CAIT-UTC-066

Life Cycle Cost Reduction Road Map

FINAL REPORT
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16. Abstract

Rutgers University Center for Advanced Infrastructure and Transportation (CAIT), in collaboration with research partners within the University Transportation Center (UTC) consortium, seeks to identify knowledge gaps and chart future R&D directions that focus on Life Cycle Cost Reductions. On March 24, 2015 CAIT hosted a one-day workshop to identify opportunities for practical and breakthrough research that can reduce life cycle costs and improve decision-making in the transportation industry. The slate of participants included CAIT partners from multiple universities, transportation industry representatives, insurance providers, and national and regional government stakeholders in the transportation sector. The workshop identified pressing challenges in reducing life cycle costs, cutting-edge solutions to develop quantitative life cycle methods and opportunities for future research.

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Life-cycle, cost reduction, Maintenance practices, asset preservation, Deferred maintenance, Asset management strategies, Structural Health Monitoring (SHM), Risk Informed Optimization, Data driven decision making, Deterioration modeling

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Introduction and Description of the Problem

This report summarizes discussions that were held at the Rutgers University Center for Advanced Infrastructure and Transportation (CAIT) to identify research needs and priorities that CAIT can use to create a research roadmap on Life Cycle Cost Reduction, and ultimately a Life Cycle Cost Reduction Guideline for asset owners and operators.

In 2015, the American Society of Civil Engineers (ASCE) introduced a Grand Challenge (ASCE 2015) to "reduce the life cycle cost of infrastructure by 50 percent by 2025 and foster the optimization of infrastructure investments for society." In addition, new regulations such as the Moving Ahead for Progress in the 21st Century Act (MAP-21) (MAP-21 2012) and the Fixing America's Surface Transportation (FAST) Act (Fast Act 2015) have created challenging new requirements for managers in forecasting deterioration to prioritize preservation. With the aid of data analytics, there is now impetus to develop new guidelines and innovative approaches for reducing the total cost of building and maintaining assets. For example, new standards such as ISO 55000 (ISO 2014) provide guidance on how to deliver the best cradle-to-grave value, optimized for a range of stakeholders over a long period.

Approach and Methodology

As one of the five National Department of Transportation (DOT) University Transportation Centers (UTC), CAIT leads a consortium of eminent university research partners, and collaborates with agencies and industry partners in pursuit of long-term goals to generate solutions for the growing problems in our complex, interrelated transportation and energy infrastructures. Prior to the Council of University Transportation Centers (CUTC) meetings at Rutgers University between June 1-3, 2015, the CAIT partners initiated plans to collaboratively identify knowledge gaps and to develop a cutting edge document that addresses the challenge many infrastructure asset owners face and provide critical decision-making tools to optimize both network-level and project specific improvements. On March 24, 2015 CAIT hosted a Life Cycle Cost Reduction in Transportation Infrastructure Workshop, bringing together invited representatives from public agencies, industry, and academia to asset management best practices, cost reduction techniques and use of innovative materials.

The overarching objective of the workshop was to develop a strategic roadmap that aligns research priorities to address critical transportation infrastructure needs with the strengths and capabilities of CAIT's partners. Our intended audience is the research community, transportation owners and operators, insurance providers, and government stakeholders, each offering their unique insight and expertise. Contributing diverse perspectives, workshop participants discussed strategies to (1) build awareness of the challenges in implementing life cycle cost reduction and asset management in transportation infrastructure, (2) develop and implement cutting-edge solutions—from design/build innovations to sensing and data analytics—to help achieve optimal transportation infrastructure performance, and (3) identify opportunities for practical and breakthrough CAIT research to help the transportation industry reduce life cycle cost and improve decision-making. Prior to the workshop, participants were invited to complete an online survey related to identify: (1) challenges for reducing life cycle costs of transportation systems in the near term (2-5 years) and longer term (5-10 years), and (2) innovative capabilities (tools, methods, models) that can optimize the costs invested in infrastructure systems. The survey inputs were considered in formulating topics for full-group discussion and three parallel breakout sessions. The breakout sessions examined in more detail the aspects of the three influence areas that the participants deemed to be most important.

Brief presentations by the invited speakers launched the one-day meeting, providing examples, experiences, and context for discussion. CAIT's mission, capabilities, and current research related to transportation resilience were introduced by Ali Maher. The speakers shared their perspectives and expertise related to: (1) Defining the Life Cycle Cost Reduction Grand Challenge (Natale 2016); (2) Defining life cycle costs (Prieto 2016); (3) Defining Risk(Moon 2016); and (4) a panel discussion of life cycle cost reductions in practice by Shawn Lenahan (Port Authority of New York and New Jersey) and Michael Salvato (New York Metro Transit Authority) (Lenahan 2016, Salvato 2016).

The discussion from the workshop including the presentations and breakout groups is summarized in the report "Life Cycle Cost Reduction in Transportation Infrastructure: Workshop Results" that is included in the Appendix A (Nexight Group 2016).

The workshop and a literature review also helped to define what we mean by life cycle cost reduction and key challenge areas that build on the ASCE's Grand Challenge. A bibliography of related literature is included in Appendix B. The following subsections present a definition of life cycle cost reduction and the four areas related to the grand challenge.

Defining Life Cycle Cost Reduction

Asset owners and managers face complex challenges in maintaining a state of good repair for transportation infrastructure assets. The past century witnessed a vast growth of real assets to the tune of $3.6 trillion dollars in infrastructure (ASCE 2013) in the United States. Yet since then, there has been a steady decrease in financial resources set aside for maintenance and preservation. This creates an infrastructure funding gap that cannot be closed with new resources alone. It will require new life cycle cost analysis capabilities that support engineers in developing strategies to *reduce* the life cycle cost of infrastructure and *optimize* the investment of limited resources into infrastructure projects that create the best value.

Following the adoption of Fixing America's Surface Transportation (FAST) Act, the USDOT has increased its focus on improving mobility of people and goods, reducing congestion, promoting safety and preserving the environment. Within this context, there is an impetus to improve the durability and extend the service life of transportation infrastructure. Given the current state of the infrastructure, and the extent of built assets already in service, there is increasing pressure to preserve the existing transportation system.

Current understanding of the durability of materials resides in laboratory research of material performance, as well as in-situ, field evaluations. New technologies have been developed over the past decades that augment the capability of measuring material performance in a more quantitative means.

Through the thorough understanding of material performance, asset owners can improve their forecasting ability and better predict remaining service life.

In addition to understanding material performance, an owner's ability to extend the service life of a structure greatly depends on the timeliness of conducting critical preventive maintenance interventions. Identifying appropriate thresholds for interventions requires both extensive heuristics as well as highly-granular condition assessments. Field data collected can be analyzed and processed to determine precursors to failure mechanisms. Such indicators can provide asset owners benchmarks for action. Incorporating these benchmarks in forecasting can enhance asset management through maintaining optimal transportation infrastructure performance.

The vision of a life cycle cost reduction policy is therefore to evaluate an asset's performance over its service life considering initial capital investment as well as preventive and corrective maintenance in order to optimize costs over the life of the asset until the point of decommissioning or replacement. Figure 1 depicts the relevant areas of infrastructure research that can be engaged throughout an asset's life-cycle to enhance its optimal service life. Early in the life cycle, researchers may focus on investment strategies, planning, evaluating environmental impacts, improving feasibility study metrics, and enhanced socio-economic measurements. During the period of an asset's life where preventive and corrective maintenance is required research may focus on condition monitoring, enhanced deterioration models (both probabilistic and parametric-based), asset-wide management tools, innovative advance materials to improve repair performance, enhanced construction methods and health monitoring devices and systems. Lastly, upon an assets decommissioning, research can focus on decision-making methods for reconstruction and rebuilding, methods of decommissioning, and establishing relevant metrics for life-cycle performance of the asset.

