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Wireless remote strain monitoring equipment, J.F.K. Bridge, Ohio River at Louisville

Railway overpass of advanced, weldable, weathering steel, Lake Villa, Illinois

Slip form paving to extend Illinois North–South Tollway (I-355)

Research Agenda for Transportation Infrastructure Preservation and Renewal

Reports from a Conference

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TRANSPORTATION RESEARCH BOARD
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Developing a Research Agenda for Transportation Infrastructure

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Introduction

Many elements of the nation's surface transportation infrastructure are deteriorating as a consequence of aging and growing stresses. The American Recovery and Reinvestment Act of 2009 provides an initial infusion of funds for transportation infrastructure renewal and restoration, but these resources are not yet sufficient for rebuilding and sustaining the condition and performance of that infrastructure. Under these circumstances, it is particularly important to develop and deploy the best methods and technologies to support effective management of transportation infrastructure.

To respond to this challenge, the USDOT Research and Innovative Technology Administration sponsored a conference organized by the Transportation Research Board that brought infrastructure owners and decision makers together with researchers to consider problems, needs, and achievements, and to define the directions for essential research to manage and preserve the nation's surface transportation infrastructure. Participants used presentations, breakout discussions, and posters showcasing research successes to outline the challenges and opportunities facing the highway, public transit, and rail systems, and then developed a road map to help guide future research that builds on those opportunities and meets those challenges.

The work of the conference was focused on four research areas believed to be key to successful preservation and renewal of surface transportation infrastructure:

- Inventory and condition assessment methods, including technologies for intelligent infrastructure health monitoring, remote, automated sensing, and reporting;
- Innovative and environmentally responsible materials and methods for preservation, restoration, and reconstruction of transportation infrastructure;
- Strategies for rapid repair and rehabilitation, including new designs, construction procedures, contracting, incentives, and project management tools; and
- Methods to model deterioration processes, estimate life-cycle costs, and support decision making for infrastructure preservation and renewal.

There was some natural overlap among the research recommendations in these areas; this overlap provided the basis for identifying a number of important cross cutting research themes.

The research road map outlined below should serve as a guide for both research investors and producers in the deployment of resources and talent to assure the condition, performance, safety, and security of the nation's transportation system in the years ahead.

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Inventory and Condition Assessment

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One of the primary aspects of maintaining and preserving any facility is to establish records documenting the existence and condition of that facility and its components at any particular time.

The condition and performance of transportation infrastructure components and systems must be evaluated with respect to design, current and future state and expectations. How well a given facility performs is a key factor in determining its life cycle costs, needs for renewal, and in resource allocation decisions. Performance and condition measures are needed to know the current state of infrastructure components, as well as to serve as inputs to models and methods that predict that performance into the future as systems respond to environmental conditions, utilization and loading. This information can provide data-based guidance to renewal and rehabilitation decisions.

Inventory and condition assessment is a critical first step in managing and preserving transportation infrastructure; effective support for this task warrants research in at least three different areas: sensing and data collection, assessment methods, and inspection policies, standards and procedures.

1. SENSING AND DATA COLLECTION

Data collection is a key element in determining the current state of any facility. For every element of a system, there exists a *best practice* for collecting data to identify the facility and its elements, their condition and performance characteristics.

- **Create a database on sensors and their applications**. The proliferation of sensor technologies and their applications suggests the need for a unified source of information about available technologies, their most appropriate applications, their effectiveness, costs, and limitations.
- **Develop hardened sensors for field deployment**. A key concern in the deployment of infrastructure condition sensing equipment is its in-service reliability under long duration, high stress applications. Many devices are extremely sensitive and are not rugged enough for prolonged field use. There is a need to develop a tool kit of hardened sensing equipment, including both new sensors and methods to make existing systems more durable and resilient.
- **Improve data collection methods to support deterioration model development and application**. Field data from sensors is essential for developing and applying models of infrastructure system deterioration. It can be difficult to convert data streams from some sensing equipment into formats that can be readily used for model estimation and application. Research is needed to increase the compatibility between sensor outputs and models, as well as to ensure data availability for use in model development work.

2. ASSESSMENT METHODS

There are many opportunities for research that develops new methods and strategies for infrastructure system inspection and assessment. Among these are the following.

