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# Leveraging SETS resilience capabilities for safe-to-fail infrastructure under climate change

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As the rehabilitation of infrastructure is outpaced by changes in the profile, frequency, and intensity of extreme weather events, infrastructure's service disruptions and failures become increasingly likely. Safe-to-fail approaches for infrastructure planning and design improve the capacity of cities to adapt for uncertain climate futures by identifying social, ecological, and technological systems (SETS) capabilities to prepare for potential failure scenarios. In this paper, we argue for transforming infrastructure planning and design to effectively utilize safe-to-fail approaches by navigating the opportunities and trade-offs of SETS resilience capabilities. From a technological vantage point, traditional infrastructure planning approaches account for social and ecological domains as external design conditions rather than embedded system characteristics. Safe-to-fail approaches directly challenge the isolation of the technological domain by necessitating a recognition that SETS domains are interconnected and interdependent in infrastructure systems, as such risks and system capabilities for resilience must be managed cohesively.

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## Introduction

Climate change and extreme weather events continue to challenge the ability of infrastructure systems to manage resources, supply critical services like energy and water, and protect human habitats from environmental hazards. Environmental hazards — for example, extreme heat and heavy precipitation — increasingly disrupt infrastructure services in cities, making the design and retrofitting of infrastructure to withstand, readily recover, and adapt (i.e. infrastructure resilience) an imperative for urban sustainability [1]. Safe-to-fail infrastructure (STF) planning and design is emerging as a framework to manage unpredictability and build infrastructure that is more adaptable to a myriad of shocks, surprises, and environmental hazards under changing climate conditions [2•,3,4••].

Traditionally, infrastructure systems are designed by technocentric approaches that configure the capacity of physical components to resist failure against expected environmental risks, such as risk-based designs that are focused on probability predictions and advanced calculations (i.e. fail-safe infrastructure; FS) [2•,5•]. An incomplete consideration of system responses and enhancement of system rigidity via technocentric approaches in infrastructure planning has caused cities to experience substantial damages, sometimes even cascading across social, ecological, and technological systems (SETS) when infrastructure failures occur. While the primary design goal of both STF and FS is in risk mitigation, STF design expands the infrastructure design consideration by including the management of system failure and its consequential impacts across SETS.

The main difference between STF and FS is in their response behavior to hazards that exceed their design envelope (e.g. a storm beyond a designed 100-year return period). FS design primarily focuses on maintaining the system structure or functions based on hazard predictions. Thus, the FS response to 'beyond-design' hazards often results in shutting down the system function to avoid structural or physical failure. The FS response to hazards is often based on historical data. Therefore, catastrophic system failure for traditional infrastructure becomes increasingly likely in the face of anomalous climate conditions and uncertainty [5•,6]. The FS design focus on system rigidity is misaligned with climate change in that current and future conditions are increasingly characterized by non-stationarity, where the magnitudes of risks are likely to significantly shift beyond predicted design envelopes within the infrastructure life span [7]. In this paper, we argue for transforming infrastructure planning and design to effectively utilize STF approaches by navigating the opportunities and trade-offs of SETS resilience capabilities.

## Why SETS resilience?

Urban systems are composed of intertwined SETS subsystems that collectively produce essential functions and resilience dynamics characteristic of a city. Technological systems (T-systems) — such as infrastructure and the built environment — are embedded in social (e.g. institutions and infrastructure management) and ecological systems (e.g. natural resource processes). Simultaneously, T-systems shape social systems (e.g. the distribution of public services to people and protection of communities from climate hazards) and ecological systems (e.g. modifying natural resource processes and enhancing ecosystem values via engineered solutions), such that we cannot understand cities' resilience capabilities (i.e. system capacity and behavior in responding to disturbances) to climate hazards without an understanding of the interactions within and between each SETS domain [8–10].