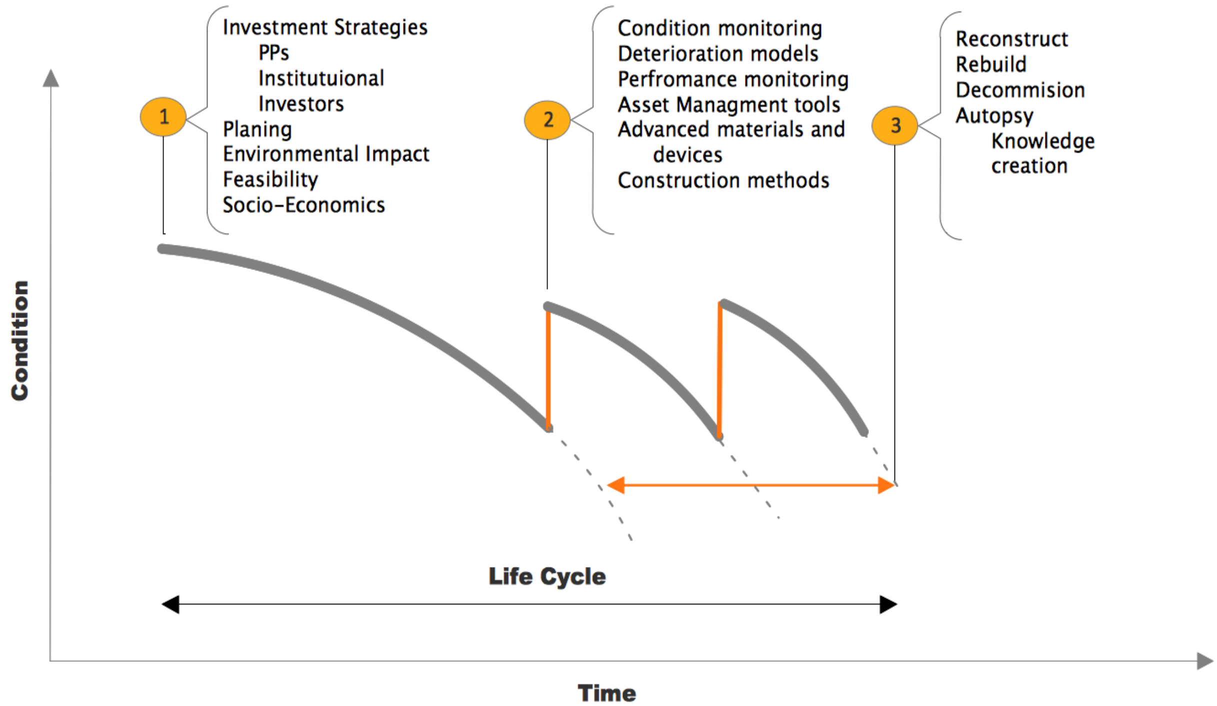

Figure 1 - life-cycle model and relevant research areas

Challenges in Life Cycle Cost Reduction

The workshop focused on identifying and addressing the main challenges faced in reducing life cycle costs of transportation infrastructure systems, identifying how cutting-edge solutions can help achieve optimal transportation infrastructure performance, and identifying opportunities for practical and breakthrough research to help reduce life cycle costs and improve decision-making.

The ASCE Grand Challenge to “reduce the life cycle cost of infrastructure by 50 percent by 2025 and foster the optimization of infrastructure investments for society” was developed as an aggressive plan to find solutions to America’s growing infrastructure crisis. The 2013 ASCE Infrastructure Report Card awarded America’s infrastructure a D+ and estimated $3.6 Trillion dollars in needed investments (ASCE 2013). Many state and local ASCE sections have followed the society’s example by creating their own local report card, outlining many similar conclusions. It is clear that the needed funding is vastly outpacing the available funding resources (Figure 2).

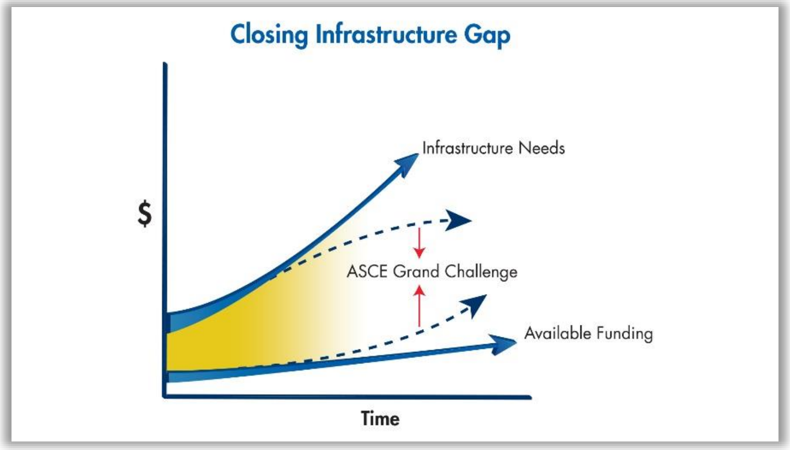

Figure 2 - ASCE Grand Challenge

ASCE recommends 4 key areas to achieve the grand challenge: life-cycle performance, performance-based standards and codes, resiliency and innovation. In addressing these key areas, ASCE formed two task committees: innovation and life-cycle analysis. Society members prepared and presented reports outlining next steps. Lastly, the ASCE Industry Leaders Council (ALC) developed a four-part strategy aligned with the key areas and created a transition committee aligned to each of the strategy elements (Natale 2016).

Using the key areas identified by ASCE, the pre-workshop survey results, the workshop presentations and the breakout discussions, four areas were identified as challenges that can be addressed by research: 1) Forecasting and data limitations; 2) Operational practices; 3) Analytic tools and methods; and 4) Institutional, political and organizational challenges. The top challenges in each of these areas are enumerated in the following section on “Findings” in a subsection on “Key Challenges”. Then building on CAITs strengths, the subsequent subsection lists solutions that can be addressed through research.

Findings

Summary of Key Challenges

Participants collectively identified the top challenges that would deliver the greatest impact if overcome. The challenges are listed in priority order in each of the four challenge areas.

