

## A Plan for Developing High-Speed, Nondestructive Testing Procedures for Both Design Evaluation and Construction Inspection

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 SHRP 2 REPORT S2-R06-RW

# A Plan for Developing High-Speed, Nondestructive Testing Procedures for Both Design Evaluation and Construction Inspection

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**SUBJECT AREAS**

Highway and Facility Design • Pavement Design, Management, and Performance  
Bridges, Other Structures, and Hydraulics and Hydrology • Soils, Geology, and Foundations

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**TRANSPORTATION RESEARCH BOARD**

WASHINGTON, D.C.  
2009  
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## The Second Strategic Highway Research Program

America's highway system is critical to meeting the mobility and economic needs of local communities, regions, and the nation. Developments in research and technology—such as advanced materials, communications technology, new data collection technologies, and human factors science—offer a new opportunity to improve the safety and reliability of this important national resource. Breakthrough resolution of significant transportation problems, however, requires concentrated resources over a short time frame. Reflecting this need, the second Strategic Highway Research Program (SHRP 2) has an intense, large-scale focus, integrates multiple fields of research and technology, and is fundamentally different from the broad, mission-oriented, discipline-based research programs that have been the mainstay of the highway research industry for half a century.

The need for SHRP 2 was identified in *TRB Special Report 260: Strategic Highway Research: Saving Lives, Reducing Congestion, Improving Quality of Life*, published in 2001 and based on a study sponsored by Congress through the Transportation Equity Act for the 21st Century (TEA-21). SHRP 2, modeled after the first Strategic Highway Research Program, is a focused, time-constrained, management-driven program designed to complement existing highway research programs. SHRP 2 focuses on applied research in four focus areas: Safety, to prevent or reduce the severity of highway crashes by understanding driver behavior; Renewal, to address the aging infrastructure through rapid design and construction methods that cause minimal disruptions and produce lasting facilities; Reliability, to reduce congestion through incident reduction, management, response, and mitigation; and Capacity, to integrate mobility, economic, environmental, and community needs in the planning and designing of new transportation capacity.

SHRP 2 was authorized in August 2005 as part of the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU). The program is managed by the Transportation Research Board (TRB) on behalf of the National Research Council (NRC). SHRP 2 is conducted under a memorandum of understanding among the American Association of State Highway and Transportation Officials (AASHTO), the Federal Highway Administration (FHWA), and the National Academy of Sciences, parent organization of TRB and NRC. The program provides for competitive, merit-based selection of research contractors; independent research project oversight; and dissemination of research results.

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Andrew J. Wimsatt, research engineer with TTI, was the project director and principal investigator. Other authors of this report were Tom Scullion and Emmanuel Fernando, research engineers at TTI; Stefan Hurlebaus, assistant professor; Robert Lytton, professor; and Dan Zollinger, professor, Department of Civil Engineering at Texas A&M University; and Roger Walker, professor, Department of Computer Science and Engineering at the University of Texas at Arlington.

The project team thanks Monica Starnes, John Popovics, Larry Jacobs, Larry Olson, David Gress, Frank Jalinoos, Geraldine Cheok, Ken Maser, Soheil Nazarian, and all the interviewees and questionnaire respondents for their input and advice.

## FOREWORD

Monica A. Starnes, *SHRP 2 Senior Program Officer*

The first project in the second Strategic Highway Research Program (SHRP 2) in the field of nondestructive evaluation (NDE) was completed in 2008. The project evaluated the existing and emerging NDE technologies and their state of implementation to satisfy NDE requirements for highway renewal. For the requirements not yet addressed with fully implemented NDE techniques, a research plan was devised for developing technologies to deal with the most pertinent requirements for bridges, pavements, tunnels, soils, and retaining walls through the life of the facility. The findings of this project related to NDE and its recommendations for subsequent research work in this area are presented in this report.

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The strategic objective of highway renewal research in SHRP 2 is to develop the necessary tools to “get in, get out, and stay out” when renewing the existing highway infrastructure. To accomplish the goals implied in this motto, technologies and processes that yield long-lasting facilities through rapid design and construction approaches while minimizing the impact to highway users are needed. Nondestructive testing (NDT) techniques that can produce rapid inspection of new construction would facilitate timely reopening of a highway after reconstruction. Adequate NDT techniques are also needed to ensure the quality of construction required for long-term performance.

Under SHRP 2 Project R06, a research team led by Andrew Wimsatt of the Texas Transportation Institute thoroughly reviewed existing and emerging NDE technologies, evaluated the existing inspection requirements, and developed a research and development (R&D) plan to address those requirements.

Initial tasks in the research focused on gathering data from literature reviews, surveys, and in-person interviews with state departments of transportation in the United States, members of the Forum of European National Highway Research Laboratories, academia, and industry. The data-gathering activities identified existing NDE techniques and practices, emerging technologies, and apparent gaps between current and future inspection requirements and existing and emerging technology. The R&D plan was developed to address the gaps.

The main audience for the R&D plan is the SHRP 2 Technical Coordinating Committee for Renewal, which will use the plan to program additional research funds for NDE. The information in this report has the potential to facilitate other agencies’ research plans in this field; thus, other research organizations and funding agencies are also possible audiences.

The research team identified more than 20 areas of study that must be addressed with subsequent research. The team also provided detailed recommendations to address the top six research needs:

- Automated methods of accurately profiling bridges;
- Changes in profiles of tunnel linings over time;
- Identification of bridge deck deterioration, including its cause;
- Continuous deflection device at the highest possible speed for pavements;
- New NDT quality assurance tools for ensuring quality construction; and
- Measurement of interlayer bonding between hot-mix asphalt layers for pavements.



# CONTENTS

1	<b>Executive Summary</b>
3	<b>CHAPTER 1 Background</b>
3	Strategic Highway Research Program 2 Background
3	Problem Statement
3	Research Objective
4	Scope of Study
5	<b>CHAPTER 2 Research Approach</b>
5	Literature Search
5	Questionnaires
5	Other Sources of Information
6	Summary of Needs
6	Discussions with Other SHRP 2 Project Teams
6	Identification of Existing and Emerging NDT Technologies
6	Existing and Emerging NDT Technologies that Address Identified Needs
6	Needs Where No NDT Technology Exists
6	Prioritization
8	<b>CHAPTER 3 Findings and Applications</b>
8	General Overview of Nondestructive Testing Applications
11	Questionnaire Responses
13	Use of NDT Technologies and Techniques by DOTs in the United States
13	Use of NDT Technologies and Techniques by FEHRL Members
13	Promising NDT Technologies and Techniques Identified from Other Sources
14	Identified Needs
18	<b>CHAPTER 4 Conclusions and Recommended Research</b>
18	Introduction
19	Recommended Research for SHRP 2 Funding
19	Descriptions of the Top Six Needs and Recommendations
28	Establishment of National NDT Calibration and Verification Sites
31	Recommended NDT Research for All Needs
36	Other Considerations
37	<b>Appendix A. Nondestructive Testing Technologies and Techniques at the Federal Highway Administration Nondestructive Evaluation Center</b>
53	<b>Appendix B. Use of Promising Nondestructive Testing Technologies by Departments of Transportation</b>
80	<b>Appendix C. Use of Promising Nondestructive Testing Technologies Identified from Other Sources</b>



84	Appendix D. Research Problem Statements for Priority 1 Needs
97	Appendix E. Bibliography
113	References

# Executive Summary

This report presents the results of a research study that generated plans to develop high-speed, nondestructive testing (NDT) procedures for design evaluation and construction inspection of highway renewal projects. The goals of the second Strategic Highway Research Program (SHRP 2) NDT renewal research effort are to reduce traffic disruption on existing facilities during preliminary engineering investigations and to provide more rapid and reliable information on as-built conditions. Similarly, rapid inspection of new construction would facilitate timely reopening of roadways and structures after reconstruction. As a result, this research study emphasized in-situ testing, technologies, and techniques that provided approximately 100% coverage of infrastructure, and technologies and techniques that can produce results ideally in real time or at least within 48 hours.

After conducting a literature review, the research team sent questionnaires concerning NDT for pavements, bridges, earthworks, tunnels, and other structures to 50 departments of transportation (DOTs) in the United States and to members of the Forum of European National Highway Research Laboratories (FEHRL). Personnel at 21 DOTs and FEHRL members from Norway and Ireland responded to the questionnaires. Additionally, team members used the questionnaires to interview personnel from six DOTs in the United States. The team also received ideas and input from various subject matter experts in academia, government, and industry through individual discussions and a brainstorming session. The plans will be used by the SHRP 2 Technical Coordinating Committee for Renewal to program additional funds concerning NDT for design evaluation and construction inspection of renewal projects.

To develop plans for this research study, the team identified needs and then developed corresponding recommendations to address them. Team members ranked the needs and corresponding recommendations, and prioritized them into three levels based on the rankings and team members' assessments and expertise. As a result, the team recommended funding projects that addressed the following top six needs:

- Automated methods of accurately profiling bridges;
- Changes in profiles of tunnel linings over time;
- Identification of bridge deck deterioration, including its cause;
- Continuous deflection device at the highest possible speed for pavements;
- New NDT quality assurance tools for ensuring quality construction; and
- Measurement of interlayer bonding between hot-mix asphalt layers for pavements.

Successful implementation of any NDT technology involves upper management support within the DOTs, continuous communication between NDT developers and users, extensive training, and technology transfer. The team noted that DOTs that are involved in implementing NDT technologies had at least one employee dedicated to the technology or technologies.

In many instances NDT implementation is more challenging than the original development of the technology. Implementation may require a different set of skills than the science and engineering required to develop and prototype equipment. Implementation involves working within organizations, establishing specifications, providing training, setting goals, documenting benefits, and establishing good overall communication channels within the agency and externally with contractors and trade organizations. These considerations must be addressed effectively if any NDT is to be implemented successfully.

## CHAPTER 1

# Background

### Strategic Highway Research Program 2 Background

To address the challenges of moving people and goods efficiently and safely on the nation's highways, Congress has created the second Strategic Highway Research Program (SHRP 2). This targeted, short-term research program is carried out through competitively awarded contracts to qualified researchers in the academic, private, and public sectors. The program addresses four strategic focus areas: the role of human behavior in highway safety (Safety); rapid highway renewal (Renewal); congestion reduction through improved travel time reliability (Reliability); and transportation planning that better integrates community, economic, and environmental considerations into new highway capacity (Capacity). Under current legislative provisions, SHRP 2 will receive approximately \$150 million over a program duration of 7 years.

The overall goal of the SHRP 2 Renewal program is to develop a consistent, systematic approach to performing highway renewal that is rapid, causes minimum disruption, and produces long-lived facilities. The renewal scope applies to all classes of roads.

### Problem Statement

The term highway renewal connotes the reconstruction or extensive rehabilitation of roadways and structures currently in service. Breaks in service are disruptive to highway users and to communities and business interests that depend on the uninterrupted use of these facilities. The public has little tolerance for repeated or extended lane closures and traffic restrictions. Lane closures and other traffic restrictions also increase personal safety risks to highway users and highway workers. Consequently, there are strong incentives to reduce to a minimum the periods of disruption related to highway design and construction. High-speed nondestructive testing

(NDT) and data collection techniques for purposes of design, construction quality control, quality assurance, and final acceptance have the potential to significantly lessen unwelcome breaks related to highway renewal. NDT or minimally destructive testing techniques can decrease traffic disruption further by improving construction quality and minimizing the need for rework and the removal and replacement of substandard work or materials. Similar techniques available to agencies could shorten the delay associated with quality assurance and acceptance, and accelerate the removal of traffic restrictions. Such techniques should also be applied to pre- and postconstruction performance monitoring and data collection, improving both design and asset management while minimizing traffic restrictions related to field data collection.

To the extent possible, data from construction inspection and acceptance tests should share attributes with data from tests for design and performance monitoring so that the attributes can be incorporated into an asset management system. The move to performance specifications and construction warranties implies that the characteristics monitored during and after construction should be related to ultimate performance and not merely properties that are convenient to measure. The move also implies that entities responsible for inspecting and monitoring roadways and structures should have test methods that assess factors critical to performance.

### Research Objective

The overall objective is to develop a process to identify existing or, if necessary, develop new and quickly implementable technologies for rapid, NDT of in-situ conditions for purposes of design, construction inspection, and performance monitoring. These technologies would limit or reduce traffic disruption on existing facilities during preliminary engineering investigations and provide more rapid and reliable information on as-built conditions. Similarly, rapid inspection of

new construction would facilitate timely reopening of roadways and structures during reconstruction.

## **Scope of Study**

The research focused on developing plans concerning the application of NDT procedures for renewal projects involving pavements, tunnels, bridges, earthworks, and other structures. Additionally, the research examined NDT for three applications: during design, during construction as quality assurance tools, and in performance monitoring.

The research team identified testing needs for highway renewal projects and then identified what it considered the most appropriate plans to address those needs. Information

to identify the needs and recommendations came from the literature review, responses to questionnaires, individual interviews and discussions with NDT experts and those involved in highway infrastructure renewal, a brainstorming session with NDT experts, and the judgment and experiences of team members.

This research study emphasized in-situ testing, technologies and techniques that provided approximately 100% coverage of infrastructure, and technologies and techniques that can produce results in real time or at least within 48 hours. The plans will be used by the SHRP 2 Technical Coordinating Committee for Renewal to program additional funds concerning NDT for design evaluation and construction inspection of renewal projects.

## CHAPTER 2

# Research Approach

### Literature Search

The research team conducted a literature search relating to non-destructive testing (NDT) applications for highway infrastructure. The team initially cataloged and reviewed 405 references relating to information needs and NDT implementation for transportation facilities. Eighty-three of the references were from the International Conferences on the Application of Geophysical and NDT Methodologies to Transportation Facilities and Infrastructure (the Federal Highway Administration [FHWA] has been a sponsor of these conferences); 208 references were from the Transportation Research Board (TRB) *Transportation Research Record* (TRR) series; 77 references were authored or coauthored by personnel from several departments of transportation (DOTs); and 19 references were authored or coauthored by FHWA personnel. The team focused on references from the TRR series and the Geophysical Conferences because team members believed that those sources had a greater chance of providing information relating to application of NDT for highway renewal projects. The team did review other sources of information, including papers in the American Society of Civil Engineers (ASCE) journals and the *Structural Materials Technology Conference Proceedings*. References from those sources were used in developing the recommendations for this study.

Findings from the most relevant references for this research are discussed in other sections of this report.

### Questionnaires

The team developed questionnaires concerning NDT for rigid pavements, flexible pavements, bridges, earthworks, tunnels, and other structures. The questionnaires were distributed to 50 DOTs in the United States; personnel at 21 DOTs responded to at least one questionnaire. Additionally, team members used the questionnaires to interview personnel from the Minnesota, Florida, Washington, California, New York, and Texas DOTs at their respective facilities and

interviewed various subject matter experts in academia, government, and industry.

The questionnaires contained candidate causes of deterioration, general information needs, and basic property needs for respondents to review, supplement, and modify. Additionally, the respondents were asked to describe their experiences with NDT and to indicate which design, construction quality assurance, or performance-monitoring needs could or should be addressed with NDT.

Questionnaires concerning existing and emerging technologies were distributed to members of the Forum of European National Highway Research Laboratories (FEHRL). Responses were received from agencies in Norway and Ireland.

Respondents provided additional literature and information concerning NDT that the team used for this research.

### Other Sources of Information

The team also relied on other sources of information for this study, including discussions with NDT experts and individuals involved in highway renewal. The following are sources of particular interest.

Stefan Hurlebaus attended the Review of Progress in Quantitative Nondestructive Evaluation (NDE) in Golden, CO, in July 2007.

Appendix A contains descriptions of NDT technologies and techniques that are or have been used at the FHWA Non-destructive Evaluation Center. Frank Jalinoos presented these technologies and techniques during the researchers' visit to the center in October 2007.

Alan Lytle and Geraldine Cheok of the National Institute of Standards and Technology (NIST) provided information concerning laser scanning technology that is incorporated in the laser scanning summary in Appendix B.

Finally, the research team presented the preliminary plan generated from this study at the First International Symposium on Non-Destructive Testing for Design Evaluation and

Construction Inspection held in Washington, D.C., on January 18, 2008. The symposium was sponsored by the TRB and the FEHRL. As described in chapter 4, the research team received information and comments from symposium participants that were considered in developing the final recommendations for this study.

## Summary of Needs

The research team developed general information, tables of basic property needs, and a general summary of the needs based on the information described earlier in this chapter. The summary is presented in chapter 3.

## Discussions with Other SHRP 2 Project Teams

The principal investigator for this study also communicated with team members of two Strategic Highway Research Program 2 (SHRP 2) projects: R01, Encouraging Innovation in Locating and Characterizing Underground Utilities, and R07, Performance Specifications for Rapid Highway Renewal. As of July 2007, the R07 team had identified the following NDT technologies and techniques that could be used for performance specifications (1):

1. High-speed ground-penetrating radar (GPR) for locating subsurface defects, voids, and moisture problems in pavements;
2. Rolling deflectometers for measuring structural soundness and deflections in asphalt pavements;
3. High-speed inertial profilers for measuring pavement smoothness;
4. High-speed skid lock test for measuring pavement friction (skid resistance);
5. Infrared technologies for measuring segregation in asphalt pavements; and
6. Ground-coupled GPR.

The R07 team was interested in any other technologies that were found promising as a result of this study.

The R01 team had also identified technologies and techniques for detecting underground utilities and had generated ideas concerning verification of results from the devices considered in developing the plans for this project.

## Identification of Existing and Emerging NDT Technologies

The team identified existing and emerging NDT technologies and techniques based on the information sources discussed, as well as the team members' assessment and expertise. A

more detailed discussion of these technologies and techniques appears in Appendices C and D.

## Existing and Emerging NDT Technologies that Address Identified Needs

All team members generated a list of project recommendations to address each need identified. Because so many needs were identified through the data-gathering process and because the funding and duration for future SHRP 2 NDT projects are limited, the team selected through consensus what members believed to be the most effective project recommendation for each need. Chapter 4 describes the recommendations and presents plans to assess these technologies.

## Needs Where No NDT Technology Exists

The team also identified needs where no relevant NDT appears to exist. Chapter 4 also describes these needs and presents plans to develop new testing methods to satisfy them.

## Prioritization

The team members who participated in the DOT interviews (Andrew J. Wimsatt, Emmanuel Fernando, Tom Scullion, and Stefan Hurlebaus) prioritized the needs and corresponding recommendations into three levels for each of the five categories (pavements, earthworks, bridges, tunnels, and other structures) based on the information sources described earlier and on team members' assessment and expertise. The priorities were based on a simple ranking system. Each team member ranked each need and corresponding recommendation based on four criteria, using a scale from one to five. The criteria and rating scales were as follows:

1. The importance of having the technology or technique to provide approximately 100% coverage (in which a score of one indicates low importance and five indicates high importance);
2. The likelihood that the recommendation would generate a NDT technology or technique that would be quickly implementable, ideally by 2011 (in which a score of one indicates a low probability and five indicates a high probability);
3. The degree to which the need and corresponding recommendation addressed highway infrastructure renewal needs (in which a score of one indicates low effectiveness and five indicates high effectiveness); and
4. The likelihood that the recommendation would result in significantly higher-speed testing than is currently avail-

able (in which a score of one indicates a low probability and five indicates a high probability).

In their prioritizing and ranking, the team members considered information and comments from the First International Symposium on Non-Destructive Testing for Design Evaluation and Construction Inspection. The team considered NDT measurement quality and significance when assigning a score to the third criterion (the degree to which the need and corresponding recommendation addressed highway infrastructure renewal needs).

Team members discussed the possibility of using weighted ranking schemes so that, for example, NDT recommendations

for tunnels would have lower overall scores because there are fewer tunnels than there are bridges. Members decided that each criterion would carry equal weight so that recommendations for NDT innovations in all categories could be considered.

The team then produced research problem statements with an approximate cost for the Priority 1 need recommendations, totaling approximately \$9.7 million. Because the SHRP 2 budget for such research is approximately \$4.7 million, the team used the ranking scores to generate the recommended research problem statements for SHRP 2 funding. The team members reviewed and concurred with the ranking results. Those priorities, rankings, and recommendations are described in chapter 4.



## CHAPTER 3

# Findings and Applications

### General Overview of Nondestructive Testing Applications

The research team cataloged and reviewed 405 references relating to information needs and nondestructive testing (NDT) implementation for transportation facilities.

The following excerpts from three references provide general overviews of the use of technologies or techniques intended for NDT of transportation infrastructure. The excerpts are extensive because the team believes that the findings are especially relevant to developing NDT plans. References relating to specific NDT applications are cited in chapter 4 and in the relevant appendices.

#### ***National Cooperative Highway Research Program (NCHRP) Synthesis 357, Use of Geophysics for Transportation Projects (2)***

This 2006 synthesis “presents the state of the practice regarding the use of geophysics for transportation projects. The report focuses on U.S. state and Canadian provincial departments of transportation (DOTs), and U.S. federal transportation agencies. The main points addressed include who is using geophysics and why, which methods and applications are the most commonly used, the use of in-house expertise compared with contracting private consultants, and how geophysical service contracts are procured and implemented. The scope was limited to how geophysics is being applied by geotechnical engineers during highway planning and construction activities.”

The synthesis also states: “The objective of the synthesis is to address and document these items as they are currently being implemented by U.S. and Canadian transportation agencies. For the purpose of this synthesis, geophysics is defined as the application of physical principles to define geology and study earth (geo-) materials. Engineering geophysics is used to eval-

uate natural and artificial foundation materials—soil and rock; however, this synthesis focuses on its application toward geotechnical problems.”

The synthesis summary concludes: “Based on information gathered for this synthesis and previous discussions with hundreds of geotechnical engineers, it appears likely that as formal training occurs and successful project experiences among transportation agencies increase, using trained in-house professionals and qualified service providers, geophysics will become more widely accepted and implemented as another tool for the transportation industry. This synthesis determined that design and construction engineers are beginning to appreciate the benefits of geophysics through use and exposure over just the past 5 years. The majority of survey respondents believe that using geophysics has the potential to save governmental agency funds and time, and reduce the risk associated with unknown subsurface conditions.”

In particular, the synthesis reported the following:

- “The three most commonly used geophysical methods are (1) seismic, (2) ground-penetrating radar, and (3) vibration monitoring.
- “The top three ‘greatest values’ for using geophysics are (1) speed of data acquisition, (2) cost benefits, and (3) better characterization of the subsurface.
- “The three greatest deterrents to using geophysics are (1) lack of understanding, (2) nonuniqueness of results, and (3) lack of confidence.
- “Three items that can overcome the deterrents are (1) training, (2) experience (and sharing thereof), and (3) implementation of standards.”

The following excerpts from the synthesis are also of particular interest:

- “It can be construed that because it was not until 1992 that an international professional geophysical society was formed

[the Environmental and Engineering Geophysical Society (EEGS)], the use and application of geophysics for shallow investigations (<30 m/100 ft) is relatively new. Over the past 10 years the increased need to reduce risk for the design and construction of engineered structures has dictated better instrumentation and data processing software, as well as added educational opportunities, to effectively make geophysical technologies available. EEGS and its members have worked to educate end-users on the correct application of geophysics.

- “The emergence of non-destructive testing (NDT) technology is even more recent. Although the science of NDT has undergone approximately 10 to 12 years of development, it has become standard practice in the transportation industry for only the last 6 to 7 years. For the purposes of this synthesis, it is important to distinguish between the terms ‘geophysics’ and ‘NDT.’ NDT uses many (if not all) of the physical principles used in geophysics; however, it is the application of the technology that separates the two. NDT is used to image and evaluate engineered structures; that is, man-made features such as bridges, walls, and drilled shafts.
- “Approximately 50% of the respondents began implementing geophysics as part of their geotechnical investigations within the last 10 years; thus, for most agencies it is a relatively new investigation tool. Only a few agencies reported having in-house capabilities. Two agencies (of 58) indicated that funds are allocated annually for geophysics. The majority of agencies fund geophysical investigations through their design branches (departments) and procure the work under contracts to architect and engineering firms as part of their larger geotechnical investigations or under lump-sum/fixed-price subcontracts. The primary mode of solicitation among the respondents is ‘limited solicitation’ or ‘sole-source’ contracting.
- “The typical number of geophysical investigations conducted each year ranges from one to five for more than half of the respondents. Contract values are predominantly less than \$10,000 per geophysical investigation; however, there are agencies that routinely use geophysics that will spend more than \$100,000 annually conducting geophysical investigations. These agencies tend to carry large on-call Indefinite Delivery/Indefinite Quantity-type contracts to easily access qualified service providers for projects. Such contracts ranged from \$300,000 per year to \$5 million for 3 years (with two service providers).
- “Between 50% and 60% of the agencies and individuals completing the survey provided an experience rating of ‘good’ to ‘excellent’ for their use of geophysics. However, several factors were identified as limitations to the implementation of geophysics, including difficult field instrumentation and software for data interpretation, poorly

qualified service providers, and subjective and nonunique results. However, the majority of respondents indicated that inadequate understanding and knowledge of geophysics was the single greatest limitation. The results of this synthesis suggest that the majority of in-house geoscientists and engineers have insufficient knowledge regarding the advantages of geophysics. As experiences (e.g., case histories) are shared and educational opportunities provided for transportation engineers and agencies, these advantages will be better understood, which could lead to more routine use of this technology on their projects. Because highway engineers acknowledge this, the survey respondents requested that additional training resources be made available, including the development of a National Highway Institute course. Although FHWA recently published and distributed the manual, *Application of Geophysical Methods to Highway Related Problems*, nearly 35% of the respondent agencies were not aware of it, more than half of the agencies did not have it or were not sure if they did, and approximately 45% have not used it. Since its publication in 2004 as a web-based document designed around problem solving and applications (not around geophysics), it is apparent that the effort to create the website and distribute the hard copy has not been fully realized.

“The ten most important results derived from this synthesis are:

- “Sixty-eight percent of respondents do not use geophysics very often (i.e., ‘occasionally’), and 45% of the agencies have used geophysics only in the past 10 years.
- “Approximately 60% of the agencies mentioned that there is an increase in their level of effort to implement geophysics, with approximately 25% indicating an increase of between 50% and 100%.
- “The three most commonly used geophysical methods are (1) seismic, (2) ground-penetrating radar, and (3) vibration monitoring.
- “The top three geotechnical engineering applications for geophysics are (1) bedrock mapping, (2) mapping (characterizing) soil deposits, and (3) roadway subsidence. An interesting note is that non-destructive testing ranked second on the list; however, it is not a qualified result because it is not part of this synthesis. This point emphasizes a general lack of understanding concerning the two technologies.
- “The top three ‘greatest values’ for using geophysics are (1) speed of data acquisition, (2) cost benefits, and (3) better characterization of the subsurface.
- “The three greatest deterrents to using geophysics are (1) lack of understanding, (2) nonuniqueness of results, and (3) lack of confidence.

- “Three items that can overcome the deterrents are (1) training, (2) experience (and sharing thereof), and (3) implementation of standards.
- “Very few agencies allocate funds in their annual budgets specifically for geophysical investigations, and the majority of projects cost less than \$10,000.
- “Limited or sole-source solicitations are the primary means of contracting geophysical providers; however, seven agencies are using large, on-call, multiyear contracts.
- “A successful-to-unsuccessful project ratio of 7:1 was shown to exist for the set of entire responses, and similar ratios have been observed at other agencies.”

The synthesis included a list of case histories as shown in Table 1. The table includes successful and unsuccessful cases.

***State-of-the-Practice Survey, Federal Highway Administration Report (Moore et al., 2001); Highway Bridge Inspection (3) and State of Practice of NDE Technologies in Bridge Inspection (4)***

The abstract of *Highway Bridge Inspection*, an FHWA report, states: “The congressionally mandated National Bridge Inspection program requires States to periodically inventory, inspect,

Agency	Case History Provided by Agency	Method (Technique)	Application	Status
Caltrans	Faulting Structures for California Interstate Project Case History 1—Appendix D	Seismic (Reflection)	Detection of faulting	U
Central Federal Lands Highway Division	Lava Tubes	Seismic (Reflection), Resistivity (Ohm-Mapper), GPR, Magnetics, EM	Locate voids (lava tubes) beneath the ground surface and roadway	S
Colorado DOT	Idaho Springs Mineshaft, I-70	GPR	Sinkhole/mineshaft	S
Kansas DOT	K-18 over the Kansas River Case History 3—Appendix D	Resistivity	Bedrock depth	U
Kansas DOT	K-18 over the Kansas River Case History 3—Appendix D	Seismic (Refraction)	Bedrock depth	U
Massachusetts DOT	Route 44 Carver, Massachusetts	Resistivity (Ohm-Mapper)	Detection of peat deposit	
Manitoba	Refraction Seismic Surveys near Falcon Lake, Manitoba	Seismic (Refraction)	Bedrock depth	S
Manitoba	Refraction Seismic Surveys near Falcon Lake, Manitoba	FDEM	Soil characterization	S
Maryland DOT	www.highwaygeologysymposium.org	(multiple case histories available)		
Minnesota DOT	IH35W Bridge 9613	Vibration monitoring	Establish safe vibration levels for pile driving	S
New Hampshire DOT	Report FHWA-NH-RD-12323U, Enhancing Geotechnical Information with Ground Penetrating Radar	GPR	Bedrock depth and fractures	S
New Hampshire DOT	Report FHWA-NH-RD-12323U, Enhancing Geotechnical Information with Ground Penetrating Radar	GPR	Composition, sub-bottom profiling, and voids	U
New Hampshire DOT	Rochester Bridge	Resistivity	Abutment imaging	S
New Hampshire DOT	NH Route 25 Warren-Benton 13209	GPR	Bedrock profile	S
New Hampshire DOT	NH Route 25 Warren-Benton 13209	Resistivity	Bedrock profile	S
New Hampshire DOT	NH Route 25 Warren-Benton 13209	GPR	Subsurface characterization	S
New Hampshire DOT	NH Route 102 Improvements Hudson 13743	Resistivity	Pipe	S
New Hampshire DOT	NH Route 102 Improvements Hudson 13743	GPR	Pipe	S
New Hampshire DOT	US Routes 4 and 202 and NH Route 9, Chichester 13922	Resistivity	Assess extent of organic soil	U

**Table 1. Case Histories (2)**

Agency	Case History Provided by Agency	Method (Technique)	Application	Status
Ohio DOT	Geotechnical Research Project Reports and Implementation Plans	www.dot.state.oh.us/research/Geotechnical.htm (multiple case histories available)		
Ohio DOT	Construction Diary of the SR32 Mine Remediation Project Constructed 1998–1999	www.dot.state.oh.us/mines/FebMar99.htm (multiple case histories available)		
Port Authority of New York and New Jersey	Microtunneling at JFK International Airport	Seismic (Crosshole)	Microtunnel steel casings under an active runway	S
Port Authority of New York and New Jersey	Microtunneling at JFK International Airport	SASW	Microtunnel steel casings under an active runway	S
Saskatchewan	Stony Rapids Airfield Case History 2—Appendix D	GPR	Runway subsidence	S
Wisconsin DOT	US Highway 53 Birch Street Interchange Site Case History 4—Appendix D	EM	Delineate landfill	S
Wisconsin DOT	US Highway 53 Birch Street Interchange Site Case History 4—Appendix D	GPR	Delineate landfill	S

## Notes:

U = Unsuccessful project case history  
EM = Electromagnetic

S = Successful project case history  
GPR = Ground Penetrating Radar

FDEM = Frequency-Domain  
Electromagnetic

SASW = Spectral Analysis of Surface Waves

Source: Andrew Wimsatt, SHRP 2 R06

**Table 1. (Continued).**

and rate all highway bridges on public roads. The National Bridge Inspection Standards, implemented in 1971, prescribe minimum requirements for the inspection of highway bridges in the United States. Visual Inspection is the primary tool used to perform these inspections.

“A survey was conducted to help determine current policies and practices that may affect the accuracy and reliability of Visual Inspection. The survey had three main objectives. The first objective was to compile a state-of-the-practice report for bridge inspection, particularly as it pertains to Visual Inspection. The second objective was to gather information on bridge inspection management to study how inspection management may influence the reliability of inspections. The final objective was to gather data about the current use of nondestructive evaluation technologies and to identify current and future research needs.

“Participants included State departments of transportation, as well as some local-level departments of transportation (the 99 Iowa counties) and select bridge inspection contractors. Responses were received from 42 State departments of transportation, 72 Iowa county departments of transportation, and 6 inspection contractors. The combined response rate for the three target groups was 72 percent.

“Results from the questionnaires are presented in a question-by-question format. The motivation behind each question and the response percentages for each question start the discus-

sion, followed by the results obtained. Included within each question are comments that will highlight the results.”

Yu and Yu (4) generated results of the FHWA report in a tabular and graphical format. Table 2 presents the results for the survey question “What NDE techniques are currently utilized on bridges under your jurisdiction?” The most commonly used NDE methods were liquid penetrant, ultrasonics, and magnetic particle for steel; mechanical sounding, the cover meter, and the rebound hammer for concrete; and mechanical sounding for timber.

Figure 1, also from Yu and Yu (4), shows how NDE application has evolved in the United States from 1993 to 1998, based on Moore et al. (3). Yu and Yu’s report states: “NDE methods that are effective in assessing bridge conditions rapidly gained popularity; while the application of NDE methods that only applies under certain conditions (such as eddy current method) remains steady. This implies that NDE techniques have to possess demonstrated advantages in order to be widely accepted. This is also a guide for the development of new NDT techniques.”

## Questionnaire Responses

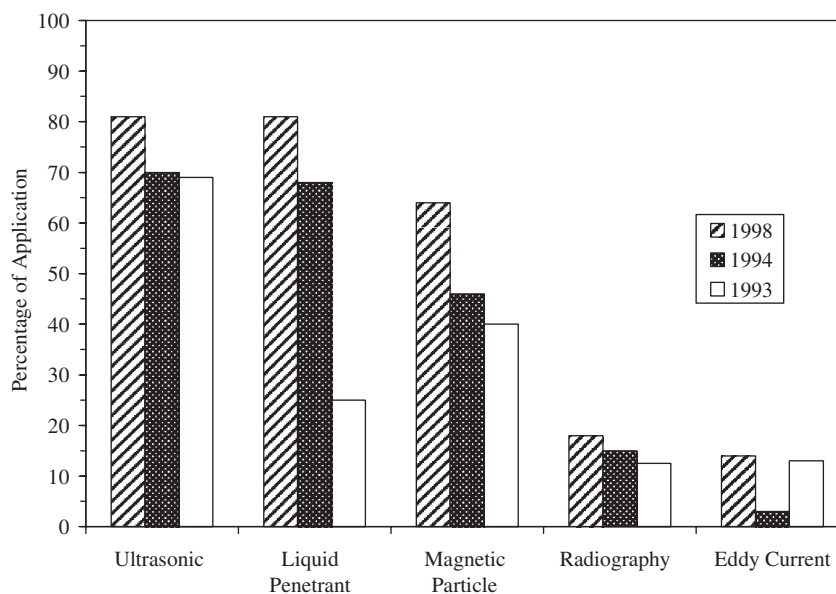
The research team developed and distributed questionnaires concerning rigid pavements, flexible pavements, bridges, earthworks, tunnels, and other structures. Personnel from the

Inspection Method	Bridge Type		
	Steel	Concrete	Timber
Visual Inspection	95.2	90.5	85.7
Liquid Penetrant	81	—	—
Ultrasonics	81	19	—
Magnetic Particle	64.3	—	—
Radiography	16.7	0	0
Acoustic Emission	11.9	2.4	0
Vibration Analysis	9.5	0	—
Eddy Current	9.5	—	—
Other Electromagnetic Techniques for Steel	2.4	—	—
Mechanical Sounding	0	76.2	83.3
Thermal/Infrared	0	11.9	—
Other—Sonic Force	2.4	—	—
Other—D-meter	0	—	—
Cover Meter	—	50	—
Rebound Hammer	—	45.2	—
Electrical Potential Measurements	—	26.2	—
Radar	—	21.4	—
Moisture Meter	—	—	11.9
Stress Wave Analysis	—	—	4.8
Other—Boring/Coring	—	—	9.5
Other—Inspection Pick	—	—	4.8
Other—Timber Decay Detecting Drill	—	—	4.8

Note: “—” means that the NDE is not applicable for this type of bridge

Source: Andrew Wimsatt, SHRP 2 R06

**Table 2. NDE Techniques Used for Bridge Inspection, Compiled from Moore et al. (3, 4)**



**Figure 1. Evolution of nondestructive evaluation (NDE) application in the United States generated from data in Moore et al. (3) and Yu and Yu (4). (A. Wimsatt)**



following state DOTs responded to at least one questionnaire: Alabama, Arkansas, California, Colorado, Delaware, Florida, Georgia, Illinois, Indiana, Louisiana, Maine, Minnesota, Mississippi, Montana, New York, North Dakota, Ohio, Oregon, South Carolina, Texas, and Washington. Additionally, team members used the questionnaires to interview personnel from the Minnesota, Florida, Washington, California, New York, and Texas DOTs at their facilities.

Questionnaires concerning existing and emerging technologies were also distributed to members of the Forum of European National Highway Research Laboratories (FEHRL). The team received responses to the questionnaires from agencies in Norway and Ireland.

