Cornell's Urban Sustainability Initiatives

ACSF Lunch Summary

Compiled by Marianne Krasny (NTRES), Helene Dillard (CCE), and Marvin Pritts (Hort)

Goals and Summary

The goal of the topical lunch was to outline steps that Cornell could take to define an urban sustainability initiative in collaboration with ACSF. In particular, we focused on multiple mechanisms for facilitating urban research, teaching, and outreach that are complementary to, but cover areas not necessarily included in, the NYC Tech Campus. While recognizing the unique value of the Tech Campus, it is apparent that Cornell urban programs are more comprehensive than what the Tech Campus now encompasses. At the same time, given global demographics and those of our student body, it is important for Cornell to more broadly address urban sustainability issues. Our initiative dovetails with concerns Cornell University and Cornell Cooperative Extension have about addressing diversity among students, program audiences and participants, and staff. A possible outcome of this lunch is work toward focusing Cornell's cross-college capacity in urban and diversity issues for larger impact.

Twenty-eight faculty and extension and academic staff attended the 21 March 2013, ACSF Urban Sustainability Initiatives lunch. After introductions of participants, Josh Cerra (Landscape Architecture) gave an overview of Cornell's Urban Landscape Group, which is working with the NY Tech Campus to develop a living research and learning lab (plan attached to report), and has created the Urban Eden Cornell campus program to apply and test principles of landscape sustainability. ACSF Director Frank DiSalvo mentioned ongoing multiple efforts related to sustainable communities, which might overlap with a potential urban sustainability initiative. Susan Riha (EAS), Jonathan Russell-Anelli (CSS), Ruth Richardson (CEE), and others talked about the potential for "re-envisioning the urban infrastructure of the future," including water, waste, energy, food/soils, and transportation systems, and Josh Cerra presented the landscape architecture view of cities as integrative systems. Also along the topic of infrastructure, Rich Geddes (PAM), Tim Mount (AEM), Stephan Schmidt (CRP), and others spoke about issues of financial investment, as well as innovative financial models for water and other infrastructure. David Cutter (Campus Planning) spoke to the university's interest in value-added campus infrastructure. Finally, Kieran Donaghy mentioned a chapter he wrote entitled *Managing Change in Urban Infrastructure Systems*, which is attached to this report.

We were privileged to have two county-based Cornell Cooperative Extension Executive Directors as participants, including David Skeval from Onondaga County, who shared a grassroots initiative to address urban forestry and water run-off (Save the Rain), and Ron Bunce from Oneida County, who spoke about sustainability initiatives conducted in cooperation with Landscape Architecture in the ethnically diverse communities of Utica NY (Rust 2 Green). Kathy Bunting-Howarth (SeaGrant) spoke of an emerging research/extension effort to address multiple destructive events in NYC and its environs. David Kay (CARDI) talked about the importance of considering the urban-rural interface and Tom Whitlow spoke to the trans-disciplinary and trans-spatial issues involved in addressing urban agriculture and other urban sustainability issues.

Overall the group expressed interest in collaboration with the NYC Tech Campus as well as enthusiasm for forming parallel initiatives that capture, grow, and apply Cornell's cross-department and cross-college urban sustainability expertise and commitments.

Follow up Recommendations

White paper. ACSF is open to requests to support teams that lay out a white paper on sustainability issues. Given the cross-college interest in urban infrastructure issues, we should consider identifying a leader or co-leaders for such a team.

Cluster hires. ACSF is open to proposals for cluster hires. A cluster hire in urban sustainability could be coordinated across multiple departments and colleges, to address the technical and socio-economic perspectives on urban sustainability or urban infrastructure more specifically, using a whole or integrated systems approach.

NY Tech Campus theme. Approach the NY Tech Campus about adding a new theme focused on infrastructure.

Development. Market a Cornell urban sustainability initiative for NYC donors who have been contacting Cornell and CCE about such issues as food production through green roofs.

Next steps. We propose forming a smaller leadership team to push these and possibly other efforts forward. Suggestions for membership welcomed.

Attendees

Organizers

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Dillard	Helene	hrd1	CCE	
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Participant RSVP (attending)

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Cerra	Josh	jfc299	LANAR	
Chambliss	Lauren	elc55	ACSF	
Chen	Xi	xc62	DNR	
Cutter	David	dmc86	Campus Planning	
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DiSalvo	Frank	fjd3	ACSF	
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Mount	Timothy	tdm2	AEM	
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Richardson	Ruth	rer26	CEE	
Russell-Anelli	Jonathan	jmr5	CSS	
Schmidt	Stephan	sjs96	CRP	
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Appendix I. *Research Ideas from Cornell Faculty for the Roosevelt Island Landscape* (Nina Bassuk et al)

Appendix II. *Managing Change in Urban Infrastructure Systems* (Kieran Donaghy)

Research Ideas From Cornell Faculty For The Roosevelt Island Landscape

Faculty from Cornell's College of Agriculture and Life Sciences who have been working together for several months have a strong interest in developing the NYC Tech campus as a learning landscape that demonstrates, measures and improves landscape ecosystem services.