Forecasting and Data Limitations

- Limited high-quality data on costs, maintenance, and deterioration
- Lack of infrastructure deterioration models
- Limited capabilities to use data from real-time monitoring to operate, maintain, and control assets
- Lack of historical price and cost records
- Difficulty determining the eventual durability and steady-state costs of emerging technologies
- Difficulty quantifying cost of consequences in determining risk
- No database of the thousands of past failures to analyze and learn from

Operational Practices

- Migrating from design standards to life cycle performance-based standards
- Introducing performance-based contracting – capital delivery is separate from O&M
- Embedding advancements in BIM and digital technology into asset management
- Providing training on new software programs and methods to compare projects consistently
- Developing skills and knowledge in the practical implementation of asset information
- Sharing data and information across industry stakeholders to improve customer experience

Analytic Tools and Methods

- Lack of decision-making tools to evaluate alternatives from a life cycle perspective
- Under-utilization of large quantities of performance data as it is hard to clean, organize, integrate
- Difficulty analyzing the multiple factors that determine the economic "sweet spot" of when to invest in rehab/replacement
- Few qualitative risk management tools to understand the value of risk mitigations
- Lack of standardized LCC analysis methodologies
- Absence of analysis with integrated performance costs to maximize performance outcomes for same cost

Institutional/Political/Organizational

- Need to adjusting funding mechanisms to prioritize life cycle (not up-front) costs
- Focus on culture of cheap, "first cost" that is difficult to overcome
- Need political support for LCCR even though payoffs may not deliver near-term cost reductions.
- Short term outlook of policymakers/politicians.
- Resistance to change from industry and politicians.
- Need to shift from requiring state of good repair to asset fit for purpose – changes decision making

Top solutions

Participants split into three breakout groups to identify potential solutions in the areas of monitoring and data collection, analytic tools and methods, and implementation (including operational practices and institutional and political change).

Monitoring and Data Collection

- Develop standard data protocols for an improved data platform to create a data registry for extraction, analysis, and dashboards
- Design analysis-driven data collection: Define deterioration > Examine past data > determine if it gave the data we needed > use analysis needs to redefine deterioration data needs
- Develop material deterioration models specific to several highly variable environments, and forecast how these may change with time
- Develop a strategy to collect hard-to-obtain data that is a collectively funded a collaborative study with states/agencies
- Adopt/improve scientific-based data analytics to best utilize limited data samples, extrapolate data larger populations, and improve accuracy

Analytic Tools and Methods

- Quantify performance from the end users' point of view—considering the public's and asset owner's perceived risk vs. the actual risk—and develop a methodology to assign value to reducing elements of risk to inform decision-making
- Define the value of assets in terms of their interdependencies in the region/network and incorporate this value in decision-making
- Develop a guidance document that outlines standardized metrics for different types of value (e.g., maintenance, safety, environment)
- Tie monitoring information to a real decision-making framework that supplies users with "actionable information" by developing "automated" data reduction algorithms to turn data into information
- Identify the type of data upper management uses to make rehab/replacement decisions, and ensure engineers are supplying the right data to give the appropriate message/context

Implementation Methods

- Develop and foster institutional knowledge through agency-university partnerships
- Prioritize training and education as a continuous process (relates to program strategy)
- Host a Legislative Day to bring asset management "money ball" to executives and legislators
- Develop a communication plan to promote LCCR concept and educate the "ecosystem" of politicians, engineers, maintenance crews, the public, and other key stakeholders; partner with APTA and AASHTO to deliver the message
- Educate stakeholders on the importance of key concepts: fit for purpose, value for money, and triple bottom line considerations (economic, environmental, and social)

Conclusions and Recommendations

Infrastructure continues to age and is in increasing disrepair as a result of dwindling funding sources. Simultaneously, asset owners are being challenged to extend the service life of assets and forecast long-term performance to establish funding needs. There is opportunity to establish fundamental changes to address the life cycle of assets and optimize for the best use of funding resources. Indeed, federal legislation and regulation is codifying the use of innovative forecasting practices to increase the efficiency of public financing. The use of life-cycle cost analysis, risk and value based assessments all provide the needed information to aid decision-makers in complying with such regulation.

Stakeholders have called upon university research to participate in the needed investigations and studies to identify technologies and methodologies that will enhance and validate forecasting, risk assessment and value-based decision-making methods. Together with agencies, designers and construction contractors, researchers can develop and help implement these new technologies and methods. In the coming decade, workshop participants and stakeholders have identified big data warehousing, analytics, risk-based prioritization methodologies and agency-university partnerships as critical areas of research. The previous section identified additional topics that can be explored and studied within the context of the stakeholder policies and procedures to better integrate technology within existing culture. Such integrations will be best accomplished through seamless and “invisible” transitions. University Transportation Centers (UTC) and consortium partners should focus on research proposals addressing these key areas.

Together with current initiatives, UTC research can help advance LCCR methodologies. The ASCE grand challenge provides a platform for agencies and universities to collaborate in implementing innovative practices by combining heuristics with advanced modeling practices, technology and innovation to establish ever more efficient forecasting tools. Ultimately this will involve both vertical and horizontal integration of effort to support collaboration and cooperation.

Finally, selecting, assembling, codifying and sharing research outcomes and lessons learned as best practices is key to successful implementation. This final step also leverages the collaborations and cooperation between and among the different levels of government, public and private sectors, and community stakeholders.

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Appendix A – Workshop Summary

Rutgers Center for Advanced Infrastructure and Transportation

Life Cycle Cost Reduction in Transportation Infrastructure

Workshop Results

March 24, 2016
Rutgers University

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Workshop Organizing Committee

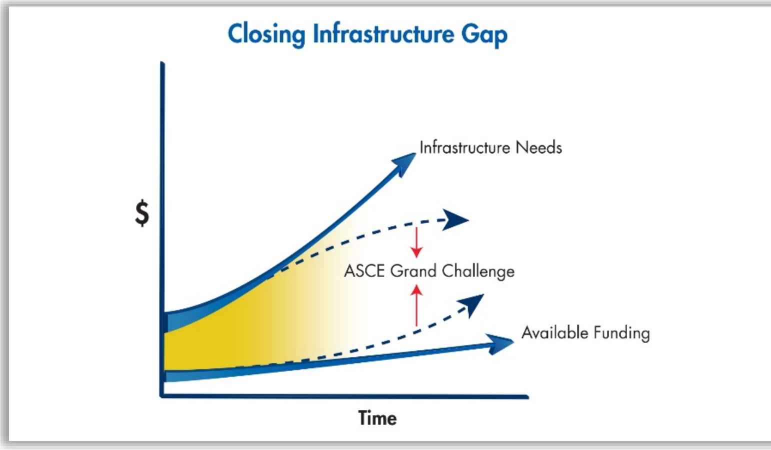
- Ali Maher, Rutgers University
- Andrés Roda, Rutgers University
- Gordana Herning, Rutgers University
- Marta Zurbriggen, Rutgers University
- Sue McNeil, University of Delaware

Facilitation Support

- Jack Eisenhauer, Nexight Group
- Lindsay Kishter, Nexight Group

WORKSHOP INTRODUCTION AND SUMMARY

Asset owners and managers face complex challenges in maintaining a state of good repair for transportation infrastructure assets. The past century witnessed a vast growth of real assets to the tune of $3 trillion dollars in infrastructure in the United States. Yet since then, there has been a steady decrease in financial resources set aside for maintenance and preservation. This creates an infrastructure funding gap that cannot be closed with new resources alone. It will require new life cycle cost analysis capabilities that support engineers in developing strategies to *reduce* the life cycle cost of infrastructure and *optimize* the investment of limited resources into infrastructure projects that create the best value.



Credit: American Society of Civil Engineers

In 2015, the American Society of Civil Engineers (ASCE) introduced a Grand Challenge to "reduce the life cycle cost of infrastructure by 50 percent by 2025 and foster the optimization of infrastructure investments for society." In addition, new regulations such as the Moving Ahead for Progress in the 21st Century Act (MAP-21) and the Fixing America's Surface Transportation (FAST) Act have created challenging new requirements for managers in forecasting deterioration to prioritize preservation. With the aid of data analytics, there is now impetus to develop new guidelines and innovative approaches for reducing the total cost of building and maintaining assets. For example, new standards such as ISO 55000 provide guidance on how to deliver the best cradle-to-grave value, optimized for a range of stakeholders over a long period.

