Challenges of combined indicators for cross-sectoral urban infrastructure assessments and urban social-ecological-technological sustainability

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I. Introduction
What Are Indicators and Why Do We Need Them?

Indicators systematize knowledge and support consistent comparisons

Indicator structure:

- Indicators consist of a numerator and a denominator and defining and quantifying these components is critical to their goals. Examples (Stern and Feinberg, eds. 1996: 50):
  - Numerators: death, injury, loss of life expectancy, physical destruction, economic and social damages
  - Denominators: per capita, per GDP, per facility, per level of exposure, per level of concentration of a harmful substance

- Indicator outcomes can vary depending on what is measured and how, e.g.,
  - Parameter selection
  - Numerical scales used for parameters
  - Spatial scale of the data
  - Quantitative formulations used to combine indicators
  - Assumptions behind each of these data elements
Sensitivity of Outcomes to Indicator Structure: Numerator/Denominator Issues

Numerator/denominator selection

- Indicators must have both numerators and denominators, that is, a specific measure, metric or value should be expressed relative to something else.

- Example of how denominator selection can affect results: Evaluating and Interpreting Trends in Accidental Deaths from Coal Mining, U.S. 1950-1970
  - Per ton of coal mined (million tons) shows a declining trend
  - Per employee in coal mining (thousand employees) shows a generally increasing trend

Sensitivity of Outcomes to Indicator Structure: Other Structural Characteristics

- “Green” calculators provide instructive lessons for climate-related infrastructure indicators, e.g., Walkscore, Global Footprint Network, U.S. EPA “Household Emissions”, NYS MTA “Transit Effect”)

- Results are sensitive to factors included in the calculator – they are pre-selected, i.e., the user doesn’t choose

- Results can be sensitive to the scale structure (ordinal, interval) and number of divisions, and such metric structures may not reflect the degree of precision of the measurements

- Weighting systems provide some adjustment for linearity but introduce some of their own biases

- Results usually reflect “expressed preferences” which may not correspond to actual behavior

- Calculators vary in the degree of detail about climate and its impacts

Indicators versus Indexes

- Indexes are distinct from indicators, in that they are aggregates of some property, often expressed as aggregates of indicators. As in the case of indicators, they are expressed as a scale or set of ordered values, but not usually possessing numerators or denominators.

- Different indexes can produce vastly different results depending upon how they are aggregated and use weighting factors. Bakkensen et al (2017) compared five indexes and identified variations in the conclusions, since they used different data, scales and geographic units for similar measures.

II. Application of Indicators to Infrastructure: Single Infrastructures

• Traditional infrastructure indicators generally do not take into account interdependencies and or climate and extreme event related factors directly, but could

• Infrastructure indicators rarely explicitly connect infrastructure physical characteristics to social preferences and needs including environmental justice
1. Indicator of Impervious Surfaces (Roads)
Land Consumption by Roads in Selected Countries, per capita, 2010

Road Kilometers per 1,000 Persons

China, Japan, France, Germany, United Kingdom, Canada, Mexico, United States

Source: U.S. Department of Transportation, Federal Highway Administration (FHWA) (October 2010) Highway Statistics 2009 Road System Measures for Selected Countries (Metrics), Table IN-3
2. Indicators of Road Congestion: Level of Service

3. Indicators of Transit Performance (Used by Provider)

User delay-related measures:
- Mean distance between breakdowns
- Number of miles between emergency calls
- Vehicle age (years) over expected lifetime
- Maintenance expenditures
- Monthly Ridership
- Weekday 24-hour On-Time Performance
- Wait Assessment
- Enroute Schedule Adherence

User safety-related measures:
- Customer Accident Injury Rate
- Miscellaneous services, e.g., elevators

Source: MTA Web Site http://web.mta.info/developers/performance.html
Example of Trends for a Traditional Indicator of Transit Performance:
Mean Distance Between Failures, NYC Transit, 2006 and 2007

Interpretation: the smaller the distance, the worse the performance.

From August 2013 to August 2014, MDBF increased from 129,081 to 143,592.


“Subway Mean Distance Between Failure (MDBF) is the measure of subway car fleet reliability and is calculated as revenue car miles divided by the number of delay incidents attributed to car related causes.”

Source: http://www.mta.info/mta/ind-perform/month/nyct-s-mdbf.htm. MDBF: “Average number of miles a subway car travels in service before a mechanical failure that makes the train arrive at its final destination later than 5 minutes”
4. Challenges of Indicator-Based Measures of Equity: Social Benefits of Transit in terms of Transit Accessibility and Employment

Brookings Institution:

- Access of workers to transit to commute to work and the quality of the commute (time and cost) varies geographically.
- In the 100 largest metropolitan areas, 70 percent of working age residents have access to transit.
- Access is much greater in the large cities of the far west and northeast.

