Ch. 5 - Climate-resilient transportation infrastructure in coastal cities

Michael V. Martello[1]; Andrew J. Whittle, Sc.D[1]

[1]Department of Civil & Environmental Engineering, Massachusetts Institute of Technology

Abstract

Climate change, sea level rise, and associated increases in climate-related risks pose significant threats to transportation infrastructure in coastal cities. In order to improve resilience of the transportation infrastructure it is necessary to understand projected future climate extremes, inherent system characteristics, and relationships to local and regional socio-economic and socio-political systems. We provide an overview of the theoretical and practical dimensions of the design of climate-resilient transportation systems and relevant dimensions for infrastructure adaptation and planning, including valuation and assessment of equity. Highlighting existing gaps in literature, we note further research is needed to better relate natural hazard exposure to \physical and operational consequences (e.g., disruption durations, asset-level damages, interdependencies) and improved methods for assessing the adaptive capacity of organizations managing transportation infrastructure systems. Climate-resilient transportation infrastructure systems will require paradigms shifts in infrastructure engineering, planning, and design. We also highlight the need for new frameworks for evaluating benefits in the financing of adaptation projects to improve resilience.

Keywords

Climate change, resilient infrastructure, adaptation, infrastructure valuation, transportation planning, adaptation equity

5.1. Introduction

Reliable and safe transportation infrastructure systems underpin well-functioning economies and societies, serving as the foundation of supply chains, and providing individual human mobility and access. Infrastructure assets for surface (road, rail, inland waterways, pipelines), marine, and air transportation systems (Table 1) are typically designed for a long service life (>50-100 years) and must perform under a range of extreme loading conditions informed by historic observations of natural hazards. Anthropogenic climate change, driven by greenhouse gas emissions, is increasing global surface temperatures, and diminishing polar sea ice, leading to an increase in mean sea levels. While the long-term severity of these changes in climate can be tempered by emissions reduction and mitigation efforts, significant changes in climate-related risk are likely under all emissions scenarios (IPCC, 2022). Coupled with long-term trends in regional weather conditions (precipitation and drought patterns, drought cycles, inter-annual tidal cycles) these global trends will result in more frequent and more extreme events[1] (tropical and extra-tropical cyclones, extreme rainfall, storm surge etc.) The resultant increases in stress on existing transportation systems will have wide-ranging effects, including shortened expected asset service lifespans, significant disruptions to the flow of goods and the mobility of individuals, as well as extensive damage to physical infrastructure. Ensuring the resilience of transportation systems to climate change therefore represents a fundamental societal challenge of the 21st century that will inevitably require significant capital investments, as well as paradigms shifts in infrastructure engineering and design.

Table 1: Common transportation modes and associated transportation infrastructure assets (after NASEM, 2021)

Transportation Mode		Infrastructure Assets
Surface	Road	Roads, bridges, tunnels, culverts, traffic signals, toll collection systems, intelligent transportation systems (ITS)
	Rail	Tracks, bridges, tunnels, culverts, yards, maintenance facilities, stations, terminals, signals, power systems
	Urban Transit	Bus garages, dedicated busways, ferry docks
	Pipeline	Pipes, pumping stations, compressor stations, manifolds, storage facilities
	Waterways	Channels, locks, dams, terminals
Maritime		Docks, breakwaters, entrance channels, basins, container yards, roads and rail lines, container terminals, warehouses
Air		Airports, runways, taxiways, control towers, hangars, access roads, heliports

This chapter focuses on the resilience of transportation systems in coastal cities where climate change is expected to cause significant increases in flood exposure due to sea level rise (SLR) and changes in the magnitude and frequency of extreme precipitation events (as well associated changes to

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[1] Estimates of effects of climate change on extreme events constitute a rapidly changing facet of climate science. Tropical cyclones are drivers of extreme rainfall and surge, but their joint hazards have only recently been investigated (Gori et al., 2022). Transportation facilities are also affected indirectly by cascading effects. For example, loss of vegetation due to forest fires can promote increased landslide hazards (Gariano and Guzzetti, 2016).

riverine flood exposure[2]). More than 10% of the global population lives in low-elevation (urban or semi-urban) coastal zones (LECZ, < 10m above sea level; CIESIN, 2013) including 94.7M people in the US (29% of the population). Hallegatte at et al. (2013) estimated an average annualized loss (AAL) of $6B due to flooding in 136 major coastal cities worldwide in 2005. By 2050, they project AAL will increase to $52B due to socio-economic development alone (including growth of transportation assets). They estimate the cost of adaptation projects to maintain the same level of flood exposure in 2050 (for an estimated sea level rise of 20 cm) will be $1T/year. Their analyses also identify the 20 cities with the highest AAL in 2050 (and ratios of AAL to projected GDP), a list that includes 5 US cities[3].

Many of these coastal cities serve as major maritime and air transportation hubs that support global trade and travel, and by virtue of their locations, related transportation infrastructure assets are often vulnerable to coastal flooding. For example, Kansai Airport, located in Japan, was constructed offshore in Osaka Bay in water depths exceeding 20m. The runways, which are undergoing sizable long-term subsidence, are nominally located 3m above sea level and are protected by a 4.4 m high perimeter seawall (Le et al., 2019). During Typhoon Jebi in 2018, the walls were overtopped by the storm surge and high waves (estimated at 4.2m), resulting in flooding of the runways and airport closure that lasted more than 3 days. With climate change, such flood-related disruptions are expected to become increasingly frequent, posing a systemic risk to air transportation infrastructure. By 2100, Yesudian and Dawson (2021) estimate than more than 100 (out of a total of 1238 LECZ airports) will lie below mean sea level, with potential for annual disruption of 20% of global commercial airline routes. Similar climate resilience challenges face surface transportation networks, with significant potential service impacts to roadway networks (Testa et al., 2015) and underground rapid transit systems in LECZ, as illustrated by the extensive damage to the transportation tunnels in New York due to Hurricane Sandy (Aerts et al., 2013; Nikolaou et al., 2020).

Absent adaptation, the wide-ranging challenges posed by climate change and SLR represent an existential threat to surface transportation infrastructure systems. Here we address this topic by asking a number of basic questions: 1) How can we define and measure the climate change resilience of transport infrastructure systems? 2) How can we estimate the expected impacts of climate change and SLR on a given infrastructure system? And perhaps most importantly, 3) how can we successfully adapt infrastructure and improve the resilience of transport systems to climate change and SLR?

5.2. Climate Change Resilience of Transportation Infrastructure

The concept of resilience features prominently in a variety of fields, ranging from ecology to social sciences, engineering, and climate science, and serves as a boundary object between these fields (Brand & Jax, 2007). Definitions across fields vary depending on the indeterminacy of a system of interest, with resilience of closed engineered systems typically characterized by the return to a pre-defined system state (i.e., single equilibrium) while resilience of more indeterminate/open systems require a greater number of (normative) value judgements to describe the system itself and its multiple potential equilibria (Davidson et al., 2016; Meerow et al., 2016).

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[2] Anthropogenic subsidence is a major factor in flood risk for some delta cities, especially those that rely on local groundwater sources (Jakarta, Ho Chi Minh city).
[3] Miami, New York-Newark, New Orleans, Tampa-St Petersburg, Boston.

There are some aspects of resilience that are generally recognized across domains, despite the contextual nuances of domain-specific definitions. The National Academy of Science, Engineering, and Medicine (NASEM) defines resilience as the ability of a system to plan and prepare for adverse events and effectively absorb, recover, and adapt to adverse events (NASEM, 2012). Linkov & Trump (2019) further suggest this definition is threat agnostic, separate from conceptions of risk, and that resilience is an intrinsic property of a system that describes its ability to respond to any possible disruption event. While such a definition can be useful in the context of system design, expansion, and multi-threat analysis, it is ultimately too abstract to apply when considering a specific class of exposures and associated risks (e.g., climate change-related risks which are of primary interest here). Indeed, the physical impacts of different types of risk on individual system components can vary substantially, and hence, the concept of resilience requires a more granular interrogation of exposure-specific system characteristics. In this chapter we adopt the following definition of resilience presented by IPCC (2014):

Resilience is the endogenous capacity of the system to cope with a predefined exogenous perturbation, responding or reorganizing in ways that maintains its perceived essential function, identity, and structure, while also maintaining the capacity for adaptation and transformation.

