to remove noise from active traffic, even though the roads were being heavily used during the measurement.

Air-Coupled Ultrasonic Surface Wave Technique

During his presentation, Popovics also covered the concept of using air-coupled ultrasonic waves to measure surface waves. This could be an inexpensive technique, because each sensor set (consisting of a transducer and receiver pair) costs about \$70. The propagation source and receiver sensors can also be applied from a range of heights from the surface, but in this example they were 5 cm (2 inches).

This method allowed for the introduction of a fully contactless scanning frame, as shown in figure 5. According to Popovics, one of the most important features of a contactless scanning frame is the signal consistency. This allows for repeatability, regardless of surface roughness. In addition, this system can also measure energy attenuation to monitor surface distress. Popovics explained that using *Lamb waves* (plate waves) as the signal allows for a new method to detect the presence of delamination. By using the *multichannel analysis of surface waves* approach—involving one sender with many receivers—a delamination can be identified very quickly, with potential for eventual application at highway speeds.

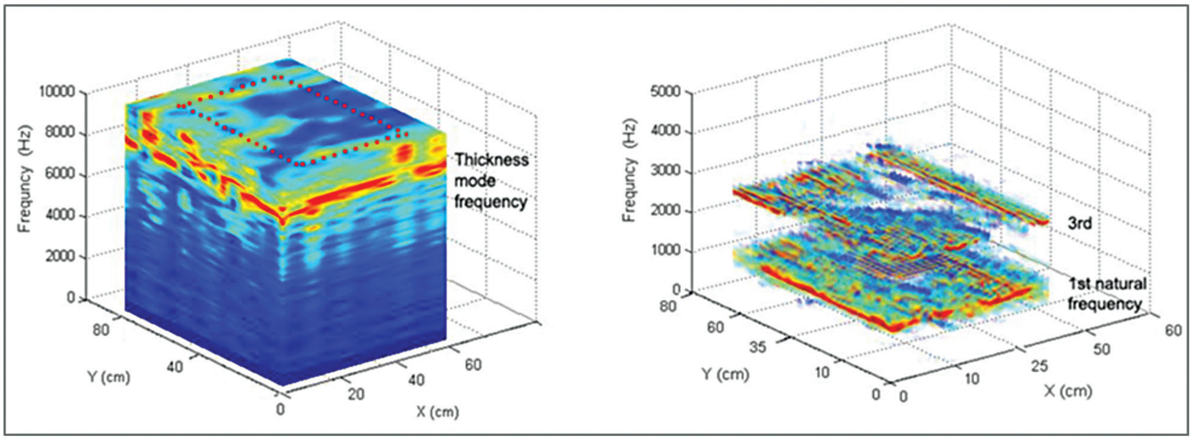

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Figure 4. Effective presentation of impact-echo data with transparency.

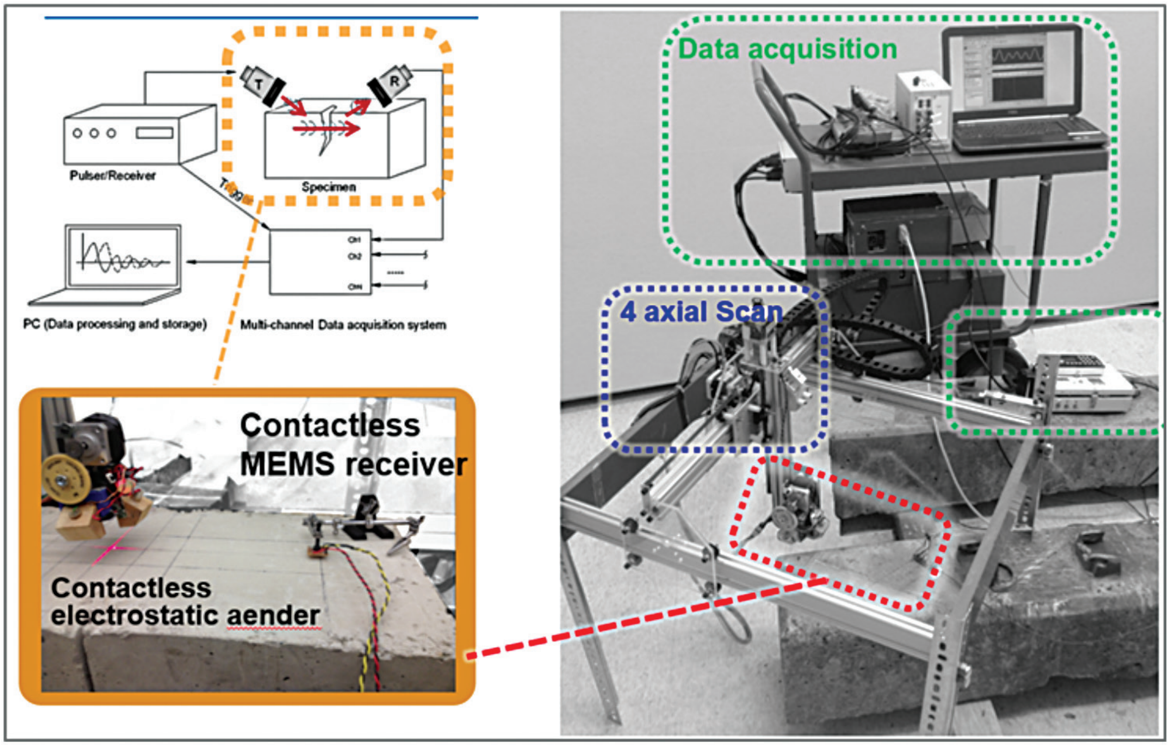

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Figure 5. Fully contactless scanning system.
(PC = personal computer, MEMS = microelectromechanical system.)

Questions

At the end of the presentation, Popovics responded to the following question from a workshop participant:

- ***Can this method be used to differentiate between different flaws?***

Popovics confirmed that, although the location of flaws with flexural resonances can be detected, the exact flaw depth is unknown.

Presentation 3: Using Vehicles as Sensors for Roadways, Bridge, and Infrastructure Health Monitoring in Connected Vehicles

Lee Mixon
Mixon Hill

Lee Mixon's presentation focused on how agencies manage and operate systems and data. Mixon explained that agencies need highly accurate and reliable information. This type of information includes baseline information characterizing the assets, current condition information, information that puts the agency in control of managing and operating the infrastructure, and also systems that give the agencies information, control, and the ability to deliver automated results. The ultimate goal is to provide enough information so that agencies know what needs to be fixed and what materials are needed without traveling to each site first.

Data Uses Analysis and Processing

Mixon highlighted a project performed for Michigan Department of Transportation (MDOT), which included connected-vehicle data use, increased data sharing, and support performance management. The data uses analysis and processing (DUAP) system collects a large volume of data, including weather, infrastructure, mobile, fleet, freight, and construction data in a map-based system, as shown in figure 6.