The Rutgers University Center for Advanced Infrastructure and Transportation (CAIT) is one of five Department of Transportation (DOT) University Transportation Centers (UTCs) charged with solving growing problems in the nation's complex, interrelated transportation and energy infrastructures. CAIT has a distinct set of capabilities and expertise to tackle critical infrastructure needs, including robust modeling tools, special access to data, relationships with owners and operators, and experience with the complex transportation infrastructure. To maintain and build its national leadership in transportation system innovation, CAIT is examining how to best design research that applies CAIT's distinct capabilities to deliver practical tools and innovate solutions to industry operators.

On March 24, 2016, CAIT hosted a workshop to identify opportunities for practical and breakthrough CAIT research that can reduce life cycle cost and improve decision-making in the transportation industry. The workshop convened 33 participants, including Center partners from multiple universities, transportation industry representatives, insurance providers, and national and regional government stakeholders in the transportation sector. Participants were challenged to identify how cutting-edge solutions—from design/build innovations to sensing and data analytics—can help achieve optimal transportation infrastructure performance.

Workshop Scope and Design

The workshop was designed to identify research needs and priorities that CAIT can use to create a research roadmap on Life Cycle Cost Reduction (LCCR), and ultimately a Life Cycle Cost Reduction Guideline for asset owners and operators.

The workshop included expert presentations and panel discussions that helped to characterize life cycle cost reduction challenges and identify lessons learned from national and international case studies. Throughout the workshop, participants engaged in interactive large-group discussions and in three breakout groups to identify:

- Pressing challenges in reducing life cycle costs of transportation infrastructure systems in all areas, including design, construction, maintenance and operations, investment and financing, asset management technology and software, and infrastructure insurance.
- Cutting-edge solutions to develop quantitative life cycle cost reduction strategies that enable end users to make better capital investment decisions and optimize cost and performance over the life of their assets.
- Priority opportunities for practical and breakthrough R&D that draw upon the strengths and capabilities of Center partners.

Next Steps from the Workshop Results

This document captures the workshop's rich discussions that identified priority challenges and cutting-edge research solutions. Top challenges and solutions are summarized in the next two pages, and the complete results are presented in detail throughout the report.

CAIT will use the workshop results to develop a roadmap that will support the development of a cutting-edge Life Cycle Cost Reduction Guideline by CAIT. The guideline will ideally address the specific challenges faced by many infrastructure asset owners and provide critical decision-making tools to optimize both network-level and project-specific improvements.

The roadmap will recognize CAIT's mission to improve the state of good repair of transportation infrastructure, safety, and economic competitiveness, and build on the capabilities of the consortium of universities engaged in the UTC.

Summary of Key Challenges

Participants collectively identified the top challenges that would deliver the greatest impact if overcome. The challenges are listed in priority order in each of the four challenge areas.

Forecasting and Data Limitations

- Limited high-quality data on costs, maintenance, and deterioration
- Lack of infrastructure deterioration models
- Limited capabilities to use data from real-time monitoring to operate, maintain, and control assets
- Lack of historical price and cost records
- Difficulty determining the eventual durability and steady-state costs of emerging technologies
- Cost of consequences is difficult to quantify in determining risk
- No database of the thousands of past failures to analyze and learn from

Analytic Tools and Methods

- Lack of decision-making tools to evaluate alternatives from a life cycle perspective
- Large quantities of performance data are not yet used—it is hard to clean, organize, integrate
- Difficulty analyzing the multiple factors that determine the economic "sweet spot" of when to invest in rehab/replacement
- Developing and applying qualitative risk management to understand the value of risk mitigations
- Lack of standardized LCC analysis methodologies
- Integrating performance costs into analysis to maximize performance outcomes for same cost

Operational Practices

- Migrating from design standards to life cycle performance-based standards
- No performance-based contracting – capital delivery is separate from O&M
- Embedding advancements in BIM and digital technology into asset management
- Lack of training on new software programs and methods to compare projects consistently
- Shortage of skills and knowledge in the practical implementation of asset information
- Sharing data and information across industry stakeholders to improve customer experience

Institutional/Political/Organizational

- Adjusting funding mechanisms to prioritize life cycle (not up-front) costs
- Cheap, "first cost" focused culture that is difficult to overcome
- LCCR payoffs may not deliver near-term cost reductions – no immediate political benefit makes it difficult to garner support
- Policymakers/politicians operating with short-term outlooks
- Industry/political resistance to change
- Shifting from requiring state of good repair to asset fit for purpose – changes decision making

Summary of Top Solutions

Participants split into three breakout groups to identify potential solutions in the areas of monitoring and data collection, analytic tools and methods, and implementation (including operational practices and institutional and political change). Participants voted on the top solutions in their breakout group. The top five solutions from each group are presented here, with number of votes indicated by dots (•).

Monitoring and Data Collection

- Develop standard data protocols for an improved data platform to create a data registry for extraction, analysis, and dashboards •••••••
- Design analysis-driven data collection: Define deterioration > Examine past data > determine if it gave the data we needed > use analysis needs to redefine deterioration data needs •••••
- Develop material deterioration models specific to several highly variable environments, and forecast how these may change with time ••••
- Collectively fund a study with states/agencies to collect hard-to-obtain data •••
- Adopt/improve scientific-based data analytics to best utilize the limited data samples, extrapolate larger populations, and improve accuracy ••

Analytic Tools and Methods

- Quantify performance from the end users' point of view—considering the public's and asset owner's perceived risk vs. the actual risk—and develop a methodology to assign value to reducing elements of risk to inform decision-making •••••
- Define the value of assets in terms of their interdependencies in the region/network and incorporate this value in decision-making ••••
- Develop a guidance document that outlines standardized metrics for different types of value (e.g., maintenance, safety, environment) ••••
- Tie monitoring information to a real decision-making framework that supplies users with "actionable information" by developing "automated" data reduction algorithms to turn data into information •••
- Identify the type of data upper management uses to make rehab/replacement decisions, and ensure engineers are supplying the right data to give the appropriate message/context •••

Implementation Methods

- Develop and foster institutional knowledge through agency-university partnerships ••••
- Prioritize training and education as a continuous process (relates to program strategy) •••
- Host a Legislative Day to Bring asset management "money ball" to executives and legislators •••
- Develop a communication plan to promote LCCR concept and educate the "ecosystem" of politicians, engineers, maintenance crews, the public, and other key stakeholders; partner with APTA and AASHTO to deliver the message •••
- Educate stakeholders on the importance of key concepts: fit for purpose, value for money, and triple bottom line considerations (economic, environmental, and social) ••

INSIGHTS FROM PRESENTATIONS AND CASE STUDIES

CAIT invited a diverse group of industry experts to present on life cycle cost reduction challenges and case studies of infrastructure projects that are implementing life cycle cost analysis to inform decision-making. Presentations and panel discussions included three topic areas:

Defining the LCCR Challenge

- **The ASCE Grand Challenge**
  Presenter: Pat Natale, Vice President Business Strategies, Mott MacDonald
- **Defining Life Cycle Costs**
  Presenter: Bob Prieto, Chairman & CEO, Strategic Program Management LLC
- **Infrastructure Risk and its Primary Components**
  Presenter: Franklin Moon, PhD, Rutgers University

LCCR in Practice (Presentations and Panel Discussion)

- **Metropolitan Transportation Authority (MTA) Enterprise Asset Management**
  Presenter: Michael Salvato, Director and Program Executive, Enterprise Information, Asset Management, and Strategic Innovation, New York MTA
- **Port Authority of New York and New Jersey (PANYNJ) Enterprise Asset Management Program**
  Presenter: Shawn Lenahan, Assistant Director, Operations Programs, Office of the Chief Operating Officer, Port Authority of New York and New Jersey

LCCR Implementation beyond the Pilot Scale

- **Using Life Cycle Cost Performance for Transportation Planning**
  Presenter: Pat Natale, Vice President Business Strategies, Mott MacDonald
- **Smart Infrastructure**
  Presenter: Ajith Parlikad, PhD, University of Cambridge

Workshop participants were given the opportunity to ask questions after each presentation, and challenges, themes, and lessons learned were captured and posted in real time.