In response to climate hazards, T-focused approaches for infrastructure resilience often emphasize recovery of physical components and mechanical processes to ensure the provision of critical services in cities (e.g. back-up electrical transmissions and redundant water supply mains). In this way, infrastructure's aftermath response emphasizes 'bouncing back' from a perturbation, where the disturbed object's inherent materiality is restored to provide critical functions like electricity and potable water [11–13]. Studies providing definitions and guidelines for infrastructure resilience abound in the engineering resilience literature, which supports the planning of T-systems that are robust to disturbances [14,15]. Engineering resilience studies tend to focus on reinforcing the ability of infrastructure systems to withstand predetermined hazard envelopes or analyzing risks to infrastructure performance in terms of probability predictions [16–19]. Such technocentric approaches are often aligned with FS design in their view of infrastructure systems resilience. Risk management decisions made without considering the social or ecological context of infrastructure often affect the overall adaptive capacity to climate hazards in cities and overlook potential impacts on other systems. For instance, elevated levees cannot control the damages to homes and ecosystems if floods overflow the levee or if the levee itself breaches [20,21•]. In addition, social factors affecting T-systems, such as limited funding available for an infrastructure project and the socially acceptable safety in design, largely contribute to infrastructure performance and their capacity to reduce vulnerability from climate hazards [22]. Hence, a few studies have advocated for a need to evaluate infrastructure systems in consideration of the interactions with social systems such as political, financial (financing and affordability), governance, community engagement, equity, decision-making, public health, education, and so on [22,23,24•,25]. The SETS perspective adds explicit consideration of these additional systems, and their dynamics, which may have been overlooked or considered in isolation previously.

The SETS perspective builds upon social-ecological systems (SES) literature, which has critically framed resilience in terms of the sustainability of human-environment interactions [26,27]. With the rapidly growing number of cities experiencing extreme weather events, the importance of understanding urban systems as SES and their resilience to climatic hazards has followed, which may help contextualize infrastructure systems [27,28]. A few key studies have extended the SES perspective to include the role of built infrastructure as a means for delivering and managing ecosystem services for society [28–31]. However, a limitation of the SES perspective in addressing urban resilience is that it overlooks T-systems as a mediating actor in complex urban systems and underrepresents technology in SES sustainability dialogue [32•]. For example, SES-based institutional analysis and development framework only consider T-systems to be contextual factors defining biophysical conditions, rather than viewing technological, social, and ecological systems as commensurate in shaping the dynamics of cities [33,34]. SES interactions with T-systems have often been marginalized in the design and management of infrastructure systems. In responding to Hurricane Maria, for example, Lugo (2020) outlines the lack of ecological monitoring and administrative capacities (e.g. emergency sensors, institutional information flows, decision autonomy) that led to insufficient anticipatory efforts, further failures, and repair delays for electrical systems in Puerto Rico [35•]. At the same time, SES perspectives usually view T-systems as a subset of social systems [28,36••,37]. However, as components of infrastructure systems are entangled among SETS components, T-systems must be addressed alongside SES. The SETS view of urban systems is necessary to uncover the synergies and conflicts across SETS domains in addressing climate challenges through infrastructure systems.

Problem framings of infrastructure systems that are approached with narrow technocentric solutions are becoming increasingly insufficient under non-stationary climate. SETS resilience approaches challenge such framings by prioritizing agility (e.g. adaptive planning) to surprises over robustness and rigidity [38]. For example, Kim *et al.* leveraged a safe-to-fail infrastructure (STF) approach to frame resilient infrastructure development as planning for system failure during design to elucidate new solution pathways that minimize the impacts when infrastructure fails (e.g. traffic service disruptions due to storm drainage overflows) [4••]. The STF response to 'beyond-design' hazards focuses on comprehensive risk management across SETS. Thus, 'anticipated' structural or functional system failure may occur based on the SETS risk management decisions in order to minimize damages to people, the economy, or ecosystems. In this paper, we argue that STF planning and design unveils the SETS view of urban systems resilience in responding to climate hazards as it requires decisions for prioritization of SETS capabilities and potential impact transfers from one domain to another upon system failure.