Researchers for the project queried all organizational functional areas and

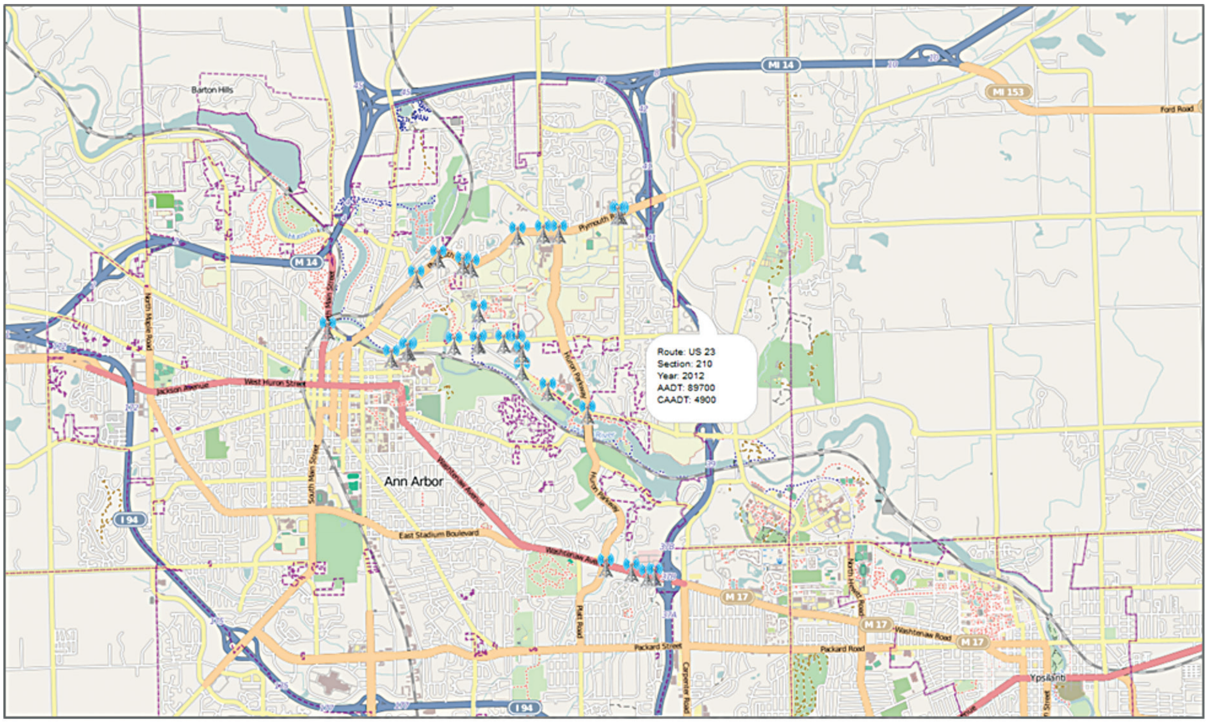

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Figure 6. Highway Performance Management System traffic data.

subareas to understand and prioritize the data needs. In addition, Mixon reminded workshop participants of the importance of data distribution and the concept of "*collect once, use many*" (shown in figure 7). During the presentation, Mixon highlighted that multiple efforts to obtain the same information occur far too often. The DUAP system includes pavement, traffic arterials, weather, maintenance-user-delay cost, incident management, construction, financial, and other information.

Vehicle-Based Information and Data Acquisition System

Mixon explained that the vehicle-based information and data acquisition system (VIDAS) collects data as employees drive maintenance and supervisory vehicles. VIDAS then transmits the information in real time and processes and updates data in the user interface. Sensors that are used in this system include weather, accelerometery, LIDAR, and radar. The system is scalable to allow for growing data collection needs.

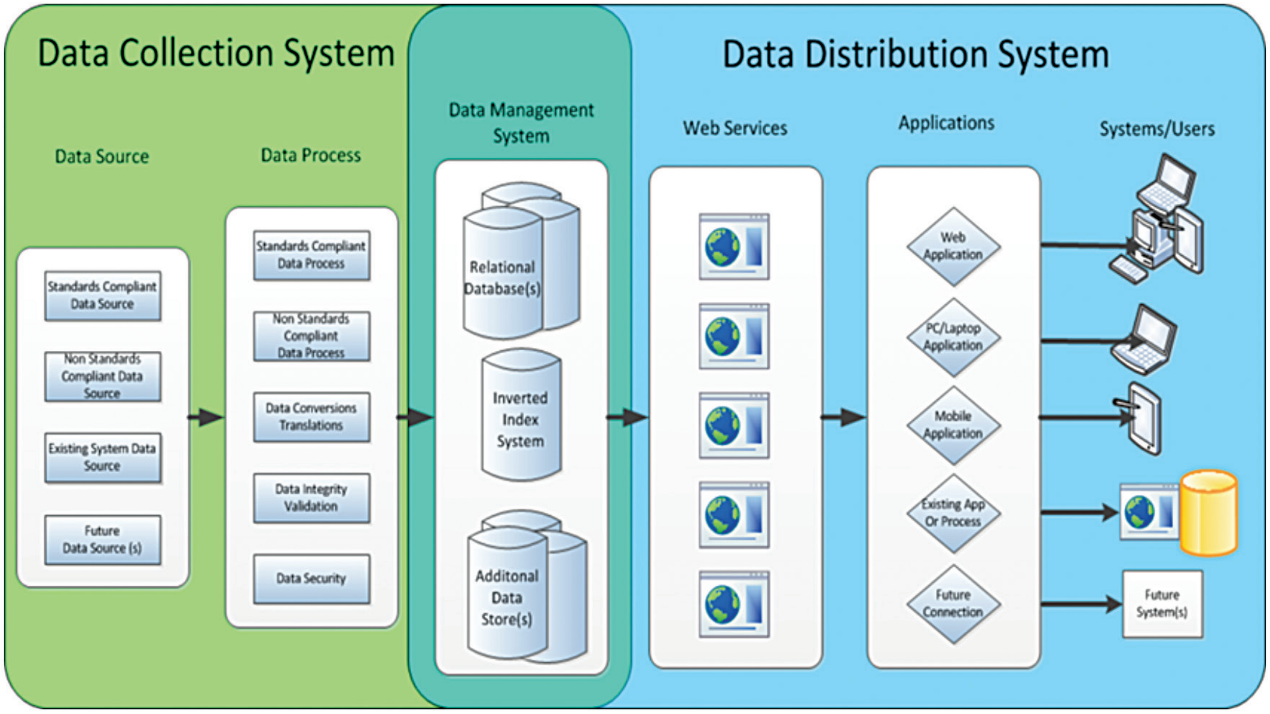

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Figure 7. Data uses and analysis and processing proposed system.

