# Sustainability and Resilience in the Urban Environment

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## *Introduction*

Urban systems are formed by a diversity of actors and activities, and consist of complex interactions involving financial, information, energy, ecological, and material stocks and flows that operate on different spatial and temporal scales. The urban systems that emerge from these interactions are continually in flux as they are constructed, replaced, and regenerated. It is essential that urban infrastructures are examined in terms of how they either enhance or hamper the system's robustness in the face of change. While scholars of all disciplines agree that urban systems form and grow from the economic surplus that they capture, less transparent are the manner in which social and organizational factors should be integrated with the ecological landscape and infrastructure decisions and designs. In this paper, a different model of urban infrastructure design is envisioned, one in which technological advances are integrated with ecological and social information to create new types of more resilient and sustainable infrastructure systems.

A central tenet of this paper is that sustainable and resilient infrastructures result from a combination of engineering analysis and design, the incorporation of technological advances, and the interplay of human adaptation and response to the physical and ecological environment (Sahely et al. 2005;Turner et al. 2003). In addition, social and economic incentive structures must be factored in as important determinants of human responses to and strategies for the promotion of resilient and sustainable infrastructures. Such an approach gives rise to a number of critical questions: What will resilient and sustainable urban infrastructures of the future look like? How will they be envisioned and designed? What measures are most appropriate for determining if one design is more sustainable and resilient than another? What will sustainable and resilient design principles of the future look like and how will we derive them?

## *Background*

Urban infrastructures have historically supported several needs of the population served: the supply of goods, materials and services upon which we rely; collection, treatment and disposal of waste products; adequate transportation alternatives; access to power and communication grids; a quality public education system; maintenance of a system of governance that is responsive, efficient and fair; generation of sufficient financial and social capital to maintain and renew the region; and insurance of the basic elements of safety and public health. Collectively, these needs have been perceived as the basic attributes needed to make an urban region livable.

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At present 80% of the US population and 66% of Japan's population, live in urban regions,[4] percentages that have grown steadily over the past one hundred years. Urban infrastructures are designed and built in response to social needs and economies of scale that urbanization has brought about. Although our urban infrastructures are in many ways remarkable achievements of engineering design that were conceived and built during times of rapid urbanization, as they have aged and, inevitably, deteriorated; significant strains on their function and ability to provide services have become evident. In its program to identify the "grand challenges" facing society in the near future, the National Academy of Engineering has proposed several focus areas, among them the restoration and improvement of urban infrastructures. Such a challenge involves the need for renewal, but presents opportunities for re-envisioning the basis of infrastructure design and function as we move forward. Urban infrastructures of the past have not generally been conceived in concert with evolutionary social and ecological processes, nor have urban infrastructures benefited from the latest technological advances. This has resulted in several characteristic attributes: conceptual models of infrastructure that perceive local ecological systems either indifferently or as obstacles to be overcome rather than assets for harmonious designs; a general reliance on centralized facilities; structures that often lack operational flexibility such that alternative uses may be precluded during times of crisis; heavy use of impervious and heat absorbing materials; systems that have become increasingly costly to maintain and that are often excessively consumptive of natural resources on a life cycle basis; and a built environment the materials and components of which are often difficult to reuse or recycle.

Our response to these challenges is to develop a new cross-disciplinary approach to the conception, design, and analysis of urban infrastructures that aims to make use of findings from the technological, ecological, and social sciences, and develop an integrated methodology for assessing their resiliency and sustainability. Both of the infrastructure systems that this research will focus on, water and transportation, are essential to the functioning of urban regions: water as an essential ingredient for livability, and transport systems to provide connectivity among individuals, firms, and institutions.