Example of Equity Considerations: Subway and Bus Connectivity by Income (Low-Income Areas), Queens and Brooklyn, NY

III. Introducing Infrastructure Dependencies and Interdependencies: Definitions

Definitions [1]
• A dependency is activity in one direction: a flow of people, information, commodities from one point to another
• An interdependency is a flow of at least two ways

Types of interdependencies
Interdependencies can occur in a number of different forms [1]:
• Functional
• Spatial (proximity)
• Cyber
• Logical

Importance of Interconnections

The broadest construction of interconnections: Social-Environmental-Technological/Infrastructural (SETs)

Source: Arizona State University lead—Urban Resilience to Extreme Weather Related Events Sustainability Research Network (UREx SRN)
Importance of Interconnections Among Infrastructure Systems for Indicator Construction

• Infrastructure interconnections provide an important foundation and challenge for indicators.

• Component level indicators, e.g. at the level of infrastructure material and design impairments from non-weather and climate incidents can be scaled to climate-related effects.
Lifeline Interdependencies: Electricity Focus

Lifeline Interdependencies: Water Focus

### Generic Infrastructure Interdependencies

<table>
<thead>
<tr>
<th>Sector Receiving the Service</th>
<th>Sector Generating or Providing the Service to Another (Receiving) Sector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy: Oil &amp; Gas</td>
<td>Fuel to operate power plant motors and generators</td>
</tr>
<tr>
<td>Energy: Electricity</td>
<td>Fuel to operate transport vehicles</td>
</tr>
<tr>
<td>Transportation</td>
<td>Fuel to operate pumps and treatment</td>
</tr>
<tr>
<td>Water</td>
<td>Fuel to maintain temperatures for equipment; fuel for backup power</td>
</tr>
</tbody>
</table>

**Energy: Oil & Gas**
- Fuel to operate power plant motors and generators
- Fuel to operate transport vehicles
- Fuel to operate pumps and treatment
- Fuel to maintain temperatures for equipment; fuel for backup power

**Energy: Electricity**
- Electricity for extraction and transport (pumps, generators)
- Power for overhead transit lines
- Electric power to operate pumps and treatment
- Energy to run cell towers and other transmission equipment

**Transportation**
- Delivery of supplies and workers
- Delivery of supplies and workers
- Delivery of supplies and workers
- Delivery of supplies and workers

**Water**
- Production water
- Cooling and production water
- Water for vehicular operation; cleaning
- Water for equipment and cleaning

**Communication**
- Breakage and leak detection and remote control of operations
- Detection and maintenance of operations and electric transmission
- Identification and location of disabled vehicles, rails, roads; the provision of user service information
- Detection and control of water supply and quality

**Sources:** From R. Zimmerman and C.E. Restrepo. 2009. Analyzing Cascading Effects within Infrastructure Sectors for Consequence Reduction. Proceedings of the HST 2009 IEEE Conference on Technologies for Homeland Security, Waltham, MA, Table 1, p. 166; pp. 165-170. DOI: 10.1109/THS.2009.5168029. Note: exchanges or interconnections within each sector (box) also occur, but are not shown here.

Note: These examples are illustrative and not intended to be comprehensive.
Electric Power and Transit Interconnections: Illustrative Cases

- **2003 northeast U.S. and Canada blackout**: Transit rail (electrified) took about 1.3 times and traffic signals 2.6 times as long to be restored relative to electric power restoration. Data also available for water systems.*

- **The Metro-North railway outage**: Large power line impairment affected transit > a week.**

- **September 29, 2011 Lightening Strike on a LIRR Computer**:*** Highly centralized network (most trains go through Jamaica station), high volume of traffic (81 million annually), few rail alternative; Multiple failures at the same time increased consequences dramatically - lightening strike disables trains west of Jamaica, programming error, third rail shut, 17 stranded trains, 9 standing trains. Opportunities for Intervention: More communication, computer training, securing facilities from natural hazards, travel alternatives

- **Transformer explosions impairing transit**: July 29, 2001 (NYC); power outages caused closures of San Francisco Bay Area and Chicago transit lines.****

- **Blackouts and intermittent power disruptions affect transit operations dependent upon power through third rail and catenary structures. Over a dozen occurred in NYC in 2017-2018**

Sources:
*** Metropolitan Transportation Authority (MTA) (October 2011), ‘Preliminary review September 29, 2011 lightning strike at Jamaica’, New York, NY, USA: MTA.
Bridge Collapses

• About a couple of dozen bridges have collapsed in the U.S. since the mid-1960s
• Age alone does not explain why bridges collapsed
• Bridges that have collapsed have generally been younger in age than the overall bridges in the U.S. even though bridge condition generally declines with age (National Bridge Inventory)

Why?

