PERFORMANCE-BASED MANAGEMENT OF THE U.S. HIGHWAY INFRASTRUCUTRE

Hamid Ghasemi[1], Robert Zobel[1], Susan Lane[1], and Ehsan Minaie[2]

Abstract

In support of MAP-21 legislation, the United States Department of Transportation (DOT) developed a strategic plan to lay out strategic goals for America's transportation system including safety, state of good repair, economic competiveness, livable communities, and environmental sustainability. This is the first highway legislation that directs the Federal Highway Administration (FHWA) to help the states and other transportation agencies in transitioning toward performance-based management of the U.S. transportation assets. This paper outlines a number of research programs and initiatives that FHWA RD&T has embarked on to help owners in managing their assets to maintain a state of good repair.

Keywords – Strategic Plan, State of Good Repair, Performance, Data-Driven Decision Making.

Introduction

United States Congress enacted the "Moving Ahead for Progress in the 21st Century" (MAP-21) law in 2012. In congruence with this recent legislation, the Federal Highway Administration (FHWA) is working with States and other transportation planning entities to implement a performance-based management approach for the United States' highway infrastructure known as Transportation Performance Management (TPM). This approach will ensure that the following seven MAP-21 goal areas are met: safety, infrastructure condition, congestion reduction, system reliability, freight movement and economic vitality, environmental sustainability, and reduced project delivery delays. These activities will be achieved by various programs and efforts, starting at a national level at the United States Department of Transportation (DOT) and continuing on state and local levels by individual bridge owners and State transportation departments.

In 2012, the U.S. DOT developed a 4-year strategic plan to lay out strategic goals for America's transportation system. This plan has been recently updated for 2014-2018 fiscal years (http://www.dot.gov/dot-strategic-plan). Of chief concern for this discussion is bringing the transportation system as a whole to a "State of Good Repair." The Long Term Bridge Performance (LTBP) program was formed as one of the research initiatives by the FHWA to develop a greater understanding of performance of the highway bridges in the U.S., to employ advanced technology tools and techniques, and to develop data-driven best practices. This long-term research effort focuses on detailed inspection, evaluation and monitoring of a large sample of bridges nationwide representing the most

[1] *Federal Highway Administration, Turner-Fairbank Highway Research Center*

[2] *Pennoni Associates Inc.*

common bridges in the national bridge inventory. This research and the associated collected data will help the bridge community to better understand bridge deterioration and performance and guide the stewards of our nation's bridges towards risk-based, data-driven decision-making process. This will result in a more efficient use of resources and create a safer, more stable infrastructure system for the public.

The U.S. DOT's Strategic Plan and the State of Good Repair

The U.S. DOT is the global leader in transportation with a mission to providing safe, secure, and reliable transportation to all its users. Since its inception in 1966 by an act of Congress, much has changed, but this mission remains as important and relevant today as it was when the DOT was established (www.dot.gov). Crafted with the input of the DOT's leadership, employees, and stakeholders, the DOT's Strategic Plan for fiscal years 2014–2018 re-imagines America's transportation system as the means by which the users connect with one another, grow the U.S. economy, and protect the environment. The plan has five strategic goals as outlined below (http://www.dot.gov/dot-strategic-plan):

- **Safety** – Improve public health and safety by reducing transportation-related fatalities and injuries.
- **State of Good Repair (SGR)** – Ensure that the United States proactively maintains its critical transportation infrastructure in a state that can serve the Nation as they are designed for in a reliable fashion.
- **Economic Competitiveness** – Promote transportation policies and investments that bring lasting and equitable economic benefits to the Nation and its citizens.
- **Livable Communities** – Foster livable communities through place-based policies and investments that increase the transportation choices and access to transportation services.
- **Environmental Sustainability** – Advance environmentally sustainable policies and investments that reduce carbon and other harmful emissions from transportation sources.

