

# Infrastructure Sustainability in a Multi-Hazard Environment

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Infrastructure faces multiple threats, including aging and deterioration, increased demand by a growing population, and natural hazards that may become more frequent with climate change. These threats result not only in physical damage, but cascading social, environmental, and economic impacts that impair the sustainability of the infrastructure system and its parent community. This discussion paper raises central issues related to the provision for infrastructure sustainability in a multi-hazard environment, such as: a) emerging methods to quantify infrastructure resilience and sustainability; b) tradeoffs in design and management of risks posed by multiple hazards; c) the importance of systems level analysis across various spatial and temporal scales; and d) the role of transdisciplinary research to achieve multi-hazard resilience and sustainability of infrastructure systems.

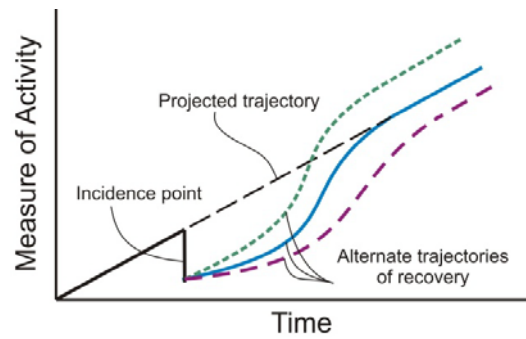
## DISCUSSION

Infrastructure is essential to supporting day to day operation, post-hazard response, long term recovery and vitality of a society. Its effective functionality supports quality of life, social and economic activity [1]. For example such systems as the transportation system, housing stock, telecommunications network, and power generation and distribution systems all serve a critical role in fueling socio-economic stability, national security, and global marketplace competitiveness. Yet these systems suffer aging and degradation throughout a lifetime of exposure to harsh environmental stressors and heightened demands from the public. This situation poses a threat not only to the quality of service provided during operational conditions but the vulnerability of infrastructure to extreme events, such as earthquakes, hurricanes, floods, or tsunamis, because of the decreased capacity to withstand hazard induced loading (see e.g. [2, 3]).

To support decision making on infrastructure design, upgrade and operation in the face of such hazards, the science of resilience quantification applied to infrastructure systems has gained momentum in recent decades. Although a broad range of definitions exist in the literature [4-6], resilience of infrastructure is generally interpreted as a measure of its capability to maintain acceptable levels of service when subjected to a shock and to recover within an appropriate period of time. Figure 1 presents a basic timeline of the incidence and recovery, noting that the measure of activity may be considered as a physical metric of the infrastructure operation (e.g. traffic carrying capacity) or of the impact on activities of the parent community (e.g. access to critical facilities). Modeling such trajectories remains a challenging task for the infrastructure risk modeling communities, and the extension of such trajectories to community activity functions transcends traditional disciplines modeling infrastructure vulnerability and recovery. Customarily the assessment of resilience in the face of natural hazards and the characterization of sustainability of the infrastructure system have been treated as two distinct problems. Although sustainability is an evolving concept

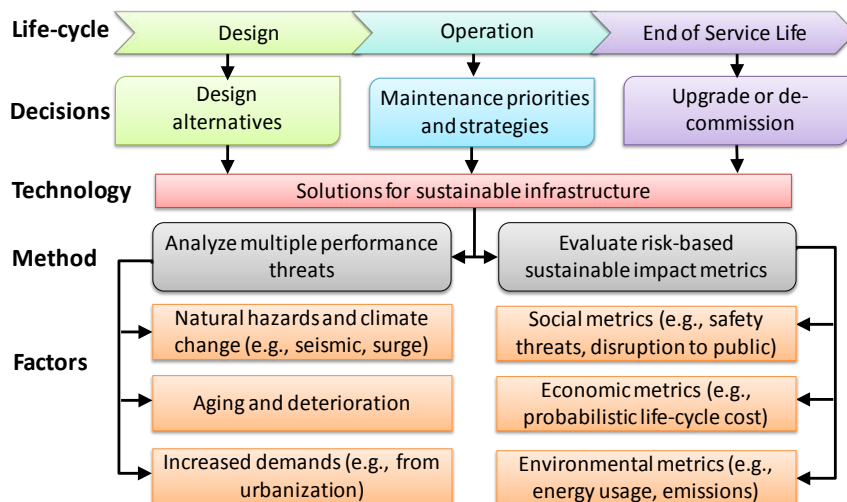
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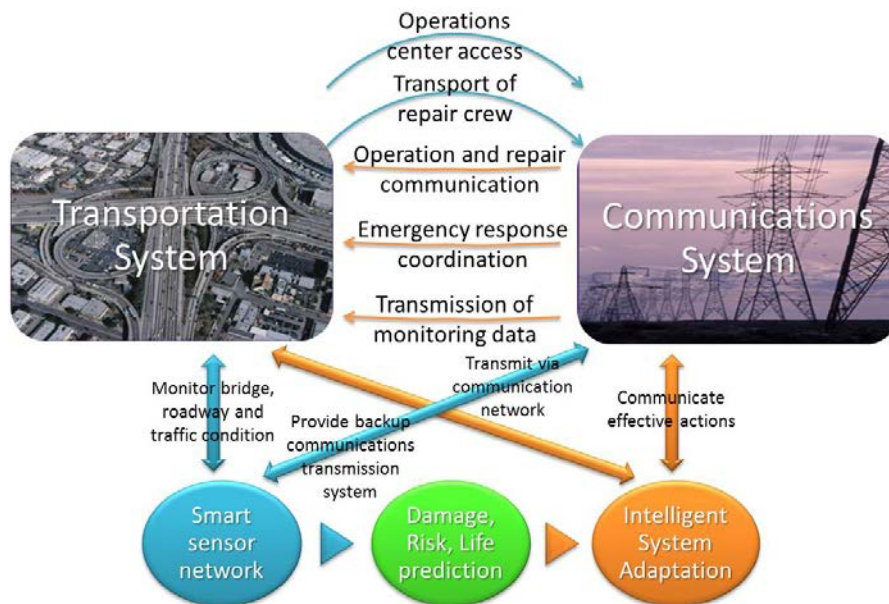
**Figure 1.** Illustration of incidence and recovery used to assess infrastructure resilience, where the measure of activity may suggest level of infrastructure service or impact on parent community.

