Chapter 1

The Interdependencies of Infrastructure

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Society depends upon infrastructure.[1] This dependency has been increasing, underscoring the need for resilient infrastructure systems capable of withstanding the many extreme conditions these systems confront. Resilience has been defined in various ways and is applicable to multiple conditions. For infrastructures and the social support they provide, resilience is alternatively the ability to:

1. return to an existing state prior to a disturbance ("bounce back")
2. not change at all in the face of disruption, that is, resist the adverse effects ("not bounce at all"), or
3. attain an improved state that is more resistant to future destruction ("bounce forward").[2]

This chapter focuses on two aspects of infrastructure: its concentration and interconnectedness, building upon and expanding previous studies that have begun to address this area.[3] Concentration and interconnectedness are significant attributes of physical and societal resilience, given their tendency to increase the complexity of interactions among infrastructures and (often) reduce flexibility to adopt alternatives that could decrease adverse impacts and increase resilience. Increased concentration of infrastructure components and their increasingly dense connections with social networks can magnify adverse impacts of disruptions. In more concentrated networks, such disruptions may extend to more elements than if they were not as concentrated. One example is the concentration of pipelines in a single conduit: a disruption of any one of them can cause the others to be damaged. Another example is the increasing capacity and global trade concentrations in large tankers that pass through narrow canals. The grounding of the *Ever Given* tanker in the Suez Canal for six days in March 2021 contributed to a massive supply chain disruption, since a substantial proportion of trade was provided by the tanker and, more significantly, by the canal itself.[4] Likewise, interconnections can result in cascading effects, where a single disruption causes others, specifically acting through the connections. For example, electric power is often interconnected with transit, and power outages or even instantaneous surges have been known to stop transit systems for days even after power is restored.[5] Concentration and interconnectedness are similar in their effects on multiple infrastructures and may act jointly or separately.

Many infrastructures have become more concentrated and interconnected. The nature of these changes and the reasons for them are the focus of this chapter. A case-based approach is used to understand how concentration and interconnection affect physical and societal resilience in different infrastructure contexts, complementing and expanding theoretical approaches to these concepts which focus on indicators and metrics.[6] Numerous infrastructures exemplify the influence of concentration and interconnection. For example, information technologies and electric power are common influences on the relationship of both concentration and interconnectivity with other infrastructures and are emphasized as a common theme in the cases presented.

The first concept, concentration, has often revealed itself as bottlenecks, choke points, and supply chain disruptions created by significant reliance upon a few modes of delivering infrastructure services that account for a large share of a given function or activity. Perrow underscored the significance of concentration and related concepts for industrial accidents, arguing that the concentration of facilities potentially vulnerable to attack is a key factor in exacerbating the effects of disasters on infrastructure.[7] He further pointed out that concentration of targets is combined with organizational concentration, defining sources of vulnerabilities to accidents in terms of concentrations of energy systems, populations, and "economic and political power."[8] In his earlier work, he focused on concepts related to concentration, namely tightly coupled systems and centralization that contributed to vulnerability, arguing that loosely coupled and decentralized systems are less prone to accidents.[9] Zimmerman, meanwhile, defined concentration as closely related to the concept of density at many scales.[10] Many indicators and metrics of concentration exist that are infrastructure specific.[11]

The second concept, interconnectivity, encompasses dependencies and interdependencies and has been given considerable attention in technical, policy, and management contexts.[12] Definitions appear frequently, generally expressed as the direction of flows of information, people, and commodities within connected infrastructure networks—whether in one direction (dependency) or multiple directions (interdependency).[13] Interconnectedness and interconnectivity are used here to encompass both dependencies (unidirectional) and interdependencies (multidirectional).[14]

Considerable variability exists in the way both concentration and connectivity are measured and where these system measurements are located along a given supply chain, for instance, at the level of production, transport of products and supplies, distribution, and consumption, as well as between these levels.

This chapter begins with a review of the literature on concentration and interconnectivity within and among infrastructure systems, providing a foundation for characterizing changes over time in both phenomena in a more dynamic way. In doing so, this section revisits and historicizes cases that were previously assumed to be synchronic. Section 2 provides a detailed case analysis focusing on concentration, while section 3 does so for interconnectivity. The order of the listing of infrastructure examples for concentration in section 2 intentionally parallels those in section 3 on interconnectivity, to allow comparisons between the two concepts and show how they reinforce one another. Finally, the last section of the chapter integrates the concepts of concentration and interconnectivity, with concentration considered as a foundation for infrastructure interconnections.