In recent years, and after the attention that has been paid to the condition of the U.S. infrastructure, (highways, bridges, transit systems, passenger rail and airport runways), it is evident that many fall short of a state of good repair. According to the U.S. DOT (www.dot.gov), the SGR for the U.S. transportation infrastructures means:

- Maintaining or improving the availability, reliability, and performance of the Nation's transportation infrastructure by ensuring that they are functioning as designed within their useful lives.
- Reducing the costs of preserving the Nation's transportation infrastructure by utilizing proven asset management practices.

Maintaining the SGR for the U.S. highway infrastructure is a challenging yet attainable goal that can be achieved through a programmatic bottom-up approach, illustrated in **Error! Reference source not found.**. The overarching goal of this approach is to collect reliable, research quality data on long-term highway infrastructure performance, convert the data to information through data fusion, interpretation and visualization, and convert the information to knowledge (deterioration, forecasting, and life-cycle models) that can be used by the infrastructure owners in decision making.

The performance data is collected using many methods, including visual inspection, material (physical) sampling, advanced Non-Destructive Evaluation (NDE) and Structural Health Monitoring (SHM) tools and methods by leveraging the protocols developed as part the LTBP Program to ensure quality and consistency of collected data. NDE encompasses techniques used to probe and sense properties and condition of various structural elements without causing damage. SHM is the process of tracking quantifiable performance metrics over time through the application of sensing technology. SHM aims to provide accurate and timely information on structure performance in an effort to identify behaviors that are unexpected, unusual, or undesirable. This sets the stage for immediate and even automated responses.

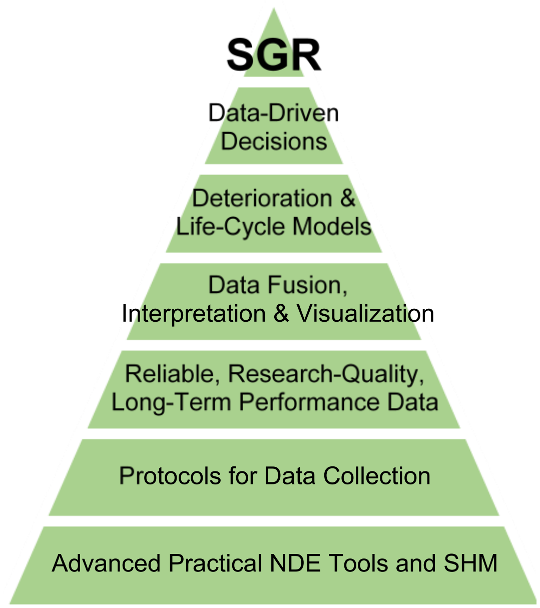

Figure 1. Programmatic Bottom-Up Approach to Achieving and Maintaining the State of Good Repair (SGR).

Data-Driven Decision Making

Federal, state and local government agencies all perform an oversight function related to the Nation’s infrastructure. FHWA oversees the safety of all bridges and tunnels nationally. State transportation department owners operate and maintain more than half of the bridge and tunnel inventories nationwide. In addition, it is estimated that there are approximately 4,000 local that operate the rest of the national bridge inventory. Although bridge inspections may be performed by local authorities, State transportation departments are ultimately responsible for the quality of data collection and reporting to FHWA. Quality data are an essential part of oversight, operation, and preservation of the U.S. infrastructure inventory at all levels.

Traditionally, owners repaired and replaced their assets on a reactionary basis. However, as resources have become more limited, infrastructure owners have been embracing NDE and SHM technologies to proactively evaluate and monitor their assets more readily, as outlined in **Error! Reference source not found.**. This more recent transition is a result of several factors. First and foremost, there has been much progress made in hardware, software, and data processing which makes the equipment easier to use while producing more consistent and reliable results. Along with these advancements in technology, both training materials and protocols for their respective use are more widely available. In addition, there is more interaction between the owners/users and the researchers/technology providers which has led to development of practical tools for specific evaluation or monitoring applications. Through the use of NDE and SHM, owners can better quantify both the presence and extent of damage or deterioration. Wireless network systems have enabled owners to remotely monitor critical infrastructure components which leads to more informed decision making and hence a greater benefit-cost ratio. Such long-term performance data can also be used to forecast system deterioration and system life cycle cost. It is likely that the use of NDE and SHM will continue to play an important role in assessment of our infrastructure.