## Use of NDT Technologies and Techniques by DOTs in the United States

Questionnaire responses from 21 DOTs indicated the following concerning use of NDT technologies and techniques:

- 17 DOTs use falling-weight deflectometers (FWD) for testing pavements.
- 15 use inertial profilers for pavement ride quality measurements.
- 13 use nuclear density gauges for testing pavements and earthworks.
- 10 use crosshole sonic logging (CSL) for drilled-shaft integrity testing.
- 10 use ultrasonic testing (UT) for such bridge components as pins and hangers.
- Nine use magnetic particle testing for bridge components.
- Eight use friction (skid resistance) measurement vehicles for pavements.
- Seven use profilographs for pavement ride quality measurements.
- Six use rebound hammers (also known as Swiss or Schmidt hammers) for testing hardened concrete.
- Five use covermeters or pachometers to detect the depth of reinforcing steel in reinforced concrete.
- Four indicated that they use ground-penetrating radar (GPR) for testing infrastructure.
- Three use the MIT-Scan device for locating and measuring placement of dowel bars in jointed concrete pavement.
- Three use acoustic emission testing on bridge components.

The team identified promising NDT technologies and techniques from the 21 DOT responses that can or have the potential to produce rapid results for highway renewal projects. The technologies are as follows and are described and discussed in Appendix B.

- Air-coupled GPR—Texas, Florida, Minnesota, and other DOTs through consultant services;

- Ground-coupled GPR—Texas, Florida, Minnesota, and other DOTs through consultant services;
- Surface profile measuring systems—used by at least 15 DOTs;
- MIT-Scan—California, Washington, and South Carolina;
- Real-time automated distress data collection—Texas, Maryland, and others through consultant services;
- Dynamic cone penetrometer—Minnesota and Texas;
- Portable lightweight FWD—Minnesota, Florida, and Texas;
- Gamma-gamma logging and CSL integration for drilled shafts—California;
- Thermal integrity testing for drilled shafts—Florida;
- Hot-mix asphalt (HMA) infrared temperature measurements immediately after laydown operations—Washington and Texas;
- Intelligent compaction—Minnesota and Texas;
- Laser scanning (LADAR or LIDAR)—California, Minnesota, Washington, and Texas;
- Portable seismic pavement analyzer and free resonant column test integration (PSPA/FFRC)—Texas;
- Rolling dynamic deflectometer—Texas;
- Soil resistivity profiling—Minnesota, Florida, and Texas;
- Vibration-based bridge monitoring—California;
- X-ray backscatter—Florida;
- Sliding profiler or smoothboard—Texas; and
- Acoustic emission—Illinois, Oregon, and Texas.

## Use of NDT Technologies and Techniques by FEHRL Members

The FEHRL questionnaire responses indicated that members in Ireland and Norway are using the following NDT technologies and techniques:

- FWD—Norway;
- GPR—Norway and Ireland;
- Pavement profile scanner—Norway;
- Road analyzer and recorder—Norway;
- Multichannel analysis of surface waves—Ireland; and
- Soil resistivity profiling (two-dimensional)—Ireland.

The Ireland respondent considers GPR and soil resistivity profiling emerging technologies.

## Promising NDT Technologies and Techniques Identified from Other Sources

The team identified promising NDT technologies and techniques applicable to highway renewal that were not indicated in the DOT or FEHRL responses. These technologies, described in Appendix C, are as follows and were identified through the information sources described in chapter 2.

- Air-coupled ultrasound—could be used for NDT of bridge decks, tunnels, and pavements;
- Field spectroscopy devices—could be used during construction for assuring the quality of construction materials (i.e., for “fingerprinting” materials);
- Magnetoresistive sensor technology—could be used for identifying corrosion rates of steel in reinforced concrete elements (i.e., rigid pavements, bridge components, and tunnel linings); and
- Nonlinear ultrasound—could be used for identifying alkali silica reactivity and delayed ettringite formation (ASR/DEF) in concrete, fatigue life in steel members, and corrosion in steel reinforcement (Georgia DOT has funded a research study with Georgia Institute of Technology concerning ASR that uses this technology).

## Identified Needs

The following identified needs were based on information sources described earlier in the chapter and the team members’ assessment and expertise. The needs are listed in order of priority under the relevant infrastructure category (bridges, pavements, earthworks, tunnels, and other structures) as described in chapter 4.

### Bridge Needs

#### *Automated Methods of Accurately Profiling Bridges (Performance Monitoring and Construction)*

Several respondents (including agency personnel and researchers) indicated that they have been using various methods to monitor movements and deformations of bridge structures. Significant changes from year to year would cause additional testing to be undertaken. More automated methods of monitoring bridge profiles are needed. This could involve driving a vehicle over the bridge to map the current profile and then comparing the baseline with subsequent evaluations. Such technology could also be used for construction purposes if DOTs decide to move toward ride specifications for bridges.

#### *Identification of Deterioration of Bridge Decks, Including the Cause of Deterioration (Design, Construction, and Performance Monitoring)*

Several respondents indicated the need to identify if bridge decks are starting to deteriorate and what is causing the deterioration (e.g., insufficient depth of reinforcing steel cover, concrete permeability, material defects) to effectively maintain or rehabilitate such decks. Additionally, one respondent indicated that his agency would like to know the condition of the interface between the deck and the bridge girders to deter-

mine if composite action is present. Personnel at one agency would like a device to monitor size, spacing, and depth of cracks as well as extent of delamination for bridge decks (i.e., bridge deck mapping).

#### *Foundation Investigation Tools Where Concerns Exist (Design, Construction, and Performance Monitoring)*

Characterizing unknown foundations is a priority for many agencies, but no NDT appears to be used by respondents for regularly characterizing such foundations. National Cooperative Highway Research Program (NCHRP) Projects 21-5 and 21-5(2) investigated the use of the following technologies and techniques for this purpose (5):

1. Sonic echo/impulse response,
2. Bending (flexural) wave,
3. Ultraseismic,
4. Spectral analysis of surface waves,
5. Dynamic foundation response,
6. Parallel seismic,
7. Borehole sonic,
8. Borehole radar, and
9. Induction field.

The first five techniques are surface techniques; the last four techniques require boreholes adjacent to the foundations. According to the Transportation Research Board (TRB)-NCHRP website, the reports were not published; the web page for NCHRP Project 21-5(2) states: “The NCHRP feels that even though the research results from Project 21-05(02) are interesting, they are inconclusive and are not of sufficient accuracy and reliability to be implemented in normal practice at this time by state DOTs” (6). Additionally, for construction purposes, 10 of the 21 states that responded to the questionnaires use CSL for newly constructed drilled-shaft integrity testing. Personnel at California and Florida DOTs have noted that this technology has significant limitations, including the inability to assess integrity outside the access tubes; personnel at Oregon DOT indicated in their response that the CSL results are often inconclusive. California DOT is using gamma-gamma logging (a nuclear technology) to supplement CSL testing (7). Florida DOT sponsored research to investigate the use of thermal integrity testing to assess drilled-shaft integrity; the results from that research appear to be promising (8).

#### *Detecting Problems at Bridge Approaches, Including Abutments (Design and Performance Monitoring)*

Some respondents indicated that they have observed significant problems with bridge approaches, such as voids under

bridge approach slabs and bumps at bridge ends. Some DOTs have used GPR to detect problems at bridge approaches, but the results have been mixed.

### ***Scour Around Bridge Support Systems (Design and Performance Monitoring)***

Many agencies rated measurement of existing scour around foundations and scour potential as a priority. Much work has been performed in this area, but no NDT technology is widely used to evaluate scour potential.

### ***Reinforcing Steel Corrosion (Design and Performance Monitoring)***

Determining the extent and severity of reinforcing steel corrosion in concrete is a priority for several respondents.

### ***Early Detection of Concrete Deterioration Mechanisms (Design and Performance Monitoring)***

Detecting early stages of such processes as ASR and sulfate attack will be beneficial for those involved in maintaining existing structures. If the problems are found early enough, various strategies could be used so that the structure does not have to be reconstructed or extensively rehabilitated.

### ***Global Testing of Bridge Structures to Identify Deficiencies in the Structure (Design and Performance Monitoring)***

Several respondents expressed the need for easier-to-conduct and more reliable global structure testing methods to quantitatively establish the load-carrying capacities of existing bridge structures and to determine if any structural elements need to be replaced or repaired. Modal analysis, which involves analyzing data from sensors (mainly accelerometers) mounted on a structure that has been excited by traffic loading or impact hammer loading, has been used for this purpose, but such testing would be used more frequently if the sensors were easier to install and the resulting data could be retrieved and analyzed more easily.

### ***Identification of Fatigue and Fracture Damage in Structural Elements (Design and Performance Monitoring)***

Detecting such damage in structural elements before it is visible is desired by several respondents. It would also be ideal if remaining life could be estimated.

### ***Corrosion of Steel Elements (Design and Performance Monitoring)***

A priority for many respondents is determining the extent and severity of steel element corrosion, especially elements that are not visible to bridge inspectors.

### ***Pavement Needs***

#### ***Continuous Deflection Device at the Highest Possible Speed (Design and Performance Monitoring)***

Many respondents use the FWD for pavement structural evaluation but want a device that can collect continuous deflection data at as high a speed as possible. Additionally, many respondents want rapid NDT to measure load transfer at joints and cracks for rigid pavements in order to develop effective pavement renewal designs. The FWD is able to assess load transfer, but it is time consuming to collect such data for every joint or crack for such projects.

The team is aware of the following high-speed deflection devices:

- Rolling dynamic deflectometer (RDD), developed at the University of Texas at Austin;
- Rolling wheel deflectometer (RWD), developed by Applied Research Associates for the FHWA;
- Airfield rolling weight deflectometer (ARWD), developed by Quest Integrated;
- Road deflection tester (RDT), developed by the Swedish National Road Administration and Swedish National Road and Transport Research Institute; and
- High-speed deflectograph (HSD), developed by the Danish Road Institute and Greenwood Engineering A/S.

A summary and evaluation of these devices can be found in a report by Arora et al. (9). Based on the latest information, of the five devices listed, only the RDD is capable of assessing load transfer. Although the RDD can assess load transfer more rapidly than the FWD, it operates at around 1 mph. A more rapid NDT device is needed for load transfer evaluation.

#### ***New Nondestructive Quality Assurance (QA) Tools for Ensuring Quality Construction (Construction)***

Relatively simple and easy-to-use NDT methods that can be used by inspectors and frontline personnel in the field are needed to ensure quality construction. Although nuclear density gauges and electrical impedance devices are available, they take discrete measurements and are not suited for rapidly providing approximately 100% coverage. Results from the new methods should be easy to interpret. Also,



performance-related specifications and warranties require such tools when the data are used in computer models to predict life.

### ***Interlayer Bonding (Design, Construction, and Performance Monitoring)***

Layer debonding is a primary cause of premature deterioration of pavement structures, especially with HMA-surfaced pavements. Many pavement renewal projects involve HMA surfaces. NDT methods to measure the degree of bonding are needed.

### ***Layer Material Properties (Design, Construction, and Performance Monitoring)***

The respondents indicated that NDT methods to accurately and precisely characterize in-situ material properties are needed, such as density (in-place air voids), modulus, Poisson's ratio, and the presence of defects. Some respondents stated that they want NDT to measure properties that are used in the *Mechanistic Empirical Pavement Design Guide* that has been adopted by the American Association of State Highway and Transportation Officials (AASHTO).

### ***Distress Measurements (Design and Performance Monitoring)***

An NDT technique that measures pavement distress in real time (rather than distress rating methods involving human beings) is a priority for several respondents.

### ***Layer Thicknesses (Design, Construction, and Performance Monitoring)***

NDT methods to accurately and precisely measure all pavement layer thicknesses are needed. GPR is used by a few state agencies for this purpose.

### ***Early Detection of Concrete Deterioration Mechanisms (Design and Performance Monitoring)***

Detecting the early stages of processes such as alkali-silica reactivity and sulfate attack will be very beneficial for those involved in maintaining existing structures. If the problems are found early enough, various strategies could be employed so that the structure does not have to be reconstructed or extensively rehabilitated.

### ***Performance Monitoring of Riding Quality Profiles and Dynamic Loads (Performance Monitoring)***

Several DOTs use inertial profilers to measure pavement ride quality for pavement management purposes. Improved

methods are needed to more accurately measure such profiles and to determine how the profiles affect dynamic loading on the pavement structure from truck traffic.

### ***Pavement Surface Properties for Safety and Noise Issues (Design, Construction, and Performance Monitoring)***

Several DOTs measure friction properties using friction (skid resistance) measurement vehicles, as well as noise properties of pavement surfaces. Improved methods that characterize the properties of the pavement surface are needed.

### ***Plant QA (Construction)***

NDT methods are needed to ensure that materials produced for highway construction are acceptable (structural steel, reinforcing steel, hot-mix asphalt [HMA] concrete, portland cement concrete, and aggregates). For HMA concrete, the National Center for Asphalt Technology produced a report that offered recommendations involving technologies that “check the consistency of the materials feeding into the HMA plant” (10).

### ***Identification of Problematic Soils (Design and Construction)***

Also expressed was a need to use NDT to help with soil treatment, such as chemical stabilization. One goal was to assist in rapidly identifying problematic soils (sulfates, organics, etc.); another request was for a procedure to measure stabilizer content.

## **Earthwork Needs**

### ***Better NDT Tools for Mapping Projects (Design)***

NDT tools that provide up to 100% coverage and can reliably detect soil strata changes, voids, and areas of excessive moisture are needed. Such methods can help engineers determine where to take borings. It can also help engineers interpolate between bore holes. Soil resistivity testing is an NDT that would fit in this category, but other methods are needed as well. Resistivity testing of new alignments has been implemented by Minnesota and Florida DOTs, and they are enthusiastic about the benefits of this technology.

### ***Validation Tools for QA (Construction)***

NDT that provides up to 100% coverage is desirable. Several respondents indicated that density measurements alone are insufficient for QA—measures of density, stiffness, and moisture content are all needed for QA. Minnesota DOT was again found to have made substantial progress in implementing new technologies for base and subgrade QA testing.

### ***Earthwork Performance Monitoring (Performance Monitoring)***

As one respondent stated, “The greatest needs in earthwork performance monitoring are those which can mimic existing technologies and provide data on earth movement and water pressures, but more importantly report those results quickly and continuously via wireless technology. With landslide-prone slopes or scour-critical bridge foundations, for example, the timing of the information retrieval is almost more important than the information itself.”

### **Tunnel Needs**

#### ***Changes in Profile over Time (Performance Monitoring)***

The consensus from discussions with DOTs was that a device that could detect early potential problems and locate areas in which intense additional testing will be required would be most useful. The research team believes that changes in tunnel profile may serve this purpose (i.e., comparing changes in profile from a baseline measurement).

#### ***Mapping Voids, Bonding, and Moisture Behind or Within Tunnel Linings (Design and Performance Monitoring)***

Such mapping was identified as a critical concern, and the DOTs indicated that little has been implemented in this

area. Most of the work appears to be from either Europe (France and Germany) or Japan. A recent paper published by TRB summarized the equipment used in Japan to inspect tunnels (11).

#### ***Deterioration of Tunnel Linings (Design and Performance Monitoring)***

Concerns were expressed about chemical deterioration of mostly concrete tunnel linings. Examples were given on the potential ASR damage in the linings of the Washington, D.C., subway system. NDT to map the extent and severity of these problems is not available.

#### ***QA of Tunnel Components (Construction)***

NDT methods that measure placement of reinforcing steel and tunnel lining thickness are needed.

### **Other Structure Needs**

#### ***Mapping Voids, Bonding, and Moisture Behind Retaining Walls (Design and Performance Monitoring)***

The main need indicated from survey responses for other structures pertained to mapping voids, bonding, and moisture behind retaining walls.

## CHAPTER 4

# Conclusions and Recommended Research

### Introduction

#### Prioritization of Needs

As discussed in chapter 2, to generate plans that could be considered based on the second Strategic Highway Research Program (SHRP 2) funding limitations, the team prioritized the needs into three levels (Priority 1, 2, and 3, with 1 being the highest priority) for each need category. The priorities were based on a simple rating system using the four criteria described in chapter 2 and on the team members' assessments and expertise. The team then generated detailed research problem statements for the Priority 1 needs which appear in Appendix D.

#### Information and Comments from the First International Symposium

The team presented the preliminary plan for this project at the First International Symposium on Nondestructive Testing for Design Evaluation and Construction Inspection. Information and comments from the symposium were considered when developing the recommendations, prioritizations, and rankings presented in this report.

In particular, the team initially classified the research study on nondestructive testing (NDT) to identify bridge deck deterioration as an experimental project. Based on comments received at the symposium, the team reclassified this study as a focused development project.

The team learned from the symposium that Florida Department of Transportation (DOT) had sponsored a study on thermal integrity testing for newly constructed drilled shafts. Because bridge renewal projects may involve widening existing bridges, the team decided to add a demonstration project concerning the use of thermal integrity testing as well as gamma-gamma logging (used by California DOT) for

evaluating new drilled shafts. This project relates to the need for bridge foundation investigation tools when concerns exist.

Feedback from the symposium resulted in the team's developing a new focused development project concerning strength determination and integrity evaluation of concrete pavement and bridge deck repairs using seismic techniques. The project relates to the need for new nondestructive quality assurance (QA) tools for ensuring quality construction.

Several symposium participants expressed concern that the team did not consider the need for automated pavement distress equipment as a priority. The team discussed this concern and decided that to produce effective and long-lasting pavement renewal projects, higher priority should be given to projects that address or can determine causes of distress. Consequently, this need was moved from Priority 3 to Priority 2.

Several participants expressed concern about the emphasis on devices that provide approximately 100% coverage, including the amount and quality of data generated from such devices. The team believes that this concern is addressed in the recommended project objectives and products described in this chapter and Appendix D. In particular, the NDT technologies and techniques specified under the recommended projects do have promise in addressing highway renewal research needs. In many instances, NDT implementation is more challenging than the original development. It may require a different set of skills than the science and engineering required to develop and prototype equipment. Application involves working within organizations, establishing specifications, providing training, setting goals, documenting benefits, and establishing overall good communication channels within the agency and externally with contractors and trade organizations. These considerations must be addressed effectively if any NDT is to be implemented successfully.

## Recommended Research for SHRP 2 Funding

The team recommends that SHRP 2 fund research to address needs identified, starting with Priority 1 needs. The recommended research can be grouped into the following types of projects:

- Demonstration projects in which proven technology and techniques exist but are not widely used; Focused development projects in which the technology exists but more development work is needed;
- Experimental research projects in which the problem is well defined but several technologies need to be evaluated to determine if they would be effective in addressing the problem; and
- Research to address an unfulfilled need in which the problem is well defined but existing NDT has been unsuccessful in addressing the problem.

Unfulfilled needs and experimental research projects address areas in which testing needs exist but no technology is available. Focused development projects address areas in which

promising technology exists that could be implemented. Demonstration projects involve technologies that are not widely used for various reasons.

Table 3 shows NDT needs for which the team believes current and emerging technologies require further study. Table 4 shows NDT needs that are unmet by current and emerging technologies. Table 5 summarizes recommended projects for Priority 1 needs. Tables 6 through 8 list rating summaries for the needs. Table 9 contains the needs ranked by the average rating score and the estimated costs for Priority 1 needs. The team recommends funding projects in the order shown in Table 9 for Priority 1 needs. Members discussed the fact that the tunnel and retaining wall needs for mapping voids, bonding, and moisture (both Priority 1 needs) did rank below several Priority 2 needs but decided to keep those needs as Priority 1 within the tunnels and retaining walls categories.

## Descriptions of the Top Six Needs and Recommendations

The visits to selected state DOTs and responses to the questionnaires identified areas in which high-speed NDT methods are necessary to support highway infrastructure renewal projects

	Design (new and rehabilitation)	Construction Activities	Performance Monitoring
<b>Bridges</b>	<ul style="list-style-type: none"> <li>• Identification and cause characterization of bridge deck deterioration</li> <li>• Detection of problem areas at bridge approaches</li> <li>• Identification of fatigue and fracture damage</li> <li>• Global testing of bridge structures</li> </ul>	<ul style="list-style-type: none"> <li>• Identification and cause characterization of bridge deck deterioration</li> <li>• Foundation investigation tools—assessing new drilled-shaft integrity</li> </ul>	<ul style="list-style-type: none"> <li>• Identification and cause characterization of bridge deck deterioration</li> <li>• Detection of problem areas at bridge approaches</li> <li>• Identification of fatigue and fracture damage</li> <li>• Global testing of bridge structures</li> </ul>
<b>Pavements</b>	<ul style="list-style-type: none"> <li>• High-speed continuous deflection device</li> <li>• Layer thickness measuring tools</li> <li>• Improved tools for measuring friction and noise properties</li> <li>• Tools for real-time automated pavement distress measurements</li> </ul>	<ul style="list-style-type: none"> <li>• QA tools to ensure quality construction</li> <li>• Layer thickness measuring tools</li> <li>• Improved tools for measuring friction and noise properties</li> </ul>	<ul style="list-style-type: none"> <li>• High-speed continuous deflection device</li> <li>• Layer thickness measuring tools</li> <li>• Tools for real-time automated pavement distress measurements</li> <li>• Improved methods for measuring profiles</li> <li>• Software for determining dynamic loading</li> <li>• Improved tools for measuring friction and noise properties</li> </ul>
<b>Earthworks</b>	<ul style="list-style-type: none"> <li>• Project mapping (100% coverage)</li> </ul>	<ul style="list-style-type: none"> <li>• Validation tools for QA</li> </ul>	
<b>Tunnels</b>		<ul style="list-style-type: none"> <li>• Tools for QA of components:                             <ul style="list-style-type: none"> <li>• Reinforcing steel</li> <li>• Tunnel lining thickness</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>• Changes in profile of linings</li> </ul>
<b>Retaining Walls</b>	<ul style="list-style-type: none"> <li>• Mapping of voids, bonding, and moisture behind retaining walls</li> </ul>		<ul style="list-style-type: none"> <li>• Mapping of voids, bonding, and moisture behind retaining walls</li> </ul>

Source: Andrew Wimsatt, SHRP 2 R06

**Table 3. NDT Needs for Which Current and Emerging Technologies Need Further Study**

	Design (new and rehabilitation)	Construction Activities	Performance Monitoring
<b>Bridges</b>	<ul style="list-style-type: none"> <li>• Foundation investigation tools</li> <li>• Measurements of existing scour and scour potential</li> <li>• Early detection of concrete deterioration mechanisms</li> <li>• Determination of extent and severity of steel corrosion (reinforcing steel and steel bridge elements)</li> </ul>	<ul style="list-style-type: none"> <li>• Foundation investigation tools</li> <li>• Automated methods for profiling bridges</li> <li>• Plant QA tools</li> </ul>	<ul style="list-style-type: none"> <li>• Foundation investigation tools</li> <li>• Automated methods for profiling bridges</li> <li>• Measurements of existing scour and scour potential</li> <li>• Identification and cause characterization of bridge deck deterioration</li> <li>• Early detection of concrete deterioration mechanisms</li> <li>• Determination of extent and severity of steel corrosion (reinforcing steel and steel bridge elements)</li> </ul>
<b>Pavements</b>	<ul style="list-style-type: none"> <li>• Methods for measuring interlayer bonding</li> <li>• Tools for in-situ material characterization</li> <li>• Tools for early detection of concrete deterioration</li> <li>• Method for identifying problematic soils</li> </ul>	<ul style="list-style-type: none"> <li>• Methods for measuring interlayer bonding</li> <li>• Plant QA tools</li> <li>• Tools for in-situ material characterization</li> <li>• Method for identifying problematic soils—procedure for measuring stabilizer content</li> </ul>	<ul style="list-style-type: none"> <li>• Methods for measuring interlayer bonding</li> <li>• Tools for in-situ material characterization</li> <li>• Tools for early detection of concrete deterioration</li> </ul>
<b>Earthworks</b>			<ul style="list-style-type: none"> <li>• Near real-time performance monitoring</li> </ul>
<b>Tunnels</b>	<ul style="list-style-type: none"> <li>• Mapping of voids, bonding, and moisture behind or within tunnel linings</li> </ul>	<ul style="list-style-type: none"> <li>• Plant QA tools</li> </ul>	<ul style="list-style-type: none"> <li>• Mapping of voids, bonding, and moisture behind or within tunnel linings</li> <li>• Deterioration of tunnel linings</li> </ul>
<b>Retaining Walls</b>		<ul style="list-style-type: none"> <li>• Plant QA tools</li> </ul>	

Source: Andrew Wimsatt, SHRP 2 R06

**Table 4. NDT Needs Unmet by Current and Emerging Technologies**

on pavements, bridges, tunnels, earthworks, and other structures. Given this information, researchers reviewed the literature and met with NDT experts in academia, government, and industry to identify existing and emerging technologies that can be used to quickly develop and implement applications for rapid nondestructive testing of in-situ conditions for purposes of design, construction inspection, and performance monitoring as stated in this project's request for proposals. The goal was to support the highway renewal philosophy of "get in, get out, and stay out." This philosophy requires implementation of NDT technologies that limit or reduce traffic disruption on existing facilities and that provide more rapid and reliable information on existing conditions to support design, as-built conditions for construction QA testing, and field performance to support asset management. As shown in Table 10, the top six needs and corresponding recommendations are for the following:

- Automated methods of accurately profiling bridges;
- Changes in profiles of tunnel linings over time;

- Identification of deterioration of bridge decks, including the cause;
- Continuous deflection device at the highest possible speed for pavements;
- New NDT QA tools for ensuring quality construction; and
- Measurement of interlayer bonding between hot-mix asphalt (HMA) layers for pavements.

Three projects would address design, four would address construction, and five would address performance-monitoring needs. All three are target areas identified in the request for proposals (RFP) for developing rapid NDT applications to support highway infrastructure renewal. The research problem statements for these and other Priority 1 projects are presented in Appendix D. Recommended projects presented in this section are based on a ranking of the needs identified during this project as well as an assessment of what existing and emerging technologies can be used to address those needs now or by 2011. To the extent that more funding can be made available within SHRP 2 or in a follow-up program, consid-

<b>Recommended Demonstration Projects</b>
Pavements—Using Both Infrared and High-Speed Ground Penetrating Radar for Uniformity Measurements on New HMA Layers
Pavements—Implementing Smoothness Specifications Based on Inertial Profilers
Bridges, Pavements, and Earthworks—Field Demonstration of Resistivity Mapping
Bridges—Demonstration of Gamma-Gamma Logging and Thermal Integrity Testing for Drilled Shafts
Tunnels—Monitoring Changes in Tunnel Profiles
<b>Recommended Focused Development Projects</b>
Tunnels—Monitoring Changes in Tunnel Profiles (if the demonstration project indicates more work is needed)
All—Using Field Spectroscopy Devices to Fingerprint Commonly Used Construction Materials
Pavements and Bridges—Strength Determination and Integrity Evaluation of Concrete Pavement and Bridge Deck Repairs Using Seismic Techniques
Pavements—Development of Continuous Deflection Sensors
Earthworks—Implementation Program for Intelligent Compaction
Pavements—Real-Time Smoothness Measurements on PCC Pavements during Construction
Bridges—Nondestructive Testing to Identify Bridge Deck Deterioration
<b>Recommended Experimental Research Projects</b>
Pavements—Nondestructive Testing to Identify Delaminations between HMA Layers
<b>Recommended Unfulfilled Needs Projects</b>
Bridges—New Technologies for Mapping Unknown Bridge Foundations
Bridges—Detecting Movement in Structures with Inertial Profile Data
Tunnels and Retaining Walls—Mapping Voids, Bonding, and Moisture behind or within Tunnel Linings and Retaining Walls

Source: Andrew Wimsatt, SHRP 2 R06

**Table 5. Recommended Projects for Priority 1 Needs**

Bridge Need	Average				Average Overall Score	Priority
	Importance of 100% Coverage	Quickly Implementable	Addresses Renewal Need	High-Speed Testing		
Automated methods of accurately profiling bridges	4.75	4.25	4.25	4.50	4.44	1
Identification of bridge deck deterioration, including the cause of deterioration	4.25	3.50	4.50	4.50	4.19	1
Foundation investigation tools where concerns exist	4.00	3.50	4.50	3.00	3.75	1
Detecting problems at bridge approaches, including abutments	4.00	3.25	3.50	3.50	3.56	2
Scour around bridge support systems	3.75	3.00	4.00	3.00	3.44	2
Reinforcing steel corrosion	2.75	2.50	4.00	3.75	3.25	2
Early detection of concrete deterioration mechanisms	2.75	2.25	4.00	3.50	3.13	2
Global testing of bridge structures to identify deficiencies in the structures	3.75	3.00	3.00	2.25	3.00	3
Identification of fatigue and fracture damage in structural elements	2.75	3.00	3.25	3.00	3.00	3
Corrosion of steel elements for steel bridges	3.50	3.00	2.75	2.75	3.00	3

Source: Andrew Wimsatt, SHRP 2 R06

**Table 6. Rating Summary for Bridge Needs**



Pavement Need	Average				Average Overall Score	Priority
	Importance of 100% Coverage	Quickly Implementable	Addresses Renewal Need	High-Speed Testing		
Continuous deflection device at the highest possible speed	4.50	4.00	4.25	4.00	4.19	1
New nondestructive quality assurance tools for ensuring quality construction	4.25	4.25	4.00	4.00	4.13	1
Interlayer bonding	4.00	3.75	4.00	4.00	3.94	1
Layer material properties	4.00	3.25	4.25	3.50	3.75	2
Distress measurements	3.75	3.00	3.25	4.25	3.56	2
Layer thicknesses	3.75	2.50	3.50	3.50	3.31	2
Early detection of concrete deterioration mechanisms	3.50	2.00	3.75	3.75	3.25	2
Performance monitoring of profiles of riding quality and dynamic loads	3.25	3.00	2.75	3.50	3.13	2
Pavement surface properties for safety and noise issues	3.00	3.25	2.25	3.25	2.94	3
Plant quality assurance	2.50	2.75	3.50	2.75	2.88	3
Identification of problematic soils	2.25	2.00	2.50	2.25	2.25	3

Source: Andrew Wimsatt, SHRP 2 R06

**Table 7. Rating Summary for Pavement Needs**

	Average				Average Overall Score	Priority
	Importance of 100% Coverage	Quickly Implementable	Addresses Renewal Need	High-Speed Testing		
<b>Earthwork Need</b>						
Better NDT tools for mapping projects	4.25	4.50	3.50	3.50	3.94	1
Validation tools for quality assurance	3.75	3.75	4.75	3.25	3.88	1
Earthwork performance monitoring	3.50	3.00	2.75	2.25	2.88	2
<b>Tunnel Need</b>						
Changes in profile over time	4.75	4.50	4.00	4.00	4.31	1
Mapping voids, bonding, and moisture behind or within tunnel linings	4.00	3.00	3.75	3.00	3.44	1
Deterioration of tunnel linings	3.50	2.75	3.25	3.50	3.25	2
Quality assurance of tunnel components	2.25	3.00	3.00	2.50	2.69	3
<b>Retaining Wall Need</b>						
Mapping voids, bonding, and moisture behind retaining walls	3.00	3.50	3.50	3.25	3.31	1

Source: Andrew Wimsatt, SHRP 2 R06

**Table 8. Rating Summary for Earthworks, Tunnels, and Retaining Walls**

Need	Category	Average Overall Score	Priority	Estimated Cost of Research \$	Cumulative Total Cost \$
Automated methods of accurately profiling bridges	Bridges	4.44	1	975,000	975,000
Changes in profile over time	Tunnels	4.31	1	900,000	1,875,000
Identification of bridge deck deterioration, including the cause of deterioration	Bridges	4.19	1	750,000	2,625,000
Continuous deflection device at the highest possible speed	Pavements	4.19	1	225,000	2,850,000
New nondestructive quality assurance tools for ensuring quality construction	Pavements	4.13	1	1,350,000	4,200,000
Interlayer bonding	Pavements	3.94	1	600,000	4,800,000
Better NDT tools for mapping projects	Earthworks	3.94	1	225,000	5,025,000
Validation tools for quality assurance	Earthworks	3.88	1	750,000	5,775,000
Foundation investigation tools where concerns exist	Bridges	3.75	1	1,800,000	7,575,000
Layer material properties	Pavements	3.75	2		7,575,000
Detecting problems at bridge approaches, including abutments	Bridges	3.56	2		7,575,000
Distress measurements	Pavements	3.56	2		7,575,000
Scour around bridge support systems	Bridges	3.44	2		7,575,000
Mapping voids, bonding, and moisture behind or within tunnel linings	Tunnels	3.44	1	1,800,000	9,375,000
Layer thicknesses	Pavements	3.31	2		
Mapping voids, bonding, and moisture behind retaining walls	Other Structures	3.31	1	Handled under tunnel research	
Reinforcing steel corrosion	Bridges	3.25	2		
Early detection of concrete deterioration mechanisms	Pavements	3.25	2		
Deterioration of tunnel linings	Tunnels	3.25	2		
Early detection of concrete deterioration mechanisms	Bridges	3.13	2		
Performance monitoring of profiles of riding quality and dynamic loads	Pavements	3.13	2		
Global testing of bridge structures to identify deficiencies in the structures	Bridges	3.00	3		
Identification of fatigue and fracture damage in structural elements	Bridges	3.00	3		
Corrosion of steel elements for steel bridges	Bridges	3.00	3		
Pavement surface properties for safety and noise issues	Pavements	2.94	3		
Plant quality assurance	Pavements	2.88	3		
Earthwork performance monitoring	Earthworks	2.88	2		
Quality assurance of tunnel components	Tunnels	2.69	3		
Identification of problematic soils	Pavements	2.25	3		

Source: Andrew Wimsatt, SHRP 2 R06

**Table 9. Needs Sorted by Average Overall Score**



Priority	Need and Recommendation	Design	Construction	Performance Monitoring
1	Automated methods of profiling bridges		✘	✘
2	Changes in tunnel profile over time			✘
3	Identification of bridge deck deterioration	✘	✘	✘
4	High-speed continuous deflection device for pavements	✘		✘
5	New NDT for construction QA		✘	
6	Methods for pavement interlayer bonding	✘	✘	✘

Source: Andrew Wimsatt, SHRP 2 R06

**Table 10. Top Six Needs and Recommendations**

eration can be given at a later time to fund additional Priority 1 projects.

The top six priorities were determined by a scoring system developed by the research team. Important factors in these rankings include the team's assessment of the needs expressed by DOTs for test methods to support highway renewal projects as well as the limited amount of funding available. Many other excellent candidate Priority 1 and 2 studies were identified but were excluded based on funding limitations.

### Automated Methods of Accurately Profiling Bridges

As of December 2007, the U.S. National Bridge Inventory (NBI) database indicated that 72,524 bridges (out of 599,766) are structurally deficient (12). The corresponding bridge deck area on those structures, according to the NBI, is 31,297,434 square yards. The FHWA estimates an average bridge replacement cost of \$1,110 per square meter, or \$928 per square yard, and the Fiscal Year 2003 Federal-Aid Highway Bridge Replacement and Rehabilitation Program had approximately \$3.35 billion in funds (13). If all the bridges had to be replaced, approximately \$29 billion would be needed. Additionally, at least 20,000 bridges that are over waterways are considered scour critical, which indicates that the foundations on those bridges may fail due to erosion (14). The FHWA indicates that more than 80,000 bridges have unknown foundations (15).

Because such concerns exist for so many bridges, a rapid screening tool is needed to identify critical conditions that warrant more detailed testing and data analysis to pinpoint problems and identify alternative solutions in a timely manner to ensure public safety. This need is related to the "get in" goal for highway renewal; such a tool can assist decision makers in prioritizing bridge rehabilitation and reconstruction projects. The proposed method involves high-speed NDT that minimizes disruption for the traveling public. For example, scour critical bridges would benefit from having a practical, implementable technology based on profile measurements

that would show engineers whether significant movements as detected in changes in bridge profiles have occurred after significant flooding events. As a result, the team recommends an unfulfilled need project to detect movement in structures with profile and video data. The team believes that the techniques resulting from this study can potentially produce methods that collect data and provide results rapidly (possibly in real time); can be potentially implemented quickly, especially because profiler and video image-processing methods are available; effectively address a renewal need, especially because the technology could potentially be applied to many bridges; and provide high-speed testing, resulting in traffic control being potentially minimized or unnecessary. The estimated cost of this project is \$975,000.

### Changes in Profiles over Time for Tunnels

There were 337 highway tunnels and 211 transit tunnels in the United States as of 2003 (16). Recently there have been some dramatic failures in tunnel linings; as a result, DOT personnel are more concerned about tunnel conditions. Although no data could be found in terms of highway tunnel conditions, the Federal Transit Administration indicated that 28% of transit underground structures are rated "substandard" or "poor" (17). Existing procedures for evaluating tunnels are localized, labor intensive, and slow.