Questions and Answers: Day 1

Following the presentations, workshop participants and presenters participated in a question-and-answer session. The participant questions and presenter responses are summarized below.

Presentation 1: What Can We Learn From Vehicle Noise and Vibration?

- ***Why not use a special tire?***

The research team does not get to choose the source, although the team members would like to try a studded or solid tire. Chain drag was tried, but there were safety concerns. In addition, each tire is a source and receiver at the same time. The research team is working on an array to have four inputs and four outputs to capture any defect between the four tires.

- ***Have you been able to determine the thickness of materials?***

The thickness of materials has been determined, and the differences in subsurfaces can be detected by using the DTPS, although it has not been codified at this point. When you start having delamination in roads, resonances occur, and that can be seen in the dynamic tire pressure.

- ***On a standard tire, how deep can you see into the material?***

It is possible to explore 91 cm (36 inches) with a standard tire.

- ***Can you tell the type and severity of the defect?***

At the surface, it is possible to differentiate between different types of defects. Examples of detectable defects include potholes, cracks, and patches. In addition, video can provide visual confirmation.

- ***You are enhancing what the dedicated vehicle can capture. Are you moving away from using passenger vehicles to capture the data?***

There is a calibration station, but this is in the research stage, so calibrations must be done and then compared to the current condition. Both passenger vehicles and dedicated vehicles could be used in the future.

Presentation 2: Seeing Below the Surface Using Acoustic-Based Sensing and Imaging

- ***Are the air-coupled sensors available off the shelf? Do they have analog inputs?***

The microphones are available off the shelf. The brand is SHURE, the model is SM58, and the cost is approximately $80. The microelectromechanical system sensors are off the shelf, but the circuitry is not included and must be set up. These sensors produce analog signals.

- ***What are the expected speeds for each technique?***

The impact-echo technique likely will never occur at highway speed, but it does work very well around 8–16 km/h (5–10 mi/h).

- ***Are there geometric constraints for microphone placement?***

There are geometric constraints. A closely spaced pair is used, and they interrogate specific places.

- ***Is there potential to merge the ideas presented in the first and second presentations?***

There is overlap that would be good to explore.

Presentation 3: Using Vehicles as Sensors for Roadways, Bridge, and Infrastructure Health Monitoring in Connected Vehicles.

- ***Is there an off-the-shelf version of VIDAS? Do you think we would need a dedicated system, or can there be real-time processing?***

VIDAS is a data acquisition system (DAS) and the goal for it is to create a set of vehicles that have a DAS that can have sensors added to it. The DAS must have a configuration data manager, use standard code, and when new sensors are added, they must be evaluated offline before being added to the overall platform.

An alternative approach would be to have each sensor coupled with its own processing power. Multiple computers could run on different operating systems, with the same positioning information that could communicate with each other through one main controller that manages the systems. Data could be automatically uploaded when the network is detected, although certain systems (e.g., GPR) could not fit in that system because of extreme DAS requirements.

- ***How big is the circuitry for these systems?***

It can vary in sizes. The components are off the shelf, but multiple systems are distributed. In addition, when thinking about outfitting passenger vehicles, another sensor will need to be added on to sense subsurface.

General Questions

- ***Do we know now what sensor we need to include in future vehicles? This idea would not be a near-term project, so what might now be considered expensive could be greatly reduced in cost with time and thorough collaboration.***

Research needs must be defined and communicated with manufacturers for them to accept the ideas and make them possible. Combining research efforts with manufacturers has increased over the past few years.

Day Two
Presentations

Presentation 1: Structural Health Monitoring Using New Technologies

Ming L. Wang
Northeastern University

Ming L. Wang's presentation focused on the project, "Versatile Onboard Traffic-Embedded Roaming Sensors." The goal of the project is to create a system that can be outfitted on cars that would lead to less congestion during infrastructure monitoring and maintenance.

Wang began by explaining that at present, infrastructure asset owners generally visually inspect a small percentage of the road every 2–5 years. Most monitoring is performed on the surface of the material, although monitoring the subsurface condition would be more effective in preventative maintenance.

The VOTERS project provides a framework and sensor systems that would be carried by cars to shift from periodic, localized inspections to continuous network-wide health monitoring of roadways and bridge decks at traffic speed. VOO, such as buses and post office vehicles, could also be used to collect surface and subsurface roadway and bridge deck condition information at traffic speed. The collected data would then be transferred to a control and visualization center for further analysis, visualization, and decisionmaking.

Wang explained that the VOTERS system uses millimeter-wave radar (MWR; 24 GHz) to detect surface conditions, such as water, ice, potholes, surface roughness, and rutting. Subsurface radar (2 GHz) is used to detect subsurface conditions, such as rebar location, delamination, rebar corrosion, pavement thickness, moisture, and voids. In addition, acoustic sensors are used to detect debonding, voids, stripping concrete, potholes, MTD, and international roughness index (IRI). Optical sensors are used to view the surface profile, rutting, shoving, cracking, and potholes.

The acoustic system includes tire impact as the source and two different types of sensors. One sensor inside the tire measures the variation in tire pressure at high sampling rates. The other sensor is a microphone behind the tire, as shown in figure 8; however, Wang noted this system is complex, so the researchers also designed a simplified system to apply to a passenger or service vehicle.

Wang explained that, by using the physics-based system as proposed in the VOTERS acoustic system with the rear-mounted microphone, asset owners can calculate the condition assessment with Weibull


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Figure 8. Microphone placement.

probability density function, variance of PCA signal, IRI, and MTD. Using the DTPS, the system can interpolate the longitudinal profile, IRI, and subsurface condition. In addition, the video inspection allows for a visual inspection of crack density, crack type, crack severity, bleeding and raveling, and condition assessment.

Wang noted that using the tire as a sensor alone is not sufficient for pothole detection, because most people try to avoid potholes when driving; however, the MWR addresses this concern. As shown in figure 9, it is an array that can detect rutting by evaluating the transverse profile, identify the surface material, and allow for condition assessment with radar longitudinal profile.

The VOTERS system can output a pavement condition index (PCI) equivalent rating by fusing collected data from the different sensors in near-real time. Moreover, the video can be used as a secondary opinion to confirm what is seen in the data. Wang highlighted that the VOTERS PCI has been compared and validated against the traditional PCI in the field. Although the traditional PCI reports one value between intersections, VOTERS can report one value for smaller stretches of road at the order of 3–20 m (10–65 ft), depending on the vehicle speed.

The DTPS measures the longitudinal road profile, and materials can be identified based on the response. In addition, the IRI can be derived by the DTPS road profile and compared with the American Society for Testing and Materials' standard for IRI. Wang noted that to evaluate subsurface, researchers tested 25 different pavement designs at the National Center for Asphalt test track and detected pavement debonding as a change in frequency, as shown in figure 10.