Ultimately, the resilience of a transportation infrastructure system is dependent on i) the exogenous (i.e., external) exposure event(s) of interest, ii) intrinsic/endogenous system characteristics that describe its response to exposure, and iii) a description of its core functionality, requiring some degree of subjective/normative judgement to contextualize system performance (e.g., daily number of passengers carried by the system). Martello et al. (2021) provide a topological mapping of concepts that inform infrastructure resilience and vulnerability in the context of urban rail transit networks (Figure 1).

Consistent with previously established definitions, system exposure, sensitivity, and adaptive capacity inform vulnerability to climate change (IPCC, 2007; FHWA, 2017), while resilience is ultimately affected by vulnerability, adaptive capacity, and contextual characterizations of system performance. The commonly accepted "4Rs" of engineering resilience (Figure 1; Bruneau et al., 2003; Ayyub, 2021), define the endogenous aspects of system resilience; i) Robustness of the system to the exposure of interest; and ii) its Rapidity (of recovery) inform sensitivity, while iii) inherent topological Redundancy and iv) Resourcefulness in the deployment of available resources inform adaptive capacity.
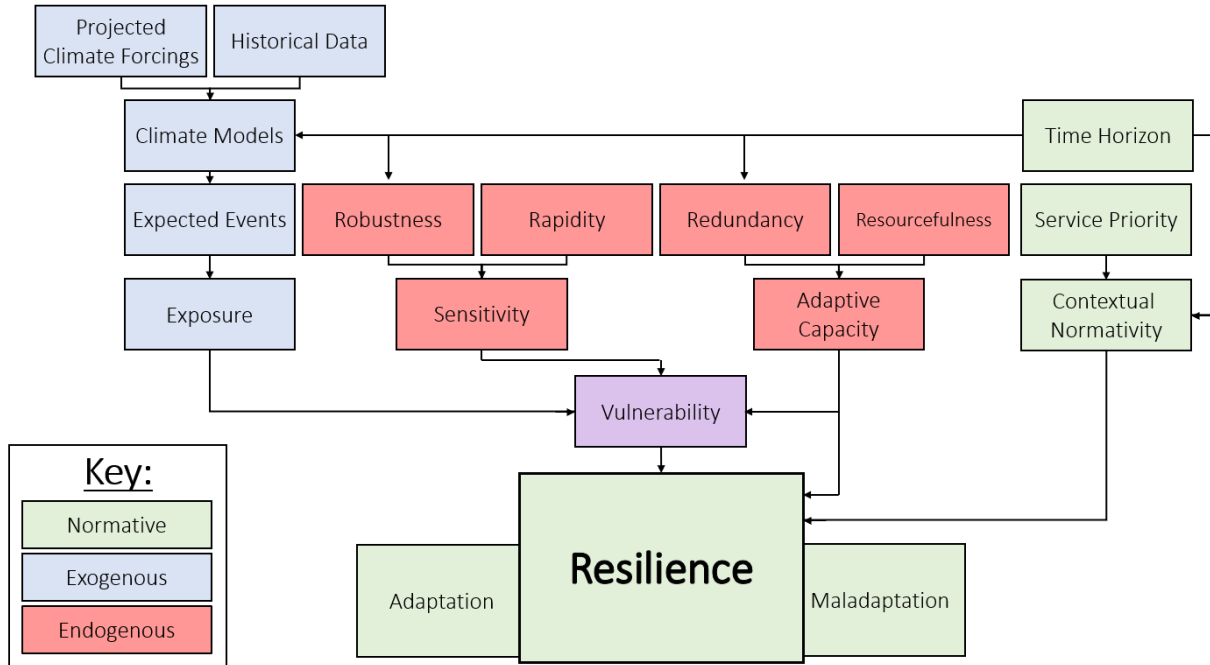
Figure 1: Topology of concepts informing resilience of infrastructure systems to climate change (Martello et al., 2021)

Within this framework, exogenous components of climate change resilience (i.e., projected climate forcings, historical data, expected climate-related events) are synthesized to inform an exposure event of interest. Endogenous components of resilience aim to describe how the physical infrastructure components respond to the exposure of interest (i.e., sensitivity), as well as the ability of the system to maintain functionality during the exposure event (i.e., adaptive capacity). The response of the system to the exposure event is contextualized by normative components of resilience, which aim to describe the relative priority of services across the system, and the time horizon of interest to decision makers. For example, for an urban transit network priority can relate to the distribution of passenger volumes among links within the network (e.g., Dall'Asta et al., 2006; Xing et al., 2017) or though further prioritization of socioeconomic factors to achieve more equitable access (Martello et al., 2021). These factors can include the relative reliance of riders on transit (e.g., inferred rates of car ownership), the relative income of passengers that rely on a given section of a transit line, or subsequent changes in mobility and accessibility of socially vulnerable groups (Sun et al., 2021).

Notably, the resilience of a system is affected by permanent changes that can influence its behavior and response to exposure events. Such changes that are made to explicitly support the resilience of the system are typically referred to as adaptations, whereas changes which are perceived to undermine and decrease the resilience of the system can be considered instances of maladaptation (Magnan et al., 2016). Measures undertaken explicitly to promote resilience have the potential to be maladaptive, particularly when such measures result in unintended path dependencies or promote adverse feedback loops that result in negative long-term outcomes (Brown, 2011; Pelling, et al., 2015; Fisichelli, et al., 2016). Determination of whether an action or measure is maladaptive can be subjective and context

dependent, particularly in situations where the benefits are distributed disproportionately across a region or over time.

5.3. Quantifying Resilience to Climate Change and Coastal Flooding

Quantification of transportation system resilience to climate change requires a working knowledge of present and projected future climate exposure events, an adequate understanding of the relevant physical and organizational characteristics of the system of interest, as well as the ability to situate the system of interest within its socioeconomic and temporal context. Proper consideration of these factors is critical to characterize system performance in response to climate-related exposure events. While quantifying resilience may strike some as overly rigorous, a measurement of current system resilience to a set of exposure events can serve as a baseline from which the effectiveness of adaptation measures can be evaluated. Further, the exercise of quantifying resilience to a set of climate stressors enables the identification of potentially vulnerable portions of a transportation system.

Resilience quantification metrics for engineered systems can be methodologically classified as either subjective, probabilistic, or recovery curve-based metrics (He, 2019). Recovery curve-based resilience metrics typically recognize a temporal dimension of system response and recovery (Henry & Ramirez-Marquez, 2012; Ayyub, 2014; Franchin & Cavalieri, 2015) and are commonly employed to evaluate transportation networks (e.g., Chan & Schofer, 2016; Li, et al., 2017; Wan et al., 2018; Zhang, et al., 2018; Zhang, et al., 2019; Martello et al., 2021). At a high level, recovery curve-based metrics aim to characterize system performance over time, $Q(t)$, where a baseline performance during a pre-disruption phase, Q_0, is compared to system performance during the disruption event (from the start of the response phase at t_0 to the end of the recovery phase at t_1, which is typically demarcated by a full recovery of baseline system performance at the post-disruption phase as shown in Figure 2 (Wan et al., 2018). Ayyub (2014) notes post-disruption system performance levels may be diminished after recovery depending on the level of component degradation or may be increased if significant system improvements are made during the recovery process.
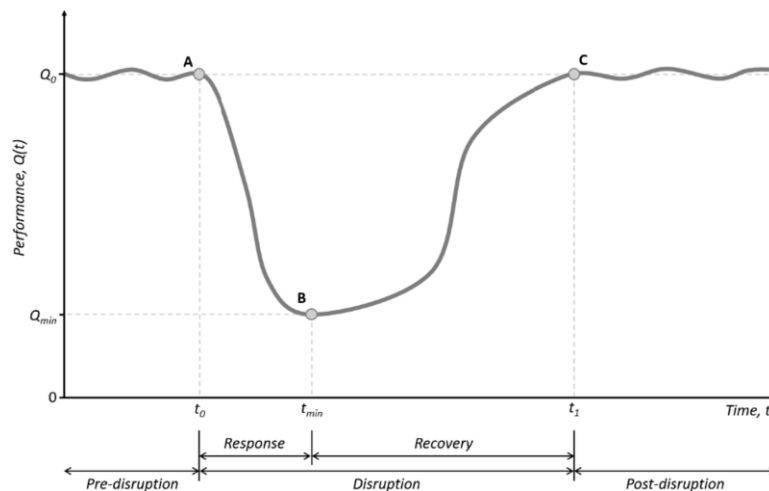

Figure 2: Generalized conception of system performance under exogenous perturbations (Martello et al., 2021).

