Infrastructure System Interconnectivity Effects on Resilience

Rae Zimmerman
Professor of Planning and Public Administration
New York University – Wagner School

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Concepts and Scope

Introduction

• Resilience and interconnectivity are addressed for infrastructure and its services including relationships to society and the environment.
• Resilience is used in numerous contexts. A generic concept for infrastructure resilience used here is: “bounce back,” “bounce forward” or don’t bounce at all.[1]
• Interconnectivity connotes multiple-directional or one-directional dependencies or interdependencies among infrastructures. It can influence vulnerability and resilience.[2]
• Many types of infrastructure resilience and interconnectivity exist and at many scales.

The Backdrop

• Environmental threats are increasing in some areas, but more importantly the consequences are increasing regardless of the extent of the threats.
• Condition, performance and investment typically do not include interconnectivity, which can exacerbate weaknesses in single infrastructures.
• Siting, material, structural, design, and resource (financial and institutional) factors contribute to the resilience of interconnectivity and resilience relationships to society.

Going Forward

• Interconnectivity, its contribution to infrastructure vulnerability, and its value in promoting resilience are key inputs to infrastructure resilience modeling.

Sources:
I. The Backdrop:

1. Selected Natural and Human Hazards Affecting Infrastructure

- Source: NOAA (2006) NOAA Celebrates 200 years


- MTA U.S. Coast Guard photo, National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling (2011) p. 88

- NOAA (2013) Service Assessment, Hurricane/Post Tropical Cyclone Sandy, Cover page


- NYC Environmental Protection
**Selected Trends in Natural Hazards**

- NOAA’s National Climate Data Center (2016) reported the continued prominence of severe storms and flooding among other weather or climate related events whose losses exceed a billion dollars.[1]
- NOAA’s National Hurricane Center reported that the recent couple of decades accounted for the most severe storms in dollar losses and other factors.[2]
- The National Climate Assessment trends and projections reported increases in most climate change-related extreme phenomena: temperature, sea level rise, heavy precipitation, hurricanes.[3]
- Swiss Re reported generally increasing trends in catastrophic losses (according to their threshold definitions based on “insured losses (claims), economic losses, and casualties”): “353 catastrophe events across the world in 2015, up from 339 in 2014. Of those, 198 were natural catastrophes, the highest ever recorded in one year,” most of which are weather-related.[4]
- NOAA reported that records are being exceeded or almost being exceeded for temperature (NOAA’s *State of the Climate*), hurricane extremes, and ice loss (NOAA National Snow and Ice Data Center).[5]

**Sources:**

[1] NOAA National Climate Data Center (2016)
[5] NOAA (2016) State of the Climate; National Snow and Ice Data Center

Note: These findings can vary by location.
2. Infrastructure Condition and Selected Factors Influencing Condition

**Condition 2013**: U.S. average is “D”, from D- (water) to C+ (bridges).[1]

**Age**: NYC infrastructure age ranges, according to CUF[2], are: sewer mains and subway facilities (about 80-90 years old) to airport support facilities (40-50 years old); water mains and bridges are in the middle.

**Design and environmental issues**: However, age may not be the whole story, since many bridge collapses have occurred in newer bridges.[3]

**Usage and capacity**:
- According to EIA, energy production and use steadily increased nationwide.[4]
- Vehicle Miles of Travel steadily increases (U.S. DOT[5]) and transit ridership also (APTA)
- CTIA indicates the exponential growth in cellular technologies.[6]
- The Pew Center [7] indicates dramatic increases in information technology usage, i.e., for the internet, computers and cell phones.

**Investment**: ASCE estimates a $3.6 trillion need to 2020.[1]

3. Siting: Population and Infrastructure Concentrations at Coasts


Siting Consequences: NYC Subway Stations Flooded in the August 8, 2007 Storm

- September 8, 2004 storm 7 lines were disrupted
- April 15, 2007, 12 were disrupted, July 18, 2007, 9 were disrupted,
- August 8, 2007, 19 lines had reduced or no service
- Most of the lines were back within 12 hours.
- In 2007, some outer areas where poorer populations live were spared flooding, but others were flooded (Brooklyn and Queens)
- 31 of 468 stations; 15 of 25 lines vulnerable

