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Collaborative Proposal on Resilience: Definitions, Measurement, Tools and Research Opportunities

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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 resilience of and interactions between the critical infrastructure sectors. In particular, lifeline sectors including transportation, energy, communication, water and wastewater, and emergency services are of interest. On December 4, 2015, CAIT hosted a one-day workshop with an aim to develop a roadmap for research priorities based on the emerging infrastructure risks and on the distinct capabilities of the Center partners. Invited participants from public agencies, industry, and universities engaged in facilitated discussions to identify top priorities for building 1) pre-event resilience, 2) characterizing hazard events, and 3) accelerating post-event resilience. Workshop conclusions and a review of published literature indicate key challenges and research opportunities including an improved understanding of interdependencies across critical sectors; establishing robust, implementable resilience metrics, more precise characterization of system vulnerabilities, and prioritization of funding for infrastructure interventions.

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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 address critical infrastructure needs, emerging challenges, and solutions that can impact the resilience of interdependent transportation and lifeline systems, which enable mobility of people and commodities and provide essential services including energy, telecommunication, water supply and emergency services.

Recognizing the sixteen critical infrastructure sectors (chemical; commercial facilities; communications; critical manufacturing; dams; defense industrial base; emergency services; energy; financial services; food and agriculture; government facilities; healthcare and public health; information technology; nuclear reactors; materials and waste; transportation systems; and water and wastewater systems) defined in Presidential Policy Directive 21 (PPD-21, 2013): Critical Infrastructure Security and Resilience, our focus is on the interdependent transportation and lifeline systems. Specifically, the lifeline systems of interest are communications, emergency services, energy, and water and wastewater.

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 chart future R&D directions that would focus on resilience of, and interactions between, the critical infrastructure sectors. On December 4, 2015 CAIT hosted a Resiliency of Transportation Infrastructure Workshop, bringing together invited representatives from public agencies, industry, and academia to discuss the emerging infrastructure risks and innovative tools that can advance the standards of resilient engineering.

The overarching objective of the workshop was to develop a research roadmap for improving infrastructure resilience that identifies critical infrastructure needs within agencies and communities, and aligns those needs with capabilities and interests of the CAIT researchers and partners. Our intended audience is the research community and stakeholders interested in understanding and improving infrastructure resilience. Contributing diverse perspectives, workshop participants characterized influences on the infrastructure condition related to: (1) anticipated hazardous events, (2) pre-event system resilience, and (3) post-event system resilience. Prior to the workshop, participants were invited to complete an online survey related to: (1) challenges in improving resilience of transportation systems in the near term (2-5 years) and long term (5-10 years), and (2) innovative capabilities such as tools, methods, and models that can advance the design of resilient 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 (Director of CAIT) and Sue McNeil (CAIT collaborator from University of Delaware), representatives of the workshop organizing committee. The speakers[1] shared their perspectives and expertise related to: (1) large-scale engineering and construction disaster response and recovery – by Bob Prieto (Strategic Program Management, LLC) (2) climate change effects on transportation system resiliency – by Michael Meyer (Parsons Brinckerhoff); (3) freight system fragility and institutional responses – by Craig Philip (Vanderbilt University); (4) risk-based analysis of complex and interdependent cyber-physical systems – by Adam Hutter (Department of Homeland Security) on behalf of Jalal Mapar (Department of Homeland Security); and (5) regional planning for transportation assets based on vulnerabilities documented after extreme weather events – by Jeff Perlman (North Jersey Transportation Planning Authority). The workshop summary (Nexight Group 2015) is included as a supplemental document. Information about the agenda, presenters and participants are contained in Appendix B and Appendix C of the workshop summary.

Transportation system disruptions arise from the growing service demands on the deteriorating infrastructure, and from the increasingly frequent, natural, anthropogenic, singular and multi-hazard extreme events. These disruptions may compound and escalate rapidly depending on structural condition and age, functional demands, system redundancy, population density, and congestion of the transportation and lifeline systems. The compounded disruptions may also arise due to the complex interdependencies that exist between the specific types of infrastructure systems. Damage or failure of one system may initiate cascading disruptions in other co-located or dependent systems, thereby increasing the potential for system-wide and regional disturbances, monetary losses, and broader social consequences. Workshop participants reflected on the importance of addressing criticalities across the interdependent sectors and prioritization of funding for infrastructure interventions as the primary challenges. These were identified as critical emergent needs in each of the three breakout sessions pertaining to pre-event resilience, hazards and events, and post-event resilience.

Related to the major challenges for achieving *pre-event resilience*, participants identified the lack of meaningful and accepted resilience goals and metrics that would be incorporated in decision-making, engineering design and operations. Also, to characterize vulnerabilities to potential damage scenarios, and better understand the behavior of regional transportation networks, data analytics of past hazard events are important. Primary concerns related to potential *hazards and events* included the effects of climate change, increased frequency, magnitude, and consequences of weather events, prioritization of limited funds to renew and upgrade aging infrastructure, and accidental or deliberate threats. Priority

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[1] Information about the speakers can be found in the workshop summary report included as a supplemental document.

areas for *post-event resilience* include development of methods to rapidly replace transportation assets that are at or near capacity, remediation measures to extend the service life of assets, response and recovery prioritization processes, and creating network redundancy through transit alternatives (e.g., high-speed rail vs. highways).

Participants considered the relative importance of the emerging challenges and potential technology solutions that would impact resilient design of infrastructure systems, which led to prioritized recommendations for pursuing advances in: (1) the enabling technology, data, and modeling solutions, and (2) new relevant research directions and opportunities. Recognizing that the research roadmap will evolve with the development of new concepts and technologies, this report summarizes the ideas that emerged from workshop discussion comprising the near-term and long-term goals for the focus areas, including: hazards and events; complex interdependencies between critical infrastructures; monitoring and extension of service life; modeling and simulation; structural systems and materials; technology transfer and policy. Suggested activities within these research areas align with the priorities for pre-disruption *assessment and mitigation* of vulnerabilities within the structural, cyber-physical, and socio-economic systems, emergency planning and *preparedness*, and identification of appropriate *response and recovery* actions that can alleviate societal losses in the aftermath of hazard events.

Defining Resilience

Consistent with the Latin word *resilio* that means to spring back, or rebound, definitions of resilience characterize the ability to rapidly recover from disruption or adversity. In the 2012 report prepared by the National Academies, resilience was defined as “the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events” (NAP 2012). The report suggests that “enhanced resilience allows better anticipation of disasters and better planning to reduce disaster losses rather than waiting for an event to occur and paying for it afterward.” As defined by Presidential Policy Directives (PPD-8 and PPD-21), resilience is “the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions.” These Directives reflect the national focus on evaluating and strengthening the critical infrastructures, including buildings, energy, water, transportation and communication sectors, which sustain the government, economy, education, culture, and health related functions in society.

Resilience has been a focus of extensive research in the social, economic, and behavioral sciences, computational and information sciences, and in engineering (e.g., Rinaldi et al. 2001, Rose 2004, Manyena 2006, Norris et al. 2007, Renschler et al. 2010). These studies illustrate a well-recognized need to integrate the socio-economic and cyber-physical aspects of resilience, and a growing interest in the research that has potential to enhance a “holistic, predictive understanding of interdependent critical infrastructures” (NSF 2015).

In one of the first conceptual frameworks that defined dimensions of community resilience related to seismic disasters, Bruneau et al. (2003) proposed four “R”s, namely robustness, redundancy, resourcefulness, and rapidity. Robustness expresses the remaining capacity of a system after it has been subjected to a specified level of load demand. Redundancy measures the potential for redistribution of the load carrying capacity among the system elements to maintain overall functionality. Resourcefulness is the ability to implement physical and technical resources to mitigate system disruption according to the prioritized goals. Rapidity distinguishes the methods that can be used to accelerate system upgrades before disruptive events occur, or can be readily initiated in the aftermath of disasters during the recovery efforts.

Drawing upon the resiliency concepts developed by Bruneau et al. (2003), McDaniels et al. (2008), and McAllister (2015), Figure 1 illustrates hypothetical mitigation and recovery scenarios to regain desirable level of functionality in a system or a network following hazard events that disrupt their operation. The degree of system functionality at an initial state is denoted by the solid line marked ***1*** – "Pre-event Resilience", whereas the dashed line marked ***1*** represents potential effects of mitigation decisions and activities that take place prior to a disruptive event to improve the system performance. Occurrence of disruptive events and the resulting losses related to the system functionality are represented by ***2*** – "Events and Hazards". The condition of the system prior to the hazard event and preparedness for post-event rehabilitation influence system resilience, likelihood of failure due to disruption, as well as the consequences, time, and costs associated with the return to full functionality. Hypothetical return paths to full functionality are denoted by ***3*** – "Post-event Resilience". Presumably, the higher level of pre-event resilience is associated with the more effective recovery path in terms of the lesser functionality loss and the shorter recovery time, as illustrated by the post-event resilience curve on the left hand side in Fig. 1. While this construct provides interesting insights into the concept of resilience and its impacts, there is little empirical evidence to support these concepts, and few studies that relate resilience concepts to investments in mitigation strategies and preparedness.