Major Themes and Lessons

- **Reaching the ASCE Grand Challenge of 50% reduction in life cycle costs by 2025 will require new opportunities to attack cost reduction throughout the full project life**: permitting, design, procurement, construction, operations, maintenance, and end of life.
  - Planning, execution, and delivery is only 20% of the project life cycle. Reductions often come from unpacking the entire value chain and making incremental improvements.
  - Analysis should consider all revenues and costs, including indirect asset costs, externalities, risk/uncertainty, initial and future capital costs, O&M costs, and user costs.
  - Time must be valued in project planning. Inefficient planning and design increase total cost, yet we often treat time like it is free. “Analysis paralysis” can eat up cost savings elsewhere.
- **Life cycle cost analysis (LCCA) and enterprise asset management (EAM) require a huge, transformational change.** Companies require sophisticated capabilities to re-engineer business processes throughout and trigger a significant cultural shift. These are very large efforts—

particularly at the beginning and during operation—that require individuals in all departments to change the way they operate. Life cycle cost analysis cannot be done in a vacuum.
    - The high-level concept of LCCA and EAM does not always resonate with the day-to-day functions and responsibilities of those involved. Behavioral change is required.
    - Businesses must understand that LCCA and EAM is mission imperative.
    - The finance community is now a fundamental stakeholder in asset management.
    - For the MTA, enterprise asset management required perhaps the largest scale transformational change since the organization's inception.
    - Operators are facing a combination of climate change risks, resilience requirements, and ongoing digitization that require this large-scale change.
- **Enterprise asset management can *create value*, not simply limit cost.** Asset management can improve efficiency, reliability, safety, operations and service, asset utilization, bond ratings, and insurance premiums.
    - Understanding value for money is essential for value creation.
- **The industry must change the focus away from only initial costs to achieve life cycle cost reduction.** Decision makers need to understand where greater investment up front might reduce maintenance requirements or extend the life of an asset. This is a significant political, cultural, and operational hurdle.
    - Current budget processes are not designed to consider life cycle cost.
    - Life cycle cost reductions aim to close the wide gap between available funding and current need—not to decrease overall funding. A two-pronged approach of increasing funding and reducing cost are needed.
- **User costs are difficult to value, but they should be considered in life cycle costs and investment decision-making.** Owners may choose higher capital projects if they produce lower user impact (costs).
- **Developing performance-based procurement standards allows bidders to innovate on means and methods in construction to reduce overall costs**.
    - Civil engineers are the stewards of infrastructure and need to be front and center in driving the cultural and behavioral change.
    - Different means and methods plus innovative design equals lowers costs—a potential 50% reduction may be possible.
    - When assets are turned over to a facility for operation, maintenance requirements should be included.
- **Companies frequently get stuck when investing in the digital infrastructure** to maintain and analyze large amounts of new data from smart infrastructure and asset management. There is no one tool to fit all needs.
    - The success of life cycle cost reduction models can be limited when data collection, cleaning, integration, and analysis capabilities are not built-in business processes.
    - Businesses must be data savvy at multiple levels of the organization to perform analysis.

CHALLENGES TO LIFE CYCLE COST ANALYSIS AND OPTIMIZATION

Workshop participants developed an organized and prioritized set of challenges to developing and implementing strategies for life cycle cost analysis and optimization in all areas—including design, construction, maintenance and operations, investment and financing, asset management technology and software, and infrastructure insurance.

Prior to the workshop, participants submitted their input via survey on the top 3–5 pressing challenges for reducing the life cycle costs of transportation systems. During the workshop, presentations from expert speakers and large group discussions also contributed additional challenges. These inputs provided a critical starting point for the breakout group discussions on specific technology, data, modeling, and institutional solutions and CAIT R&D opportunities.

Note on Prioritization

The full group of participants prioritized the list of challenges by each voting on the 4 most important challenges, considering: 1) the greatest benefit if the challenge is overcome, and 2) the ability of CAIT to contribute to a solution.

Each participant received 4 dots (representing votes), numbered in priority from 1 through 4, with 1 being the *highest* priority. Each individual number below indicates one participant vote at the indicated priority level.

Forecasting and Data Limitations (Volume, Velocity, Veracity)

- Limited high-quality data on costs, maintenance, and deterioration: **1, 1, 1, 1**, 2, 4, 4
- Using data from real-time monitoring to operate, maintain, and control assets: **1, 1**, 2, 4
- Lack of infrastructure deterioration models: **1, 1**, 2, 2, 2
- Lack of historical price and cost records: **1**, 2
- Determining eventual durability and steady-state costs of emerging technologies: **1**
- Cost of consequences is difficult to quantify in determining risk: 2, 3
- No database of thousands of failures: 3, 4
- How to treat time value of money and which factors to include: 2
- Enabling smart systems to monitor external changes on infrastructure (e.g., demand, climate): 2
- Unreliable, inconsistent, and incomplete data reporting across agency branches
- Anticipating/adapting to impacts of autonomous vehicles
- Identifying and locating assets; linking them within systems; and defining their hierarchy
- Limited availability of cost and durability data
- Assigning value to long-term risk and incorporating it into long-term analysis
- Lack of definitive and reliable data for conducting full LCCA
- Quantifying value creation, user costs, and other intangibles
- Evaluating costs that differ across the nation
- Past experience of risk may not foretell future risk

Analytic Tools and Methods

- Lack of decision-making tools to evaluate alternatives from a life cycle perspective: **1, 1, 1, 1**, 2, 2, 2, 3, 4
- Large quantities of performance data not yet being used and integrated – hard to clean, organize, integrate: 3, 3, 3, 3, 4
- Determining the "sweet spot" of when to invest in rehab/replacement – analyzing multiple factors that affect that: 2, 3, 3
- Developing and applying qualitative risk management to understand the value of risk mitigations: 2, 3, 3
- Lack of standardized LCC analysis methodologies: **1**, 3
- Integrating performance costs into analysis to maximize performance outcomes for same cost: 2
- Ability to identify proven LCC reduction strategies
- Limited tactical decision-making support from enterprise asset management systems

Additional challenges added during breakout group (not included in voting)

- Quantifying value for money – totally new and no clear methodologies
- What value metrics do we use?
    - Value = Cost, Risk, Performance
    - Implied performance is difficult to measure, e.g., reputation, beauty
- Cost is incurred at the asset level – but the value of the asset alone doesn't equal actual value. Value is network-dependent
- Incorporating feedback systems and travel time reduction into financial value
- No standard criteria for evaluating 2 different options