4. Materials: Example - Non-Absorbent, Impervious Surfaces
Selected U.S. Cities

From Litman (2011):
• Roadway area is the largest contributor to impervious surfaces for housing lots (2000 sq ft)
• Roadway area is greatest for single-family large lot homes and least for high-rise apartments
• Other impervious surface contributors are the housing area itself and parking


5. Resources: Example of Cities with Increasingly Suburban Poor Populations and Availability of Rail Transit

• About a dozen cities were identified by the Brookings Institution where the ratio of 2010 to 2000 share of poor populations exceeded 20%.[1]
• These cities were aligned with heavy rail, commuter rail and light rail, and the percent share of these types of rail transit were computed for each city.[2]
• Results showed that only one city, Chicago, exceeded a ten percent share for any rail type, and most of the cities, except for Chicago accounted for less than 5% of the share.[2]

Sources:
II. Infrastructure Interconnections: Attribute Summary

• Generic infrastructure interconnections:
  – Electric Power – with Transportation, Water, and IT;
  – Transportation – with Water, and IT;
  – Water – IT

• Specification of the direction and magnitude of flows of goods, services, and/or information among infrastructures

• Scale: Component-level connections (ranging from small parts to large multiple interrelated systems*)

• Types:
  – Temporal Interconnections
  – Physical*
  – Cyber*
  – Spatial Interconnections (geographic)*
  – Logical*

• Implications: Impact and Likelihood of Cascading Failures from Interconnections

Interconnections Potentially Vulnerable to Cascading Disruptions

Electric power and rail transport

Source: R Zimmerman photo, Salt Lake City, 2011.

Water and other infrastructures


Interconnections within Energy Systems: Pipeline Interconnections for Petroleum and Natural Gas

Pipelines and Hazardous Materials Safety Administration data reports 2.6 million miles of U.S. pipelines; almost half are natural gas distribution lines.

Petroleum

Natural Gas
Red lines added signify selected Hurricane Sandy disruptions.
Concentration as a Characteristic of Interconnections: Transportation Example

• Transportation ridership and its infrastructure are highly concentrated in a few states
  – About half of U.S. transit ridership, transit user populations, and transportation infrastructure is concentrated in just a handful of states.[1,2]
  – About half of automobile ridership (annual vehicle miles of travel) is concentrated in 9 states.[1]
  – About half of roadway mileage is within 14 states.[1]
  – Half of enplanements occur at under five % of U.S. major airports.[1]

• Transportation infrastructure and use is similarly concentrated within just a few urban areas.[3,4]

Sources:
Concentration: Energy, Water and Telecom

Energy
• About half of the petroleum refineries in the U.S. are in just a few states.[1]
• About half of the power plants in the U.S. are in about a dozen states.[1]
• Henry’s Hub is an area in the U.S. where major oil distribution lines converge.[2]
• Energy transmission lines tend to enter urban areas at only a few locations.

Water
• About 7% of community water supply systems serve half of the population.[3,4]
• A similar disproportionality exists in the area of wastewater treatment systems.
• Distribution and storage facilities for urban areas tend to be highly concentrated.

Telecom [5]
“The growth in cellular technology has been very dramatic. According to the 2010 Cellular Telecommunications and Internet Association (CTIA) semi-annual survey of the wireless industry, between 1985 and 2010, the number of estimated connections for all uses increased almost 1000-fold (889 times); Interestingly, this reflects a growing centralization and hence vulnerability, since . . . from 1985 to 2010, the connections per cell site grew from 373 to 1,197.”

Sources:
III. Consequences of Interdependencies:
General Failure Modes
(all infrastructures)

- Obliteration/inundation, e.g., submersion or debris entrainment
- Undermining
- Disintegration
- Physical impingement / structural collapse
- Corrosion; other material failures and distortions

- Facility inoperability through functional impairment
- Service disruption
- Social, economic and environmental consequences
Some Consequences, e.g., Transportation Water, and Land Interconnections

OBLITERATION/INUNDATION

Source: NOAA/NGDC, E.V. Leyendecker, USGS, Collapse of Freeway in 1989 Loma Prieta, CA Earthquake

PHYSICAL IMPINGEMENT/STRUCTURAL COLLAPSE

Source: MTA. Debris from Jamaica Bay fills Tracks Inside Broad Channel A Station on November 1, 2012.