Vision

The Cornell NYC Tech campus as a whole will be a locus of progressive education, research, and technology transfer. The landscape that surrounds the proposed buildings should reflect and contribute to this aim by demonstrating ecosystem benefits generated by landscape elements such as enhanced hydrologic functions, healthy soils and vegetation, and human health and well-being. However, sustainable landscape design in an academic setting should go beyond demonstration. Just as we build landscapes on Cornell's Ithaca campus to teach sustainable development and long-term management, the NYC Tech campus should do the same to engage students, landscape professionals and the public in sustainable landscape design. The NYC Tech landscape should be an opportunity to showcase research, teaching, and implementation of the most cost effective, cutting-edge technologies and best practices that support sustainable design.
It is the our intention that research results will inform the final landscape design of the NYC Tech campus and that this design will be accredited by the Sustainable Sites Initiative (SITES).

We envision that this research will occupy approximately 5 acres on the south end of the site (Phase 1b) with 5 general areas of interest:

1. Soil remediation and manufacture of blended soils

2. Preservation of existing quality trees

3. Enhanced stormwater capture and improved water quality.

4. Testing trees, shrubs and ground covers for adaptation to site conditions and climate change

5. Provision of compatible habitat for birds and pollinators.

Because there is a long trajectory to the development of the site and until we have healthy soils we cannot grow plants on the site or enhance hydrological function, we envision that soil health and remediation will necessarily be our first project.

1.Soil

The entire NYC Tech campus landscape is dependent on a functioning healthy soil. Currently, it is proposed to import a large volume of topsoil equivalent to 2 feet to cap the site after building demolition. Our first objective would be to explore stockpiling existing healthy soil on site and remediating the 'fill' soil later if possible. The first step would be to test the existing soil using the Cornell Soil Health Test protocol as a baseline and the 'fill' soil again after building demolition. Should the fill soil be suitable for amendment, it could be screened and amended with compost and/or sand to various proportions that would conform to the landscape functions (e.g. compaction resistance, improved water holding capacity and water infiltration, nutrient retention, etc.). This could be done on site. Short-term cover crops might be utilized to reduce erosion and improve the organic matter and nutrient availability of the soil. The various soil blends would be tested for their ability to sustain vegetation and hydrologic function/water quality and human use with and without irrigation. This will save the project considerable funds.

2. Preserving existing trees

From an inventory done on site, we know there are 115 trees. Many of these trees are Pin Oaks and some are exceptionally large, in excess of 30" diameter breast height. Although some of these trees will need to be removed to make way for construction, the period of construction is up to 30 years allowing for the preservation of trees. In addition, it may be possible to save many trees using techniques that partially excavate root systems and backfill with load-bearing structural soil so that the roots may be preserved. This would be an important large-scale test of techniques that could be used to save important trees on construction sites.

3.Hydrologic functions.

State regulations require that stormwater be retained on site. There are many possible stormwater techniques and research questions that could be investigated at the NYC Tech campus. For example, there is a concern about potential saltwater contamination. We could investigate how designed stormwater runoff infiltration (via bioswales, rain gardens, etc.) can contribute to maintaining elevated water tables and hydraulic head gradients to reduce saltwater intrusion and to improve water quality. Reduced hydraulic heads due to stormwater routing is a key issue in coastal habitats. The site dimensions relative to the river edges makes the site ideal for this question and the research space/ equipment needs would be minimal -- basically a network of 3-4, small diameter groundwater wells with water monitoring access and instrumented with electronic pressure gauges and sampling of typical water contaminates. In addition, porous pavements with and without structural soil underneath could capture precipitation and stormwater runoff to replenish the water table, improve water quality and provide a medium for growing trees. These trees could assist with stormwater capture and cool the pavement, thus reducing urban heat island effect and promoting human health and well-being.

4.Testing trees, shrubs and ground covers for adaptation to site conditions and as a bioassay for climate change.

The microclimate of an island in the middle of the East River may provide conditions that mirror climate change. The diversity of existing tree species on site is very limited, but many species might grow very well under these conditions. By testing numerous species we could contribute to vegetation biodiversity on the site while providing guidelines for those trees that would meet design intentions. Successful test trees could be grown in the soil and then transplanted into the designed campus areas. Additionally, low maintenance turf and turf substitutes will be tested for use on site. For sites with traffic tolerance needs and for general lawn use, traditional low maintenance cool-season turfgrass species (*Festuca spp.*) with varying water use characteristics will be evaluated for storm water reduction (instrumented with simple runoff collectors) and for carbon/nitrogen sequestration. Non-traditional warm-season grass species will be evaluated for climate change adaptation.

5. Compatible habitat for birds and pollinators.

Urban ecosystems play important roles in sustainable development of cities. How bird species use urban ecosystems, particularly in cities like NYC that exist along major migration corridors like the Atlantic Flyway, is an active topic of urban ecological research. In partial association with testing of vegetation in (4) above, applied research at NYC tech campus could investigate which plant species and habitat features, and their bird-safe placement, can best provide avian habitat support, and be compatible with both 1) the existing and future site conditions on Roosevelt Island; and 2) the desired functional, programmatic and aesthetic features that are planned for the NYC tech campus. Similar investigations into pollinator support and compatibility with the design program for NYC Tech campus could also be made. Implementation of landscape research outcomes and guidelines could provide additional project benefit with potentially little inherent project cost.