A more rapid method for assessing the condition of tunnels, in particular tunnel linings, is needed to ensure the safety of the traveling public and effectively schedule rehabilitation and repair projects. This need is related to the "get in" goal for highway renewal; such a tool can assist decision makers in prioritizing tunnel rehabilitation and reconstruction projects and pinpointing specific areas in the tunnel that require rehabilitation or reconstruction. This method would be considerably faster than current tunnel testing and monitoring techniques, minimizing disruption for the traveling public. Scanning laser technology is available and has been used outside the United States to obtain three-dimensional profiles of tunnels that

provide a quantitative measurement of the condition of tunnel linings and provide images of cracks, spalling, water leaks, and other surface irregularities. Because of the precision with which measurements can be made, scanning laser technology can potentially provide a useful performance monitoring tool for early detection of structural problems before they become visible to the naked eye. This advantage enables engineers to provide a more timely response to structural problems developing within tunnel linings, possibly reducing the cost of corrective work and enhancing user safety. For less precise but faster and less costly measurements, integrating the scanning laser with digital video equipment can provide a useful screening tool for engineers. The team recommends a demonstration project to address this need using existing methodologies and, if necessary, focused development to make such systems applicable for use by DOTs. The team believes that the techniques resulting from this study can potentially produce methods that collect data and provide results rapidly (possibly in real time); can be potentially implemented quickly, especially because such technologies are available; effectively address a renewal need, especially because the technology could potentially be applied to all tunnels; and provide high-speed testing, possibly minimizing traffic control or making it unnecessary. The estimated cost of this project is \$900,000.

### Identification of Deterioration of Bridge Decks

In a Transportation Research Board (TRB) millennium paper, Chase and Laman (18) stated: “The largest problem identified for the NHS [National Highway System] bridges is bridge decks, which are either in poor structural condition or too narrow. It is estimated that over \$1 billion is spent on bridge decks each year. Over 88 percent of all bridge deck area (2.8 billion square feet) is concrete, and about half of those bridge decks have a wearing surface over the concrete. . . . There is a need to develop network-level bridge deck evaluation methods that can provide an accurate assessment of bridge deck condition for decks with wearing surfaces. . . . In addition, cost overruns are very common on bridge deck replacement projects, resulting in a need for improved project-level deck evaluation technologies.”

The issues presented in this paper are still considered valid.

Techniques that minimize traffic delays and supply reliable, 100% coverage data about the severity and extent of subsurface deterioration are definitely needed so that the optimal repair strategy can be selected; this need is related to the “stay out” goal of highway renewal. The extent and severity of subsurface deterioration, particularly on asphalt-covered bridge decks, are the critical factors in the design process. The system proposed would minimize risk; the worst fear of designers is that subsurface conditions are more severe than indicated by visual surveys and limited coring.

The team recommends a focused development project to address this need using existing technologies such as ground-penetrating radar (GPR) and infrared integrated with digital video. The team believes that the techniques resulting from this study can potentially produce methods that collect data and provide results rapidly (possibly in real time); can be potentially implemented quickly (but possibly not as quickly as the other five projects), especially because such technologies are available; effectively address a renewal need because the technology could possibly be applied to all bridge decks; and provide high-speed testing, potentially significantly reducing the need for traffic control. The estimated cost of this project is \$750,000.

### Continuous Deflection Device at the Highest Possible Speed

As a result of the interviews conducted, the team found that one of the biggest challenges DOTs face in the pavement renewal area is selecting the optimum rehabilitation strategy for distressed jointed concrete pavements. Most agencies have deteriorated jointed concrete pavements as a significant percentage of their truck network. Based on highway statistics from 2006, 22% of the rural interstate system and 31% of the urban interstate system are classified as composite pavements (i.e., HMA overlays of concrete pavement). Additionally, 27% of the rural interstate system and 32% of the urban interstate system are classified as rigid (concrete) pavement (19).

HMA overlays of concrete pavement are commonly used nationwide as a rehabilitation alternative, but because of reflection cracking, such overlays are generally recognized as short-term strategies. Other frequently used alternatives include joint replacement, dowel bar retrofit, and, on badly distressed pavements, slab fracturing techniques. The key engineering property that governs the selection of the optimum repair strategy is the load transfer efficiency (LTE) of all joints and cracks. LTE can be measured with existing deflection equipment, such as the falling-weight deflectometer, but this device is slow, cost prohibitive, and sometimes potentially dangerous on high-volume roadways. Consequently, often only a small percentage of joints are tested on current rehabilitation projects. Rehabilitation costs for all concrete pavements are high, and in order to develop long-lasting pavement rehabilitation designs, a device that can rapidly provide 100% coverage of existing joint condition is urgently needed. Quantifying the number and location of poor joints is critical in developing cost-effective rehabilitation strategies.

The team recommends a focused development project to create sensors for a continuous deflection device that can operate at speeds higher than 5 mph and collect load transfer efficiency information. It is proposed that the sensors be designed to be portable so that they can be used with existing

equipment, such as vibratory steel wheel or pneumatic rollers. The proposed device will reduce disruption for the traveling public compared with current evaluation techniques. Additionally, the data generated by this device can be used by designers to develop longer lasting pavement rehabilitation projects, again relating to the “stay out” goal of highway renewal. The team believes that the results from this study can potentially produce a device that can collect data and provide near real-time results more rapidly than currently possible; can be potentially implemented quickly; can effectively address a renewal need because the technology could potentially be applied to many (if not all) pavement renewal projects (especially jointed pavement projects); and can potentially provide significantly higher speed testing than what is available now. The estimated cost of this project is \$225,000.

### **New NDT QA Tools for Ensuring Quality Construction**

The stated goals of “get in, get out, and stay out” of rapid renewal projects can be realistically achieved only if defect-free quality layers are placed that meet the design requirements. Ensuring quality is increasingly difficult, given the fact that a large percentage of renewal projects on high-volume roadways involve around-the-clock or night construction typically under traffic. To achieve the stated goals, it is critical to promote, develop, and implement the latest generation of QA tools. These actions should be high priorities in the SHRP 2 NDT development effort. The tools used to measure quality have changed little in the past 10 years, and few of the existing devices provide 100% coverage.

As a result, the team recommends five projects in this area: four for QA testing of in-place materials and one for acceptance of the quality of materials at the source. Although team members believe that tools to check the quality of production work at the plant are also needed to produce a quality product, they think that more focus should be placed on evaluating the quality of in-place construction, preferably during or immediately after placement. The team believes that the results from these projects can potentially produce methods that collect data and provide results rapidly (possibly in real time); can be implemented quickly, especially because promising technologies and techniques are already available; effectively address renewal needs, especially because the technology could potentially be applied to many (if not all) pavement renewal construction projects; improve the construction quality of such projects; and provide high-speed testing, significantly reducing the need for traffic control or making it unnecessary.

The following five projects are intended to improve the quality of highway construction (i.e., achieve the “stay out” goal of highway renewal).

- A focused development project to further develop technology for measuring smoothness on new portland cement concrete (PCC) pavements in real time during construction with devices that provide approximately 100% coverage. Smoothness of new construction is expected by the traveling public and is the most practical method of measuring the quality of a contractor’s operation. Removing bumps from concrete pavements requires grinding, which is expensive and leaves permanent blemishes. This is a high-priority area for the concrete paving industry, and several prototype devices are under development. The proposed project would be aimed at accelerating the development and implementation of these products. Equipment designed to detect bumps and dips in real time during concrete placement can help contractors minimize, if not eliminate, the need for grinding to smooth out bumps that detract from good ride quality. Diamond grinding adds significantly to the cost of a project, amounting to about \$5 a square yard based on recent construction cost figures. For one 10-foot-long bump over a 12-foot-wide lane, this unit cost translates to about \$67 per bump. Without a method for monitoring the surface profile during concrete placement, the added cost to the project can be significant, depending on the number of bumps that need to be removed over the project lane miles. Thus, a device for early bump detection on concrete pavements can help contractors provide smooth concrete pavements without the cost and surface scars associated with grinding. The estimated cost of this project is \$300,000.
- A demonstration project involving HMA quality measurements using GPR and infrared temperature-measuring technologies. Temperature segregation continues to be a frequently reported defect in new HMA overlays, and such segregation is difficult to detect with traditional techniques during mat placement. Thermally segregated areas result in periodic low-density areas in new mats, which let water enter lower layers, significantly shortening the performance life of new overlay. Real-time NDT procedures are required to provide immediate feedback to paving crews so that corrective action can be taken. Promising studies have shown that infrared technologies can be used to identify segregated layers during paving operations. GPR can also be used to measure in real time the density of HMA layers both during and after compaction. Both technologies can be used to provide approximately 100% coverage of constructed layers, in contrast to other existing technologies, such as nuclear density gauges and electrical impedance devices that take discrete measurements. Although these technologies are not new, little progress has been made in implementing them in construction specifications. Washington DOT is leading the implementation of infrared temperature measurements in construction QA, and no

agencies in the United States have incorporated GPR data collection into their construction specifications. The Finland Road Authority has used GPR for HMA density (20), and this was implemented in 2002 as an accepted method for measuring HMA layer density. The estimated cost of this project is \$150,000.

- A focused development project that would involve the use of seismic techniques (stress wave and wave propagation) to assess the integrity and in-situ strength of concrete pavement and bridge deck repairs for construction QA purposes and for determining when such repairs can be exposed to traffic loading. A key requirement of renewal projects is rapid repair, and one critical issue in the renewal process is to allow traffic on the repaired sections as soon as possible. Existing studies have demonstrated that the concrete stiffness, which is rapidly measured by seismic equipment, is directly correlated to the key engineering properties of concrete. The research team believes that seismic technologies can be used to reliably and expeditiously check the quality of repaired areas to determine when to open those areas to traffic. Although the techniques are not new, such testing has not been incorporated into DOT construction specifications. The estimated cost of this project is \$450,000.
- A demonstration project that advances the application of inertial profilers for smoothness QA testing. Research findings from NCHRP Project 1-31 showed that initial pavement smoothness affects the performance of the as-built pavement (21). For example, a 10% roughness reduction can result in an average increase in pavement life of 5% for asphalt concrete pavements and 7% for PCC pavements. The corresponding projected annual savings for a 1-mile, 6-lane highway over a 20-year design period could be approximately \$3,684 per year; considering that possibly hundreds of lane miles of concrete pavement are placed per year, substantial savings can result. Additionally, test results at WesTrack showed a 4.5% improvement in fuel efficiency for a 10% reduction in roughness (22). Assuming a gasoline consumption rate of 4 miles per gallon for trucks, the 10% reduction in roughness translates to a cost savings of about 5 cents per mile based on \$4 per gallon of diesel fuel. For a truck that travels 50,000 miles a year, this could translate to an annual savings of \$2,500. Considering that there are approximately 2 million such vehicles registered in the United States, the cost savings could be dramatic (19). This proposed project targets three areas: PCC pavements, equipment verification testing, and operator training. The research team believes that these target areas are complementary to recent and ongoing efforts to evaluate the effect of texture on ride quality measurements and to develop reference profilers for equipment verification testing. This project will provide an opportunity to implement results from other research efforts. The estimated cost of this project is \$150,000.

- A focused development project that would further develop field spectroscopy devices (x-ray fluorescence, Raman, and Fourier transform infrared) to “fingerprint” construction materials for source acceptance. These new technologies can rapidly produce a chemical spectra of commonly used construction materials, including asphalts, cements, asphalt emulsions, and paints. Acceptance tests are typically conducted at the beginning of a construction project, and there is no efficient and effective way of monitoring the day-to-day variances of the materials from suppliers. Tests are laboratory based and often take several days to complete. The potential for these new spectroscopy devices is significant, but their capabilities and limitations are unknown. In any case, major evaluation and implementation efforts are under way in other geological and engineering industrial areas. Although these devices may not provide 100% coverage, the team noted that the devices are commercially available and can produce results in real time. They could be a significant benefit to inspectors who need to assess the quality of materials used in construction and can be applicable for all highway infrastructure construction materials. The estimated cost of this project is \$300,000.

### **Interlayer Bonding Between HMA Layers**

To address the need for assessing interlayer bonding between HMA layers, the team recommends an experimental research project concerning NDT to identify delaminations between layers. One stated goal of SHRP 2 is to produce long-life facilities. This goal can only be achieved for pavements if the layers are well constructed and bonded together. Numerous instances have been documented in which a lack of bond between layers has led to major premature pavement distress when the pavement is subjected to shear forces resulting from breaking or cornering actions. Furthermore, in the pavement thickness design process, it is assumed that all the layers are completely bonded together; unbonded or partially bonded layers fail much earlier than designed. Undetected delaminations provide paths for moisture to enter lower layers, accelerating structural failure. Many pavement renewal projects use HMA overlays; layer delaminations on such projects are a serious concern. Tools are also required to define the extent and depth of bonding problems in existing sections so that the appropriate rehabilitation strategy can be determined. The research team is aware of numerous projects in which layer debonding has occurred and resulted in serious performance problems, including an instance at the NCAT test track (23). The team believes that the techniques resulting from this project can potentially produce methods that collect data and provide results rapidly (possibly in real time); can be potentially implemented quickly; effectively address renewal needs because the technology could potentially be applied to many (if not all) pavement renewal construction projects; and could potentially



provide high-speed testing, possibly minimizing traffic control. The estimated cost of this project is \$600,000.

## Establishment of National NDT Calibration and Verification Sites

One major issue with NDT implementation is that a few unsuccessful applications of any particular technology or technique may cause it to be immediately rejected for use in future projects or applications, even though the technology or technique may have promise. For example, personnel at several agencies have been reluctant to use GPR because they have had poor experiences with it in the past. GPR can be used effectively in some situations as long as the advantages and limitations are known by those who use GPR data to make decisions.

To address this concern, to provide areas in which NDT technologies can be developed, and to conduct effective experimental designs for the recommended projects, the team recommends that national NDT calibration and verification sites be established. It is also recommended that a survey of agencies, universities, and research institutions be conducted to identify such sites and to determine their applicability to the proposed research studies. The survey should be conducted under another effort (not necessarily under SHRP 2). For the projects recommended under this study, sites will need to be identified to verify the results of technologies or techniques examined or developed under the research.

The team recommends that a formal network of such sites be established. The FHWA has a Nondestructive Evaluation Center that calibrates and verifies some NDT technologies; Florida DOT is in the process of establishing such a facility;

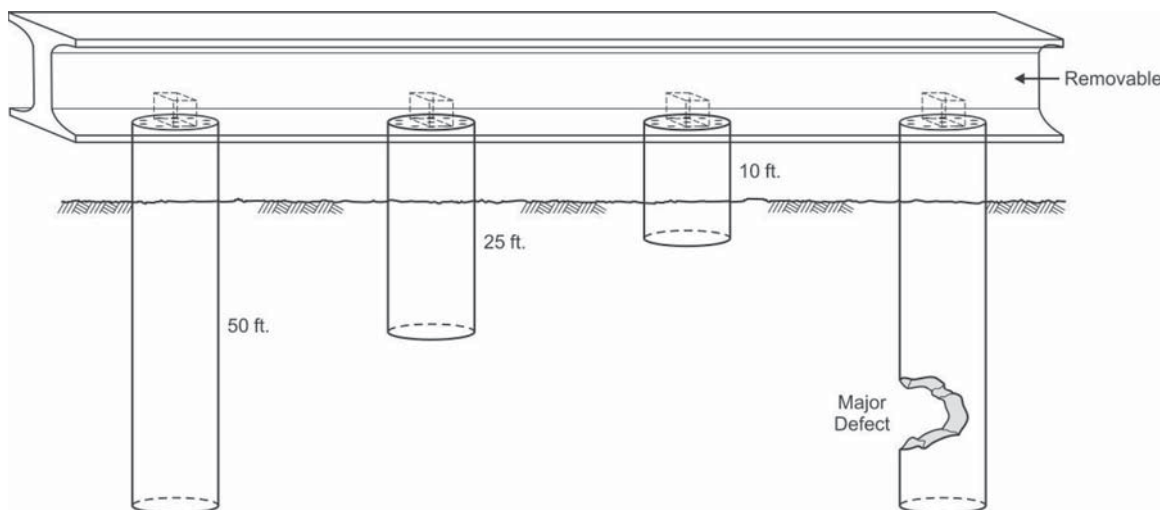
the Texas Transportation Institute has facilities in place for evaluating various technologies, including GPR and pavement profile equipment; the University of Illinois has sites for pavements; and Northwestern University has a site consisting of concrete piles. In Germany the Federal Institute for Materials Research and Testing is in the process of establishing a center for research, validation, and training in NDT for civil engineering applications.

Figures 2 through 9 contain conceptual designs for bridge foundations, HMA pavement, concrete pavement, bridge decks, and retaining walls that the sites would need so that technologies could be evaluated under realistic conditions.

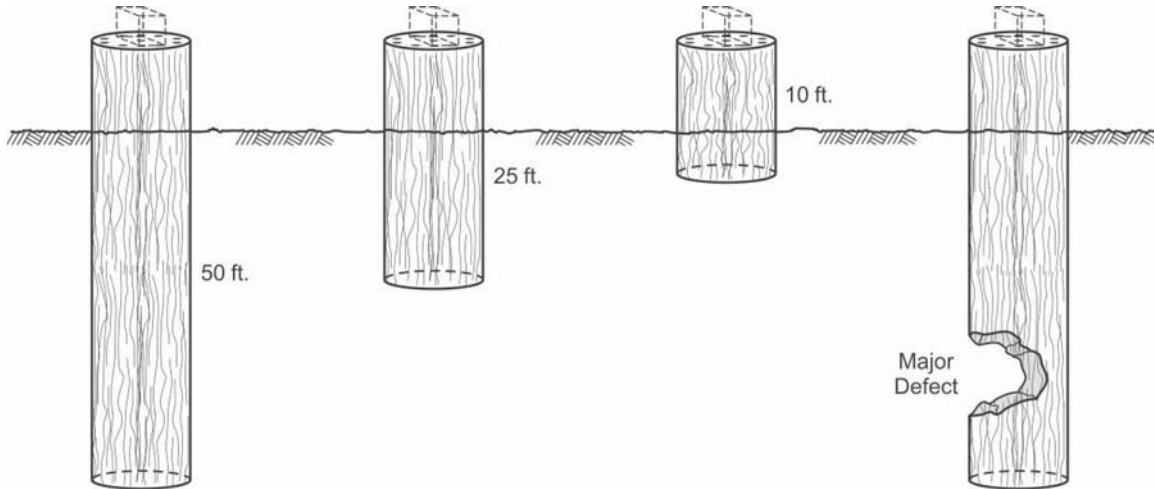
Experts need to be consulted to determine the actual requirements for new sites that can be used by proposed research. The following suggestions are offered concerning the facilities to be constructed at the proposed center.

To verify NDT for bridge foundations, various foundation types consisting of piles with different material properties (timber, steel, and concrete), reinforced concrete drilled shafts, and reinforced concrete spread footings should be constructed. The facility should be set up so that a simulated bridge superstructure could be placed over the foundations. Additionally, the facility should use soils with different known densities, different moisture contents, and different mineralogies (i.e., sand, clay, and silt materials). Voids or defects of various sizes and shapes located at varying depths also need to be established. Figures 2 through 4 show the conceptual diagrams for bridge foundations.

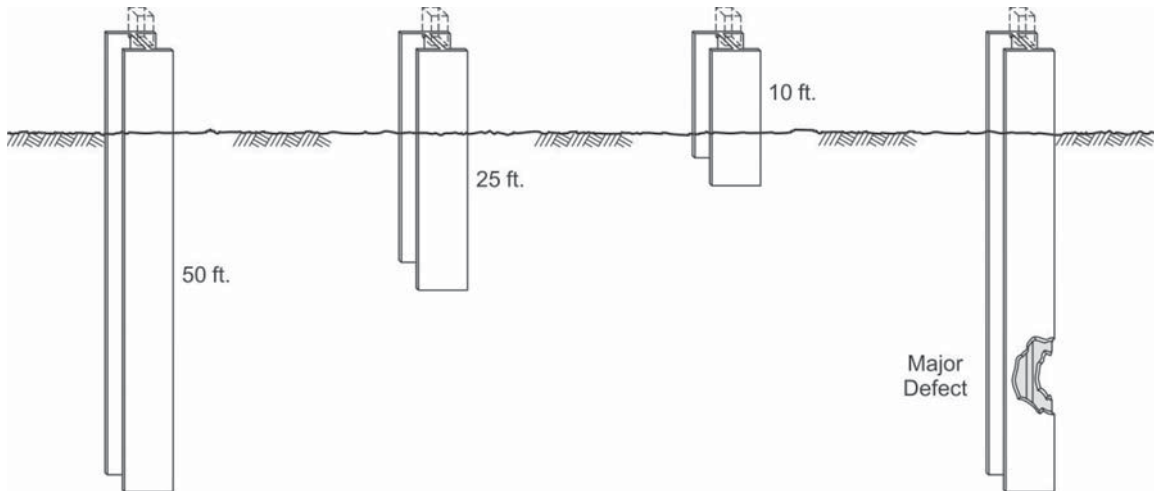
For pavements, both HMA and concrete layers should be constructed with various voids and defects located within the HMA layer, within the concrete layer, and underneath the concrete layer. The concrete layer should contain reinforcing steel in half of the section. Figure 5 shows the conceptual dia-



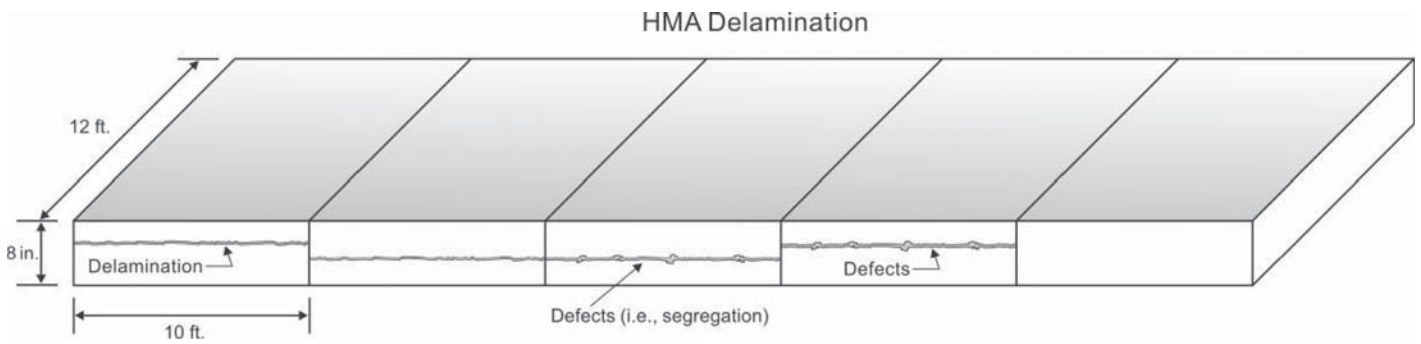
**Figure 2. Conceptual diagram of concrete drilled-shaft foundations to be used for validating unknown foundation NDT technologies. (A. Wimsatt)**



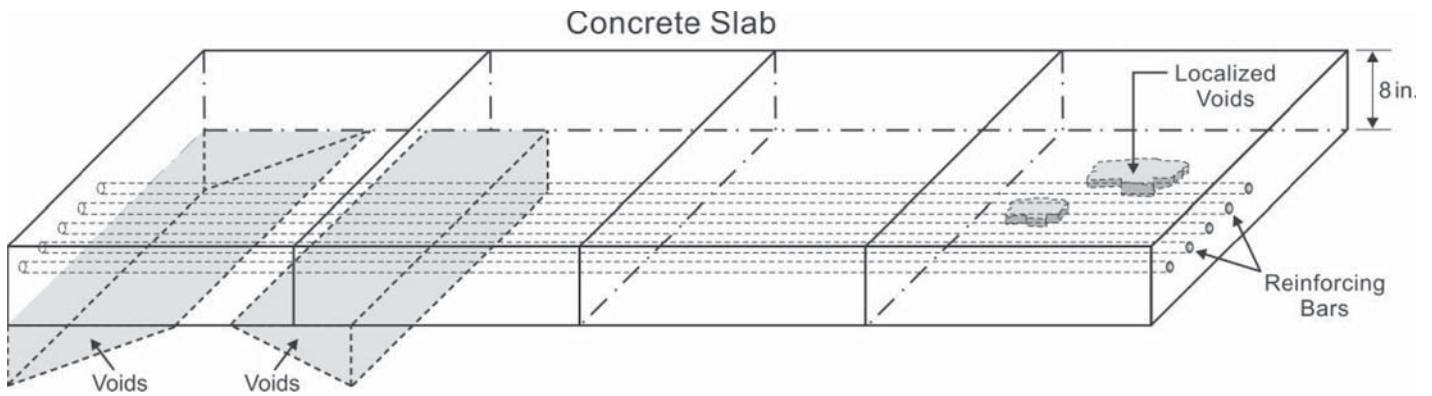
**Figure 3. Conceptual diagram of timber pile foundations to be used for validating unknown foundation NDT technologies. (A. Wimsatt)**



**Figure 4. Conceptual diagram of steel H-pile foundations to be used for validating unknown foundation NDT technologies. (A. Wimsatt)**



**Figure 5. Conceptual diagram of HMA test sections to be used for validating NDT technologies that detect delaminations and defects in HMA layers. (A. Wimsatt)**



**Figure 6. Conceptual diagram of 8-inch-thick concrete pavement test sections to be used for validating NDT technologies that detect voids and defects for concrete pavements. (A. Wimsatt)**

gram for HMA layers. Figures 6 and 7 show the conceptual diagrams for concrete layers.

Figure 8 shows the conceptual diagram for bridge decks. Half the deck should be overlaid with at least 2 inches of HMA. Delaminations should be included to determine if NDT technologies can detect them.

To verify NDT for bridge components, bridge structures should be constructed of various defects with varying depths of reinforcing steel. For example, Pherigo and Pherigo (24) describe “methods used to implant flaws in typical structural materials.”

Figure 9 shows the conceptual diagram for retaining walls. The walls could be placed horizontally (rather than vertically) to reduce the cost of construction; sections should also be easier to place and replace. Voids within and underneath the retaining walls need to be included.

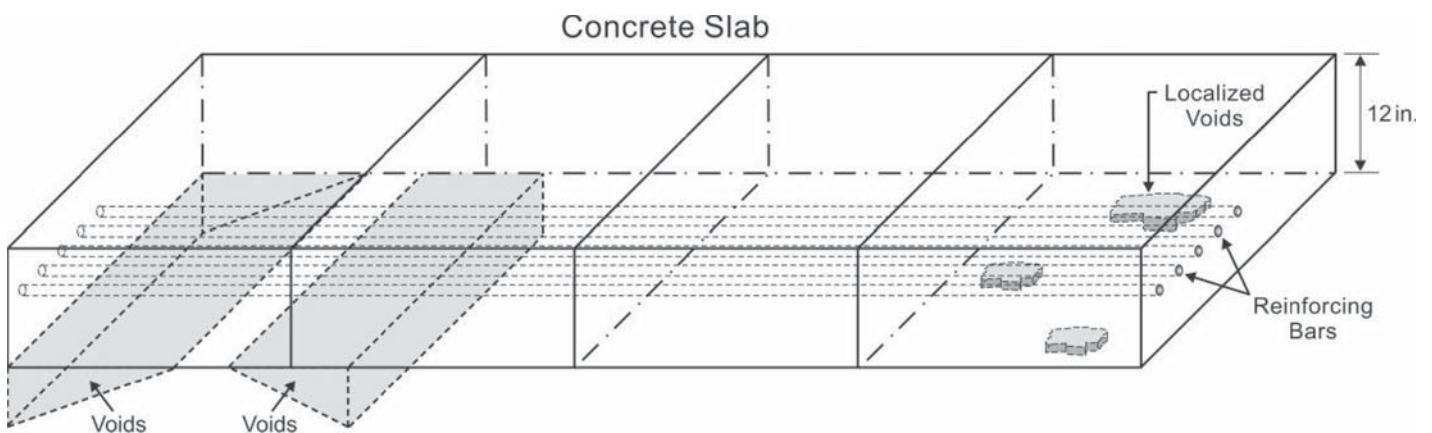
For NDT to be used for tunnels, tunnel segments should be constructed of tunnel liners with various defects (e.g., voids

and honeycombing), varying depths of reinforcing steel, and voids behind the tunnel liners. The segments should have varying geometries to test the effectiveness of tunnel profiling equipment, and ideally, they should be movable to simulate changes in profiles.

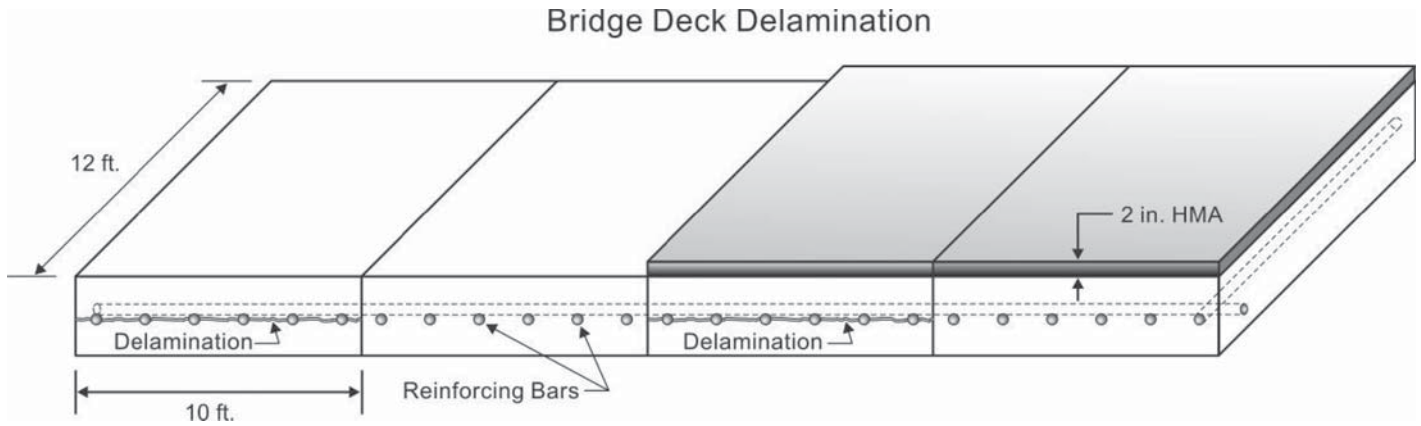
### Experimental Design Criteria

As mentioned in the previous section, the team recommends that national NDT calibration and verification sites be established to conduct effective experiment designs. Some experimental design criteria would be established in constructing new sites. Project-specific criteria would need to be established.

For the recommended experimental and unfulfilled need research projects, the respective SHRP 2 project monitoring committee members should decide on one of the following strategies concerning experimental design criteria:



**Figure 7. Conceptual diagram of 12-inch-thick concrete pavement test sections to be used for validating NDT technologies that detect voids and defects for concrete pavements. (A. Wimsatt)**



**Figure 8. Conceptual diagram of bridge deck sections to be used for validating NDT technologies that detect delaminations in bridge decks. (A. Wimsatt)**

- Establish the criteria in the request for proposals,
- Include a statement in the request for proposals that the proposals need to include experimental design criteria, or
- Require that the criteria be established in the initial phase of the study and be approved by the project monitoring committee.

The respective SHRP 2 committees may need to establish a panel of subject matter experts to determine which strategy is most appropriate for each project. The panel could also establish the criteria or review the recommended criteria.

For example, the committees for NCHRP Projects 21-5 and 21-5(2) that investigated NDT technologies to characterize unknown foundations indicated that the NDT results were not sufficiently accurate or reliable. For the recommended SHRP 2 study on developing NDT for unknown foundations, a panel of subject matter experts including bridge foundation designers, scour experts, and bridge inspectors should agree on the required accuracy and reliability for characterizing such foundations.

It is important to establish the criteria early in the project so that the end users have confidence in the NDT techniques and technologies developed by those projects.

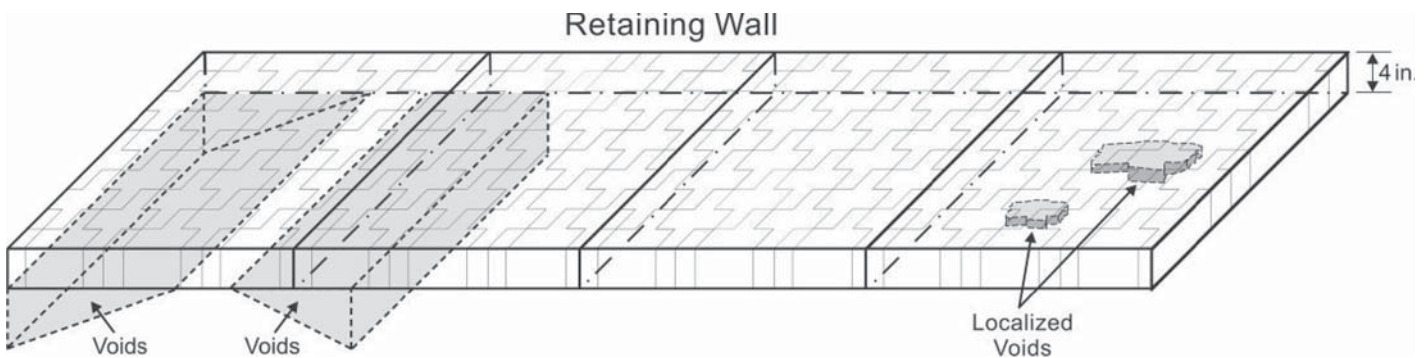
## Recommended NDT Research for All Needs

Prioritized needs with the team's recommendations for all the needs follows. Appendix D contains detailed research problem statements for Priority 1 needs.

### Bridges

#### **Priority 1—Automated Methods of Accurately Profiling Bridges (Performance Monitoring and Construction)**

The team considers this an unfulfilled need. It recommends funding a project to detect movements in structures with profile and video data. The research would address diagnostic activities. The estimated cost of this project is \$975,000.



**Figure 9. Conceptual diagram of retaining wall test sections to be used for validating NDT technologies that detect voids and defects for retaining walls. (A. Wimsatt)**



***Priority 1—Identification of Deterioration of Bridge Decks, Including the Cause of Deterioration (Design, Construction, and Performance Monitoring)***

The team recommends funding focused development research to evaluate and, if necessary, integrate various tools for assessing existing bridge decks. The research would address diagnostic activities. The estimated cost of this project is \$750,000. The following promising technologies were identified to be considered for the research:

- GPR for locating reinforcing steel and possibly onset of alkali silica reactivity (ASR),
- X-ray backscatter,
- Acoustic emission for detecting the noise level generated by debonding of the deck from the girders or deck delamination,
- Air-coupled ultrasound for detecting defects and delaminations, and
- Infrared technologies for detecting delaminations.

The team also recommends a focused development project that would involve the use of seismic techniques (stress wave and wave propagation) to assess the integrity and in-situ strength of concrete pavement and bridge deck repairs for construction QA purposes and for determining when such repairs can be exposed to traffic loading. The research would address diagnostic and QA activities. Although the techniques are not new, such testing has not been incorporated into DOT construction specifications. The estimated cost of this project is \$300,000.

***Priority 1—Foundation Investigation Tools Where Concerns Exist (Design, Construction, and Performance Monitoring)***

The team considers this an unfulfilled need and recommends funding a project to develop and validate unknown foundation NDT technologies. The research would mainly address diagnostic activities, but it could result in addressing construction QA activities. It may be a repeat of the NCHRP 21-5 study with the latest technology. An important part of this project would be to identify the necessary level of accuracy. The estimated cost of this project is \$1,500,000.

The team also recommends funding a demonstration project for gamma-gamma logging and thermal integrity testing to assess the integrity of newly constructed drilled shafts. The research would address QA activities. The estimated cost of this project is \$300,000. The FHWA Central Federal Lands Highway Division has sponsored research concerning drilled-shaft defects. The resulting report documents a study that involved “the development of a basic guideline or ‘roadmap’

that leads the engineer from the initial detected anomalies to the integrity assessment of the drilled-shaft foundations.” Crosshole sonic logging, gamma-gamma logging, and temperature logging are covered in the report (25).

***Priority 2—Detecting Problems at Bridge Approaches, Including Abutments (Design and Performance Monitoring)***

The team recommends funding a GPR demonstration project to address this need. The research would address diagnostic activities. Some DOTs reported poor results with GPR. The project needs to define which equipment to select, address the technology’s limitations, and address how to validate the results.

***Priority 2—Scour Around Bridge Support Systems (Design and Performance Monitoring)***

The team recommends funding an experimental research project to develop real-time scour-monitoring systems. The research would address diagnostic activities. Texas DOT is sponsoring a project at the Texas Transportation Institute titled “Real-Time Monitoring of Scour Events Using Remote Monitoring Technology,” so the results of that study should be reviewed before this project is funded (26).

***Priority 2—Reinforcing Steel Corrosion (Design and Performance Monitoring)***

The team recommends funding experimental research to identify and integrate various tools for addressing this need. The research would address diagnostic activities. The following promising technologies were identified to be considered for the research:

- Measure electrical resistance across the structural elements to monitor the progression of corrosion,
- Network analysis of electrical resistivity and capacitance for reinforcing bar networks,
- X-ray backscatter, and
- Magnetoresistive sensor technology.

***Priority 2—Early Detection of Concrete Deterioration Mechanisms (Design and Performance Monitoring)***

The team recommends funding experimental research to identify and integrate various tools for addressing this need. The research would address diagnostic activities. The following promising technologies were identified to be considered for the research:

- GPR (most deterioration mechanisms are impacted by moisture ingress [gel or ettringite formation] that could potentially be detected by GPR);
- Nonlinear ultrasound (hardware and software development is needed); and
- Air-coupled ultrasound to detect defects and delaminations.

### ***Priority 3—Global Testing of Bridge Structures to Identify Deficiencies in the Structures (Design and Performance Monitoring)***

The team recommends funding a demonstration project involving modal (vibration) analysis using traffic for excitation if problems are suspected. The research would address diagnostic activities. The method would be applied to bridges that appear to be moving.