In maintaining the infrastructure at the bridge level, it is important to determine not only what repair or renovation should be performed but also when it should be performed. In order to perform the right action at the right time on the right bridge, quality data from NDE and SHM can provide insight that might not otherwise be possible.

As emphasized in MAP-21 and the TPM program, proactive and effective management of transportation infrastructure assets requires Data-Driven knowledge. **Error! Reference source not found.** illustrates this process at a transportation infrastructure agency that manages and maintains transportation assets. Based on the performance and condition knowledge provided to the management, a decision to repair or replace an asset can be made (data-driven decision making).

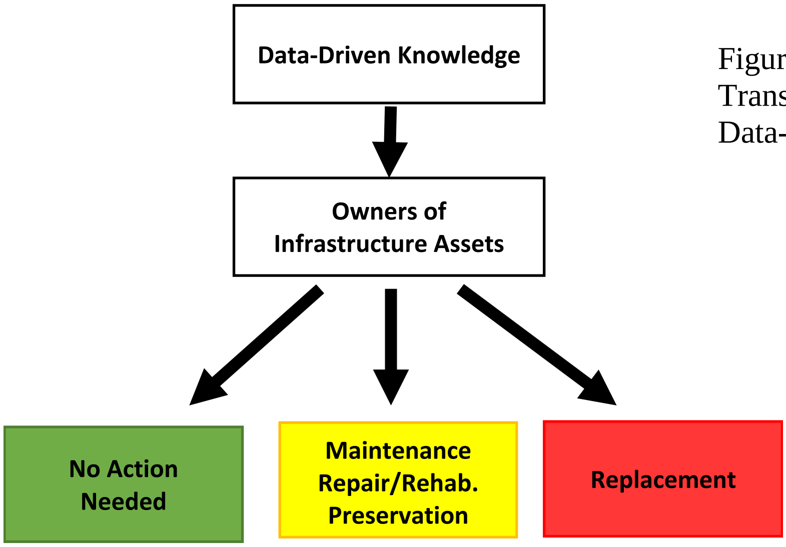

Figure 2. Decision Making at Transportation Agencies using Data-Driven Knowledge.

Research at FHWA

The Turner–Fairbank Highway Research Center (TFHRC) provides FHWA and the global highway community with research and development related to new highway technologies. The research focuses on providing solutions to complex technical problems through the development of more economical, environmentally-sensitive designs; more efficient, quality-controlled construction practices; and more durable materials. FHWA has conducted many large-scale research programs with a focus on the safety and reliability of the highway transportation system. Among which, the Long-Term Pavement Performance (LTPP) and the LTBP programs are considered the two flagship research programs.

The LTPP program monitors more than 2,400 asphalt and Portland cement concrete pavement (PCC) test sections throughout the United States and Canada. A total of 792 of the LTPP test sections contain the common types of pavement in use in the U.S. (general pavement studies), and 1,250 other test sections have been specially constructed to study certain engineering factors in pavement design (specific pavement studies). At each general and specific pavement study site, data on distress, roughness, structural capacity, traffic, and other variables are systematically collected. In addition, workgroups of highway engineers periodically visit the sites to get a firsthand look at the pavements and record their subjective observations.

The LTBP Program is a long-term research effort, authorized by the U.S. Congress in 2006, to collect high-quality bridge data from a representative sample of highway bridges nationwide that will help the bridge community better understand bridge deterioration and performance. The products from this program will be a collection of data-driven tools, including predictive and forecasting models that will enhance the abilities of bridge owners to optimize their management of bridges. Development work is ongoing for a key deliverable of the LTBP Program—the LTBP Bridge Portal. The Bridge Portal is more than just a database. It not only contains bridge performance-related data mined from existing sources (National Bridge Inventory, State Highway Agency bridge element level data, national weather data, traffic data, weigh-in-motion data, bridge maintenance data if available, and other data sources), but it also serves as a central repository for all field data collected through the LTBP program. In addition, the Bridge Portal will also function as a research and decision-making tool by implementing bridge life cycle, deterioration, and forecasting modeling using both mined data sources as well as LTBP-acquired field data to allow users to investigate bridge performance on many different levels.