More formally, the resilience of a system to a predefined exogenous perturbation (e.g., flood event) is the level of system performance maintained during the response and recovery phases of a

disruption relative to the expected performance based on a pre-disruption baseline over the same period. Several authors (Franchin & Cavalieri, 2015; Zhang et al., 2018; Saadat et al., 2019; Martello et al., 2021; Ayyub et al., 2021) mathematically represent this resilience metric, R, as:

$$R = \frac{\int_{t_0}^{t_1} Q(t)dt}{(t_1 - t_0)Q_0} \tag{1}$$

Given the inherently networked structure of transportation infrastructure, graph theoretic measures of overall system connectivity (e.g., network efficiency; Latora & Marchiori, 2001) are an efficient way to characterize system performance of transportation networks (e.g., Testa et al., 2015; Li et al., 2017; Xing et al., 2017; Zhang et al., 2018; Zhang et al., 2019; Saadat et al., 2019; Ayyub et al., 2021; Martello et al., 2021).

Based on this definition, the speed of recovery and the shape of the performance curve through the disruption phase have a significant impact on the system resilience. However, cases of transportation network performance during and after natural-hazard events are poorly documented (Dawson et al., 2018). One notable exception is Chan & Schofer (2016) who provide insight into the recovery of the New York City rail rapid transit system to several natural hazards, including Hurricane Sandy. Other authors provide estimates of recovery time by formulating optimal system recovery strategies based on node restoration priority (e.g., Sela et al., 2016; Bhatia et al., 2020), though such studies neglect physical and temporal aspects of recovery and do not attempt to provide meaningful estimates of recovery times. Absent methods for estimating recovery over time, basic assumptions on the shape of the performance curve can approximate temporal recovery pattens. Martello et al. (2021) suggest the shape of the system performance curves through the response and recovery events corresponds to the level of disruption severity, with more severe events requiring a temporary system closure. Regardless of the shape of the recovery curve, the severity of performance loss primarily informs the level of system resilience. In the following subsections, we outline available methods of assessing present and future coastal flood exposure and how flood exposure relates to performance loss.

*5.3.1. Assessing Present and Future Coastal Flood Risk*

Current climate projections and expected sea level rise (SLR) suggest the frequency and severity of extreme weather and coastal flood events will increase throughout the 21st century (Kopp et al., 2014; Buchanan et al., 2016). This expected increase in coastal flooding poses particular challenges for urban transportation infrastructure in coastal cities. In particular, current and future coastal flood risk represent a significant threat to rail rapid transit infrastructure (Martello et al., 2021) as demonstrated firsthand by the significant and extensive damage caused by Hurricane Sandy in 2012 (Aerts et al., 2013).

In practice, understanding the resilience of transportation infrastructure to climate change requires a reliable and robust characterization of present and expected future climate stressors (i.e., exogenous components of resilience). Without sufficient data on the projected frequency and intensity of future climate stressors of interest, it is a practical impossibility to characterize the resilience of transportation infrastructure to climate change. As such, the availability of relevant climate projections is a necessary prerequisite for climate resilience or vulnerability analysis (FHWA, 2017).

In the absence of such climate projections, there may be preexisting publicly available data characterizing climate risks based on present climate conditions. For example, local, national, and international building codes typically provide maximum wind speeds for use in structural design, which can be used to estimate resilience due to extreme wind events. Similarly, federal agencies (e.g., US

Federal Emergency Management Agency; FEMA) typically publish flood maps, which consider historic flooding and expectations of present precipitation, riverine, and coastal flood risks. Local meteorological data, such as temperature extremes and tide gauge records can also be used to characterize present levels of climate risk.

In many cases, federal, state, and/or local government agencies have already performed more thorough investigations into both present and projected future coastal flood risks, making the information publicly available and readily accessible. For example, recent modeling work commissioned by MassDOT (Bosma et al., 2015; WHG, 2021) has characterized coastal flood risk with SLR for Greater Boston (Figure 3) and has informed subsequent studies of future precipitation-based flood risk for the city of Boston (BWSC, 2020). In circumstances where relevant information is lacking, additional modeling work can be undertaken to better characterize present and future climate risks, though there exists an inherent tradeoff between computational efficiency and model fidelity (Deierlein & Zsarnóczay, 2019). There are a variety of open source and commercial software available for modelling coastal flood risk. Coastal flood risk models are typically coupled models, wherein topometric, bathymetric, and meteorological inputs inform a model of wind shear-induced storm surge and long-period waves (e.g., ADCIRC, GEOCLAW) which in turn informs a near-shore wave model that attempts to capture shoreline wave dynamics (e.g., SWAN, STWAVE) thereby enabling high fidelity dynamic modeling of coastal flood events (Deierlein & Zsarnóczay, 2019). Less computationally expensive coastal flood modeling alternatives, such as the GEOCLAW-based model presented by Miura et al. (2021) can also allow for more rapid characterizations of present and future coastal flood risks.
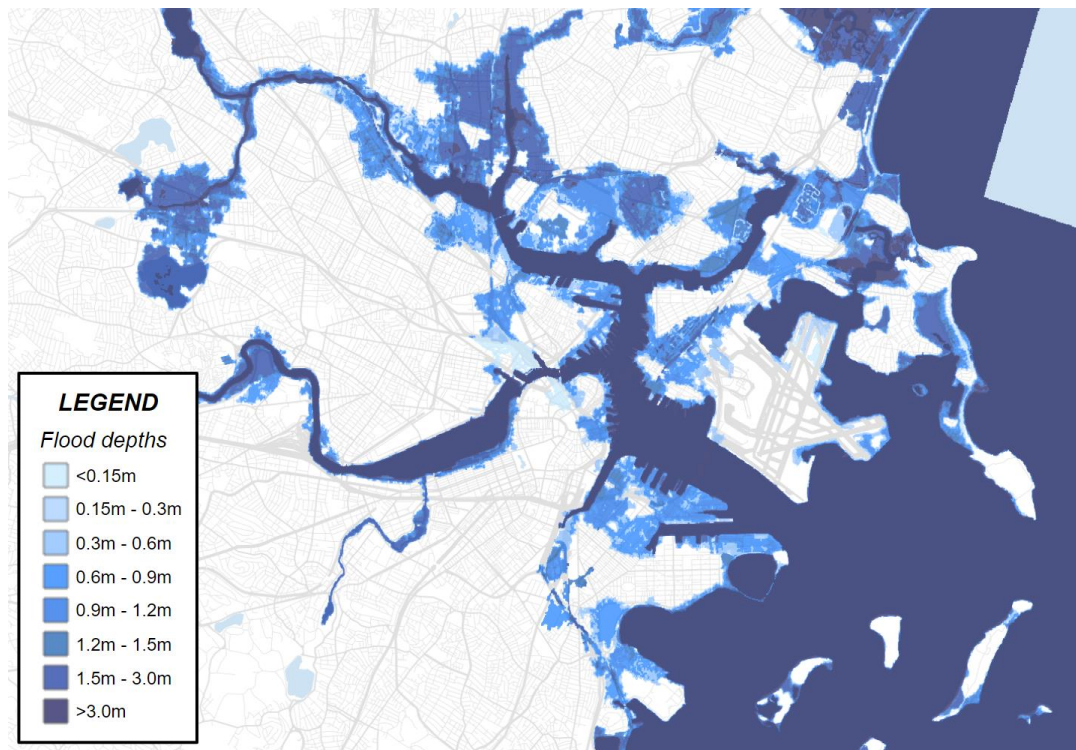
Figure 3: Projected 1-100 year coastal flood depths under +0.79 m SLR relative to year 2000 baseline (WHG, 2021). Flood projections based on statistical analysis of hydrodynamic simulations of a large, representative sample of synthetic tropical and extratropical storms expected to impact Greater Boston. The Massachusetts Coastal Flood Risk Model (MC-FRM) has a vertical resolution of <10 cm and a horizontal resolution of up to 3 m.