Wang proceeded to explain to workshop participants how, by using the millimeter array, the transverse and longitudinal

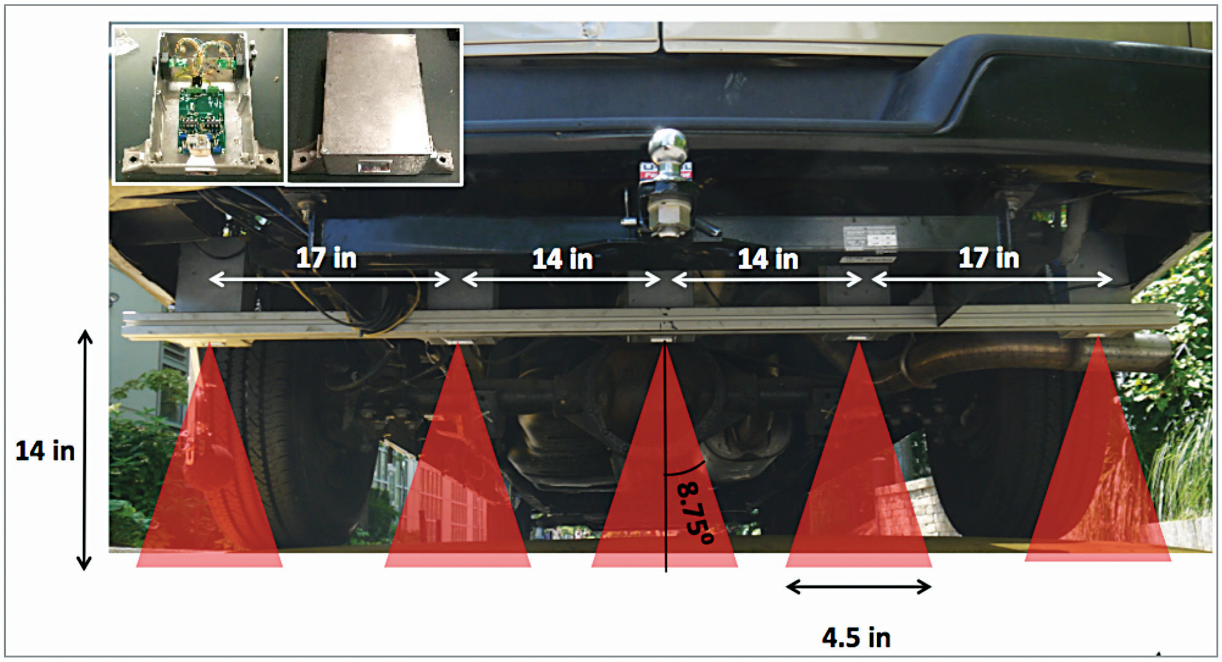

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Figure 9. 24-GHz millimeter-wave radar array.

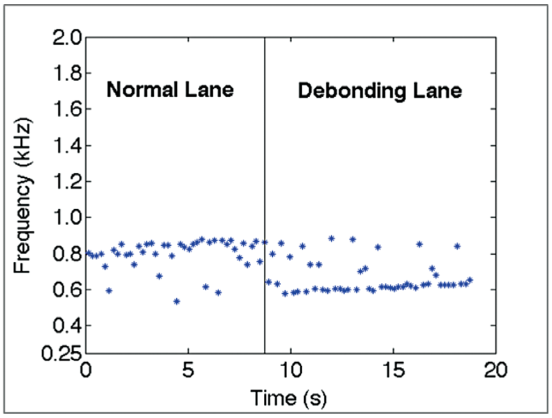

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Figure 10. Pavement debonding detection.

directions are measured and types of issues and materials can be identified, as shown in figure 11.

Wang also noted that the sensors used in the VOTERS system confirm and complement each other to identify types of issues and materials, as shown in figure 12.

Detailed Inspection

During the presentation, Wang explained that it is necessary to conduct a detailed inspection for areas with a lot of degradation. In events like this, a service vehicle with more robust equipment can inspect these locations, for example, a mobile acoustic subsurface sensing (MASS) vehicle could interrogate every meter of the roadway at walking speed. The impact source is also important, for example, if using a high, wide-band frequency, the material can be evaluated around 1-m (3-ft) deep; however, if the impact is short and a high frequency is used, the material can only be evaluated very close to the surface.

Wang explained that the system described in this presentation uses a frequency below 100,000 Hz and a 113 kg (250 lb) impact and that the depths and modal elasticity of the materials can be extracted from the collected data. The MASS vehicle system is a noncontact sensing system that uses microphones, mechanical and software noise filtering, and fast-processing algorithms that processes data in roughly 2–3 seconds during collection.

Gen-3 Ground Penetrating Radar System

According to Wang, the GPR system can inspect at 80–96 km/h (50–60 mi/h) and consists of an array of 8 to 10 channels that are small enough to fit under a car chassis or can be hand-held. Wang explained that the development of the antennae was a large focus of this effort, and after many iterations, the research team selected an antennae

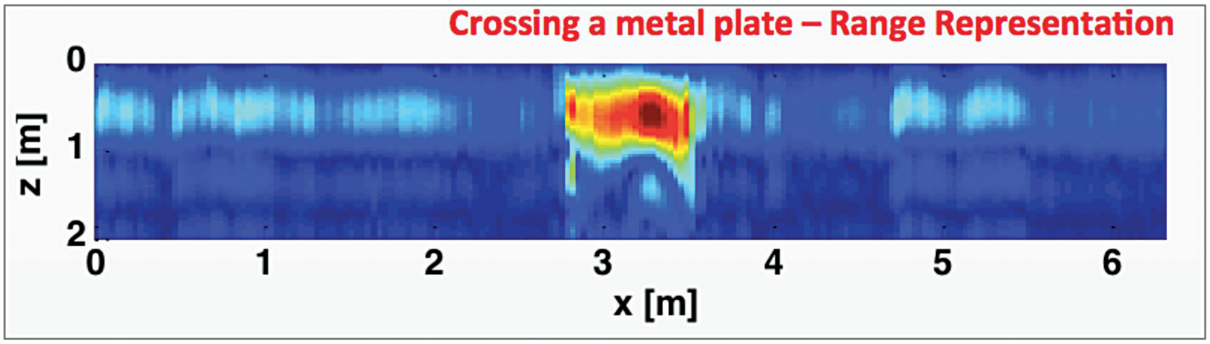

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Figure 11. Metal characterization example.