In the recent decades, many important research studies, policy guidelines, and initiatives have addressed the aspects of infrastructure and community resilience, encompassing myriad actions to reduce consequences of disruptions and accelerate recovery. General and sector-specific frameworks, methods, and tools have been suggested to assess vulnerabilities, measure performance, and to improve functionality of the built infrastructure including the buildings, lifelines, transportation facilities, and cyber-physical networks. To inform workshop discussion and development of the CAIT research roadmap, the authors reviewed the existing approaches to estimating infrastructure resilience with an aim to identify critical needs, accomplishments, and knowledge gaps in subject areas that align with the CAIT mission, capabilities, and

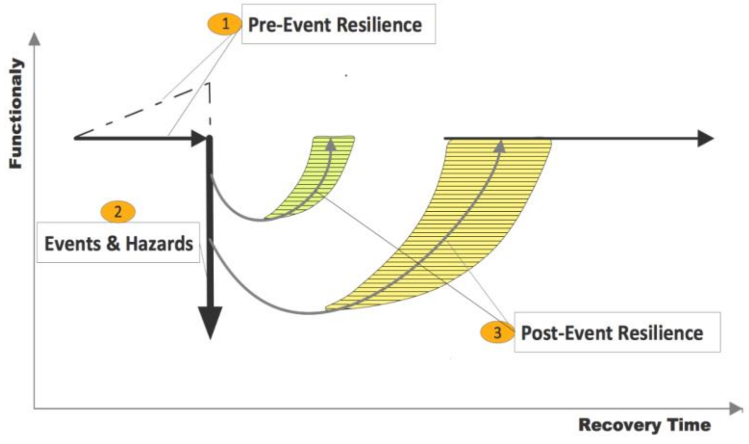

Figure 1. Infrastructure Resilience (adapted from Bruneau et al. 2003, McDaniels et al. 2008, and McAllister 2015)

interests. The following summary of recent research illustrates the attention in several fields to creating more effective methods for assessment and strengthening of the existing systems, and for engineering the new, improved systems.

Indicators of Resilient Interdependent Infrastructures

Communities support human activity and well-being through systems that function in multiple domains and at various scales under day-to-day conditions, and mobilize recovery when extraordinary events occur. Comprised of socio-economic, cultural, and political organizations, the natural environment, and constructed physical and communication systems, community systems interact as they provide services fulfilling dynamic demographic needs. Communities therefore respond to various levels of demand as a "system of systems," demonstrating inherent robustness, capability to adapt, and resourcefulness in compensating for capacity insufficiencies.

Spatial and functional relationships between the constructed facilities, transportation corridors, lifelines, and telecommunications contribute to the operational complexity of the individual and coupled systems, as well as to the uncertainty of impacts from hazards that these infrastructures may face. To define and communicate acceptable robustness and performance levels, assess present conditions, and predict future functionality of interdependent systems, indicators and metrics that capture relevant attributes of resilient communities have been increasingly investigated. These analyses map the relationships between system characteristics and behavior, and identify design, inspection, and maintenance solutions that can enhance overall system reliability.

Drawing upon damage data from the 1994 Northridge earthquake and simulated seismic events, Shinozuka (2009) analyzed the impact of damage to electric power-generating equipment on the electricity flow and power restoration times across an urban area. The resulting risk curves relate seismic risk to potential levels of damage to the power system, equipment rehabilitation scenarios, and the regional economic impacts (which were measured as percent of gross regional product (GRP) that is lost). The simulated regional restoration of power, represented in a geographic information system (GIS) format, was validated using the reported spatial-temporal progress of restoration in the Northridge earthquake. Considering cumulative effects of random, multiple hazards (e.g., equipment failures, vegetation impacts, human error) and hurricanes, Ouyang et al. (2012) compared expected annual resilience of the power transmission systems to these hazards, and evaluated cost-effectiveness of infrastructure improvements vs. rapid recovery measures for particular hazard scenarios.

Oswald Beiler et al. (2013) explored relevant performance measures that can lead to integrated decision making along corridors linking several metropolitan areas with high-density transportation networks. Faturechi and Miller-Hooks (2014) provide a comprehensive literature review focused on qualitative and quantitative approaches to measure performance of transportation systems that are subjected to extensive physical damage due to nonrecurring and sudden hazard impacts.

Mieler et al. (2015) drew upon the concepts for design, analysis and regulation of the U.S. commercial nuclear power plants to propose a framework establishing design criteria for individual systems based on performance goals ensuring overall resilience of a community. Likelihood of significant outmigration of residents following a disaster was used as community-level performance goal that is linked to the hazard level characterized by an earthquake with a specific return period.

The concepts related to enhancing resilience of communities in seismic areas in terms of functionality of and access to the health care facilities subjected to multiple hazards were proposed by Bruneau and Reihorn (2007), Cimellaro et al. (2010), Mitrani-Reiser et al. (2012), and Jacques et al. (2014). These studies exemplify analysis of recovery through redistribution of services and extend the resilience analysis of a single hospital to the groups of hospital structures in a region, while also considering the road links and lifelines that provide access and services to the hospitals.

Integrating Risk Appraisal into Decision Making

Risk analysis and performance-based approaches can be used to quantify reliability of infrastructure, inform prioritization of interventions, assess life-cycle outcomes related to infrastructure management decisions, and achieve performance objectives beyond those that are currently available in the prescriptive civil engineering codes. Engineering standards and codes focus on protecting life safety as the principal objective in the design of civil infrastructure, which may not adequately consider performance of structures during major hazard events and potential reductions of structural or nonstructural integrity. When hazards that affect numerous structures (e.g., earthquake, hurricane, tsunami) are considered, applying this approach to design across a region could extend functional disruptions, socio-economic consequences, and recovery (Ellingwood 2009, Mieler et al. 2015). In addition, durability issues of a deteriorating facility, or its configuration, may impact its performance and trigger structural weakness, making the facility vulnerable to damage or progressive collapse. If damage sustained by a component of a system (e.g., structural member in a structure, or a node in a transportation network) can lead to disproportionate consequences, measures to reconcile the system vulnerability based on the likelihood of a hazard are needed (Agarwal et al. 2003, Miller-Hooks et al. 2012, Hearn 2015).

When achieving continued serviceability, occupancy, or damage prevention are required performance levels under rare hazard events, risk-based criteria can be used to relate, in probabilistic terms, hazard occurrence and the resulting consequences for a facility. Performance-based criteria for design, maintenance, and repair activities can be established to link functional objectives (i.e., continued service, percent functionality, life-safety) and probabilistically-specified external demands, in order to plan these activities based on achieving a tolerable level of uncertainty regarding the level of system performance. For example, critical infrastructure, such as the emergency care facilities and the associated roadway links, power stations, water supplies, and telecommunication towers should remain operational during extreme events. Other facilities that support vital community activities should sustain limited damage, requiring minimal repair before they return to functionality within a reasonably short time period.

Probabilistic assessment of safety or suitability for service involves quantitative analysis of the likely hazards, including the physical aging processes, deferred repair, extreme disruptions, and aims to quantify uncertainty in the capacity of a structure or an infrastructure network. These hazards over the course of time, due to the aging process, or gradual increase of the load/service demand, or abruptly (as a result of unanticipated damaging events).

Development of risk-based methods, combined with recent advances in computing and simulation, has enabled probabilistic assessment of infrastructure, and response prediction based on specified external stressors, structural behavior, and deterioration mechanisms. A deliberately transparent and scientific method, risk appraisal has increasingly gained importance as the basis for analyzing and communicating information about safety, hazards, and risk acceptance levels (FTA 2004, ISO 2009, MAP-21 2012, SYNER-G 2013). Research is needed to develop risk-informed frameworks that support decision making, and operationalize risk principles within agencies overseeing inspection, maintenance and renewal of infrastructure.

Theoretical basis for risk assessment and communication, tolerance criteria, and risk-reduction measures has been addressed by several researchers, including Morgan et al. (2002), Renn (2008), Faber and Stewart (2003), Ellingwood (2005), Ayyub (2009), and DHS (2010). Since the 1990s major developments in probabilistic risk modeling and performance-based methodology have been incorporated into guidelines for earthquake engineering (ATC 2012). Over the course of several decades risk-based methods were also refined within the operational and regulatory frameworks for commercial nuclear power plants, chemical processes, and commercial aerospace systems (Mieler et al. 2015, McCann and Viz 2015). Methods that were created in these fields provide conceptual understanding of design, behavior, and analysis of complex and dynamic systems, and more importantly, they model how probabilistic performance-based methodology can be adapted and applied to optimizing performance of transportation networks.

Next generation of management systems will increase prediction accuracy for agencies to anticipate future funding needs, as well as to provide quantitative rationale for decisions related to maintaining, improving, and replacing transportation and lifeline facilities. Decision support tools based on probabilistic analysis of risks and consequences can complement currently used deterministic approaches, heuristics, and assessments that are largely based on visual inspection of facilities. For example, Brühwiler and Adey (2005) proposed a probabilistic model to determine optimal time and method for maintenance of bridges by optimizing life-cycle costs and benefits related to structural performance. In this model, costs related to inadequate serviceability are considered in addition to the typical costs associated with failure and maintenance interventions. Brühwiler and Adey (2005) also examine how intervention prioritization changes when simultaneous cases of inadequate serviceability exist at multiple bridges in a network due to excessive traffic and scour caused by flooding.

Planning Post Disaster Recovery

Building more resilient communities requires a continuity of decisions supporting effective measures to achieve long-term safety under the repeated threats. These measures may include enhancing system robustness by augmenting design standards, considering preventive (vs. reactive) maintenance to preempt structural deterioration, reducing exposure to direct risk, and devising disaster preparedness and recovery strategies. A growing body of research is devoted to the "top-down" approach, where decisions concerning system components or individual structures are based on community-level implications (e.g., Baker et al. 2008, Croope and McNeil 2011, Mieler et al. 2015).

For example, design and detailing actions would consider potential damage scenarios and load redistribution paths to provide system redundancies, and lead to reduction of community-wide losses that are disproportionate to the hazard causing the damage. In addition to the design actions that are aimed at reducing the *likelihood* of failure, decisions would focus on alleviating the *consequences* of failure by the use of sensor systems for improved damage detection and initiation of alerts for evacuation (Baker et al. 2008).

Croope and McNeil (2011) analyzed interactions within critical infrastructure systems based on spatial and hazard parameters (by using GIS and HAZUS-MH [FEMA 2007] models), cost-benefit ratios for pre-event mitigation vs. post-event recovery options, and life-cycle considerations, to quantify tradeoffs for selecting mitigation and recovery activities. Miller-Hooks et al. (2012) examined resiliency as an indicator of recovery capability in intermodal freight transport (trains, ships, planes, and trucks) and proposed a methodology based on stochastically-modeled impacts of preparedness and rapid post-disaster recovery activities that are completed under budget.