Absent the time, skill, or resources to complete a high-fidelity hydrodynamic coastal flood risk modeling exercise, a simple bath-tub approach can be employed instead, wherein the severity of a flood event at a given location is modulated by a SLR value and considered as the flood elevation across an entire region (e.g., see Rasmussen et al., 2020; Oddo et al., 2020). Such an approach will neglect non-linearities in flood severity arising from regional bathymetry, wave dynamics, and storm direction, but can provide a reasonable approximation of flood risk for evaluating transportation system resilience and relative performance of potential adaptation options.

5.3.2. Assessing the Consequences of Exposure

Understanding the resilience of transportation infrastructure to climate change or climate-related hazards requires an understanding of the physical consequences of hazard exposure. In the particular case of assessing resilience to flood exposure, the lowest critical elevations (LCEs) of a given transportation infrastructure system serve as the primary indicator of inundation and impact to system performance (Jacob, 2008; Martello et al., 2021). LCEs are locations where flood water could conceivably inundate a system of interest and affect its operations, such as low-lying sections of roadway, subway station entrances, or ventilation shafts (Figure 4; Jacob, 2008; Rosenzweig et al., 2011).

Further characterization of the right of way (ROW) location and elevation, as well as pertinent operational characteristics, such as vehicle dispatch locations, or track switch locations can then enable a more detailed understanding of the operational consequences of flood events (Martello et al., 2021). Detailed transportation infrastructure asset identification and geospatial characterization can also enable the prediction of asset-level flood damages and estimation of monetary losses (Compton et al., 2009; Kellerman et al., 2016). In many cases, the data required to characterize transportation system sensitivity and adaptive capacity is readily available within transportation agencies, though it may not be centrally located and may lack required geospatial metadata (FHWA, 2017).

Figure 4. Sample Lowest Critical Elevation (LCE), a ventilation shaft at street level directly above Courthouse Station along the MBTA Silver Line in South Boston (Google, n.d.)

The performance of transportation networks can also be affected by adjacent interdependent infrastructure systems. Interdependencies can result in cascading failures (NIST, 2015; NASEM, 2017; Linkov & Trump, 2019, NASEM, 2021). For example, failure of the power grid can affect downstream transit infrastructure assets, such as traction power substations, resulting in significant systemwide disruptions (Miura et al., 2021). Failure of a tide gate for a stormwater sewer outfall could cause backflow in a storm surge potentially inundating low-lying road networks or rail rapid transit tunnels (Sullivan, 2022). Despite the potential for such disruptions arising from cascading failures, infrastructure interdependencies are at present typically poorly characterized by infrastructure managers (Chester et al., 2021). Where sufficient information is available, the characterization of such system interdependencies can allow for the prediction of cascading failures, enabling an improved understanding of transportation system resilience in the broader context of the adjacent built environment.

5.4. Achieving Climate Resilience Through Adaptation

Ultimately, efforts undertaken to understand and quantify the climate change resilience of transport infrastructure systems are motivated by the need to adapt these systems such that they can better resist present and future extreme climate stressors. Without adaptation, the expected increases in frequency and severity of climate-related exposure events (Kopp et al., 2014; Buchanan et al., 2016; Strauss et al. 2021) will inevitably decrease the resilience of transportation systems and impinge upon their core functionality (Ayyub et al., 2021; Martello et al., 2021). While post-disaster response and recovery can be leveraged to enhance the resilience of a transportation network (Chester et al., 2021), proactively incorporating resilience into asset management and capital investment practices can enable the identification of vulnerabilities and opportunities to increase preparedness before a significant disruption event occurs (Caldera et al., 2021; Chester et al., 2021; Chen & Bartle, 2022).

Efforts undertaken to adapt to climate change can take a wide variety of forms and span several spatial and temporal scales. Viewing potential adaptation measures through the lens of infrastructure resilience as defined above, adaptation can be broadly classified along four separate categories of system improvement: robustness, rapidity, redundancy, or resourcefulness[4] (Dawson et al., 2018; Caldera et al., 2021).

5.4.1: Adaptation Decision-Making Frameworks

There are several dimensions to adaptation, not the least of which is the characterization and structuring of an appropriate decision-making process. Existing capital investment planning processes, are often insufficient for holistic needs of climate change adaptation planning. The inherent and deep uncertainty of climate change and its consequences makes for a particularly challenging decision environment. Several authors have proposed a variety of decision-making approaches, such as robust decision making (RDM), dynamic adaptive policy pathways (DAPP), real options analysis (ROA), and flood damage allowances, specifically to accommodate the uncertain nature of adaptation planning (Ramm et al., 2018; Sriver et al., 2019; de Neufville et al., 2019; Oddo et al., 2020; Rasmussen et al.,

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[4]As we note in a subsequent section, transportation system resilience can also improve as a consequence of exposure reduction, such as by the completion of a regional flood protection project outside the boundaries of the transportation infrastructure system.

2020; Ginbo et al., 2021). Regardless of the particularities, the fundamental aim of a given approach is to prepare a systematic framework that relies on available observations and projections to calibrate and inform an adaptation strategy given the prevailing uncertainty of future SLR and associated coastal flood risks. For example, in a DAPP approach, this can be as straightforward as the determination of pre-set condition/state (e.g., future sea level condition) that will trigger a specific adaptation pathway (Ramm et al., 2018). More sophisticated approaches such as the flood damage allowance framework, attempt to calibrate adaptation policy by matching present and future annualized monetary flood losses (Rasmussen et al., 2020). While any of these decision-making frameworks can help calibrate and balance adaptation measures into the future, they nonetheless require a predefined decision space, particularly if alternative adaptation measures are under consideration. In the following subsections, we define and explore this decision space specifically for climate resilience-enhancing transportation infrastructure adaptation measures.

5.4.2. Scales of Adaptation

Adaptation alternatives exist across spatial, temporal, and organizational dimensions (Mesdaghi et al., 2022). Generally, as the spatial scale of an adaptation measure increases, so too does its temporal and organizational scale (i.e., bigger projects are more likely to be designed to last for a longer time and involve a greater number of public and private stakeholders; Mesdaghi et al., 2022). An inherent tradeoff exists between adaptation flexibility and scale, as the potentially greater benefits of larger projects typically arise from greater project complexity, a decrease in agency of individual decision-makers (i.e., increasing need for cooperation), and a decrease in implementation flexibility (de Neufville et al., 2019).

In contrast with climate change mitigation, in which actions and outcomes are truly global in scale, climate adaptation is an inherently local issue (Cradock-Henry & Frame, 2021). While this aspect of adaptation is well-recognized throughout the literature, existing research largely focuses on the preparation of regional-level adaptation plans, generally neglecting the potential for individual organizations or stakeholders to adapt at smaller scales (e.g., Kirshen et al., 2020; Rasmussen et al. 2020). Further, while there is an emerging understanding of the organizational dimension of (public sector) adaptation planning (e.g., Dawson et al., 2018; Mesdaghi et al., 2022), there have been few attempts to systematically characterize this dimension of adaptation planning, leaving researchers and practitioners to rely on institutional knowledge and intuition to ascertain the probable limits of intra- and inter-agency adaptation planning capabilities.

Given the limited resources and capital constraints of transportation agencies, understanding the range of potential adaptation options across spatial, organizational, and temporal dimensions (i.e., the feasible decision space) represents a crucial initial step in adaptation planning. While an organization can choose to implement local, self-contained asset-level adaptation projects, without much interaction with other organizations, neighborhood-level adaptation projects will likely require coordination with additional organizations (e.g., municipalities, government agencies, private sector corporations). The coordination between these organizations has the potential to introduce conflict, particularly if there are preexisting institutional cross-agency barriers to collaboration (Mesdaghi et al., 2022) or a degree of institutional rigidity limiting the adaptive capacity of organizations (Pelling et al., 2015). Such barriers can frustrate adaptation efforts, particularly if the interrelation and inter-agency dynamics between involved institutions is poorly understood. As such, an understanding of the organizational complexity inherent in potential adaptation options is salient and crucial for deciding among and between potential options.