- **Define methods for rapid testing of materials and designs**. It would be easier and more efficient to bring new materials and designs into the field if credible, rapid testing methods were available. There is a need for research to expand the variety of rapid testing methods available to support new materials and technologies.
- **Establish measurement and assessment methods for new applications**. Some key transportation infrastructure elements cannot currently be inspected and evaluated because they are invisible and/or inaccessible. One example is the tie-back systems for Mechanically Stabilized Earth (MSE) retaining walls, which are buried in the fill being retained. The condition and long-term performance of these tie-backs and other invisible infrastructure components are unknown. New sensors and measurement devices are needed to fill this critical gap and thereby to ensure the functionality and safety of transportation infrastructure systems.
- **Develop nonintrusive inspection techniques**. Many inspection techniques require closure or disruption of infrastructure facilities during inspection or inspection setup. These disruptions cost time and money to users and pose risks to both users and inspection teams. Research is needed to develop unobtrusive inspection systems, including vehicle-mounted technologies that can be used in motion and high speed ground penetrating radar for detecting defects beneath a roadway surface. This equipment must be affordable to promote acquisition and use.
- **Improve bridge management systems**. Additional research is needed to improve comprehensive bridge management systems to make them more user-friendly and easily applied. The systems currently in use have strong points that could become the foundation for developing improved bridge management systems.
- **Integrate inspectability and maintainability into infrastructure design**. As new materials and designs become available, particular consideration needs to be given to ensuring their inspectability when deployed. Research is needed to define design-integrated inspection standards and to develop both inspectable designs as well as new inspection methods and technologies that support the use of advanced materials and designs.

3. INSPECTION POLICIES, STANDARDS, AND PROCEDURES

There are needs for improved policies to guide the application of inspection and monitoring techniques to reflect needs, risks, and resources. These include the following:

- **Develop risk-based assessment policies**. Newer structures should typically require less frequent inspection than older and deteriorating facilities; inspection policies should also be based on utilization, design, and functional role. Research is needed to develop inspection and monitoring policies based on such factors. That research should identify factors driving inspection strategies and establish policies that balance risk against resource limitations.
- **Create inspection policies for all transportation assets**. Transportation infrastructure assets go beyond pavements and bridges to include signs and signals, drainage systems, snow removal and de-icing systems, guard rails, and other essential components.

There is a need to develop inspection policies, standards, and technologies for these transportation assets, as well.

- **Establish uniform inventory and assessment standards**. There is a need for uniformity of inspection and inventory processes across locations and assets so that direct comparisons may be across locations, inspectors, and assets to support consistent and fact-based renewal and rehabilitation decision making.
- **Estimate the value of infrastructure monitoring**. Long term, continuous and automated monitoring of facilities and systems has become a practical option in many cases. To assure appropriate priorities on deployment of such technologies, research is needed to estimate the value and cost-benefit relationships of monitoring schemes that produce ongoing data streams for infrastructure management.
- **Develop procedures to estimate the value of infrastructure preservation**. Methods are needed to estimate the life cycle value of preservation activities to support preservation and renewal decisions. When resources are scarce, it is important to account for the total value of preservation activities when evaluating alternative investments and reinvestments.

Innovative Materials for Preservation, Restoration, and Reconstruction

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Materials are the physical building blocks that form the transportation infrastructure system, underpinning multi-modal transportation infrastructures systems that support our economy and quality of life. Research and development to find cost-effective, functional and superior performing materials is a cross cutting theme among many industries including automotive, aviation, and chemical industries. However, in transportation infrastructure, where traditional materials such as steel, concrete, asphalt and their derivatives are commonly used, introduction of new materials and material enhancing technologies is relatively slow, due to barriers to implementation: "innovation in materials is likely to follow, rather to lead, the development of infrastructure systems"*1*.

A robust materials research agenda requires a holistic view of how research can bridge the gap between system performance, sustainability, and safety and the way transportation infrastructure is planned, designed, built and managed. The materials research agenda takes into account the complex nature of materials in developing a context and a list of priorities for research in preservation and restoration of transportation infrastructure.