Frangopol and Bocchini (2012) proposed a method to prioritize bridge restoration after a disaster by employing multi-objective genetic algorithms (GA) to optimize conflicting criteria, such as the minimum cost of interventions and maximum network functionality. The latter is based on travel time and distance that affect highway users over a time period. Risk-based decision framework that can be adapted for use at different organizational levels (i.e., to manage individual projects, portfolio of assets, or agency-wide policy) was proposed by Lin et al. (2015). Illustrative applications of this framework in the state of Colorado include (1) conversion of qualitative inspection data for mast arms into quantitative evaluation of risk, leading to suggested changes for the inspection regime, and (2) analyses to quantify risk for non-seismically designed bridges due to revisions of the seismic design code.

Outline of this Report

Having defined resilience and reviewed the relevant literature in the introduction, this report documents the methodology used to develop a research road map for infrastructure resilience and each of the five research areas identified in the workshop. Each section includes a description of the areas, an overview potential research topics and a review of related research. The research areas are:

- Hazards and Events,
- Complex Interdependencies between Critical Infrastructures,

- Monitoring and Extension of Service Life,
- Modeling and Simulation,
- Structural Systems and Materials, and
- Technology Transfer and Policy.

The report concludes with a summary of next steps including issues not covered in the workshop. References are listed at the end of report and the workshop summary is included in an appendix.

APPROACH AND METHODOLOGY

Building on a review of relevant literature and recent research initiatives, an interdisciplinary workshop was held to brainstorm concepts, frameworks and ideas for improving resilience and develop a roadmap for future research related to resilience and transportation infrastructure, specifically state of good repair. The one-day workshop, held in December 2015, served as the primary vehicle for developing the roadmap. Key stakeholders from academia, government and industry were invited to participate in the workshop along with consortium members – a total of about 25-30 people. Short presentations by three to four stakeholders reviewing the state of the practice and research needs facilitated discussion. A professional facilitator was used to help structure the workshop agenda, keep the discussion on track and synthesize the outcomes.

Relevant literature was tabulated prior to the workshop and served as background material for the workshop. A survey of participants prior to the workshop also provided key inputs. The workshop report, included in the appendix, documents the processes used in and the organization of the workshop. The one day workshop was intended to provide the elements of the roadmap: an identification and prioritization of research needs, strategies for developing these research needs, milestones along the way, and resources needed. Participants were expected to be engaged in the professionally facilitated discussion that brought together infrastructure owners and operators, and researchers, to identify priorities and activities needed to renew existing infrastructure and build resilient transportation systems. Key ideas that emerged from full-group conversations and theme-focused breakout sessions were summarized in the workshop report and shared with participants for review and comment.

Drawing on the outcomes of the workshop, the research roadmap built around five key areas was developed and reported in the following section.

FINDINGS – POTENTIAL RESEARCH AREAS

The following sections review the potential research areas identified in the workshop. The areas serve as the backbone of the research roadmap.

Hazards and Events

Over its lifetime, a structure must withstand multiple hazards, some of which occur concurrently, such as increased service demand and condition deterioration, hurricane winds and flooding, wave inundation and marine vessel impact, fire following earthquake, and outage of lifeline systems (e.g., energy and water). Predictive technologies that enable real-time characterization of disruptive events and assessment of risks that can be communicated to the general public, first responders, public authorities, and infrastructure operators, are needed to plan pre-event mitigation projects, post-disaster response and relief efforts, and recovery.

Improved characterization of low-likelihood high-consequence events is needed to develop risk models that account for the occurrence of rare events that are stochastic in nature, yet may lead to catastrophic consequences. Examples include maximum credible earthquakes, super storms (that occur due to rare concurrence of impacts, such as from high tide and storm surge during the 2012 Superstorm Sandy), black-swan events (extreme, unforeseen events relative to historic records and current knowledge), and nuclear power plant malfunctions.

Development of design requirements for transportation structures and lifelines to resist multi-hazard (MH) extreme events that occur simultaneously, or in close succession, is an emerging subject area. Characterization and codification of design loads related to single extreme events, such as earthquakes, coastal storms, vessel collisions, flash flooding, and blasts, has resulted in recent advancements of bridge design specifications (e.g., AASHTO 2010a, AASHTO 2010b, AASHTO 2011). AASHTO provisions recognize that multiple extreme events can occur concurrently and sequentially, in addition cascading failures can exacerbate the impact of hazards. Evaluation of data from historical MH events and probabilistic analysis of load demands are needed to assess the relative likelihood of hazards occurring simultaneously, and the expected loading intensities due to the combined, cascading, and escalating hazards (Barbato et al. 2013, Lin and Vanmarcke 2008, Khorasani et al. 2015, Alipour et al. 2013). Recent bridge engineering research has investigated MH loading cases that combine the effects of scour + earthquake, wave action + wind + vessel collision, scour + storm surge + wind. Examples of cascading events are: hurricane → windborne debris + flood + rainfall; hurricane → storm surge + vessel collision; vehicular collision + wind → fire; wind → vehicular collision; flood → vessel collision; earthquake → vehicular collision + fire; earthquake → tsunami; earthquake → lifeline disruptions. Each event can result in infrastructure damage and lifeline disruptions.

Water and wastewater pipelines, power, gas, and telecommunication lifelines are interrelated as a result of physical proximity, and dependent functions. In cities where sewer systems were built prior to the 1930s, storm drains were typically combined with sanitary sewers from residential and commercial buildings. Urban growth, aged sewer systems, and inundation during heavy storms and flooding have led to increased risk of combined stormwater-sewage overflows (CSOs). CSOs result in discharge of untreated sewer and stormwater into the local stream network, posing health risks to the public and the ecosystem. Environmentally responsible solutions for reducing the volume of stormwater discharged from urban developments and roadways are needed to mitigate the threat of pollution and health risks.

Analysis of disruptive events that have shorter return periods, impacts of a lesser degree, or affect a smaller geographic area, would provide valuable insights into the patterns of behavior within interdependent infrastructures. Study of commonalities between large-scale events and these smaller-scale events can uncover relevant vulnerability triggers, cascading event patterns, best practices for resolution, communication, and recovery following the disruptions. However, such analysis and study should be approached with caution given the qualitative and quantitative differences between catastrophes, disasters and emergencies (Quarantelli 1997).

Complex Interdependencies between Critical Infrastructures

Transportation networks and lifeline systems provide services that are considered vital for maintaining the dynamic flow of people and goods in a modern society. With increasing density of population, built structures, socio-economic services, and cyber-physical infrastructures, urban areas have evolved into complex networks of co-located, interacting, and intertwined systems and components. For the components and networks to operate adequately under service-level demands, and to preserve essential functionality under extraordinary conditions, interrelated infrastructures should contribute to the recovery during interruptions, and not exacerbate the damage.

Continuity of electric power supply is essential for distribution of oil, natural gas, and potable water. Disruption and damage of power systems may lead to interruption of health services, water treatment and delivery, wireless and internet infrastructure, communications, commerce, loss of data and perishable goods, resulting in direct and indirect costs of restoring the power grid and the operations within other sectors that depend on electricity. Train derailments and bridge closures can disrupt access to commerce, education, health services, as well as undermine evacuation and emergency response in case of hazard events. Past disruptive events have highlighted the reciprocity of services needed for the critical infrastructures to operate, and also the pathways by which disturbances can propagate and escalate from one system to another following an initial event.

Recognition of the shared risks among the correlated physical and socio-economic systems has increased with evidence from recent large-scale disasters including the 2001 World Trade Center collapse, the 2005 Hurricane Katrina, the 2011 Tohoku Earthquake, and the 2012 Superstorm Sandy. These events have demonstrated the vulnerable and the resilient attributes of communities, as well as the potential ripple effects through various systems that the society may experience.

Among the many devastating facets of the World Trade Center disaster, the impact forces on the structures also caused the rupture of water mains and underground pipelines, resulting in flooding of the vaults that housed a telecommunications center of global importance. This led to losses of assets necessary for the operation of major telecommunications network circuits and the New York Stock Exchange (O’Rourke 2007). After Hurricane Katrina, electric power outage at the pumping stations of major regional pipelines interrupted transmission of crude oil and petroleum products, impacting gasoline production in the U.S. for several weeks. Similarly, power loss due to the Superstorm Sandy had massive impacts on the wireless and internet infrastructure, transportation, financial services, and oil and natural gas production and delivery. The Fukushima Daiichi nuclear power plant disaster followed a rare aggregation of extreme events: a magnitude 9.0 Tohoku Earthquake and up to 45 ft high tsunami inundation, which initiated a sequence of system failures. Following the power grid outage due to the earthquake, the backup generators also could not supply the electricity needed to run the power plant water pumping system as they were inoperable after being flooded by the tsunami. (Generator placement was based on historic tsunami height data supporting the assumption that walls protecting the plant from tsunamis could not be breached.) The absence of water supply that was needed to cool nuclear fuel rods resulted in accumulation of explosive hydrogen gasses which, combined with organizational and technical difficulties under time constraints, ultimately led to the buildup of excessive pressure, plant explosion, and major nuclear contamination (Budnitz 2011). These disasters demonstrate the significance of systemic vulnerabilities that exist because of the interdependencies among lifeline systems and, as potential precursors of cascading negative outcomes, warrant detailed technical and socio-economic study.

Multi-disciplinary investigation of the cause-and-effect paths between systems is needed to inform development of frameworks, ontologies, and conceptualizations necessary to understand better the relationships between the interdependent physical, cyber-physical, and social infrastructures. A holistic understanding of interdependencies that govern dynamic behavior and adaptive mechanisms at the “system of systems” scale is needed to engineer infrastructure elements and processes by optimizing the beneficial correlations while assuaging the potentially adverse ones. This integrative role of infrastructure engineers can facilitate decision-making from the systemic, risk-based perspective, which is increasingly being emphasized through government initiatives and mandates, research programs, and by the leaders in the engineering profession (e.g., PPD-21, NAP 2012, MAP-21 2012, NIST 2015, DHS 2015, NSF 2015, Mieler et al. 2015, Aktan et al. 2016, Baker et al. 2008, O’Rourke 2007, Ellingwood 2005, Bruneau et al. 2003).