Operational Practices

- Migrating from design standards to life cycle performance-based standards: 3, 3, 4, 4
- No performance-based contracting – capital delivery is separate from O&M: **1**
- Embedding advancements in BIM and digital technology into asset management: 2, 4
- Lack of training on new software program and methods to compare projects consistently: 3, 4
- Shortage of skills and knowledge in the practical implementation of asset information: 3, 3
- Sharing data and information across industry stakeholders to improve customer experience: 4, 4
- Creating coordinated, enterprise asset management plans when pieces of organization have short-term requirements to deliver asset management plans
- Substantial deferred maintenance on existing systems
- Scheduling need-based bridge inspections vs. biannual inspections
- Asset owner's budget processes are not built for life cycle analysis
- How do people actually use information form models to make decisions?
- Lack of outcome + performance-based procurement + standards + difficulty of implementing that shift
- Building O&M considerations into project initiation and design

- Designing asset management plans to be flexible and adaptive to future tech and process innovations

Institutional/Political/Organizational

- Adjusting funding mechanisms to prioritize life cycle (not up-front) costs: **1**, 3, 4
- Policymakers/politicians with short-term view: **1**, 2, 4
- Resistance to change: **1**, 2
- State of good repair vs. fit for purpose – changes decision making: 2, 3
- Cheap, "first cost" focused culture: 4, 4, 4
- LCCR payoffs may not deliver near-term cost reductions – no immediate political benefit: 4
- Inconsistent agency-wide LCCA standards
- Changing "we cannot afford x" to "we cannot afford not to do x"
- Limited state and agency leadership to drive LCCR practices
- Lack of LCCA coordination within organizations (design through operation stage)
- Institutional "quirks" and funding strategies often determine the extent to which best practices are implemented
- Facilitation of knowledge transfer from other successful organizations and learn from them
- Achieving buy-in for near-term investments in LCC reduction in a constrained fiscal environment
- Limited incentives and budget constraints limit ability of some agencies to create LCCA programs
- Future O&M info only needed for a few years beyond plan, implementation, not over the asset life
- 2/4 year election cycle prevents politicians from making smart, long-term decisions
- Individual/cultural perspectives create stove piping of assets and silos
- Political decisions can trump the best option as determined by LCCA

Other

- Intermodal transit LCC analysis may offer additional opportunities for cost reduction
- Coordinating bus-bike-walk-park-rail connections for commuters and transit systems
- Difficult to reduce LCC on existing systems
- How to achieve grand challenge: 50% reduction in life cycle costs by 2025
- How to "move the needle" on innovation?
- Communication to agencies/policymakers/public why some investments are in best interest of public

BREAKOUT 1: MONITORING AND DATA COLLECTION

Participants worked in a breakout group of about 10 people to brainstorm cutting-edge solutions and priority research needs that will address the top challenges. Brainstorming focused on where CAIT's distinct capabilities can best be used and expanded to address high-priority needs.

Challenges Addressed

The Monitoring and Data Collection breakout group addressed challenges identified during the morning sessions in the **Forecasting and Data Limitations** topic area.

Potential Solutions

Breakout group participants each received three votes to select the best research solutions. After voting, breakout groups spent more time organizing, combing, and fleshing out the top ideas.

Note: Each * indicates one participant vote.

- Standard data protocols for an improved data platform to create a data registry for extraction, analysis, and dashboards
    - Better platforms for gathering and collecting data = better input/exportation ****
    - Set up standardized data collection and integration framework procedure across agencies and within an agency (format, consistency) **
    - Standard data-collection protocols for infrastructure (LTBP has them for bridges) *
    - Standard LCCA data analysis protocols (LTBP has begun for bridges)
- Process: Define deterioration > Examine past data > determine if it gave the data we needed > use analysis needs to redefine deterioration data needs
    - Analysis-driven data collection designs: "exploration vs. exploitation" *****
    - Define deterioration
- Expand material deterioration models: leverage work with weathering steel to other materials; include materials scientists, climatologists in order to inform design methods
    - Material deterioration models specific to various, highly variable environments – and forecasting how these may change with time ****
- Pool fund study with state/agencies to collect hard-to-obtain data ***
    - Key questions:
        - Who is collecting it?
        - How are they collecting it?
        - Will they share it?
        - What is the benefit to them for sharing it?
- Adopt/improve scientific-based data analytics to best utilize the limited data samples and extrapolate larger populations, improve accuracy **
- Approaches for dealing with imperfect data *
- Seek new technology to improve data quality *
- Interpretation as basis for data to be collected: *
    - Evaluate structural behavior
    - Precursors to large damage

- Incorporate periodic data to refine performance models *
- Incorporate into models at various stages: *
    - Materials science
    - Strategic Analysis
    - SHM
    - Inspection
- Means for incorporating design changes in forecasting life cycle
- Develop a real-time intelligent QC/data validation system
- Maintenance and technology purchase consolidation (with vendors)
- How many sensors are too many? Figure out how to optimize
- Identify existing useful data – what data is "good enough"? And how much?
- Interagency and public-private forums to share data approaches and train
- Connect new databases with existing ones

BREAKOUT 2: ANALYTIC TOOLS AND METHODS

Participants worked in a breakout group of about 10 people to brainstorm cutting-edge solutions and priority research needs that will address the top challenges. Brainstorming focused on where CAIT's distinct capabilities can best be used and expanded to address high-priority needs.

Challenges Addressed

The Analytic Tools and Methods breakout group addressed challenges identified during the morning sessions in the **Analytic Tools and Methods** topic area.

Potential Solutions

Breakout group participants each received three votes to select the best research solutions. After voting, breakout groups spent more time organizing, combing, and fleshing out the top ideas.

Note: Each * indicates one participant vote.

- Quantify performance from the end users' point of view**
  - Consider perceived risk vs. actual risk: **
    - Public's perceived risk
    - Owner's perceived risk
  - Develop a methodology to assign value to reducing elements of risk to inform decision-making *
- Define network value of assets and relate that value to decision-making
  - Define value of assets in terms of network dependencies ****
- Develop a guidance document that outlines standardized metrics for different types of value (e.g., maintenance, safety, environment) ****
- Tie monitoring information to a real decision-making framework – "actionable information" **
  - Develop "automated" data reduction algorithms to turn data into information *
- Identify the type of data upper management uses to make rehab/replacement decisions, and ensure engineers are supplying the right data to give the appropriate message/context ***
  - Research how owners make rehab/replace decisions and use data
    - Executives – fewest information, most correct
    - Others – more detailed data that combine up into one number at top
- Develop owner-specific, weighted evaluation criteria for various acts via cross-disciplinary surveys ***
  - Include everyone across organization to get automatic buy-in
- Develop best practice tools for decision-making process for: **
  - Regional priority projects
  - Risk management
  - LCCR opportunities
  - Refresh annual
  - Be the "Think tank" for NY/NJ/PA region (solutions that can apply to other regions)
- Develop performance based specifications for infrastructure *
  - Build an O&M-maintaining standard

- Develop data analytics tools that combine condition and operation data to deliver insight for decisions *
- Utilize ‘BEAST’ to quickly evaluate life cycle of various accelerated bridge construction concepts *
    - Accelerate aging of new systems to evaluate against conventional
- Compare value engineering process to LCCA
    - Accurately analyze data to know where it’s leading – be predictive
- Quantify user performance metrics across intermodal transit network
- Assign value to tangible components to define business case for trade-offs
    - Trade-offs now are comparing cost + risk: don’t easily compare
- Develop tools for developing a business case for technology investment
    - Systematic way of determining worth of digital infrastructure
- Determine which factors are considered in cost-benefit analysis of rehab vs. repair, or determining ideal timing - may vary year to year; how do you prove the value proposition?
    - Need a complex model to evaluate
- Use randomized sampling of data sets to determine asset condition
- Research synthesis of LCCA practices to determine best practices:
    - Within Transport
    - Across other industries
- Identify best practices in value chain from manufacturing – apply to infrastructure
    - Already done a lot of research into how to quantify value