• A combination of causes related to interdependencies usually contributes to bridge collapses, including drainage failures (water management interconnection)
• Non-redundant design, common in the mid-20th century can contribute to the severity of consequences of bridge collapses from susceptibility to water interdependencies
• Environmental conditions, including weather, can also be contributing factors

Interdependent Infrastructure Indicators: Transportation and Water Infrastructure
Schoharie Bridge, NYS Thruway I-90 Collapse, near Amsterdam, NY

• Background
  • April 5, 1987: One of the piers of New York Thruway (I-90) Bridge over the Schoharie Creek, near Amsterdam, NY gave way followed by the collapse of another pier 90 minutes later, and the resulting collapse of the spans fatally injuring 10 people

• Initiated and Connected Causes and Conditions
  • Design elements did not capture population growth rates and their flooding effects
  • Supporting elements were non-redundant
  • Modifications of the distance between bridge piers during construction placed piers in the water and increased water flows between them
  • Repairs only focused on concrete pitting but not pier stability
  • Inspection and oversight procedures did not incorporate bridge scour
  • Heavy uncontrolled storm-related floodwaters stressed piers and causes collapse
  • Weather communication was insufficient to warn of dangers

• Lessons Learned: How to Intervene
  • Design to accommodate population growth estimates and their flooding impacts
  • Review and control modifications made during and after construction
  • Change inspection procedures to incorporate bridge scour (done)

Interdependent Infrastructure Indicators: Transportation and Water Infrastructure
Mianus Bridge (I-95) Collapse near Greenwich, CT

- **Background**
  - June 28, 1983. A span of the I-95 bridge collapsed over the Mianus River near Greenwich CT killing 3 people, seriously injuring 3 others.

- **Initial conditions and causes**
  - Non-redundant pin and hanger structure
  - Pin thickness not subject to professional standards
  - Maintenance deficiencies affecting the condition of steel components (e.g., painting), bridge decking, and drainage to channel water away from steel to avoid rusting
  - Examination of the condition of the pins not incorporated into inspection procedures

- **Lessons learned**
  - Design: Bigger pins, redundant support elements
  - Maintenance: Routine painting of pins to prevent rusting; ensure drainage to avoid water in contact with steel elements
  - Inspection: Inspect sub-deck elements for rusting

IV. Introducing Climate-Related Factors
Electric Power and Transportation Interconnections: Effects of Heat

• Trains that rely upon overhead power lines through pantograph /catenary connections, are affected when the lines sag from overheating and the connections become tangled in the lines.

• Hodges (2011: 23) noted incidents of this for NJ Transit, LA Metro, and TriMet.

Example of catenary and pantograph interconnections with electric power lines
Source: Northeast Corridor Commissions (NEC)
http://www.nec-commission.com/cin_projects/catenary-power-supply-systems/
Infrastructure Disruptions from Extreme Weather: Electric Power

• Electric power outages: Simonoff, Restrepo and Zimmerman (2007)* analyzed electric power outages in the U.S. and Canada from 1994-2004 (a total of 396 and 97 in each country respectively) and found that:
  – Weather accounted for almost half of the outages in the U.S. and a third in Canada (p. 549)
  – Weather-related outages last longer than those caused by equipment failure (p. 558, 560, 562)
  – Weather is increasing over time since mid-1990s as a factor contributing to outages (p. 562)

• Similar analyses have been conducted for the effects of weather on other types of infrastructure, e.g. pipelines, where individual events are aggregated into large datasets

Case-based Recovery Rates Reflecting Interconnections: Illustrations for Hurricane Sandy

• **Transportation (Transit):** Full and Partial Restoration of New York City Subway Lines due to both electric power outages and failures of water infrastructure for drainage, 10/28/12-11/12/12
  – October 28, 2012 - impact: Pre-emptive shut down of transit
  – November 9, 2012 – partial restoration: Approximately 80% of subway lines were operating normally and 20% were partially operating (segments)

• **Electric Power:** Customers Lost as a Percentage of Customers Served and Customers Out (Cumulative) NYC Total and by Borough, October 29-November 7, 2012
  – October 29-31, 2012 - impact: Citywide, 20% of total customers served were without power, ranging from 8% in Brooklyn to 63% in Staten Island
  – November 3, 2012 – partial recovery: Power was restored to almost half of customers who lost power citywide, ranging from 88% in Manhattan to a third in the Bronx

Source: R. Zimmerman, RAPID/Collaborative Research: Collection of Perishable Hurricane Sandy Data on Weather-Related Damage to Urban Power and Transit Infrastructure,” National Science Foundation, the U. of Washington (lead), Louisiana State University, and New York University. Electric power findings calculated from Con Edison news releases.; Transit findings are computed from selected NYC Transit data.