### ***Priority 3—Identification of Fatigue and Fracture Damage in Structural Elements (Design and Performance Monitoring)***

The team recommends funding a demonstration project that involves ultrasonic scanning. Such a technique would be used if other methods detect a problem with a particular structural element. The research would address diagnostic activities. The FHWA announced the launch of a steel bridge testing program in September 2007 that appears to be addressing this need for steel bridge elements (27).

### ***Priority 3—Corrosion of Steel Elements for Steel Bridges (Design and Performance Monitoring)***

The team recommends funding an experimental project to measure electrical resistance across the structural elements to monitor the progression of corrosion. The research would address diagnostic activities. As mentioned earlier, the FHWA announced the launch of a steel bridge testing program in September 2007 that appears to be addressing this need for steel bridge elements (27).

## **Pavements**

### ***Priority 1—Continuous Deflection Device at the Highest Possible Speed (Design and Performance Monitoring)***

The team recommends funding a focused development project to develop sensors for a continuous deflection device that can operate at speeds higher than 5 mph and collect load transfer efficiency information. The research would address diagnostic activities. The estimated cost of this project is \$225,000.

### ***Priority 1—New Nondestructive QA Tools for Ensuring Quality Construction (Construction)***

The team recommends the following projects to address this need. All projects would deal with QA activities.

- A focused development project to further develop technology for measuring smoothness on new PCC pavements in real time during construction with devices that provide approximately 100% coverage. The estimated cost of this project is \$300,000.
- A demonstration project involving HMA quality measurements using GPR and infrared temperature-measuring technologies. Infrared technologies can be used to identify segregated layers immediately after paving operations. GPR can be used to measure the density of HMA layers. Both technologies can be used to provide approximately 100% coverage of constructed layers. Although the technologies are not new, apparently Washington DOT is the only agency in the United States that uses infrared temperature measurements in construction specifications, and no agencies in the United States have incorporated GPR data analysis results into construction specifications. Finland has used GPR for measuring HMA density (20). The estimated cost of this project is \$150,000.
- A focused development project that would involve the use of seismic techniques (stress wave and wave propagation) to assess the integrity and in-situ strength of concrete pavement and bridge deck repairs for construction QA purposes and for determining when such repairs can be exposed to traffic loading. Although the techniques are not new, such testing has not been incorporated into construction specifications. The estimated cost of this project is \$450,000.
- A demonstration project that advances the application of inertial profilers for smoothness QA testing. Several agencies have not implemented the technology for QA purposes. The estimated cost of this project is \$150,000.
- A focused development project that would further develop field spectroscopy devices to “fingerprint” construction materials for construction QA purposes. Although these devices may not provide 100% coverage, the team noted that the devices are commercially available and can produce results in real time. They could be a significant benefit to construction inspectors who need to assess the quality of materials used in construction and can be applicable for all highway infrastructure construction materials. The estimated cost of this project is \$300,000.

### ***Priority 1—Interlayer Bonding (Design, Construction, and Performance Monitoring)***

The team recommends funding an experimental research project for evaluating technologies that can identify delaminations

between HMA layers. The research would address diagnostic and QA activities. The estimated cost of this project is \$600,000. The following promising technologies were identified to be considered for the research:

- GPR,
- Acoustic emission,
- Air-coupled ultrasound, and
- Portable seismic pavement analyzer (PSPA).

### ***Priority 2—Layer Material Properties (Design, Construction, and Performance Monitoring)***

The team recommends funding an experimental research project that merges technologies such as GPR, air-coupled ultrasound, and seismic techniques such as the PSPA for determining layer material properties. The research would address diagnostic and QA activities.

### ***Priority 2—Distress Measurements (Design and Performance Monitoring)***

The team recommends funding a demonstration project using various automated distress measurement techniques to determine if the technology could be an effective replacement for human visual distress raters. The research would address diagnostic activities.

### ***Priority 2—Layer Thicknesses (Design, Construction, and Performance Monitoring)***

The team recommends funding a project to demonstrate the application of GPR for determining layer thicknesses. The research would address diagnostic and QA activities. An ASTM specification exists for this application. Much of the work has already been completed, but there is limited success on concrete pavement, and many DOTs have been disappointed with this technology application.

The team also recommends funding a development project for air-coupled ultrasound for determining layer thicknesses. This technology could be used when GPR cannot detect layer thicknesses.

### ***Priority 2—Early Detection of Concrete Deterioration Mechanisms (Design and Performance Monitoring)***

The team recommends funding an experimental research project to evaluate and integrate various tools to address this need. The research would address diagnostic activities. The following promising technologies were identified to be considered for the research:

- GPR (most deterioration mechanisms are impacted by moisture ingress [gel or ettringite formation] that could potentially be detected by GPR);
- Nonlinear ultrasound (hardware and software development is needed); and
- Air-coupled ultrasound to detect defects and delaminations.

### ***Priority 2—Performance Monitoring of Profiles of Riding Quality and Dynamic Loads (Performance Monitoring)***

The team recommends funding a focused development project to generate improved methods to measure profiles using existing inertial profiler equipment (i.e., reduce the effect of textured pavements on measured International Roughness Index measurements). The research would address diagnostic activities.

### ***Priority 3—Pavement Surface Properties for Safety and Noise Issues (Design, Construction, and Performance Monitoring)***

The team recommends funding a focused development project for laser-based systems to address this need. The research would address diagnostic activities. Work has been done in the past, but considerable advances have been made in laser technology. Several DOTs have experimented with the new lasers, and it appears that they can be effectively used for this purpose.

### ***Priority 3—Plant QA (Construction)***

The team recommends funding an experimental research project to demonstrate the applications of various tools with a view toward generating an integrated QA package for plants. The research would address QA activities and could also apply to all highway infrastructure construction materials. The following promising technologies were identified to be considered for the research:

- GPR to monitor moisture on belt feeds, asphalt content measurements of loose material in the truck, density, and so on;
- Imaging systems;
- Infrared technology for monitoring temperature at the plant; and
- Field spectroscopy devices to “fingerprint” asphalt and emulsions and possibly to indicate the amount of aging induced at the batch plant.

Additionally, the research should consider the recommendations concerning HMA concrete production in West (10).

Although team members believe that tools to check the quality of production work at the plant are also needed to produce a quality product, they believe that more focus should be placed on evaluating the quality of in-place construction.

### ***Priority 3—Identification of Problematic Soils (Design and Construction)***

The team considers this an unfulfilled need and recommends funding a project to develop NDT methods to measure stabilizer content and ensure uniform application. The research would address diagnostic activities. No known equipment exists, but resistivity or absorption spectra may have potential for addressing this need.

## **Earthworks**

### ***Priority 1—Better NDT Tools for Mapping Projects (Design)***

The team recommends that a demonstration project on resistivity mapping be considered for SHRP 2 funding. The research would address diagnostic activities. This technique is used by Minnesota and Florida DOTs for geotechnical investigations; Texas DOT is also investigating this technology. It could also be applicable for pavement and bridge foundation design purposes. The estimated cost of this project is \$225,000.

### ***Priority 1—Validation Tools for QA (Construction)***

The team recommends funding a focused development project to implement intelligent compaction technology. The research would address QA activities. The team recommends that SHRP 2 coordinate with the FHWA because that agency is leading a national pooled-fund study concerning this issue. Minnesota DOT is sponsoring a research project with Iowa State University concerning this technology; Texas DOT has also sponsored research in this area at the Texas Transportation Institute. There is much interest in this technology, although there is uncertainty about what it actually measures. There is also a need for improved mechanics models to interpret the data collected from this technology. The estimated cost of this project is \$750,000.

### ***Priority 2—Earthwork Performance Monitoring (Performance Monitoring)***

The team recommends that early detection of movement using laser or acoustic technology and targets would be the most appropriate technology to consider for SHRP 2 funding. The research would address diagnostic activities.

## **Tunnels**

### ***Priority 1—Changes in Profile over Time (Performance Monitoring)***

To address this need, the team recommends a two-part project: a demonstration project on mapping changes in tunnel profiles over time using technology identified in Europe and Japan and, if necessary, a focused development project to adapt the European and Japanese technologies in the United States. For example, Krieger and Friebe (28) described a laser system that was being developed to scan tunnels in Germany.

The research would address diagnostic activities. The estimated cost of this project is \$900,000.

### ***Priority 1—Mapping Voids, Bonding, and Moisture Behind or Within Tunnel Linings (Design and Performance Monitoring)***

The team considers this an unfulfilled need and recommends funding a project to develop technology that can map voids, bonding, and moisture behind tunnel linings and retaining walls. The research would address diagnostic activities. The estimated cost of this project is \$1,800,000.

### ***Priority 2—Deterioration of Tunnel Linings (Design and Performance Monitoring)***

The team recommends funding an experimental research project to evaluate and integrate NDT methods that can detect chemical deterioration such as alkali silica reactivity (ASR), delayed ettringite formation (DEF), and external sulfate attack. The research would address diagnostic activities. Because most of these deterioration mechanisms involve moisture intrusion in concrete, the team thought that GPR could have potential for addressing this need.

### ***Priority 3—QA of Tunnel Components (Construction)***

The team recommends funding a demonstration project involving the use of GPR for measuring thickness of tunnel linings and placement of reinforcing steel. The research would address QA activities.

## **Other Structures**

### ***Priority 1—Mapping Voids, Bonding, and Moisture Behind Retaining Walls (Design and Performance Monitoring)***

Because this is considered an unfulfilled need, the team recommends funding a project to develop technology that can

map voids, bonding, and moisture behind or within tunnel linings and retaining walls, as mentioned earlier. The research would address diagnostic activities.

## Other Considerations

After the recommended research is completed, the team suggests that individual NDT technologies that are installed in moving vehicles be integrated into one vehicle, if possible. In this regard, Texas DOT issued a request for proposal to integrate nondestructive testing devices in a single vehicle that can measure pavement thickness, stiffness, stability, and uniformity as well as obtain right-of-way images, pavement surface images, and precise location data of pavement layers. The request for proposal indicates that remote digital display, GPR, video imaging, and global positioning system technologies should be integrated into such a vehicle (29). Additionally, the FHWA has developed a digital highway measurement van that integrates several technologies to measure horizontal and vertical alignments of the roadway, collect data to develop detailed cross sections, collect roadway and roadside

video from two stereoscopic digital cameras, measure longitudinal texture and roughness in each vehicle wheel path and at the vehicle's center, and continuously measure road surface temperature (30).

Successful implementation of any NDT technology involves obtaining upper management support within the DOTs, continuous communication between NDT developers and users, extensive training, and technology transfer. The team noted that DOTs involved in implementing NDT technologies had at least one employee dedicated to the technology or technologies.

In many instances NDT implementation is more challenging than the original development. Implementation certainly may require a different set of skills than the science and engineering required to develop and prototype equipment. It involves working within organizations, establishing specifications, providing training, setting goals, documenting benefits, and establishing overall good communication channels within the agency and externally with contractors and trade organizations. These considerations need to be addressed effectively if any NDT is to be implemented successfully.



## A P P E N D I X A

# Nondestructive Testing Technologies and Techniques at the Federal Highway Administration Nondestructive Evaluation Center

### Federal Highway Administration Nondestructive Evaluation Center

The following list and brief description of nondestructive testing (NDT) technologies and techniques were presented during the researchers' visit to the Federal Highway Administration (FHWA) Nondestructive Evaluation Validation Center on October 22, 2007. Frank Jalinoos provided summary information on these technologies and techniques, which is included in this appendix; the second Strategic Highway Research Program (SHRP 2) R06 team reviewed this information.

#### NDT Technologies and Techniques

Handheld technician-driven systems for inspection of in-service bridges:

- Ultrasonic testing for pin inspection, penetration weld inspections, length measurements, and thickness measurements;
- Eddy current for detecting near-surface defects through paint;
- Ground-penetrating radar (GPR) for detecting thickness location, reinforcement location, and depth of cover in concrete;
- Impact echo for detecting defect depths;
- Ultrasonic pulse velocity; and
- Infrared thermography to indicate deteriorated areas.

Automated ultrasonic testing for fabrication inspection of welds in steel girders. The center is evaluating this technology as a possible replacement for radiographic testing that is used for fabrication inspection of butt-welds in steel bridges.

Infrared deck inspection system to detect delaminated areas in bridge decks.

Impulse response to evaluate concrete slabs.

A high-accuracy laser system to measure the deflection of bridge girders in the field as well as movements and deformations of structural objects in the laboratory.

Chloride detection in concrete based on prompt gamma neutron activation.

Concrete resistivity measurement to give an indication of corrosion of concrete reinforcement and to assess concrete permeability.

Crack detection in steel bridges using phased array ultrasonics, meandering winding magnetometer eddy current array, electrochemical fatigue sensor, acoustic emissions, and eddy current.

Detecting delaminations in concrete bridge decks using GPR, impact echo, equipotential half-cell, and infrared thermography.

Detection of dowel bar corrosion in concrete using GPR.

Application of x-ray computed tomography to concrete and asphalt specimens in the laboratory.

#### Other Information

Frank Jalinoos provided other information that did not directly relate to this study but was interesting. Summaries are included in this appendix on the following topics:







- Development of nonlinear bridge models for nondestructive evaluation and structural health monitoring (SHM) analyses
- Analysis of wind- and rain-induced vibration in Fred Hartman Bridge, Texas
- Smart Systems, nonlinear finite element (NLFE) bridge model simulations and chaos theory analysis applied to highway bridges



Nondestructive Evaluation Center  
Federal Highway Administration

## Comparison of NDE Methods

### Hand-Held Technician-Driven Systems

Method	Advantages	Limitations
<b>Ultrasonic Testing (UT)</b> 	UT makes use of mechanical vibrations similar to sound waves but of higher frequency. Used for pin inspection, penetration welds (plate girder flanges, circumferential welds in pipe, etc.), length and thickness measurements.	Surface condition critical. Permanent record has limited value.
<b>Eddy Current (EC)</b> 	Can detect near-surface defects through paint.	Magnetic properties of weld material can influence results. Orientation of probe during scanning can effect results.
<b>Ground Penetrating Radar</b> 	A technique that utilizes electromagnetic waves to interrogate concrete and other non-ferrous materials. Detection of embedded metals and thickness of materials is possible. Mapping of reinforcement location and depth of cover.	Testing equipment is fairly expensive and a trained operator is required. Interpretation of images requires training.
<b>Impact Echo (IE)</b> 	Access to only one side of the structure is needed, and it gives information on the depth of the defect.	Not commercially available and an experienced operator is needed. It is applicable to only a limited member thickness.
<b>Ultrasonic Pulse Velocity (UPV)</b> 	Portable equipment that is easy to use.	For testing, access to both sides is needed. No information on the depth of a defect is provided.
<b>Infrared Thermography</b> 	A global technique that covers greater areas than other test methods, making it cost effective. Provides an indication of the percentage of deteriorated area in a surveyed region.	Testing equipment is expensive. The proper environmental conditions are required for testing. Anomalies are difficult to detect the deeper they are in the concrete. Trained operators are needed to ensure proper data interpretation.



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# Automated Ultrasonic Testing (AUT)

## Fabrication Inspection of Welds in Steel Girders

### Background – Butt-Welds

Butt-welds are generally used on a joint between two members aligned in the same plane.



### Welding Process

- Can introduce internal defects, or discontinuities that are not observable by visual inspection
- Discontinuities can reduce the strength of the weld and act as fatigue crack initiation sites
- Discontinuities can be described as:
  - Volumetric (i.e. slag inclusions or porosity)
  - Planar (i.e. cracks or lack-of-fusion)

### Inspection of Welds at Fabrication Shop

- Inspection identifies internal discontinuities
- Inspection determines severity of discontinuity so that significant discontinuities can be repaired during the fabrication process

### Current State-of-the-Practice

- Radiographic Testing (RT) provides hard-copy radiograph of weld
  - Causes health hazard shielding is required to protect workers
  - Does not provide depth information
- Conventional ultrasonic testing (UT) is used to complement RT to determine depth of defect
- Fracture Critical Members (FCM) must be inspected by both RT and UT (AASHTO/AWS D1.5M/D1.5:2002 of Bridge Welding Code)



### Objectives

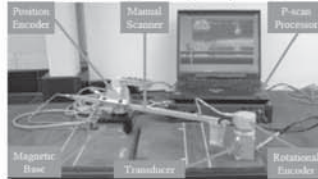
- Assess feasibility of AUT as a replacement for RT for the fabrication inspection of butt-welds in steel bridges

#### Concerns:

- Does AUT provide equivalent or improved inspection results relative to RT?
- Does UT procedure described in the AASHTO/AWS Code apply to AUT?
- Is it feasible to use AUT in a shop environment?
- Does AUT provide an effective quality control tool?
- Is AUT equipment or training cost effective?

### AUT (Projection Imaging Scanning (P-Scan)) System

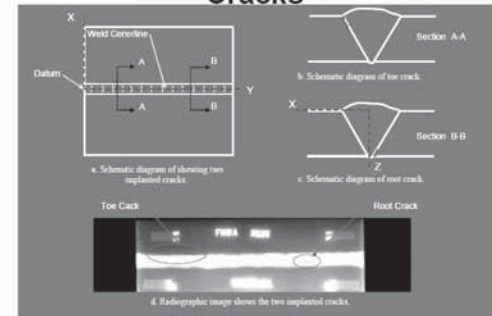
- AUT is a computer-controlled UT and analysis system
- AUT records transducer position and characteristics of signal
- AUT permanently archives raw and processed data
- AUT displays ultrasonic data on a graph with 3 dimensions (X, Y positions and amplitude of received signal in color)
- AUT creates "Images" of detected discontinuities on 3 perpendicular projection planes (C-scan, B-scan, D-scan)
- AUT "Images" reveal severity, X and Y positions, length, depth and orientation of discontinuities
- AUT "Images" show the extent of the area inspected, providing evidence that a weld has been fully inspected



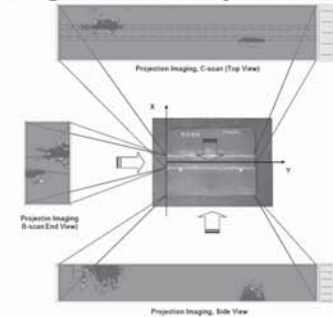
### Future Direction

- AUT equipped with robotic scanner and phased array

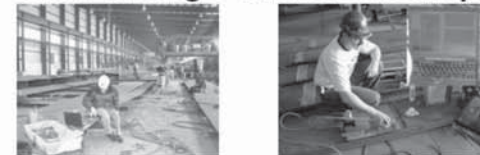
### Butt-Welded Plate with Implanted Cracks



### AUT Images on 3-Projection Planes



### Field Testing – Fabrication Shop

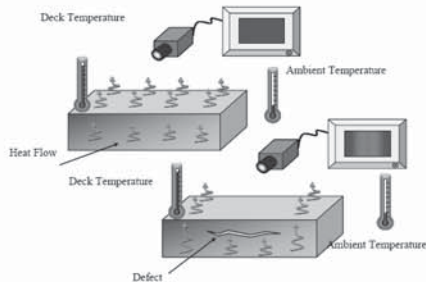


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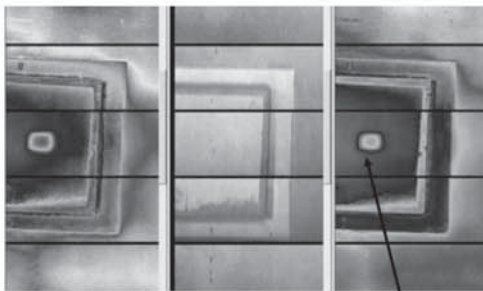
# Infrared Deck Inspection System



LW IR

Video

SW IR



Simulated Defect

## Principles

- The NDE Center Infrared (IR) deck inspection system is a custom-designed tool that measures bridge decks to detect delaminated areas. The system is designed primarily for fiber reinforced polymer (FRP) deck overlays or steel deck overlays. The instrument uses thermal cameras to take images of a bridge deck in order to determine defect areas. Here heat will flow different in a deck in sound areas as opposed to areas with a defect.
- The NDE Center IR system is unique in that it automatically captures full digital IR and video data in a structured and formatted manner based on measurement vehicle position. Here all records are stored in a system database for automatic presentation.

### System Features:

- Automated operation
- Dual IR camera data collection
- Video collection
- Data capture with position reference
- Data stored in system database

## Applications

The NDE Center is used for the following types of bridge decks:

- Bare concrete
- Steel deck with wearing surface
- FRP deck with wearing surface

## Advantages

- Automatic data collection and storage
- System database of all test data
- Easy-to-interpret presentation of data

## Limitations

- Best suited to thin material surfaces
- Highly dependant on environmental conditions
- Only near-surface defects measurable



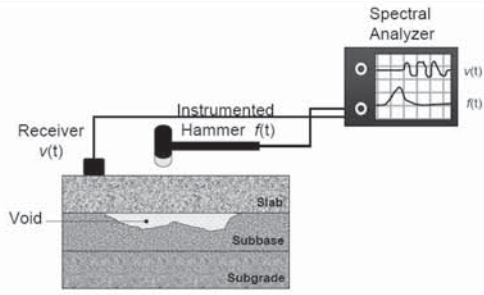
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# Impulse Response (IR) Evaluation of Concrete Slabs

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## Principles of IR

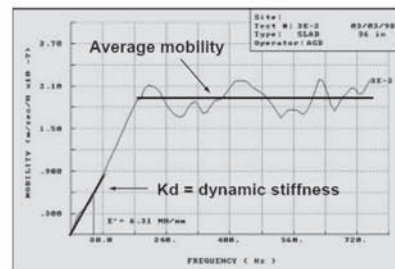
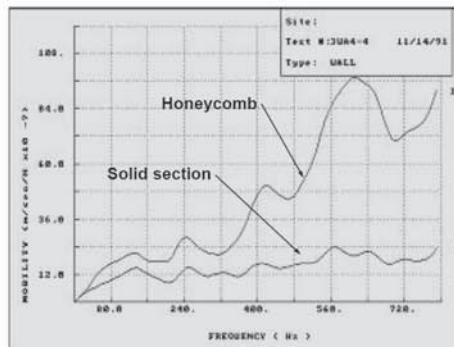
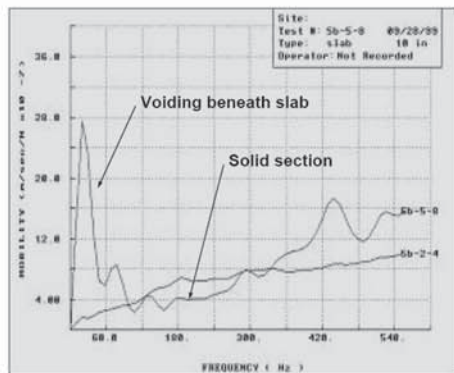
- Impulse Response (IR) is a nondestructive testing technique in which mobility of the test structure is measured. Slab IR is used primarily to identify poor support condition zones below pavements, and to map out the extent of the voids. It is also able to evaluate the effectiveness of repairs to the slab-subgrade, by comparing test results before and after repairs are made. The pavements can be either concrete or asphalt, with or without reinforcement.
- To perform an impulse-response test, an operator strikes the surface being tested with an instrumented hammer, generating a stress pulse with a wide range of frequencies. A soft rubber-tipped hammer generates frequencies up to 1,000 Hz, and a metal-tipped hammer generates frequencies up to 3,000 Hz. A geophone (receiver) near the point of impact measures the vibrations of the structure.



GI S'Mash System

## Typical Procedures

- A plot of the geophone particle velocity divided by the hammer vibration force ( $v/f$ ), known as mobility, versus frequency is used to assess the condition of the structure. The signals from the hammer and the geophone are sent to the screen and the data is processed in the field using the FFT (Fast Fourier Transform) algorithm.
- A typical test plot can be divided into two portions:
  - Low frequencies (less than 100 Hz): The initial linear portion of the plot (0 to 50 Hz) yields the slope or the compliance. Its inverse is the dynamic stiffness. This is a property of the structure-soil composite. It can be used to assess the structure on a comparative basis and to establish uniformity.
  - High frequencies (greater than 100 Hz): When testing piles, this portion of the plot represents their longitudinal resonance and is a function of shaft length and the degree of toe anchorage. The relative amplitude is a function of lateral soil damping. When testing a plate element, the mean mobility (from 100 to 1,000 Hz) is related to the density and thickness of the element. Cracking or honeycombing in the element will decrease the stability of the mobility plot from 50 to 1,000 Hz, reducing damping of the signal. If delaminations or voids are present, there will be an increase in the ratio of peak mobility to average mobility.
- The hammer impact generates only a small amount of energy. Soil damping limits the depth where useful information can be obtained for both piles and pavements. For slabs with a thickness greater than 0.6 m (2 feet), data interpretation becomes difficult. The stiffness of the system is controlled by the pavement and not by the support under the slab. However even if the high frequency response is not present, the dynamic stiffness can be used to assess the structure.

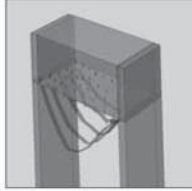


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## Laser System



Laser System Measuring  
Full-Sized Steel Bridge Girders



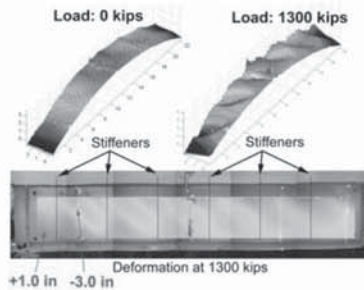
FHWA Curved Girder Bridge  
FHWC Structures Laboratory



Laser Scanner  
Mounted on Lab Wall



Operator Workstation



Deformation at 1300 kips  
+1.0 in -3.0 in



## Principles

- The NDE Center Laser System is a three-dimensional (3D) optical coordinate measurement machine. This instrument has a unique combination of both high-accuracy measurements and a large measurement volume. The instrument specifications are unmatched in any other commercial system.
- The system is a non-contact laser scanner that does not require a special target. A mechanical scanner directs a laser beam to the portion of the structure to be measured allowing multiple points to be measured from one instrument location. A full three-dimension coordinate for a measurement is obtained from the laser range measurement and two position measurements of the mechanical scanner. The system uses a frequency modulated laser signal that makes the system immune to ambient lighting conditions. The laser modulation also allows measurements on a variety of surface conditions directly without a special target. Measurements can be made directly on common structural materials such as painted steel, bare or weathering steel, and concrete.

### Key Specifications:

- Volume: 100-ft radius
- Accuracy: 0.0039-in at 32.8-ft (0.0094-in at 78.7-ft)

## Applications

- The NDE Center Laser System has been used to measure the deflection of bridge girders in the field. It is also used as a tool in a large structural laboratory to measure complex movements and deformations of structural objects Bare concrete
- Bridge Load Testing
- Can measure deflections with minimal setup time and with little disruption to traffic
- Long term bridge movement
- Laboratory structural testing

## Advantages

- High-resolution measurements over a large volume
- Non-contact measurements
- Mobile system

## Limitations

- 100-foot measurement range
- Line-of-sight measurements
- Cost of equipment



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# Laser System

## Deflection / Displacement Measurement

### FHWA NDE Center Laser System

- Portable laser scanning system capable of measuring displacement or deflection of a structure
- Computer controlled scanning system
- Range is between 7 to 98 feet
- Rapid measurement (100 readings per minute)
- Sub-millimeter accuracy
- Requires no special target or surface preparation
- Can be used in steel or concrete bridges
- Commercially available

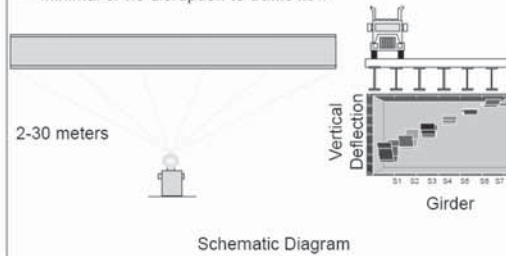


### Applications

- Measurement system for bridge load testing
- Rapid measurement of the 3D deflection response of a bridge loaded by a heavy truck
- Quantitatively measures if any part of the bridge has moved since the last time the bridge was scanned

### Bridge Load Testing

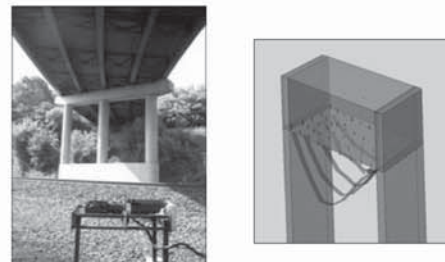
- Remote or non-contact deflection/displacement measurement
- Measure deflection of bridge due to traffic loads
- Minimal or no disruption to traffic flow



### Field Testing



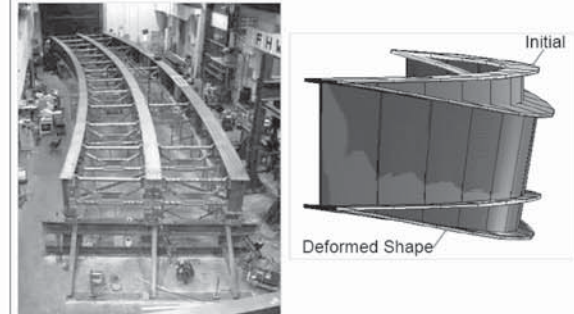
Concrete bridge over Clara Barton Parkway, Carderock, MD



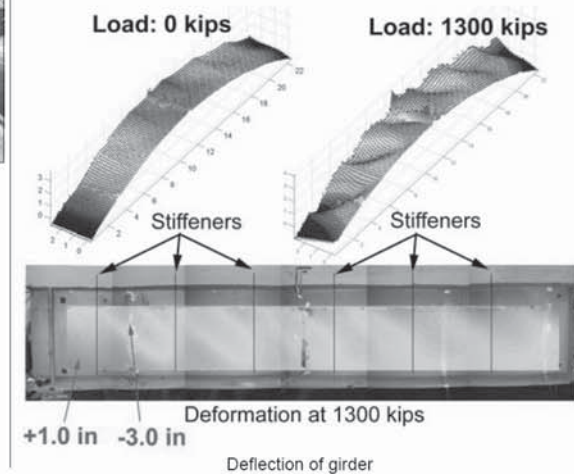
5-Girder steel bridge loaded at mid-span with two load trucks

### Laboratory Load Testing

- Laser was utilized on indoor full-scale curved girder bridge prototype to measure deflection and buckling of the component girder



TFHRC's Structural Laboratory curved girder testing project

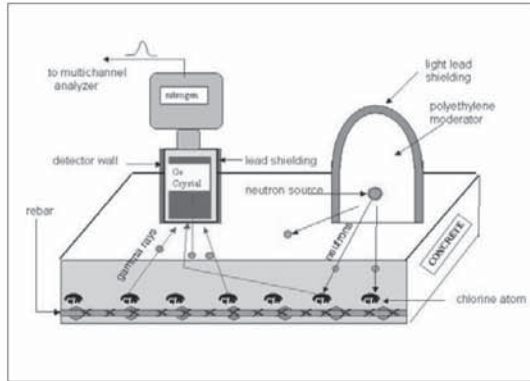


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# Chloride Detector Based on Prompt Gamma Neutron Activation

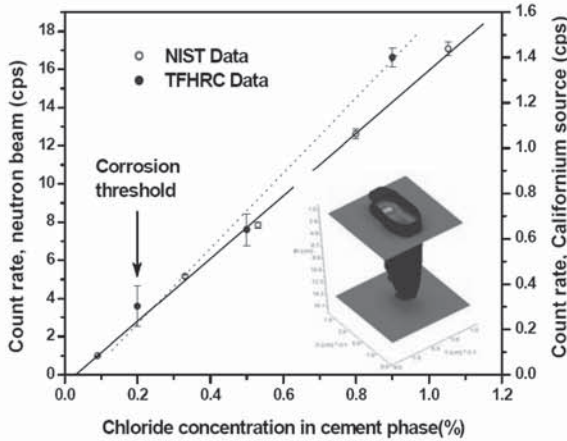


Schematic diagram of neutron-based chloride measurement system

## System Operation

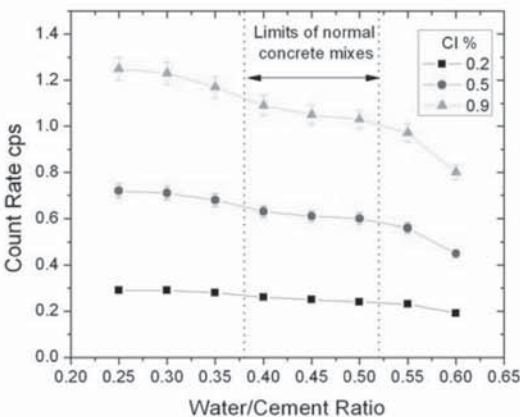
In prompt gamma neutron activation (PGNA), neutrons are captured by nuclei in the target and gamma-rays of characteristic energy are emitted. The reaction  $^{35}\text{Cl}(n, \gamma)^{36}\text{Cl}$  is especially useful because of its large neutron capture cross-section which is 33.2 barns and also because of the emission of several gamma rays covering a wide range of energies

The  $^{252}\text{Cf}$  radioisotope neutron source generates fast neutrons with typical energies in the 1-5 MeV range (Fig 2), while PGNA requires thermal neutrons ( $2.57 \times 10^{-8}$  MeV). Therefore it is necessary to use a moderator to slow down the neutrons. Moderator design for field applications is not yet an exact science. Ideally, the moderator should maximize the delivery of thermal neutrons to the target while minimizing losses due to capture, and at the same time minimizing the radiation exposure to the operators. The moderator design currently used was developed with MCNP simulations (see below) and consists of a solid cylinder of polyethylene 15 cm in radius with a hemispherical end cap.



## Calibration

The system was calibrated in two stages. First, the detector itself was calibrated using the PGNA setup at the NIST Center for Neutron Research. Very samples of sodium chloride were placed in the reactor-generated cold neutron beam, and the detector was used to measure the resulting gamma-ray spectrum. In the second stage, the system including the  $^{252}\text{Cf}$  neutron source was used to measure the chloride in mortar test slabs prepared at TFHRC. As shown in the figure, both stages yielded a very linear calibration function and both had a detectable signal at the threshold for corrosion. However, the count rates are very different, reflecting the differences in neutron sources and the geometry of the experiment



## Numerical Simulations

In order to better understand the effect of various parameters on the performance of the system, numerical simulations have been carried out using the MCNP (Monte Carlo N-Particle) code originally developed for nuclear weapons by Los Alamos National Lab. This is used to determine the neutron numbers and energies in the moderator and the concrete. The transport of the emitted gamma-rays is then modeled using conventional optical ray tracing methods. The figure on the left below is the sampled volume, defined as the contour within which 99% of the detected gamma rays originate. The graph on the right shows the effect of water/cement ratio of the detected chloride signal. The water content of the concrete acts as both an absorber and moderator of neutrons, but over the range of normal w/c ratios, the variation is negligible.



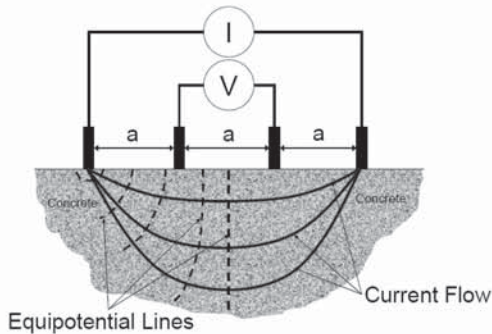
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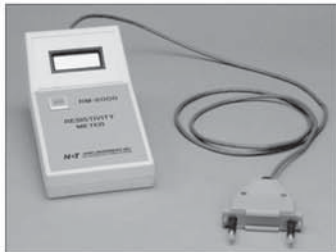
# Concrete Resistivity



Equipotential Lines  
**4-point Wenner Resistivity Apparatus**



**Corvib RESI  
Resistivity Meter**



**NDT James RM-8000  
Resistivity Meter**

## Principles of Resistivity

- The electrical resistance of concrete, which depends on the microstructure of the paste, moisture content of the concrete and chloride content, affects the ionic current flow between anode and cathode and hence the rate at which corrosion can occur.
- A high concrete resistivity decreases current flow and impedes the corrosion process.
- A highly permeable concrete will have a high conductivity and low electrical resistance. Because resistivity is proportional to current flow, the measurement of the electrical resistance of concrete provides a measure of the possible rate of corrosion.
- The rate at which the corrosion reaction can proceed is governed by the amount of oxygen available to the reaction, the alkaline state of the concrete, and the resistivity of the concrete. Measuring resistivity in concrete is specified in ASTM D3633.

## Typical Procedures

- The equipment relies on four equally spaced electrodes placed in drilled holes. The outer probes are connected to an alternating current. The inner probes are connected to a voltmeter. The apparent resistivity,  $\rho$ , is given by

$$\rho = 2\pi sV / I$$

Where:  $s$  = spacing of probes,  $V$  = measured voltage between inner electrodes and  $I$  = current between outer electrodes.