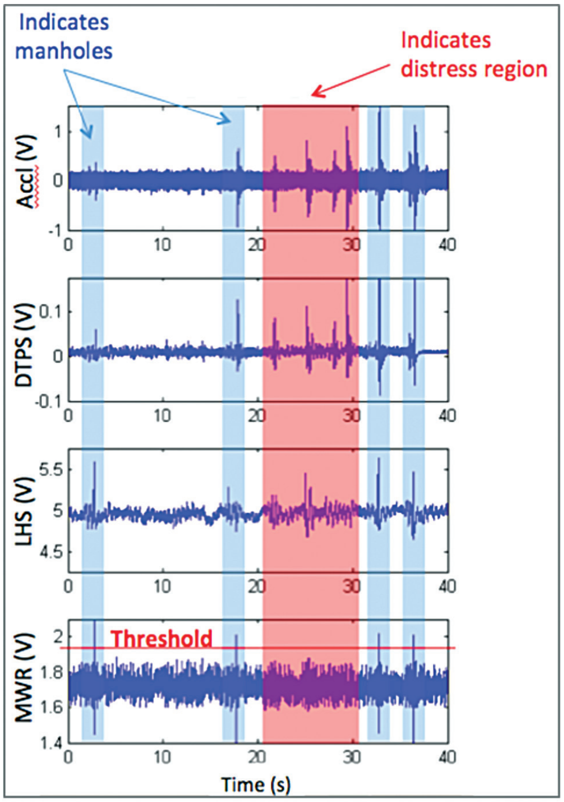

Figure 12. Multiple sensor confirmation.
(Accl = acceleration, DTPS = dynamic tire pressure sensor, LHS = laser height sensor, MWR = millimeter-wave radar.)

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called *Pacman Bowtie*. By using two Pacman antennae together as a transmitter–receiver pair, the researchers can evaluate depth, height, and property of the subsurface conditions. In addition, the GPR can detect areas of corroded rebar shown by comparing the reflection amplitudes to half-cell potential measurements. Wang noted that statistical analysis of GPR rebar amplitudes allows for immediate deck condition results.

Pavement Monitoring System

The VOTERS project also focuses on system integration to allow for full automation. Wang explained how, after fusing the data and integrating the data into the system, it could be visualized with the GIS-based pavement monitoring (PAVEMON) system. The system also uses colors to represent road condition and tracks the condition every 3 m (10 ft). As shown in figure 13, the data is overlaid on a map provided by Google Maps™. Wang noted that the PAVEMON visualizations can be compared and validated against historic PCI ratings of surveyed streets.

Lifecycle Analysis

According to Wang, asset owners typically conduct a lifecycle analysis by developing a pavement performance curve during the design phase to approximate lifetime costs and a repair schedule. The VOTERS system can monitor conditions more frequently to determine position on the performance curve during the lifetime, allowing the repair schedule to be updated and optimized. Wang noted that pavement deterioration

Figure 13. Pavement monitoring system visualization.

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modeling was used to estimate repairs and lifecycle costs. By holding the PCI at 77, the research team found that using the VOTERS system and sealing cracks resulted in substantial cost savings. Wang summarized the overall VOTERS vision as being able to inspect and repair in the right time, right place, and right way.

VOTERS Deployment Options

Wang outlined several deployment options during the presentation, as follows:

- Many single vehicles, widespread deployment, single channel, level-one sensors.
- Fleet vehicles, widespread deployment, arrays of level-one sensors.
- Service vehicles, dedicated and targeted surveys, arrays of level one and two sensors.

Wang also defined the following sensor levels during the presentation:

1. DTPS, microphone, accelerometer, MWR.
2. Level one, plus GPR array and video.

Questions

At the end of the presentation, Wang responded to the following questions from workshop participants:

- ***Has the use of a microphone on each tire been considered, instead of the millimeter-wave radar, to get the same resolution?***

Wang confirmed a microphone can be used behind each of the tires. Moreover, there is also the potential and existing capability to outfit a regular passenger car with a DTPS system or with a concealer microphone array underneath the car. Wang explained that the MWR is designed to be a very inexpensive system that identifies other properties, such as potholes, routing, and surface materials. Therefore, one cannot replace the other—they are complementary.

- ***Has a standard vehicle been considered for the dynamic sensors?***

Wang confirmed that this sensor is specifically designed to measure only the variation of tire pressure (dynamic) and can be modified for use on a regular car.

Presentation 2: Decision Support System for Remote-Sensing and Geographic Information System Technologies

Colin Brooks
Michigan Tech Research Institute

Colin Brooks' presentation focused on the integration and display for DSS. Workshop participants were given an overview of the project, "Bridge Condition Assessment with Remote Sensors." Brooks explained that remote sensing is the collection of data about an object, area, or phenomenon from a distance with a device that is not in contact with the object. This can be thought of as another form of NDE. Technologies used in this project include three-dimensional (3D) optics, thermal IR, digital image correlation, and ultra-wide band radar.

Three-Dimensional Optical Bridge Evaluation System

Brooks explained that the idea was to take high-resolution and overlapping photographs to create a high-resolution 3D model of the bridge deck to evaluate spalling, cracking, and other issues. In accordance, the research team mounted a camera to a frame 3 m (10 ft) above the bridge deck. As shown in figure 14, this camera was used to collect images of the bridge deck as the vehicle it was attached to maintained a speed of 3 km/h (2 mi/h) to collect images that overlapped by 60 percent. The 3D data was accurate to 2 mm (0.08 inches) in the X, Y, and Z directions.

Brooks informed workshop participants about a new version of this project called "NDE Bridge Decks at Near-Highway Speed." The investigators are currently developing a system that operates at a minimum of 72 km/h (45 mi/h) and will run simultaneously with the thermal IR camera from Talon Research's BridgeGuard system. The system will process images using the program, AgiSoft Photoscan, to create a digital 3D model of the bridge deck and integrate images to produce a 1-mm (0.039-inches) bridge deck photo (shown in figure 15).

Figure 16 shows a selection of images produced from the automatic spall analysis, compared with the actual spall location on the pavement. Brooks explained that the algorithm used in the spall detection analysis is programmed in Python and uses ArcPy to utilize ArcGIS geospatial tools. The focal statistics tool is used to find potential spalls, shapefiles (a geospatial vector data format)

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Figure 14. Three-dimensional optical bridge evaluation system.

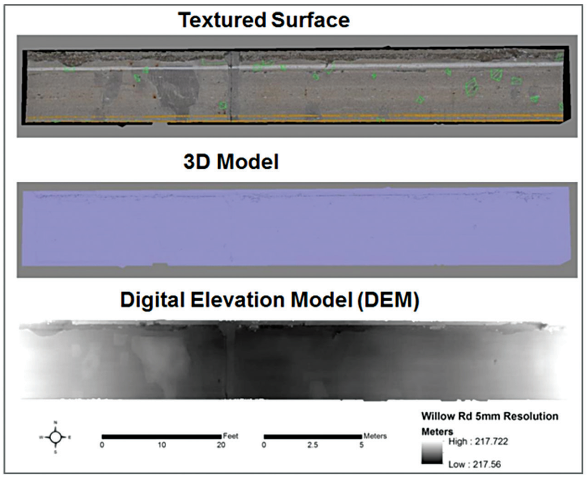

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Figure 15. Bridge deck three-dimensional model.

are generated for detected spalls, and a table is generated with spall sizes and volumes. Brooks noted that the computation time for this analysis can be reduced if a spall-size threshold is included.