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In addition to varying scales of organizational complexity, adaptation projects exist across spatial scales and can range from asset-level, and neighborhood-level measures, as well as to regional measures that can span municipalities and benefit large metropolitan areas (Solecki & Rosenzweig, 2022). Asset-level adaptation measures are typically organizationally self-contained and can range from comparatively short-term measures, such as the installation of deployable flood barriers at the entrances of Aquarium Station in Boston (MassDOT, 2021b; inset, Figure 5), to longer-term measures, such as permanent elevation of infrastructure assets, such as traction power substations along the New York MTA Metro North's Hudson Line (Figure 6; MTA, 2019). Larger, neighborhood-level adaptation measures, such as the proposed creation of a continuous elevated park along the waterfront in Downtown Boston (City of Boston, 2020b), typically require increasing collaboration across the domain of relevant public agencies, as well as private sector stakeholders and the public at-large (Figure 5). These measures are typically designed as longer-term adaptation solutions (e.g., 50-year useful lifespans), though intolerable levels of preexisting risk and budgetary constraints may require shorter-term solutions (e.g., the in-kind replacement of a deteriorated coastally adjacent section of roadway).

Figure 5: Example of neighborhood-level adaptation plan proposed for Long Wharf in Downtown Boston (City of Boston, 2020b). Inset: example asset-level adaptation project (deployable flood barriers) recently completed to protect entrances to the MBTA Aquarium Station (MassDOT, 2021b).

Regional measures (e.g., USACE, 2019) also have the capacity to provide significant wide-ranging benefits to (public and private) agents in cities or metropolitan areas, and associated ancillary benefits to transportation infrastructure. Such large-scale projects often require significant lead times (potentially a decade or more) due to extensive environmental review and federal permitting requirements (Kirshen et al., 2018) and consequently take a long-term planning approach (i.e., 50-100 years). Due to their wide reach, transportation agencies are, at best, likely to play only a supporting role in the

development, formulation, or implementation of such adaptation options, though coordinated transportation infrastructure system improvements may have a role in regional adaptation measures (Aerts et al., 2013). As such, in the absence of endogenous changes to transportation infrastructure, regional measures can perhaps be better conceptualized as an exogenous reduction in climate exposure, rather than as transportation infrastructure adaptation.

5.4.3. Increasing Robustness

Adaptations to SLR and coastal flood risk often take the form of physical interventions requiring significant capital investments (e.g., MTA, 2017; City of Boston, 2020b). Physical interventions intended to harden a given asset, neighborhood, or region to flood risk such that it may better withstand future climate hazards are ultimately aimed at increasing the robustness of a transportation system to climate hazards. Adaptation measures to increase robustness can be as simple as elevating critical assets above a design flood elevation (MTA, 2019) or comparatively more complicated projects, such as the installation of shore-based solutions that span across several organizational boundaries (e.g., Figure 5).

Shorter term hardening measures, such as the installation of deployable flood walls, (MBTA, 2019a; MassDOT, 2021b; Figure 5 inset) or subway station entrance closures (MTA, 2019) can effectively limit the operational impact of flood events. Oftentimes, several adaptation measures aimed at increasing robustness will be dependent upon one another to be effective, particularly in situations where multiple flood pathways expose the same portions of a transportation system (e.g., multiple lowest critical locations where water could flow into a subway system; Martello & Whittle, 2021). Installation of deployable hardening measures, such as flood doors or tunnel plugs either as a stand-alone solution (Sosa et al., 2017; MTA, 2019; MBTA, 2020), or as part of a larger regional solution (Mooyaart et al., 2014; USACE, 2015a) can also provide short-term protection during flood events, provided they are closed properly and in a timely manner. The non-stationarity of climate risks (e.g., increase in coastal flood risk due to SLR) will limit the useful life of deployable strategies, as they require increasingly frequent operation to ensure protection against climate extremes (Kirshen et al., 2018; Umgiesser, 2020). Deployable solutions are also prone to reliability issues, deployment failures, and operational errors, particularly if they are not regularly or properly maintained (Jonkman et al., 2013).

By contrast, elevation of transportation infrastructure assets is a comparatively more passive adaptation measure to increase robustness. Where appropriate, elevating transportation infrastructure can ensure critical infrastructure components are undamaged during a flood event, potentially enabling a quicker performance recovery or the avoidance of operational impact and network disruption entirely (Figure 6). Localized elevation of infrastructure assets, such as the elevation of commuter rail system substations above a SLR-informed design flood elevation (MTA, 2019) can enable the temporary accommodation of flood waters with minimal losses to infrastructure, allowing for a more rapid post-event recovery. Neighborhood-level solutions can also incorporate the elevation of transportation assets, such as the elevation of transit station entrances and ventilation shafts as part of a broader coastal adaptation plan (e.g., see City of Boston, 2020b).
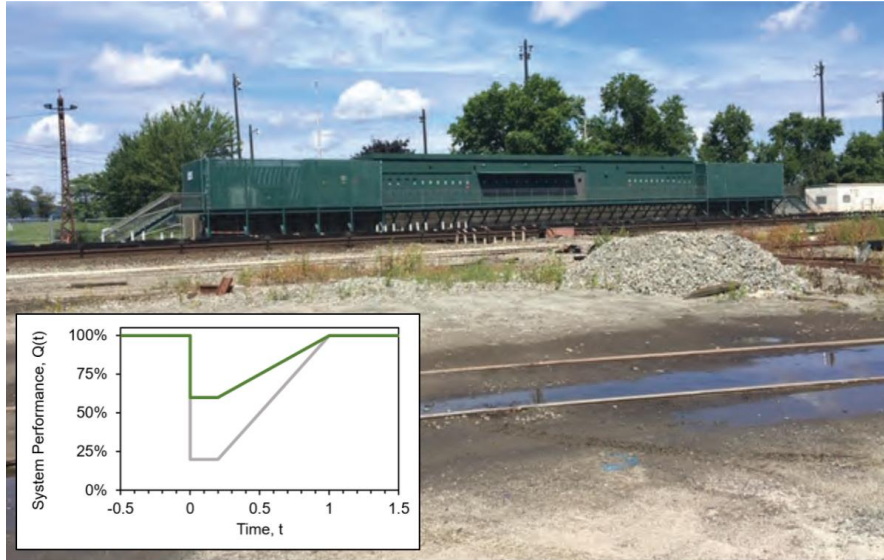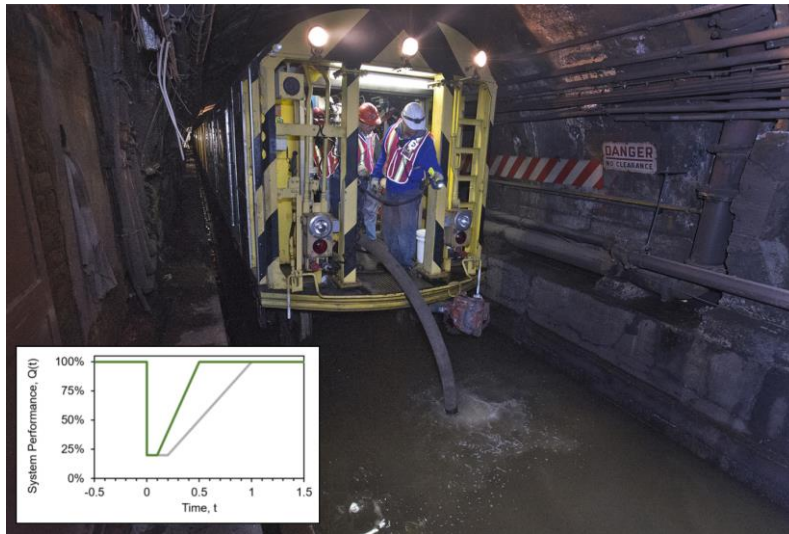
Figure 6: Example adaptation measure increasing system robustness. Elevation of an electrical substation along the MTA Metro North Hudson Line in Tarrytown, NY (MTA, 2019). By elevating the substation above the design flood elevation (DFE), damage during a flood event can be minimized or avoided entirely. This lessens the system performance loss during a flood event (inset) thereby improving transportation system resilience.