The organizing theme for the research agenda classifies transportation infrastructure material into three categories:

1. Existing and traditional materials;
2. Recycled materials; and
3. Innovative, advanced and smart materials.

In each category four thrust areas were identified in which advances in research, development and training can make the highest impact in filling knowledge gaps and contributing to overall system performance. These areas are: performance/intelligence, sustainability, safety, and work force development. For example, sustainability in its environmental, economical and societal dimensions is the primary driver for the use of recycled and secondary materials in transportation infrastructure. However, barriers to implementation such as environmental impact, safety, constructability and lack of functional specifications/ guidelines are areas where research can have the highest impact. Moreover outreach, education and work force training are essential actions for raising awareness and accelerating implementation.

1. EXISTING AND TRADITIONAL MATERIALS

The traditional materials used in transportation infrastructure are concrete, asphalt, various geo-aggregates, and steel. Most earthworks, pavements, railways, airports and waterways use these materials and combinations of them. The main problem to address is how to enhance the performance of these materials with due consideration for performance, sustainability and safety. A number of research topics were identified that are expected to have the highest impact

on the practice of infrastructure preservation and renewal. These topics are classified as focusing on either performance/intelligence, sustainability and safety.

Performance/Intelligence

- Develop rapid performance testing and screening tools for identification of alkali silica reactive materials, and entrained air measurement.
- Investigate the long-term performance of warm mix asphalts.
- Investigate the performance of bio-binders under service conditions.
- Investigate the performance of asphalt modifiers used for lower volume roadways as their predominant mode of failure is from environmental effects,—e.g., oxidative aging, and results in fatigue or raveling distresses later in a low volume roadways' life.
- Investigate the long-term performance of bridge deck sealants.

Sustainability

- Investigate the environmental and health benefits associated with reduced asphalt production temperatures including: lower greenhouse gas emissions, lower fuel consumption, and reduced exposure of workers to asphalt fumes.
- Expand the current knowledge on high reflectance asphalt materials and pavement surface treatments that are suitable for use in parking lots and other large paved surfaces.
- Investigate the technical and economic prospects in utilizing biorenewable resources to produce bio-binders as direct alternatives to petroleum-derived binders (100% replacement), as bitumen extenders (25% to 75% bitumen replacement), or as bitumen modifiers (<10% bitumen replacement).
- Investigate the long-term performance of asphalt modified pavements for use in low-volume roads.
- Investigate the feasibility of improving the current cement manufacturing process to minimize energy usage.

Safety

- Investigate the impact of reduced exposure of workers to asphalt fumes using warm-mix asphalt.
- Develop tools for integrity assessment of mechanically stabilized earth structures.

Crosscutting Themes

- Develop methods for accelerated testing and evaluation of materials under full-scale service conditions
- Develop improved work force training programs for using enhanced materials.

2. RECYCLED AND ALTERNATIVE MATERIALS

The global move toward sustainable infrastructure demands increased usage of recycled and alternative materials in construction. There is a wealth of information available on the physical/engineering and chemical characteristics of recycled materials from many U.S and international sources. The Recycled Material Information Database developed by FHWA (NCHRP 25-9 and 4-25), for example, provides information on 21 recycled materials for use in transportation-related applications. However, there are impediments to high volume usage including the

lack of long-term performance data. Reid outlined the main barriers to implementation as: (*a*) specifications, (*b*) test methods, (*c*) reliability and quality control, (*d*) environmental concerns, (*e*) waste regulations, (*f*) condition of contract, (*g*) planning, (*h*) supply and demand, (*i*) economics, and (*j*) lack of awareness *2*. Future research, therefore, needs to address these barriers in the context of thrust areas of performance, sustainability, safety and work-force training. A list of identified high impact research areas is given below:

Performance/Intelligence

- Investigate the feasibility of applying standards used for natural materials to recycled and alternative materials.
- Assess long-term performance of constructed systems with recycled and alternative materials under service conditions,—i.e., recycled asphalt pavements (RAP), recycled asphalt concrete (RAC), and recycled asphalt shingles (RAS).

Sustainability

- Develop materials-specific test methods and screening measures to assess environmental impacts.
- Assess constructability including processing and field placement using standard equipment.
- Develop reliability standards to account for materials variability and quality.
- Collect data and develop reliable life-cycle cost for systems built with recycled materials.

Safety

- Assess vapor emissions and leaching of contaminants.

Crosscutting Themes

- Develop and apply accelerated testing and evaluation procedures for materials under full-scale service conditions.
- Develop improved work force training programs for using recycled materials.