Much has been written about the connections between resiliency and sustainability, a relationship that is confounded by the many definitions of each, and the contexts in which they are applied. Berkes (2007) suggests the resiliency of complex human-natural systems, of which urban systems are prime examples, lies in their capacity to maintain essential organization and function in response to disturbances (of both long and short duration). A complimentary view, inspired by traditional ecological and economic thought (e.g. Holling 1996), focuses on the degree of damage a system can withstand without exhibiting a "regime shift", defined as a transition that changes the structure and functioning of the system from one state to another as a result of one or more independent factors. Upon exceeding a given threshold, the system shifts to a new alternative state that may not be readily reversed through manipulation of causative factors (EPA 2007; Collie *et al.* 2004; Scheffer *et al.* 2001). In the context of human-natural systems, regime shifts can have significant consequences, and not all shifts are preferred by the human component of the system. To the extent that change of some

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[4] The term "urban region" is used throughout this paper according to the definitions of the US Census Bureau as an urbanized area comprised of one or more places ("central place") and the adjacent densely settled surrounding territory ("urban fringe") that together have a minimum of 50,000 persons. The urban fringe generally consists of contiguous territory having a density of at least 1,000 persons/mi$^2$.

order is a given property of essentially all dynamic systems, “preferred” resiliency might be viewed as the extent to which human societies can adapt to such shifts with acceptable levels of impacts. Resilient infrastructures, then, are those that most readily facilitate such adaptation. Much of the foregoing discussion applies to sustainability, with the added constraints of the sustainability paradigm: the equitable and responsible distribution of resources among humans, present and future, in ways that do not harm, and ideally reinforce, the social and biological systems upon which human society is based. In other words, not all preferred regimes are sustainable.

In the context of infrastructure design, the interrelationship between resiliency and sustainability is similar, although the specific attributes of each must be interpreted in terms of design concepts. Thus the capacity of urban infrastructures to promote resiliency and sustainability is rooted in many design factors: network organization, built-in design redundancy or decentralization, the use of advanced materials, the ease-of-renewal or reconstruction, the extent to which the infrastructure is integrated with ecological systems, self-diagnostic and healing capabilities, and the ability to acquire accurate information that is communicated back into the functioning of the system (Allenby and Fink 2005; Turner *et al.* 2003). Further, the sustainability of these systems includes measures of capital economy and longevity, but as importantly the material and energy demands of the system (natural capital) over the complete life cycle from the refining, fabrication, and acquisition of materials, construction, use patterns, and end-of-life disposition of the infrastructural components.

## **Resiliency and Sustainability Metrics**.

As noted previously, there are two general considerations associated with the assessment of resilience and sustainability, the overarching consumption, distribution, and use of resources, and the detection of systemic regime shifts. Table 1 summarizes some of the metrics currently in use for quantifying these factors. Each of the measures listed has advantages and disadvantages for quantifying the condition, state, or dynamics of complex systems, as noted, thus the overaching approach focuses on the goal of discerning *comparative directionality* (i.e. more or less resilient, sustainable) for alternative designs and scenarios.

The evaluation of regime shifts, which can be interpreted as resulting from both unsustainable and poorly resilient systems, requires an integrative measure of system character. We believe the key to this integration lies in the ability to discern how the behavioral regimes of a system change over time and in response to perturbations, both relatively short term, and of longer duration (Holling and Gunderson 2002). The approach envisioned will rely on the application of information theory (IT) to the analysis of the problem. In this context, IT is used to discern the progression of order in a system. Perfectly ordered systems do not display shifts over time while perfectly disordered systems display shifts in which observable variables not only change but are uncorrelated. Virtually all real systems display behaviors in between these extremes. For example, well functioning ecosystems exist in ordered dynamic regimes in which predictable patterns are observable, yet may evolve to different states over time.