5.4.4. Increasing Rapidity

In certain circumstances, increasing robustness to flooding may not be feasible, practical, or economically justifiable. In such instances, an alternative adaptation approach is to focus on the rate of service restoration during the recovery phase of a disruption event. Increases in rapidity can take the form of optimizing recovery strategies to minimize system downtime given prevailing resource constraints (Chang, 2021). Alternatively, the development of recovery strategies that aim to maximize overall system functionality can also increase time rate of recovery (e.g., Sela et al., 2017; Bhatia et al., 2020). While the formulation of optimal recovery strategies can perhaps be equally conceptualized as improvements in rapidity and resourcefulness, we include them here, as they are principally aimed at increasing the speed of system recovery.

Aside from improved resource deployment strategies, system rapidity can also be increased by accommodating floodwaters[5]. Adaptation measures that accommodate floodwaters can take the form of permanent design changes or shorter-term harm reduction measures. For example, in the aftermath of Hurricane Sandy, New York City Transit deployed significant additional pumping capacity, enabling the transit service to return more quickly than it would have been able to otherwise (MTA, 2017; Figure 7). Additional rapidity improving adaptations include drainage and culvert improvements, particularly in locations where legacy infrastructure is presently inadequate for conveying design storm flows.

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[5] Adaptation measures that are aimed at accommodating floodwaters can also be characterized as improvements in resourcefulness, particularly if they rely on deployment of resources.

Figure 7: Example adaptation measure increasing system rapidity. Deployment of a pump train in the L train tunnel under the East River after Hurricane Sandy (MTA, 2012). Deployment of additional pump capacity enabled more rapid dewatering of flooded tunnels, thereby increasing system recovery. As such, system performance during a flood event can recover more rapidly (inset) thereby improving transportation system resilience.

Rapidity improvements can also be part of neighborhood-scale coordinated floodwater accommodation efforts aimed at minimizing localized flood impacts, such as the localized elevation of roadway segments to enable upsizing of drainage culverts (e.g., Hylan Boulevard reconstruction, NYGOSR, 2018). More ambitious neighborhood or city scale elevation efforts for accommodating floodwaters have few historic parallels, though the historic "raising of Chicago", in which the streets and adjacent buildings were elevated by approximately seven feet to accommodate a combined sewer system (Chicago Daily Tribune, 1857), can serve as an extreme case study of regional accommodation by elevation.

5.4.5. Increasing Redundancy

For some types of transportation infrastructure systems, increasing redundancy is a prohibitively expensive adaptation measure. This is particularly true for rail rapid transit systems and roadway networks, where the installation of additional network segments, particularly in urban environments, requires either the acquisition of right of way, tunnel, and/or bridge construction. Consequently, investments in additional network segments typically takes a significant amount of time and capital. Even if the right of way is already owned by an infrastructure manager, a project as simple as double tracking a section of a rail network is likely to be a multi-million dollar capital investment (MassDOT, 2021a). Given the outsized costs, absent any substantial co-benefits (e.g., expansion of service to a dense urban area, or increasing peak hourly capacity) it is highly unlikely that such investments would be made solely to improve system redundancy, even if such additional links would provide significant value during disruptions. Recent global supply chain bottlenecks and related research on vaccine supply chains (Golan et al., 2021) suggests there is a clear tradeoff between system efficiency and resilience, wherein system

efficiency is most often prioritized in practice. Absent a clear elucidation of the risk management benefits, substantial investments in system redundancy are unlikely (Jin et al., 2021).

Other transportation systems, such as bus rapid transit and maritime transportation systems are comparatively more flexible and more capable of reorganizing without significant capital expenditures. Introducing additional network links connecting pre-existing nodes (e.g., transit or bus stops, ferry terminals, coastal ports) can be readily considered during network redesign. For example, if considered jointly, the resilience of a bus and rail rapid transit network could be improved via the introduction of complimentary bus route parallel to a rail corridor, as well as via the introduction of bus service between rail rapid transit stations on separate lines (Jin et al., 2014). For example, several redundant bus (and subway) routes run parallel to the NYC MTA's 1 train line, such as the M104 route from 125th Street in Harlem to Times Square 42nd Street stations (Figure 8). In the event of a disruption (flood-related or otherwise) at rail transit stations along a portion of this route (e.g., 110th Street and 103rd Street stations) riders can transfer to the M104 bus running above the subway. In addition to incorporating redundancy directly into service planning and network design, additional bus transit service can also be introduced in real time in response to disruption events. Often referred to as bus bridging, the temporary provision of service between high travel rail transit stations and in place of disrupted transit lines can significantly increase the capacity of a disrupted network (Kepaptsoglou & Karlaftis, 2009; Jenelius & Cats, 2015) as demonstrated by the NYCT in response to Hurricane Sandy in 2012 (MTA, 2017).
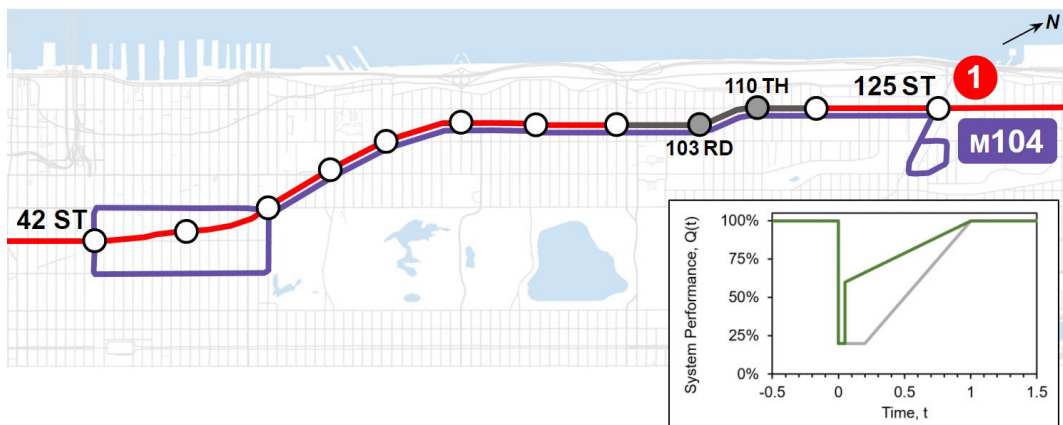

Figure 8: Example adaptation measure increasing system redundancy. Designing public transit networks to include parallel bus and rail service (e.g., the M104 which runs parallel to the 1 train in the NYC MTA system) can enable riders to quickly switch between modes during a disruption event (e.g., loss of rail service at 103rd and 110th Street stations). This can lessen the system performance loss during a flood event (inset) thereby improving public transportation system resilience.

5.4.6. Increasing Resourcefulness

Increasing resourcefulness can be viewed as an exercise in increasing the flexibility in the management of the transportation infrastructure system, better enabling agile responses to unexpected disruptions (Chester et al., 2021). Adaptation approaches which deliberately build in implementation flexibility can also help infrastructure managers better react as uncertainties are reduced in future over the lifespan of a project, thereby minimizing *adaptation regret* (Brisely et al., 2015). In addition to optimizing recovery strategies and bus bridging, there are a variety of additional adaptation measures that

can be employed to increase system resourcefulness. For example, improved sharing of real-time information to users (e.g., provision of road or transit station closure information) can better enable individuals to reorient and find alternative routes through a network during a disruption event, thereby minimizing overall system performance degradation (Mo et al., 2022).

In addition to measures aimed at improving real-time operational flexibility, increases in resourcefulness can also be more organizational in nature, such as the development and implementation of new climate resilience design standards (e.g., MTA, 2019; Stoothoff, 2019) or capital investment criteria that explicitly consider resilience to climate-related hazards (MBTA, 2019b). Such changes enable infrastructure managers to shift internal resources and attention towards climate resilience without significant additional capital investment requirements.