SUBMERSION

Source: FEMA New Orleans, LA 9/4/05 -- School buses have been swamped by the floodwaters following Hurricane Katrina. Photo by: Liz Roll, 9/4/05 ID: busses.jpg 14794

Hurricane Katrina
Source: FEMA

Electric Power and Other Infrastructures: Impacts of Loss of an Electric Power Distribution Substation

**Electric Power Outage Scenario (2003)**

<table>
<thead>
<tr>
<th>Action/Event</th>
<th>Initial Consequences</th>
<th>Possible 2nd Level Consequences e.g., to Other Infrastructure</th>
<th>Possible 3rd Level Consequences to Users</th>
<th>Restoration Scenarios</th>
</tr>
</thead>
</table>
| Electric Power Disruption  
• Substation disrupted  
• Distribution line breach (not break) | Dysfunction/Stoppage of energy distribution systems | Communication Disruption  
• Internet  
• Phones  
• etc. | Goods movement stops | Scenario 1  
*Repair or Replace* Infrastructure after it breaks |
| OR | | | People can’t get to jobs | Scenario 2  
*Harden* infrastructure beforehand to reduce the magnitude of destruction |
| Cyber Failure | | | Business impacts, including agricultural machinery  
Disruption in access to capital, e.g., ATM machines  
Property value impacts | Scenario 3  
*Backup* systems to reduce impact of outages |
| Electric Power Disruption  
• Actual Break of Transmission Lines | Water/Sewer/Sanitation stops | Health impacts from polluted drinking water  
No water (supply); impaired water  
Recreation: beach pollution  
Spread of toxins and pathogens | |

**1. INFRASTRUCTURE VULNERABILITY ASSESSMENT**
Uses engineering and environmental models to identify and forecast likelihood of breakage or stoppage

**2. RISK AND CONSEQUENCE ANALYSIS**

**3. ECONOMIC IMPACT ANALYSIS**

Source: Created by R. Zimmerman, NYU-Wagner School
Using Energy Connections with Transportation and Water to Estimate Recovery from Electricity Outages, 2003 Blackout

Outage Durations, August 2003 Blackout (Total Duration = approx. 42-72 hrs)

<table>
<thead>
<tr>
<th>Infrastructure Outage/Electricity Outage</th>
<th>T(i)/T(e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transit-electrified rail (NYC)</td>
<td>1.3</td>
</tr>
<tr>
<td>Traffic Signals (NYC)</td>
<td>2.6</td>
</tr>
<tr>
<td>Cleveland Water Supply System</td>
<td>2.0</td>
</tr>
<tr>
<td>Detroit Water Supply System</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Full and Partial Restoration of New York City Subway Lines, Post-Hurricane Sandy, 10/28/12-11/12/12

Picture: MTA. Fixing A Train
Tracks on the “flats” near Jamaica Bay

Electric power recovery as a % of customers served

Failure Mode Examples for Infrastructure Interconnections:

Electric Power, Transportation, Water, IT

• **IT and all infrastructures**: [1]
  - In 2012, ICF-CERT reported the following based on 198 attacks: 41% (82) in energy; 3% (6) in nuclear; 15% (29) in water, and 3% (5) in transportation;
  - By 2013, based on 256 attacks they reported: 59% (151) in energy; 3% (8) in nuclear; 5% (13) in water, and 5% (12) in the transportation sector

• **Electric Power and Transportation**:
  - Hurricane Sandy resulted in extensive flooding of electric power infrastructure that was a key factor in transit vehicle, signal, and switch outages and lighting and signal outages for road transportation[2]

• **Transportation and Water**:
  - For water management, unavailable or blocked drainage infrastructure can cause road, rail and vehicle flooding in the short-run and material disruptions in the long run [3]

Note: Only examples of two-way infrastructure interconnections are given, but in reality, many examples exist of more complex interconnections

Sources:


[3] A contributing factor to the Mianus Bridge Collapse in CT was the paving over of drainage facilities which created water damage to steel components on the bridge. NTSB (1984), Highway Accident Report: Collapse of a Suspended Span of Interstate Rte 95 Highway Bridge over the Mianus R. Greenwich, CT. 6/28/83, Washington, DC, USA, NTSB.
IV. From Failure Modes to Resilience: A Basis for Modeling

Conventional infrastructure interdependencies are potentially vulnerable to breaks in single links that can cause cascading damages across multiple infrastructure systems.

