Covid-19 as a harbinger of transforming infrastructure resilience

Health & Medicine

Introduction

As COVID-19 propagates rapidly through cities across the world and presents a multitude of public health, social, and economic challenges, a new landscape of issues is emerging for infrastructure that warrants scrutiny. Challenges for healthcare systems are more directly evident, but the extended nature of the pandemic is changing how cities operate and re-shaping approaches to critical infrastructure (CI) systems (Bliss, 2020a ; Florida, 2020). CI are the systems that deliver critical services such as power, water, mobility, healthcare, and telecommunications. Amid the outbreak, opportunities for reflection, research, and action abound. A framing of the primary challenges and opportunities for CI based on COVID-19 impacts is needed to construct a pathway toward coping with current challenges and improving resilience to future pandemics and other disturbances.

Infrastructure systems – here framed as consisting of physical assets, governance and institutions, and education – have an important role in shaping human activity and supporting public needs during pandemics. Given CI's role in absorbing impacts, maintaining essential services, and facilitating societal adaptation in the face of unforeseen events like COVID-19, how we frame infrastructure resilience is essential. Conditions in the coming decades will be unlike the past (Steffen et al., 2015), and a clear framing of major infrastructure challenges during COVID-19 can help illuminate the research and capacities for resilience in a dynamic and changing world.

Unlike other hazards for which infrastructure managers are more accustomed to planning, pandemics differ significantly mainly in terms of spatio-temporal scale and interdependencies between infrastructure sectors. As opposed to more regionally isolated hazards, modern pandemics can become global-scale phenomena that occur as successive waves unique to different viruses, making them difficult to predict where, how, and to what scale impacts will propagate (Cohen, 2009 ; Woods et al., 2020). While there are no direct physical threats to infrastructure, pandemics induce devastating impacts to their sustainment, previously framed as impacts to critical infrastructure workforce (Ryan, 2008 ; Hessel, 2009 ; Dietz and Black, 2012). Infrastructure planning must consider sustaining monitoring and response mechanisms for months to years amid economic disruption and workforce challenges (i. e., infected laborers and social distancing), conditions not adequately addressed in national response plans (Dietz and Black, 2012). Measures to " flatten the curve" for the number of cases can increase the capacity for systems to absorb impacts in terms of systems functionality curves (i. e., resilience curves), which differ between sectors (e. g., communications, healthcare, power, and water) (Jovanovic et al., 2020). While studies have long highlighted alarming gaps in preparedness (Osterholm, 2005 ; Adalja et al., 2012), hospitals also depend on CI, as for example, all modern medicine depends on electrical systems in some way (Osterholm and Kelley, 2009). Yet, planning often doesn't consider such complexities, interdependencies, and second and third order effects (e. g., supply chains for PPE) (Itzwerth et al., 2006 ; Huff et al., 2015). CI is not only vulnerable, but responsible for on-going support and adaptation (Hendrickson and Rilett, 2020).

While devastating pandemics like the Spanish Flu (1918) have happened in the past, infrastructure for pandemics in the Anthropocene are not well understood (Williams, 2007 ; Ryan, 2008 ; Cohen, 2009). COVID-19 is an emerging risk (i. e., previously not widely considered), which poses the greatest challenges to resilience because knowledge and information is vague or missing, maturity of risk management is low, and regulatory frameworks are missing or inconsistent (Jovanovic et al., 2020). Moreover, these challenges can be exacerbated and accelerated by the changing relationship between people and their environments in increasingly complex social (e. g., norms, urbanization, international travel and trade), ecological (e. g., climate change), political (e. g., public health breakdowns, land-use policy), and built environment systems (Bogich et al., 2012 ; Bedford et al., 2019). Ultimately, the coupled evolution of human, built, and ecological systems presents new levels of complexity, rapidity, and scales for hazards such as pandemics and their impacts (Chester et al., 2020).

COVID-19 has revealed four major themes that warrant examination: (1) Planning for concurrent hazards, (2) Flexibility in how we assess the criticality of infrastructure, (3) Managing trade-offs between efficiency and resilience, and (4) Expanding institutional resilience to include leadership for both stable and unstable conditions. These competencies are in line with broader challenges for infrastructure in the Anthropocene (Chester and Allenby, 2019a). We discuss these four themes with the goal of identifying future research pathways and areas for more comprehensive treatment toward guiding resilient infrastructure design and policies for a future characterized by accelerating, increasingly uncertain, and increasingly complex conditions.