The History of Concentration within Individual Infrastructures

Measures of points of concentration introduce additional complexities for connected infrastructure networks.[15] Specifically, Zimmerman has presented definitions of concentration and its relationship to interconnectivity and related concepts such as density.[16] She defines concentration as "the convergence or density of facilities or activities at many different scales or levels of aggregation."[17] For individual infrastructures, concentration and changes within it over time are an important starting point for understanding infrastructure connectivity and its evolution. Concentration potentially can contribute to infrastructure vulnerability in allowing more services and users to be affected by a single disruption. Conceptually, points of concentration comprise a subset of network properties where distances between nodes or links (edges) converge or where the number of nodes or links is restricted.

Moreover, such concentration points have been shown to be related to population density as Fu, Wilkinson, and Dawson have demonstrated, using England to illustrate the patterns.[18] The history of increasing physical and functional concentration in infrastructure in part also reflects an emphasis on economies of scale for water, electric power, and fossil fuel infrastructure.[19]

Methods for measuring spatial concentration have emerged in different forms, providing important tools for characterizing or defining concentration characteristics and how they have changed over time. One traditional regional economic tool, called "shift-share" analysis, expresses the distribution of facilities as ratios of those located in a smaller geographical unit to those in a larger space or unit.[20] Another commonly applied method is the Herfindahl-Hirschman index, which Zimmerman used to compare indicators for different mass transit configurations and degrees of concentration of ridership in New York City in extreme events or partial system outages.[21] In addition to such indices, concentration can also be measured using location quotients defined as the ratio of particular type of infrastructure facilities, usage, or activities in one location versus those in a larger area, such as a country.[22] Thus, these methods primarily characterize concentration as a ratio, though they vary in the way the ratio is constructed or quantified. The methods typically use a numerator comprising a component of a given type of infrastructure and a denominator consisting of a quantified total or population reflecting the given type of infrastructure in the numerator.

Examples of infrastructure concentration are classified here by type of infrastructure, expanding previous research.[23] The proposed categories cover roads, bridges, energy (pipelines, tankers, and electric power production), telecommunications, and drinking water and wastewater treatment. These categories capture the evolution of concentration over time for specific types of infrastructure with similar characteristics. Concentration is defined for these cases in a number of alternative ways, for example, as the share that a given infrastructure facility has of a total set of such infrastructures or alternatively in terms of density.

Roads

Road concentration can be expressed in terms of the density of road networks (proximity of roads to one another), as well as the volume or intensity of traffic on the roads. Road congestion expressed as traffic volume often varies over time along road networks.[24] This is often due to roadway design, configuration, construction activity, and usage relative to capacity and can be subject to traffic management interventions. Over time, road congestion has been identified as an increasing problem in many areas, particularly in cities in the United States.[25] This is in part reflected by a commonly used traffic measurement, vehicle miles of travel (VMT).[26]

Road congestion is typically measured in terms of scales or levels of traffic based on road volume (of vehicles) to design capacity ratios. INRIX defines congestion “as a speed below 65 percent of the free-flow speed.”[27] INRIX has used several measures to capture road concentration or congestion; on the city level, these include “peak hours spent in congestion” aimed primarily at commuters, a “congestion index” weighted by volume and travel time, an “average congestion rate” averaged over different time periods, and cost of delay.[28]

In assessing trends with INRIX data and methodology, the 2016–2017 comparison seems most useful, since according to INRIX, urban boundaries were standardized for those two time periods.[29] Namely, increases in hours wasted in delay for two of the most congested US corridors from 2016–2017 were as follows:

The NYC Cross-Bronx expressway I-95 (from I-278 to the Alexander Hamilton Bridge) increased by 37 percent.[30]
The Los Angeles I-10 corridor (between I-405 and I-110) increased by 12 percent.[31]

Bridge Crossings

Bridge crossings are often extensions of road networks, although usually more spatially constrained. Like some road segments, many bridges account for the bulk of travel between two single points and concentrate either passenger or freight transport or both. Two bridges in the United States are used to illustrate bridge concentration: the Peace Bridge (connecting Buffalo, New York, and Canada) and the George Washington Bridge connecting New York City and northeastern New Jersey.[32]

The Peace Bridge connects downtown Buffalo with Fort Erie, Ontario, across the Niagara River. Over time it has been expanded to three twelve-foot-wide lanes supporting an estimated $40 billion in trade annually. In 2011 it saw the passage of 4.77 million automobiles and has been considered by the Buffalo and Fort Erie Public Bridge Authority to be “the second busiest border crossing between the United States and Canada.”[33] Connectivity to land-based roadways is indicated by the agency as the reason why the Peace Bridge, together with the second largest bridge to the north, the Lewiston-Queenston Bridge, has supported such a high volume of nonlocal traffic. The volume has remained high even while the authority reported a generally consistent decline in Peace Bridge traffic, from 7.252 million autos, trucks, and buses in 2003 to 5.260 million in 2018, or a decline of 28 percent.[34] Either traffic in general declined during that period or vehicle operators selected other routes, implying a decline in concentration. Nevertheless, Peace Bridge traffic still accounts for the second highest amount of travel at the US-Canada border.