3. INNOVATIVE, ADVANCED, AND SMART MATERIALS

Application of advanced materials in transportation infrastructure lags behind other industries largely because material innovation is not a driver behind development of infrastructure systems. Nevertheless, the many facets of transportation infrastructure such as construction, monitoring, maintenance and system management can greatly benefit from recent advances in materials science. The vast network of our aging multi-modal infrastructure is an excellent proving ground for development and implementation of next generation intelligent structural materials, monitoring devices, and energy harvesting systems. The growing focus of these innovations is on sharpening material properties by working at the nanoscale, on the order of a few thousands atoms or molecules. The main areas where nanotechnology might have the most impact are safety (fire protection), aesthetics (design and color), comfort (climate control, temperature and noise), maintenance (self-healing, self-cleaning) and energy conservation and production (solar). For now, limited application areas and cost are the main barriers for the use of advanced materials in general and nanotechnology in particular. The transportation

infrastructure construction industry is highly risk averse, has little engagement in research, and thus is slow in adopting new material technologies. Nevertheless, the massive size and scale of the industry means that any improvement in material performance can have a significant economic impact. A summary of high-impact research areas within the established thrust areas is given below:

Performance/Intelligence

- Develop self-healing cementitious materials by design—active self-healing materials that can initiate healing by both internal and external stimuli.
- Develop better understanding of the inherent self-healing capability of cementitious materials, e.g., ways to accelerate the reaction between unhydrated cement and carbon dioxide dissolved in water to form calcium carbonate.
- Evaluate self-healing coatings made up of microcapsules on structural steel: identify best polymer building blocks and catalysts for coatings, sealants and waterproofing agents.
- Develop practical specifications for the use of shock-absorbing polyurethane that rebound to their original shape—shock barriers and guardrails.
- Identify the mechanism responsible for self-healing of microcracks in steel. Study model alloys with neutrons, X-rays, and positron techniques in combination with thermal and mechanical treatments.
- Promote practical applications of embedded sensors such as fiberoptics, nanopowders and piezo-composites for building intelligence into materials.

Sustainability/Energy

- Develop and assess innovative materials and systems to generate energy for infrastructure system operation, including: solid oxide fuel cells, high power lithium-ion batteries, hydrogen storage materials, solar cell and fuel cell materials, piezo-composites in pavement structures to convert mechanical energy to electrical power, and road-side wind turbines.

Safety

- Investigate the potential of carbon nanotubes for improving the flame retardancy of polymeric materials in lieu of toxic chemicals.
- Develop heat generating materials or technology to reduce or eliminate freezing of bridge deck surfaces.

Crosscutting Theme

- Develop and apply accelerated testing and evaluation procedures for materials under full-scale service conditions.
- Develop education and training programs for end-user engineers, constructors, and inspectors

Sources

1. *Intelligent Infrastructure Futures: The Scenarios—Toward 2055*. Foresight Programme, U. K. Office of Science and Technology, London, 2005.
2. Reid, J. M., Recycling in Transport Infrastructure. *Proceedings of the Institution of Civil Engineers, Transport*, Vol. 153, No. 4, pp. 255–262 (2002).

Strategies for Rapid Repair and Rehabilitation

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Among, the consequences of deficient and obsolete bridges and structures, pavements, and other transportation components are increased user costs, traffic delays, crashes, load limitations, facility closures, and greater uncertainty for owners and users. Rapid repair and rehabilitation techniques are highly desirable to minimize the road user and community impacts of both facility deterioration and the rehabilitation process itself. These techniques include accelerated repair and rehabilitation techniques using resilient and sustainable materials, innovative construction and contracting techniques, and improved decision making and management tools.

Among the key research thrusts that have high promise in the area of rapid repair and rehabilitation are the following:

1. ACCELERATED CONSTRUCTION METHODS

Accelerated rapid repair and rehabilitation methods minimize traffic disruption and thereby reduce the impacts of the work on the travelling public and adjacent communities. Example research activities include the following:

- Develop and test prefabricated replacement systems; rapid repair techniques and materials (i.e., composites, rapid set concrete).
- Develop rapid repair techniques that can be undertaken during limited system use (i.e., at night) or concurrently while a portion of the structure or system remains in operation (i.e., flexible techniques).
- Develop enhanced manufacturing processes including prefabricated systems for rapid repair materials and techniques—e.g., new process for manufacturing carbon fiber strengthening composite systems that make them (*a*) more cost-effective, because cost is a problem right now; and (*b*) more flexible for field installation.