Brooks explained that the research team also used thermal IR technology to find delaminations based on local temperature deviations and additional measurement methods, including chain drag. The thermal imaging and chain-drag method both found defects, but they did not always find the same defects. In figure 17, the red areas are the defects that were detected by the thermal IR method, and the green areas are the defects that were found by using the chain-drag method.

The research team also used other remote-sensing technologies in this study, including remote-camera photo inventory with high-resolution location-tagged photos, LIDAR, satellite and aerial photos, interferometric synthetic aperture radar, and speckle image processing.

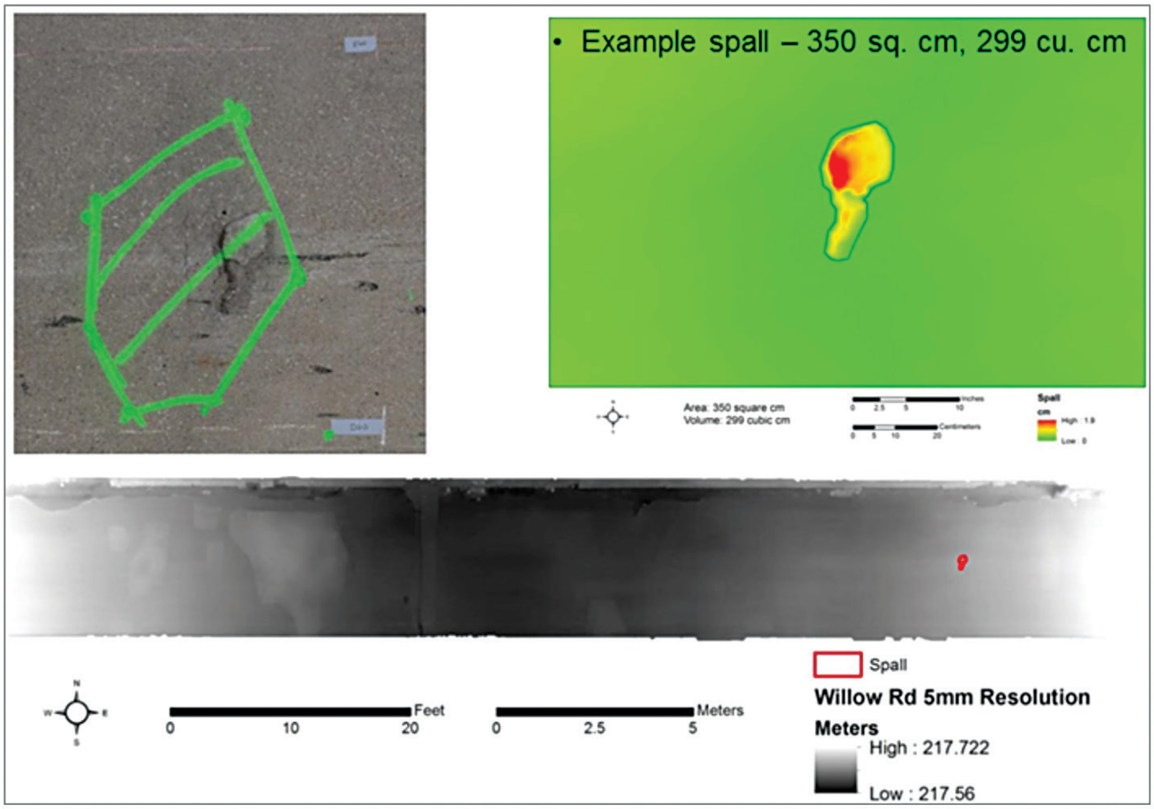

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Figure 16. Spall analysis.

Integrating Remote-Sensing

Brooks informed workshop participants that the goals for integration include a comparison of remote-sensing observations to established measures, a comparison of remote-sensing observations to one another, and a way to derive established measures from remote-sensing observations.

Existing Decision Support Systems

Brooks proceeded to outline a selection of existing decision support systems, as follows:

Pontis AASHTO BRIDGEWare System
Over 45 agencies throughout the United States and abroad have adopted this system. It represents bridges as sets of structural elements and supports optimization and asset management workflows. One gap in this system is that agencies cannot integrate remote-sensing NDE data directly in a geographic environment at this time.

Michigan Bridge Reporting System
This system is a prototype for MDOT that integrates remote-sensing NDE data into MDOT's existing data.

Online Long-Term Bridge Performance National Bridge Inventory
The LTBP program is researching sensor data integration.

Asset Management

During the presentation, Brooks explained that components of the asset management decision process include previous bridge inspection reports, visual inspection, remote sensors, the National Bridge Inventory (NBI) rating and Pontis condition, decisions on maintenance, and bridge inspections. A bridge deck surface rating could provide a comparison to the NBI rating to assist with decisions on maintenance. Moreover, IRI can also be calculated from the data.

Software

Brooks explained that the decision support software is open source, can be viewed in any browser, and can access all inventory data. In addition, through the interface, users can access typical features, as shown in figure 18. These include existing inspection data, sorted by region or county, and additional sorting features, such as driving directions and NBI deck ratings. Remote-