Recovery of Transit and Electric Power (Comparison) Post-Hurricane Sandy (Interdependent Infrastructures)

- Two weeks after Hurricane Sandy, about 80% of the transit lines were fully recovered and others were partially recovered along their routes.
- In 2012 after Hurricane Sandy compared to a similar period in 2011, system ridership declined on average about 14%.

Electric power recovery followed patterns similar to transit.

Transit required electric power to function for third rails, signals, switches, ventilation, lighting, and to pump out excess water; energy required robust transit infrastructure for physical support and to transport workers to repair sites.

**Figure 10. Duration of Refinery Shut Downs during 2005 and 2008 Hurricanes**

**Figure 2. Electricity Customer Outages from 2005 and 2008 Hurricanes**

**Figure 5. Comparison of Power Outage Restoration Percentages by Storm**

**Figure 6. Comparison of Power Outage Restoration Percentages by Storm**

**GUSTAV, IKE, KATRINA, RITA, WILMA**
http://www.oe.netl.doe.gov/docs/HurricaneComp0508r2.pdf

**IRENE, SANDY**
Resiliency as the Ability to Recover Electric Power Connections to Transportation and Water, U.S. Canada 2003 Blackout

Electric Power Outages: Outage Durations, August 2003, approximately 42-72 hours

<table>
<thead>
<tr>
<th></th>
<th>T(i)/T(e)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electric - Transportation</strong></td>
<td></td>
</tr>
<tr>
<td>Transit-electrified Signals (NYC)</td>
<td>1.3</td>
</tr>
<tr>
<td>Traffic Signals (NYC)</td>
<td>2.6</td>
</tr>
<tr>
<td><strong>Electric - Water</strong></td>
<td></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>

Effect of water distribution lines on other infrastructure or “Effect Ratios”

<table>
<thead>
<tr>
<th>Type of Infrastructure</th>
<th># of Times Infrastructure (Column 1) Caused Failure of Other Infrastructure</th>
<th># of Times Infrastructure (Column 1) was Affected by Other Infrastructure Failures</th>
<th>Ratio of Causing vs. Affected by Failure (Col. 2 divided by Col. 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water mains</td>
<td>34</td>
<td>10</td>
<td>3.4</td>
</tr>
<tr>
<td>Roads</td>
<td>25</td>
<td>18</td>
<td>1.4</td>
</tr>
<tr>
<td>Gas lines</td>
<td>19</td>
<td>36</td>
<td>0.5</td>
</tr>
<tr>
<td>Electric Lines</td>
<td>12</td>
<td>14</td>
<td>0.9</td>
</tr>
<tr>
<td>Cyber/ Fiber Optic/ Telephone</td>
<td>8</td>
<td>15</td>
<td>0.5</td>
</tr>
<tr>
<td>Sewers/ sewage treatment</td>
<td>8</td>
<td>6</td>
<td>1.3</td>
</tr>
</tbody>
</table>

V. Recommendations and Conclusions for Climate-Based Infrastructure Indicators, NYC Panel on Climate Change, 2019

- Indicators were developed in two infrastructure categories – transportation and energy – and also for interdependencies:
  - Transportation and energy indicators were primarily expressed as the “number, frequency, duration, and geographic extent” of disruptions and ultimate the cost of the delays
  - Interdependencies were likelihood and severity of the combinations and connections on infrastructure services
- It is difficult to separate out climate from non-climate factors affecting infrastructure
- Tracking of indicators is critical over time and space
- Financial indicators were addressed
  - Credit ratings were considered useful indicators
  - Climate seems to have a small effect on New York City’s ratings
- Co-generated indicators are an important component of indicator development, to obtain stakeholder input, necessary not only for inclusiveness and equity, but also for the viability of implementation

Observations and Conclusions

- Indicators are critical to systematic knowledge about the state of infrastructure and the impact of climate change.
- Many existing indicators and indexes have not taken climate change into account directly with respect to its effects on all of the components and dimensions infrastructure and its services, though individual research is making great strides and suggesting alternatives.
- Given the considerable attention to infrastructure indicators at a broad or global level it is now time to do a deep dive into the details of how infrastructure materials and design play out with environmental factors.
- Fine-grained information is needed at the level not only of physical materials and design but also how users are affected by them.
- Climate change consequences are linked to one another, for example, sea level rise, heat, and indicators need to reflect those connections.

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