The George Washington (GW) Bridge has connected New York and New Jersey across the Hudson River since its completion in 1931, and is one of six bridge crossings operated by the Port Authority of New York and New Jersey (PANYNJ).[35] The bridge's capacity was gradually expanded to accommodate more traffic, thereby increasing concentration, with the opening of two center lanes in 1946 and the six lane lower roadway in 1962.[36] The GW Bridge is another example of concentrated bridge traffic, accounting for a substantial portion of traffic within the largest metropolitan area in the United States. According to PANYNJ statistics, the bridge has consistently accounted for over a third of the annual traffic volume of PANYNJ bridges; most of this traffic consists of automobiles. Moreover, traffic volumes have generally increased slightly over time, for example by 2.3 percent between 2011 and 2018, reflecting a modest increase in concentration in terms of a vehicular usage criterion.[37] Reinforcing this trend is the urban context: New York City is considered one of the major traffic bottlenecks in the country, ranked third by INRIX among the twenty-five top congested cities.[38] The GW Bridge connects to one of the most consistently congested corridors in the United States—the Cross-Bronx Expressway, whose congestion has been increasing over time, as pointed out earlier.[39]

Rail Transit

Rail transit displays concentrations of ridership at specific hubs similar to the way road arteries concentrate traffic. According to the American Public Transportation Association (APTA), transit traffic volume has been increasing overall (by 34 percent between 1997 and 2017), though in the short term there have been modest declines (for example, by 2.3 percent between 2016 and 2017).[40] Furthermore, according to APTA, prior to 2020 transit systems had been increasing over time in terms of ridership, services offered, and service miles.[41] Limited capacity expansion has paralleled growth in rail traffic prior to the pandemic, leading to increased concentration within the systems, though differences in the rate of capacity changes and traffic exist by line as well as by type of rail transit (the types often used are heavy rail, commuter rail, and light rail). APTA reports some expansions in the form of new systems (mostly light rail) or additional lines.[42] Long distance rail, represented by Amtrak, has 21,300 route miles and over five hundred stations along them but has had relatively little capacity increase over time while ridership has generally remained stable or increased slightly (1.5 percent between FY 2016 and FY 2017).[43] This trend has also occurred over the entire system.[44] True, in recent years Amtrak reported an increase in ridership, from 30.9 million in 2013 to 31.7 million in 2018.[45] It must be acknowledged, however, that the COVID-19 pandemic has reversed much of this growth.

Several rail systems rank highest in volume in the United States, namely those owned and operated by the New York State Metropolitan Transportation Authority (MTA), which is the largest by volume of passenger trips, passenger miles traveled, and ridership per capita.[46] Within the MTA system, the Long Island Railroad (LIRR) is highly concentrated physically, since many of its lines converge on a single station, Jamaica Station.[47] The LIRR has the highest commuter rail travel volume in the United States, ranking thirteenth among all United States transit agencies in terms of passenger trips.[48] In summary, the increases in transit system characteristics that have occurred over time have been in terms of passenger travel, transit services, and mileage traveled.[49]

Energy Transport and Production

Energy systems consist of an extensive network of facilities that include sources of fuel (such as mines), treatment facilities (such as refineries), production sites, storage facilities and transport systems. They can vary from one another in the extent to which concentration has changed over time. Two categories of selected energy facilities are addressed here: transport and production, which are also connected with one another along the energy supply chain.

Pipelines exemplify one form of fuel transport. The Colonial pipeline, one of the largest existing pipeline transport systems, conveys about half of the petroleum products between Gulf coast refineries and the northeastern United States and moves 100 million gallons of liquid petroleum products between Texas and New York Harbor.[50] Its management is also concentrated under one company name.[51] Ownership is shared by six companies, according to McKinsey and Company.[52] It is considered the largest pipeline system by volume transporting refined petroleum products in the United States, spanning 5,500 miles, and from the early 1960s, the company reported gradual expansions and acquisitions that increased the volume of products shipped and the extent and spatial coverage of the physical system.[53] During and following Hurricane Sandy, the pipeline was shut down for many days, affecting a large portion of the East Coast fuel supply; its full recovery extended over a few weeks.