Public education

Public access would be accommodated at all research sites. There is a central spine that runs the length of Phase Ib to accommodate visitors and researchers alike. Along the first section of this pathway, a series of botanical garden beds that would flank both sides could be developed with each bed dedicated to some aspect of changing technology or the environment. Further, this would be a dynamic garden, in which particular collections and/or their interpretation will change as the campus is built and new research emphases evolve.

For example, among the themes that could be portrayed in the garden beds are:

- An explanation of research on site;
- How the changing climate is altering the patterns of native plants;
- How biotechnology is being used to create new plant forms;
- How plants are being used to address world food and energy needs;
- How changing phenology (dates of flowering) is affecting plant/pollinator relationships.

Advantages of having the botanical beds be the first section visitors would experience in Phase Ib are: that they would be highly attractive and therefore inviting to the public; they would signal to visitors that this is a section of the campus landscape based on researchable concepts; and they would foster a respect for how the land should be treated and respected.

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CHAPTER 4

MANAGING CHANGE IN URBAN INFRASTRUCTURE SYSTEMS

KIERAN P. DONAGHY

INTRODUCTION

The spatial agglomerations we call cities would be inconceivable without infrastructure systems. Streets, bridges, harbor facilities, transit systems, water and sewe systems, (more recently) systems of electrical power generation and distribution and communications systems are what make safe, sanitary, and productive urba living possible. Indeed, it is the quality of urban infrastructure systems that is ofte used to evaluate the quality of urban living conditions. Infrastructure systems ar widely acknowledged to have influenced the evolution of urban spatial structur (Anas, Arnott, and Small 1998). And now that most of the world's population reside in urban areas and most economic activity occurs in such areas, one can reasonabl infer that urban infrastructure systems are absolutely critical to the continuatio and improvement of social and economic life the world over (Grimond 2007).

Interurban infrastructure systems also make possible commerce, travel, th sharing of resources (e.g., electrical power and information), and collaboratio between residents of far-flung cities. Improvements in technologies embedded i transport infrastructure systems and communications systems in particular hav contributed to such developments as the fragmentation of production processes the lengthening of supply chains, and globalization, which has significantly increase the interdependence of cities (Castells 2000; Jones and Kierzkowski 2001). We ma view city systems as networks of flows supported by urban infrastructure systems (Donaghy 2009b).

The history of cities has also been the history of decay and reconstruction of infrastructure systems. One can see in the archaeological crypts of Paris, Rome, and other ancient cities how parts of old walls and aqueducts of one age have been incorporated into building projects of the next through adaptive reuse.

At the time of this book's writing, much of the urban infrastructure built within the last century has reached the end of its service life. The American Society of Civil Engineers estimates that nearly 30 percent of the bridges in the United States are structurally deficient or functionally obsolete (ASCE, 2009b). The number of unsafe dams has increased by nearly 33 percent, and funding for public transit facilities, drinking water, and wastewater management is deemed to be grossly inadequate.[1] A similar state of affairs confronts many European and Asian countries (see Estache 2004; Jones 2006; Katz, Puentes, and Geissler 2009; Timmins 2010).

According to *Cohen and Steers's Global Infrastructure Report 2009*, cited by Timmins, the world is poised (or needs) to undertake $40 trillion in both new and sustaining infrastructural investment over the twenty-five-year period of 2005–2030, most of which will be in or around cities (table 4.1).

At points in history such as this, societies have been confronted with choices to make regarding the lumpy, long-lived investments that infrastructure systems represent. Do they rebuild for a past period, reimposing or preserving old constraints on land uses and activity patterns, or do they seize the opportunity to develop new infrastructure systems, embodying new technologies and possibilities (see, e.g., Crooks 2009; Cookson 2010)? Perhaps they embrace a combination of the two. Presently, it would appear that many U.S. cities cannot afford to rebuild or even maintain basic infrastructure systems—Detroit and Cleveland, for example—and must develop *triage* strategies to determine which infrastructure systems to salvage and which to abandon.

Table 4.1 Projected Infrastructure by Region and Sector in $Trillion, 2005–2030

	North America	Latin America	Europe	Africa	Middle East	Asia Pacific	Total
Water	3.62	4.97	4.52	0.23	0.23	9.04	22.61
Electricity	1.53	1.44	1.08	0.54	0.18	4.23	9.00
Road and rail	0.94	1.01	3.12	0.31	0.31	2.11	7.80
Air and seaport	0.43	0.06	0.43	0.02	0.14	0.51	1.59
Total	6.52	7.48	9.15	1.10	0.86	15.89	41.00

Source: Cohen and Steers Global Infrastructure Report 2009: The $40 Trillion Challenge.

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[1] See also the President's Commission on Critical Infrastructure Protection (1997) and Rinaldi, Peerenboom, and Kelly (2001).