Monitoring & Extension of Service Life

The majority of the U.S. infrastructure was built between the 1950s-1980s. As a result the average age of the US bridges is approximately 42 years (NBI 2015). This underscores the need to precisely characterize these systems regarding their current performance and capacity to withstand future demands. The challenges posed by inadequate serviceability, natural aging processes, emerging risks, and increasing complexity of infrastructures in large urban areas, combined with the awareness of limited resources that are available for maintenance and upgrades, serve as a compelling argument for a paradigm shift toward new methods for strategic renewal and preservation of the existing infrastructure.

A large proportion of the existing infrastructure will continue to serve its original purpose in the coming decades. Therefore, integration of innovative monitoring technologies and sensor systems in the design, construction, inspection and maintenance offers an important opportunity to correctly assess the capacity of these systems, and to prioritize allocation of resources for their repair. These monitoring tools will also enable creation of new concepts and approaches for detecting precursors to large damage and predicting damage and distress propagation for structural elements, thereby potentially augmenting the testing and evaluation protocols, and maintenance recommendations.

Bridge condition determines the envelope of acceptable serviceability and structural responses for the given loading and environmental stressors. Because of the uncertainty related to the in-service loads and the material degradation mechanisms affecting structural components, innovative methods for accurate assessment of capacity are needed to determine the likely structural performance and to estimate the life expectancy based on maintenance alternatives. Currently, condition assessment is predominantly based on visual inspection of accessible structural components at recurrent time intervals (which are based on experience or engineering judgment), or in response to a reported problem. Limited access to observe structures (e.g., underground and congested pipelines, underwater bridge substructures, enclosed bridge connections), variable quality of inspections, and subjective assignment of numerical ratings based on qualitative evaluations, may lead to ineffective assessments. Moreover, visual inspection may fail to differentiate indicators of structural behavior from surface-level changes, missing an opportunity to identify precursors of larger-scale damage.

To improve the effectiveness of infrastructure damage detection, innovative hybrid approaches to assessment can be developed through careful integration of complementary methods such as physics-based numerical modeling, risk-based quantitative (and qualitative) hazard and vulnerability evaluation, nondestructive evaluation and testing techniques (NDE/NDT), structural health monitoring (SHM), structural identification (St-Id), and inspection using new technologies such as LiDAR and UAVs (Unmanned Aerial Vehicles). For example, an innovative rehabilitation approach for bridge decks, ANDERS (Automated Nondestructive Evaluation and Rehabilitation System), integrates non-invasive monitoring techniques, structural health assessment, and strengthening operations to enable early detection and rapid arrest of concrete cracking (Gucunski and Moon, 2011). Preventive maintenance strategies, rather than the traditional reactive methods, can be developed and implemented based on quantitative condition metrics, and on predictive modeling of the time to reach degradation thresholds (e.g., chloride ingress at initiation of corrosion in the concrete element reinforcement). The predictive ability allows quantitative evaluation of intervention scenarios (including the “no-intervention” scenario) in terms of the projected extension of the service life and the cost-benefit tradeoffs of mitigating the identified vulnerabilities. Based on structural characteristics, how critical a structure is within the network, and the observed changes, optimal methods and time intervals for assessment and maintenance can be specified.

Modeling and Simulation

Simulation using experimental, computational, or hybrid methodologies is essential for predicting behavior of critical systems, understanding functional complexities between components and systems, and managing uncertainty increases related to the phenomena that affect individual and coupled infrastructures. For example, merging dependent processes may involve coupling the analysis of bridge degradation mechanisms and models that capture the impact of deterioration on a transportation network. Similarly, characterizing structural damage at a critical facility under possible external threats and human behavioral patterns related to response and evacuation can inform optimization of both the preemptive and recovery interventions. Meta-models are needed to better understand how systems of infrastructure systems operate under the routine and extraordinary conditions. With that broader perspective of the goals for resilient infrastructure, performance objectives for individual components and coupled systems can be defined in terms of the complex adaptive behavior, efficiency, redundancy, and intervention trade-offs.

Integration of existing models for specific hazards in order to simulate the effects of multi-hazard and cascading events, can lead to design of systems that can self-organize and adapt in order to restore functionality prior to subsequent disruption(s). Information sharing across infrastructure sectors, data analytics, and visualization models can reveal important patterns in performance, and allow for estimating network vulnerabilities, and planning interventions that have the greatest impact. For example, network intervention efficiencies can be achieved by generating degradation models for representative bridges with similar configuration, design approach, and material characteristics. Effective platforms for integrating, managing, and visualizing real-time and historic data obtained through SHM would broaden the implementation of 'smart' systems in preserving the existing bridges and in the design of new bridges. Such platforms could provide a user-required level of detail regarding bridge condition, structural behavior, characteristics of the monitoring system and bridge components, and generate early warnings in the case of the operational or safety problems (Glisic et al. 2014).

Analysis based on visualization tools such as the geographic information systems (GIS) can be used to capture, store, analyze, interpret, and display data that relates the spatial and temporal characteristics of data represented geographically. Data about land use (industrial, rural, urban), hazard potential (e.g., flood zone, coastal inundation zone), demographic information (socio-economic status, occupations, access to transportation), population density, characteristics of built facilities (e.g., capacity to shelter people or goods), technical capabilities (e.g., power supply in a service area), healthcare availability (population density relative to the number of hospitals), reliability of access routes (redundancy, connectivity, travel time), can be organized on maps in "data layers", enabling analysis and synthesis of correlations into risk curves that can be used to quantify regional resilience. Changes in data over time can be recorded and analyzed in GIS, allowing temporal-spatial monitoring of resilience indicators, such as percentage of healthy population, regional economic output, population migration patterns, frequency of presidential disaster declarations, transportation network congestion, efficiency of power grid repair and restoration (Bruneau and Reinhorn 2007, Oswald Beiler et al. 2013, Mieler et al. 2015, Shinozuka 2009).

Significant advances in analytical modeling have enabled creation of tools to support decisions for optimal inspection and maintenance frequency based on criteria such as minimal operating costs or extension of service life. However, the complexity of the models often precludes their implementation in day-to-day practice. A challenge remains to develop suitable models that can be adapted for practical implementation and meet the real-world needs while providing the benefits of the research-based analysis and simulation.

The new Bridge Evaluation and Accelerated Structural Testing (BEAST) laboratory at Rutgers University will enable scientific study and quantification of decades-long deterioration by performing "time-compressed", realistic simulations of in-service conditions, emulating the environmental, traffic, and chemical stressors on typical full-scale bridges. The accelerated simulation of aging is expected to reveal within several months of simulations the patterns of decaying effects typically seen after 15-20 years of service life. This knowledge will enable agencies to tailor selection of state-of-the-art materials by a priori considering the entire service life of a structure, inform the bridge superstructure design and detailing practice, and allow specifying of deck preservation methods and schedules by using performance-based assessments of durability, costs, and benefits associated with particular decisions.

Structural Systems and Materials

Thinking about infrastructure as a structural system rather than an assembly of individual elements presents opportunities for enhancing resilience. For example, performance-based design of bridges relates the likelihood that the bridge would degrade gracefully, rather than catastrophically, and the risk of a seismic event of a given intensity. Similarly, deployable, adaptable structures can add redundancy to infrastructure systems or specific facilities resulting in a more efficient use of resources and supporting critical functionality across the network. Disproportionate damage propagation in individual structures subject to extreme loads (such as earthquake or blast) has been addressed through design against progressive collapse. However, probabilistic performance criteria that relate design loads for extreme hazards (such as fire, blast, storm surge, tornadoes, and impact events) and structural response require further development (McAllister 2013). Finally, prioritizing structures for retrofit based on assessment and risk of failure recognizes opportunities for passive protection of individual facilities, and engineering systems for long-term performance.

Structural systems and components that enable structures to rebound to their original level of functionality after an extreme event, requiring only minor repairs, are a specific example of resilience-based design. Re-centering systems for critical building and bridge structures can be designed to limit the damage to 'acceptable' levels, and minimize the risk of collapse due to major earthquakes, allowing their continued occupancy and service in the aftermath of disruptive events (Garlock et al. 2007, Deierlein et al. 2011, Lee and Billington 2011).

Innovative and new materials also show promise. Self-diagnosing (using NDE), self-healing structures (using self-healing repair materials) will lead to more robust systems. The concept of "smart", autoadaptive structures with embedded components that self-actuate and control system response to the external loads or improve structural attributes such as damping and stiffness have been investigated, but will require new advances in the fundamental science and engineering.

The ability to implement, as standard practice, accelerated bridge construction (ABC) methods for retrofit or replacement of structures that are approaching a threshold of acceptable functionality, or to mobilize rapid reconstruction after the extraordinary events, relates to the resourcefulness and rapidity dimensions of resilient bridge networks (Bruneau et al. 2003, Bruneau and Reinhorn 2007). Developing effective ABC methods is important considering that approximately 25% of more than 600,000 bridges nationwide are designated as functionally obsolete or structurally deficient, requiring upgrades or replacement (NBI 2015, LTBP Portal 2015). As evident from historic data, mitigation of deficiencies prior to disruptive events reduces damage, losses, and downtime of infrastructure in the aftermath of an extreme event. Challenges for broader implementation of ABC include quantifying and demonstrating direct and indirect cost savings that result from a compressed construction schedule; integration of risk-based decision tools to identify viable ABC projects; development of light and efficient structural systems, simplified element connections and materials for improved constructability and extended bridge service life; standardization of successful designs to achieve economy of scale; maintaining the feedback loop between researchers, designers, owners, and contractors to promote technical familiarity and organizational transparency necessary for implementation of the ABC systems.

Accident-prone roadway sections where icy conditions threaten passenger safety would benefit from development of cost-effective, innovative pavement materials with an inherent de-icing capability. For example, concrete mix containing electrically conductive materials such as steel and carbon particles can be used to maintain above-freezing temperature of the concrete surface connected to a source of electricity, which can be supplied manually (e.g., for impending snow storms) or auto-activated based on the exceedance of a threshold temperature (Tuan 2004). Similar solutions have been implemented based on the use of renewable geothermal energy for bridges, train platforms, and pedestrian pavements (Eugster 2007). Stabilized pavement temperature year-round and the absence of de-icing salts would improve roadway durability (related to freeze-thaw cycling, thermal expansion, cracking, and ingress of corrosive chlorides), while reducing maintenance needs and keeping safe highly travelled and critical transportation nodes, access roads, ramps, tunnel entrances, and sections with steep grades and curves, by using environmentally responsible technology.