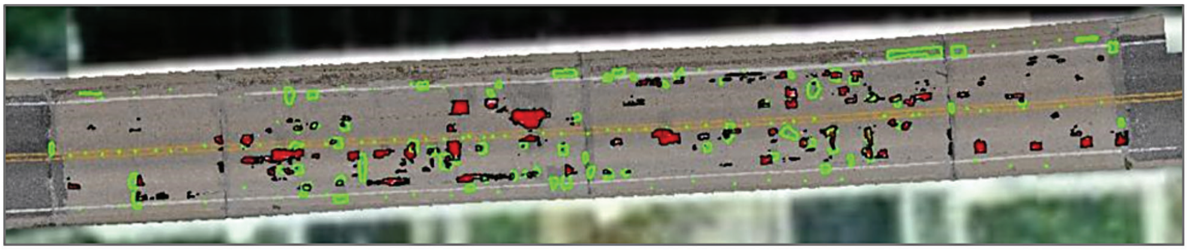

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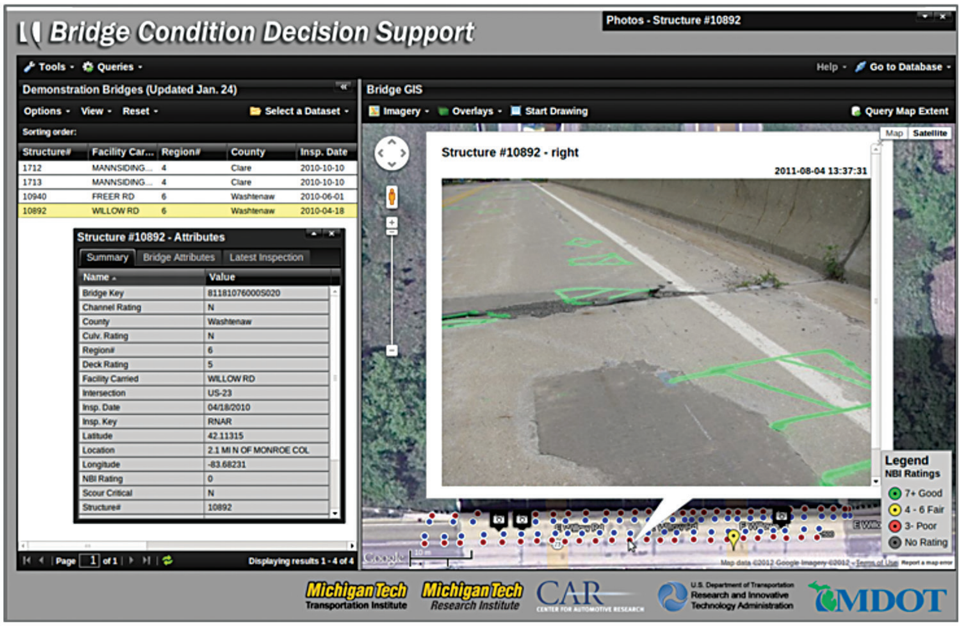
Figure 17. Bridge deck delamination by thermal infrared and chain drag.



Structure#	Facility Car...	Region#	County	Insp. Date
1712	MANNSIDING...	4	Clare	2010-10-10
1713	MANNSIDING...	4	Clare	2010-10-10
10940	FREER RD	6	Washtenaw	2010-06-01
10892	WILLOW RD	6	Washtenaw	2010-04-18

Name	Value
Bridge Key	81181076000S020
Channel Rating	N
County	Washtenaw
Culv. Rating	N
Region#	6
Deck Rating	5
Facility Carried	WILLOW RD
Intersection	US-23
Insp. Date	04/18/2010
Insp. Key	RNAR
Latitude	42.11315
Location	2.1 MI N OF MONROE COL
Longitude	-83.68231
NBI Rating	0
Scour Critical	N
Structure#	10892

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Figure 18. The decision support software interface.

sensing data is integrated, and users can click on a bridge and view directions, remote-sensing data, IRI ratings for each lane, the percent spalled, the percent delaminated, crack density, and images. Brooks noted that the main challenge with this system is the way bridge data is not stored with a focus on integrating the data rapidly into an online mapping tool.

Questions

At the end of the presentation, Brooks responded to the following questions from workshop participants:

- ***What limits optical resolution? Is it vibration?***

Brooks explained that the vehicle speed relative to frame rate must be considered to minimize motion blur.

- ***When compared over a period of time, do different camera-mounting positions matter?***

Brooks confirmed that the key is to have a base layer that all other images will use as a reference.

- ***Could the system work on unpaved roads?***

Brooks suggested that this could perhaps work, but the investigators had not considered it.

Facilitated Discussion

Research Directions

Following the presentations, workshop participants and presenters took part in a facilitated discussion. A summary for each topic of discussion is provided below.

Data Needs

During the discussion, workshop participants suggested that multiple data needs can be addressed. For example, MDOT is creating a fleet to constantly analyze the material conditions and also to collect weather and traffic conditions.

Participants also discussed how trending data over time will allow for learning about degradation over time and what factors contributed to the degradation. In addition, monitoring and trending of data can lead to a better understanding of actionable information, which ties into the DSS. In summary, criteria for actionable information must be defined now and could be improved over time.

Equipment Needs

During the discussion, workshop participants noted that having precise geolocation information is key for data integration—this is not something commercial vehicles currently have. Some participants suggested that an inexpensive GPS unit's accuracy could be improved toward 3 m (10 ft) by using triangulation; however, triangulation is not considered a reliable method because satellites are turned off intermittently. Participants noted that this method could still have potential if bad data are thrown out, or by referencing data to a base layer that has very high resolution. Moreover, stitching together overlapping acoustical data from a known location could provide precise location data, although this would not be in real time.

Another equipment need discussed included the concept of how using multiple passenger cars provides many measurements of the same segment. A participant noted that hard points, such as manholes or bridge joints, provide references.

A possible starting point, put forward during discussion, is to explore existing passenger and service vehicle controllers. A workshop participant suggested that it is likely that existing controller sampling rates are much lower than what acoustic data require. Existing features, such as anti-lock braking systems (ABS), could be explored further since the technologies are similar in the sense that they are both looking for variations between tires.

As part of this discussion, participants stated that new technologies that could be added to vehicles should be explored now. For example, the DTPS could be installed on any commercial vehicle and is very robust. Participants also noted that likely solutions may be found through a combination of technologies.

Asset Needs

Workshop participants identified two levels of needs during this discussion, as follows:

- Reporting infrastructure conditions and performance.
- Management needs for maintenance planning.

Participants noted a common reporting metric that can be measured at high- or low-vehicle speed is desired. At present, high-speed IRI measurements are the only industry standard, but this is only applicable for a subset of roads. Distress data, collected at slow speeds, are not as repeatable as IRI measurements, have limitations, and are subjective. Several participants highlighted that the driver for this common metric is to reduce reactive maintenance. One potential solution put forward during discussion is to use a tire pressure sensor to provide IRI or to develop an empirical model to correlate PCI and IRI. A participant noted that PCI should also be improved because it only evaluates the surface of a material. For subsurface information, a map could be produced from sensor data to show the probability of a defect under the surface. Then, issues can be prioritized at a local level for maintenance.

Calibration

During discussion, participants highlighted that calibration can be performed while driving. Participants noted that data sets can be scaled based on something that is known along the course. Bi-annual or annual calibrations could be performed by using a short test strip. One participant noted that if sensors are applied on all four tires then, during calibration, all four tires should read the same. In summary, participants noted that fixed and mobile sources of data could lead to quality checking. Fixed-point sources already exist and just need to be integrated into the system.

Evaluation Processes and Weather Considerations

Participants suggested that pavement conditions will be evaluated for damage or degradation with results in near-real time by sensing changes in the road between the sensors. Participants noted that this process does not rely on comparing conditions to previous measurements; however, data can be used to observe trends over time. This means that factors, such as weather or seasonal variation, do not impact the process of detecting present damage or degradation.