## Advantages

- In combination with other tests, such as the half cell test, resistivity measurements may give an indication of corrosion. Concrete with high resistivity, at locations where half cell results show corrosion, indicates a very slow corrosion rate.
- Resistivity measurements can also be used to assess permeability

## Limitations

- There are no generally agreed upon interpretation guidelines. Resistivity equipment suppliers and Bungey (Bungey, J. H. 1989) recommend:
 

>20	k $\Omega$ -cm	Low corrosion rate
10-20	k $\Omega$ -cm	Low to moderate corrosion rates
5-10	k $\Omega$ -cm	High corrosion rates
< 5	k $\Omega$ -cm	Very high corrosion rates
- Other researchers (Feliu, S. et al., 1996) and Manning (Manning, D.G. 1985) have recommended alternative guidelines
- Since carbonation seriously affects surface resistance, measurement on the concrete surface should be avoided



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# Crack Detection in Steel Bridges

## Steel Bridge Testing Program

### Introduction

- Steel Bridge Testing Program is a part of SAFETEA-LU Transportation Authorization Bill
- Program Description – Test steel bridges using a nondestructive technology that is able to detect growing cracks, including subsurface flaws as small as 0.010 in. in length or depth, in bridges

### Current State-of-the-Practice

- Visual Inspection, Dye Penetrant, Magnetic Particle, Conventional Ultrasonic Testing (UT), Conventional Eddy Current

### Objectives

- Facilitate the development and field deployment of NDE technologies that are able to detect fatigue cracks in steel girder components and details at fatigue prone and high stress areas
- Develop an informational database of commercial, state-of-the-art, developmental, and prototype technologies and their capabilities

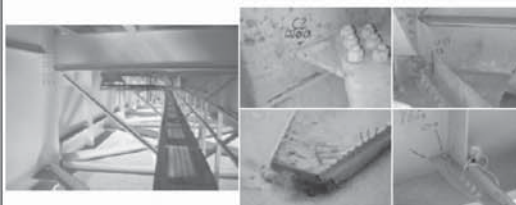
### Technology Characteristics

- Capable of detecting both surface and subsurface cracks in steel
- Require minimal, if any, surface preparation
- Can be implemented on uneven surfaces to detect cracks in crown, toe or root of the weld
- Ability to detect cracks through surface coatings or the rust coat on weathering steels
- Portable and field deployable

### Work Plan

- Phase-I
  - Commercially Available Technologies
  - Research Prototypes (BBA)
- Phase-II
  - Laboratory Testing and Evaluation
- Phase-III
  - Field Deployment and Evaluation

### Girder Connections or Details



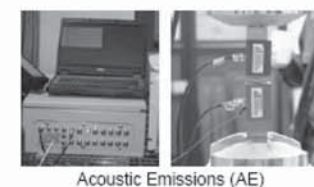
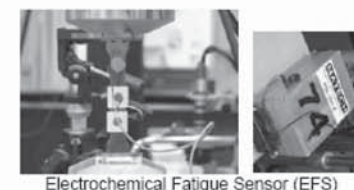
### Details Prone to Fatigue Cracking

- Fatigue-prone details in the AASHTO fatigue categories subjected to nominal or primary stresses
- Poor detail categories (i.e. D, E, E')

### Informational Database – NDE Web Manual

NDE Web Manual		Bridges/Girders/Trusses/Steel Beam/Girder Crack Detection in Steel Girders Crack Detection with Eddy Current			
Technology	Capability	Rating	Comment		
Coating/Non-Coating	Crack detection	1-1	Usually used for crack detection		
Coating/Non-Coating	Crack growth detection	0	Not periodic inspection		
Surface Defects	Detect length of surface cracks	4-5	Not suited to surface defect detection		
Surface Defects	Detect depth of surface cracks	1-1	No depth information provided		
Surface Defects	Detect orientation of surface cracks	4-5			
Sub-Surface Defects	Detect orientation of surface cracks	1-1	Not periodic inspection		
Sub-Surface Defects	Detect length of sub-surface cracks	4-5	Some surface defects may be detected		
Sub-Surface Defects	Detect depth of sub-surface cracks	1-1	No depth information provided		
Sub-Surface Defects	Detect orientation of sub-surface cracks	4-5			
Sub-Surface Defects	Detect growth rate of sub-surface cracks	1-1	Not periodic inspection		
Defect Location	Detect cracks in stress surface	4-5	Not suited to fatigue surface		
Defect Location	Detect cracks in toe of weld	1-1	Not suited for stressed area		
Defect Location	Detect cracks in toe of weld	1-1	Not suited for stressed area		
Defect Location	Detect cracks in root of weld	1-1	Not suited for stressed area		

### Selected Commercial Technologies



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# Detecting Delaminations in Concrete Decks

Comparison of NDE Technologies – Van Buren Road Bridge

## Introduction

- The FHWA NDE Center in collaboration with the University of Vermont and Rutgers University evaluated the performance of several different measurement techniques for assessing the condition of reinforced concrete bridge decks.

## Description of Structure

- Virginia Structure # 609, crosses Quantico Creek, Virginia, USA. Three steel beam spans, bare concrete deck, built in 1963. Data shown from the north span; 60 feet long and 20 feet wide.

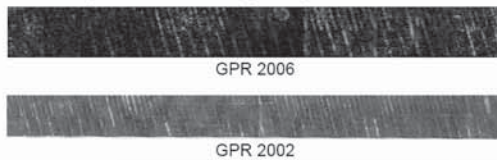
## NDE Test Methods

Six (6) different NDE Methods were used:

- Visual Inspection (VI)** – including digital image recording
- Chain Drag and Impulse Hammer** – hear delaminated areas
- Impact Echo (IE)** – ultrasonic data detects delaminated concrete
  - > PSPA – Geomeia R&D, USA
  - > Stepper – Bam, Germany
- Ground Penetrating Radar (GPR)** - Detects rebar corrosion, moisture and possibly delamination using electromagnetic waves
  - > Impulse Multipoint HERMES II –FHWA NDE Center
  - > Step-Frequency Multi-Antenna – 3d-Radar - Norway
- Half-Cell Electrochemical Potential** – Detects probability of corrosion by measuring equipotential maps.
- Infrared Thermography (IR)** – FHWA NDE Center; Detects surface discontinuities related to subsurface delamination

## SHM by Periodic NDE

- GPR, coring, and chloride testing were performed in 2002 and 2006



Chain Drag



Hammer Sounding



Infrared Thermography (NDE Center)



Step Frequency 3D Radar



HERMES-II (NDE Center, Univ. of Vermont)



Half-Cell Potential



PSPA Impact Echo (Geomeia R&D)



PSPA Impact Echo (Geomeia R&D)



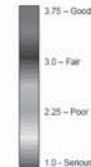
Stepper Impact Echo (BAM)

Ground Penetrating Radar (GPR)

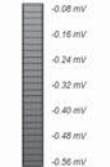
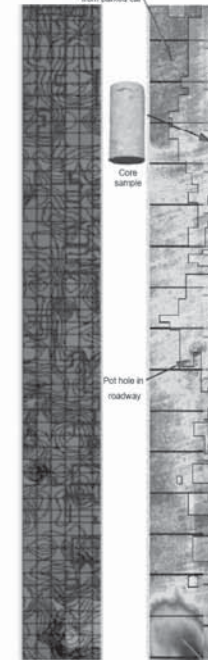


Delaminated area detected by chain drag

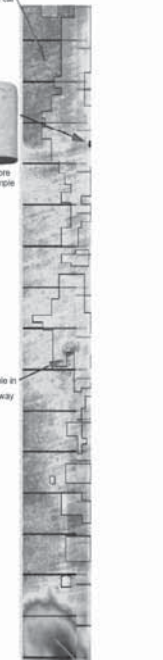
Impact Echo (IE)



Equipotential Half-Cell Map



Infrared Thermography (IR)



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# Detection of Dowel Bar Corrosion in Concrete

## Effect of Chloride Contamination on Ground Penetrating Radar Data

### OBJECTIVE

The purpose of our study was to determine the reliability of ground penetrating radar, as an inspection tool, for examining corrosion resistance of pavement joint dowel bars of different material properties in an accelerated corrosion environment.



### RADIO WAVE PROPAGATION

- Wave reflections occur at a boundary between two mediums with different dielectric permittivity
- Depth of penetration is effected by high electrical conductivity

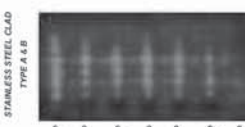
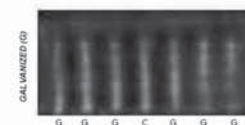
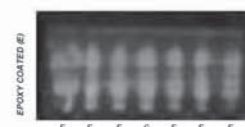
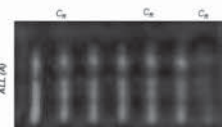
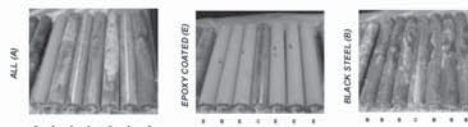
### GPR DATA ANALYSIS

Changes in GPR amplitude may be due to:

- dowel bar corrosion
- salt concentration
- moisture content
- chemically altered concrete
- delamination



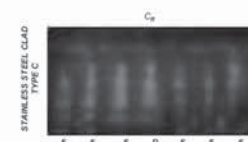
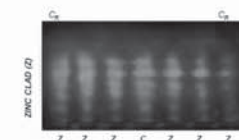
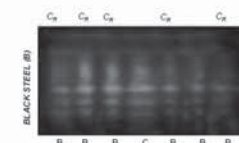
- Number of slabs: 7
  - Concrete: w/c=0.5; slump=1.5 in.; without fly ash and other pozzolanic ingredients; wet curing for 7 days followed by air drying for 21 days and curing compound.
  - Coarse aggregate: Limestone.
  - Concrete clear cover: 2.0 in.
  - Artificial crack: **0.22 in. (thickness); 1.5 in. (depth).**
- Accelerated testing with 15 wt. % NaCl solution.
  - The slabs were exposed weekly to 15% wt. NaCl solution during the four-day wet cycle and ~100 °F during the 3-day drying cycle.
  - Test duration: ~15 months.
- Each slab contains 6 of the same-material dowel bars plus 1 solid stainless steel control bar (cathode).
- All of the dowel bars in 6 slabs are coated with "Duogard" bond breaker; the 7th (ALL) slab contains lubricant-free dowel bars.



**LEGEND**  
A - ALL  
E - EPOXY COATED  
G - GALVANIZED  
S<sub>A</sub> - STAINLESS STEEL CLAD - Type A  
S<sub>B</sub> - STAINLESS STEEL CLAD - Type B  
Z - ZINC CLAD  
B - BLACK STEEL  
C - CONTROL BAR (SOLID STAINLESS STEEL)  
C<sub>s</sub> - OBSERVED SURFACE CRACK



- 3 IMPLANTED DEFECTS ON TOP OF BAR - 1/4\"/>
- 3 IMPLANTED DEFECTS ON TOP OF BAR - 1/8\"/>



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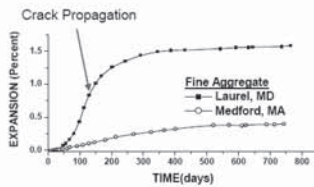
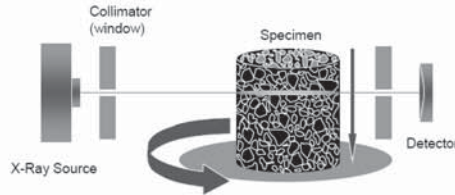


# Application of X-ray Computed Tomography to Concrete and Asphalt

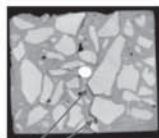
Nondestructive Evaluation Center  
Federal Highway Administration

## ACTIS Computed Tomography System

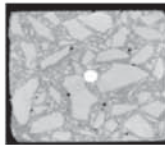
- X-Ray Source: 420 keV Tungsten rotating anode tube
- X-Ray Detector: 512 channels linear array detector
- Slice Thickness: 0.1 mm – 5mm
- Image Size: 256 x 256, 512 x 512, or 1024 x 1024 pixels
- Resolution:
  - 50 mm for small specimens
  - 200 mm for large specimens
- Maximum Thickness:
  - Concrete and asphalt concrete: 10 in.
  - Steel: 2 in.
- Maximum Height: 40 in.



Laurel Sand, 14 Months



Medford Sand, 14 Months



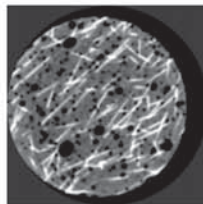
Cracks

## Expansion Mechanisms in Concrete Damage

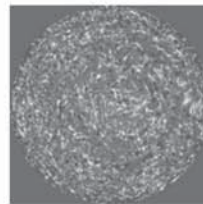
Concrete prisms were cast with different types of fine aggregate from the state of Maryland. The expansion of the prisms over time was measured while they were stored in lime water. The expansion of the Laurel sand specimens was much greater and more nonlinear with time than the Medford sand specimens. The CT images showed that increase in the expansion rate of the Laurel sand specimens was due to crack propagation along the aggregate/cement paste interface rather than simple uniform volumetric expansion.

## Steel Fiber Orientation in Reactive Powder Concrete (RPC)

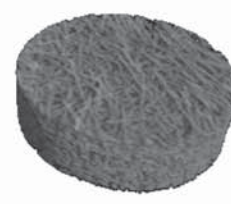
RPC is made with fine steel fibers in place of aggregates. The CT image of the core from concrete slab showed a linear preferred orientation parallel to the surface of the slab. The cast specimen showed a circular orientation concentric with the cylindrical wall of the mold.



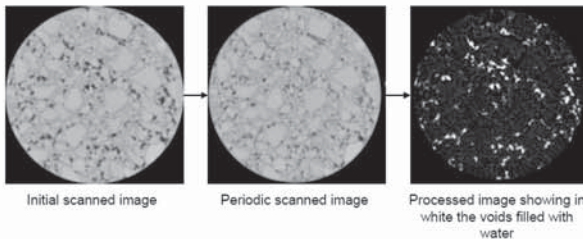
2 in. Core from Concrete Slab



4 in. Cast Concrete Cylinder



3-D Reconstruction of Core



## Moisture Transport in Asphalt

Water causes damage in asphalt by stripping of the binder from the aggregates. The asphalt specimen was initially scanned to quantify the connectivity of the voids by automated image analysis. The specimen was rescanned after being immersed in water. Subtraction of the first image from the second produced an image of the water distribution.



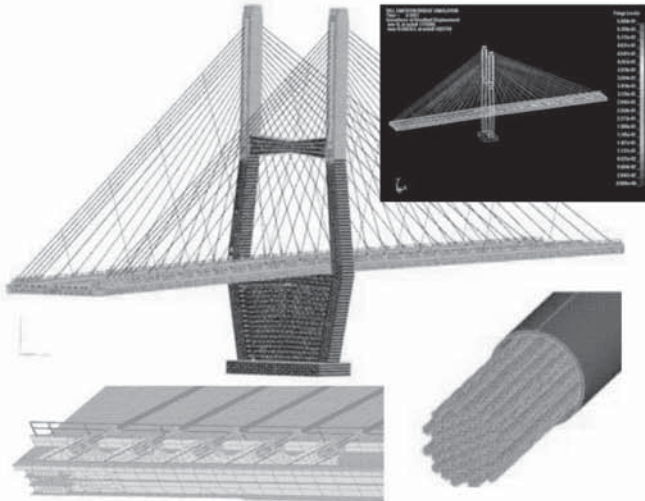
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## Development of Nonlinear Bridge Models for NDE and SHM Analyses

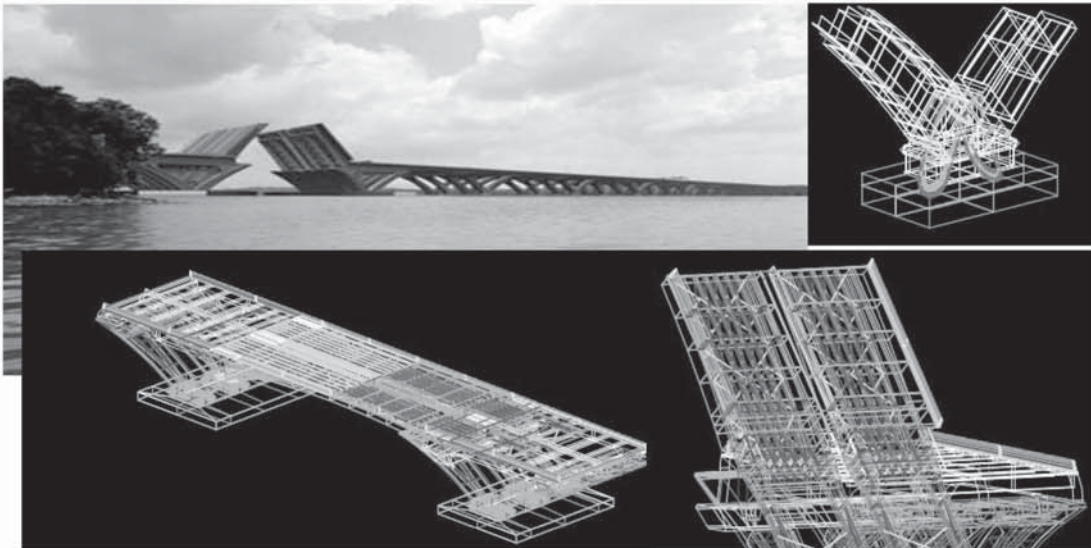


### Nonlinear finite element model of the Bill Emerson Memorial Bridge, MO

- Detailed nonlinear finite element model for the Bill Emerson Memorial bridge has been developed using FEMAP and LSDYNA
- The nonlinear FE model of this bridge addressed: detailed real geometry modeling, more realistic material models, and structural joints and moving traffic flow loads in service conditions to ensure the predictions of the bridge behavior
- The model consists about 540k elements and 1254 structural parts
- Extensive computer simulations were performed to collect the bridge response due to traffic flow and earthquake excitations

### Nonlinear finite element model of the new Woodrow Wilson Bridge

- Nonlinear finite element model for the new Woodrow Wilson Bridge has been developed, addressing detailed real geometry modeling, realistic material models, structural joints and dynamics loads in service conditions
- The new bascule draw bridge consists of a new V-pier design and multiple spans
- Extensive computer simulations will be performed to collect the bridge response due to traffic flow loads



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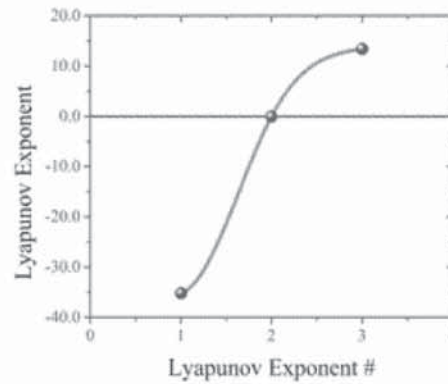
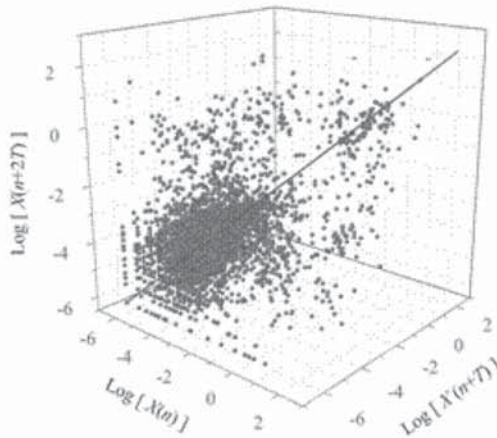
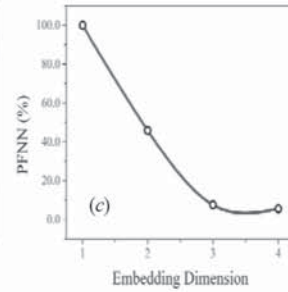
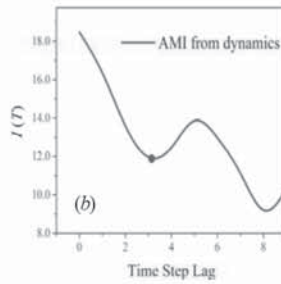
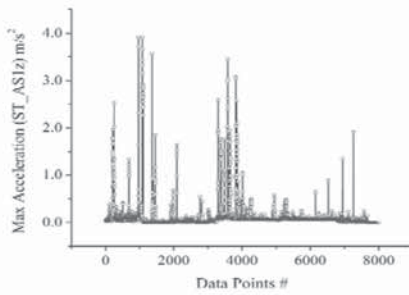
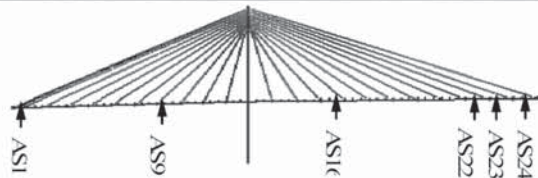
# Analysis of Wind/Rain Induced Vibration in Fred Hartman Bridge, TX

Nondestructive Evaluation Center  
Federal Highway Administration



## Chaos Theory Analysis

- Response monitoring data sets from each sensor channel were unfolded into an optimal phase space
- The nonlinear system invariants, Lyapunov exponents, were extracted for each sensor channel
- Significant positive Lyapunov exponent indicates nonlinear chaotic behavior in the cable-stayed bridge



• Analysis result reveals that significant chaotic behavior exhibits at certain bridge deck locations which excites the stay cables into a strong chaotic regime with significantly amplified chaotic motions.



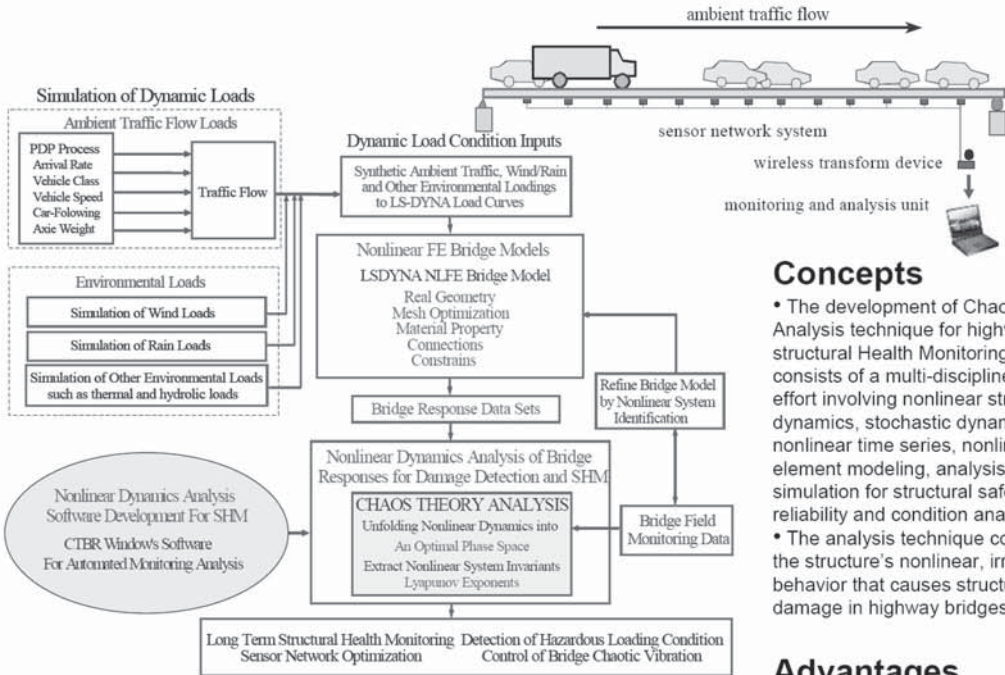
FHWA Nondestructive Evaluation Center





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Federal Highway Administration

# Smart Systems, NLFE Bridge Model Simulations and Chaos Theory Analysis Applied to Highway Bridges

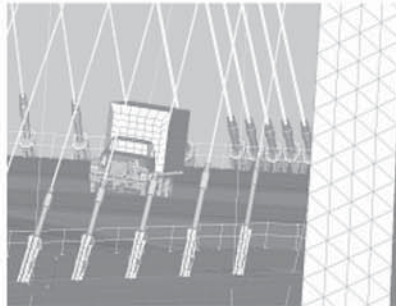
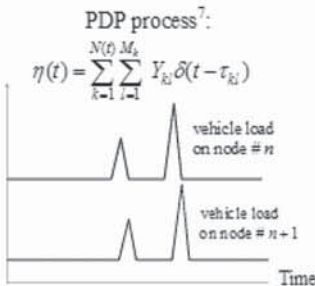


## Concepts

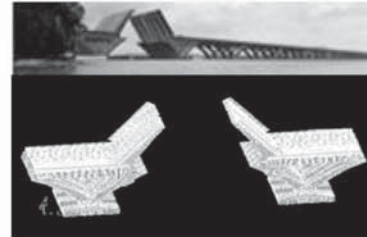
- The development of Chaos Theory Analysis technique for highway structural Health Monitoring (SHM) consists of a multi-discipline research effort involving nonlinear structural dynamics, stochastic dynamics, nonlinear time series, nonlinear finite element modeling, analysis, simulation for structural safety, reliability and condition analysis.
- The analysis technique concerns the structure's nonlinear, irregular behavior that causes structural damage in highway bridges.

## Advantages

- Directly uses the monitored structural responses to extract the invariants of a general nonlinear system.
- Both local and regional property changes in a system caused by damage can be revealed.
- Not limited in real-time structural condition assessment by complex material properties, environmental and loading conditions in general highway infrastructures.
- Significant advantages over most conventional NDE/NDT techniques
- Cost effective in advanced research by computer simulations



- Simulation of realistic traffic flow loads is developed by stochastic model of PDP processes
- Highly detailed bridge models are developed for extensive computer simulation of the bridge's nonlinear behavior



FHWA Nondestructive Evaluation Center

## APPENDIX B

# Use of Promising Nondestructive Testing Technologies by Departments of Transportation

### Air-Coupled Ground-Penetrating Radar (GPR)



#### Technology Use

Texas, Florida, and Minnesota Departments of Transportation (DOTs) have in-house capabilities for this technology. Other DOTs use equipment through consultants.

#### Applications

- Hot-mix asphalt (HMA) layer thicknesses for design and construction;
- HMA construction quality variability based on surface dielectric calculations (i.e., changes in density for the mat and joints);
- Unbound granular material moisture estimates based on surface dielectric calculations for design purposes and forensic studies;

- Detection of defects such as stripping, voids, and areas of excessive moisture for design purposes and forensic studies;
- Bridge deck condition;
- Thickness of pavement layers;
- Defects in base (wet areas);
- Defects in hot mix layers (stripping, trapped moisture);
- Detection of areas of segregation and poor joint density;
- Deterioration in asphalt-covered bridge decks;
- Base wash-outs;
- Water-filled voids under portland cement concrete (PCC); and
- Pavement rehabilitation studies (identifying changes in structure).

#### Advantages

- Air-launched GPR data can be collected quickly (for pavement evaluation purposes, data can be collected at highway speeds).
- This is the only technology available for subsurface evaluations at highway speeds.
- It can greatly improve structural evaluations with deflection devices by providing layer information.

#### Limitations

- Depth of penetration with 1 GHz limited to top 2 ft (0.6 m).
- GPR data analysis can be difficult, particularly on older pavements.
- HMA layer thickness calculations from GPR data are usually within 0.5 to 1 in. of actual thicknesses, according to Florida and Minnesota DOTs (Texas DOT has seen smaller differences).
- Layer thickness calculations may be erroneous when the HMA layer contains lightweight aggregate or if the data is collected on open graded courses (such as permeable friction courses or drainage layers); such layers tend to trap moisture, which causes reflections within the layers.

- Sometimes granular base layer thicknesses cannot be determined when the dielectric value of the granular base is similar to that of the underlying soil.
- GPR data analysis cannot discriminate between layers with similar dielectrics.
- Most defects and anomalies in pavement structure can be detected only through visual interpretation of the data; verification of defects must be performed by field coring.
- GPR data is not effective in conductive environments (i.e., where clay layers with significant moisture contents are present).
- Federal Communications Commission regulations have resulted in fewer companies manufacturing and selling air-launched GPR equipment. Currently, 1 GHz antennas are not manufactured.

### Hardware

- Texas DOT uses Pulse Radar and Wavebounce 1-GHz antennas. The systems are calibrated on a regular basis at Texas Transportation Institute (TTI).
- Florida and Minnesota DOTs use Geophysical Survey Systems, Inc. (GSSI) equipment.

### Data Acquisition Software

- Texas DOT uses software developed at TTI for data acquisition and processing.
- Florida and Minnesota DOTs use GSSI software.

### Training of Operators

TTI and Texas DOT have experienced staff who train GPR data collection operators.

### Data Analysis Software

- Texas DOT uses software developed at TTI for data analysis (Colormap).
- Florida and Minnesota DOTs use GSSI software. Florida DOT personnel indicate that the software has improved, based mainly on input from Florida DOT.

### Training of Data Analyzers

Texas DOT conducts courses on data analysis and distributes CDs concerning GPR data collection and analysis to new users.

### Costs

Air-launched GPR equipment usually costs between \$80,000 and \$100,000. Training of operators costs approximately \$1,000 per person. Training of data analyzers also costs

approximately \$1,000 per person. GPR calibration and maintenance usually costs around \$2,000 per event.

### Risks That May Impede Implementation

Several DOTs have had experiences with air-coupled GPR (ACGPR) in which conclusions from data analysis were wrong (i.e., data analysis indicated stripping HMA layers or poor-quality layers but actually the layers were in good condition). As a result, personnel at those DOTs are reluctant to try GPR technology again.

Sometimes capabilities are oversold. Training of DOT personnel is essential. Coring is needed to validate results.

### Speed

ACGPR data can be obtained at highway speeds with data collected at 5-ft spacing. For data collected at closer spacing, the GPR data has to be collected at slower speeds (20 mph maximum).

### Ease of Use

Procedures for mounting air-coupled GPR (ACGPR) equipment on the data collection vehicle and data collection are simple and straightforward.

### Accuracy and Precision

- HMA layer thickness calculations from GPR data are usually within 0.5 to 1 in. of actual thicknesses, according to Florida and Minnesota DOTs (Texas DOT has seen smaller differences).
- Layer thickness calculations may be erroneous when the HMA layer contains lightweight aggregate or if the data is collected on open graded courses (PFCs, drainage layers).
- Granular base layer thicknesses usually cannot be determined because the dielectric values of the granular bases are usually similar to those of the underlying soil.
- GPR data analysis cannot discriminate between layers with similar dielectrics.
- Most defects and anomalies in the pavement structure can be detected only through visual interpretation of the data.

In terms of the ACGPR data, repeatability and reproducibility have been good as long as the site conditions have not changed and the equipment has been properly calibrated and maintained.

### Relevance

ACGPR can be used for design, construction activities, and performance monitoring; this technology has not been fully implemented for construction inspection.



## Case Histories

Texas DOT has implemented this technology for pavement design and forensic investigation purposes. On one project in Johnson County, TX, the designers changed the proposed pavement rehabilitation strategy based on the GPR data analysis, which resulted in an estimated construction cost savings of \$500,000 (31).

Florida DOT is in the implementation process for this technology to estimate pavement surface thicknesses for pavement design purposes. The data is used to reduce the number of cores needed for thickness determination and to indicate where cores may need to be obtained.

## Other Information

Norwegian manufacturers have developed an air-coupled 3-D GPR system that is capable of testing entire roadways in one pass. The system is shown in the figure below. Only limited demonstrations have been conducted with this device in the United States. It can be used to potentially test bridge decks and highways in a single pass. Its main purpose is to locate buried subsurface defects during project evaluation. Such a system was used to evaluate the Natchez Trace Parkway (32).



3-D GPR system (Source: Roadscanners, Inc., Finland).

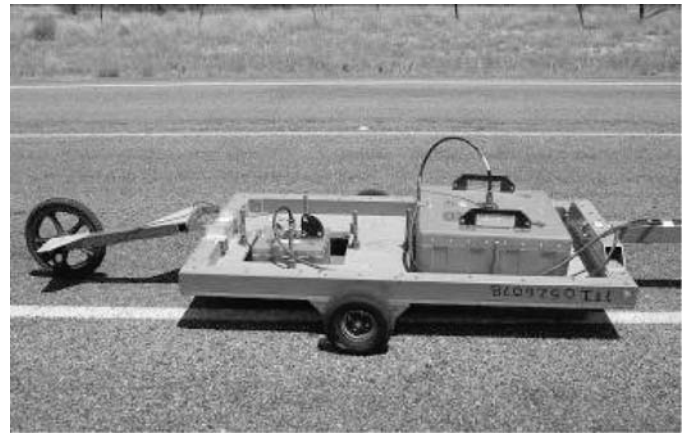
## Ground-Coupled GPR

### Technology Use

Texas, Florida, and Minnesota DOTs use this technology, as well as numerous others through consultants.

### Applications

Ground-coupled GPR (GCGPR) has been available for almost 50 years. The technology was developed in the United States, and the initial applications were in mining. Recently, these



devices have been used for a whole range of highway, bridge, and tunnel applications. The technology is relatively slow because the GPR antenna must remain close to the surface under test. The setup shown above can collect data at 10 mph; often the data is collected by hand-dragging the antenna. The benefit of this GPR is the depth of penetration. Low-frequency ground-coupled systems, such as a 200-MHz system, can penetrate in certain soils to depths in excess of 10 ft. Higher-frequency systems provide excellent resolutions and have been widely used to identify near-surface anomalies, detect voids, and locate rebar and dowel bars.

### Advantages

- The technology is proven and mature.
- Hardware and software are readily available.

### Limitations

- GPR data analysis can be difficult and often requires an expert.
- GPR data analysis cannot discriminate between layers with similar dielectrics.
- Most defects and anomalies in the pavement structure can be detected only through visual interpretation of the data.
- GPR data is not effective in conductive environments (i.e., where clay layers with significant moisture contents are present).

### Hardware

Texas, Minnesota, and Florida DOTs use hardware manufactured by GSSI. Several other vendors exist, such as Sensors and Software and others.

### Data Acquisition Software

All vendors provide data acquisition software that also shows a real-time visual display of the data.

## Data Analysis Software

Various software packages can be used to analyze the data.

## Training of Data Analyzers

Training takes approximately two days.

## Costs

GCGPR equipment usually costs between \$50,000 and \$60,000 for multiple antenna configurations. Training of operators costs approximately \$1,000 per person. Training of data analysts also costs approximately \$1,000 per person. GPR calibration and maintenance usually costs around \$2,000 per event.

## Risks That May Impede Implementation

Several DOTs have had experiences with GPR in which the conclusions from data analysis were wrong. As a result, personnel at those DOTs are reluctant to try GPR technology again.

## Speed

The maximum data collection speed for this technology is about 10 mph.

## Ease of Use

The equipment is considered easy to use in terms of data collection.

## Accuracy and Precision

In terms of the data, repeatability and reproducibility have been good as long as site conditions have not changed and the equipment has been properly calibrated and maintained.

## Relevance

GCGPR can be used for design, construction activities, and performance monitoring; this technology has not been fully implemented for construction inspection. Although it has not been used extensively in the United States for design work to map subsurface conditions of proposed construction projects, GCGPR is reported to be widely used in Europe for that purpose.

## Case Histories

Texas and Florida DOTs have successfully used this technology to locate voids, sinkholes, karst, and high-moisture areas (springs) underneath pavement structures for design and forensic investigations. In Texas the equipment was used to detect

the limits of excessive moisture in the soil resulting from a spring; the limits were needed so that a drainage layer and pipe underdrain could be placed in the most effective location before the construction of an overlying embankment with retaining walls (31). Other applications include identification of buried tanks along construction projects. High-frequency systems have been used to locate the presence and depth of steel in concrete. Europeans report using it for identifying soil changes along proposed highway construction routes.

## Surface Profile Measuring Systems

### Technology Use

Several state DOTs, pavement consultants, and paving contractors use this technology.

### Applications

- Profile measurements for network level inventory of ride quality;
- Quality control and quality assurance (QC/QA) testing of pavement smoothness on new construction, reconstruction, and rehabilitation projects;
- Programming of resurfacing projects;
- Forensic investigations;
- Weigh-in-motion site selection; and
- Research projects.

### Advantages

These measuring systems provide a way to quickly obtain objective ride and other pavement condition information. The technology has matured so that means are available to ensure reliable data.

### Limitations

Profilers are not capable of measuring long wavelengths and thus cannot provide true or reference profiles. Inertial profilers must be operated at constant speed that is at or above the minimum specified by the equipment manufacturer. Good profiles cannot be obtained under stop-and-go driving conditions.

### Hardware

All necessary electronics and sensors are typically installed in the survey vehicle or housed within attachable modules for portable devices.

### Data Acquisition Software

Profile acquisition software is provided by the profiler manufacturer.



### Data Analysis Software

Analysis software to compute various ride statistics, perform profilograph and straightedge simulations, and evaluate localized roughness to identify grind and fill areas are typically provided by the profiler manufacturer. Additionally, Federal Highway Administration (FHWA) has developed a computer program known as ProVAL for viewing and analyzing profile data and has made it available to the general public.

### Training of Data Analyzers

Training is typically provided by the equipment manufacturer. FHWA also has offered training classes on using the ProVAL computer program.

### Costs

Cost ranges from \$50,000 to \$300,000, depending on the features and capabilities required of the profiling system. Lightweight inertial profilers equipped with dual-path sensors can typically be purchased for \$50,000. High-speed portable pro-

filers typically cost \$50,000 to \$60,000, plus the cost of the vehicle.

### Risks That May Impede Implementation

Lack of training on proper use of equipment and lack of understanding on what the equipment can or cannot do can impede successful NDT implementation. Lack of specifications or standards for verifying profiler performance will also seriously hinder the application of inertial profilers for QC/QA of initial pavement smoothness on road construction projects. A program for verifying the operational worthiness of inertial profilers is particularly critical when the smoothness specification places the responsibility for quality assurance testing on the contractor.