Resourcefulness can also be improved by shorter-term (i.e., 1-3 years) financially-based approaches, such as risk transfer. This can take the form of more conventional indemnity flood insurance policies (where the policy payout is directly proportional to the cost of damages up to the coverage limit), or more sophisticated reinsurance measures, such as the issuance of parametric catastrophe bonds (Chen & Bartle, 2022). For example, the New York City Metropolitan Transit Authority (MTA) has issued several series of parametric catastrophe bonds, thereby providing $100M of flood (re)insurance coverage should a coastal flood event result in a certain level of flooding, as measured by local tide gauges (Evans, 2020). Such catastrophe bonds issuances enable transportation agencies to underwrite climate risks that might otherwise be uninsurable, though the cost of underwriting this risk is directly proportional to the occurrence probability of the insured event (Lee & Yu, 2002; Ma & Ma, 2013). As such, given that sea level rise will increasingly expose a larger proportion of assets to coastal flood risk with greater frequency, such risk transfer strategies are liable to become prohibitively expensive without substantive adaptation interventions. Risk transfer can nonetheless be a useful tool to limit the severity of low-probability climate risk by providing an immediate increase in short-term financial reserves immediately after a disruption event, thereby affording a more flexible deployment of existing resources, as well as the capacity to deploy additional resources outside standard operational capacities in response to disruption.

Increases in resourcefulness do not necessarily require real-time data sharing, development of new design standards, or the creation of complicated financial instruments. For example, during seasonally high tides in Venice (colloquially known as "Acqua Alta") pedestrian infrastructure is routinely modified to accommodate floodwaters, thereby enabling pedestrians to navigate city streets at a diminished capacity before floodwaters recede (Flaxington et al., 2015). While the implementation of such measures is admittedly suboptimal compared to simply avoiding flooding entirely, the temporary installation of walkways enables a higher level of system performance during a disruption event (i.e., for the duration of one or more high tide cycles). Given the fact that raising street levels or building floodwalls adjacent to canals is culturally and politically untenable in Venice, accommodating measures that maintain pedestrian traffic flow during disruption are an effective alternative, particularly in the absences of more regional flood protection projects, such as the recently completed MOSE barrier (Umgiesser, 2020).

5.5. Valuing Climate Resilient Infrastructure

Climate change adaptation measures will generally require significant capital investment, and will require financial justification. As such, valuation of climate change adaptation projects cannot be easily overlooked, as adaptation projects must be justified relative to other potential public investments if they

are to successfully compete for the limited quantity of available public funds. In other words, the benefits of an adaptation project should outweigh its costs. While the life cycle costs of an adaptation project or pathway are typically rather straightforward to conceptualize and quantify (e.g., the costs of a new floodwall consists of an upfront capital cost and sustained operation and maintenance costs) similar to other public infrastructure projects, the benefits of climate adaptation projects affect a wide range of stakeholders, providing indirect societal benefits that are less straightforward to conceptualize and quantify (Chen & Bartle, 2022).

While indirect societal benefits can be difficult to fully assess and capture, the direct benefits of an adaptation project, the avoidance of damage-related losses during extreme events, is generally regarded as monetarily quantifiable, particularly for flood protection projects. Avoided flood-related losses can be characterized via the unit loss method, in which (avoided) losses (i.e., damage costs) are a function of the replacement cost and a damage factor relating flood severity to (avoided) damage for all assets of interest (de Moel, 2012; Wagenaar et al., 2016). The damage factor relates flood characteristics and associated asset-specific sensitivity to the estimated severity of damage. While many factors, such as wave action, flood duration, water salinity, sediment load, water quality, flood timing, asset age, and construction typology can all influence actual flood damage, these factors are generally not considered in current methods of flood damage estimation (USACE, 1992; Pistrika et al., 2014; USACE, 2015; Dottori et al., 2016; Franco et al., 2020). Instead, flood depth is used as the sole/primary indicator of damage severity in standard flood damage cost estimation practices (Kok et al, 2004; de Moel, 2012; Wagenaar et al., 2016; Gerl et al., 2016). As such, the damage factor is typically described by a depth-damage function (Kok et al., 2004; de Moel, 2012; Budiyono et al., 2015; USACE, 2015b; Wagenaar et al., 2016).

These depth-damage functions are often created to characterize specific types of assets (e.g., single family residential structures; USACE, 2006; USACE, 2015) and reflect asset-specific sensitivity to flood exposure. Unfortunately, there are at present few depth-damage curves potentially relevant for transportation infrastructure, with only a handful of relevant references in the academic literature (Vanneuville et al., 2003; Kok et al., 2004; de Moel & Aerts, 2011; Habermann & Hedel, 2018). Assuming a relevant depth-damage relationship exists for all transportation system assets of interest, adaptation benefits under a single flood event with a given return probability, $f_B(p)$, can therefore be expressed as the following:

$$f_B(p) = \sum_{i=1}^{n} RC_i f_i^{DD}(h_i(p)) \qquad (2)$$

where n denotes the number of flooded assets, RC_i the replacement cost of an asset of interest, $h_i(p)$ the flood depth at the asset of interest under the return probability, p, and $f_{DD}(x)$ the depth-damage relationship for the asset of interest.

In this manner, adaptation benefits (i.e., avoided flood-related losses) can be characterized for several flood events of varying return probability for a given level of risk. Considering the benefits across all flood probabilities under a given level of climate risk (e.g., a given level of SLR), the benefits of an adaptation project in any given year, B_t, are equivalent to the expected annualized avoided losses ($EAAL_t$), which are determined by the area under the avoided hazard damage probability distribution, $f_B(p)$, (Meyer et al., 2009; de Moel, 2012; Saint-Geours et al., 2015):

$$B_t = EAAL_t = \int_0^1 f_B(p)dp \qquad (3)$$

Thus, from a benefit-cost ratio (BCR) perspective, for an adaptation project to be financially justifiable, the present value of its expected costs, must not exceed the present value of the cumulative EAAL over its anticipated lifespan[6]. Framing this mathematically:

$$BCR = \sum_{t=0}^{y} \frac{B_t}{(1+r)^t} \div \sum_{t=0}^{y} \frac{C_t}{(1+r)^t} \geq 1 \qquad (4)$$

where B_t and C_t are the benefit and costs in year t respectively, r is the discount rate, and y is the lifespan of the adaptation project.

Rephrased from a cost-benefit analysis perspective, for an adaptation project to be a viable investment, its net present value should be greater than zero:

$$NPV \geq \sum_{t=0}^{y} \frac{B_t}{(1+r)^t} - \frac{C_t}{(1+r)^t} \qquad (5)$$

Note the selection of the discount rate, r, has a disproportionate impact on the perceived value of an infrastructure investment project, particularly those for which benefits accrue over an extended period (Lee & Ellingwood, 2015). Despite the sensitivity of valuation on discount rate selection, many authors do not critically examine discount rate selection choices and there is at present a lack of consensus on appropriate discounting approaches.

While private sector actors and a small subset of the economic literature for public-sector financing considers risk-adjusted discounting approaches (e.g., Lucas & Montesinos, 2020; Gollier, 2021) the prevailing infrastructure investment discounting approaches presented in the literature are largely governed by policy and regulatory guidance set forth by public sector agencies (Stewart & Bastidas-Arteaga, 2019). There is significance variance in discounting rationales employed by government agencies and further variance in interpretation among authors who apply one of four main approaches: i) use an accepted social discount rate[7] (HM Treasury, 2020; Vousdoukas et al., 2020; Lee & Ellingwood, 2015); ii) set a schedule of declining discount rates (Lowe, 2008; Lee & Ellingwood, 2015; Stewart & Bastidas-Arteaga, 2019); iii) compare results across a range of discount rates (Lincke & Hinkel, 2018; Oddo et al., 2020); or iv) avoid discounting entirely (Hallegatte et al., 2013; Buchanan, et al., 2016; Rasmussen et al., 2020; Neumann et al., 2021).

Notwithstanding the prevailing ambiguity surrounding discount rate selection, particularly in situations where benefits significantly outweigh the costs, a proper attempt at valuation enables a clearer presentation of the business case for adaptation projects. A defensible valuation can better enable public agencies to justify bond issuances to fund adaptation projects, thereby improving the likelihood of financing and tendering of the project. Clear delineation of project benefits can also enable the issuance of green bonds, which represent an emerging alternative method of accessing capital markets to finance adaptation projects (Keenan, 2019; TRB & NASEM, 2021; Chen & Bartle, 2022).