Another pipeline system, the Henry Hub in Erath, Louisiana, is used as the benchmark for natural gas and liquid natural gas pricing futures for trading purposes ("spot pricing"). Since it began operations in the 1950s, the convergence of pipelines at the site has increased, to the point that it is currently the connector for "four intrastate and nine interstate pipelines, including the Transcontinental, Acadian and Sabine pipelines."[54]

Tankers are another key form of fuel transport. The US Energy Information Administration (EIA) has identified seven choke points internationally (down from eight in an earlier report) for the transport of oil via tankers accounting for almost two-thirds of maritime oil transport and about a fifth of oil transport in general. These choke points are defined by the EIA as "narrow channels along widely-used global sea routes, some so narrow that restrictions are placed on the size of the vessel that can navigate through them;" the largest one by volume is the Strait of Hormuz, where the volume handled has increased from 15.7 million barrels per day in 2013 to 17 million by 2017; all seven have contributed to an overall increase in maritime transport of oil.[55] This concentration of facilities has made it vulnerable to attacks.

Turning now to production within the energy system, electric power production consists of key points of concentration. Measured in British thermal units (Btu), total electric power production (all sources) has continued on an upward trend since 1960 (the earliest time period for which we have EIA published records for production), almost doubling from 1960 through 2017. According to EIA data, Texas and Wyoming are the top ranking states for energy production, together generally accounting for about 29 percent of the total US production from 2007 through 2017.[56] Earlier accounts of the location of energy production also identified considerable concentration.[57] Generally, the degree of concentration of energy production at least as defined at the state level is substantial but has remained the same over those time periods for the top two production states. Two trends may affect the degree of concentration of electric power production in opposite directions. One is the increasing centralization of production and distribution of fossil fuel-based power as the energy needs of urban areas draw resources from longer distances. The other is the increasing decentralization of production brought about by expansion in the use of renewable power.

Information Technology and Telecommunications

Within telecommunications, both the number of subscriptions and cell sites have been increasing dramatically.[58] Moreover, new subscriptions for cellular services on average are being concentrated at fewer and fewer locations, that is, becoming increasingly more concentrated. Both subscriptions and cell site location are indicators of concentration. For example, they became a thousandfold more concentrated between 1985 and 2010, as Zimmerman has computed using the 2010 Cellular Telecommunications and Internet Association (CTIA) semiannual survey of the wireless industry: cell sites increased 276 times and connections per cell site almost tripled.[59] Information technology (IT) growth overall is reflected in the increasing number and diversification of IT products.[60]

Drinking Water and Wastewater Treatment

As cities have grown in population, their demand for water supply has also increased, often exceeding the supply.[61] To satisfy demand, cities have often had to reach beyond their borders for additional water resources. For example, New York City and Los Angeles have tapped water sources hundreds of miles away, expanding their systems incrementally over the course of the twentieth century.[62] Given the large distances the transmission lines traverse, the facilities associated with these supplies, such as reservoirs and aqueducts, necessarily concentrated the transmission and supply infrastructure. New York City gradually expanded its sources of supply over one hundred miles to the north. Expansion led, somewhat paradoxically, to greater concentration, as just a few large aqueducts were used to transport the water to the city, which was stored in only a couple of reservoirs before entering New York City.

Another indication of concentration is the share community water supplies have accounted for relative to population served. In 2015 community water supplies accounted for 87 percent of domestic water use; the very large systems, serving more than one hundred thousand people and constituting 1 percent of the community water supply systems, served 46 percent of the US population.[63] This disparity indicates a high degree of concentration, which is likely to increase as urbanization increases and more stringent regulations emerge, moving water consumption from individual private wells to centralized community water supply systems.

Similar to water supply systems, publicly owned wastewater treatment plants (POTWs) have been serving more and more people at least since 1950, becoming more concentrated in terms of the number of people each plant serves. The average POTW served 7,790 people in 1950; by 1996, the number had risen to 11,838.[64] By 2012 the average person per plant was 16,151, representing more than a doubling of users per plant between 1950 and 2012.[65] Below are some additional figures that show similar trends over time:

1996: 189.7 million people, 16,024 POTWs—Population served per POTW: 11,838[66]
2000: 207.8 million people, 16,255 POTWs—Population served per POTW: 12,784[67]
2015: 227 million people, 16,500 POTWs—Population served per POTW: 13,757[68]
2016: 238.2 million people, 14,748 POTWs—Population served per POTW: 16,151[69]

Summary of Infrastructure Concentration

Using different infrastructure-specific measures of concentration, we can see that infrastructures vary with respect to the degree of and trends in concentration over time. Yet they share in common the expanding concentration of users and facilities in a given space. Efforts to counteract these trends have also been increasing over the twentieth and twenty-first centuries (including such actions as removing dams and freeways), even where such infrastructures are located far from their point of usage. The outcomes generally aim at reducing infrastructure resource or production facility concentration rather than the concentration of distribution systems.