**Table 1. Common Resiliency and Sustainability Metrics** (adapted from Mayer et al. 2004)

| Concept | Metric | Advantages | Disadvantages |
|---|---|---|---|
| Resilience | System recovery time and path relative to intensity of disturbance | Inherently dynamic measure/incorporates infrastructural and ecological uncertainty/variability | Prediction of ultimate recovery regime difficult/some regimes more desirable than others |
| Resilience | Mitigation of aggregate risk | Common basis for assessing degree of recovery | Relation between human and ecological risk often not clear |
| Sustainability | Ecological footprint/carrying capacity/maximum sustainable yield | Balances waste emissions/withdrawal of goods/use of services with ecosystem functioning | Rates at which ecosystems supply goods and services often not well understood |
| Sustainability | Life cycle inventory and assessment | Relates results of human commerce to common sets of impacts | Data needs may be onerous/impact analysis often imprecise |
| Sustainability | Thermodynamic accounting (e.g. exergy, emergy) | Unity of expression related to fundamental system properties | Human adaptability not considered |

The concept of *Fisher Information* (FI) holds promise as being particularly useful as an integrated metric that can provide a quantitative framework for describing system regimes for which only partial or uncertain knowledge is available (Fisher 1925). FI is concerned with the ability to estimate the amount of information that can be extracted from a set of data using derivative constructs from time-dependent data. Since it can operate on many types of data, it is an important step for integrating across social, technological, and ecological domains. FI is a measure of dynamic order. Steadily decreasing FI indicates a loss of dynamic order (a system that is shifting to more disordered and less functional states), while increasing FI signifies a system that is changing, but is doing so with its essential organization and function intact. The necessary condition for ordered transitions is the averaged FI over time must be constant (i.e. $\partial \langle FI \rangle / \partial t \approx 0$).

There have been several applications of the FI approach to complex systems as a means of defining their stability, degree of order, sustainability, and resiliency, beginning with ecological, but progressing to industrial, economic, social, and governmental systems (Cabezas *et al.* 2003; Fath *et al.* 2003; Mayer *et al.* 2006). The results show consistency across systems, with clear indications of system-wide regime shifts. Further, FI approaches show considerable promise as a means for defining integrative indices and trends that describe the dynamic regimes of a system and make plausible projections (for a given set of information) on its future state. It should be noted that although FI operates on time series information, the period over which shifts may occur is not limited by the temporal interval, thus both long term and short term simulations can be analyzed.

## Engineering Design and Analysis.

Once a system has been conceptually identified, and its design constraints articulated, the analysis of its components, development of a physical design, and determination of its behavior over time are needed. The materials and systems for design and building the civil infrastructure of the future should allow for resiliency and sustainability in terms of efficiency in construction, in-service performance, durability, required redundancy, environmental affability, social acceptability and flexibility for future changes. It should have the attribute of a low overall design cycle cost. Achievement of these goals requires dramatic transformations in every aspect of infrastructure engineering design and analysis.