2. INTEGRATE LIFE-CYCLE RESOURCE COSTS IN REHABILITATION DECISIONS

Initial (re)construction costs are often the driving factor associated with decisions about repair and renewal methods. Improved models and methods to estimate the life-cycle costs associated with various systems will result in an overall cost savings and more resilient systems. Example research activities include the following:

- Develop effective techniques to measure benefits (impacts) of renewal and rehabilitation efforts including: O&M cost, traffic delays as a function of rapidity of repair.
- Develop improved models to examine the life-cycle costs that capture the benefits of rapid repair and rehabilitation for all stakeholders.

- Develop improved methods and tools (i.e. NDE/T tools) to evaluate field performance to aid in decision making for extending service life through maintenance, repair, rehabilitation, etc.

3. SUSTAINABLE MATERIALS—WITH ENHANCED DURABILITY

Durable and recyclable materials that have a reduced impact on the environment (energy consumption and CO_2 emissions) can reduce the overall costs of repair and rehabilitation over the service life of structures. Example research activities include the following:

- Develop rapid repair and rehabilitation materials with improved long-term durability including materials that are non-corrosive and green.
- Develop rapid repair materials with self-healing characteristics and integral monitoring/NDE features.
- Develop methods to maximize efficiency of resource utilization (i.e., materials that can be recycled within the rapid repair-rehabilitation work zone).
- Develop sustainable materials measured in terms of the entire carbon footprint of a material from production through construction, operation (maintenance, repair, and amortization) and demolition (i.e., its entire service life).

4. SAFETY

Fatalities and injuries of both the traveling public and construction workforce in work zones are ever-growing issues because of increased traffic and congestion during repair and rehabilitation projects. Strategies that can greatly reduce the construction timeline through accelerated techniques, and also address safety of all stakeholders (i.e., eliminate traffic fatalities/injuries) will be critical components of accelerated repair and rehabilitation under traffic. Example research activities include the following:

- Evaluate the risk associated with rapid and 24/7 pace of construction.
- Develop methods and techniques to reduce exposure of the traveling public to construction activities.
- Measure and assess the long-term safety benefit of selected technologies.

5. SPECIFICATION AND STANDARDS

Developing guides and standards for material, design, and construction are the key features in this thrust area. A principal barrier to the implementation of new products and materials for rapid repair/rehabilitation is the fact that specifications and standards were written for older methods and materials. The absence of flexible standards and specifications can block the adoption of new approaches. Example research activities include the following:

- Develop new or modified material, design, and construction standards and specifications that support new products or materials.

- Develop inspection standards for new techniques as well as the NDE tools to aid inspectors.
- Evaluate the risks associated with rapid renewal (quality control and assurance).

6. PROJECT DELIVERY: TECHNICAL AND CONTRACTING

The construction timeline can be accelerated through incentive contracting and more efficient deployment of work forces in construction zones. Example research activities include the following:

- Identify and disseminate best organizational and technical practices for accelerating repair and rehabilitation. This may be accomplished through scanning tours, seminars and webinars.
- Develop and implement appropriate training practices to prepare professionals, inspectors, and construction workers to use advance techniques. .
- Design implementation strategies to accelerate the transition from demonstration to holistic or system wide application of innovations.
- Develop guides and tools to aid in project delivery, e.g., best practices with respect to assignment of risk to parties (owner or contractor) best able to manage such risks.
- Develop more effective reward and incentive construction programs to accelerate work without sacrificing safety or project quality.

Decision Support Methods for Infrastructure Preservation and Renewal

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Effective and efficient selection of policies and actions to monitor, report, and maintain deteriorating transportation facilities requires the ability to predict facility deterioration and life-cycle impacts. While the influences of traffic loads, design, and environmental factors on facility deterioration are widely recognized, the precise nature, extent and trajectory of this deterioration over time is difficult to quantify, model and predict. When and as facility condition deteriorates, user costs and risks also increase.