The LTBP program has also developed a multifunctional autonomous NDE platform to enhance assessment of bridge decks with greater accuracy in a consistent manner and at faster rate compared to conventional NDE tools. The RABIT™ bridge deck assessment tool was developed as a research tool by deploying a suite of NDE technologies simultaneously. Figure 3 shows the technologies incorporated into the robot-assisted, autonomous RABIT™ bridge deck assessment tool.

1. Panoramic Camera
2. High-Definition Imaging
3. Electrical Resistivity (ER)
4. Impact Echo (IE) and Ultrasonic Surface Waves (USW)
5. Ground Penetrating Radar (GPR)
6. Global Positioning System (GPS)

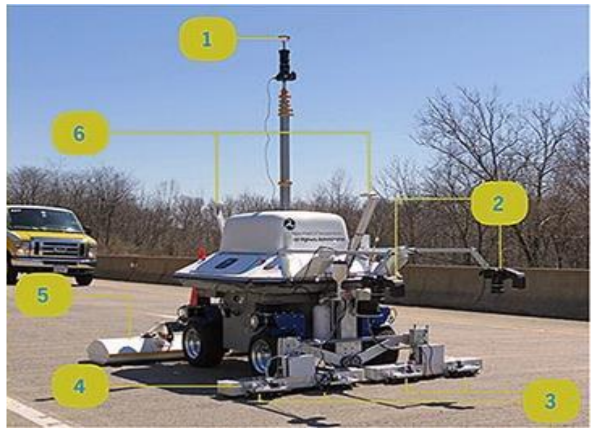

Figure 1. The RABIT™ Bridge Deck Assessment Tool Collects Comprehensive Data On Surface And Subsurface Conditions Automatically And Simultaneously.

In addition to the LTPP, LTBP, and other infrastructure management research such as NDE, materials, construction, hydraulics (scour), and geotechnical performance of bridges, and culverts, FHWA conducts longer term and higher risk breakthrough exploratory research.

The NDE Center at FHWA was established in 1998 in an effort to centralize and better coordinate research related to nondestructive testing. Since its establishment, the center has acted as a resource to the FHWA and U.S. States for information and expertise on nondestructive testing tools and technologies.(1) A goal for the NDE Center is to provide advanced NDE research within the context of an integrated view of highway facilities that include bridges, pavements, and other structures such as culverts, retaining walls, and tunnels. The key aspect of this vision is to augment the research focus to not only the internal elements of a highway bridge but also to global structural health monitoring (SHM) so that a bridge is viewed as a component in the overall highway system. The NDE Center has also developed a hands-on training course to expose State transportation department personnel to commercially available NDE instruments. Known as the Bridge Inspector NDE Showcase (BINS), the course seeks to familiarize bridge inspectors with various NDE tools. The FHWA NDE Web Manual supplements this training with a fundamental understanding of NDE tools. As a result of BINS and the NDE Web Manual, updates will likely be provided to the National Highway Institute's (NHI) Bridge Inspector's Reference Manual and other inspection-related courses offered by the NHI.(2)

Case studies

FHWA, as part of the LTBP Program, sponsored a series of surveys to collect performance data. The LTBP team utilized various NDE methods as well as the RABIT™ bridge deck assessment tool during these data collections to obtain research-quality performance related data that will become part of an overall long-term performance database. The collected data was then interpreted and used for evaluation of the bridge components and validation of NDE technologies and tools developed through LTBP Program. Approximately 150 protocols have been developed to ensure consistency and repetitiveness in data collection. This section outlines two examples of such surveys and their findings.