Infrastructure interconnections addressed in the next section offer an important way of analyzing the effects of concentration, including whether adverse consequences of concentrations are increasing or not, for example, where the negative impacts of interconnections in the form of cascading effects exceed benefits.[70] Furthermore, characteristics of interconnectivity are analyzed, in part through the lens of infrastructure concentration.

Infrastructure Interconnections

There are many conceptual models that both define and portray dependencies and interdependencies.[71] One set pertains to the duration of disruptions in terms of relative recovery rates, where interconnected infrastructures are involved and multiple interconnected infrastructures are required to restore services.[72] A second set comprises resource intensity, usage, or dependency rates. A third set consists of economic approaches.[73] A fourth set originates from engineering disciplines.[74] A fifth set of approaches is risk-based.[75]

Regardless of discipline, many of the relevant approaches are based upon network theory.[76] Networks are particularly suitable for portraying both infrastructure concentration and interconnections, given their ability to integrate physical, social, and environmental systems. Several network-related criteria for connectivity are useful not only for identifying interconnectivity but also for observing changes in such interconnectivity over time.[77]

> One measure is the ratio of the number of nodes to the number of links, which reflects functional connectivity. The smaller the ratio, that is, the more links per node, the greater the functional connectivity.
>
> Another more conventional network measure is “betweeness” or “closeness,” which signifies distances between or among nodes.[78] These reflect geographic

or spatial connectivity. The closer links or nodes are to one another, the greater potential they have for spatial connectivity.

Congestion measures specific to particular infrastructures such as transportation developed by INRIX in 2018 also reflect spatial connectivity, ultimately affecting functional connectivity as well.[79] In this context, concentration can be considered a characteristic or special case of the properties of nodes, links, or node-link combinations.

Though the extent of physical infrastructure, services, and their use has generally increased over time, changes in the extent and nature of infrastructure interconnections, whether dependencies or interdependencies, are more difficult to capture and frequently appear less in the literature employing empirical data. Much of the evidence is largely anecdotal and it is difficult to separate out real time trends from trends in increased attention to and reporting for interconnected phenomena.

The conceptual origin of infrastructure interdependencies is elusive. In the late twentieth-century literature, the work of the President's Commission on Critical Infrastructure Protection (PCCIP) is often cited as a starting point.[80] Massive extreme events have underscored the impacts of interconnections through cascading phenomena from one infrastructure to another. Considerable literature associating these extreme events with interdependencies appeared in the early twenty-first century.[81]

Looking back historically with a focus on social trends, as population densities of urban areas increased dramatically—especially in the United States in the early part of the twentieth century—anecdotal evidence indicated that infrastructures were becoming more interconnected to meet social needs and increasingly dense population centers.[82] Geographic or spatial interconnections are very evident in the famous archival picture of the street cutaway in Lower Manhattan revealing a tangle of different co-located infrastructure conduits. In *Filthy Dirty: A Social History of Unsanitary Philadelphia in the Late Nineteenth Century*, Alewitz describes late nineteenth-century interconnections in a particularly detailed way. Specifically, he references water supply, wastewater, solid waste (human and animal) and street systems in Philadelphia that led to extremely adverse social conditions, in this case in the form of unsanitary conditions that served as potential precursors to diseases of epidemic proportions: "The cleanliness of the city [Philadelphia] remained a problem throughout the nineteenth century, especially in the crowded working-class wards. Street dirt (manure) and garbage was piled in the gutters, blocked sewer inlets, flooded and saturated the streets, and made pedestrian crossings hazardous. The great evil was not only the sight and smell that overwhelmed the senses, but that much of the filth that was left behind on the dirty streets found its way into the city's drinking water."[83]

As cities reached out beyond their borders for resources to meet a growing demand, interconnections grew. In the latter twentieth and early twenty-first centuries, considerable attention emerged to the existence and often adverse impacts of widespread infrastructure interconnectivity. This was particularly true during extreme events, in which the consequences could be magnified when combined with concentrated infrastructures. Unsurprisingly, many US federal agencies focused on infrastructure interdependencies. The National Science Foundation (NSF) developed the Resilient Interdependent Infrastructure Processes and Systems (RIPS) and Critical Resilient Interdependent Infrastructure Systems and Processes (CRISP) programs specifically incorporating infrastructure interdependencies. The Department of Homeland Security recognized that interconnections may threaten the security of critical infrastructures, emphasizing such conditions in sector-specific infrastructure plans, particularly for water and energy in the National Infrastructure Protection Plan (NIPP).[84] The Department of Energy developed a series of analyses, including metrics between energy and water sectors.[85] This trend expanded to the food sector, with a NSF and Department of Agriculture annual research program called Innovations at the Nexus of Food, Energy and Water Systems (INFEWS).