## Addressing SETS irreducibility through safe-to-fail infrastructure

The STF infrastructure planning and design incorporate resilience strategies with a consideration of how SETS and their subsystems interact with the infrastructure [2•,4••]. We define this STF design process as 'leveraging SETS resilience capabilities', that is, identifying components and functions across SETS that can be substituted to deal with critical service loss or system failure impacts, to proactively plan for infrastructure failures for comprehensive risk management in urban areas. Unlike traditional infrastructure planning that follows a set of technical design specifications for safety management, STF planning and design requires an understanding of regional SETS capabilities (e.g. identification of socioeconomic vulnerability to climate risks, institutional readiness to extreme weather events, financial capacity for recovery, adequate infrastructure system, ecosystem responses to hazards, emergency planning, etc.) and trade-offs (i.e. risk management decisions that compromise incompatible SETS resilience capabilities; vulnerability transfers among affected SETS) within the decision context for improved adaptive capacity and more comprehensive urban climate risk management. In comparison to FS approaches, STF urges stakeholders to critically examine trade-offs across SETS due to the unintended transfer of vulnerability from one domain to another or within components of each SETS domain. For instance, a dense city experiencing housing problems may allow developments close to floodplains and vegetated flood mitigation buffers to overflow but equip the area with advanced flood warning systems and flood insurance programs [39,40]. Thus, the risk of physical damage in the ecological and built environment domain is substituted by additional institutional capacities in the social domain. In Table 1, we summarize the design principles of traditional infrastructure (i.e. FS) and STF in responding to climate hazards.

STF approaches address the irreducibility of SETS through *the Infrastructure Trolley Problem* [4••]. *The Infrastructure Trolley Problem*, where there is a strategic choice between what and who is impacted by a failure, reveals the inherent moral dilemma of incorporating failure in design and planning. It also underscores the potential consequences of infrastructure failures that may be experienced differently by SETS attributes in a city. In other words, the consequences of STF infrastructure failure will have varying levels of impact and be judged by different values along SETS dimensions in cities. Infrastructure managers implementing a STF approach must identify potential disturbances and associated failure consequences, prioritize diverse values of stakeholders, and navigate the associated trade-offs to implement a design [4••,6]. This navigation encourages infrastructure managers to prioritize impacts and identify trade-offs across SETS. However, infrastructure managers must also adhere to rules and regulations that lower risks, such as emphasizing public safety and reducing environmental impact [41,42]. Therefore, infrastructure failure is additionally defined by the consequences on the social and ecological domains — again highlighting the irreducibility of SETS systems. Failure management is not a simple task given the complex urban systems in which infrastructure operates, requiring STF approaches to be iterative with reassessments of prioritizations and trade-offs throughout the infrastructure systems life. Ultimately, for resilience efforts and objectives to be fully realized, SES frameworks should strive to more explicitly recognize and consider the influence and importance of technological systems (i.e. move from SES to SETS perspectives), while T-systems should strive to more explicitly anticipate, consider, and balance the social and ecological impacts that can arise from failure (i.e. move from FS to STF perspectives).

As a process of navigating tensions across SETS resilience capabilities, which remains largely unexplored, the STF approach provides a critical opportunity to incorporate SETS dynamics into the system design and planning. For instance, infrastructure has empowered humans to live in harsh environments (e.g. large-scale movement of water via canals and pipelines in dry areas, implementation of dams and levees in flood-prone areas, and adoption of refrigeration and air conditioning in hot areas), connect distant and remote locations (e.g. transportation of people and goods via ship, rail, road, and air), and create global economies (e.g. identification, extraction, and transformation of natural resources into products). Thus, underappreciation of T-systems can translate to an underappreciation of risks/vulnerabilities within the urban system, as well as mechanisms by which resilience can be enhanced. In addition, given the role of infrastructure as a key intermediary in connecting social and ecological systems, risk and resilience principles (or lack thereof) within T-systems are implicitly integrated into the broader SES dynamics. Therefore, SES approaches to resilience appear to be unwittingly underappreciating sources of catastrophic failure by underappreciating the influence of T-systems across SETS. Conversely, technocentric FS approaches overappreciate T-systems and