Arlington Memorial Bridge

The Arlington Memorial Bridge (AMB) is a steel, masonry, and stone arch bridge with a central bascule that crosses the Potomac River, between Arlington, VA, and Washington, D.C. The bridge, originally constructed in 1932, is currently owned by the National Park Service and registered as a historic structure. The bridge has 9 lanes and a total length of 2,138 feet (641 m) (Figure 2). The bridge deck width is 90 feet (27 m), with sidewalks measuring 15 feet (4.5 m) and the six-lane roadway measuring 60 feet (18 m) (10 feet per lane). The deck is 1-foot (30 cm) thick concrete with 4 to 6 inches of (10 cm) asphalt overlay and two reinforcing steel layers.

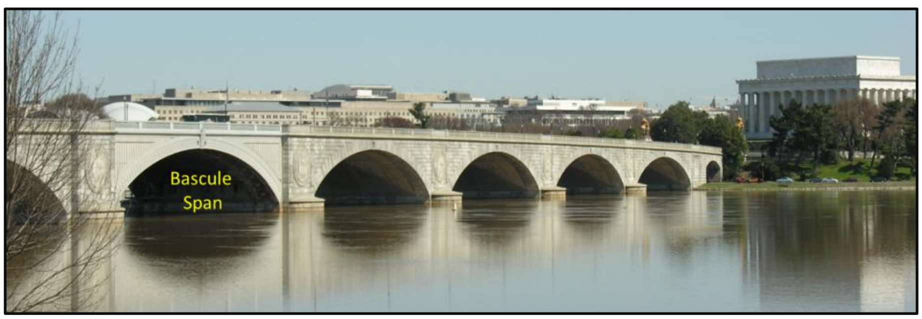

Figure 2. Overview of Arlington Memorial Bridge (AMB)

The survey of the AMB deck was a coordinated effort between the LTBP program, the FHWA Eastern Federal Lands Highway Division (EFLHD), and the U.S. Park services to test and validate the viability of the LTBP NDE research tools on concrete bridge decks with asphalt overlay and also to obtain an overall condition assessment of the deck. The survey was conducted by the LTBP team during three days on February 20, 21, and 25, 2013 (only 5 hours per day including equipment set up). Typically, it would take a few weeks to complete a similar detailed inspection using convectional inspection methods.

The two main objectives of the survey were condition evaluation and assessment of the deck with respect to (1) the concrete quality (degradation) and corrosive environment, and (2) the extent and severity of delamination and overlay debonding in the deck.

A number of semi-automated NDE technologies were utilized during the survey: (1) impact echo for asphalt debonding and deck delamination assessment, (2) ground penetrating radar to assess the condition of the underlying concrete bridge deck, and (3) ultrasonic surface waves to provide an indication of the quality of the underlying concrete by estimating concrete modulus through measuring wave propagation properties (Figure 3).

Figure 3. Manual NDE Tools used during the Arlington Memorial Bridge (AMB) Survey.

In addition, the LTBP team used the RABIT™ bridge deck assessment tool to collect the NDE data in an autonomous fashion (Figure 4). The purpose was to conduct a comparison between the manually and automatically collected data. The comparison demonstrated very good correlation between such data. In addition, the LTBP data collection protocols for NDE tools were validated during this survey.


Figure 4. The RABIT™ Bridge Deck Assessment Tool on the Arlington Memorial Bridge.

The following results of the NDE surveys indicated a high level of deterioration in the deck:

- Based on the IE survey, almost 80 percent of the deck was delaminated. A high percentage of the deck, varying from about 30 percent to more than 60 percent, was already in a severe condition.

- The concrete modulus for nearly 80 percent of the deck was less than 3,000 ksi (20,700 MPa). The modulus was on a low side of typical values of concrete modulus in bridge decks, which in most cases was measured between 4,000 and 6,000 ksi (27,600 to 41,400 MPa).
- The GPR survey resulted also described a significant percentage of the deck area to be deteriorated and/or in a state of high corrosion.