Many of the infrastructure concentrations cited in section 2 for single infrastructure categories are described below with respect to interconnections with other infrastructures, as a foundation for the argument that concentration and interconnectivity are in some way associated with one another, which acting together can magnify impacts of infrastructure on physical facilities and users. IT plays a large role in interconnectivity; thus, the interconnectivity categories below begin with those that incorporate IT, including roads, rail, electric power, and other infrastructures. Subsequently, water and electric power interconnectivity are addressed together, ending with a discussion of their association with IT.

Road Transportation and IT

Over time, road systems have become increasingly dependent upon information technologies for communication and control aimed at managing, alleviating, or reducing concentration manifested in the form of road congestion. For example, Zimmerman evaluated selected US Department of Transportation (DOT) databases for IT use in transportation cited in Zimmerman's 2017 paper, between 2008 and 2014.[86] The analysis covered seventy-eight metropolitan areas over the latter part of the twentieth and early part of the twenty-first centuries. The evaluation focused on two aspects of the database: (1) the percentage of systems that deployed IT and (2) the change in that deployment between 1997 and 2006, 2000 and 2006, and for one function, between 2000 and 2013. All ten transportation functions from the DOT database showed some increase in IT deployment from 1997 to 2006. However, between 2000 and 2006 there was an intensification, as IT deployment increased in eight of ten sectors. The following summary captures some results of the study:

> Vehicle location devices showed an IT deployment rate in 2006 in a little over half of the systems. At the same time these interconnections showed the most dramatic increase since 1997 compared to other IT devices (an 80 percent increase).
>
> Emergency dispatch showed a relatively high usage of IT in the early twenty-first century—about three quarters of the systems showed such usage, jumping to the highest in 2006 with 81 percent deployment and indicating a 20 percent increase between 2000 and 2006, with an even higher percent increase from 1997, probably reflecting dramatic events such as the September 11, 2001, attacks and extreme weather events and electric power outages.
>
> IT usage for public information dissemination was low in 1997 but jumped in 2000 and between 2000 and 2006, with a 65 percent increase in deployment.
>
> The use of IT for real-time traffic data collection, which had a more extended database, showed a steady increase through 2013, from about 25 percent in 2000 to just over 60 percent in 2013.
>
> In contrast to other sectors, surveillance of highway rail intersections not only had the lowest percent of IT deployment across the decade but also showed a dramatic decline in use (primarily due to the low level of use to begin with).

This growth in IT usage in transportation has important implications for the vulnerability of automated and autonomous vehicles, for example from cyber attacks and computer malfunctions, since they are wholly dependent upon IT.

The examples above illustrate dependencies between roads and IT, but interdependencies may also be apparent. IT connections to transportation infrastructure potentially can enhance or encourage growth and diversification of IT infrastructure, though cause and effect is difficult to establish.

In the cases presented above for road concentration, the most concentrated arteries are located in a highly interconnected network of other arteries.

Rail Transit, Electric Power, and IT

As indicated above, the LIRR is a highly concentrated rail system and its degree of concentration has been increasing in terms of ridership levels. It is heavily interconnected with both electric power and information networks. A lightning strike on September 29, 2011, disabled a computer and—coupled with a programming error—brought large portions of the rail system to a standstill because it knocked out a station where train lines converged.[87] Whether connectivity with IT has been increasing is difficult to ascertain, though increasing budgetary allocations for IT are an indication of increasing connectivity.

Rail transit systems are often affected by electric power outages, and the NYC subway system is a case in point. Over the years, electric power systems that serve transit have been concentrated geographically, which may have contributed to power outages producing widespread and lengthy transit service disruptions, for example when power went out at a central location in midtown Manhattan in mid-July 2019. In light of these challenges, Schabas has emphasized the vulnerability of centralized power for transit.[88] In 2017 a series of electric power outages occurred that motivated New York State to take systematic and extensive actions to strengthen the grid and its support of mass transit. Still, the impacts of electric power outages and other power-related conditions have persisted. For example, in 2021 an instantaneous power surge in NYC (hardly felt by building occupants) disrupted a number of subway lines for many days; this incident was not related to weather conditions.[89] Transit-electric power relationships, another type of rail transportation-related interconnection, have been modeled for alternative ridership distribution among four major transit stations and electric power outage scenarios for NYC.[90] Transit-IT relationships are another type of interconnectivity. The NYC rail transit system is highly dependent on computerized controls, and computerized communication disruptions have produced service disruptions, some of which have been increasing over time. For example, the power surge on August 29, 2021, resulted in disruptions in communication systems that prevented operators from knowing what had happened.