The present situation is more complicated still not only because of the interdependence of the infrastructure systems and the interdependence of cities but also because of the need to use infrastructure investments to transition to more sustainable lifestyles and, some would argue, to rebuild industries in decline (Nagurney 2002; Rotmans 2006; Donaghy 2007; Katz, Puentes, and Geissler 2009).[2]

As remarked upon in this volume's introduction, the analyses solicited for this book were intended to be problem-driven but theoretically informed. One can characterize the overarching problem with which *planning in the public sphere* (at least) is concerned, as managing change in territorial systems (Friedmann 1987). The specific problem with which this chapter is concerned is *how to manage changes in interdependent infrastructure-based networked systems*—or urban infrastructure systems, for short.

As infrastructure planners and other interested parties confront the reality described here, they will surely ask themselves the following questions, with some of which urban economics may be of assistance:

- Just what is infrastructure, and what are its essential properties?
- What counts as a properly functioning urban infrastructure system (or system of infrastructure systems)?
- What interdependent decisions are associated with managing changes in urban infrastructure systems?
- What theoretical and methodological resources are available for supporting such decisions?
- How can changes in urban infrastructure systems be financed, and are there other relevant policy considerations?
- Where is research on the management of urban infrastructure systems needed?

The remaining sections of this chapter will address these questions.

WHAT IS INFRASTRUCTURE, AND WHAT ARE ITS ESSENTIAL PROPERTIES?

Most basically, infrastructure includes capital investments in communications, energy supply, and transportation. Transportation infrastructure may be broken down further into the categories of roads, rail, waterways, airports, seaports, and

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[2] There is a well-developed literature on the impact of infrastructure investments, especially in transportation, on economic development. Much recent analysis has focused on experience with regional policy in the European Union. See in particular Vickerman (1995), Puga (2002), Knapp and Oosterhaven (2004), and Venables (2004). See Wright (2009) and *The Economist* (2010) on current aspirations for high-speed rail investment-led growth.

pipelines. More generously construed, we might take infrastructure to also comprise capital investments pertaining to water management, environmental management, education, health service provision, sports and tourist facilities, social infrastructure, cultural facilities, and natural endowments.[3] Infrastructure *systems* include both the fixed assets and the control system and software of buildings and other facilities, transportation infrastructure, telecommunications networks, the power grid, and environmental systems.

Infrastructure is often seen to have a *public good* character (when it is nonexcludable and nonrival); a public park and a public radio station are often used as examples to illustrate what a public good is. Yet, as Bröcker and Rietveld (2009) point out, "Important parts of what is considered infrastructure... involve services that are excludable (users can be forced to pay for services that they consume). Thus, in a strict sense, only a small part of what is commonly understood by infrastructure really is a public good" (153). These authors favor the use of the term *collective good*.

Infrastructure may also be viewed as capital that is publicly provided or in whose provision the public sector plays a large role. But Bröcker and Rietveld remark that the role played by the public sector varies among countries and that the overlap between infrastructure and publicly provided capital would appear to be decreasing.

Infrastructure can be measured in physical and in value terms. Apart from difficulties that measurement in value terms presents, Bröcker and Rietveld suggest that physical measures make more sense "in that they provide a natural starting point for the measurement of infrastructure services [e.g., vehicle miles traveled], which are the result of combining the infrastructure stock with other forms of capital [vehicles]. Further, the concept of accessibility, being an indicator of the potential of interaction provided by an infrastructure network linking nodes with different features, may be considered as an indicator of potential services generated" (155).[4]

Measuring the impact of infrastructure systems on economic development has recently come to occupy the attention of many economists and econometricians (Blum 1982; Aschauer 1989; Gramlich 1994; Martin and Rogers 1995; Seitz 1995; Townroe and Dabinett 1995; Rietveld and Bruinsma 1998; Bröcker 2002; Bröcker and Rietveld 2009). Producing conclusions that meet with wide agreement is fraught with difficulty in terms of measuring the infrastructure itself, adopting a time frame of appropriate length, and capturing endogenous changes in trade and spatial agglomerations that ensue from the investments.

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[3] According to the *American Heritage Dictionary of the English Language*, 4th ed. (2000), the term *infrastructure* has been used since 1927 to refer collectively to the roads, bridges, rail lines, and similar public works that are required for an industrial economy, or portions of it, to function.

[4] Bröcker and Rietveld (2009) provide a nice discussion of difficulties in measuring the value of infrastructure. They note that the "quality of infrastructure services measured in terms of indicators like spread, reliability, availability, and safety" is a "theme with considerable scientific merit" (155).

WHAT COUNTS AS A PROPERLY FUNCTIONING URBAN INFRASTRUCTURE SYSTEM (OR SYSTEM OF INFRASTRUCTURE SYSTEMS)?

Since infrastructure systems are usually instrumental to achieving some objective outside of a system itself, we need overall systems performance criteria and other external criteria to evaluate them. Among systems criteria, we might include reliability, unit/cost performance or other efficiency measures, and compatibility with other systems. We might consider any of the following to be candidate objectives that infrastructure systems are instrumental in achieving: social welfare (taken as an aggregate measure of fully informed willingness to pay by members of society), some measure of development or economic performance (volume of commerce), some measure of equitable distribution (accessibility), or systems properties—diversity, resilience, and sustainability.