Virginia Pilot Bridge

As another example of data collection surveys, a pilot bridge was selected in northern Virginia. Seven Pilot bridges nationally were initially chosen for field studies prior to embarking on a national data collection effort in order to vet the processes and procedures used in the field. This geographic region represents a mixed-humid climatic zone, as defined by the U.S. Department of Energy, which allows monitoring the effects of environmental factors such as frequent freeze-thaw cycles and application of de-icing agents.

The Virginia Pilot Bridge is located in Haymarket, VA, on U.S. Route 15 (James Madison Highway) over Interstate 66 (I-66), approximately 38 miles west of Washington, DC. The bridge was constructed in 1979 and is a two-span, six-girder steel built-up superstructure with a bare, cast-in-place reinforced concrete deck constructed with removable forms. The structure carries two southbound lanes of traffic.

Among the factors influencing the selection of this structure, other than bridge type, was the high annual average daily traffic (AADT) of approximately 16,500 vehicles, of which 6 percent are heavy trucks. The age of the structure was also of interest, particularly because the bridge is showing signs of deck and superstructure degradation.

Access was also a major consideration in the selection of the structure. Though it spans an interstate highway, approximately half of each span is over the shoulder and grass. Consequently, traffic control requirements under the bridge during detailed inspection and live-load testing are minimal and lane closure is only necessary when researchers access mid-span or the half of the main span above the I-66 travel lanes (Figure 7).

Figure 7. Overview of the Virginia Pilot Bridge in Prince William County, VA

During this survey, a number of semi-autonomous NDE technologies were utilized including (1) for corrosion assessment - half-cell potential (HCP), electrical resistivity (ER), ground penetrating radar (GPR), and Moist Scan – a proprietary moisture measurement device, (2) for concrete degradation - ultrasonic surface waves (USW) and GPR, and (3) for concrete delamination – impact echo (IE), and GPR.

As an example of how such data can augment the decision-making process, refer to the contour plots shown in Figure 8. Half-cell potential readings are shown for two consecutive rounds of data collection on the Virginia Pilot Bridge, one in 2009 and a second in 2011. Zones of high probability of corrosion activity are depicted in by "warmer" colors such as red, yellow, and orange. The increase in the size of these zones is quite evident when comparing the results of half-cell potential assessments from 2009 and 2011. The same trends were evident in the results of the other NDE technologies that were deployed in both 2009 and 2011.

Additionally, the results of such NDE assessments can also be the basis for developing a numerical performance measure for bridge decks. Again, as an example, HCP results from 2009 and 20011 (Figure 8) were used to develop a segmented map of the bridge deck wherein each cell or segment was assigned a numerical value (using a scale of 0 to 100) associated with the dominant HCP readings within the cell/segment. The resulting segment maps based on HCP data from 2009 and 2011 are shown in Figure 9.

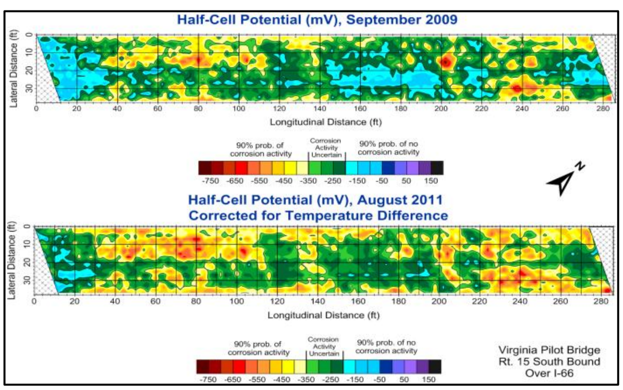

Figure 8 Half-Cell Potential (HCP) results from 2009 and 2011 taken from the LTBP Virginia Pilot Bridge

Again, when comparing these segment maps as was done for the HCP data itself, progression of the size of the corrosive environment is evident. By simply determining the average numerical value of all segments, a numerical "performance measure" based on HCP can be determined. Similar analysis and segmentation was performed based on the results of all of the various NDE assessments that were performed on the Virginia Pilot bridge and are shown in Table 1. Again, using a very simplistic averaging approach, a numerical data-driven "performance measure" can be developed. The segmentation can be further subdivided by lane and/or shoulder to visualize trends as are evident in Figure 10 when comparing the fast lane, the slow lane, and the shoulder of the bridge deck. Such further segmentation and analysis results are shown in Table 2.