**Table 1**

**Design principles of fail-safe and safe-to-fail infrastructure and examples showing how these design approaches leverage social, ecological, and technological systems (SETS) capabilities for infrastructure resilience**

| | Fail-safe | Safe-to-fail |
|---|---|---|
| Design principle | - Preservation of status quo<br>- Failure prevention | - Adaptation to changing conditions<br>- Failure impacts management |
| Design focus | - Advanced risk probability calculations & safety margins<br>- System shut-down for a rare, catastrophic event | - Comprehensive risk impact assessments<br>- Compromised system function for a rare, catastrophic event |
| Failure response | - Rebuild<br>- Back to normal or decision limited by lock-in | - Recovery<br>- Adapting to new normal |
| Example of SETS capabilities/trade-offs in design | Strengthen/back-up engineered system capabilities (T) to maintain the system function or to avoid structural failures such as dam/levee spillways and oversized/backup storm drainage pipelines | Lowered and reinforced road sections (T) in floodplains that are designed to allow the controlled overflow of stormwater drainage systems during the intense flooding and direct them to wetlands and recharges (E) despite the traffic disruption (S, trade-off). |

account for social and ecological domains as external design conditions rather than embedded system characteristics. STF approaches directly challenge the reduction of complex urban systems as narrowly technological or as strictly socio-ecological systems, and necessitate a recognition that SETS domains are interconnected and interdependent [36••,43–45]. Because of this level of complexity, it is necessary to anticipate that known and unknown hazards will occur, which highlights the irreducibility of SETS resilience considerations in STF infrastructure planning and design.

## Challenges and opportunities of safe-to-fail infrastructure transformation

Several questions for constructing and operating STF, with a SETS lens, still need to be answered to address the issues related to resilience governance [46], including (but not limited to): i) who is responsible for navigating trade-offs of SETS resilience capabilities?; ii) how to engage with stakeholders for prioritizing decisions in addressing *the Infrastructure Trolley Problem*?; and iii) how might the role of institutions change to encourage STF approaches? With the necessity for considering failure consequences in STF infrastructure development, practitioners need to decide whom, where, and why people and infrastructure systems experience certain failure outcomes. In addition, these decisions must entail how resources across SETS will be provided and how the community will respond after the failure (e.g. emergency response plan). FS decisions allow decision-makers to transfer the responsibility of failing infrastructure systems to technological capabilities based on design manuals and climate prediction models or to those that own, operate, or use them. On the other hand, STF infrastructure development allocates the responsibility to domain experts and stakeholders across SETS dimensions. While this distribution of power allows for clearer understandings of dynamics between the domains and potential consequences of infrastructure failure, it also diffuses responsibility for that failure. In turn, this diffusion of responsibility can confound recovery efforts if the domain experts and stakeholders remain isolated from one another. Therefore, in order to provide space for effective STF planning and design — and acknowledge the irreducibility of SETS — infrastructure organizations should re-evaluate their organizational structures and relationships with stakeholders to support collaboration.

### Who is responsible for navigating trade-offs of SETS resilience capabilities?

A STF approach asserts that stakeholders — willing to participate across SETS domains and from varying levels of authority — are responsible for the effective operations of infrastructure services. Therefore, stakeholder engagement (i.e. knowledge co-production) is critical for assessing SETS resilience capabilities and trade-offs within STF planning and design. For instance, when considering climate hazard impact profiles, tangible costs of infrastructure failure, like property loss, can be easily assumed in absolute economic terms, but additional impact categories considered in SETS capabilities are not easily captured without the inclusion of broad stakeholder opinion or valuing [47–49]. Infrastructure failure consequences such as displacement, homelessness, livelihood damage, unemployment, environmental losses, and health impacts may be uniquely experienced depending on the affected stakeholders' capacity to respond and adjust to each disturbance [4••,50]. Thus, two challenges emerge: i) ensuring social equity in risk mitigation [51] and ii) providing equitable opportunities for all stakeholders wishing to contribute to decision-making processes [32•,52]. Stakeholders affected by development decisions across SETS domains must be informed and consulted in the decision-making process, which will require active deconstruction of existing power dynamics regarding ownership of infrastructure systems [22]. For example, if stakeholder engagement is not effective at including vulnerable populations who have a lower capacity to respond to health issues or unemployment caused by infrastructure failures, then SETS trade-off decisions may make the same people more vulnerable to planned failures [53]. Notably, complete stakeholder engagement is an inherent challenge, especially in cities with large, diverse populations [23,54,55].