Electric Power and IT

In many ways, electric power has been considered the infrastructure that drives many other interconnections.[91] However, the role of IT in such interconnections may be increasing. IT and electric power are highly interconnected, with IT relying on electric power for its equipment, and electric power heavily dependent on IT to support an ever-increasing digitized grid.[92] As indicated above, according to EIA data the use of electric power has steadily increased across the twentieth and twenty-first centuries, necessitating a growing dependency on IT to support it.[93]

The fuel transport systems identified above—pipelines and tankers—are dependent upon IT systems for operational control. The Colonial pipeline's interconnectivity with IT was cited in connection with a major 2016 failure in the southeastern United States.[94] This interconnectivity was revealed in a particularly significant way in 2021 by a severe cyber attack in the form of Ransomware, which resulted in the closure of the pipeline for a number of days with impact extending for weeks across numerous supply chains.[95]

As indicated earlier in connection with infrastructure concentration, energy production is comprised of numerous subsystems, and the connections among them just within the energy system can be very complex.

IT and Other Infrastructures

Two databases are used here to illustrate the pervasiveness of IT and its interconnectedness with other infrastructures and changes in those relationships over time, highlighting the potential vulnerabilities of these other infrastructures to IT disruptions (from cyber attacks, for example). Numerous disruptions have occurred already.

On the one hand, there have been dramatic declines in the share of cyber attacks accounted for by the energy sector relative to other infrastructure sectors; however, energy still exceeded the share of such attacks compared to other sectors. At the same time, the communications sector gradually increased its share of attacks and in 2016 slightly exceeded the energy share; meanwhile, transportation and water shares of attacks had increased but not as much as shares accounted for by the other sectors. In fact the shares of those two sectors declined in 2016, according to analyses of the data from the Industrial Control Systems Cyber Emergency Response Team (ICS-CERT).[96] This database records interconnections emphasizing cyber attacks between IT and four critical infrastructures across the sectors over five years from 2012 to 2016. Cyber-related IT/critical infrastructure interconnections have also been underscored in national infrastructure policy.[97] Zimmerman evaluated these interconnections using ICS-CERT data.[98]

Another database illustrating interconnectivity, and changes in these aspects of infrastructure systems over time, is the Repository of Industrial Security Incidents (RISI).[99] That database covers five infrastructure sectors: automotive, petroleum, power and utilities, transportation, and water/wastewater. A subset located in the United States is analyzed here, for incidents from 1982 to 2014, complementing the ICS-CERT data mentioned above. Zimmerman coded the

Table 1.1 RISI cases over time, non-cyber-attack and cyber-attack related, 1982–2014

Year	% Non-Cyber Attacks (n=57)	% Cyber Attacks (n=38)
2000 and earlier	8.8%	7.9%
2001–2005	15.8	42.1
2006–2010	52.6	23.7
2011–2014	22.8	26.3

Source: Constructed by the author from RISI data. Exida.com LLC, Repository of Industrial Security Incidents (RISI) Online Incident Database, 2017, https://www.risidata.com/.

database from case descriptions by infrastructure sector and how impacts were described for both cyber-attack and non-cyber-attack cases.[100] The cases all involved some type of computer control of other infrastructures that became inoperative from human error, technological accidents, or extreme weather disabling one or more of the infrastructure sectors. Zimmerman analyzed a portion of the RISI data, which showed that the percentage distribution of cyber attack events by sector across the five sectors is generally similar to the distribution of the sectors. Selected results over time are shown in table 1.1.[101]

The first column of results in the table gives the distribution for four time periods for fifty-seven cases coded as being computer-, but non-cyber-attack related. The second column gives those that were cyber attacks (thirty-eight cases). The results shown in table 1.1 show a low level of cases prior to the late 2000s, after which the majority of cases begin to emerge. For non-cyber attacks the percentage of cases increases over time. For cyber attacks the percentage increases only in the earlier time period, stabilizing thereafter. Declines from 2011 onward in both sets probably reflect the discontinuation of the database.