Theme 1: Planning for Concurrent Hazards

We are entering an era of concurrent crises where global connectivity enables the propagation of shocks through interdependent critical infrastructure systems (Biggs et al., 2011). In Puerto Rico, the pandemic coincides with long-term recovery efforts related to Hurricane Maria, frequent and intense earthquakes due to a newly discovered fault line and an on-going drought (Rosa and Robles, 2020 ; USGS, 2020). Unlike past disasters, widespread unemployment and limitations for social aggregation caused by the pandemic are undercutting otherwise present capacities for disaster resilience (e. g., income, health insurance, shelters) (Rosa and Robles, 2020). Amid Cyclone Amphan in India and Bangladesh, floods impacted health centers and other CI, while compliance to evacuation protocols was challenged by public fear of COVID-19 (Begum et al., 2020 ; Ellis-Petersen and Ratcliffe, 2020 ; Gettleman et al., 2020).

As COVID-19 extends for several months or years, the pandemic will increasingly overlap with other hazards. Entering the summer season, many cities must manage infrastructure under COVID-19 along with other events that threaten public safety including extreme heat (Anderson et al., 2018 ; Calma, 2020), wildfires (U. S. Department of the Interior, 2020), floods (Einhorn, 2020 ; Zhong, 2020), hail (Cappucci, 2020), and hurricanes (

Vann, 2020). Infrastructure in disrepair will fail, and cyberattacks are likely to increase (Chester and Allenby, 2020). Traditional infrastructure responses and operations to extreme events are complicated by the scale and scope of a global pandemic, and recovery efforts are challenged by the shortage of resources and difficulties in safely operating rescue protocols.

Unlike most hazards which are local in nature, COVID-19 is global and presents an opportunity for developing knowledge systems to prepare our critical systems under shared goals (Sarewitz, 2020). Emergency response often assumes that non-affected regions are capable of supporting recovery efforts through the supply chain of goods, backup labor, and mobilization of infrastructure services. However, cooperative recovery efforts have been challenged due to the global scale, urgency, and uncertainty of the pandemic (Ryan, 2008 ; Mogul and Hurt, 2020 ; Villarreal, 2020). For example, the United States wildfire season is usually combated by local, regional, and international firefighting crews. Due to travel restrictions, local crews are extinguishing all fires regardless of severity, a technique abandoned to allow controlled ecosystem disturbances, and conducting virtual fire risk assessments (Gibbens, 2020 ; McDowell, 2020).

Cities will need to develop creative ways to provide public infrastructure and community services while tackling hazards. Since the outbreak, innovative responses highlighted the importance of infrastructure resilience. Cooling centers, congregational spaces for vulnerable populations to escape extreme heat, were initially closed to enforce social distancing. As extreme heat events unfolded, cities began leveraging multifunctionality by placing vulnerable populations in hotel rooms, re-opening conventional cooling centers (e. g., libraries, parks, splash pads), and adapting additional venues (e. g., sporting facilities, stationary buses) (Chilukuri, 2020 ; Cooling Centers-Map, 2020 ; Flavelle, 2020). Functionally redundant systems are also being implemented such as utility financial assistance, utility shut-down restrictions, and providing air conditioning units (CDC, 2020a ; NYC, 2020). Creatively leveraging capacities that enable infrastructure flexibility can aid in shifting infrastructure functions and extending operability in the face of unprecedented hazards (Gilrein et al., 2019).

Among these capacities is a culture of learning from past failure and success. After Hurricane Maria, when clinicians in Puerto Rico dealt with treatment interruptions, transportation limitations, and scarce equipment and medicine, practical emergency measures were developed that paid off in maintaining functions while containing the spread of COVID-19 among vulnerable cancer patients (Gay et al., 2019 ; Rivera et al., 2020). In facing competing resource-scarcity and disasters, infrastructure agencies pursuing resilience may benefit from adopting multi-hazards approaches (Ryan, 2008), where investments for agility to unforeseen scales, types, and combinations of disasters are emphasized over hazard-specific robustness.

Theme 2: Changing Nature of Criticality

COVID-19 challenges our industry and defense-based framing around criticality of engineered systems (e. g., energy, healthcare, information and communication systems), in favor of one that considers human capabilities. The Department of Homeland Security (DHS), for example, defines CI as, “

systems and assets that are so vital to the United States that their incapacity or destruction would have a debilitating impact on our physical or economic security or public health or safety.” Defining which systems are CI results in a prioritization of resources during extreme events (Theoharidou et al., 2009). However, COVID-19 illustrates potential problems with industry-based framings that do not consider differences between hazards, and the interdependencies inherent in solutions (e. g., ventilators were a healthcare, manufacturing, supply chain, and fiscal challenge). Parks, for example, are typically considered a non-essential service. However, during COVID-19, parks have proven their value by serving as field hospitals (Fink, 2020), providing alternative shelters for socially vulnerable groups (CDC, 2020a ; Welsh, 2020), and promoting physical, emotional, and mental well-being (Friedman et al., 2020 ; Olin, 2020 ; Surico, 2020). Criticality varies between events, and the ability to adjust short term resources accordingly as well as long term resource planning is important.