Agencies can apply a wide range of maintenance and repair policies and related actions to mitigate or even reverse deterioration. Selecting the appropriate policies or actions and the optimal timing across the network or for specific facilities is a challenging problem requiring:

- Infrastructure deterioration models using facility performance as the dependent variable and cumulative loading, design attributes, environmental conditions, past deterioration and maintenance history as the explanatory variables.
- Capturing infrastructure performance using experimental or field data.
- Data and models of agency and user cost and other impacts to capture the consequences of the actions and policies.
- Tools for strategy selection including optimization and prioritization methods that account for budget constraints, network structure and natural hazards.

Specific challenges include

- How to take advantage of the large quantities of data available through advanced inspection technologies.
- Methods to translate these large quantities of data into useable information.
- Integration of experimental data with field data.
- Recognition of the value of bottom up and top down decision making strategies.
- Accounting for the interdependencies among system components.
- Accounting for potential failures due to natural hazards by considering risk and including reliability as a performance measure.

The research agenda for decision support methods focuses on the needs of practitioners. Practitioners need documented, defensible models to support the decision making process. Existing gaps and limitations in the available models mean that systematic process or decision support systems are not used because the supporting information is not available or the results are not believable due to the quality of the inputs. Research to address these gaps will enhance the overall condition of our infrastructure and extend its life. Four thrust areas were identified as presenting both high need and high promise for success.

1. DATA AND DETERIORATION MODELS

Data and deterioration models are needed for rail, transit, and waterways and non-pavement and bridge assets associated with highways. To date, much of the focus has been on pavement and bridge assets. While these assets will continue to be important and existing models continue to be enhanced, emphasis needs to be extended to the assets associated with other modes and highway assets including signs, markings, guardrails, and other elements.

Research includes the design of conceptual models, data acquisition to support model development and prediction, and data management, including the connection between model development and decision support. The ability to access data for research and within organizations is a common limiting factor. The integration of new data collection and data management techniques is a promising area given advances in technology. Statistical issues in model development represent an ongoing concern. Examples of specific research topics include:

- Capture the value of information assessment and sharing;
- Advance applications of geospatial techniques including geographic information systems and spatial analysis;
- Develop new technologies for data collection, including
  - Wireless sensor systems,
  - Distributed sensor networks, and
  - Integrated survey equipment; and
- Create tools to integrate agency data into deterioration models.

2. BENEFITS AND PERFORMANCE

Benefit assessment and performance measurement drive the decision making process. While some agencies track an overwhelming number of performance measures, there is a need to determine the minimum set of measures that capture the performance of transportation infrastructure facilities and systems to support decision making. These measures should be driven by information needs, not by measurement capabilities. Identifying the appropriate measures and connecting them to performance objectives is also important and promising area. Ensuring that the measures reflect safety and can be used within and across modes is important. Both consequences and risks need to be managed, particularly when dealing with natural hazards. The benefits of an integrated systems approach needs to be reflected in the measures. Specific research topics include:

- Link asset management and performance management more tightly. Both are data driven processes but there are disconnects. For example, improving safety is often used as a performance goal, and many asset management activities improve safety. However, safety improvements per se are often not included in asset management strategies. Another example is using asset management tools to evaluate and improve system performance.
- Assess the impacts of strategic disinvestment so that decision makers understand the implications of their decisions.
- Promote the use of existing evaluation tools such as BCA.net.

3. SUSTAINABILITY

Sustainability includes environmental, economic and social sustainability. The use of cross modal and cross asset methods is one approach to addressing this broad definition. Life cycle assessments, which recognize environmental and energy impacts, as well as social issues, should be integrated into the decision-making process. This approach would help address such issues as climate change and stewardship. Financial sustainability is also important, and it includes not building infrastructure unless it can be maintained and operated effectively. Developing an "owner's manual" defining what is needed to operate and maintain different assets is one useful approach to identifying long term implications of infrastructure actions. Resource allocation and tradeoffs—the ability to analyze resource allocations and tradeoffs across asset classes, across modes, across infrastructure systems, and across different stages in the life cycle—are important areas for methods research.

This topic is particularly important because it captures many of the emerging issues—climate change, particularly adaptation; recognition of the potential for catastrophic failure and the impacts of natural hazards in the decision making process, protection of infrastructure resources for future generations; environmental and social impacts; and fiscal responsibility. Tools include life cycle assessment, multiobjective optimization methods, risk analysis, and vulnerability analysis.