Technology Transfer and Policy

Interest in transportation infrastructure resilience has increased with the passage of the two most recent surface transportation reauthorizations. MAP-21 (2012) required each State to develop a risk-based asset management plan for the National Highway System (NHS) to improve or preserve the condition of the assets and the performance of the system. (Public Law 112-141, Moving Ahead for Progress in the 21st Century Act (Map-21), 2012). The act also placed significant emphasis on performance-based planning. A potential 35% reduction in Federal funding for states that do not implement such a management plan is stipulated (MAP-21, 2012, 1106, Sec. 119(e)(5)). The FAST Act (2015) reinforced the concepts and process presented in MAP-21 but explicitly added "resilience" as an element of performance (Public Law 114-94, the Fixing America's Surface Transportation Act (FAST Act), 2015).

A wide range of initiatives based in professional organizations and foundations served to advance the state of the practice of enhancing infrastructure to be more resilient and support technology transfer. Examples include:

- AASHTO Special Committee on Transportation Security & Emergency Management (SCOTSEM)
- ASCE Infrastructure Resilience Division
- National Academies Resilient America
- Rockefeller Foundation "100 Resilience Cities"
- Transportation Research Board Committee on Critical Transportation Infrastructure Protection and Transportation Systems Resilience Section

Nevertheless, the concept of resilience is difficult to operationalize due to the diversity of stakeholders interested in the concept and the challenges associated with risk communication. NIST's "Community Resilience Planning Guide for Buildings and Infrastructure Systems" serves as an initial blueprint for addressing implementation issues (NIST, 2015).

Past disasters have made transparent the technical and socio-political dimensions of community resilience. These events highlight the difference that effective leadership and institutional response can make in the planning, operations, and recovery efforts. Severe droughts, flooding, hurricanes, and ice have affected freight and maritime operations on the U.S. coast and inland waterways in the recent decades. The extraordinary adversity resulting from inundation by extreme climate events on the infrastructure weakened by underinvestment in maintenance and renewal has been counteracted by robust and flexible operation framework, and progressive regulations (Philip 2015). During the 1988-1989 drought, the lowest recorded water levels to date on the Mississippi River, heat waves, and numerous wildfires in the western states contributed to the costliest natural disaster on record prior to Hurricane Katrina. The Great Flood of 1993 inundated 20 million acres of land along the Missouri and Mississippi Rivers. The U.S. Coast Guard "Prevention by People" program, the US Army Corps of Engineers operating at the local level, and network-wide waterway action plans were part of the resilient response framework based on after-action reviews, building trust, familiarity, and transparency (Philip 2015).

Technology transfer across disciplines (e.g., engineering; natural, social, economic, and computational sciences) and organizational levels (e.g., federal, state, and local agencies; the private sector; and academic institutions) can facilitate application of the state-of-the-art technology solutions to address infrastructure challenges based on real-world data that reflect critical knowledge needs. Envisioned as a catalyst for resilience improvements, multiple aspects of technology transfer would: (1) enable communication of practitioners' needs through practice-oriented research projects, workshops, formal feedback loops and mechanisms for sharing the lessons learned; (2) engage collaborative research across engineering, computational, and socio-economic disciplines to improve our understanding of how infrastructure disturbances ripple through the interdependent social-economic-cyber-physical systems;

(3) adopt new technologies by incorporating the related guidelines in design codes and asset management standards; (4) learn from and adapt previously developed design/operational frameworks for related fields and systems (e.g., nuclear power plants, seismic engineering, aerospace industry); and (5) build research-industry partnerships to commercialize breakthrough innovations and incrementally integrate new tools into the existing systems (e.g., 'researcher-entrepreneur' model, or validate implementation within the context of performance-based engineering).

CONCLUSIONS, RECOMMENDATIONS AND NEXT STEPS

The previous sections identified six research areas and documented potential research topics and relevant literature. While not explicitly discussed in the workshop, it is important that potential research projects be considered in the context of whole community, recognize the need to cooperate and collaborate between all levels of government, industry and academia, and translate into lessons learned and best practices that organizations and agencies can implement.

The Department of Homeland Security's "Whole Community" approach to emergency management extends to infrastructure resilience. For example, at the federal level, Homeland Security and US Department of Transportation have important roles in providing resources for mitigation and setting policies, but federal agencies depend on state and local governments and communities to use these resources, and implement the policies. At the same time, although several lifeline systems are public sector resources, the vast majority of the critical infrastructure is in the hands of the private sector. To be effective universities will need to work with both public and private sector stakeholders, and communities to improve resilience. 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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SUPPLEMENTAL DOCUMENT – WORKSHOP SUMMARY

RUTGERS

Center for Advanced
Infrastructure and
Transportation

Resiliency of Transportation Infrastructure Workshop

Workshop Results

December 4, 2015
Rutgers University

TABLE OF CONTENTS

Workshop Organizing Committee

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WORKSHOP INTRODUCTION

Transportation system disruptions—often resulting from the failure of aging or under-maintained infrastructure and the increasing frequency and severity of extreme weather events—can cause large economic damages and severe cascading impacts on other infrastructure systems and the community. There is increasing national interest to make transportation systems and other critical infrastructures more resilient to emerging risks by implementing advanced technologies, new predictive and decision-making tools, and innovative infrastructure designs.

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 urban context of transportation infrastructure. The challenge is to determine how best to integrate and focus these capabilities to address priority needs that will make transportation systems more resilient to a host of emerging risks.

Groundbreaking solutions can only result from aligning the interests of CAIT's diverse research community with the specific needs of infrastructure owners and operators who ultimately apply new technologies and designs to transportation assets and systems. Research must effectively target critical resilience needs to accelerate solutions that enable infrastructure monitoring, new material characterization, data acquisition and data-driven decision making, disaster preparedness and response, and maintenance improvements that all result in more robust engineering and improved operations, response, and recovery capabilities.

On December 4, 2015, CAIT hosted a workshop to identify priority infrastructure needs and resilience challenges in the transportation infrastructure and generate potential technology solutions and opportunities for R&D that target these critical needs. The workshop convened 33 participants, including Center partners from multiple universities, transportation industry representatives, and national and regional government stakeholders in the transportation sector.

Workshop Scope and Design

Participants engaged in interactive large-group discussions and in three breakout groups to identify:

- Emerging resilience challenges and gaps in all modes of transportation, including bridges, roadways, aviation, transit, railways, and interdependent sectors such as energy, communications systems, and water supply.
- Potential technology, data, and modeling solutions that can fill resilience gaps.
- Priority opportunities for R&D that draw upon the strengths and capabilities of Center partners.

Workshop Results and Next Steps

To maintain and build its national leadership in transportation system innovation, CAIT will use the workshop results to develop a strategic roadmap that aligns CAIT's research priorities with critical transportation infrastructure needs and best applies the strengths and capabilities of Center partners.

Summary of Key Results

The top priorities from the workshop's three breakout sessions—Pre-Event Resilience, Defining Events and Hazards, and Post-Event Resilience—are shown in the table below.

Pre-Event Resilience	Defining Events and Hazards	Post-Event Resilience
Top Technology, Data, and Modeling Solutions		
• **Model system interdependencies and cascading impacts** • **Identify accurate baseline asset conditions and conduct continuous monitoring to determine if asset performance meets expectations** • **Conduct a peer review of asset inspection processes across states and systems to determine best practices** • **Develop non-subjective asset condition assessments that use more discrete, quantitative data**	• Real-time, big data analytics (the Internet of Things) • Conduct performance modeling of extreme events to determine how they affect expected failure rates • Enable predictive modeling of events • Reduce the footprint of infrastructure elevated systems	• Conduct large-scale simulations of infrastructure networks • Establish and publish recovery time objectives for critical infrastructure assets and capabilities to guide prioritization • Develop a simple measurement of resilience quantitatively - for structures • Train engineers in first response and liability coverage
Top Opportunities for CAIT R&D		
• Examine best practices for asset inspection, develop a non-subjective rating system, and develop technology and sensors to determine asset conditions • Conduct case studies of network breakdowns and map the interdependencies and how interventions would change the result • **Design assets for rebounding/recovery, making them predictable and repairable**	• Develop models or methodologies that enable cross-asset optimization of investments: how to prioritize investments considering multiple system and network benefits • Conduct back-end modeling development and customization for various models than can ultimately be applied to specific infrastructure systems • Conduct independent validation of models	• Develop robust, performance-based resilience metrics for transportation infrastructure • Establish the engineer as an urban first responder • Develop tools for modeling, simulation, and analysis of large-scale, interdependent infrastructure systems to enable holistic mitigation approaches

EMERGING RESILIENCE CHALLENGES AND POTENTIAL SOLUTIONS

Prior to the workshop, participants submitted their input on the top three emerging challenges for improving the resilience of transportation systems and the top three innovative capabilities—including tools, methods, models, and R&D—that can advance the design of resilient infrastructure systems. Expert speakers also concluded their presentations with their take on the top resilience challenges and potential solutions. These inputs provided a critical starting point for the breakout group discussions on specific technology, data, and modeling solutions and CAIT R&D opportunities.

Emerging Resilience Challenges

Emerging resilience challenges were categorized into three topic areas: Pre-Event Resilience, Defining Hazards and Events, and Post-Event Resilience. See Appendix A for description of the resilience construct.