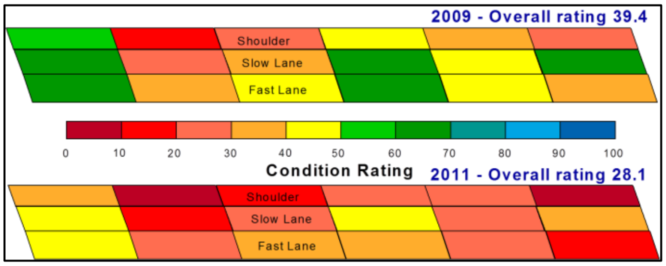

Figure 9 - Segment Map of Half-Cell Potential (HCP) results from 2009 and 2011 taken from the LTBP Virginia Pilot Bridge

Table 1 - Segmentation Analysis of Virginia Pilot Bridge

	2009	2011
Corrosive Environment	39.4	28.1
Delamination Assessment	70.0	57.2
Concrete Quality	48.1	35.3
Combined Rating	52.5	40.2

Table 2 – Segmentation Analysis of Lanes of Virginia Pilot Bridge

	2009			2011		
	Fast Lane	Slow Lane	Shoulder	Fast Lane	Slow Lane	Shoulder
Corrosive Environment	50	50	32	30	32	17
Delamination Assessment	70	72	66	58	59	54
Concrete Quality	40	60	30	27	45	16
Combined Rating	53.3	60.7	42.7	35	45.3	29

Conclusions

In 2012, and in support of MAP-21, the U.S. DOT developed a 4-year strategic plan to lay out strategic goals for America's transportation system. Of chief concern for this discussion is bringing the system as a whole to a "State of Good Repair." FHWA is working with States and other transportation planning entities in transitioning toward performance-based management of the U.S. transportation assets (Transportation Performance Management) to meet the goals of the DOT's strategic plan.

This paper outlines the different research tools and technologies developed through LTBP program to better understand performance of bridges. Two case studies were discussed in which the owner, in collaboration with the FHWA and the LTBP team, utilized semi-autonomous and autonomous NDE technologies to collected performance data on their assets. It was also discussed how the collected data was converted to information and then to Data-Driven knowledge for the owners to use in making decisions with regard to repair of their assets.

It is evident that in a time of limited resources, where the public rightfully demands the smartest, most cost-effective investment, the use of advanced assessment technologies (i.e., NDE and SHM) is of paramount importance. The future is in managing our highway assets by taking advantage of the newest technologies to ensure safety of travelling public through prioritization of repair, preservation and replacement projects by investing the limited resources where they make the highest impact on the condition of the highway network. This requires a better understanding of the condition of transportation assets which could be achieved as part of the FHWA RD&T research initiatives. The public and the Congress demand more data-driven decisions, and therefore, it is the responsibility of the engineering community to work together and develop practical tools and technologies to support our stakeholders' needs.

Acknowledgements

Special acknowledgement should be made of the contributions to this paper by Yamayra Ramirez (FHWA – Turner Fairbank Highway Research Center) and Heather Mathieson (Pennoni Associates Inc./Maraton).

References

1. "Nondestructive Evaluation Center Laboratory Fact Sheet", FHWA Publication Number FHWA-HRT-10-036.
2. Federal Highway Administration. (2004). FHWA Bridge Inspector's Reference Manual, Report No. FHWA-NHI 03-001,002,004, Department of Transportation, Washington, DC.