### Speed

Lightweight inertial profilers are typically operated at speeds of 12 to 20 mph and require traffic control that conforms to applicable DOT standards. High-speed profilers permit measurements at the posted highway speed limit (typically 55 to 70 mph).



## Ease of Use

It is not difficult for a trained individual to run the profiler. Profile measurements typically require at least two persons: one to drive the vehicle and one to run the equipment, particularly for surveys that are taken at highway speed under traffic.

## Accuracy and Precision

Comparisons of international roughness indices (IRIs) computed from inertial profile data with corresponding statistics from reference profile measurements typically show that inertial profiler IRIs are within 6 in. per mile of the reference IRIs for data collected on dense-grade HMA concrete surfaces with IRIs ranging from 50 to 125 in. per mile. Point-to-point comparisons of inertial profiler data with reference profiles on such surfaces typically show average absolute differences below 40 mils and average differences within 10 mils.

As to precision, data from tests conducted on dense-grade HMA concrete surfaces typically show the average point-to-point repeatability to be within 30 mils and the IRI repeatability to be within 1.5 in. per mile.

## Relevance

Equipment is highly relevant for measuring ride quality and determining localized roughness to identify corrective measures needed to improve ride.

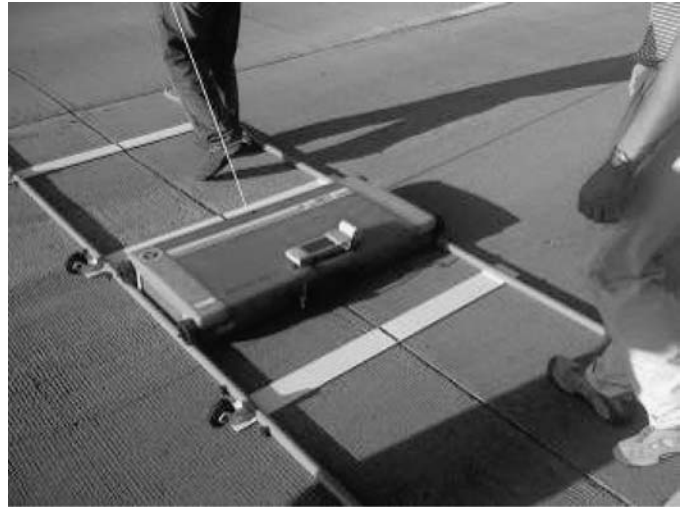
## Case Histories

A number of state agencies have used profilers to support pavement management applications for more than 20 years. Texas DOT has implemented this technology for construction project ride quality specifications on HMA, PCC, and thin-surfaced pavements. For the latter, the surface material consists of one- to two-course surface treatments.

## Other Information

Pavement surface profile measuring systems have been in use since the first profilometer was built by General Motors Research Laboratory in the mid-1960s. The systems are primarily used for measuring pavement smoothness at network and project levels. Several DOTs use inertial profilers for pavement management purposes. For these systems, network-level profiles are obtained at high speed, and the resulting profiles are used for computing smoothness or ride statistics. Profiler systems fall into three classes: portable, slow-speed, and high-speed. Budras has written a good synopsis on current equipment used for measuring pavement smoothness (33).

## Magnetic Imaging Tools— Scan Device for Locating and Measuring Placement of Dowel Bars and Reinforcing Steel Bars in Concrete Pavement



## Technology Use

Washington, California, and South Carolina DOTs and FHWA use this technology developed by Magnetic Imaging Tools (MIT) GmbH of Dresden, Germany.

## Applications

This device locates position and depth of placement for dowel bars and reinforcing steel in concrete pavement.

## Advantages

- Accurate nondestructive method that is easy to use, according to Washington DOT and Caltrans personnel;
- Can be used on newly placed concrete pavement to monitor dowel bars during construction; and
- Not affected by water or changing moisture conditions.

## Limitations

- The system requires that cores be taken to verify the results. Caltrans personnel indicated that this limitation may be overcome in the future; the manufacturer is apparently planning to double the number of sensors.
- Dowel bar basket assemblies may affect the results.
- The upper limit for dowel bar placement is 190 mm. For bars placed deeper than 180 mm, the measurement error starts to grow with increasing depth.

Applications of equipment are limited to bar types included in the equipment's parameter files. Other bar types require additional calibrations of the MIT scan.

### Hardware

- Sensor unit that emits electromagnetic pulses and detects the induced magnetic field. The sensor unit contains five sensors: one at the center and two on either side. The sensors are evenly spaced and centered (approximately) along the line directly below the white line of the MIT logo on the box.
- Onboard computer that runs the test, collects and stores the test data, and performs the preliminary evaluation.
- Glassfiber-reinforced plastic rail system that guides the sensor unit along the joint, parallel to the pavement surface, and at a constant elevation.

### Data Acquisition Software

The onboard computer contains the data acquisition software.

### Data Analysis Software

Personal computer-based software (MagnoProof) is provided with the equipment.

### Training of Data Analyzers

Training appears to be straightforward and usually takes a maximum of one day.

### Costs

According to California DOT personnel, the device cost was \$48,000 in 2003.

### Risks That May Impede Implementation

The limitations listed above may impede successful implementation.

### Speed

Data collection is less than 1 min for each joint.

### Ease of Use

The device is easy to use according to Washington and California DOT personnel. The principal investigator for this SHRP 2 project observed the equipment operating on a roadway in Bryan, TX, in November 2007 and noted that it appeared to be easy to use.

### Accuracy and Precision

Accuracy is reported to be 5 mm for a 95% reliability level on horizontal and vertical misalignment. Repeatability and reproducibility appear to be good as long as the equipment is properly maintained and calibrated.

### Relevance

The device is highly relevant for inspection and construction QC/QA applications.

### Case Histories

Washington, California, and South Carolina DOT personnel have used this device on several projects and were satisfied with the results. Washington DOT personnel reported that on a dowel bar retrofit project, the device detected dowel bars on a section of jointed concrete pavement. That finding resulted in a cost savings of approximately \$30,000 because dowel bar retrofit operations did not need to be conducted on that pavement section.

FHWA is sponsoring a project to demonstrate the equipment for DOT personnel (34).

### Real-Time Automated Distress Data Collection and Analysis



### Technology Use

Several DOTs are looking at or are in the process of implementing this technology. Maryland DOT uses software that requires manual assistance. Texas DOT is developing changes in-house; most are proceeding through consultant contracts.

## Applications

Measure cracking and other distresses on asphalt-surfaced pavements for design and performance monitoring purposes.

## Advantages

The cracking can be measured and classified in real time at highway speeds.

## Limitations

Lighting conditions can affect data collection. Recent developments in lighting strobes have resulted in devices that provide uniform lighting conditions. Data results can be significantly different from those generated by human raters.

Surface texture (on asphalt surfaces) and tining (on concrete) can present problems.

## Hardware

The data collection vehicle contains cameras and on-board computers to collect and analyze data in real time.

## Data Acquisition Software

Commercial applications exist and are under development. Texas DOT uses software developed by the University of Texas and Texas DOT for data acquisition.

## Training of Operators

Training varies, depending on the software used.

## Data Analysis Software

Commercial applications exist and are under development. Maryland DOT uses software that requires manual assistance. Texas DOT uses software developed by the University of Texas and Texas DOT for data analysis.

## Training of Data Analyzers

Training depends on the software used. One manufacturer's software usually requires five days of training.

## Costs

Costs for such systems vary from \$250,000 to more than \$400,000.

## Risks That May Impede Implementation

Personnel who are practiced in rating pavements may not believe the results from this technology for several reasons,

including the fact that it may detect more cracking than the raters would find. The results produced using this technology for testing are usually different from those arrived at by human raters.

## Speed

Data can be obtained and analyzed at highway speeds.

## Ease of Use

Because data collection and analysis is handled by the computer, from the operator's perspective the system is easy to use.

## Accuracy and Precision

The Texas system collects and appears to reliably analyze the data based on multiple runs over the same pavement sections, but the results may be considerably different from those arrived at by human raters.

Repeatability and reproducibility of the Texas system to detect cracking with the light bar have been reported to be good as long as site conditions have not changed and as long as the equipment has been properly calibrated and maintained. In Texas the researchers developing a system for Texas DOT reported a regression correlation coefficient,  $R^2$ , greater than 0.9 for multiple runs on several pavement sections (35, 36).

## Relevance

The equipment can be used for design and performance monitoring.

## Case Histories

Texas DOT is in the implementation stage of this device. Maryland DOT is using software that requires manual assistance.

## Other Information

More work appears to be needed in terms of providing durable and reliable equipment for production-level data collection purposes.

Private consulting firms and commercial enterprises also collect and analyze data with such systems.

## Dynamic Cone Penetrometer

### Technology Use

Minnesota and Texas DOTs use this technology.



### Applications

- Measure thickness and stiffness of natural soils and fine-grained unbound granular bases, and
- Determine if chemical stabilization of subgrade is effective.

### Advantages

- Portable,
- Easy to use,
- Easy to observe and measure stiffness, and
- Nonnuclear technology.

### Limitations

- Labor intensive,
- Measurements at discrete points, and
- Slow.

### Hardware

Dynamic cone penetrometer (DCP) with measuring tape or other measurement device.

### Data Acquisition Software

Data is recorded manually with the device shown above. Equipment can be installed with the DCP to record the data electronically.

### Data Analysis Software

Data can be input into a Microsoft Excel or other spreadsheet program.

### Training of Data Analyzers

Training takes approximately 1 h.

### Costs

The manual DCP, shown at left, currently costs around \$2,000. Automated DCPs have been developed and their estimated cost is \$40,000.

### Risks That May Impede Implementation

The DCP is labor intensive. Analyzers will need to become accustomed to what the device measures (penetration rate) and how to use the information.

### Speed

For most earthworks, data collection takes approximately 5 min per location.

### Ease of Use

The DCP is easy to use.

### Accuracy and Precision

Accuracy, repeatability and reproducibility are good as long as the device is in proper working condition.

### Relevance

The DCP is considered highly relevant as a construction QC/QA inspection tool.

### Case Histories

Minnesota DOT has a specification that uses DCP data (in terms of penetration rate) to determine if acceptable earthwork compaction has been achieved. Texas DOT regularly uses the DCP for pavement design and forensic studies. For example, Texas DOT personnel use the DCP to verify information obtained from falling-weight deflectometer (FWD) testing on pavement sections and to verify the presence of stabilized soil layers.

### Other Information

The DCP is a nonnuclear technology that has applications for earthworks and unbound granular materials. It can be used



to verify results from other NDT technologies or techniques. Automated versions of this device exist as well but are not as portable as the manual version.

## Portable Lightweight Falling-Weight Deflectometer



### Technology Use

Minnesota, Florida, and Texas DOTs are in the process of implementing this device.

### Applications

- Test stiffness of granular bases, soils, and fine-grained pavement layers, and
- Determine if chemical stabilization of subgrade is effective.

### Advantages

Portable device that can be used in areas where falling-weight deflectometers (FWDs) cannot be used.

### Limitations

- Cannot impart loads similar to truck traffic loads;
- Measurements at discrete points.

Unit shown has single load and deflection sensor so it provides a composite stiffness for the layer being tested. Multisensor units (up to three sensors) are available. Need to improve software to obtain multilayer stiffness values.

### Hardware

The portable FWD consists of a load plate with a geophone and load cell. Two additional geophones can be mounted on the device to obtain a deflection bowl.

### Data Acquisition Software

Acquisition software is provided with the device.

### Data Analysis Software

The load and deflection data can be imported into a Microsoft Excel spreadsheet for data analysis.

### Training of Data Analyzers

A half-day training course is assumed to be needed.

### Costs

Costs may range from \$5,000 to \$10,000, depending on the manufacturer.

### Risks That May Impede Implementation

Personnel will need to become accustomed to what the device measures (deflection) and how to use the information.

### Speed

Data collection at each measurement point is within 10 s. Data analysis can be performed within 1 h.

### Ease of Use

The device is considered easy to use.

### Accuracy and Precision

Accuracy, repeatability, and reproducibility of the data are considered good as long as the geophones and load cells are properly maintained and calibrated.

### Relevance

The portable FWD is considered highly relevant for inspection and construction QC/QA applications, but so far it has not been used for that purpose.

### Case Histories

Minnesota DOT has been evaluating the device to see if it can be used in place of the DCP for their specifications. Texas DOT personnel have been evaluating the device on construction projects.

### Other Information

The portable FWD can be used to verify results from other NDT technologies and techniques. Minnesota DOT is spon-

soring a study with Iowa State University concerning intelligent compaction; portable FWDs are used in the study to verify results from intelligent compaction technologies (37).

## Gamma-Gamma Logging and Crosshole Sonic Logging Integration for Drill Shafts

### Technology Use

California DOT uses these technologies.

### Applications

These technologies are used to assess the integrity of drill shafts or piles immediately after construction. As shown in the illustration at right, gamma-gamma logging (GGL) can assess the exterior of the shaft, whereas crosshole sonic logging (CSL) can assess the shaft interior.

### Advantages

- Ability to assess drill shaft or pile integrity, and
- Ability to determine if and where repairs are needed.

### Limitations

- GGL is a nuclear technology.
- The methods require the installation of access tubes.

### Hardware

- For GGL: hardware is similar to that for nuclear density gauges.
- For CSL: standard hardware is used for acoustic devices.

### Data Acquisition Software

Software is provided by the equipment manufacturers.

### Data Analysis Software

Software is provided by the equipment manufacturers.

### Training of Data Analyzers

- For GGL: the operator has to be licensed (the process is similar to that for nuclear density gauge licensing).
- For CSL: training is expected to take at least 1 day.

### Costs

- GGL equipment costs approximately \$28,000 per unit.
- CSL equipment costs approximately \$5,000 per unit.

### Risks That May Impede Implementation

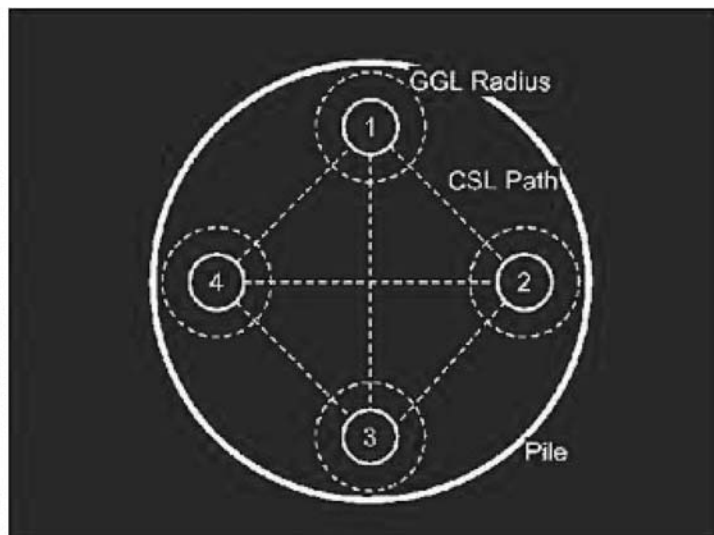
- GGL is a nuclear technology. Several DOTs have indicated that they would like to move away from nuclear technology.
- Access tubes need to be provided.

### Speed

Data can be collected and analyzed within 24 h.

### Ease of Use

The devices are relatively easy to use, although the nuclear technology associated with GGL requires the operator to be especially careful with the equipment.



Source: Brian Liebich, California Department of Transportation.

## Accuracy and Precision

Accuracy and precision are considered good as long as the equipment is properly maintained and calibrated.

## Relevance

These devices are considered highly relevant as inspection and construction QC/QA tools.

## Case Histories

California DOT has implemented and regularly uses GGL and CSL as part of construction QC/QA operations. The testing is included in their specifications.

## Other Information

Information was provided by Brian A. Liebich, Senior Transportation Engineer, Foundation Testing Branch, California DOT (7).

## Thermal Integrity Testing of Drill Shafts

### Technology Use

Florida DOT is considering using this technology.

## Applications

Assess the integrity of drill shafts or piles using infrared temperature measurements.

## Advantages

- Ability to assess drill shaft or pile integrity.
- Ability to determine if and where repairs are needed.
- Nonnuclear technology.

## Limitations

- The method requires the installation of access tubes. The method appears to be effective only when the concrete is hydrating.

## Hardware

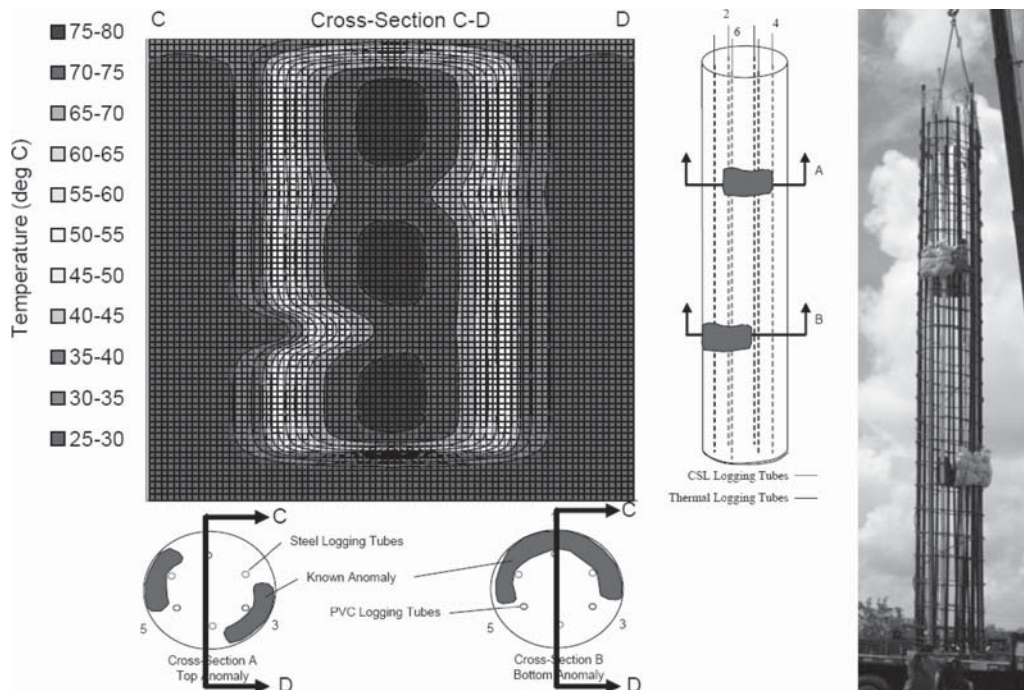
Hardware is provided by the equipment manufacturer.

## Data Acquisition Software

Software is provided by the equipment manufacturer.

## Data Analysis Software

Software is provided by the equipment manufacturer.



Source: Mullins et al. (8).

## Training of Data Analyzers

Training appears to be needed for at least 1 day.

## Costs

Costs are unknown.

## Risks That May Impede Implementation

Access tubes need to be provided.

## Speed

Data can be collected and analyzed within 24 h.

## Ease of Use

The technique appears to be relatively easy to use.

## Accuracy and Precision

Accuracy and precision are considered good as long as the equipment is properly maintained and calibrated.

## Relevance

These technologies are considered highly relevant as inspection and construction QC/QA tools.

## Case Histories

Florida DOT funded research with the University of South Florida, which used this technique to evaluate test drill shafts; results in the report show promise for this technology.

## HMA Infrared Temperature Measurements Immediately After Laydown Operations

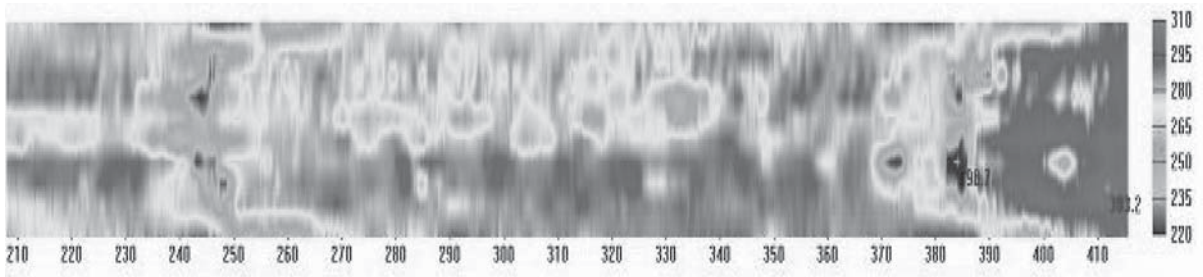
### Technology Use

Washington DOT has implemented this technology. Texas DOT is in the process of implementing this technology. Numerous DOTs are reviewing infrared specifications.

### Applications

Washington DOT has a specification requirement for temperature behind HMA laydown operations to prevent thermal segregation of the HMA mat. It uses infrared cameras to measure and record temperature.

Texas DOT funded a research study to produce the infrared bar device shown in the photo. The bar contains infrared sensors that continuously measure temperature. Texas DOT is considering implementing a temperature specification that can use data from the device.





## Advantages of Infrared Systems

- Visual data easy to interpret;
- Infrared bar automatically logs data, does not require personnel to operate; and
- Collects data on 100% of project.

## Limitations

- Equipment developed for Texas DOT has to be mounted to the laydown machine.
- Cameras are useful for spot checking but not for 100% coverage.

## Hardware

- Washington DOT personnel use an infrared camera.
- The equipment developed for Texas DOT uses off-the-shelf components.

## Data Acquisition Software

- The cameras used by Washington DOT use built-in software.
- TTI developed data acquisition software for the Texas DOT–developed equipment.

## Data Analysis Software

- The cameras used by Washington DOT come with data analysis software so that the temperatures can be shown at any location where the infrared picture was taken.
- TTI developed data analysis software to generate temperature maps, as shown in the second photo.

## Training of Data Analyzers

Training users of the data analysis software for Texas DOT and Washington DOT equipment takes only about 2 h.

## Costs

- The infrared cameras purchased by Washington DOT cost \$5,000 to \$7,000.
- The infrared bar developed for Texas DOT costs about \$20,000 (including software).

## Risks That May Impede Implementation

- Mounting equipment to the laydown machine may dissuade users from using the infrared bar.
- Questions still exist as to what temperatures result in poor HMA mat quality and durability. Some binders and mix types are more forgiving of temperature variations.

## Speed

The equipment operates at the speed of the laydown machine.

## Ease of Use

The equipment is considered easy to use, although installation on some laydown machines may be problematic.

## Accuracy and Precision

Temperatures using either device are considered accurate and are repeatable and reproducible as long as the equipment is properly maintained and calibrated.

## Relevance

Infrared technology is considered highly relevant for inspection and construction QC/QA applications. Segregation is a significant distress in new HMA surfacing.

## Case Histories

Washington DOT uses infrared cameras for determining specification compliance in terms of temperature. This compliance is achieved by permitting DOT personnel to select validation coring locations from infrared data.

Texas DOT has used the infrared bar on several projects and is considering implementation of temperature requirements in the specifications that would use data from the infrared bar.

On one project in Texas the contractor wanted to determine if an HMA material transfer device would be needed for a new construction project. Infrared measurements indicated that such a device was needed (38).

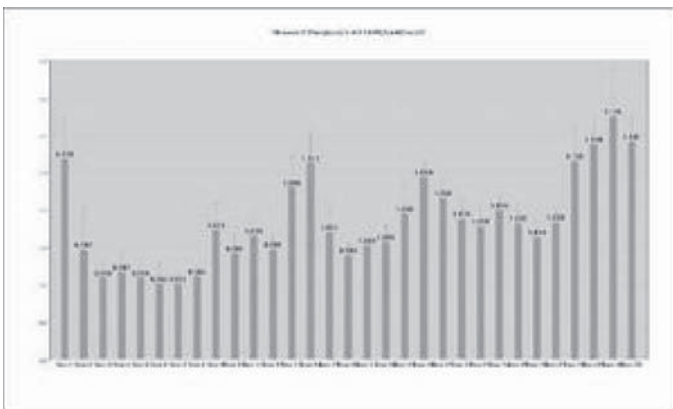
## Intelligent Compaction

### Technology Use

Minnesota DOT is in the process of implementing this technology. Texas DOT is considering implementation.

### Applications

An important aspect of highway construction that has received little recent attention in the United States is improved procedures for measuring the quality and uniformity of earthworks. Europeans have made much greater strides in developing intelligent compaction technologies. This technology has not made significant inroads in the United States. One reason for this lag is the lack of available sensors and software. Current



systems are commercially available in Europe, but they are provided by roller manufacturers as an add-on option with the purchase of a new roller. New rollers cost upward of \$80,000 and the intelligent compaction package adds another \$20,000 to \$30,000.

The components of the intelligent compaction system are simple. The system is based on an accelerometer to measure drum vibration, a distance measuring system, and a laptop with data acquisition and processing systems. Such a system has been developed at TTI. The concept is that this is an add-on package that can be added to any vibratory roller.

The system shown in the photo above has been field tested on several construction projects. A typical set of data from this unit is shown in the other figure. The vertical bars represent the average deflection for 20-ft-long sections of a soil under construction. The low areas are locations where the soil is soft and more compaction is required. This type of graph can be used to locate problem areas and to alert roller operators when adequate uniformity has been achieved.

### Advantages

- Rapidly assesses soil compaction effectiveness;
- Provides close to 100% coverage; and

- Relates to layer stiffness, which is now used for structural design.

### Limitations

- Based on testing in Texas, instrumentation on roller appears to measure stiffness of material several feet below surface;
- Not correlated to layer density;
- Requires changes to QC/QA philosophy before implementation can occur because contractors typically not responsible for weak spots several feet down; and
- No national standards because each manufacturer has its own way of processing data.

### Hardware

Accelerometers and data acquisition equipment are installed on the rollers and commonly provided as custom packages from the roller manufacturer. The Texas system may be added to any roller operating at around 30 Hz.

### Data Acquisition Software

Software is provided by the roller manufacturers.

### Data Analysis Software

Software is provided by the roller manufacturers.

### Training of Data Analyzers

Training takes one day at the most.

### Costs

Equipment is typically not sold separately but as an option when purchasing a new roller; cost is about \$20,000 to \$30,000.

### Risks That May Impede Implementation

Based on testing in Texas, it appears that the instrumentation on the roller measures the stiffness of the material 3 ft below the surface and deeper (i.e., the instrumentation does not measure the upper 3 ft of material).

### Speed

The speed of data collection depends on the speed of the roller. Data analysis is in real time.

### Ease of Use

The devices are easy to use.

## Accuracy and Precision

Accuracy and precision of the accelerometers are considered good as long as they are kept in proper working order.

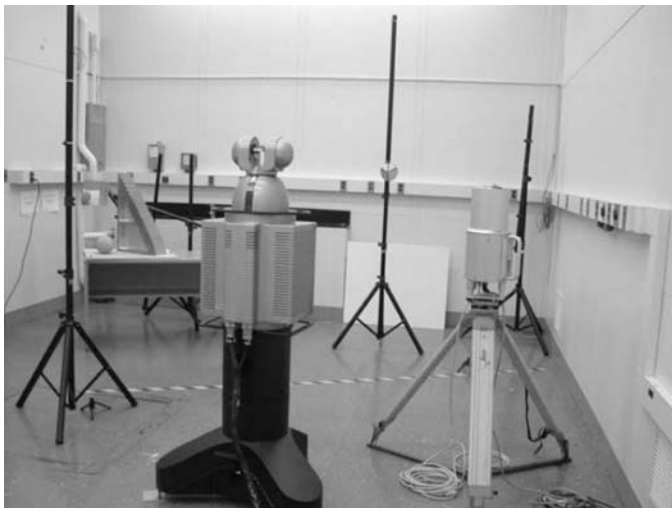
## Relevance

The instrumentation is considered highly relevant for inspection and construction QC/QA applications. These systems can find the weakest point in any new layer and could replace random test location selection.

## Case Histories

Minnesota DOT is working with Iowa State University to assess the effectiveness of intelligent compaction equipment. Texas DOT sponsored a study with TTI to assess the equipment as well (37, 39).

## Laser Scanning (LADAR or LIDAR)



## Technology Use

The technology is used by California, Minnesota, Texas, and Washington DOTs; FHWA; and National Institute of Standards and Technology (NIST).

## Applications

Laser scanning is an optical remote sensing technology that uses lasers to find range between sensor and target and measure other properties, such as the reflectance of the target surface that corresponds to the magnitude of the backscattered laser energy. The technique has numerous applications, including:

- Monitoring movements and deformations of highway infrastructure (tunnel linings, retaining walls, bridge girders, etc.), and rock slopes,
- Condition assessment and inspection of tunnels,
- 3-D mapping and modeling,
- Aerial surveying,
- Visualization,
- Distance measurements, and
- Characterization of aggregate characteristics.

High-resolution images capturing details of the target surface can be achieved. Figure B.1 shows an image of a tunnel niche taken with a laser range scanner. The identification number 56 at the top of the niche is clearly visible as well as the number 14 on the side. Figure B.2 shows a clear image of two intersecting cracks on a tunnel wall.

## Advantages

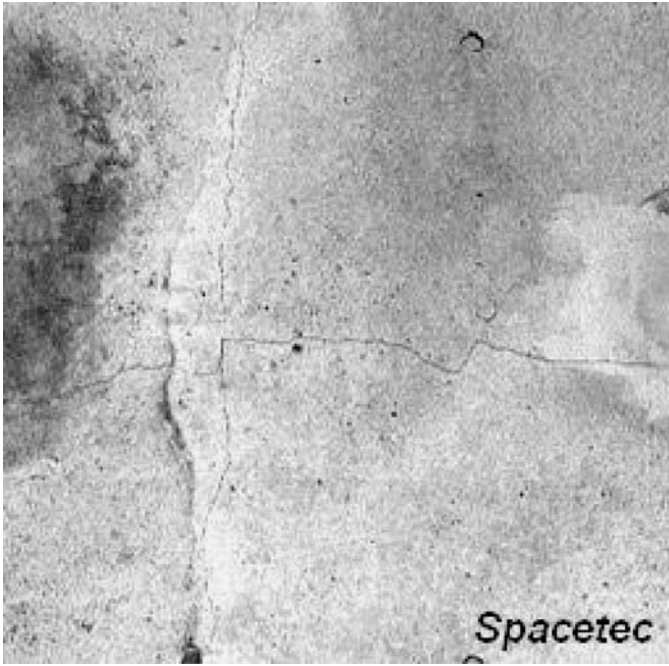
- Captures “as is” conditions,
- Creates 3-D models,
- Attains 100% coverage, and
- Allows continuous monitoring.

## Limitations

The equipment collects data only for objects within the line of sight. Laser range measurements can be influenced by



**Figure B.1. Image of tunnel niche from laser scanner (40).**



**Figure B.2.** Image of intersecting cracks on tunnel wall.

atmospheric conditions (air temperature and pressure) and may require corrections for atmospheric effects.

### Hardware

The hardware depends on the manufacturer but generally consists of a laser emitter, a mirror system for deflecting the laser beam and collecting the backscattered laser light cone, and electronics for data acquisition and processing.

### Data Acquisition Software

Software comes with the unit.

### Data Analysis Software

Software is usually provided by the manufacturer.

### Training of Data Analyzers

Training takes about a week. A surveyor could probably be trained faster and would be more knowledgeable about scanner positioning, registration, and so on.

### Costs

Most scanners cost between \$100,000 and \$150,000 and come with software for limited modeling. Other, more sophisti-

cated software ranges from \$10,000 to \$25,000 for annual licenses. Service providers are available to assist with customer-specific applications.

The FHWA Nondestructive Evaluation (NDE) Center owns a scanner that costs approximately \$300,000.

### Risks That May Impede Implementation

The following excerpt is from “LADAR Sensing Applications for Construction” by Cheek and Stone (41).

“There are a number of presently unresolved issues that will severely limit the emergence of LADAR technology at construction job sites. These include, in order of importance:

- “Lack of Traceability: There are presently no standards against which to compare LADAR systems. Contractors and business owners need the assurance that the work they pay for is what was done. Artifact-traceable standards are needed for instrument calibration, scene registration, and object recognition. Confidence limits have to be established for derived quantities, position, and pose determination.
- “High Cost: While pricing and availability of existing sensors may be acceptable for military missions and the development of national performance metrics, they are beyond the resources of most contractors. Thus, the development of a low cost, high-resolution system is paramount. A cost reduction of 100 to 1 is likely needed to achieve ubiquitous use.
- “Large Size: Presently available LADAR systems with accuracy sufficient for construction control are too large for ubiquitous use, eye safety issues notwithstanding. Many automation experts believe that coffee-cup sized LADAR units, mounted on construction assembly systems, will be crucial to automating construction as well as to achieving automated tracking of construction materials. A size reduction of 10 to 1 is needed to achieve this objective.
- “Robust Post-processing Software: Although substantial efforts are under way at several LADAR-based startups, algorithms that can automatically process LADAR data are still in the nascent research stage. Application specific programs to automatically calculate billable quantities and to automatically generate as-built CAD data sets for constructed infrastructure remain the holy grail in this field.

“The first of these issues is currently being addressed by efforts at NIST to develop a national artifact standard LADAR test course and to develop web-accessible metrics for LADAR performance. Given the small size of most companies working on LADAR development, and the high risk of attempting radical new technology integration, it appears certain that the only means by which the second and third issues will be resolved will be via a concerted government/industry consortium. If



the first three issues can be resolved, the private sector and academia are well positioned to provide the fourth.”

### Speed

- The time needed to collect data with the method (i.e., the speed of testing) is less than a minute to minutes, depending on point density and area of coverage.
- Point clouds may be used immediately for visualization and distance measurements. Postprocessing modeling, CAD drawings, fitting, and so on are on the order of weeks.

### Ease of Use

As stated earlier, training takes about a week. A surveyor could probably be trained faster and would be more knowledgeable about scanner positioning, registration, and so on.

### Accuracy and Precision

For most of the instruments that would be used for construction applications, the manufacturer specifications vary from 5 to 10 mm. No standard method of verifying these numbers exists. The FHWA NDE Center used a system that had a reported accuracy of 0.0039 in. at 32.8 ft and 0.0094 in. at 78.7 ft. Repeatability and reproducibility are assumed to be good.

### Relevance

Such systems have been used for inspection and QC/QA.

### Case Histories

Several DOTs, including Texas and Minnesota, are using this technology. Minnesota DOT is using this technology to track changes in tunnel linings. Texas DOT used this technology to monitor movements in retaining walls.

The FHWA NDE Center used a system to effectively measure bridge girder deflections in the field. The equipment has potential for bridge load testing.

### Other Information

Geraldine Cheok from NIST provided much of the information for this data sheet. Frank Jalinoos at the FHWA NDE Center provided information concerning the use of their equipment for measuring bridge girder deflections.

## Portable Seismic Pavement Analyzer/Free-Free Resonant Column Test Integration



Source: Nazarian et al. (43).

### Technology Use

Texas DOT is in the process of implementing this technology.

### Applications

Texas DOT Implementation Project 5-1735, Quality Management of Asphalt Concrete Pavement (ACP) and Base, involved the use of the portable seismic pavement analyzer (PSPA) and the free-free resonant column (FFRC) device. The PSPA is computer-operated and consists of two transducers and a signal source. It is used in the field to directly measure the modulus of pavement layers (43). The device has the potential to replace the nuclear density gauge for construction QC/QA purposes. Texas DOT is considering using these devices for evaluating ACP and granular base layers.

The FFRC device measures modulus values from laboratory specimens. The results from the laboratory testing are used to determine appropriate modulus values that should be measured in the field with the PSPA.

Additionally, the FFRC and PSPA could be used for acceptance testing of concrete pavement. In a study for the Innovative Pavement Research Foundation, Nazarian et al. stated, “This study shows that concrete strength can be estimated from either seismic modulus or maturity or both with appropriate calibrations. The pavement thickness measurement is a by-product of the seismic test conducted for the strength estimate” (42).

### Advantages

The PSPA and FFRC can be used to reduce the number of destructive tests required to determine pavement layer properties. Results can be obtained within 2 min for both tests because the data is analyzed on site.

### Limitations

Testing is discrete by nature (i.e., testing measures properties at a single point per test and takes 2 min per test). As with the FWD, it is unsuitable for rapid 100% coverage testing.

### Hardware

Researchers at University of Texas, El Paso, developed the hardware shown in the photos at the beginning of this section.

### Data Acquisition Software

Researchers at University of Texas, El Paso, developed the acquisition software.

### Data Analysis Software

Researchers at University of Texas, El Paso, developed the analysis software. Data analysis is conducted on site by the software.

### Training of Data Analyzers

- Training for operation and data interpretation with the FFRC takes 1 day.
- Training for operation of PSPA takes 1 day and training for data interpretation takes 1 day.

### Costs

- PSPA—\$20,000 to \$30,000, with \$5 to \$10 per specimen for preparation and testing.
- FFRC—\$10,000 to \$15,000, with \$15 to \$20 per specimen for preparation and testing.

### Risks That May Impede Implementation

Agencies may be unwilling to use this technology because it does not measure strength of materials. Some questions exist as to whether seismic modulus can accurately be related to strength, although the published literature indicates that it can be possible. Thickness estimates using the PSPA may not be accurate enough for some agencies.

### Speed

Measurement speed is 2 min.

### Ease of Use

The equipment is easy to use, based on the Principal Investigator’s experience.

### Accuracy and Precision

The accuracy reported by Nazarian et al. (42) for thickness is between 3% and 4%. Additionally, Nazarian et al. report that the accuracy for the seismic modulus is good, indicating that, “results are more sensitive to properties of the top half of the pavement” (42).