Distributed or alternative infrastructure systems enable more flexible, relatively simpler interconnections by adding additional resources that can perform and connect independently (dashed lines) or through traditional interdependent system linkages (dashed double arrows). Lines exemplify linkages.

Note: Only two-way, simple infrastructure interconnections are shown, but more complex interconnections occur involving more infrastructures. Created by R. Zimmerman, NYU-Wagner School.
Using Interconnectivity to Promote Resilience

• Selected Measures
  – Intersection of hazards and infrastructure nodes and links
  – Recovery time

• Illustrative Methods
  – Multiple routes, modes, and resources (decentralized, redundant, shared, and “slack resources”)
  – Redundant structures and functions
  – Effective communication
  – Hazard mitigation and emergency planning

• Components
  – Resources
  – Physical Systems
  – Environmental Systems
  – Social Systems

1. Resources

Valuing Infrastructure

• Contributions to the economy:
  – Infrastructure capital as a contributor to the Gross Domestic Product (GDP) (World Bank)
  – High value of infrastructure assets (in the trillions of dollars) (U.S. Bureau of the Census)

• How do we capture that value to support future infrastructure investment?

• The cost of not investing

• Reliance on disaster funding in the short-term
Financing via Emergency Funding: Disaster Relief Appropriations Act of 2013 (DRAA)

Appropriations categorized by Program Theme

<table>
<thead>
<tr>
<th>Program Theme</th>
<th>Appropriations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infrastructure Systems</td>
<td>$18.0</td>
</tr>
<tr>
<td>Economic</td>
<td>$1.0</td>
</tr>
<tr>
<td>Natural and Cultural Resources</td>
<td>$1.0</td>
</tr>
<tr>
<td>Federal Asset Restoration</td>
<td>$0.8</td>
</tr>
<tr>
<td>Health and Social Services</td>
<td>$0.8</td>
</tr>
<tr>
<td>Program Support and Research</td>
<td>$0.3</td>
</tr>
<tr>
<td>Oversight</td>
<td>$0.03</td>
</tr>
<tr>
<td>Multiple*</td>
<td>$26.1</td>
</tr>
</tbody>
</table>

Note: This includes 2 programs: HUD's Community Development Block Grant - Disaster Recovery Assistance and FEMA's Disaster Relief Program. These programs fund a variety of activities across multiple themes.

Financing via Capital Budgeting
Selected Permanent Restorations After Hurricane Sandy - Making Old Things New, 2013 and beyond

• April 4, 2013. Number 1-train service to South Ferry substituted by service through the old South Ferry station[1]
• May 31, 2013. A-train service to the Rockaways restored[1]
• Other tunnels, stations, and transit facilities under construction to 2016 and beyond[4]

Source: Based on data compiled by R. Zimmerman from MTA public information sources:
[1]*http://web.mta.info/sandy/timeline.htm,
[4]MTA CPOIC April 2014 presentations

- **Electric Power and Transportation:**
  - Back up power (short-term)
  - Decentralized power and alternative transportation modes with different energy inputs (long term)
  - Alter Transportation to Avoid Disabled or Vulnerable Electric Power Systems: Modes (demand responses, surface vs. rail), Routes, Timing, Usage, e.g., telecommuting
  - Technology – robotics
  - Facility design: Elevate, Relocate

- **Electric Power and Water**
  - Alternative/backup power
  - Alternative water sources
  - Alternative supplies and supply routes

- **Electric Power distribution and production with all other Infrastructure:** Strengthen, Relocate, Underground, Seal*

Alternatives for Avoiding Adverse Effects of Interconnections between Water and Energy

• Energy Usage for Water Reduction
  – Water recycling in energy systems
  – Fluids other than water for energy cooling systems

• Water Usage for Energy Reduction
  – Energy recovery
  – Alternative (renewable) energy sources
  – Less energy and/or water intensive products or methods of production, including those in other infrastructure sectors, e.g., transportation

Adapting Interconnectivity for Resilience: IT

• IT and all infrastructure
  – Capacity expansion
  – Alternative communication modes
  – Alternative structures
  – Alternative procedures to improve communication management