whose interpretation is sensitive to disciplinary perspectives [7], often lifetime environmental, social, and economic performance are jointly considered. Hence performance in the face of extreme events can play a key role in affecting infrastructure sustainability. Emerging methods to evaluate infrastructure sustainability include qualitative or point based sustainability rating systems [8], as well as deterministic or probabilistic life-cycle modeling techniques [9-11] although often performance under extreme events is neglected. The interrelationship between hazard resilience and infrastructure sustainability has become increasingly acknowledged; Padgett and Tapia [12] synthesize some of the key linkages including the basic case that hazard damage may yield adverse social, environmental and economic impacts, such as casualties, waste generation or energy expenditure for repair, and direct and indirect costs. Typically a tradeoff exists between upfront investment in promoting hazard resilience and long term sustainability benefits realized. Furthermore, the traditional approach for designing, analyzing and upgrading infrastructure tends to focus on performance under an individual hazard. However, strategies to enhance infrastructure resilience under one hazard such as a hurricane may actually exacerbate the vulnerability to another, such as an earthquake. To support such an evaluation, Figure 2 presents a concept model for SSIMT, Sustainable Solutions to Infrastructure Subjected to Multiple Threats, where multi-hazard mitigation decisions are cast within the contextual framework of sustainability by coupling hazard risk assessment and life-cycle modeling. Realizing such a framework for a range of realistic infrastructure systems remains a timely challenge.



**Figure 2.** Concept model for Sustainable Solutions to Infrastructure Subjected to Multiple Threats (SSIMT) demonstrating key decision phases throughout the infrastructure life-cycle.

Central to advancing the assessment and provision for infrastructure resilience and sustainability is characterization of system level performance when subjected to various hazards. Vulnerability modeling of distributed infrastructure systems, either portfolios of structures or networks of interconnected components, introduces unique considerations with respect to spatial and temporal analyses that remain ripe for future research. These include such items as quantifying the correlation in failure probability of components distributed across a region especially when considering coupled deterioration and natural hazard exposure [13, 14], or modeling the priority and timing of interventions to upgrade components pre-event or restore system functionality post-event [15, 16]. The scalability of such infrastructure vulnerability and resilience models also poses a challenge with respect to computational complexity as well as validity of assumptions or validation of input parameters across community, regional and national scales. Of particular interest has also been mathematical modeling of the interdependency between infrastructure systems and how the failure or survival of one system affects the performance of another [17-20]. An example of this interdependence is shown in Figure 3 depicting the relationship between the communication system and transportation system (whose role in infrastructure interdependency analysis has received relatively little attention). The figure also suggests the added complexity as future intelligence is built into infrastructure systems. The need for an elevated systems level perspective is further reinforced when considering the role of public behavior, operator decisions, or policy impacts within post-hazard infrastructure performance and interdependency analyses.



**Figure 3.** Example of interdependencies between the transportation and communication system and illustration of the opportunity yet added complexity as the infrastructure becomes more intelligent.

It has been suggested that “transdisciplinary” research is essential to achieve global aims for sustainability [21], and suggested herein that the complexity of tackling issues of infrastructure resilience and sustainability in a multi-hazard environment also require such an approach to the problem. An assembly of definitions characterizes transdisciplinary research as that which evolves multiple disciplinary boundaries into a hybridized, synergistic team that includes perspectives from researchers as well as public and private sectors to generate new knowledge and synthesis driven by the need to address complex real world problems

[21]. Developing solutions to achieve multi-hazard resilience and sustainability of infrastructure systems calls for such a research approach, acknowledging the feedback loops between infrastructure performance subjected to extreme events and the social, political, environmental, and economic systems of the parent community (at various scales) in which that infrastructure resides.

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