Critical infrastructure definitions should account for the changing services and functions of industries during hazards. The DHS lists commercial facilities as CI, yet many commercial facilities have been shut down. Some industries have been able to shift production from non-essential to essential products, while others have not and are in trouble. While this strategy provides some revenue, these industries recognized the social value of essential products and adapted accordingly. Perfume and beer bottlers began packaging hand sanitizer, hockey equipment companies began making medical face shields, and vacuum companies began making ventilators (Domonoske, 2020). Flexibility and agility as environments change (Allenby and Chester, 2018) appears to be critical, but is not captured by static CI definitions. In order to address a dynamic definition of CI and better embrace environments of change, organizations will need to implement Enabling Leadership rather than Administrative Leadership, as explored in a following section.

Framing infrastructure criticality in terms of human capabilities can enable a more dynamic and effective approach to directing resources. " Capability refers to the set of valuable functionings that a person has effective access to," where functionings are realized uses of resources that infrastructure systems provide (Clark et al., 2018)." Infrastructure becomes critical as it enables human capabilities, for example, following Maslow's hierarchy of needs. In the example of the industries producing essential products, production chains became critical in order to enhance the capabilities of people to access sanitation products. How we meet sheltering and nutritional needs during a pandemic may be different from other crises like heat waves, hurricanes, or even terrorist attacks. Therefore, treating criticality as dynamic (and maintaining flexibility to define and plan for it accordingly) appears crucial to identifying how to meet basic needs through infrastructure changes as hazards vary (or arise concurrently).

Theme 3: Managing the Trade-Off Between Efficiency and Resilience

COVID-19 spotlights challenges that emerge when too much emphasis is placed on efficiency at the expense of resilience (e. g., not having enough ICU beds, testing supplies, staff, etc., in the right places at the right times) (Allenby and Chester, 2020 ; Tenner, 2020). Efficiency relates to the optimal response to an existing environment (i. e., prioritizing the reduction of waste in terms of time, effort, and resources), whereas resilience relates to the capacity to adapt to disruptive changes in the environment (i. e., increased slack, redundancy, and diversity – features efficiency might consider waste) (Martin, 2019). Thus, there is an unavoidable tension between efficiency and resilience that has historically leaned toward efficiency (Tenner, 2020). While there are certainly limits (i. e., resource constraints) to the amount of " slack"/redundancies that can be implemented in a system, COVID-19 shows the importance of having both efficiency and resilience within our systems and ensuring that a proper balance between them is maintained. This perspective is summed up nicely by Ridley (2019) , " Efficiency is not fragility, nor is resilience wasteful. Rather, these are design choices that we need to be aware of when designing processes and businesses." The need to reconcile the disconnect between efficiency and resilience is further illustrated by recent COVID-19 guidelines from the United States Centers for Disease Control (CDC) that emphasize " optimizing" the deployment of stockpiled ventilators and supply of personal protective equipment (CDC, 2020a , b).

Whereas a focus on efficiency and optimization is most applicable for operating in stable conditions, it becomes difficult to maintain and effectively apply in conditions of rapid change and widespread uncertainty such as a global pandemic. How organizations respond to the sudden and large-scale impacts of COVID-19 provides valuable insights into what it means to transition between stable (i. e., efficiency) and unstable (i. e., resilience) environments. Natural disasters often play out over the course of days or weeks, and are usually isolated to specific regions. If a crisis affects a particular area for a relatively short period of time, then certain concepts of efficiency may be applicable (e. g., transfer of resources like generators). This approach breaks-down when the geographic scale of the disruption develops globally, and the temporal scale extends into months or years. COVID-19 highlights the need to allow for some level of " inefficiency" in the form of redundancy and diversity of services and assets, along with enhancing institutional, knowledge, and leadership capabilities to manage, mobilize, and implement such resilience capacities. However, there needs to be a limit to add capacity to be resilient; a system needs to have multifunctionality and be able to alter its functionality when needed, discussed in the " Theme 1: Planning for Concurrent Hazards section."