Lastly, in addition to the avoidance of direct damages, adaptation project benefits can also include the avoidance of indirect damages, such as the avoidance of emergency response costs, or lost farebox revenue. Other indirect societal co-benefits, such as the avoidance of disruption for commuters (Sun et al.,

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[6] The lifespan or service life of an infrastructure project is ultimately project dependent. Typical lifespans for larger-scale infrastructure projects are in the range of 50-75 years (Lee & Ellingwood, 2015).
[7] The social discount rate adjusts for the value society attaches to present (over future) consumption and long-term expectations that future generations will be wealthier than present generations (HM Treasury, 2020). The social discount rate aims to capture society's (i.e., taxpayers') expectation of return on public sector investments.

2021) freight delays, or regional economic interruption can also be quantified to further evaluate the potential benefits of adaptation projects (NASEM, 2020).

5.5.1. Adapting Equitably

While it is important to ensure a given adaptation project provides a return on investment and makes financial sense, it is also important to ensure that benefits and burdens are equitably distributed. Climate change adaptation projects framed exclusively through the lens of enhancing resilience of engineered systems are liable to neglect adjacent social structures and institutional context, thereby increasing the likelihood that proposed solutions will perpetuate existing social inequities (Malloy & Ashcraft, 2020). More generally, the advancement and implementation of apolitical and technocratic adaptation solutions can effectively serve to disenfranchise vulnerable populations and the community at-large from the decision-making process, leaving no room for contestation of official plans (Adger et al., 2005; Yarina, 2018). Adaptation projects that neglect sociopolitical dimensions of planning have the capacity to exacerbate, redistribute, and create new forms of socio-spatial inequities across diverse urban contexts (Swanson, 2021).

There is a rapidly expanding body of research focused on climate adaptation equity, as well as a separate body of research focused on transportation equity. While both areas of research focus on equity in the context of planning, transportation equity focuses to a greater extent on distributional equity and justice. Philosophically underpinned by either a Rawls' egalitarian or capabilities approach (Pereira et al., 2017), distributive justice underpins commonly employed measures of transportation equity, such as mobility and accessibility (Sun et al., 2021). Accessibility refers to the ability to reach preferred destinations (e.g., job opportunities) and mobility refers to the ease with which individuals can travel to such preferred destinations, often measured in average travel time (Sun et al., 2021). Given sufficient information on demographics, user behavior, and impacts of adaptation, such measures can be employed to characterize the distributive equity of transportation infrastructure adaptation projects and subsequently inform decision making.

Taking a more expansive view, existing adaptation equity literature suggests equitable adaptation efforts not only promote distributive justice, but also procedural, and recognition justice (Malloy & Ashcraft, 2020; Malloy, 2021; Swanson, 2021). Malloy and Ashcraft (2020) argue that equitable adaptation to climate change requires not only the engagement of vulnerable populations, but also agency in the decision-making process. Through the enfranchisement of vulnerable populations, planners and decision-makers are better positioned to negotiate normative aspects of planning with the community (i.e., consider community values and motivations), thereby increasing the likelihood of producing solutions that equitably provide value to all members of the community.

Economic measures of equity can also be applied to further interrogate the distributive justice of adaptation infrastructure investments. Under the lens of a typical cost-benefit analysis, the best investment projects are those which provide the maximum net present value, irrespective of how these benefits are distributed across society. For example, traditional transportation planning approaches often ascribe value of time savings to transport users via market-based approaches; consequently, benefits accruing to wealthier users are valued more highly than those accruing to poorer users, all else being equal (Martens, 2017). Rather than simply measure the dollar value of benefits, Kind et al. (2017) instead provides a framework to measure the utility of benefits by scaling dollar values in accordance with measures of diminishing marginal utility and risk aversion. Through consideration of the marginal utility of benefits and costs in lieu of their absolute value, subsequent valuations instead allow decision-makers

to maximize the net welfare rather than the net present value of a given investment (Pereira et al., 2017; Kind et al., 2017; Keenan, 2019). Though equity-weighted valuation methods typically lie outside existing public investment valuation frameworks, such valuations can provide decision makers with a useful method of comparing the equity of several economically viable adaptation alternatives (Keenan, 2019).

5.6. Conclusion and Future Trends

Resilience is a useful heuristic for framing and conceptualizing climate change adaptation of transportation infrastructure systems. When coupled with an adaptation decision-making framework and equitable planning practices, resilient design can ensure sensible, sustainable, and equitable investments are made in transportation infrastructure. Yet, there are several operational gaps in the literature which will need to be addressed in order for resilient design practices and infrastructure adaptation planning to become widely adopted.

While there is an emerging understanding within the transportation field that natural hazards can significantly affect networked measures of infrastructure performance (e.g., Sela et al., 2016; Bhatia et al., 2020; Chang, 2021), there is a significant lack of performance models that attempt to explicitly relate physical infrastructure characteristics and climate-related vulnerabilities to performance degradation. There is a growing body of research aiming to address this gap for transportation infrastructure (e.g., Rosenzweig et al., 2011; Testa et al., 2015; Zhang et al., 2019; Martello et al., 2021) though additional research is needed to better understand the physical implications of climate exposure on transport infrastructure at a systemwide level.

There is at present a significant lack of research relating the fragility of transportation infrastructure to potential climate-related damages or to quantify the benefits of adaptation projects (NASEM, 2021). While there is an emerging literature focused on other types of infrastructure (e.g., power grid infrastructure Chang, 2021; Haggag et al., 2021) and characterizations of general transportation infrastructure sensitivity to flood risk (e.g., Vanneuville et al., 2003; Kok et al., 2004; de Moel & Aerts, 2011) future research is needed to further elucidate the fragility of specific types of transportation infrastructure assets to specific climate stressors. Without an understanding of transportation infrastructure fragility to climate stressors, proper evaluation of the economic benefits of adaptation is not possible. Furthermore, while financial evaluation of transportation infrastructure investments typically guides investment decision frameworks (NASEM, 2021), few climate adaptation valuation methods fully consider climate-related uncertainty or the full range of physical and financial outcomes (Ginbo et al., 2021, de Neufville et al., 2019). Improved methods of valuing climate change adaptation projects that enhance the resilience of transportation infrastructure are clearly needed.

Better characterization of infrastructure interdependencies should also be a priority area for research and practice (Chester et al., 2022) in order to understand how the performance of transportation infrastructure depends on adjacent infrastructure systems, such as the electric grid, stormwater systems etc. As transit agencies contribute to climate change mitigation through the conversion to electric vehicle fleets, there will be increased interdependencies with the electric power grid, which is also increasingly vulnerable to disruption in extreme weather events (Rosenzweig et al., 2011; Haggag et al., 2021).

Further research is needed to improve the assessment of the adaptive capacity inherent in existing transport infrastructure systems. Here it is critical to improve the understanding of internal institutional

structures, and which institutional actors are responsible for the climate change adaptation, finance, and risk management. The mapping of institutional practices relating to climate adaptation and risk management is an emerging area of research (Mesdaghi et al., 2022) with the potential to enable efficient maneuverability of existing institutions to better create and design climate resilient transportation infrastructure. A better understanding of intra- and inter-agency dynamics can further enable researchers, policy makers, and decision makers to identify and realize the benefits of cross-agency collaboration in the pursuit of climate change resilience for transportation infrastructure systems.

Enhancing the climate resilience of transport infrastructure will become an increasingly critical component of the responsible stewardship of our built environment. Designing climate resilient transportation infrastructure requires an understanding of projected future climate extremes, inherent transportation system characteristics, and an understanding of how transportation infrastructure relates to adjacent socio-economic and socio-political systems. A theoretical and practical understanding of these external, internal, and contextual dimensions of resilience can better enable infrastructure managers to formulate system- and hazard-specific adaptation projects. Without such adaptation, the wide-ranging challenges posed by climate change and SLR will represent an existential threat to our transportation infrastructure systems.

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