• IT and Transportation
  – Capacity expansion
  – Redundancy
  – Improved operational performance and usage training

• IT and Water
  – Capacity expansion
  – Sensor technologies to detect contamination, adhere to water quality standards, detect intrusions, and other IT security

• IT and Electric Power (both fossil fuels and renewables):
  – IT has considerable value for energy systems in detecting anomalies, managing production, routing, accident avoidance through detection, distribution under normal conditions (bringing dispersed resources from extraction sites to concentrated production points and concentrated production resources to dispersed consumption points), and emergency conditions, e.g., detecting conditions that warrant preemptive shutdowns
Fueling Station Location for Alternative Fuels, miles from interstate highways, U.S.*:

- Only about 10% were under one quarter mile
- Almost half were between one quarter mile and 5 miles
- About a third were greater than 10 miles

Flexibility Through Multi-Modal Interconnections: Bus Connections at Subway Stations, NYC

• Connections between buses and subways do and can continue to provide alternative transportation modes in emergencies
• Nationally, bus connectivity is highest with rail transit
• The New York City subway stations vary in numbers of buses stopping at stations from a couple of dozen to none
• Bus connectivity is in part related to the number of train tracks located at each station

Adaptation for Flood Protection by Integrating Innovative Pedestrian Transportation Corridors, St. Jean de Luz

Photograph by R. Zimmerman
Interconnecting Wastewater Treatment, Electric Power, and Water Management Infrastructure, NYC Post-Hurricane Sandy

Changing Materials to Balance Heat Exchange
Changes in Cooling over Time for Concrete and Asphalt

Innovative Streets: Controlling Water, Heat and Other Factors

• Strategies
  – Spatial and temporal adaptations
  – Reducing Roadways: Decentralizing streets; Deconstructing large roadways

• Specialized Approaches
  – Cooling pavement surfaces for heat absorption
  – Green corridors for ecological protection
  – Green corridors for pedestrian thoroughfares
  – Streets for stormwater control (Kuala Lumpur, Malaysia)
  – Streets for waste recycling (glasphalt, plastic bags)
  – Streets for electric power generation
  – Streets as utility corridors

3. Environmental Systems and Infrastructure: Wildlife Corridors at Roads and Bridges

Water & Transportation Infrastructure Interconnectivity

Roadside Swale, Salt Lake City, Utah

Street and Subway Flooding Protection: Elevated Grate Barriers, NYC

Source: Photos by R. Zimmerman 2012
Connecting CSO Basins (Gray Infrastructure) with Green Infrastructure Technologies

4. Social Systems
Role of Human Behavior: Will People Adapt

Transportation Example: Psychological and Social Determinants of Route Choice

Potential Factors Influencing Individual Choice of Transportation Routes

- Crowding, congestion
- Reliability
- Predictability / certainty
- Number of transfers required
- Time (transfer among modes and waiting time)
- Cost
- Safety
- Number of alternatives
- Aesthetics (including cleanliness)
- Access to other non-transit related resources (stops for shopping, etc.)

Potential Factors Contributing to Variations in Individual Choice Decisions

- Income
- Trip purpose
- Trip length (scale)
- Health status
- Miscellaneous travel preferences and customs

How We Use Land
Population Density, Household Characteristics and Transportation Per Household CO₂ Emissions, U.S.

Exhibit 2 – Household Characteristics and Est. Annual CO₂ Emissions from Travel

Source: U.S.DOT, FHWA (March 2009) NHTS Brief. The Carbon Footprint of Travel, p. 2
http://nhts.ornl.gov/briefs/Carbon%20Footprint%20of%20Travel.pdf
Alternative Land Adaptation Measures, NYC Department of City Planning

V. Future Research Needs and Lessons for Policy as Inputs to Modeling

• Provide greater specification and quantification of linkages, e.g., in terms of flows, inputs and outputs, acknowledging the uncertainty and variability

• Understand overall conditions (internal/external to systems) under which interconnections are strengthened or weakened (network theory; concentration effects)

• Identify interventions that change adverse cascading effects: Address concentration effects by reducing them through alternative designs

• Understand the role of and how to shape human behavior to support interconnections that reinforce resilience
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Disclaimer: The views expressed in this presentation are the opinions of the author and not necessarily those of the NSF or the U.S. DOT.