CAIT-Specific Research Opportunities

CAIT work with NJ DOT for ABC policies and guidelines

- Add performance metrics
- Go beyond activity-based costs
- Define decision-making criteria/categories and score each category
- Challenges:
    - Calibrating results vs. expectations
    - Matching results to user’s expectation
- Automated scoring system that matches results
- How to consider different stakeholder perspectives (e.g., user, owner)
- Remove initial cost from initial consideration – focus on the expectations
- Focus nationally w/state DOTs – same methodology that can have state-specific criteria

Identify all third-party stakeholders in transport projects that must be brought in early

- Where are the interdependencies that might factor into optimized decisions?
- Identify *when* it is critical to bring them in
- Brings in multiple investors – optimize across industries
- Need to bring in third parties (RR, utilities) before design: their constraints may impact cost

Public Communication: Explain what and why, Explain tradeoffs, Celebrate successes

- Identify/research what the public values most (what drives perception)
- Develop guidance on how to communicate that

Expand risk-based prioritization of asset management to include life cycle cost

- NJ DOT Bridge – how do you prioritize maintenance/replacement based on risk?
- What is your definition of risk?
- Expand to value-based prioritization (which includes risk)
- What are the factors of stakeholder perception of risk?
- Challenge: Systematize risk-based prioritization and publicize framework around it

BREAKOUT 3: IMPLEMENTATION METHODS

Participants worked in a breakout group of about 10 people to brainstorm cutting-edge solutions and priority research needs that will address the top challenges. Brainstorming focused on where CAIT's distinct capabilities can best be used and expanded to address high-priority needs.

Challenges Addressed

The Analytic Tools and Methods breakout group addressed challenges identified during the morning sessions in the **Operational Practices** and **Institutional/Political/Organizational** topic areas.

Potential Solutions

Breakout group participants each received three votes to select the best research solutions. After voting, breakout groups spent more time organizing, combing, and fleshing out the top ideas.

Note: Each * indicates one participant vote.

- Develop and foster institutional knowledge through agency-university partnerships ****
- Prioritize training and education as a continuous process > relates to program strategy ***
- Host a Legislative Day – bring asset management "money ball" to executives and legislators ***
- Develop a communication plan to promote LCCR concept and educate the "ecosystem" *
    - Political
    - Engineers
    - Maintenance crews
    - Public
    - Other stakeholders
    - Partner with APTA and AASHTO to deliver message **
    - Collaborate with ACSE for national exposure
- Educate stakeholders on the importance of key concepts: fit for purpose, value for money, and triple bottom line considerations (economic, environmental, and social) **
- Host/convene industry-government-academic partnership with innovation labs *
- Collaborate with CSIC to develop a U.S. model *
- Stick to the basics and follow: crawl, walk, run
- Create and educate owners on data modeling forecasting
- Develop failure-mode analysis/models of critical assets with international knowledge transfer
- BIM-GIS-AM data integration
- Develop a certification for asset managers:
    - Body of knowledge
    - Maintenance and asset management
- Holistic approach
    - Multiple disciplines
    - Triple bottom line
- Innovation transfer between informational academic institutions
- Facilitate tech transfer informationally
- Host a webinar series (various stakeholder presentations)

- Leverage issues – failure to act to think long-term
- Spotlight on transformational improvements
    - Big Dig
    - MTA
    - WTC Site
- Mind shift – managing assets vs. value
- Bring awareness to the disruptive potential of Internet of Things and smart infrastructure
- ADKAR change management model (awareness; desire; knowledge; ability; reinforcement)

SOLUTIONS IDENTIFIED IN PRE-WORKSHOP INPUTS

Prior to the workshop, participants submitted their input via survey on the top 3–5 innovative capabilities—including tools, models, and methods—that can optimize the costs invested in transportation systems. Participants reviewed these solutions during large group discussions to stimulate brainstorming in the breakout groups.

Data Analysis and Decision-Making

- Develop sensors and analysis tools for managing slow processes such as deterioration
- Develop methodologies to simplify quantitative risk management and risk-based decision-making
- Develop methodologies to incorporate environment/sustainability into asset management decisions
- Develop decision-making tools based on physics-based deterioration models
- Apply value engineering analysis during the design process
- Identify resilience measures/metrics to incorporate into life cycle decision-making

Data Collection

- Connect multiple data sources to integration operations, incident, and asset management
- Conduct horizon scanning and assessment of rapidly evolving digital technologies and inform industry partners
- Develop a framework for quantifying life cycle costs due to environmental impact
- Crowdsource maintenance problems (e.g. streetbump.org)
- Collect improved data on material performance in variable climates

Asset Design and Management

- Define meaningful degradation coefficients and link them to performance to enable condition-based maintenance
- Develop NDE technologies to identify deterioration early and enable preventative action (not repair)
- Design asset management systems to capture capital and O&M costs and generate LCC KPIs
- Design for disassembly and end-of-life strategies
- Explore innovations in logistics
- Develop life cycle cost models that incorporate risk, uncertainty, and data from enterprise asset management systems
- Conduct R&D for advanced materials
- Streamlining design standards, O&M, and time can eliminate large costs

Standards and Guidance

- Develop guidance for implementing new design standards
- Incorporate ISO 55000 into other quality management frameworks
- Develop asset management training modules for industry partners
- Create guidance on reducing inventory costs through standardization and just-in-time supply chains
- Develop a transportation system best practices and benchmark database

Contracting and Funding

- Design contracting mechanisms that include performance over a specified time window
- Enable participatory design and mapping of infrastructure systems
- Develop performance-based (availability-based) contracting models