### How to engage with stakeholders for prioritizing decisions in addressing the infrastructure trolley problem?

Several studies have demonstrated approaches for integrating diverse stakeholder views to help assess risk vulnerability, prioritize decisions with diverse objectives, and elucidate the SETS resilience capabilities for climate risk management, that is, addressing *the Infrastructure Trolley Problem*. Walpole *et al.* incorporated practitioners' mental models into ecological restoration decisions [56] and Kim *et al.* addressed the practitioners' shared/discrete views in implementing resilience strategies for infrastructure development [57]. Bessette *et al.* developed a values-informed mental model for understanding communities' climate risk management decisions [49] and York *et al.* demonstrated an inter-level feedback process for collective climate actions decision-making across individuals and organizations [58]. Particularly, Perrone *et al.* demonstrated the value of stakeholder engagement in evaluating the causes, consequences, and policies for flood management from both environmental and socio-economic perspectives through a participatory modeling approach for the Bradano River, Italy [59••]. In an effort to engage historically underrepresented communities and address social equity in urban adaptation planning, Amorim-Maia *et al.* proposed the adoption of place-based and place-making approaches, as well as the promotion of cross-identity climate action and community resilience building [60]. Nonetheless, an exhaustive study for integrating SETS resilience capabilities, revealed through stakeholder engagement, into infrastructure decisions appears warranted for future STF planning.

### How might the role of institutions change to encourage STF approaches?

Institutions that manage infrastructure systems will need to adapt to accommodate STF infrastructure transformation. Whereas current infrastructure regulations focus on refining design guidelines for system construction and maintenance, STF regulations may also require additional governance capabilities such as community-building (internal and external) and knowledge sharing so organizations may learn from one another [61]. For example, STF development may require sharing of data on infrastructure performance, decision criteria for prioritizing the SETS capabilities, protocols for emergency system operation, and compensation of failure impacts. One regulatory shift that promotes STF development is for city governments to require insurance companies to provide accumulated information on infrastructure risks and damages experienced in the region. This information may be shared with the city government and the affected stakeholders to assess the current SETS capabilities based on the empirical data. Shifts in one sector (e.g. design firms) will require shifts in other sectors, like governmental organizations, utilities, insurance companies, operation, and regulation [62].

Transformation to infrastructure solutions that incorporate SETS resilience capabilities with STF design is steadily occurring. Incremental adaptation (organic but gradual system evolution that is tightly coupled to established paths, for example, strengthening infrastructure) and transformation (intentional deviations from the status quo during 'windows of opportunity' often found in the aftermath of extreme disturbances, for example, rapid adoption of an emergent technology) are two mediums for infrastructure transformation [63,64•,65]. Similarly, resilient infrastructure planning methods are being developed to incorporate SETS thinking into future solutions [66]. While STF infrastructure transformation is happening in the course of incremental adaptation, it is challenging because it requires design practices to be less path-dependent than previously established approaches. The most approachable window of opportunity for the rapid adoption of STF infrastructure would be when existing infrastructure systems reach design capacity and need to be upgraded or replaced, but technological solutions are not always ideal candidate solutions. While projects can focus myopically on efficient optimization for infrastructure planning, commonly featuring path dependency and business-as-usual solutions [65], SETS thinking uses a larger toolset of solution possibilities, which ought to increase the probability of reaching a sustainable solution. For example, as summer temperatures increase in Phoenix, Arizona, cooling and electrical demand loads increase, pushing the power grid closer to critical limits [67]. Power failure during critical summer temperatures can have impacts that ultimately lead to human deaths. Technical solutions such as updating aging power lines and adding backup generators, while a necessary component of the solution, cannot be the only solution considering costs and technical thresholds for extreme temperatures [68]. The city has been working with vulnerable communities to diversify responses to power system failures that leverage the various components of SETS capabilities. Social programs included educational programs to show children how to operate safely in the heat during summer break and providing funding for residents to improve insulation in homes. Ecological solutions included strategic green-space development to decrease ambient air temperatures and increase shade. Technological solutions included installing strategically placed drinking fountains and constructing splash pads. This example shows how SETS resilience capabilities are leveraged to provide safe-to-fail infrastructure responses to deal with extreme heat for the identified communities [69].