The scale and scope of this thrust area suggests that initial research focus on providing some structure to the topic, recognizing the diverse interests of the stakeholders.

4. IMPLEMENTATION

It is important to address organizational barriers to the application of new tools for infrastructure renewal decision making. While much has been accomplished in terms of decision methods and tools, and the models needed to support decision making, few agencies have implemented sophisticated, comprehensive decision support systems. Barriers include the political process, a risk averse culture among decision makers, the fragmentation of infrastructure ownership, the complexities of the hierarchical decision making process and the challenges imposed by bidding requirements. Specific areas for research include the following:

- Develop processes and policies for better integrating decision making and data.
- Identify approaches to improving current processes and policies, including communication strategies, obtaining buy-in through demonstrations, prototypes, and partnerships.
- Create learning organizations that value innovative problem solutions.
- Develop improved strategies for workforce development. Workforce development is critical to the missions of the UTCs and RITA. The increasing interdisciplinary scope of this area underscores the limitations of existing education and training programs and argues for broader approaches.
- Create educational programs that address innovative contracting mechanisms, which also present implementation issues. Future professionals should have opportunities to learn about contract design, either through a cookbook approach or a more substantive training.

In addition to these four research thrust areas—data and deterioration models, benefits and performance, sustainability, and implementation—there are also needs and opportunities to pursue research on

- Economics and finance, including the economic impact of infrastructure, public private partnerships, estimation of benefits, and integration of risk into the decision making.
- Networks and operations, including scheduling of renewal projects and recognition of risk.

Crosscutting Themes

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A number of research and development needs arose in several areas addressed by the conference. The first five of these crosscutting needs directly address key barriers to implementing new concepts, and thus investments in these topics are likely to produce broad and important impacts on the field. The sixth, advancing technologies for condition and performance monitoring, aims to improve the quality and cost-effectiveness of information for infrastructure management decisions.

1. Methods for rapid testing of new materials and designs. Implementation of new materials and methods is commonly slowed by uncertainties about long-term effective and efficient performance. Validated and reliable accelerated testing techniques will help overcome uncertainty about such innovations. Accelerated testing techniques must be sensitive to the effects of environmental, utilization, and aging factors on component and system condition and performance. These techniques should target new and recycled materials, innovative designs, and construction methods

2. Responsive and flexible standards and specifications for new, advanced, and recycled materials, designs and systems. An important barrier to innovation and implementation is reliance on standards and specifications grounded in traditional materials and methods. A new concept may be rejected because there is no specification to support it, rather than because of inherent limitations. Updated and performance-based standards and specifications will help to advance innovation in infrastructure preservation and renewal.

3. Updated inspection standards and policies. The value of advanced sensor and monitoring technologies is limited by outdated inspection procedures. Modern and more flexible inspection standards and policies are needed to make effective use of new sensors and automated continuous monitoring capabilities, to manage inspection based on risk and condition, and to cover new materials and additional components of the transportation system.

4. Valuation methods to support infrastructure management processes. Reliable and credible information on the values of infrastructure options is needed to support more informed investment and management decisions. Research is needed to develop objective, quantitative, and monetary methods and models to estimate life cycle values for (*a*) automated monitoring technologies and methods; (*b*) preservation and renewal actions; and (*c*) keeping transportation facilities and systems in a state of good repair.

5. Training and education. Limitations of knowledge and skills about new materials and methods slow innovation in infrastructure renewal and preservation, creating a critical need to invest in transportation infrastructure education and training in universities, private entities, and public agencies. While training is not a research function, knowledge transmission is an integral part of the research process, both in academic institutions which have this dual mission, and research organizations that have a mandate to move products into practice. The training challenge is exacerbated by the need to renew the transportation infrastructure workforce at both the professional and technical levels, and it is accelerated by the rate of development of new technologies.

6. Continued development of infrastructure condition and performance sensors.

While there has been much progress on new, automated sensors and remote monitoring technologies, a variety of enhancements are needed. In particular, sensors are needed to monitor a broader range of transportation system components extending beyond pavements and bridges. Advanced technologies that can monitor hidden and inaccessible components represent special needs. New sensors are also needed that can be easily deployed with minimum disruption to operations, are hardened for long life, and are responsive to new materials and designs.

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