Pre-Event Resilience

- No common platform for owners and operators in energy/ transportation/ interdependent sectors to share information and plan cross-sector resilience
- No official cross-sector policy planning to address interdependencies
- Lack of clear and accepted definition of resilience or resilience goals in the transportation sector
- Lack of meaningful resilience measures/metrics that enable cross-asset prioritization and decision making
    - Determining asset recovery requirements—what needs to be recovered by when to ensure resilience
- Lack of good standards to measure state of good repair
- Lack of good condition and maintenance data of transportation assets at the state level
- Limited data on systems as built and on past storms to understand regional networks
- Identifying methods for rapid, affordable assessment of infrastructure health and performance
    - Identifying infrastructure assets and assessing their condition
    - Implementing structural health monitoring (SHM) in the long term
- Conducting contingency planning and assessment impact among multiple owners and operations in a network
- New management theory needed for large, complex infrastructure projects
- Determining how to best assess and realize multiple co-benefits of resilience investments—including safety and efficiency—to help build the business case
- Determining effective methods to build resilience into planning, project development, engineering, and operations

Define Hazards and Events

- More frequent extreme hazards such as hurricanes
- Using SHM data to predict how vulnerabilities evolve and conduct cost-benefit analyses on investments
- Methods for evaluating infrastructure vulnerability based on health assessments
- Rail shipments of oil and hazardous materials
- More frequent/extreme weather events from climate change
- Developing a process to prioritize infrastructure asset improvements
- Criticalities/risks in one sector are not obvious to other sectors
- Determining high risk areas or assets data now is often bad quality or nonexistent
- Need better understanding of climate projections and extreme events at owner/operator and asset level
- Need mechanisms for prioritizing limited investment

Post-Event Resilience

- Many bridges are at/near capacity – how do we replace?
- How do we proceed when some major crossings/bridges are not practical to replace?
- Need for new remediation approaches to extend service life
- Addressing culvert functionality, tree management, and roadway flooding
- Understanding and planning for lifecycle risks and funding mitigations
- Limited funding for physical security (fencing, lighting, cameras)
- Improving infrastructure condition
- Creating transit alternatives to highway travel (e.g. high-speed rail)
- Designing now to make future replacements/rebuilds faster and easier (e.g. modular builds and standardization)
- Incorporating flexibility in engineering design
- Network redundancy or substitution needed
- Rapid rebuilding vs opportunity to rebuild stronger
- Limited coordination among designers and actual operators
- Designs should account for real use: limited maintenance, anticipated failure
- Post-event assessment
- Given assessment: constraints, alternatives/options, decision making, implementation
- Transition from response to recovery
- Being able to identify core capabilities for restoration and recovery
- Sufficient resilience index for structures – how detailed?
- Understanding of integrated system impacts post-event for different scenarios
- Increasing integration of:
  - Physical cyber systems
  - Dependent infrastructures
  - Adjacent jurisdictions

Potential Capabilities, Solutions, and R&D Needs

Technology and Materials

Materials

- Accelerated bridge construction and self-propelled modular transporters
- Deployable/retractable/moveable smart structures
- Fiber-reinforced polymer wraps for strengthening and intumescent paint for fire resistance
- Improved cyber-physical system security
- LiDAR asset location with webcam streaming (which requires huge data storage)

Monitoring

- Built-in remote condition monitoring capabilities
- Integration of structural health monitoring (SHM) in design

Design

- Modified design standards and inputs (e.g., design rainfall, flows, temps, winds) that incorporate life cycle modeling
- New design philosophies that do not prioritize economy of materials above all (example: labor = 90% bridge cost; reducing material cost has little effect in this case)
- Engineers moving to lifecycle risk and performance-based standards will drive resilience
- Improving build practices to eliminate maintenance regulations (e.g., less field welding reduces lifecycle maintenance)
- Enterprise asset management – enables asset inventory, condition tracking, and prioritization of repairs

Modeling

- Analytical tools to model interdependencies and mitigations
- Smart technologies integrated into assets that enable data-driven decision making
- Using artificial intelligence to predict preliminary infrastructure project costs
- Catastrophic modeling capabilities to replace existing models (cannot model large, complex systems *normally* because they behave catastrophically)
- Design using scenario and risk-based multivariate optimization under certainty
- 7-dimensional building information modeling
- Models that provide methodologies for project prioritization
- Models that can examine both asset damage potential and service disruption potential to understand network impacts

Data and Measures

- Big data management and analysis
- GIS-based tools to collect and manage network data
- Advanced analytics of asset failure trends to enable proactive and predictive maintenance that extends asset lifecycles and can prioritize limited funds
- Data analytics applied to transportation infrastructure databases to enable new predictive capabilities
- Applying text mining to accident and investigation reports to help understand trends and frequent problems
- Development of resilience metrics that are performance-driven
- Outcomes-based engineering and performance-based standards

Policy and Framework

- New infrastructure development and maintenance policies that enable and encourage resilience
- Infrastructure policies that understand the difference between funding and financing projects
- Robust institutional frameworks for response and recovery
  - Event recovery framework should include *non-engineering* options and have logistics and authority for non-normal operations built in
  - Enables "prevention through people" by embracing operational flexibility and practicing it regularly to build trust

PRE-EVENT RESILIENCE

The Pre-Event Resilience Breakout Group focused on solutions and R&D opportunities to help identify and characterize the social dimensions of resilience, characterize transportation systems, and define goals for resilience.

A star (☆) indicates the number of votes the solution or R&D opportunity received during prioritization.

Technology, Data, and Modeling Solutions

- **Model system interdependencies, focusing especially on cascading impacts ☆ ☆ ☆ ☆**
- **Identify accurate information on the baseline conditions and performance of assets to determine the current condition of existing structures, and develop methods to conduct continuous monitoring of assets against baseline to determine if performance meets expectations ☆ ☆ ☆ ☆**
- **Conduct a peer review of inspection processes across states and systems (including international systems) to determine best practices for inspection ☆ ☆ ☆**
- **Non-subjective asset condition assessments that use more discrete, quantitative data ☆ ☆ ☆**
- Develop a framework for more standardized, objective, inspection scores across inspectors ☆ ☆
- Develop resilience metrics that identify how assets must perform under specific hazards, considering their likelihood of occurrence ☆ ☆
- Institute a sustainable infrastructure by creating and adopting resilience standards ☆
- Develop a unified methodology for recording incidents (TRANSCOM) to improve real-time traffic information ☆
- Identify and characterize factors that reduce asset life span: ☆
    - Deferred maintenance
    - Aggressive environment
    - Traffic patterns
    - Load capacity
- Develop a unified, standard format for asset data
- Advanced sensors built into assets
- Develop methods for predictive maintenance
    - Entails significant data collection, including historical information on asset condition and historical maintenance data
- Research new designs and materials for resilience performance

Opportunities for CAIT R&D

Examine best practices for asset inspection, develop a non-subjective rating system, and develop technology and sensors to determine asset conditions ☆ ☆ ☆ ☆ ☆ ☆ ☆ ☆

- Conduct a survey of state DOTs to determine best practices for inspecting and monitoring bridges and other assets. Examine best practices in other industries as well (e.g., aviation)
    - Examine best practices for asset inspection across sectors and states
    - Examine bridge contracts for maintenance to identify trends in asset maintenance needs and areas where inspection ratings may be misleading

    - Identify bridge/roadway components that are relevant to resilience, working with owners, engineers, and contractors
- Develop a quantitative bridge/roadway rating system and adopt it
- Develop new technologies and methods (e.g., sensors) that collect and analyze conditions data

Conduct case studies of network breakdowns and map the interdependencies and how interventions would change the result ☆ ☆ ☆ ☆ ☆

- Develop a GIS model layered with traffic signals and other infrastructure systems
- Incorporate models of multi-modal freight flows
- Model cascading impacts and where interventions would change things
- Model single component failure analysis in a network

Design assets for rebounding/recovery, making them predictable and repairable ☆ ☆ ☆

- Study thermal/extreme heat impacts on the bridges and roadways ☆

DEFINE HAZARDS AND EVENTS

The Define Events and Hazards Breakout Group focused on solutions and R&D opportunities to help identify prevailing and emerging hazards and conduct catastrophic modeling to help decision makers determine the impact of those hazards, including climate change impacts.

A star (☆) indicates the number of votes the solution or R&D opportunity received during prioritization.

Technology, Data, and Modeling Solutions

- **Real-time, big data analytics (the Internet of Things) ☆ ☆ ☆ ☆**
- **Performance modeling during extreme events – how do they affect expected failure rates? ☆ ☆ ☆ ☆**
- **Predictive modeling of events ☆ ☆ ☆**
- **Reduce the footprint of infrastructure elevated systems ☆ ☆**
- Standardized data collecting protocols on historical and predictive data ☆
- Research on reducing greenhouse gas emissions ☆
- Land use studies to better position assets for future threats ☆
- Remote sensing and data collection ☆
- Standardized data collection ☆
    - Catastrophic event data
    - Pre- and post-event data
    - Quantitative vs. qualitative data
- Multi-threat algorithms
- Bringing together big data with heuristics

Prioritized Hazards to Focus Development of Solutions

- Natural hazards (flood, wind, seismic) ☆ ☆ ☆ ☆ ☆ ☆ ☆
- Interdependencies cascading failures – network failures ☆ ☆ ☆ ☆
- Man-made hazards ☆ ☆ ☆ ☆
- Human factors (users/operators) ☆ ☆
- Life-cycle events – aging infrastructure ☆ ☆ ☆ ☆
- Network failures – specific events, congestion, rail interruptions ☆ ☆ ☆
- Investigate conditional probability
- Local and regional fire hazards
- Disruptive technologies (including materials science advances)

Opportunities for CAIT R&D

Develop models or methodologies that enable cross-asset optimization of investments: how to prioritize investments considering multiple system and network benefits ☆ ☆ ☆ ☆ ☆

Conduct back-end modeling development and customization for various models than can ultimately be applied to specific infrastructure systems ☆ ☆ ☆ ☆

- Write algorithms and coding for models and then customize

Conduct independent validation of models ☆ ☆ ☆ ☆

Additional high-priority R&D opportunities

- **Conduct autonomous network simulation to determine network deterioration and cost advantages of metered traffic flow from potentially high adoption of autonomous vehicles☆ ☆**
    - Multi-modal impacts of adoption ☆
    - Deterioration of assets from increased use
    - Cost savings from reduced traffic and accidents
- **Conduct post-processing and prioritization of data and data cleaning to support multiple CAIT efforts for modeling and data analytics ☆**
- **Develop modeling and analysis tools that combine asset condition assessment with risk assessment to enable effective maintenance, repair, and replacement decision making at the owner/operator level ☆**
- Develop refined/customized economic impact models at the asset level (then aggregate)
- Model the cost of the missed benefits from transportation upgrades that have been limited or prevented by policy to help policymakers better understand the impact of policy decisions on the transportation system
- Examine different highway designs needed to enable autonomous cars and the corresponding new data requirements and capabilities:
    - Sensors of road conditions
    - Capacity data
    - Vehicle to vehicle communication
    - Build on the current simulation/test bed for autonomous vehicle impacts (current CAIT project)
- Conduct large-scale data collection (e.g., legacy, environmental, and insurance data) and integrate data sets to analyze multiple impacts
    - May require building CAIT capabilities to look at larger quantities of data that are now less centralized (e.g., asset data, traffic pattern data, sensor data may all be held by different entities)
- Conduct sensitivity analysis

POST-EVENT RESILIENCE

The Post-Event Resilience Breakout Group focused on solutions and R&D opportunities that help to define anticipated asset and system performance, characterize recovery, support incident management, and implement remedial measures, including design improvements and advanced tools.