## Conclusions

Leveraging the resilience capabilities across SETS domains in STF approaches appears to support graceful extensibility in resilience engineering. Contemporary framings of infrastructure resilience describe strategies when systems are perturbed within and beyond their design conditions [70]. Within their design conditions, rebound (bouncing back) and robustness (hardening) are appropriate. However, when perturbations exceed design conditions then extensibility becomes appropriate — extending adaptive capacity in the face of surprise. Extending the capacity of such large and extensive infrastructure systems is a monumental challenge. If the extension is viewed purely through a technological lens, then few options exist — for example, how do you provide water through an alternative technology to millions of city residents when the primary drinking water system has failed? Or how do you decide on the size of drainage pipes when the intensity of a 100-year storm keeps changing? STF leveraging SETS resilience capabilities offers pathways towards graceful extensibility by leveraging social and ecosystem capabilities in anticipating and planning for failure. For example, The Netherlands' Room for the River calls on social systems when rivers flood and infrastructure fail, to subsidize farmers for lost crops — far cheaper than elevating and maintaining levees [71]. Arizona's Indian Bend Wash has initially leveraged ecosystem capabilities to attenuate flooding when monsoon rains overwhelm the stormwater system [72]. And more recently, the City of Scottsdale is working on an updated master plan for infrastructure through multiple rounds of community feedback, which not only responds to the shifting hydrologic risks by updating aging infrastructure for flood management, but also asks the question of how social and ecological values of Indian Bend Wash as recreational parks and aquatic centers might affect the community when they are compromised by overflow [73]. In contrast to how other resilience frameworks incorporate capabilities of the three domains, STF appears to be better suited for leveraging SETS capabilities during the design phase to open up new adaptation strategies and infrastructure transformations — aligning it with traits of graceful extensibility upon surprises.

STF infrastructure planning and design offer transformational opportunities for infrastructure systems to evolve from a techno-centric or SES-centric solution space to an interactive system leveraging various SETS resilience capabilities — presenting new strategies for navigating uncertainties and disasters in the Anthropocene. External shocks such as extreme weather phenomena are not only disrupting the infrastructure system itself, but also the urban environment including people and property. Despite traditional infrastructure protection achieved by ensuring the robustness of built systems, climate change is altering the perspectives of cities to recognize infrastructure risks that are not predicted with climate models. Thus, there is a coupling between STF infrastructure planning, SETS climate adaptations, desired urban futures, and the likelihood of unprecedented non-stationary weather events. Major institutional and technological changes happening with national and international climate adaptation plans should give cities a chance to adapt to the change by transforming the processes that have contributed to vulnerability rather than focusing on reducing specific risks of climate change by a set of interventions [74]. Hence, infrastructure transformations towards resilience in the face of climate uncertainties and non-stationarity must take what we know now and proceed to STF approaches that incorporate SETS capabilities.

## Conflict of interest statement

Nothing declared.

## CRediT authorship contribution statement

**Yeowon Kim:** Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Funding acquisition. **Thomaz Carvalhaes:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Alysha Helmrich:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Samuel Markolf:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Ryan Hoff:** Investigation, Writing – original draft, Writing – review & editing. **Mikhail Chester:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Funding acquisition. **Rui Li:** Conceptualization, Investigation, Writing – original draft. **Nasir Ahmad:** Conceptualization, Investigation.

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