Some considerations of functionality come together in the matter of *optimal provision* of infrastructure.[5] Consider the example of a single road given by Bröcker and Rietveld (2009). If consumer sovereignty is a reasonable assumption, whether or not the amount of infrastructure provided is optimal will depend both on the amount of installed capacity and on the intensity of its use, that is, on *both* supply and demand being attuned to the other. And since "the decision to use the capacity of this collective good is decentralized, price incentives are needed for obtaining optimal use" (165). In this example, there is a set of identical users, each of whom enjoys benefit $B(x)$ for x many trips. Measured in monetary terms, $B(x)$ is the user's willingness to pay for level of use x. Assuming demand is distributed uniformly over time, the user incurs congestion cost $c(nx, k)$ per trip, also in monetary terms. In this cost expression, n is the number of users, and k is the cost of capacity. Congestion cost is increasing in nx and decreasing in k. For a typical user, total net welfare is given by

$$W^{o}(x, k, n) := B(x) - xc(nx, k) - k/n$$

Assuming more welfare is better, then optimizing welfare with respect to all three arguments yields the following first-order necessary conditions:

$$B_x = c + nxc_{nx}, \tag{4.1}$$

$$-nxc_k = 1, \tag{4.2}$$

$$x^2 nc_{nx} = k/n. \tag{4.3}$$

Equation (4.1), which gives the condition of optimal use, implies that marginal social benefit must equal marginal social cost. Equation (4.2) gives the optimal

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[5] More complete discussions of relevant transport economics can be found in Reynolds-Feighan and Vickerman's contribution to this volume, Arnott and Kraus (2003), and Small (1996).

investment rule, which indicates that optimal capacity occurs when the marginal cost of capacity offsets the joint marginal congestion cost saving. Equation (4.3) specifies the optimal membership condition, which indicates that the average cost per club member must equal the marginal congestion cost of an additional member. These three conditions jointly define an optimal club from the perspective of members of the club.

Appealing to Buchanan's (1965) *theory of clubs*, Bröcker and Rietveld observe that the state of affairs characterized by equations (4.1) through (4.3) will also be optimal for society as a whole if the entire population N can be partitioned into groups (or clubs) of size n^* without remainder, where n^* is the optimal number of members. In terms of this example, N/n^* is both the number of clubs and the number of parallel road links. If the population cannot be partitioned into clubs of size n^* without remainder, the within-club and societal viewpoints will differ to the extent society cares about people unserved by clubs.

In discussing this example further, Bröcker and Rietveld demonstrate that under the given assumptions, an optimal road will always be self-financing, provided users pay a fee for each trip that covers the amount of the externality, nxc_{nx}.[6] Bröcker and Rietveld consider implications of this example for private provision of infrastructures and conclude that, while there will be increasing opportunities for private provision under low exclusion cost, public provision is likely to dominate for decades.

Focusing on the marginal changes in value of the capital invested in an infrastructure system alone fails to capture qualitative changes in the nature of infrastructure services, for example, supplying a missing link in a transportation network. Another criterion that might be appealed to in planning investments in urban infrastructure systems, and which features considerations of social equity more prominently, is that of network accessibility.

Forslund and Johansson (1995) use an accessibility concept to represent the network properties of transport networks. Citing their work, Bröcker and Rietveld (2009) write: "A typical indicator for accessibility . . . would be

$$Acc_r = \log \sum\nolimits_s \exp\{V_{rs}\} = \log \sum\nolimits_s \exp\{a \cdot x_s - b \cdot c_{rs}\}, \tag{4.4}$$

where x and c are as defined above. This formulation defines the accessibility of region r as the log sum of utilities of interaction with all other regions s. These utilities depend on the relative qualities of the other regions x_r and on c_{rs}, the interaction costs between r and s, broadly defined. . . . Note that the accessibility concept enables the researcher to incorporate the relevant aspects of network morphology" (161).

Another measure of systems performance pertaining to infrastructure networks, and one related to the notion of resilience, is *diversity*. Nijkamp and Reggiani

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[6] Generally speaking, when users pay the marginal cost to society of providing a service, the outcome is said to be "first best."

(1998) define diversity of network performance mathematically in terms of Wilson's (1971) *entropy* formulation as follows. For some network of type n, with nodes l and m connected by network links, along which flow appropriate media observed or measured as f^n_{lm}, the diversity of the network, D^n, is given by

$$D^n = -\sum_{l,m} f^n_{\mathrm{lm}} \ln\left(f^n_{\mathrm{lm}}\right).^{7} \tag{4.5}$$

This formulation allows for nesting and multilayering as in Donaghy et al. (2005).

Ulanowicz et al. (2009) provide other measures of *sustainability* and *resilience* in networks based on information theory.

WHAT INTERDEPENDENT DECISIONS ARE ASSOCIATED WITH MANAGING CHANGES IN URBAN INFRASTRUCTURE SYSTEMS?

As in most planning problems, managing changes in urban infrastructure systems will entail determining—not just once, but in a recurring fashion—*what is to be done by whom, when*, and *where*, and *by how much*. Each element of this determination is critical to an appropriate planning response (see Donaghy and Schintler 1998). Of course, given the complexity of the relationships between interdependent infrastructure-based networked systems, their jurisdictions, their controllers, and the nature of their financing, it is clear that there will be multiple agents—both public and private—facing this planning problem, that their decisions will affect each other, and that the overall infrastructure system will be a complex adaptive one that is likely to give rise to emergent outcomes that no single "network controller" will have intended (see Donaghy 2009b; Torrance 2009; and discussion of financing below). Perhaps the best we can hope to accomplish is to identify plans that are compatible within a web of overlapping plans of agents and planning jurisdictions (see Donaghy and Hopkins 2006).