According to Nazarian et al., “The seismic method is more precise than conventional concrete strength tests, and tests can be carried out at a larger number of locations on a pavement. Thus, a PWL analysis based on this method may be more favorable to both the owner and contractor” (42).

Also, according to Nazarian et al., “The COVs at a confidence level of 50% are less than 1% for FFRC, less than 3% for compressive strength, and less than 5% for the flexural strength and the PSPA measurements” (42).

### Relevance

These techniques appear to be highly relevant as inspection and QC/QA tools.

### Case Histories

Nazarian et al. contain several case studies using these techniques (42). Texas DOT is still considering implementing these techniques.

## Rolling Dynamic Deflectometer

### Technology Use

Texas DOT has implemented this technology.

### Applications

Texas DOT has made great progress at building and implementing rolling deflectometer technology for evaluation of joints and cracks in concrete pavements (44). The system shown in the figure above was developed by University of Texas, Austin. This device travels at 1.5 mph and collects deflection data for every 2 ft of travel. The system has at least two rolling geophones for measuring surface deflection under sinusoidal loading conditions. It is excellent for collecting load transfer data on jointed concrete pavements. Unlike other systems, it can test every joint in a project and identify which ones need to be replaced. It has been used extensively in concrete pavement rehabilitation jobs in Texas. It has also been used on several major airport runway evaluations. The existing rolling dynamic deflectometer (RDD) system is more than 10 years old; it is based on existing oilfield vibrosis equipment. Texas DOT was so impressed with the

potential of this device that another system is being developed. The new system will have the potential for collecting project-level deflection data at 1-ft intervals at 5 mph.

### Advantages

The RDD provides nearly continuous deflection data.

### Limitations

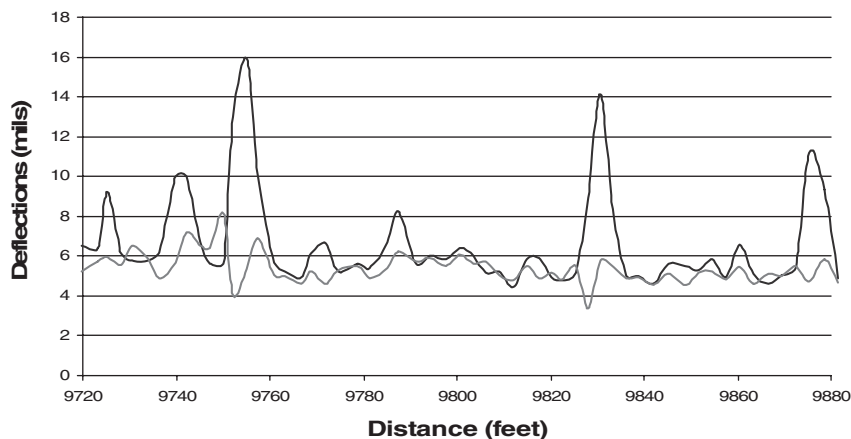
Because the RDD operates at a speed of 1.5 mph, traffic control is required.

### Hardware

As stated earlier, oilfield vibrosis equipment, at least two rolling geophones for measuring surface deflection under sinusoidal loading conditions, and data acquisition equipment.

### Data Acquisition Software

Software was developed by University of Texas.



## Data Analysis Software

Data is exported into a Microsoft Excel spreadsheet for analysis.

## Training of Data Analyzers

The data analyzer needs only to know how to use Microsoft Excel. Data analysis involves only mapping the deflections and determining where the deflections are unusually high.

## Costs

The device above was produced by a Texas DOT–sponsored research project. No production devices exist. The estimated cost for a new RDD is believed to be around \$300,000.

## Risks That May Impede Implementation

Because traffic control is needed, DOT personnel may not be willing to use the device on high-traffic-volume roadways.

## Speed

The RDD collects data at 1.5 mph and is expensive. The data can be analyzed easily within 2 h.

## Ease of Use

The RDD is considered to be relatively easy to use.

## Accuracy and Precision

The data produced from this device was compared with FWD data on the same roadways. The data trends do match, but because the method of loading between the RDD and FWD is different, the magnitude of the deflections is different.

Repeatability and reproducibility are assumed to be good based on past experiences.

## Relevance

The RDD has potential for inspection and construction QC/QA purposes but has not been used in that regard.

## Case Histories

The RDD is used regularly by Texas DOT to determine the structural condition of existing jointed pavements and has helped designers generate more effective pavement rehabilitation strategies. It has also been used on airport runways and taxiways.

## Soil Resistivity Profiling

### Technology Use

Florida, Minnesota, Texas, and New Hampshire DOTs.

### Applications

Soil resistivity is used to detect changes in soil strata. Once the data is collected, the data analysis can be produced within 2 h.

### Advantages

- Resistivity information can be used to determine where to take borings.
- Readings can be obtained hundreds of feet deep.

### Limitations

- Data analysis has to be verified by boring or sampling.
- Different materials may have similar resistivity ranges.
- The setup is labor intensive and time-consuming. For a two-dimensional soil survey, it usually takes three persons 1 day to collect data for a ½-mi length using 2-m spacing between electrodes.

### Hardware

Florida and Minnesota DOTs purchased soil resistivity equipment from Advanced Geosciences, Inc. (AGI). Texas DOT has started to evaluate soil resistivity profiling, using AGI equipment. AGI is one of only two equipment providers in the United States.

### Data Acquisition Software

Texas, Florida, and Minnesota DOTs used software developed by AGI that comes with the equipment.

### Training of Operators

AGI conducts courses for beginners and advanced users. The cost per person per class is approximately \$750.

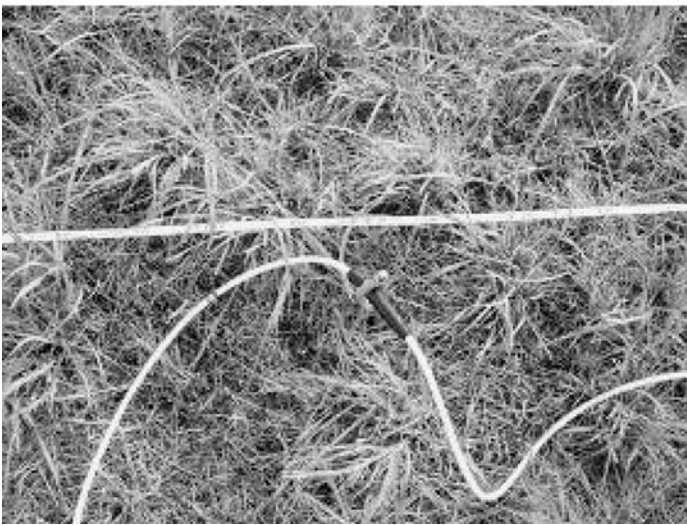
### Data Analysis Software

Texas, Florida, and Minnesota DOTs used software developed by AGI.

### Training of Data Analyzers

AGI conducts courses for beginners and advanced users. The cost per person per class is approximately \$750.





### Costs

AGI's 56-electrode system is \$45,000. Minnesota DOT purchased an AGI system with underwater drag cables for \$75,000. The cost includes data analysis software.

### Risks That May Impede Implementation

The data collection process is labor intensive and time-consuming because the data analysis has to be verified by boring and because resistivity values may not discriminate between soil types. For these reasons, potential users may be wary of using such equipment.

### Speed

It usually takes three persons 1 day to collect a ½-mi length using a 2-m spacing between electrodes for a two-dimensional soil survey. Data analysis can be produced within 2 h.

### Ease of Use

The equipment is relatively easy to use after the electrodes have been placed.

### Accuracy and Precision

The resolution is a function of the spacing between electrodes. For example, 2-m spacing between electrodes produces about a 1-m accuracy. In terms of the resistivity data, repeatability and reproducibility have been good as long as site conditions have not changed and the equipment has been properly calibrated and maintained.

### Relevance

Soil resistivity can be used for design and performance monitoring. This technology has not been fully implemented for construction inspection.

## Case Histories

Minnesota and Florida DOTs regularly use soil resistivity profiling for geotechnical investigations.

## Other Information

Florida DOT is evaluating the Ohm-Mapper system manufactured by Geometrics, Incorporated, which does not involve using electrodes that have to be driven into the soil. This equipment also appears to be promising for use by other DOTs.

## Vibration-Based Bridge Monitoring



## Technology Use

California DOT has used this technology.

## Applications

- Damage detection due to structural degradation of bridges, such as corrosion of rebar and ASR/DEF;
- Determination of fatigue and fracture;
- Damage detection due to earthquakes; and
- Identification of stiffness changes in bridge piers and girders.

## Advantages

Because the system works on a global base, only a limited number of sensors is required to monitor a large bridge.

## Limitations

- Even though a lot of previous work exists in this area, the method is limited because of data interpretation.
- It is difficult to relate changes in eigenfrequencies and modal shapes to damage detection because changes in environmental conditions, such as temperature and humidity, also cause changes in modal parameters.

- Once the damage is located in a vibration node, the eigenfrequency is not affected, thus the identification of the results is incorrect.
- The localization of a defect is difficult because only a few sensors are used, and with this limited information, accuracy is not high.

## Hardware

Hardware consists mostly of commercially available sensors, such as accelerometers, linear variable differential transformers, temperature sensors, and humidity sensors as well as data acquisition systems (fast Fourier analyzers). Newer approaches consider wireless sensor networks for measurement and data acquisition.

## Data Acquisition Software

Software is either hardware specific or commercially available.

## Data Analysis Software

Because this stage is under development, data analysis software is usually written in research institutions, such as Texas A&M University (time domain decomposition, frequency domain decomposition, and damage index method) and Los Alamos National Laboratory.

## Training of Data Analyzers

Training is required.

## Costs

System costs range from \$5,000 to \$100,000.

## Risks That May Impede Implementation

The limitations listed earlier may impede more widespread implementation of this technology.

## Speed

Data analysis results can be available within 48 h.

## Ease of Use

The system is easy to use, but data interpretation requires expert knowledge.

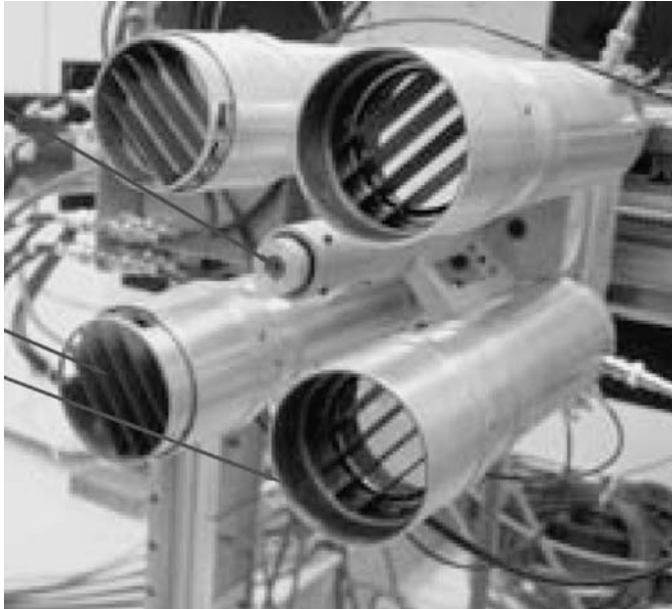
## Accuracy and Precision

Accuracy depends on environmental conditions and generally is fairly low. Repeatability and reproducibility also depend on environmental conditions.

## Relevance

The system can be used for design, construction activities, and performance monitoring.

## X-Ray Backscatter Technology



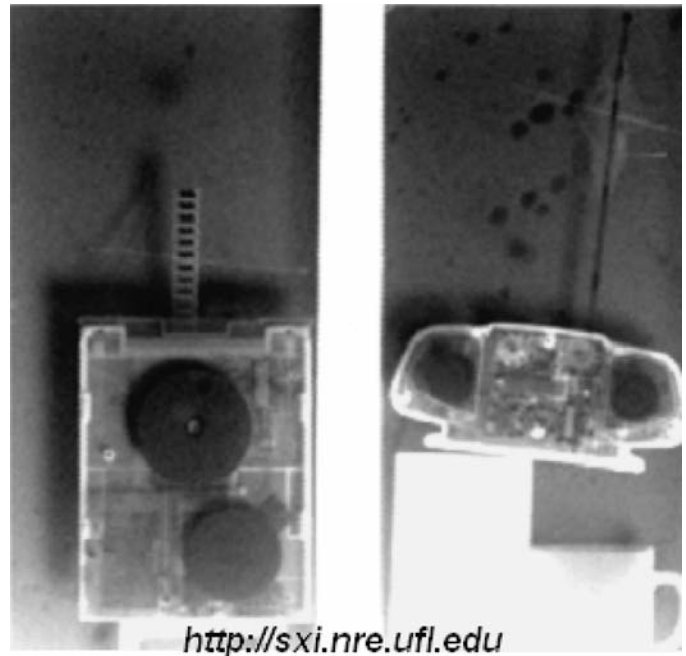
Source: Shedlock et al. (45).

## Technology Use

Florida DOT is considering applications of this technology.

## Applications

X-ray backscatter technology has potential applications for mapping defects in bridge decks and pavement surfaces, including corrosion of reinforcing steel. This technology has successfully been used to detect landmines, find flaws and defects in metallic aircraft components, detect boric



**Figure B.3.** X-ray backscatter scan revealing inside components of radio.

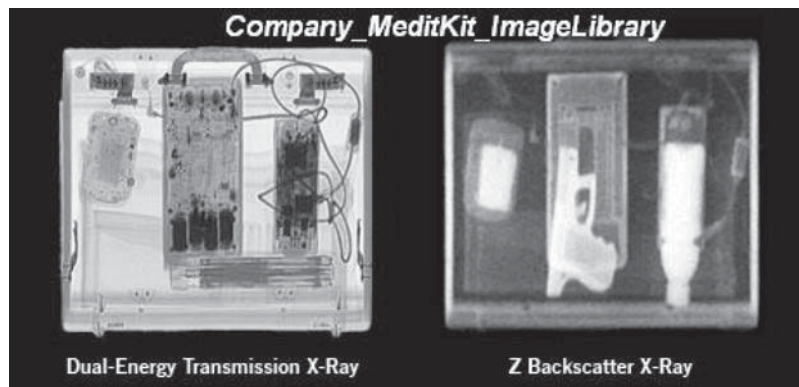
acid deposits in nuclear reactor pressure vessels, and security scanning at airports and water ports. High-resolution images, such as illustrated in Figures B.3 and B.4, can be obtained using X-ray backscatter technology.

## Advantages

The equipment can be installed in a van and operated at around 5 mph.

## Limitations

- Penetration depth is only about 8 inches.
- Nuclear technology.



**Figure B.4.** Comparison of images from same test target with conventional X-ray machine (left) and backscatter scanner (right).



## Hardware

In contrast to the conventional X-ray machine that images by the variation in transmission through a target, the backscatter X-ray technique detects the radiation that comes back from the target. Figure B.5 shows a schematic setup of X-ray backscatter imaging based on the method of radiography by selective detection (RSD). RSD allows for preferential detection of backscatter components that are responsible for improving image contrast. The detection is accomplished through a set of specially designed detectors and both fixed and movable detector collimators.

## Data Acquisition and Analysis Software

It is not known whether data acquisition and processing software specifically tailored for nondestructive testing of bridge decks and pavement surfaces has been developed. It is possible that existing software used for detecting flaws and defects (including corrosion) of metallic components might be adapted for testing bridges and pavement surfaces.

## Training of Data Analyzers

Training would be needed.

## Costs

The equipment currently costs approximately \$100,000.

## Risks That May Impede Implementation

This is considered a nuclear technology. Also, the lack of training and understanding of what the technology can or cannot do might hinder the successful implementation of X-ray backscatter technology.

## Speed

Approximately 5 mph.

## Ease of Use

Not established at this time.

## Accuracy and Precision

Apparently very good according to Bjorn Birgisson, formerly of the University of Florida, whom researchers visited during the state surveys conducted for this project.

## Relevance

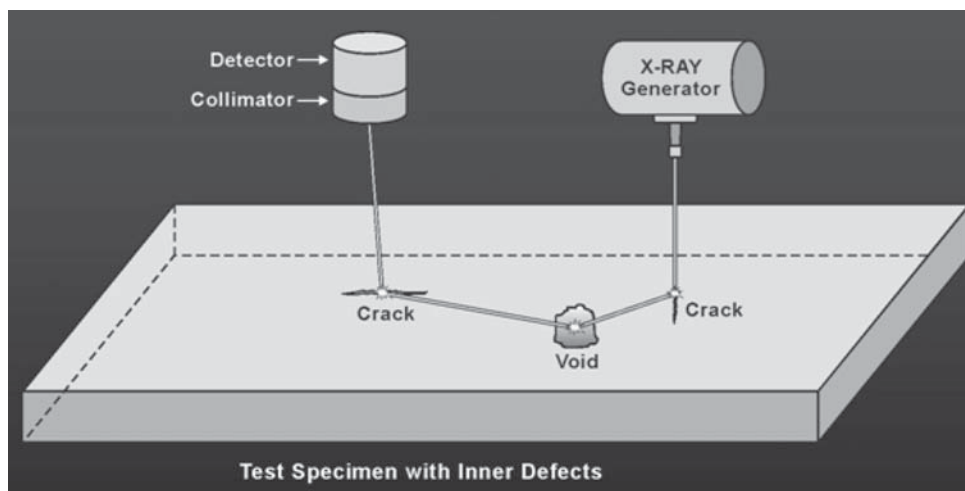
This technology is considered highly relevant for inspection purposes.

## Case Histories

One test case in Florida (unpublished). See Other Information, which follows.

## Other Information

Bjorn Birgisson is very positive about X-ray based backscatter imaging (a nuclear technology that is used by some airports for screening people and luggage). University of Florida researchers have developed and used this technology for NASA to analyze space shuttle elements. It consists of flat X-ray tubes and receivers. Birgisson indicated that he used it for spotting corrosion of reinforcing steel in concrete structural elements. It can detect cracks and corrosion. A vehicle with the equipment was able to collect data around 5 mph. He indicated that real time results are possible. The cost of the

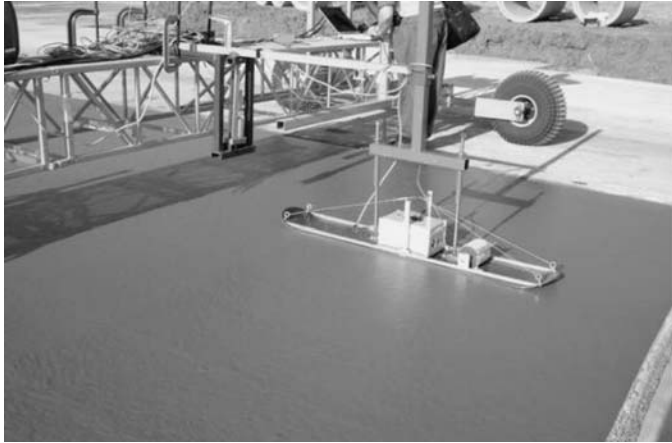


**Figure B.5. Schematic setup of X-ray backscatter technology based on RSD.**



vehicle and the equipment is around \$100,000. Birgisson expected that development of this equipment for transportation infrastructure applications will last 4 to 5 years.

## Sliding Profiler or Smoothboard



### Technology Use

The Texas DOT is in the initial implementation stage for concrete pavement. A training session attended by Texas DOT and industry representatives was conducted at U.T. Arlington in August 2007. Implementation for QC on asphalt concrete pavement projects has not yet been attempted at this time (46).

### Applications

Quality control of concrete pavement smoothness during material placement.

### Advantages

Equipment is designed to detect bumps and dips while the concrete is being placed. If a bump or dip is detected, the sliding profiler flashes a signal to notify the finishers that an area of localized roughness has been detected, thus providing them the opportunity to correct the bump or dip while the concrete is plastic. If successfully implemented, this capability can help contractors minimize, if not eliminate, the need for grinding to smooth out bumps that detract from good ride quality.

### Limitations

None identified at this time since implementation is at an early stage.

### Hardware

Instrumentation box mounted on snow board, distance wheel, mounting equipment, and power cable to attach to slip form paver's battery with switch box to turn the sliding profiler on

and off and to control actuator to lift smoothboard up or lower it down on the concrete.

### Data Acquisition Software

Embedded PC with Windows CE operating system runs sliding profiler control program.

### Data Analysis Software

Real-time processing of data from instrumentation box and distance wheel is accomplished with software running on the embedded PC found in the instrumentation box to estimate profile and find defects while concrete is being placed.

### Training of Data Analyzers

Not applicable. The sliding profiler was developed to find bumps or dips as the concrete is being placed to permit the finishers to smooth out defects while the concrete is still plastic. The operator does not run any data analysis program. Data collection and processing are all done internally on the sliding profiler's embedded PC.

### Costs

Relatively cheap (about \$5,000 at cost price per unit). Multiple units can be used to find defects on different wheel paths.

### Risks That May Impede Implementation

Lack of training on proper use of equipment; lack of understanding of what the equipment can or cannot do.

### Speed

Works at the speed of the paving train.

### Ease of Use

Readily hooked up with a paver, simple to operate. The equipment was designed to simply hook up with paver and go.

### Accuracy and Precision

Not enough data at this time to establish accuracy or precision.

### Relevance

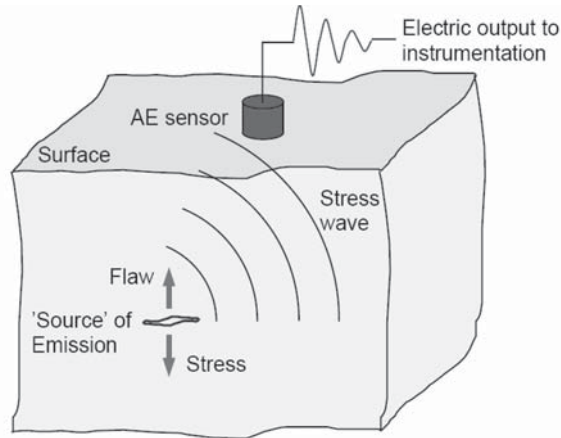
Equipment is highly relevant for QC of concrete pavement smoothness.

### Case Histories

Limited experience on field use of equipment at this time. The sliding profiler was tested on a number of projects dur-

ing the development stage. Comparisons with profile data taken with the walking profiler and rod and level after construction showed agreement with bumps determined from the sliding profiler data.

## Acoustic Emission



### Technology Use

Oregon, Illinois, and Texas DOTs have used this technology.

### Applications

- Detection of debonding of bridge deck from the girders,
- Detection of delaminations,
- Detection of wire breaks in cable stays, and
- Detection of crack growth in structural members.

### Advantages

Elementary processes of deformation and fracture near a crack edge, such as delamination or debonding, in a stressed structure generate mechanical wave motions which are collectively termed “acoustic emission” (AE). It is possible to monitor the tip velocity of a propagating crack if there is a monitoring system that localizes the AE source at different times. The advantage of this technique is that it is passive and does not require any excitation of ultrasonic signals.

### Limitations

The sensors embedded in the structure “listen” to AE signals; therefore, it is possible to relate the debonding or delamination to the number of AE signals received. Because the history of AE signals cannot be caught on existing structures, it is difficult to estimate the structural integrity of existing structures.

### Hardware

Hardware for AE technology is developed for field use.

### Data Acquisition Software

Software depends on the data acquisition system used.

### Data Analysis Software

Data analysis software has to be adapted to the specific application on detecting debonding of the deck from the girders and delamination.

### Training of Data Analyzers

Not applicable.

### Costs

Costs depend on the number of sensors applied.

### Risks That May Impede Implementation

Not yet known.

### Speed

It is anticipated that the sensors are permanently attached to the structure and that the data is available immediately.

### Ease of Use

The software can be programmed in a user-friendly manner.

### Accuracy and Precision

Not yet known.

### Relevance

The system can be used for design, construction activities, and performance monitoring.

### Case Histories

Texas DOT used AE testing for fiber-reinforced polymer bridge girders to determine fabrication and structural adequacy.

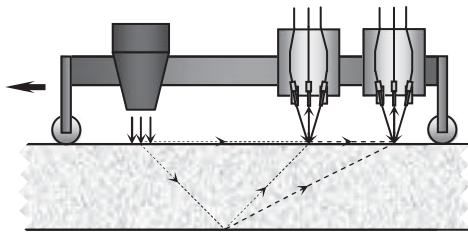
Illinois DOT used AE testing to detect wire breaks in cable stays. They did detect at least one wire break.

Oregon DOT used AE testing for detecting crack growth in steel or concrete members. According to an Oregon DOT respondent, AE testing “works well if you have correct array of sensors, but background noise of in-service structures needs to be scrubbed properly and significant expert interpretation is necessary.”

## APPENDIX C

# Use of Promising Nondestructive Testing Technologies Identified from Other Sources

### Air-Coupled Ultrasound



#### Applications

- Identification of pavement thickness,
- Identification of complex modulus of elasticity of pavements,
- Nondestructive testing of bridge decks, and
- Nondestructive testing of tunnels.

#### Advantages

This methodology is based on air-coupled ultrasound generation and air-coupled detection using microphones. The technique is completely noncontact and nondestructive; hence, it is a candidate for high-speed measurement and evaluation.

#### Limitations

Not yet known.

#### Hardware

The hardware for ultrasound generation consists of a function generator, an amplifier, and several ultrasonic transducers that build a line source; the hardware for ultrasound detection consists of microphones, preamplifiers, and a data acquisition system.

#### Data Acquisition Software

The software depends on the data acquisition system used. It can be LabView, Matlab, or any other common data acquisition software.

#### Data Analysis Software

The data analysis software can be written in Matlab.

#### Training of Data Analyzers

The training of data analyzers is similar to that for ultrasonic techniques.

#### Costs

Cost depends on the size of the unit but should be less than \$50,000.

#### Risks That May Impede Implementation

Not yet known.

#### Speed

Because the device will be designed for noncontact measurements, it can be implemented in a running vehicle.

#### Ease of Use

The software can be programmed in a user-friendly manner so that it is easy to use.

#### Accuracy and Precision

Not yet known.

## Relevance

The system can be used for design, construction activities, and performance monitoring.

## Other Information

Further information can be found at Blum et al. (47) and Zhu and Popovics (48).

## Field Spectroscopy Devices

### Applications

Several handheld spectroscopy devices are commercially available. They include X-Ray Fluorescence (XRF), Fourier Transform Infrared Spectroscopy (FTIR), and Raman devices. FTIR has been used for transportation materials on a limited basis, particularly for fingerprinting materials, such as deicing compounds and antistripping agents and occasionally for quantitative analyses, such as polymer content in asphalt. XRF has been used for paint coatings analysis, and Raman devices have been used for investigating rock mineralogy. There is potential for much broader use of these technologies for other quality assurance tests (e.g., for testing cements, paints, thermoplastics, epoxies, and asphalt emulsions). In the geotechnical area, help is needed to quantify the amount of sulfates and organics in soils because they greatly impact the effectiveness of chemical stabilization. Use of these technologies for many applications rather than traditional chemical tests can often allow faster, more accurate measurements. Typically, they also use small sample sizes, and testing can be performed in the field.

The basic operation of these units is that the field guns contain predefined chemical spectra of the material under test. The gun can be used to test that the sample in the field is in reasonable agreement with the control sample. This would be ideal for checking, for example, the supply of asphalt emulsions to construction projects. They are point-and-shoot applications that could potentially be used by field technicians. If this technology proves to be successful, individual deliveries of project materials can be tested before their use. The new equipment has become more available because of the lower cost of the device and software applications that allow easy interpretation of the results. Consequently, the use of the instrument for a wider range of applications has become much more practical.

### Advantages

- Possibility to use for a wide range of construction materials.
- Faster and cheaper than laboratory testing procedures.

## Limitations

Unknown at this time.

## Hardware

Various manufacturers provide this equipment.

## Data Acquisition Software

The software is provided by the manufacturer.

## Training of Operators

Training is needed.

## Data Analysis Software

Software is provided by the manufacturer.

## Training of Data Analyzers

Training is needed.

## Costs

The laboratory reference benchtop equipment costs approximately \$70,000. Handheld devices that use information from the benchtop equipment cost approximately \$25,000. Benchtop units may not be required if chemical spectra are available for the material under test.

## Risks That May Impede Implementation

Unknown at this time.

## Speed

Results can be obtained in minutes.

## Ease of Use

The handheld equipment appears to be easy to use. The larger laboratory reference equipment is also relatively easy to use.

## Accuracy and Precision

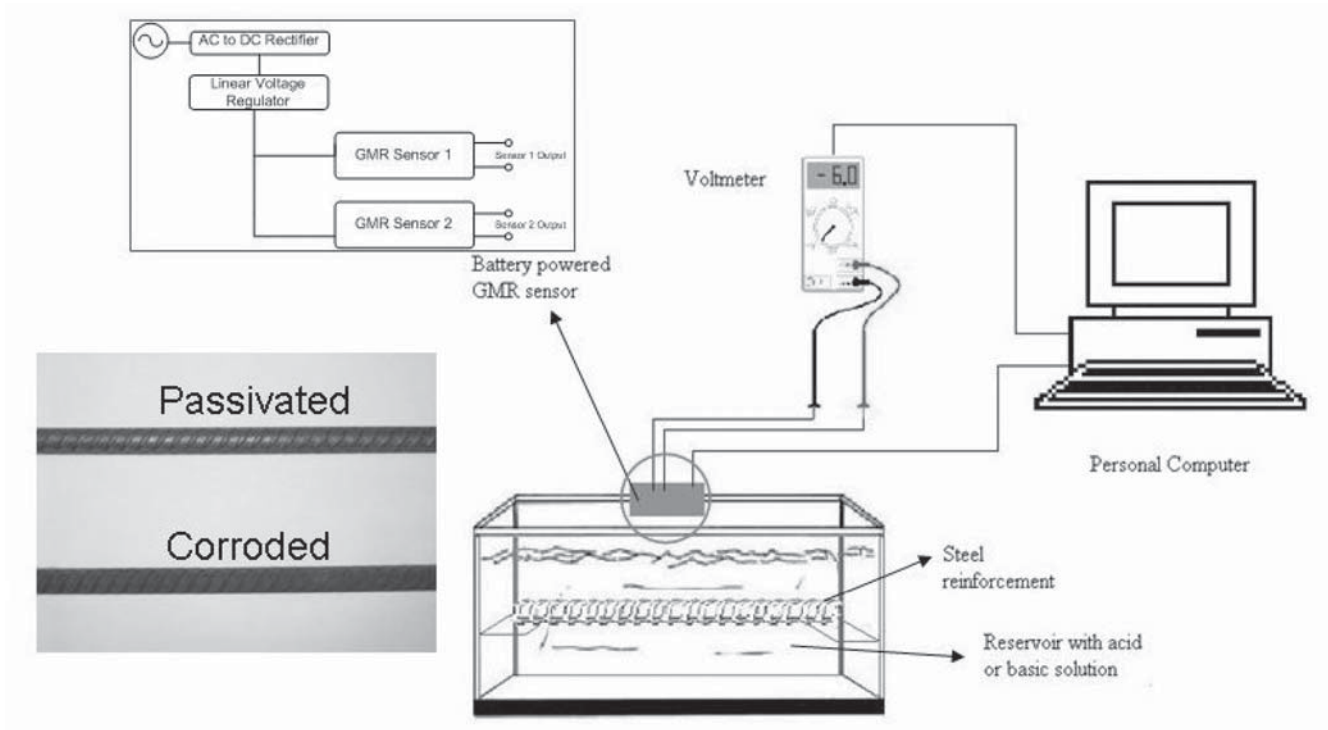
The accuracy and precision of the data are assumed to be good as long as the equipment is properly maintained and calibrated.

## Relevance

FTIR appears to be relevant for construction inspection applications.



## Magneto-resistive Sensor Technology



Experimental Setup with Giant Magneto-resistive (GMR) Sensor (49).

### Applications

Identification of corrosion rate and extent in rigid pavements, bridge components, and tunnels.

### Advantages

The magnetic (GMR) sensor offers promise for magnetic sensing of extent and rate of corrosion in concrete without having direct contact with the steel. The sensors have high sensitivity and are inexpensive and small.

### Limitations

Not yet known.

### Hardware

The hardware for corrosion sensing based on magneto-resistive sensor technology is not yet developed for field use.

### Data Acquisition Software

The software depends on the data acquisition system used. It can be LabView, Matlab, or any other common data acquisition software.

### Data Analysis Software

The data analysis software has to be developed.

### Training of Data Analyzers

Not applicable.

### Costs

The cost depends on the size of the unit but should be less than \$10,000.

### Risks That May Impede Implementation

Not yet known.

### Speed

The device can be placed in a running vehicle and instant information on the corrosion rate and extend could be obtained.

### Ease of Use

The software can be programmed in a user-friendly manner.

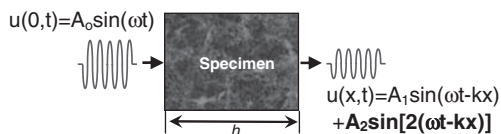
### Accuracy and Precision

Not yet known.

## Relevance

The system can be used for design, construction activities, and performance monitoring.

## Nonlinear Ultrasound



## Applications

- Identification of alkali-silica reactivity and delayed ettringite formation (ASR/DEF) deterioration in rigid pavements, bridges, and tunnels;
- Identification of fatigue life in steel members; and
- Identification of corrosion in steel reinforcement.

## Advantages

The acoustic nonlinearity parameter is an absolute material constant that can be related to the higher-order elastic constants of a material; the parameter is a directly measurable acoustic parameter that is linked to the state of material damage. As a result, nonlinear ultrasonics is unparalleled in its potential to provide a robust, quantitative characterization of fatigue damage, ASR/DEF deterioration, and corrosion in in-service structural components.

## Limitations

The acoustic nonlinearity associated with fatigue damage is small and can be easily overwhelmed by a number of other factors, especially instrumentation nonlinearity inherent to the measurement procedure. Therefore, a systematic experimental procedure that can identify and remove spurious sources of nonlinearity has to be developed, isolating only those contributions caused by the material and associated damage.

## Hardware

The hardware for nonlinear ultrasound is basically the same as for conventional ultrasonic equipment (function generator, transducers, data acquisition). Special care has to be taken of the possible nonlinear behavior of the equipment.

## Data Acquisition Software

The software depends on the data acquisition system used. It can be LabView, Matlab, or any other common data acquisition software.

## Data Analysis Software

The data analysis software has to be developed.

## Training of Data Analyzers

Training of data analyzers is needed.

## Costs

The cost depends on the size of the unit but should be less than \$50,000.

## Risks That May Impede Implementation

Not applicable.

## Speed

Because the device can be coupled with air-coupled ultrasound for noncontact measurements, it can be implemented in a running vehicle.

## Ease of Use

The software can be programmed in a user-friendly manner so that it is easy to use.

## Accuracy and Precision

Not yet known.

## Relevance

The system can be used for design, construction activities, and performance monitoring.

## Case Histories

Georgia DOT funded a research study with Georgia Institute of Technology that is using this technology for ASR detection in cement-based materials.

## A P P E N D I X D

# Research Problem Statements for Priority 1 Needs

### Demonstration Project

#### Using Both Infrared and High-Speed Ground-Penetrating Radar for Uniformity Measurements on New Hot-Mix Asphalt Layers

##### Problem Statement

There is a continuing need to improve monitoring of new hot-mix asphalt (HMA) surfaces. This is an increasingly high priority among most departments of transportation (DOTs) because:

- Many high-volume roadways are paved at night, where it is difficult to use traditional methods, and
- The adoption of the Superpave® binder and mix design standards has resulted in mixes that are stiffer and, in some instances, more difficult to compact.

Methods for monitoring quality assurance (QA) have changed little in past decades and are typically based on field cores obtained for laboratory density analysis. This method is considered slow and tedious, requires lane closures, and provides discrete sampling intervals for estimating project-level acceptance. Additionally, pavement coring is a destructive process that generates discontinuities in the pavement surface.

Two new high-speed nondestructive testing (NDT) technologies are now available that can potentially assist in this area and also provide 100% coverage. Washington DOT has pioneered infrared (IR) technologies, and has extensively used IR cameras in real time to identify thermal segregation issues with new HMA surfaces. The use of IR measurements has been incorporated into their specifications. In other areas DOTs have started to look at GPR as a potential technology to evaluate mat densities after compaction. Published reports allege that high-speed GPR technology can be used to estimate the volumetric properties of asphalt, most specifically in-place

relative compaction. An in-depth evaluation is needed to determine if both technologies can improve the QA testing of new surfaces.

##### Objectives

IR and GPR technologies have been evaluated over the past 10 years. These technologies need to be demonstrated to DOTs and recommendations made for how they can be incorporated into existing DOT specifications.

This study is divided into two phases:

- Phase 1 consists of a literature review, assembling IR and GPR technologies and demonstrating their use on a limited number of construction projects in one state. In each case validation testing will be conducted to validate that the NDT measurements do correlate with significant engineering properties. On completion of this testing, a Phase 1 report will be produced with plans on how to conduct similar tests in at least five additional DOTs.
- Phase 2 involves conducting tests at five DOTs. The project will provide training and recommendations for implementation.

##### Products

The products for this project shall consist of the following:

- Recommend ways to implement new methodologies into existing specification processes for construction purposes,
- Recommend a plan for implementing the developed methodologies, and
- Provide training materials on the developed methodologies and implementation.