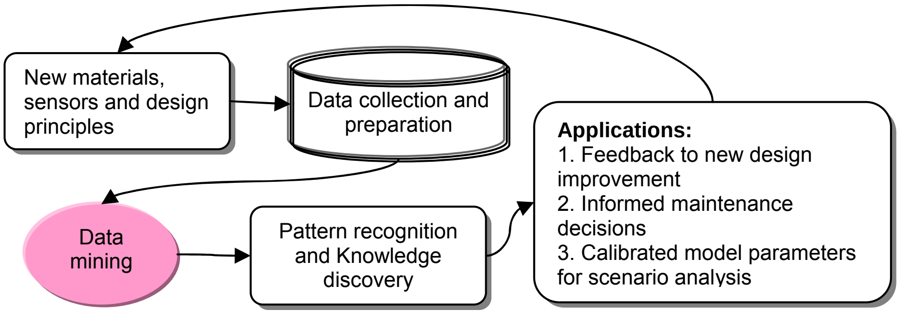


**Figure 1. Integrated Engineering Design and Analysis**

Breakthroughs in intelligent sensor technology, high speed computing, parallel processing, neural network behavior, control systems, and robotics have greatly enhanced our technological and information gathering capabilities. The development of intelligent infrastructure designs, (i.e. physical systems possessing an integrated means of sensing their surrounding environment, processing the sensory information, and responding in a beneficial and controlled way to the changing environment due to their capabilities to produce a desired function or response), consists in itself of an integrating set of tasks, shown in Figure 1, that includes the layout of the system, the properties of materials of which it is composed, innovative fabrication methods, anticipated loadings and flows, incorporation of advanced sensor technology, construction (or renewal) and deconstruction methods, and a cost analysis. The agent-based modeling approach, coupled with the derivation of metrics, will provide feedback to designs that guide engineers toward those with the most resilient and sustainable characteristics.

Achieving these designs will require the inclusion of five key considerations:

- Use of high performance materials, such as fiber reinforced composites for structural members, in order to achieve high strength-to-weight ratio, superior durability and flexibility, recyclability, energy efficiency, and constructability.
- Shift in construction practice from onsite building of components to in-plant manufacturing of structural elements for modular construction when possible. New and unconventional construction materials and manufactured structural components prompt the need for incorporation of advanced modular construction, splicing and de-splicing techniques for use and re-use, and robotics operations. This assures systematic production of components with assured qualities and attributes subjected to the latest quality assurance and control (QA/QC) standards, and allow better specification of sustainable assembly practices.
- Embedding of sensors (e.g. stream gauges, optical fibers, and other nano-based sensors) within the components of the design and design of feedback networks for analyzing and interpreting data signals. These applications of sensor data require extensive data mining for pattern recognition and knowledge discovery. The sensory systems within the infrastructural components serve as a self-diagnostic tools to provide information about the state-of-the component and the system as a whole, alarm for overloads or incipient failures, and mobility and demographic information.

- Application of modern computational design tools that include: multi-scale computational modeling at the systems level.
- Use of advanced life-cycle cost and performance analysis tools in the assessment stage, including the societal and economic impacts. A probabilistic approach might be implemented such that lifetime structural performance can be optimally improved under budget constraints. This requires (a) reliable modeling of loadings, including extreme loads, and continuous deterioration processes and their effects on structural capacity, (b) accurate prediction of structural reliability and performance evolution, (c) good estimation of costs of interventions, such as, maintenance, repair, and replacement over the specified time horizon, and (d) generations of solutions that balance life-cycle costs and lifetime structural performance in an optimum way resulting in lowest total life-cycle cost.

## Agent-based Modeling

Agent-based modeling (ABM) is an ideal method for analyzing urban systems because they require the analysis of forces and behaviors that originated in, and are modified by, the interaction of heterogeneous physical landscapes (including infrastructure and ecological) and actors, operating at different spatial and temporal scales. The explicit representation of socio-economic, political and ecological processes and the feedback mechanisms connecting them with the built environment makes agent-based modeling useful to examine complex multi-dimensional systems (Batty and Torrens 2001, Hoffman *et al.* 2003, Parker *et al.* 2003). Such models can be used to test the effect of various infrastructure designs on an array of sustainability and resiliency measures applied to urban regions, including aggregate and disaggregate physical and social variables (e.g. energy use, pollution emission and carbon sequestration, agent utility levels, damage and time for recovery due to perturbations).