A star (☆) indicates the number of votes the solution or R&D opportunity received during prioritization.

Technology, Data, and Modeling Solutions

Solutions include tools for modeling, simulation, and analysis of large-scale, interdependent infrastructure systems and holistic mitigation approaches.

- **Large scale simulations of infrastructure networks ☆ ☆ ☆ ☆ ☆ ☆ ☆**
    - Model interdependencies between systems (e.g., electricity, transportation, food and water, oil and gas, emergency response, etc.) and how effects of one system on another can have cascading effects to other parts of the network
    - Better understanding of interdependencies through real life and simulation analyses
    - Taking in holistic system approaches/systems
    - Tools to model interdependencies for use in response
    - Analytical tools to model interdependencies and mitigations
    - Understanding the role of emergent issues and organizations
- **Establish and publish recovery time objectives for critical infrastructure assets and capabilities to guide prioritization ☆ ☆ ☆ ☆ ☆**
    - Tools/processes: understanding consequences of decisions, prioritizing actions
    - Methodologies for project prioritization
- **A simple measurement of resilience quantitatively - for structures ☆ ☆ ☆ ☆**
    - Resilience metrics that are performance-driven
    - Tools to inventory available materials, personnel, institutions and capabilities across jurisdiction ☆
    - Institutional frameworks for sharing data and resources
    - Facilitate into agency and intermodal coordination – break down silos
    - Establish/update performance standard for resilience in immediate post-event phase to guide rebuilding
- **Engineers trained in first response and liability coverage ☆ ☆ ☆**
- **Evaluate the most critical link/system within a community (with goals to make more robust) ☆ ☆**
    - How to measure community resilience (not just transportation, but transportation will play a large role)
- **Increase use/reliance of critical infrastructure on distributed, renewable power ☆**
- **Evaluate/develop strategies to 3D print replacement for critical infrastructure to reduce logistical burdens ☆**
- Define what elements are needed for a preparedness or rapid recovery report
- Provide guidance on how to procure on-call contracts for rapid response materials (temporary bridges, etc.)

- Modified, pre-positioned institutional and approval frameworks

Opportunities for CAIT R&D

Develop robust, performance-based resilience metrics for transportation infrastructure

- Outcome-based metric, performance based achievement
- Recovery time targets – need to consider time vs cost
- Methodology for defining recovery times
- Recovery time identified for various levels of service
- Limited resilience performance metrics
- Validating recovery time
- Can test with simulation model

Establish the engineer as an urban first responder

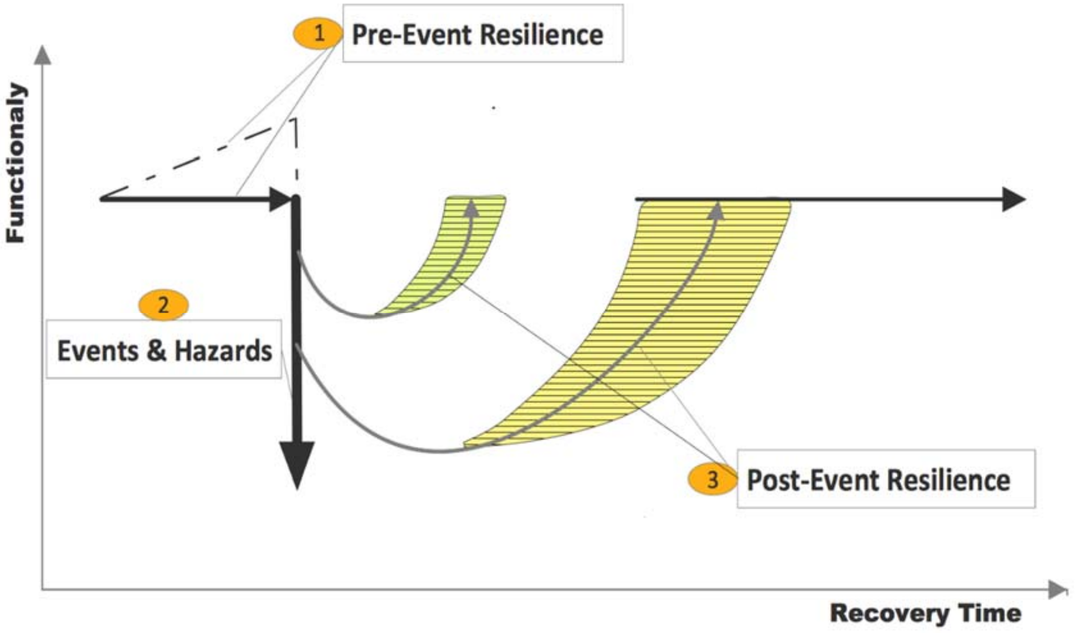
- Identify requirements and role definition
- Skills and training – forensic engineering
- Identify needs, define frameworks, required capabilities and skills
- Development of a resilience code
- Rutgers school of public policy
- Training – Local Technical Assistance Program for sectors

Develop tools for modeling, simulation, and analysis of large-scale, interdependent infrastructure systems to enable holistic mitigation approaches

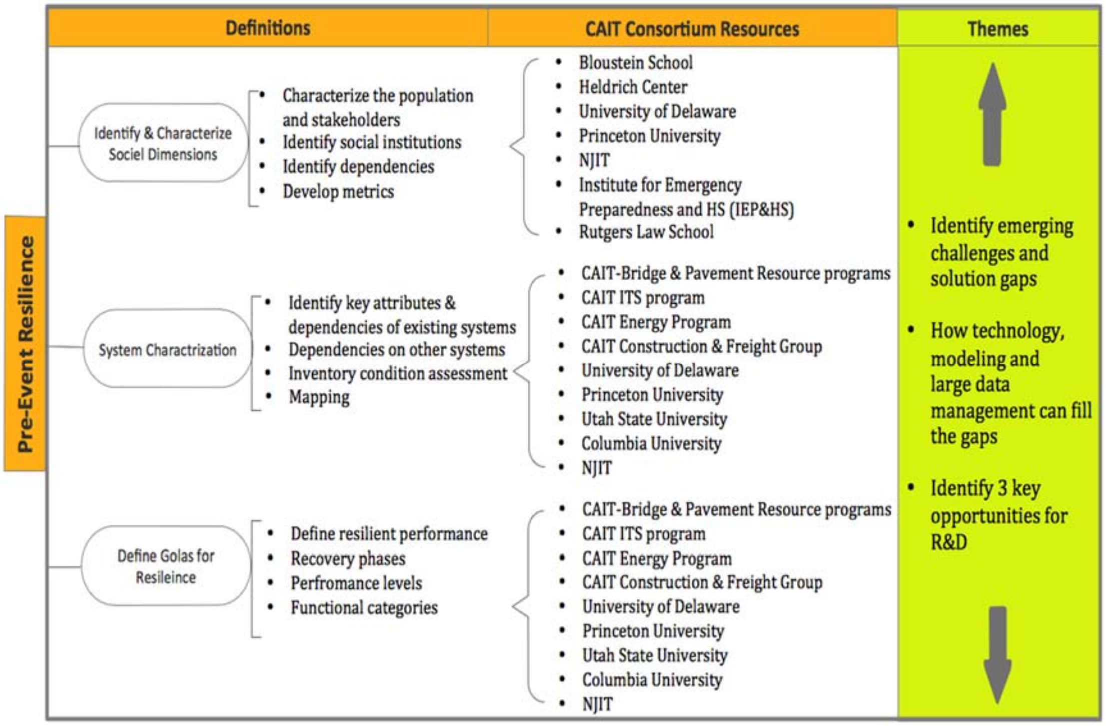
- Objective: understand system behavior under stress and inform decision making, policies, and mitigation
- Model fragility and connectedness: physical structure, connections, flows
- Ability to examine network behavior under disturbance
- Research to understand human behavior and choices during disturbances
- Identify existing tools, models, data to integrate
- Understand: source behavior, sink behavior, time dimension
- Model verification under different conditions and locations
- Link between activity and network models
- Build knowledge base and use cases
- Collection of data from post-disaster behavior
- CAIT has a robust set of capabilities and tools across consortium to tackle this R&D