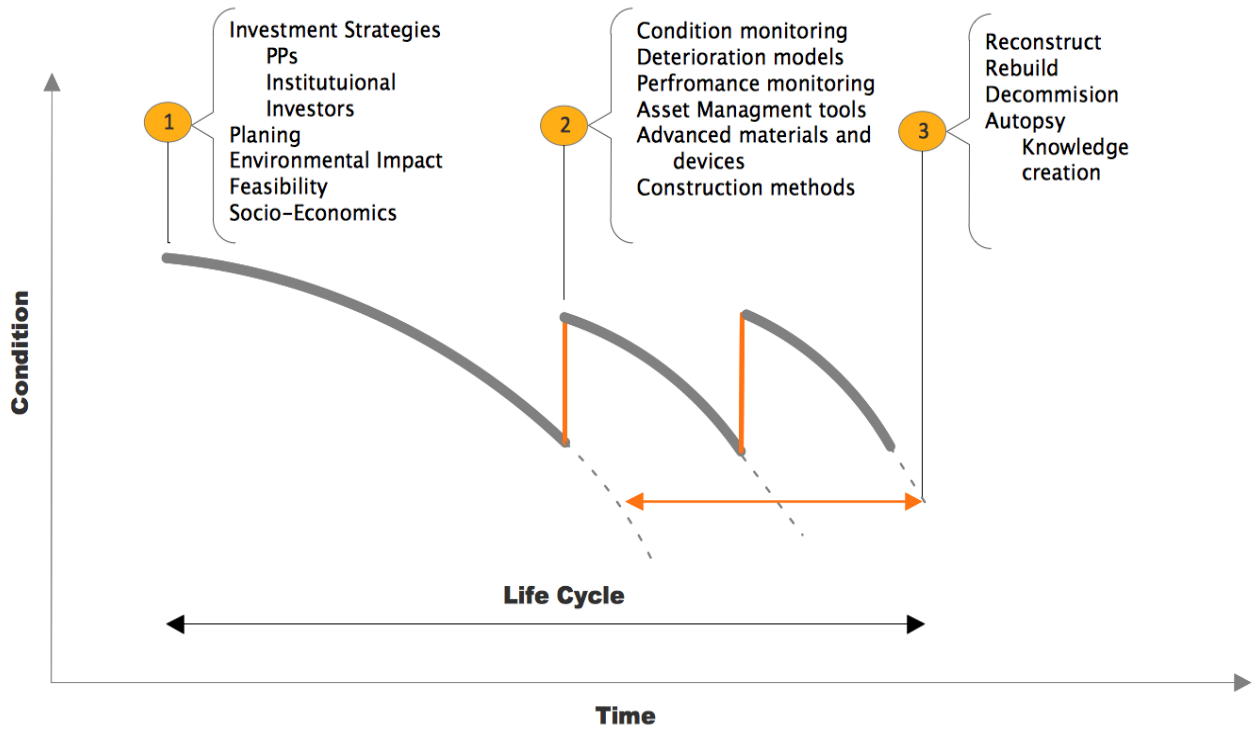
APPENDIX A: TRANSITIONING STATE OF GOOD REPAIR TO IMPROVED DURABILITY AND EXTENDED LIFE

CAIT is one of five DOT University Transportation Centers, and it has a distinct focus on the state of good repair in a complex, high-volume, multimodal corridor environment.

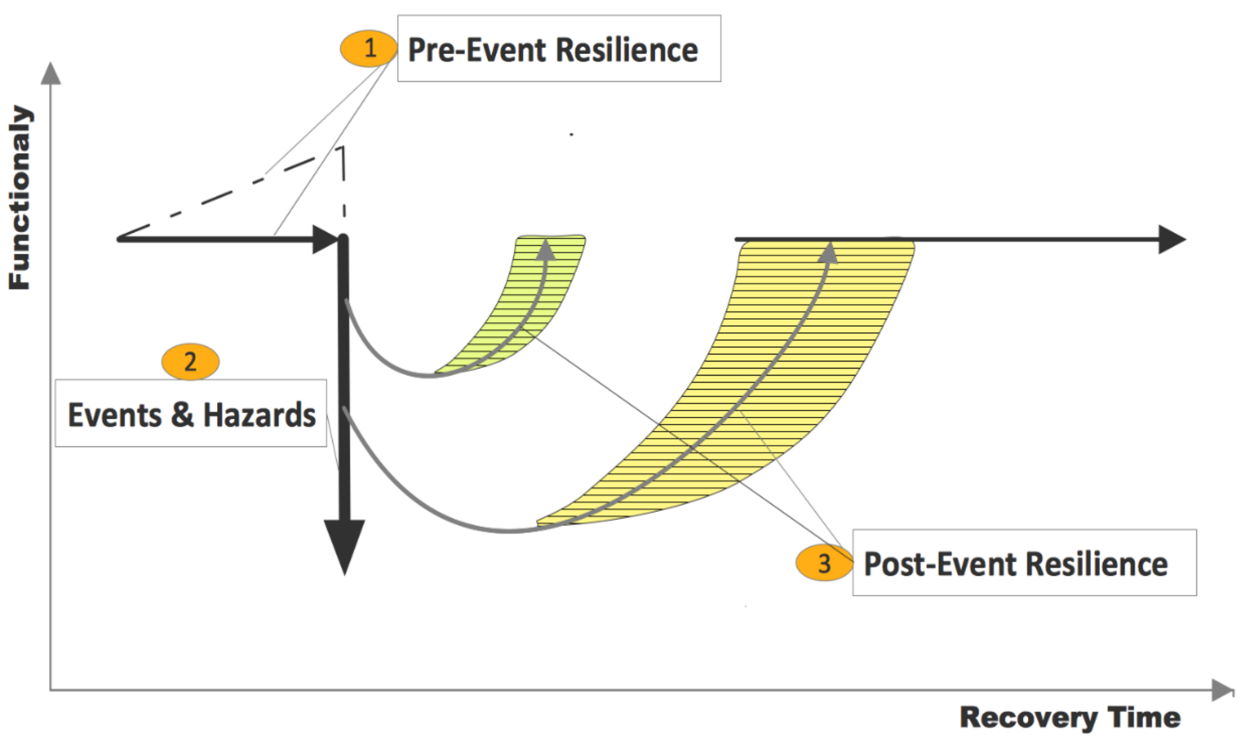
With the release of the Fixing America's Surface Transportation (FAST) Act, the transportation industry—and the CAIT research partnership—is expanding its focus to not only preserving the existing transportation system, but improving the durability and extending the life of the transportation infrastructure.

CAIT leaders recognize that if infrastructure owners and operators can reduce the life cycle cost of the transportation infrastructure while simultaneously making it more resilient, these improvements will address a host of challenges and achieve multiple FAST Act priorities. The following diagrams represent the relevant life cycle cost reduction areas and infrastructure resilience areas where CAIT is working to align its research with priority industry needs.

Relevant Life Cycle Research Areas



Infrastructure Resilience Framework



APPENDIX B: WORKSHOP AGENDA

Time	Activity	Presenter
8:00 – 8:30 am	Breakfast and registration	
8:30 – 9:00 am	**Welcome, Introductions, and Objectives** • CAIT's mission and capabilities	Ali Maher
9:00 – 9:45 am	**Defining the LCCR Challenge:** • Life-Cycle and the Grand Challenge • Defining Life Cycle Costs • Defining Risk	 A. Bartolomeo Bob Prieto Frank Moon
9:45 – 10:00 am	**Q&A and Summary of Key Points**	Facilitator
10:00 – 10:15 am	Break	
10:15 – 10:55 am	**Panel Discussion – LCCR in Practice:** • PANYNJ • MTA	 Shawn Lenahan Michael Salvato
10:55 – 11:00 am	**Summary of Key Points**	Facilitator
11:00 – 12:00	**Facilitated Discussion: Challenges of Implementing LCCR**	Facilitator
12:00 – 1:00 pm	Lunch and networking	
1:00 – 1:40 pm	**LCCR Implementation Beyond the Pilot Scale:** • Using Life Cycle Cost Performance • International Perspective	 Patrick J. Natale Ajith Parlikad, Ph.D.
1:40 – 1:45 pm	Instructions for Breakout Discussions	Facilitator
1:45 – 2:30 pm	**Breakout Groups: Research Needs to Address LCCR Challenges**	Facilitator
2:30 – 2:45 pm	**Report outs**	
2:45 – 3:00 pm	Break	
3:00 – 3:45 pm	**Breakout Groups: Aligning UTC Capabilities to Priority Research Needs**	Facilitator
3:45 – 4:00 pm	**Report outs**	
4:00 – 4:15 pm	**Integrating Priorities**	Facilitator
4:15 – 4:30 pm	**Next Steps**	Ali Maher
4:30 pm	Adjourn	

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Appendix B – Bibiliography – Related Literature

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