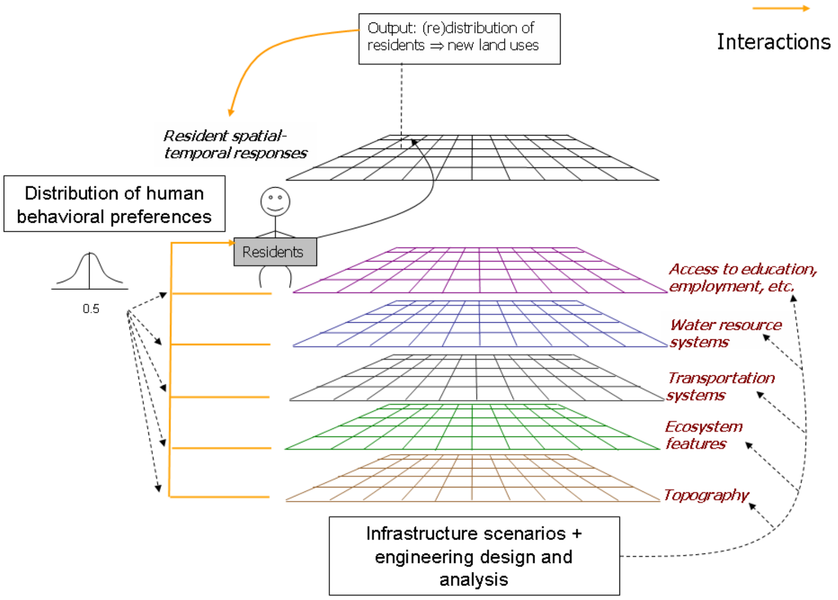
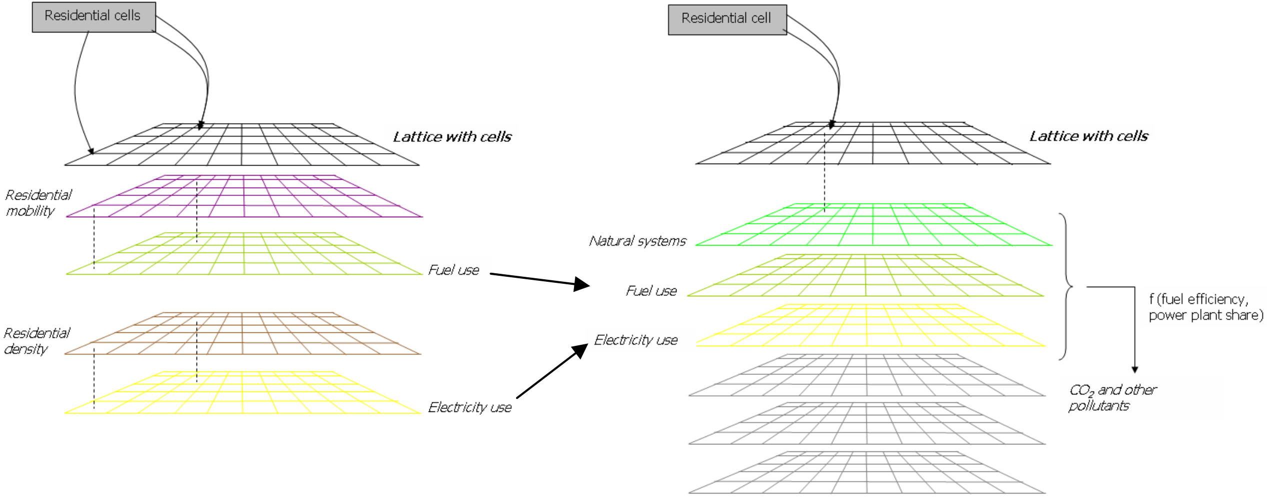


**Figure 2. General assembly of urban agent-based models (Zellner et al 2008).**

Agent-based models include appropriate agents (e.g. residents, developers, firms, governing bodies) making choices about location (resulting in population distributions, stationary source emissions, willingness to invest in housing/schools, and extent of sprawl, etc.), modes and frequency of transportation (which establish patterns of movement and mobile source emissions), and demands on other forms of resource consumption that lead to material and energy demands and waste generation (e.g. wastewater and solid wastes). These human-infrastructure-environment interactions will affect the sustainability and resilience of the urban system. Residents adopt adaptive strategies that depend as much upon the physical infrastructure as on individuals' socio-economic characteristics, such as estimates of risk that are based on heuristics or "rules of thumb" (Tversky and Kahneman 1974), which might either agree with social consensus or rely on available information and prior experience (Payne *et al.* 1993; Trumbo 1999). Agents can be assigned prior experience, heuristics, and risk perceptions that determine the overall response of the population to an extreme event, as a product of the direct impact of the disturbance and of the interaction of agents with each other and the environment.