One possibility for instilling these characteristics into systems, communities, and institutions, is to give stronger credence to the idea that resilience is a public good (Galston, 2020). Considering resilience as a common pool resource like air or water, its absence becomes a negative externality (i. e., The Tragedy of the Commons). Externalities are often addressed by government intervention, and in the case of externalities associated with the lack of resilience, entities such as the Federal Emergency Management Agency (FEMA) and the National Flood Insurance Program have been created. Although these programs help reduce negative externalities, they exhibit limitations due to their primary focus on post-disaster rebound and recovery. COVID-19 shows the limitations of these reactionary approaches, and illustrates the need for more proactive, large-scale (spatially and temporally), and dynamic efforts to address the fragility-related externalities that permeate our systems. For example, externalities associated with air and water pollution occur across extensive geographic and temporal scales. In response, the Clean Air Act and Clean Water Act were passed by Congress and administered by the Environmental Protection Agency and the States to address related environmental externalities. Perhaps it is time to consider whether a National Resilience Act, Agency, or Department are needed, and what they may entail. Given the stark reality that society will increasingly face multiple risks, considering resilience as a public good can significantly aid toward striking the right balance between efficiency and resilience, and in turn, enhance our ability to navigate stable, chaotic, and complex conditions.

Theme 4: Improving Institutional Resilience Through Leadership

The rapidity and scale of COVID-19 has emphasized the importance of institutional flexibility for infrastructure resilience. Different types of leadership, including some currently lacking in infrastructure management, enable such flexibility. In stable times, Administrative Leadership emphasizes efficiency-focused efforts (formalized bureaucracies, structures, organizations, and roles well-suited for operating in stable conditions), whereas during periods of instability Adaptive Leadership (an emphasis on learning, adaptability, and creativity that enable operation in uncertain and complex conditions) facilitates rapid and appropriate efforts (Uhl-Bien et al., 2007). However, Enabling Leadership is also necessary to create flexible knowledge, and the financial and structural conditions needed to alternate between Administrative and Adaptive Leadership modes as conditions shift between stable and chaotic (Uhl-Bien et al., 2007). All three leadership models are necessary, but infrastructure agencies have predominantly been modeled around Administrative Leadership.

As COVID-19 shocks infrastructure demands, deficiencies of Administrative Leadership, where management has been designed for stable conditions, emerge. For example, transit financing and operations appear to have been structured around assumptions of a fairly stable demand envelope, and as systems around the world have experienced rapid reductions in demand, the viability of public transit models has been tested. While Administrative Leadership can typically execute orders quickly due to a clear power structure, it is unable to navigate complex environments effectively (Uhl-Bien et al., 2007). Transit agencies – like other infrastructure – have scrambled to restructure operations given the rapid changes in demand, a vulnerable workforce, and social distancing guidelines, but there are many indications that lock-in driven by policies, finance, and technology for stable conditions limits their ability to adapt (e. g., Bliss, 2020b ; Guse, 2020). Adaptive leadership for uncertainty has become critical, as has the ability to shift from leadership in stable to unstable conditions.

Through continuous navigation between Administrative and Adaptive Leadership, an organization's leadership becomes flexible – or Enabling. For example, telecommunications operate in a rapidly changing environment defined by emerging technologies and novel demands (Bourgeois and Eisenhardt, 1988 ; Vecchiato, 2015). Enabling Leadership allowed video communication technology providers, such as Zoom Video Communications, to change their management approaches and assets to meet exponential demand increases (Gilbert, 2020). There were hurdles along the way, such as " Zoom-bombing" (Bond, 2020), but the ability to satisfice (Chester and Allenby, 2019b) between formal top-down decisions (e. g., increasing bandwidth) and creative solutions (e. g., expanding accessibility) to emerging demands allowed Zoom to adapt services. From managing daily operations to redefining CI to enduring crises, Enabling Leadership proactively catalyzes a flexible and effective response by facilitating interaction between Administrative and Adaptive Leaderships (Uhl-Bien et al., 2007). COVID-19 has emphasized the importance of flexible leadership in infrastructure resilience to remain effective in a complex and uncertain world.

Discussion

In a future defined by acceleration, increasing uncertainty, and increasing complexity, COVID-19 provides a glimpse of how best practices that were developed under past conditions that focus on efficiency and stability are becoming increasingly insufficient. Consideration of concurrent hazards, the reframing of infrastructure criticality, understanding the balance between resilience and efficiency, and enabling flexible leadership must be addressed together to revise how we govern and build systems that provide critical services. Overarching these themes is the ability to creatively shift between modes, functions, and leadership capabilities. While the right kind of assets are certainly important and necessary to adapt amid pandemics, it is equally (and often more) important to maintain the human capacity and institutional ability to be dynamic and flexible.