**Estimated Cost: \$150,000**

## Demonstration Project

### Gamma-Gamma Logging and Thermal Integrity Testing for Newly Constructed Drill Shafts

#### Problem Statement

Ten of the 21 states that responded to a recent SHRP 2 research project questionnaire use crosshole sonic logging (CSL) for newly constructed drill-shaft integrity testing. Personnel at California and Florida DOTs have noted that this technology has significant limitations, including the inability of the method to assess integrity outside the access tubes; personnel at Oregon DOT indicated in their response that CSL results often are inconclusive. As a result, California DOT is using gamma-gamma logging to supplement CSL testing (7). Florida DOT sponsored research to investigate the use of thermal integrity testing to assess drill-shaft integrity; the results from that research do appear to be promising (8).

#### Objectives

These technologies need to be demonstrated to DOTs and recommendations made for how these technologies can be incorporated into existing DOT specifications.

This study is divided into two phases:

- Phase 1 consists of a literature review, assembling both technologies and demonstrating their use on a limited number of construction projects in one state. In each case validation testing will be conducted to validate that NDT measurements correlate with significant engineering properties. On completion of this testing, a report will be produced with plans on how to conduct similar tests in at least five additional DOTs.
- Phase 2 involves conducting tests at five DOTs. The project will provide training and recommendations for implementation.

#### Products

The products for this project shall consist of the following:

- Recommend ways of implementing these methodologies into existing specification processes for construction purposes,
- Recommend a plan for implementing the developed methodologies, and
- Provide training materials on the developed methodologies and implementation.

**Estimated Cost: \$300,000**

## Demonstration Project

### Advancing the Application of Inertial Profilers for Smoothness QA Testing

#### Problem Statement

For the traveling public, the quality of a road is typically judged by how smooth it rides. Although this may be largely subjective, measurable roadway characteristics, such as pavement roughness and road profile, are strongly related to user perception of ride quality. In fact, smooth roads have become a standard measure of pavement quality. Smooth roads are associated with lower road user costs, favorable user perceptions of quality and acceptability, longer pavement service lives, and lower life-cycle costs.

DOTs around the nation are implementing end-result smoothness specifications for their quality control/QA (QC/QA) programs. The past decade has seen a gradual but consistent transition by DOTs to move from profilograph-to profile-based smoothness specifications that use inertial profilers for QA testing of pavement smoothness for new construction and rehabilitation projects. Figures D1 and D2 summarize the state-of-practice on pavement smoothness specifications. The following observations are noted:

- Figure D1 shows that 27 states implement international roughness index (IRI)-based smoothness specifications for HMA concrete pavements, with six other states implementing smoothness specifications based on some other smoothness statistic.
- Unlike with HMA, relatively fewer states are using profile-based smoothness specifications on portland cement concrete (PCC) pavements. Out of 50 states, only seven have implemented IRI-based smoothness specifications, with five other states implementing PCC specifications based on some other ride statistic.

The survey of current practice does not include data on thin-surfaced low-volume roads that constitute a significant percentage of the road network in many states. Of the states using profile-based smoothness specifications, Texas has implemented a smoothness specification that covers QA testing of thin-surfaced roadways, for which the wearing surface consists of a one- or two-course surface treatment placed on top of the granular base. This ride specification places an IRI requirement on the finished granular base before placement of the surface treatment and was developed to improve the ride quality of the state's low-volume roadways. These roadways constitute a large chunk of the state-maintained highway network that is not covered under the state's HMA and PCC ride specifications.





Given the state-of-practice, the improvements that have been made in profiling technology, and the efforts that have been spent at state and national levels to develop implementable specifications for construction QA testing of initial pavement smoothness, this demonstration project aims to further advance the implementation of profile-based smoothness specifications by targeting three key areas:

- PCC pavements,
- Equipment verification testing, and
- Operator training.

### **Objectives**

State DOTs have used inertial profilers since the 1970s to inventory the ride quality of their highway networks. To effectively manage these networks and provide for the needs of the traveling public, agencies need to consistently measure pavement smoothness from the time the pavement is built to the time it becomes deficient. Considering the availability and affordability of inertial profilers, this project seeks to demonstrate the implementation of the technology for QC/QA testing of initial pavement smoothness and to develop recommendations on how existing and emerging methods of surface profile measurement can be incorporated into existing DOT ride specifications.

### **Work Plan**

It is proposed that the project be conducted in two phases: Phase 1 will review the state-of-practice, assembling information on agencies that have successfully transitioned from profilograph-based ride specifications to smoothness specifications based on inertial profile measurements. This review will identify key implementation issues that agencies faced and the steps taken to address them. The review will also compile the ride specifications and test methods implemented by different agencies for acceptance testing of initial pavement smoothness and verification testing of inertial profilers to ensure measurement quality. Results of ongoing national efforts, in particular the pooled fund study on “Improving the Quality of Pavement Profiler Measurement” (TPF-5[063]), shall also be reviewed to identify test standards for measuring pavement smoothness and verifying equipment that is important to successfully implementing profile-based ride specifications. On completion of Phase 1, the consultants shall prepare a technical report to document the state-of-practice and present plans for demonstrating the implementation of profile-based smoothness specifications on actual state DOT construction projects, specifically PCC pavements and thin-surfaced roadways. It is expected that these demonstrations will cover shadow testing on selected paving projects in two

or three participating DOTs. The plans shall also include demonstrations of equipment verification testing and training and certification of personnel on QA testing of pavement smoothness using inertial profilers.

After review of the Phase 1 report and on recommendation of the technical panel, the consultants will conduct the demonstration projects proposed in the Phase 1 report. It is envisioned that these trial implementation projects will cover and execute plans on how inertial profilers can be applied into existing or proposed ride specifications for construction purposes, demonstrate a process for verifying profilers to ensure the quality of test measurements, and include a program to educate DOT and contractor personnel on new procedures for acceptance testing of pavement smoothness. The consultants shall prepare a report at the end of Phase 2 to document the experience with these demonstration projects and present recommendations on how states should proceed with implementing profile-based smoothness specifications for PCC pavements and thin-surfaced low-volume roads.

### **Anticipated Products**

The anticipated products for this project shall consist of the following:

- State-of-practice of successful DOT implementation of profile-based smoothness specifications,
- Recommendations on implementing inertial profilers for QA testing of pavement smoothness on PCC pavements and thin-surfaced roadways,
- Recommendations on a process for verifying operation of inertial profilers to ensure measurement quality,
- Recommendations on a process for training DOT and contractor personnel on use of inertial profilers for QC/QA of pavement smoothness during construction, and
- Guidance document for DOT personnel on application of smoothness specifications based on inertial profilers for acceptance testing of pavement smoothness on PCC and surface treatment projects.

**Estimated Cost: \$150,000**

## **Demonstration Project**

### **Field Demonstration of Resistivity Mapping**

#### **Problem Statement**

Resistivity measurements have shown promise as an effective tool for identifying change in moisture and chemical constituents of soils below ground surface. This method supplements GPR in clayey soils, which GPR signals cannot penetrate. If proven for effective use on roadways, the resistivity method

would be an additional economical tool for geotechnical soil surveys. In conjunction with the soil borings for verification, a continuous variation in soil profile will be available to the designer. A continuous soil profile will help to provide a better design, indicate where to take borings, minimize construction delays and potential costly change orders, and reduce future maintenance costs.

### **Objectives**

Resistivity technologies need to be demonstrated to DOT personnel in order to determine the value of this technology for highway design purposes.

This study will be divided into two phases:

- Phase 1 would be a 1-year study to catalog and evaluate the systems that are already commercially available and to demonstrate systems on at least three actual highway projects under design. Personnel at Minnesota and Florida DOTs should also be contacted to document their experiences with resistivity mapping. At the end of Phase 1, the project monitoring committee will decide whether or not to proceed to Phase 2, depending on the practicality and usefulness of the demonstration testing.
- Phase 2 will involve developing or modifying existing equipment and procedures for a usable and practical field system. The system must be capable of being used on roadway pavement and for the terrain from the paved roadway edge out to the right-of-way line. It must be capable of capturing and analyzing soil data accurately to a depth of 75 ft.

### **Products**

The products for this project shall consist of the following:

- Recommend ways of implementing resistivity mapping for design purposes,
- Recommend a plan for implementing resistivity mapping, and
- Provide training materials.

**Estimated Cost: \$225,000**

## **Demonstration Project/ Focused Development**

### **Monitoring Changes in Tunnel Profiles**

#### **Project Description**

Periodic inspection of tunnels to assess changes in structural condition over time is critical to timely detection and remediation of problems to ensure road user safety. Tunnel struc-

tural problems considered widespread and potentially serious are tunnel leaks, concrete cracking, concrete spalling, concrete delamination, steel corrosion, and drainage. Monitoring of tunnel condition is the key to determining the appropriate schedule of maintenance and rehabilitation activities to remedy structural problems that might lead to accelerated deterioration and sudden tunnel failures that could cause serious injury and even fatalities.

Tunnel inspection is a challenging problem. Tunnels typically service high-volume traffic and operate in aggressive environments. Keeping tunnels open during inspection and minimizing tunnel closures and user delays must be carefully balanced with the need to conduct detailed inspections to ensure the safety of tunnel users. Consequently, non-destructive, noncontact test methods that are more automated, quantitative, and rapid and provide continuous coverage compared with conventional visual inspections need to be identified and evaluated. In this regard, a number of automated tunnel inspection systems have been developed and used in Europe and Japan. Of particular interest are systems that scan tunnel linings to detect such problems as water leaks, cracks, spalls, and delaminations. Applications of scanning laser instruments for highway condition assessment have been developed, used, and reported. There is a need to evaluate if the methodologies built into these applications can similarly be applied for assessing the condition of tunnels to provide a system for rapid early detection and screening of structural problems as a first-stage tool in a tiered diagnostic framework for tunnel condition evaluation.

### **Objective**

The objective of the proposed research is to establish a non-destructive, noncontact test method for monitoring tunnel lining profiles to provide early detection and screening of structural problems on the tunnel lining surface. It is proposed that the project be conducted in three phases:

- Phase 1 is a demonstration project of existing methodologies. This phase will cover a review of the state-of-practice in monitoring the surface condition of tunnel linings, with particular emphasis on scanning methods that offer close to 100% coverage. This review will also include scanning systems for highway condition assessment to identify data collection and processing techniques and sensors that might also be applicable for the purpose of tunnel condition assessment. Based on the review of the state-of-practice, available systems will be identified and selected for evaluation in demonstration projects proposed in Phase 1. The researchers or consultants must develop a plan for the demonstration projects that will establish criteria for evaluating the available tunnel scanning systems as to their

implementation readiness. The plan should also lay out the proposed field and laboratory tests on which the selected systems will be run as well as lay out the benchmark measurements that need to be made for verifying the output from these systems. The plan may include tests conducted in simulated tunnels under a controlled laboratory environment. Based on the test results and the review of the state-of-practice, the consultants or researchers should then provide an assessment of the status of existing technology with a view toward identifying what can be implemented in the near term and which, if any, additional development work or enhancements to existing systems are needed. Further development work will be carried out in Phase 2.

- Phase 2 is envisioned to focus on additional work that needs to be conducted to make tunnel scanning systems applicable for use in a DOT environment. This work is expected to result in enhancements to existing systems in terms of better sensors and data processing algorithms. Verification testing of the enhanced tunnel scanning systems is also to be conducted in this phase. For this purpose, the consultants or researchers should develop and execute a plan for testing the systems to verify their results. Successful systems shall move on to Phase 3.
- Phase 3 is envisioned to provide for implementation of validated tunnel scanning systems from Phase 2. This phase will provide for information dissemination and exchange to make users aware of new developments. It will include tasks to provide training on the use of the tunnel inspection and monitoring tools developed from Phase 2.

### ***Anticipated Products***

The expected products from the proposed project are automated, nondestructive, noncontact test methods for condition assessment of tunnel linings. These tools are expected to be used for early detection and screening of structural problems in a tiered diagnostic framework for tunnel condition assessment.

***Estimated Cost: \$900,000***

## **Focused NDT Development Research**

### **Strength Determination and Integrity Evaluation of Concrete Pavement and Bridge Deck Repairs Using Seismic Techniques**

#### ***Project Description***

There is a need to assess the quality of in-place road and bridge deck concrete repairs and determine when repairs can be opened to traffic. This is an increasingly high priority

among agencies because many rigid roadways and bridges are heavily trafficked where it is difficult to use traditional methods, and decisions on the opening of these repairs to traffic under accelerated construction practices are difficult.

Seismic-based NDT technologies have become automated to a level that they can provide information that can be used to assess the quality and gain in strength of the replaced materials in less than a minute. These technologies have been evaluated by such organizations as the Federal Highway Administration (FHWA) and the Department of Defense. More development is needed specifically for including data from these technologies in construction specifications relating to concrete pavement and bridge deck repairs.

### ***Objectives***

Seismic technologies need to be demonstrated to DOTs and recommendations made for how these technologies can be incorporated into existing DOT specifications.

This study will be divided into two phases:

- Phase 1 will first consist of a review of available seismic technologies that show promise for assessing strength and integrity of concrete pavement and bridge deck repairs. Then the appropriate seismic technology or technologies will be used on a limited number of construction projects in one state. In each case, validation testing will be conducted to confirm that NDT measurements correlate with significant engineering properties. On completion of this testing, a Phase 1 report will be produced with plans on how to conduct similar tests in at least five additional DOTs.
- Phase 2 will involve conducting tests at five DOTs, including training for data collection and analysis. Recommendations for implementation will be generated at the end of this phase.

### ***Products***

The products for this project shall consist of the following:

- Laboratory testing plan for how to establish target levels for seismic stiffness values (DOTs are using a range of cements with different setting characteristics; the plan will need to correlate seismic stiffness and wave speed to critical engineering properties of strength or modulus of rupture);
- Recommendations for implementing new methodologies into existing specification processes for construction purposes; and
- Training materials on the developed methodologies/implementation.

***Estimated Cost: \$450,000***



## Focused NDT Development Research

### Evaluating Applications of Field Spectroscopy Devices to Fingerprint Commonly Used Construction Materials

#### *Project Description*

Several DOTs have reported QC issues with many of the materials routinely used in highway construction. Fourier transform infrared spectroscopy (FTIR), X-ray fluorescence (XRF), and Raman technologies have been used for transportation materials on a limited basis, particularly for fingerprinting such materials as deicing compounds and antistripping agents and occasionally for such quantitative analyses as polymer content in asphalt and sulfate content of soils. There is the potential for much broader use of these technologies for other QA tests (e.g., testing of cements, paints, thermoplastics, epoxies, and asphalt emulsions). Using these new technologies for some of these applications rather than traditional chemical tests can often allow faster, more accurate measurements. Typically, the new equipment will use a small sample size that is easy to clean up.

Many advances have been made in the equipment area. The chemical composition of typical materials requires developing acceptable spectra with laboratory-based equipment. Low-cost (around \$20,000) field “guns” have become available for validating that the delivered materials have similar chemical spectra to those obtained in the laboratory. These are point-and-shoot applications that could potentially be used by field technicians. If this technology is successful, individual deliveries of project materials can be tested before they are used. The new equipment has become more available because of the lower cost of the device and software application, which allow easy interpretation of the results. Consequently, use of the instrument for a wider range of applications has become much more practical.

#### *Objectives*

The capabilities and ideal application of these guns are unknown at this time, but the potential is great. An exploratory focused development study is proposed.

The purpose of this project is to look into practical applications of XRF, FTIR, and Raman for quantitative analyses of paving materials. The researchers will need to perform a literature review to discover applications that are promising and that may have already been investigated by others. The researchers will then perform the necessary work to develop the new test procedures based on SHRP 2/DOT interest in the proposed methods. In the first round of tests it is envi-

sioned that, as a minimum, the following materials will be included:

- Determination of antistripping agents quantity,
- Determination of the quality and uniformity of asphalt emulsions and neat binders,
- Determination of the polymer content in asphalt binders,
- Determination of quality and uniformity of curing membranes,
- Determination of quality and uniformity of epoxy materials used for concrete spall repair, and
- Determination of quality and uniformity of cements.

For each material the research team will demonstrate in the laboratory how any of these technologies can capture the basic fingerprint for the material. If the material can be tested, then a sensitivity analysis will need to be conducted to determine which change in chemical composition can be readily detected. It will also be necessary to determine the feasibility of using this technology in the field on construction projects. The two materials that appear most promising for implementation will be field tested.

#### *Products*

The products for this project shall consist of the following:

- Recommendations on equipment availability, costs, reliability, capabilities, and so on;
- Results from typical construction materials; and
- Draft test procedures for any new methods developed, with guidance on equipment needed for the tests.

***Estimated Cost: \$300,000***

## Focused NDT Development Research

### Development of Continuous Deflection Sensors

#### *Project Description*

Many DOTs in the United States have large networks of distressed jointed concrete pavements in need of pavement rehabilitation. The critical factor in determining the level of repairs needed on these pavements is the condition of the joints, in particular the load transfer efficiency (LTE) of the joints. Although the LTE can be measured with traditional equipment, such as falling-weight deflectometers (FWDs), it rarely is because the measurements take too long. For long-lasting concrete pavement rehabilitation designs, it is also

critical to obtain LTE on every joint, which is cost prohibitive with the FWD. Continuous deflection profiles provide 100% coverage and permit the engineer to evaluate the entire project, locating sections that may need more extensive repair. The benefits of continuous deflection in terms of better pavement designs and improved safety for DOT personnel and the traveling public are well understood.

One device, the rolling dynamic deflectometer, can collect load transfer efficiency data more rapidly than the FWD, but its current operating speed is limited to 1 mph, which is dangerous in urban situations. Additionally, to prevent traffic congestion, the length of the project to be collected is limited because of the operation speed. Several systems are available to apply loads on pavements. Deflection sensors are needed (either contact or noncontact) that can collect load transfer efficiency data and operate at higher speeds.

### **Objective**

The purpose of this project is to initiate the development of the next-generation rolling deflection device for use on jointed concrete pavements with a target operating speed of more than 5 mph. The minimum 5-mph speed permits most project-level studies to be completed in a matter of hours rather than days.

The following tasks are envisioned as a minimum:

- **Task 1.** Develop new sensor array technology that supports continuous deflection operations of more than 5 mph. Demonstrate these sensors in a laboratory environment. Simulate field conditions with pavement timing and faulted joints.
- **Task 2.** Provide a deflection device with new-generation sensors and data acquisition capable of handling the amount of data generated. Develop the necessary hardware and software to collect, filter, and report continuous deflection data. The new system will be targeted on measuring concrete pavement deflections that are typically less than 20 mm.
- **Task 3.** Demonstrate the system. Compare the deflection device output with that obtained from a traditional deflection device, such as an FWD.

### **Products**

The products for this project shall consist of the following:

- New sensor array for a continuous deflection device,
- Data acquisition unit and data acquisition program, and
- User manual for new sensor array.

**Estimated Cost: \$225,000**

## **Focused NDT Development Research**

### **Implementation Program for Intelligent Compaction**

#### **Project Description**

Intelligent compaction technology appears to offer DOTs a 100% coverage device to test the uniformity of support immediately after compaction before the placement of the next layer. To balance the push for more rapid construction, it is critical to ensure that uniform, well-compacted support layers are being constructed. Several major problems have been documented in which large settlements and premature pavement cracking have been related to poor control when constructing lower layers. Besides the QA aspect of intelligent compaction, these systems can be used to guide the contractor as to when compaction is complete. This technology was developed in Europe over the past two decades, and efforts have been made to introduce it into the United States. The systems themselves consist of an accelerometer mounted on the vibrating drum of the steel wheel roller and a data acquisition, processing, and display system. Developments to date have been promoted by roller manufacturers, and the systems are proprietary and typically sold as options on existing rollers.

In workshops conducted by manufacturers claims are made that intelligent compaction technology can be used to test all layers in the pavement structure, including subgrade, base, and HMA. The claims have not been validated in a systematic manner. The technology often involves measuring roller movements in the z direction. Some newer systems also include a shear measurement. When changes are measured by the sensors, it is unclear which property of which layer is causing the change in readings. For example, if measurements are made on top of a base layer, are changes in sensor readings associated with variations in engineering properties of the base or the supporting layers?

Failure to implement intelligent compaction is based on a lack of understanding of which engineering property or layer is being measured. From the work completed to date, it appears that these systems are excellent at monitoring overall support condition and locating weak areas, but these weak areas may be several feet below the surface. In addition to further developing this technology, one major obstacle that needs to be addressed is how to incorporate these measurements into the contracting process and specifications. Intelligent compaction does not appear capable of replacing layer density control, which is commonly used in current contracts.

## Objective

The purpose of this project is to further develop and field test intelligent compaction technology. This will require close coordination with existing FHWA and pooled fund development efforts. The tasks for these studies are being formulated, and the work plan for this study will be designed to further promote and accelerate implementation while avoiding duplication of effort.

The following tasks are envisioned as a minimum:

- **Task 1.** Survey the availability of equipment, data processing software, applications, and international specifications that involve use of this technology. Assemble intelligent compaction technologies for use in Tasks 2 and 3 of this project.
- **Task 2.** Construct test sections with known materials of measured engineering properties. One section will be subgrade soils only, and a second will have granular base over subgrade soils. Variables in this study will be in-place stiffness and thickness of the base layer.
- **Task 3.** Demonstrate the assembled systems on the test sections constructed in Task 2. Develop a testing and validation plan.
- **Task 4.** Field demonstrate on full projects under construction.
- **Task 5.** Establish training schools for DOT personnel.
- **Task 6.** Develop tentative equipment and operator certification programs for intelligent compaction equipment.
- **Task 7.** Develop specifications on how the technology could be included in future DOT projects.

## Products

The products for this project shall consist of the following:

- Field validation of intelligent compaction technology,
- Equipment and operator certification program, and
- Tentative specifications for use by DOTs.

**Estimated Cost: \$750,000**

## Focused NDT Development Research

### Real-Time Smoothness Measurements on PCC Pavements During Construction

#### Project Description

DOTs recognize the importance of smooth riding pavements to the traveling public. Several states have already implemented smoothness specifications based on inertial profilers that offer

more accurate measurements of surface profile than the profilograph and are faster and safer to use. These specifications require measurements of surface smoothness on the finished pavement for acceptance testing. For PCC pavements, QA tests can result in significant expenditures to correct bumps after the concrete has hardened. In such instances, diamond grinding is typically done to improve ride quality, but this method of correction results in a permanent scar and a reduction of the slab thickness specified in the plans. A construction QC tool for detecting bumps during concrete placement can minimize, if not eliminate, the need for grinding by enabling the finishers to smooth out the bump while the concrete is still plastic. The potential result is a smooth riding pavement at less cost.

Efforts at developing a method for real-time measurement of PCC pavement smoothness during construction have been made. For example, in a recent research project funded by Texas DOT, a device based on a smooth board was developed for detecting bumps on newly placed concrete. There is a need to establish the level of development work conducted to date to determine and execute a plan for providing the highway community with a QC tool for real-time measurement and monitoring of PCC pavement smoothness during concrete placement.

## Objective

The proposed project seeks to develop and implement a method for real-time measurement of PCC pavement smoothness during construction that permits contractors to perform corrective actions for achieving the desired ride quality while the concrete is still plastic. The following tasks are envisioned as a minimum:

- **Task 1.** Conduct a review of recent development work in this area. Establish which methods are available for real-time measurement of PCC pavement smoothness during construction. Prepare a plan for testing existing technology.
- **Task 2.** Based on the Task 1 technology review, conduct tests on available methodologies to establish existing capabilities. It is envisioned that these tests would include laboratory and field measurements. Evaluate the test data and formulate a plan for additional development work, as necessary.
- **Task 3.** Perform the development work proposed in Task 2. Provide a proof-of-concept for the prototype developed in this task through controlled laboratory and field experiments. Prepare a plan for pilot testing the prototype on actual construction projects.
- **Task 4.** Conduct pilot equipment tests on actual construction projects following the approved plan from Task 3. Discuss proposed tests and results with engineers and contractors.

- **Task 5.** As necessary, perform modifications and refinements to the prototype based on the experience from the field tests conducted in Task 4. Conduct tests on two or three additional projects of the production version.
- **Task 6.** Document the development work in a technical report. Provide schematics of the product developed from this project, associated software, and the accompanying user manual. Present recommendations for implementing the product into existing DOT specifications for construction purposes.

### ***Anticipated Product***

The expected product from the proposed project is a QC tool for real-time measurement of PCC pavement smoothness during concrete placement. The product will include the electronics for real-time measurement of concrete smoothness, hardware for using the product with paving equipment, data acquisition and processing software, and a user manual.

***Estimated Cost: \$300,000***

## **Focused Development NDT Research**

### **Nondestructive Testing to Identify Bridge Deck Deterioration**

#### ***Project Description***

Highway agencies need to evaluate bridge deck condition to optimize the effective timing of preventive maintenance, prioritize bridge deck repair and rehabilitation, determine the scope of the required repairs, and make repair and replace decisions. The problem is that deck deterioration takes place below the surface and cannot be readily evaluated by visual means. Most older decks now have asphalt concrete or PCC overlays, making subsurface deterioration conditions even more difficult to detect. Traditional deck inspection methods, such as chain drag, half-cell potentials, and chloride content, are slow, require closures, and are not necessarily effective. Since 1999, higher-speed technologies, such as GPR, infrared thermography, and scanning impact-echo, have been developed and implemented to some extent by highway agencies to meet their needs for bridge deck condition assessment. These technologies have not been widely adapted or accepted. Agencies are not fully aware of the capabilities and limitations of these methods and how they should best be used. Some have had less than positive experiences, possibly because of unrealistic expectations and improper use.

### ***Objectives***

The objectives of this project are:

- Evaluate the strengths and limitations of bridge deck non-destructive evaluation technologies currently in use (literature review, agency interviews, and technology assessment).
- Identify different deck applications and deck types, and identify the deck inspection technologies that are most suited to these applications and deck types (review of deck and overlay designs, agency policies, and NDE technology capabilities).
- Characterize the accuracy and reliability of the technologies identified in step 2 (field evaluations of in-service decks, with follow-up ground truth).
- Recommend methodologies and protocols for the most effective application of the bridge deck NDE methods evaluated in steps 2 and 3.

### ***Products***

The products for this project shall consist of the following:

- Comprehensive review and documentation of existing procedures and equipment used for identifying deterioration in bridge decks;
- Development and documentation of a rapid, economical test or tests to be used to determine the presence, extent, and cause of deterioration; and
- Documented field verification of recommended nondestructive testing procedures and equipment.

***Estimated Cost: \$750,000***

## **Experimental NDT Research**

### **Nondestructive Testing to Identify Delaminations Between HMA Layers**

#### ***Project Description***

One of the more serious problems that can occur in HMA pavements is delaminations between HMA layers. Several instances have been documented in which pavements with delamination problems have experienced significant damage when subjected to breaking or turning action. Undetected delamination and discontinuities in asphalt pavement provide paths for moisture damage and development of other distresses, such as slippage cracks, pavement deformation, and reduction in pavement strength. A rapid, nondestructive test method is needed to determine the existence and extent of delamination and discontinuities in asphalt pavements.



## Objectives

The objective of this study is to provide a comprehensive procedure and guidance to identify the presence and extent of HMA delaminations in flexible pavements. The procedures developed in this study shall concentrate on the capability of identifying delamination and discontinuities within the upper 5 in. of asphalt pavement but not limited to the upper 5 in. The selected researchers shall investigate common conditions of past instances of major damage to HMA pavements resulting from delamination and determine key indicators that may be used to identify potential areas of delamination. Additionally, the study shall identify existing NDT procedures and equipment that have been used to evaluate the problem and determine if these methods, modifications of these methods, or new methods should be pursued to provide a rapid, effective way to determine if pavements have delamination. Although the causes of delamination and discontinuities of asphalt pavement are important, no significant time is expected to be devoted to that element in this project. The main objective of this study is to identify and develop nondestructive procedures that are capable of locating areas of delamination and discontinuities.

This study is divided into two phases:

- Phase 1 will consist of a literature review of the historical records of pavement delamination failures, methods used to identify delamination and discontinuities, and proposal of a comprehensive study/experimental plan to validate recommended approaches.
- Phase 2 shall consist of modifications, if needed, to the recommended procedures and equipment and of experiments to verify that the procedure is applicable to HMA pavements. The validation will be conducted on experimental test sections identified or constructed by the researchers. For the technologies that are successful in the first evaluation, full-scale testing on field projects will be performed.

Multiple awards are possible for researchers who propose different technologies.

## Products

The products for this project shall consist of the following:

- Comprehensive review and documentation of existing procedures and equipment used for identifying delamination and discontinuities in HMA pavements,
- Development and documentation of a rapid, economical test to determine the presence of delamination of HMA pavements, and
- Documented field verification of recommended non-destructive testing procedures and equipment.

**Estimated Cost: \$600,000**

## Unfulfilled Need

### New Technologies for Mapping Unknown Bridge Foundations

#### Project Description

For approximately 86,000 bridges in the United States the foundations are unknown. This is a significant issue because the FHWA requires agencies to conduct scour susceptibility evaluations for bridges over waterways, and foundation information is needed to conduct effective scour evaluations. A survey of state DOTs indicates that nondestructive testing to characterize unknown foundations is a top priority, but apparently no nondestructive testing technologies or techniques are used for regularly characterizing such foundations. NCHRP Projects 21-5, Determination of Unknown Subsurface Bridge Foundations, and 21-5(2), Unknown Subsurface Bridge Foundation Testing, investigated the use of various technologies for this purpose, but the project panel indicated that the results were inconclusive (6).

#### Objectives

The objective of this project is to generate effective NDT technologies that can characterize unknown foundations for bridges. Different technologies may be needed based on the construction materials used for the foundations (i.e., timber, steel, or concrete). It is proposed that the project be conducted in three phases:

Phase 1 will involve the following tasks:

- Establish experimental design criteria for characterizing unknown foundations. In particular, the accuracy level for nondestructive testing needs to be established so that end users can have confidence in the technology.
- Review past research to identify promising applications that may have been investigated by others, including the work conducted by the NCHRP 21-5 and 21-5(2) projects.

At the end of Phase 1, the research project team will recommend technologies to the project monitoring committee for approval.

- Phase 2 will involve performing the necessary work to develop the new technologies, including modifying recommended technologies, if necessary, and conducting experiments to verify that the technologies are effective in characterizing unknown foundations. The validation will be conducted on test sections identified or constructed by the researchers.
- Phase 3 is envisioned to provide for implementation of the technologies from Phase 2. This phase will provide for information dissemination and exchange to make users aware of the new developments. It will include tasks to provide training on the technologies developed from Phase 2.

### **Anticipated Products**

The anticipated products for this project shall consist of the following:

- Technologies that effectively characterize unknown bridge foundations;
- Recommendations on equipment availability, costs, reliability, capabilities, and so on;
- Results from field verification testing; and
- Draft test procedures for any new methods developed, with guidance on equipment needed for the tests.

**Estimated Cost: \$1,500,000**

### **Unfulfilled Need**

#### **Detecting Movement in Structures with Profile and Video Data**

##### **Project Description**

Most state highway networks include a large number of bridges, overpasses, and similar structures. These structures are periodically inspected using various methods. NDT methods typically provide relatively quick means to establish whether a structure is still in a serviceable condition, and maintenance programs are often prepared based on the results of these and other close inspections. More and better test methods to establish the condition of structures before damage has occurred are always needed. Even with the diligent periodic implementation of accepted procedures, bridge failures occur. The 2007 disaster in Minnesota is a painful reminder of this fact.

Many states are collecting periodic measurement of network-level ride, rut, and cracking data. Considering the availability and affordability of inertial profilers, profile data of bridge structures can easily be obtained by using these systems. Texas DOT, for example, began including inertial profile with their annual network-level data collection. Bridge and overpass structures are an important part of the network and often can deteriorate much faster because of design, dynamic loads, soil conditions, climate, and so on. The effects of these destructive factors are often subtle and not initially noticed. Dynamic loads from truck traffic alone can accelerate structural and surface damages over time. The characteristics of bridges can further affect dynamic loads and be detrimental to the bridge structure. An analysis of profile data has revealed that certain pavement structures have similar characteristics or signatures. By periodically monitoring profile characteristics of these structures, changes or movements in the structures that could result in their failures could be noted. Synchronization of video and profile data methods could enhance the process.

### **Objective**

The objective of this proposed research is to develop a method for periodically monitoring profiles from bridges and other such structures by developing a database of their profile characteristics. Common characteristics will be identified and then compared with data collected in preceding years. A procedure will be developed to detect changes in these characteristics for closer inspection. The research would include as a minimum the following tasks:

- **Task 1.** Conduct a review of development work of network-level NDT video and profile systems that could be used for characterizing bridges and other such structures in the highway system. Investigate methods for using inertial or reference profile data for detecting earth or structural movement or changes. Determine the availability of such data for use in the project. Obtain samples of this data from one or more states marking the locations of bridges or other such structures of interest. If possible, obtain recent and previous profile or video of these structures.
- **Task 2.** Develop methods for identifying the characteristics of these structures. Determine if various classes of bridge structures can be developed. Select a specific set of bridges and acquire current and past maintenance records. Develop a general bridge or overpass template or signature for the selected set. Compare surface profiles from previous years and examine for similarities. Discuss results with state engineers responsible for monitoring and establishing maintenance procedures for these structures.
- **Task 3.** Work with one or more states to establish initial procedures for periodic monitoring of bridges of the selected states. Identify methods for detecting changes in the inertial and reference profile data. If video is included, investigate methods for incorporating image processing methods that could illustrate or further clarify changes. These profiles could then be monitored periodically for surface changes. Procedures would be used for detecting small changes in specific target signatures, which could reflect earth movements and provide an early warning of changes that are detrimental to the bridge or other such structure. Discuss proposed tests and results with engineers and contractors. Implement this procedure the following year. As necessary, perform modifications and refinements to the procedure based on results.
- **Task 4.** Document the development work in a technical report. Provide the procedures developed from the project, associated software, and an accompanying user manual. Present recommendations for implementing the methods into existing DOT data collection procedures.

### **Anticipated Product**

The expected product from the proposed project is a tool to be followed for collecting and analyzing bridge profile and

video data for noting changes in these structures and how the changes can be used along with other NDT methods for determining bridge status.

**Estimated Cost: \$975,000**

## Unfulfilled Need

### Mapping Voids, Bonding, and Moisture Behind or Within Tunnel Linings and Retaining Walls

#### Project Description

Periodic inspection of tunnels to assess changes in structural condition over time is critical to timely detection and remediation of problems to ensure road user safety. Tunnel structural problems considered widespread and potentially serious are tunnel leaks, concrete cracking, concrete spalling, concrete delamination, steel corrosion, and drainage. Monitoring of tunnel condition is key to determining the appropriate schedule of maintenance and rehabilitation activities to remedy structural problems that might lead to accelerated deterioration and sudden tunnel failures that could cause serious injury and even fatalities.

Tunnel inspection is a challenging problem. Tunnels typically service high-volume traffic and operate in aggressive environments. Keeping tunnels open during inspection and minimizing tunnel closures and user delays must be carefully balanced with the need to conduct detailed inspections to ensure the safety of tunnel users. Consequently, nondestructive testing methods that are more automated, quantitative, and rapid and provide continuous coverage compared with conventional visual inspections need to be identified and evaluated. Apparently no high-speed nondestructive testing method for locating voids or moisture behind or within tunnel linings or to assess the bonding between tunnel linings and the outlying material is available. Nor is there such technology available for retaining walls, so it is expected that any technology developed for tunnels can also be applied to retaining walls.

#### Objective

The objective of the proposed research is to establish high-speed nondestructive test methods for locating voids and moisture behind or within tunnel linings and retaining walls

and to assess the bonding between tunnel linings or retaining walls and the outlying material. It is proposed that the project be conducted in three phases:

Phase 1 will involve the following tasks:

- **Task 1.** Establish experimental design criteria for characterizing voids, moisture, and bonding. In particular, the accuracy level for nondestructive testing needs to be established so that end users can have confidence in the technology.
- **Task 2.** Review past research to identify promising applications that may have been investigated by others.

At the end of Phase 1, the research project team will recommend technologies to the project monitoring committee for approval.

- Phase 2 will involve performing the necessary work to develop the new technologies, including modifying the recommended technologies, if necessary, and conducting experiments to verify that the technologies are effective in characterizing voids, moisture, and bonding. The validation will be conducted on test sections identified or constructed by the researchers.
- Phase 3 is envisioned to provide for implementation of the technologies from Phase 2. This phase will provide for information dissemination and exchange to make users aware of the new developments. It will include tasks to provide training on the technologies developed from Phase 2.

#### Anticipated Products

The anticipated products for this project shall consist of the following:

- Technologies that effectively characterize voids, bonding, and moisture behind tunnels and retaining walls;
- Recommendations on equipment availability, costs, reliability, capabilities, and so on;
- Results from verification testing; and
- Draft test procedures for any new methods developed, with guidance on equipment needed for the tests.

**Estimated Cost: \$1,800,000**

## APPENDIX E

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\*Membership as of August 2009.

## Related SHRP 2 Research

- NDT for Concrete Bridge Decks (R06-A)
- Evaluating Field Spectroscopy Devices (R06-B)
- GPR for Measuring Uniformity of New HMA Layers (R06-C)
- NDT to Identify HMA Delamination (R06-D)
- Real-Time Smoothness Measurements During Construction of PCC Pavements (R06-E)
- Developing a Continuous Deflection Device (R06-F)
- NDT for Mapping Tunnel Lining Defects (R06-G)

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