As an example, Figure 3 depicts schematically how a model might integrate the social and the biophysical dimensions that affect and are affected by water resources and transportation subsystems. The biophysical environment is represented as a two-dimensional lattice of cells containing natural (e.g. topography, landscape cover, natural boundaries), infrastructure (i.e. the principal materials and design aspects of the waterway/water supply and transportation network infrastructure as portrayed in a given scenario), households locations, and socially important features and attributes (e.g. zoning density restrictions, parks, health services, schools), Residents' decisions are affected by their behavioral preferences, which are heterogeneously distributed across the population. Physical and behavioral input can be hypothetical (as informed by theory), scenario-based or empirically-based.



(a) (b)

**Figures 3. (a) and (b) Urban ABM energy consumption and air emission sub-modules**

Agent-based models can produce a range of spatially and temporally varying results. As an example, energy consumption and resultant air quality emissions submodules are depicted in Figures 3a and 3b. Such models can be programmed to link such outputs to perturbations, and to social impacts and responses to such perturbations, computing the extent of damage (e.g. area affected, population exposure, schools affected, housing and insurance costs) and both short and long term impacts. Once these links are established, a set of alternative design methods for infrastructure planning and development can be tested on these outcomes (e.g. infrastructure modularity, use of smart materials and intelligent engineering, diversity and redundancy, and integration of socio-technical-ecological infrastructure).

## Example: Sustainability and Urban Spaces—the Role of Land Use Changes

### *(a) Agent based modeling*

As an example of the application of agent based modeling for assessment of the resiliency and sustainability to urban spaces, the emission of travel-related contaminants to the atmosphere is presented. Figure 4 shows the spatial pattern of $CO_2$ emissions for the greater Chicago urban area. The left hand map gives the extensive quantities (showing the greatest emissions in the most densely populated sectors), and the right hand map shows the same information presented intensively, i.e. per household (showing the most intensive release of $CO_2$ associated with suburban regions). This is a typical pattern for most densely populated cities.