Still, we will need to employ modeling tools to identify possibly compatible systems management plans, and so we will need to know what theoretical and methodological resources are available.

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[7] Donaghy et al. (2005) provide a detailed example of intertemporal decision making to promote a resilient set of interdependent networks—commodity-flow, gas, and electric. In this example the optimization problem is to determine what spatial and temporal combination of goods production and shipments, network infrastructure investments, electricity generation, natural gas purchases, and electricity and gas flows would maximize the combination of all three networks' links' performances in terms of diversity.

WHAT THEORETICAL AND METHODOLOGICAL RESOURCES ARE AVAILABLE FOR SUPPORTING SUCH DECISIONS?

When we survey the availability of theoretical and methodological resources to support the management of change in urban infrastructure systems, we may wish to avail ourselves of contributions from systems engineering, operations research, network science, and game theory, as well as urban economics.[8] Friesz, Mookherjee, and Peeta (2007) suggest that it is helpful to view infrastructure systems involved with the movement of goods, passengers, information, water, and energy as *general transportation networks*. Moreover, they argue that, to the extent such networked systems are interdependent, they should be viewed together as a *system of systems* (Sheffi 1985; Nagurney and Dong 2002).[9] The practical challenge of implementing a system of systems framework is to express the interdependencies between the infrastructure networks mathematically "so that richer and more informative models to support infrastructure network planning and design may be formulated and numerically solved" (Friesz, Mookherjee, and Peeta (2007, 56). One way to proceed is to represent infrastructure systems as multilayered networks with constraints upon how the layers are coupled. The layers can then be arranged in hierarchies reflecting their engineering and societal functions, and the resulting multilayered coupling of infrastructure networks will constitute a system of systems.

Friesz et al. remark that the performance of a system of systems "can be significantly influenced by decisions taken by individuals or groups at various levels in the subsystems" (59). Acknowledging this eventuality, modelers usually adopt a noncooperative game theoretic approach to representing interdependent strategic decision behavior.[10]

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[8] See Friesz (2007) passim. Network science, which identifies and describes recurring self-organizing behaviors in networks, is particularly appropriate because its insights are critical to designing intervention schemes—indicating what to do, when and where, and by how much—appropriate to a network controller's objectives (Barabasi 2002).

[9] Friesz, Mookherjee, and Peeta (2007) view the five main sources of interdependence between generalized transportation networks as being (1) physical interdependence, (2) budgetary interdependence (when public financing is involved), (3) market interdependence and spatial economic competition, (4) informational interdependence, and (5) environmental and congestion externalities. It should be noted that the American Society of Civil Engineers includes among its four guiding principles for the nation's critical infrastructure employment of an integrated systems approach (ASCE 2009a).

[10] Zhang, Peeta, and Friesz (2005) have investigated multilevel network games that correspond to systems of systems. In such games, decision makers associated with distinct tiers or subsystems may compete with other decision makers in their own tier and cooperate with other decision makers on tiers not their own.

If the layers of the system of infrastructure networks are viewed collectively as the means by which agents in a market economy complete their transactions, the modeling framework may be viewed as a spatial computable general equilibrium (SCGE) model. In such a model, the generalized transportation networks can be represented in fine enough detail to support engineering analyses. Such an articulation should also enable one to study the influence of specific infrastructure network features on all economic sectors at all locations through conventional comparative static methods.[11]

The equilibria computed with an SCGE model could in turn be used to construct a dynamic model of coupled infrastructure networks based on principles of disequilibrium adjustment. Friesz et al. note that such a model could allow study of "nonlinear synergies and catastrophes among infrastructure technologies that would go unnoticed so long as the traditional one-network-at-a-time paradigm is employed" (60).

Friesz et al. suggest that the basic features of an SCGE with integrated infrastructure networks, in the case of competitive markets, can be sketched as follows. Assuming all vectors and matrices are suitably dimensioned, let b denote a vector of resource endowments, d a vector of product demands, A an activity matrix of inter-industry sales coefficients, $c(u)$ a vector of unit costs of transportation, π a vector of supply prices, y a vector of output levels, h a vector of path flows, u a vector of transportation costs, an origin-destination pair incidence matrix, and an operator determining intermarket transportation demand. (Much of the underlying spatial-interaction behavior of resource allocation will described by Γ.) Then the solution of the model, SCGE$(b, d, A, c(h))$, can be defined as a nonnegative vector (π^*, y^*, h^*, u^*), such that the following constraints are satisfied.