APPENDIX A: INFRASTRUCTURE RESILIENCE CONSTRUCT

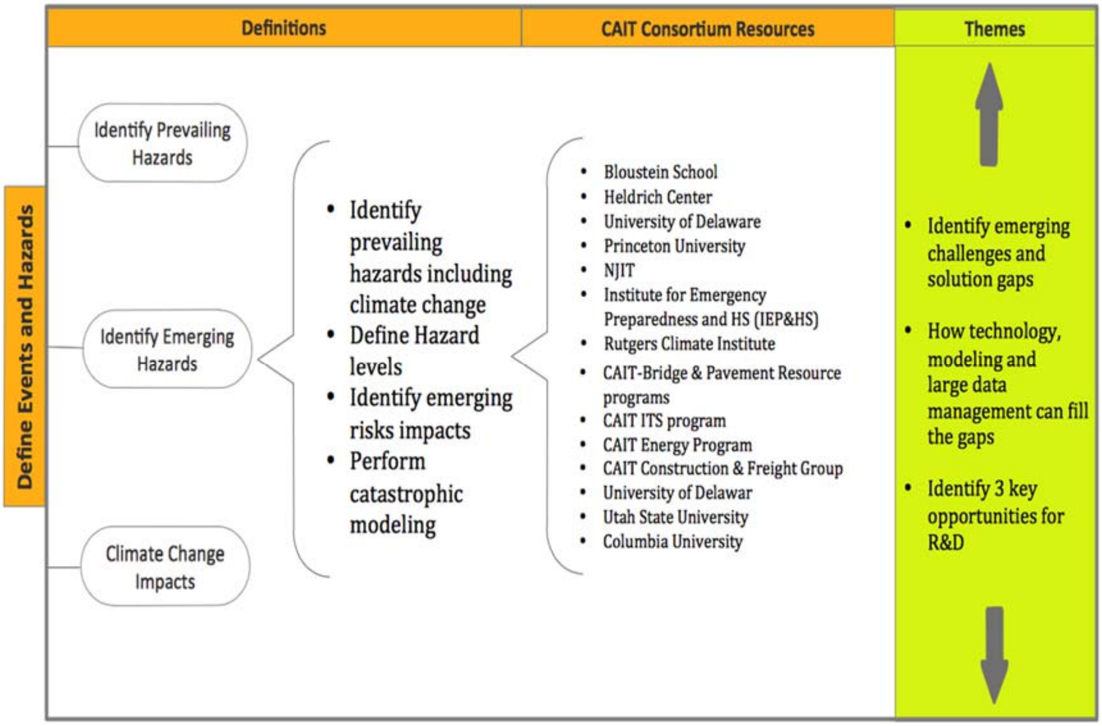
The workshop considered challenges, solutions, and opportunities for R&D in three resilience areas: Pre-Event Resilience, Define Events and Hazards, and Post-Event Resilience. This design was based on the following construct:



Prior to the workshop, CAIT further defined the resilience needs in these three areas and identified CAIT resources that could be applied to the opportunities for R&D identified during the workshop.



	Definitions		CAIT Consortium Resources	Themes
Pre-Event Resilience	Identify & Characterize Sociel Dimensions	• Characterize the population and stakeholders • Identify social institutions • Identify dependencies • Develop metrics	• Bloustein School • Heldrich Center • University of Delaware • Princeton University • NJIT • Institute for Emergency Preparedness and HS (IEP&HS) • Rutgers Law School	• Identify emerging challenges and solution gaps • How technology, modeling and large data management can fill the gaps • Identify 3 key opportunities for R&D
	System Charactrization	• Identify key attributes & dependencies of existing systems • Dependencies on other systems • Inventory condition assessment • Mapping	• CAIT-Bridge & Pavement Resource programs • CAIT ITS program • CAIT Energy Program • CAIT Construction & Freight Group • University of Delaware • Princeton University • Utah State University • Columbia University • NJIT	
	Define Golas for Resileince	• Define resilient performance • Recovery phases • Perfromance levels • Functional categories	• CAIT-Bridge & Pavement Resource programs • CAIT ITS program • CAIT Energy Program • CAIT Construction & Freight Group • University of Delaware • Princeton University • Utah State University • Columbia University • NJIT	



Definitions | CAIT Consortium Resources | Themes

Define Events and Hazards

Identify Prevailing Hazards

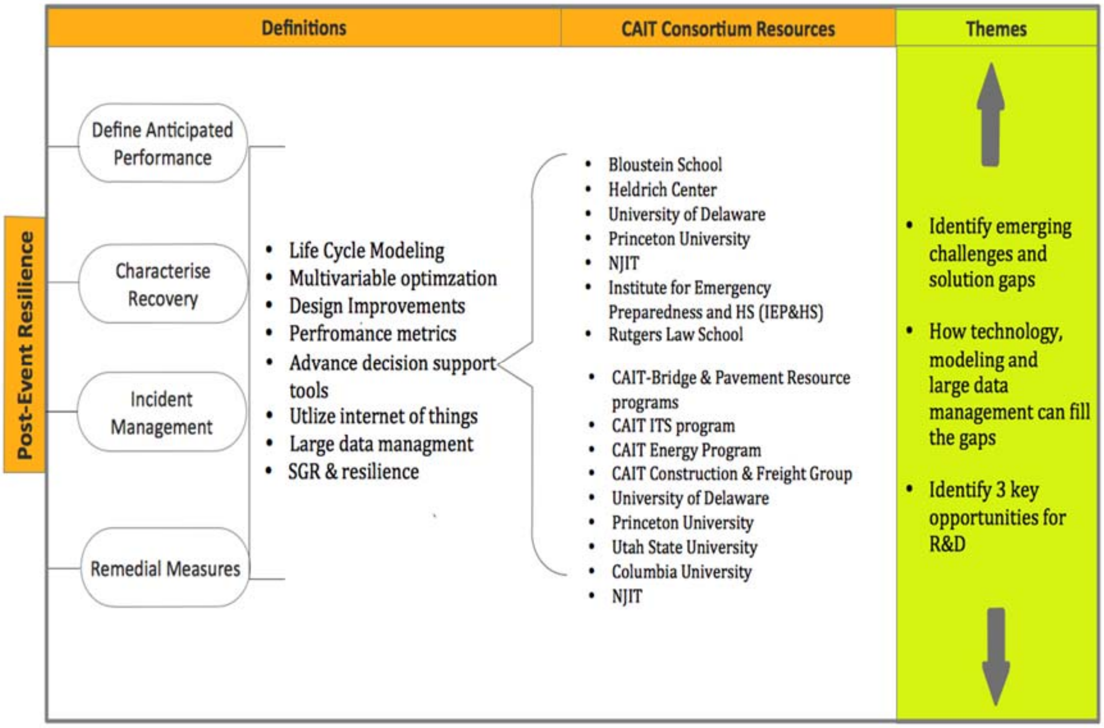
Identify Emerging Hazards

Climate Change Impacts

- Identify prevailing hazards including climate change
- Define Hazard levels
- Identify emerging risks impacts
- Perform catastrophic modeling

- Bloustein School
- Heldrich Center
- University of Delaware
- Princeton University
- NJIT
- Institute for Emergency Preparedness and HS (IEP&HS)
- Rutgers Climate Institute
- CAIT-Bridge & Pavement Resource programs
- CAIT ITS program
- CAIT Energy Program
- CAIT Construction & Freight Group
- University of Delawar
- Utah State University
- Columbia University

- Identify emerging challenges and solution gaps
- How technology, modeling and large data management can fill the gaps
- Identify 3 key opportunities for R&D



Definitions | CAIT Consortium Resources | Themes

Post-Event Resilience

Define Anticipated Performance

Characterise Recovery

Incident Management

Remedial Measures

- Life Cycle Modeling
- Multivariable optimzation
- Design Improvements
- Perfromance metrics
- Advance decision support tools
- Utlize internet of things
- Large data managment
- SGR & resilience

- Bloustein School
- Heldrich Center
- University of Delaware
- Princeton University
- NJIT
- Institute for Emergency Preparedness and HS (IEP&HS)
- Rutgers Law School
- CAIT-Bridge & Pavement Resource programs
- CAIT ITS program
- CAIT Energy Program
- CAIT Construction & Freight Group
- University of Delaware
- Princeton University
- Utah State University
- Columbia University
- NJIT

- Identify emerging challenges and solution gaps
- How technology, modeling and large data management can fill the gaps
- Identify 3 key opportunities for R&D

APPENDIX B: WORKSHOP AGENDA

Time	Activity
8:00 – 8:30 am	Breakfast and registration
8:30 – 9:00 am	**Welcome, Introductions, and Objectives** **CAIT's Mission and Capabilities** • Dr. Ali Maher, Professor and CAIT Director, Civil and Environmental Engineering, Rutgers University • Dr. Sue McNeil, Professor, Civil and Environmental Engineering, University of Delaware
9:00 – 9:45 am	**Brief presentations:** **Infrastructure Resilience: Pre and Post Event** • Bob Prieto, FCMAA, NAC, Chairman & CEO, Strategic Program Management LLC **Resilience and Climate Change** • Dr. Michael Meyer, Strategy Advisor, Parsons Brinckerhoff **Freight System Fragility and Institutional Responses** • Dr. Craig Philip, Research Professor and VECTOR Director, Civil and Environmental Engineering, Vanderbilt University
9:45 – 10:00 am	Facilitated Discussion: **Q&A and Summary of Key Points**
10:00 – 10:15 am	Break
10:15 – 10:45 am	**Brief presentations:** **DHS S&T: Resilient Systems R&D** • Dr. Adam Hutter, Director, National Urban Security Technology Laboratory Science and Technology Directorate, Department of Homeland Security (DHS) (Dr. Hutter presented on behalf of Jalal Mapar, Director, Resilient Systems Division, DHS) **A Regional Perspective** • Jeff Perlman, Manager of Environmental Planning and Mobility Programs North Jersey Transportation Planning Authority
10:45 – 11:00 am	Facilitated Discussion: **Q&A and Summary of Key Points**
11:00 – 12:00	Facilitated Discussion: **Transportation Infrastructure Priorities**
12:00 – 12:15 pm	Plan for the afternoon
12:15 – 1:00 pm	Lunch and networking
1:00 – 2:15 pm	**Breakout Groups: Research Themes, Topics, and Projects**
2:15 – 2:30 pm	**Report out**
2:30 – 2:45 pm	Break
2:45 – 3:45 pm	**Breakout Groups: Integrating Priorities**
3:45 – 4:00 pm	**Report out**
4:00 – 4:15 pm	Facilitated Discussion: **Research Logistics**
4:15 – 4:30 pm	**Next Steps and Adjourn**

APPENDIX C: WORKSHOP PARTICIPANTS

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