Ultimately, infrastructure managers and researchers must recognize the flexibility of physical and institutional aspects of infrastructure required to keep CI operational in times of disturbance. Criticality is dynamic in rapidly developing situations like COVID-19, which has shown the importance of Enabling Leadership as it can allow an organization to adapt quickly in volatile contexts. Physical infrastructure is often not as quickly adaptable, underscoring the importance of proactive competencies (e. g., multi-functionality, redundancy, planned obsolescence) that may not always align with traditional emphasis on efficiency and Administrative Leadership. Infrastructure design is rooted in stationarity, which decreases the capacity for flexibility. COVID-19 demonstrates how infrastructure demand can violate design envelopes, and how our rigid systems are unable to adapt. As social distancing continues, concurrent disturbances will emerge and infrastructure institutions operating with impaired in-person crews and remote management will need to exhibit Enabling and Adaptive Leadership to remain functional. Therefore, adaptive capacities such as culture of change, connectivity, compatibility, modularity, redundancy, multi-functionality, and planned obsolescence are essential for flexibility in the face of disturbance (Chester and Allenby, 2019a). While COVID-19 poses many difficulties to our infrastructure, it also creates an opportunity to rethink how we approach our basic and critical systems so that they are better equipped to face future challenges.

Another dynamic that deserves attention is the changing relationships between cyber and physical systems. Many of the themes discussed focus on traditional and largely physical systems, including their governance. But

COVID-19 has revealed new capabilities at the interface of legacy physical systems and cybertechnologies. Contact tracing through smart networks and phones – both voluntary and involuntary – has created the possibility of identifying and limiting the spread of the virus, while simultaneously exposing profound privacy challenges (Smith, 2019 ; Zakrzewski, 2020). Communication systems driven by smart phones have also rapidly deployed software to help diagnose COVID-19, detect hand washing, and develop image recognition responsive to mask wearing (Perez, 2020). In conjunction with these changes, applications of artificial intelligence have the potential to direct individuals toward protective behaviors, help with diagnosis, and even aid the development of a vaccine (Chen and Fast, 2020 ; Etzioni and Decario, 2020 ; Kurzweil, 2020 ; Peckham, 2020). Although these new applications and technologies have played an increasingly important role in addressing the pandemic, they are not without potential drawbacks. For instance, the rapid development and integration of new cyber-physical systems has also introduced profound challenges related to privacy (Smith, 2019 ; Zakrzewski, 2020), equity and fairness (i. e., the growing digital divide within and across nations) (Holpuch, 2020 ; Milanesi, 2020 ; Ramsetty and Adams, 2020), cyber-security (Aladenusi, 2020 ; CISA, 2020), and the preservation of individual freedoms (Funk and Linzer, 2020 ; Gilmore, 2020 ; Nguyen, 2020 ; United Nations [UN], 2020). Thus, as novel cyber-physical systems continue to evolve and emerge, it is important to recognize that the capabilities and challenges introduced by these systems will likely have profound impacts that extend far beyond mitigating and managing COVID-19. Although combating the pandemic necessitates a certain degree of urgency and expediency, deliberation and examination of the potential long-term implications of novel cyber-physical systems also appears warranted.

COVID-19 is a window of opportunity for laying new foundations for how we design, operate, and manage infrastructure in the Anthropocene. In its early stages, the pandemic has shocked infrastructure demand and created tremendous uncertainty about the future. Going forward, infrastructure can be expected to be shocked in new ways that we probably have not yet experienced. The current window is important for structural change toward the future. At a time when infrastructure agencies are struggling to cope with disrepair, emerging technologies, and climate change, COVID-19 lays bare how difficult some of the challenges will be, and the need for creative new approaches. Agencies should catalyze around this moment, critically examine how assumptions about stable demand manifest as rigidity in assets and management, and review what competencies are needed for times of stability versus instability, and the governance, management, and financial principles needed to shift between them. Additionally, they should question the relevance of their core mission in a future with more uncertainty and shocks. During this time, agencies should be supported for not simply restoring and carrying over their pre-pandemic mission, but restructuring their organizations (including assets, institutions, and education) toward the future.

Data Availability Statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author Contributions

TC and SM coordinated the team, framed the article, and contributed to the writing. AH, YK, RL, MN, EB, and NA contributed equally to the writing and editing. MC advised the team and contributed to the writing, framing, and editing. All authors contributed to the article and approved the submitted version.

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Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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