1. *No activity in any location earns a positive profit.*

$$-A(\pi^*, u^*)^T \pi^* \geq 0.^{12} \tag{4.6}$$

2. *An activity in a location that is earning a negative profit is not operated, and an operated activity earns a zero profit.*

$$[-A(\pi^*, u^*)^T \pi^*]y^* = 0. \tag{4.7}$$

3. *No commodity produced in any location is in excess demand.*

$$b + A(\pi^*, u^*) - d(\pi^*) \geq 0. \tag{4.8}$$

4. *A commodity in excess supply is free, and a positive price implies market clearing by Walras's law.*

$$[b + A(\pi^*, u^*) - d(\pi^*)]\pi^* = 0. \tag{4.9}$$

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[11] For examples of comparative statics analyses of changes or disruptions to interdependent infrastructure-based networks, see Kim, Ham, and Boyce (2002), Sohn et al. (2003), and Ham, Kim, and Boyce (2005).

[12] The superscript T denotes transposition. So, e.g., $A(\pi^*, u^*)^T$ is the transpose of $A(\pi^*, u^*)$.

5. *Excess path costs (or costs associated with paths that are longer than necessary) are nonnegative.*

$$c(h^*) - \Lambda^T u^* \geq 0. \tag{4.10}$$

6. *Utilized paths have zero excess costs, and paths with positive excess costs are not used.*

$$[c(h^*) - \Lambda^T u^*]h^* = 0 \tag{4.11}$$

7. *Generalized transportation flows are conserved.*

$$\Lambda h^* - \Gamma[A(\pi^*, u^*)]^T y^* = 0. \tag{4.12}$$

SCGE models, such as the one sketched here, can be employed to compute an equilibrium state between spatially distinct markets in terms of steady-state flows along infrastructure networks. But for planning purposes, we would also need to be able to examine time-varying flows and other transient phenomena that are critical to the success of infrastructure and network engineering projects. Hence, we need to provide an explicit formulation of adjustment dynamics in a more encompassing modeling framework whose steady-state solutions are equilibria characterized by SCGE models. Friesz et al. suggest several approaches that may be taken in constructing equilibrium-tending infrastructure network dynamics:

- employment of a disequilibrium adjustment mechanisms according to which adjustment is some fixed proportion of the distance from a steady state; and
- employment of a disequilibrium adjustment mechanism according to which adjustment is endogenously determined by conditions modeled.[13]

If models portraying dynamics of interdependent infrastructure-based networked systems are to support life-cycle management of change in such systems—and hence the allocation of resources for their construction, operation, maintenance, and replacement—one must articulate allocative criteria. Friesz et al. suggest using the net present value of benefits.[14] As discussed earlier, other criteria might include accessibility, diversity, sustainability, resilience, or maximum entropy.

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[13] One instance of such a mechanism discussed by Friesz, Mookherjee, and Peeta (2007) is a minimum norm projection operator that embeds the equilibrium solution to the SCGE model in the definition of the time rate of change of a state variable. See also Smith et al. (1997).

[14] This criterion presents problems in that the computation of the line integral corresponding to the consumer surplus is difficult. Friesz, Mookherjee, and Peeta (2007) discuss an approach to overcoming this difficulty.

With allocative criteria (or a weighted combination thereof) chosen, one can proceed to the formulation of a dynamic multilayered urban infrastructure-based networked systems management model. One such model could take the form of a *capital budgeting* model whose solution would indicate the optimal effective capacity enhancement trajectories for the arcs of the infrastructure networks and the time paths of the network flows and associated costs. The resulting management plan would be conditioned on the acknowledgment that capacity perturbations give rise to disequilibria, which in turn induce equilibrating adjustments. Such a model naturally embodies an intertemporal optimization (or optimal control) problem in which the criterion function, for example, the present value of net benefits, is maximized subject to state dynamics (or equations of motion), budget constraints, layer-to-layer coupling constraints, nonnegativity constraints on network flows, and upper-bound constraints on arc capacities.

There are a number of problems associated with the solution of such a model. First is its sheer size; the model could easily have thousands of equations. While such a dimension is not uncommon for CGE models, the model would also have explicit path variables and unavoidable nonconvexities, due to the coupling of various network layers. Consequently nontraditional numerical solution methods must be explored, including variational inequality methods, simulated annealing, genetic algorithms, and agent-based modeling methods (see Friesz, Mookherjee, and Peeta 2007; Zhang, Peeta, and Friesz 2005).

Solutions to such models will be very detailed and will need to be displayed with appropriate visualization and other decision- and planning-support tools to help stakeholders appreciate the economy-wide and spatial implications of a given infrastructure systems management plan.

HOW CAN CHANGES IN URBAN INFRASTRUCTURE SYSTEMS BE FINANCED, AND ARE THERE OTHER RELEVANT POLICY CONSIDERATIONS?

While the amounts and types of infrastructure that are needed are well documented (ACSE 2009b; Timmins 2010), financing its provision and maintenance presents problems. Many governments in the developed world have substantial deficits to reduce and, with aging populaces in addition to aging infrastructure systems, are expected to be similarly situated for quite some time. And, while private financing of infrastructure projects or public-private partnerships are increasingly common, banks have become increasingly unwilling to "lend long" after the current financial crisis.[15] Timmins observes that whereas the long-run liabilities of pension funds match up well with the long-term nature and returns from infrastructure projects, infrastructure is a specialist alternative asset class that requires disproportionate expertise to assess associated risks. Pension fund managers tend to want to invest in built assets at the point at which construction risk is low—that is, *after* an infrastructure system has been built. Moreover, some pension funds that used to invest in long-term projects have gone out of business. Generally speaking, the equity needed to assume construction risk on large projects with large liabilities is in short supply and is likely to be so for the foreseeable future.