Water Supply, Wastewater Treatment, Electric Power, and IT

Water systems rely on energy to convey and treat water, and energy in turn relies on water for processing and cooling.[102] The water-energy nexus has been studied extensively.[103] As water systems become increasingly concentrated, serving more people per plant, the move to larger and more complex systems is an important factor in their increasing dependence on electric power.

The Electric Power Research Institute indicated that between 1996 and 2013 the annual use of electric power for water supply (community water supply systems) and for wastewater treatment electric power usage increased by 39 percent and 74 percent respectively.[104] The Electric Power Research Institute has argued that the dependency of water supply systems on energy is only likely to increase given expanding water demand, regulatory stringency, aging facilities, and operational needs.[105]

Recovery provides an important perspective for infrastructure interconnectivity during and after extreme events. During Hurricane Irene, the results of a survey of water supply operators conducted by the Cadmus Group indicated that one of the major obstacles to recovery of water supply plants was the lack of power, while a second obstacle was transportation related, namely, the inability to access the water facilities due to road damage.[106]

Publicly owned treatment works or wastewater treatment plants have in general become larger and more computerized, so more people can be affected by an IT outage at a single plant. Moreover, publicly owned treatment works can become indirectly affected by IT through the electric power sector's dependency on IT. Electric power is also extensively used for water treatment processes and conveyance of wastewater and is likely to increase given similar constraints that water supply systems encounter. In addition, the Electric Power Research Institute also identifies changing technologies as a factor potentially increasing or at least changing energy demand for wastewater treatment.[107]

Summary for Changes in Infrastructure Interconnectivity

The cases used to illustrate change in concentration in section 2 that were evaluated for change in interconnections in this section indicate that associations exist between the two properties, at least for the cases and case areas evaluated. Where infrastructure concentration has been stable or increasing, interconnectivity has also increased over time for the same systems.

Conclusions

Two attributes of infrastructure, concentration and interconnectivity, and developments within them over time, have contributed to the vulnerabilities of infrastructure systems and the public services they provide, though historically they may have been introduced for economic benefits.[108] The increases in these properties appear to be occurring with respect to scale. Both attributes are spatially and functionally defined. Both have their origins in part in market forces in terms of economies of scale. These attributes were shown to be interrelated based on selected cases and trends, building upon earlier research.[109] Where high concentrations of infrastructures exist, interconnections are likely to be high. Society has increasingly depended on these services and the vulnerabilities are having serious consequences especially when extreme weather events occur; these appear to be increasing.[110]

Some of the examined interconnectivity pertained to the increasing use of electricity and communications technologies by multiple infrastructures. These dependencies translate into interdependencies, where those two infrastructures depend upon the other infrastructures they support for their own operations. Examples of concentration appear as increasing usage of infrastructures for moving people, supplies, and information at discrete geographic locations, facilities, or functional control points. Examples were given of key roadways and bridges that account for substantial amounts of traffic and which are experiencing increases in the concentration of traffic without capacity increases to accommodate it. These examples are supported by transportation trends given by INRIX for surface transportation and APTA for transit. Water and electric power transmission, distribution, and storage systems are concentrated in a few distinct facilities that support major cities.

Concentration and interconnectivity produce vulnerabilities in infrastructure in several ways. First, flexibility and availability of alternative services and the ability to take advantage of such alternatives are reduced when one concentrated or heavily interconnected service is disrupted by natural or human causes. Case histories have illustrated this conclusion.[111] Natural phenomena appear to be increasing, increasing vulnerabilities in terms of the direct impacts on infrastructures and the people they serve. Second, the ability of infrastructure services to rebound or recover after a disruption is likely to be affected when the number of interconnected systems involved is large. Distance to obtain a service is another attribute, one that is a little more complicated to consider; however, where infrastructures are seriously disabled, alternative, more distant resources are usually pursued (at least in the short term).[112]

Unless these constraints are directly addressed in infrastructure service policies, planning, and practice they will contribute to increasing degradation of the quality of the services, with the attendant social consequences. There are many innovative ways to achieve such accommodations, for example through decentralization and redundancy. Services can be substituted for one another. Users can shift to another service provider not affected by the disruption. New technologies are offering more flexibility in the form of decentralized resources. The move toward renewables in the energy sector is one example.[113] Low carbon energy sources in transportation also exemplify this decentralization.[114] Another is the use of electrical vehicles, whether cars, bikes, or scooters, that can be charged locally, even in owner homes; however, decentralization is compromised if the source of electric power is centralized power plants.[115] Finally, people can abandon the affected area or abandon the service altogether, either temporarily or permanently in extreme situations. Thus, many options exist to avoid or reduce the adverse impacts that infrastructure concentrations and connectivity may pose, especially in extreme events involving changes in the technologies and their use.