Manufacturers

During the final discussion topic, participants said that engaging manufacturers will assist with successful acceptance of this concept. Participants noted that the key is to decide on equipment and data requirements, and then manufacturers can carry out the implementation. Participants also said that data needs should be discussed widely so that those in other fields, with different motivations for the same data, can assist with the acquisition.

Conclusions

Participants came to several conclusions at the end of the workshop, which are outlined below.

Measurement Considerations

- Technologies working together can provide information on asset conditions through data integration.
    - Technologies include microphones, DTPS, electromagnetic (radar, LIDAR, optical, and IR), GPS, accelerometers, ABS, and elastomer actuators (smart shock and stability control).
- Calibration will be an important consideration. This may include:
    - Tire condition.
    - Material and reference specimen.
- Robust sensors will be important for a system.
- Sensor location and orientation will have an impact on measurement.
- Spatial- and temporal-resolution needs will influence system components and costs.
- There is a balance between many low-quality and few high-quality measurements, suggesting the following different design paths:
    - A system using sensors of opportunity on passenger vehicles.
    - A system using low-cost sensors and sensors of opportunity on fleet vehicles.
    - Higher cost sensors that can be added to existing service vehicles used for asset assessment.

Decision Support Systems

- Actionable information is the purpose of the system.
    - Agency-wide engagement is important, because different organizational elements have different needs.
    - The system needs to define what should be collected.
    - The system also needs to define what should be a trigger for maintenance or rehabilitation.
- Data analysis needs.
    - Trend data and variations in the rate of change may be more important for making decisions than a point value on condition.
    - Asset assessment and budgeting frequently takes place annually or bi-annually.

    - Providing a reference to historical data is important.
    - Improved models may be needed to compensate for external influences.
- Fixed component.
    - Trending of data.
    - Statistical model.
    - Connectivity and integration between fixed and mobile systems.
- Mobile component.
    - Manufacture engagement (original equipment manufacturer, Tiers 1, 2, and 3) is required for passenger vehicles.

Asset Needs

- Reporting needs.
    - Objective metrics to report (IRI, PCI, MTD, corrosion, and delamination).
    - High speed (highway) versus low speed (local roads).
    - Surface versus subsurface (no comparable scale currently available).
- Management needs.
    - Data to lead to better decisions.
        - "Define once, use many."
        - Proactive maintenance (intervene and preserve).
    - Performance measurement and management.

Potential System Concepts

- New technology that can be included in dedicated vehicles used for measuring asset conditions.
- Low-cost technology that could easily be added to fleet vehicles.
- Use of existing sensors and network technology found on private passenger vehicles and mobile devices.

Appendices

Appendix A: Agenda

Use of Vehicle Noise for Roadways, Bridge, and Infrastructure Health Monitoring Workshop

Turner–Fairbank Highway Research Center, McLean, VA

Tuesday, August 20, 2013

1–1:45 p.m. **Welcome and EAR Program Overview**

- Michael Trentacoste, *Associate Administrator for RD&T and Director, Turner–Fairbank Highway Research Center*
- Joe Peters, *Office of Operations R&D, Federal Highway Administration*
- Cheryl Richter, *Office of Infrastructure R&D, Federal Highway Administration*
- David Kuehn, *EAR Program Manager, Federal Highway Administration*

1:45–2:15 p.m. **Introductory Remarks**

- Mohammed Yousuf, *Office of Operations R&D, Federal Highway Administration*
- Shane Boone, *Office of Infrastructure R&D, Federal Highway Administration*

2:15–3:15 p.m. **Panel Discussion: Asset Management Current Practices, Key Issues, and Near-Term Advances**

- Shane Boone, *Office of Infrastructure R&D, Federal Highway Administration*
- Dr. John Popovics, *University of Illinois*
- Jack Stickel, *Alaska Department of Transportation*

3:15–3:30 p.m. **Break**

3:30–4:30 p.m. **Presentations**

- ***What Can We Learn From Vehicle Noise and Vibration?***
  Dr. J. Gregory McDaniel, *Boston University*
- ***Seeing Below the Surface Using Acoustic-Based Sensing***
  Dr. John Popovics, *University of Illiniois*
- ***Using Vehicles as Sensors for Roadways, Bridge, and Infrastructure Health Monitoring in Connected Vehicles***
  Lee Mixon, *Mixon Hill*

4:30–5 p.m. **Questions and Answers**

5 p.m. **Day 1 Adjourn**

Wednesday, August 21, 2013

8:30–9:45 a.m.	**Presentations** • ***Structural Health Monitoring Using New Technologies*** Dr. Ming L. Wang, *Northeastern University* • ***Decision Support System for Remote-Sensing and GIS Technologies*** Dr. Colin Brooks, *Michigan Tech Research Institute*
9:45–10 a.m.	**Break**
10 a.m.–12 p.m.	**Facilitated Discussion: Research Directions**
12–12:30 p.m.	**Recommendations, Questions, and Answers**
12:30 p.m.	**Day 2 Adjourn**

Appendix B: Workshop Participants

Ahearn, Meghan	USDOT Volpe Center
Alton, Osman	Federal Highway Administration, Office of Operations R&D
Barker, Alan	Oak Ridge National Laboratory
Birken, Ralf	Northeastern University
Boone, Shane	Federal Highway Administration, Office of Infrastructure R&D
Brooks , Colin	Michigan Tech Research Institute
Clayton, Dwight	Oak Ridge National Laboratory
Eshbaugh, Bill	Federal Highway Administration, Eastern Federal Lands
Halkyard, Terry	Federal Highway Administration, Exploratory Advanced Research Program
Hastings, Aaron	USDOT Volpe Center
Kuehn, David	Federal Highway Administration, Exploratory Advanced Research Program
McDaniel, J. Gregory	Boston University
Mixon, Lee	Mixon Hill
Peters, Joe	Federal Highway Administration, Office of Operations R&D
Popovics, John	University of Illinois
Ratliff, Tammy	Federal Highway Administration, Eastern Federal Lands
Richter, Cheryl	Federal Highway Administration, Office of Infrastructure R&D
Sivaneswaran, Nadarajah	Federal Highway Administration, Office of Infrastructure R&D
Stickel, Jack	Alaska Department of Transportation
Sturgeon, Purser	Southwest Research Institute
Trentacoste, Michael	Federal Highway Administration, Associate Administrator for RD&T, and Director, Turner-Fairbank Highway Research Center
Triandafilou, Lou	Federal Highway Administration, Office of Infrastructure R&D
Wang, Ming	Northeastern University
Wise, Larry	Federal Highway Administration, Office of Infrastructure R&D
Yousuf, Mohammed	Federal Highway Administration, Office of Operations R&D

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