Rohatyn and Ehrlich (2008) argue that, in the United States, the shortfall of public funds conceals a second problem with federal policy. Policies that are in place "are incapable of creating the incentives to manage correctly what's *already* been built... [because they misdirect] investments away from the best opportunities" (27). They also note that responsibility for infrastructure is spread across federal, state, and local governments. Many of the policies at different jurisdictional levels have been focused on new construction and were intended to help integrate infrastructure into national networks. Now that most basic infrastructure networks are built out, existing policies do not advance projects of national scope or high economic value. Moreover, they "blunt the incentive to repair and maintain existing [infrastructure]" (27). Rohatyn and Ehrlich consider it particularly unfortunate that officials in the United States are loath to consider managing road and airport use through pricing, and Timmins concurs that part of the solution lies in infrastructure use pricing (see also the chapter by Reynolds-Feighan and Vickerman in this volume).

Another policy problem Rohatyn and Ehrlich identify is that different government programs are dedicated to different types of infrastructure. This state of affairs has contributed to the creation of "bureaucratic fiefdoms... held captive to the 'iron triangle' of congresspeople, lobbyists, and bureaucrats themselves. Hence programs never compete with each other and programs aren't compared in terms of common criteria" (27).

The ineffectiveness of government regulation is related to still another problem: the shortage of construction firms with capacity to take on large projects. Timmins writes that governments must get the regulatory and planning processes right so that their countries (states, cities) are perceived by construction firms as good places in which to do business.

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[15] In the case of new and existing transport infrastructure in Europe, Nijkamp and Rienstra (1995) conclude that there is much scope for the private sector in financing and operations. Rohatyn and Ehrlich (2008) remark that groups of investors—such as the Australian company Macquarie and the New York-based investment bank Goldman and Sachs—are taking part in private financing of toll roads. Under existing arrangements, the state or city involved sells the road and the right to set and collect tolls on it to a private concern. Such arrangements amount to a new form of government borrowing.

A number of countries are considering the establishment of infrastructure banks. Such banks might operate less like conventional banks, for example, by providing less of the debt for projects but assuming more of the risk. Rohatyn and Ehrlich (2008) see the central purpose of such a bank in the United States as being to evaluate proposals and assemble a portfolio of investments to pay for them. They note that public financial institutions are usually created to correct problems in capital markets. The problem to be corrected in this case, however, is *not* the inefficiency of capital markets but rather the *inefficiency with which federal programs work and allocate funds*: "The purpose of the National Infrastructure Bank would be to use federal resources more effectively and to raise additional funding... the bank would replace the various modal programs for highways, airports, mass transit, water projects, and other infrastructure, streamlining them and folding them together into a new entity with a new culture and purpose" (28).[16]

WHERE IS RESEARCH ON THE MANAGEMENT OF URBAN INFRASTRUCTURE SYSTEMS NEEDED?

To better manage changes in urban infrastructure systems, where is research needed? Given the number and the complexity of the issues that economists, planners, engineers, risk analysts, and investors face, it is quite clear that much research is needed in many areas. I conclude by identifying just a few.

As Friesz, Mookherjee, and Peeta (2007) point out, too often infrastructure systems are studied as if they are stand-alone entities, when they are clearly interdependent and it is this interdependence that creates most of the interesting challenges to their effective management (cf. Rinaldi, Peerenboom, and Kelly 2001). This observation suggests that more system-of-systems types of studies need to be undertaken along the lines sketched earlier.

As Friesz et al. have also observed, many infrastructure systems may be viewed as generalized transportation networks through which pass water, natural gas, money, people, goods, electricity, and communications. The field of network economics is somewhat new, but it has already seen important conceptual developments—such as that of network externalities (Katz and Shapiro 1994; Liebowitz and Margolis 1994; Brennan 2008). These developments need to be studied more closely in the context of interdependent infrastructure-based networked systems (see also Donaghy 2009b).

In the European Union, where regional policies over the last few decades have contributed to massive investments in regional infrastructure systems, policy studies have been conducted with SCGE models to help anticipate impacts of infra-

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[16] See Rohatyn and Ehrlich (2008) for further details.

structure investments on trade, welfare, and labor and housing markets and to evaluate programs (see Venables 2004; Knapp and Oosterhaven 2004; and the survey provided in Donaghy 2009a). The work begun in these studies needs to be pursued further and for other locations.

We need research into more efficient solution algorithms for SCGE models and simulations conducted to aid our learning about emergent properties in complex adaptive systems. (Given the financial stakes involved, we cannot afford major mistakes.)

We need project management tools—analogous to *Civil 3D*, which combines computer-aided drawing (or CAD) capabilities with spreadsheet modeling capabilities—that enable all parties to infrastructure management decisions to share information and draw appropriate inferences. We also need research on how infrastructure systems managers can interact more productively with different stakeholders.

Finally, we need decision support tools that help us to understand how decisions made about urban infrastructure systems by single and multiple agents are interdependent and condition other, non-infrastructure-related, decisions (see Hopkins 2001; Zhang, Peeta, and Friesz 2005.)

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