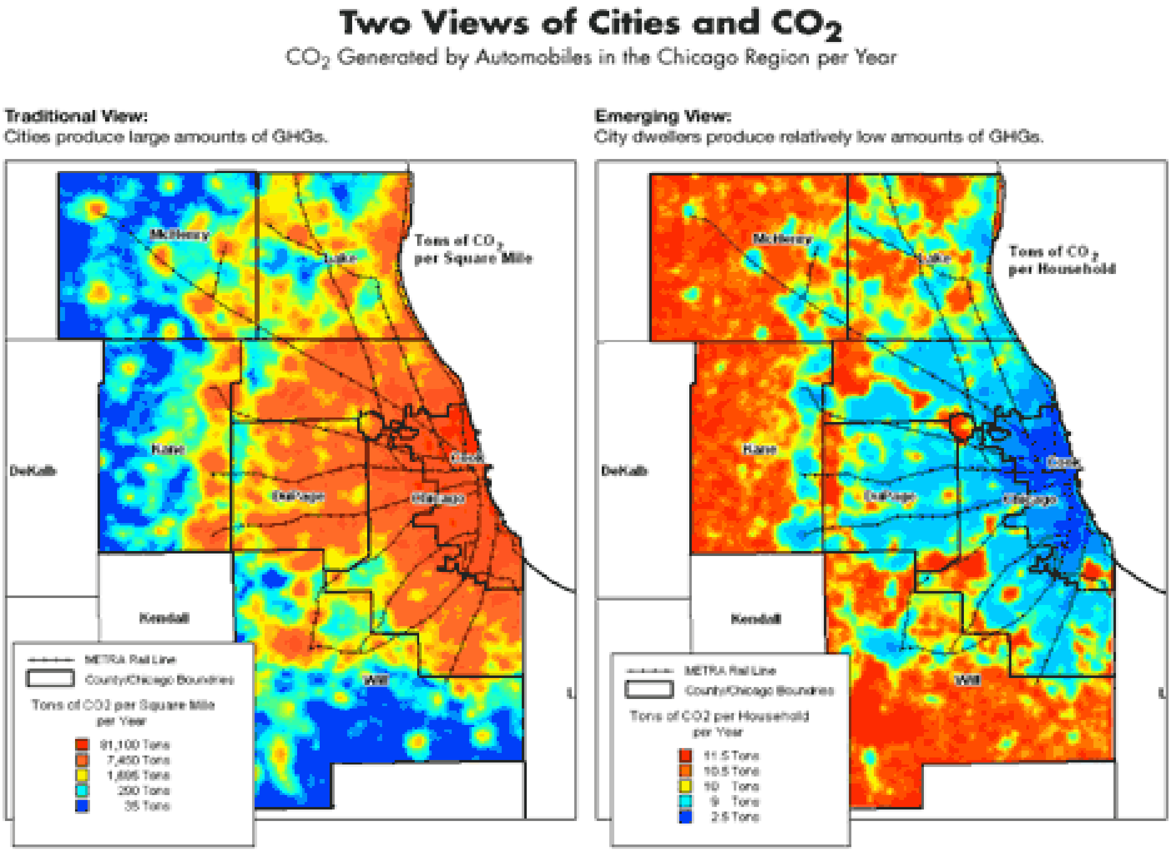


**Figure 4. CO2 Emission Patterns for the Greater Chicago Region**

In viewing Figure 4 a question that arises has to do with which land use, urban or suburban, is the more sustainable? Zellner et al. (2008) have addressed this problem using the agent based approach, developing a model known as Urban Sustainability Assessment Framework for Energy (USAFE). The urban environment is defined on a two-dimensional lattice composed of square cells of equal size, each cell representing a specific surface area. Both the lattice and the cell surface are defined by a parameter of the model. Associated to this lattice is a series of grid data layers containing natural, infrastructure, social, proximity, and policy information (Table 1).

**Table 1. Landscape quality spaces in USAFE** (from Zeller et al. 2008)

| **Land use** |
|---|
| **Natural features** |
| agricultural quality |
| septic quality |
| forest cover |

| |
|---|
| **Infrastructure** |
| presence of roads |
| municipal water coverage |
| municipal sewer coverage |
| **Social** |
| ranking of schools |
| crime rate |
| **Proximity** |
| distance to natural areas |
| distance to centre of employment |
| **Policy** |
| residential density restriction (zoning) |

Using residents as agents and defining a default case (Table 2), USAFE predicts population distributions, and associated land use shifts (from vacant to urban/suburban) over time for various scenarios, the parameters of which are historically important in defining the distributions, and travel needs, of the population (Brookings Institution 2006). The results are summarized in Table 3, including the default case, which includes 5 round trips per week (home to employment), which replicates, in a general way, the pattern of $CO_2$ emissions shown in Figure 3.

**Table 2. Default parameter values in USAFE** (from Zellner et al. 2008)

| | |
|---|---|
| Run time | 200 time steps |
| Size of grid | 200 by 166 |
| Initial land-use | All farms |
| Forest cover | 0 in all cells |
| Roads | In all cells |
| Municipal water and sewer | In all cells |
| Zoning | 311 residents/cell |
| Agricultural soil quality | Poor in all cells |
| Central business district | Center of lattice |
| Natural areas | In all cells |
| School scores | 0 in all cells |
| Crime | 0 in all cells |
| Residents per turn | 1,000 |
| Transition rate to undeveloped | 100 |
| Round trips per week | 5 |
| Residential preference for all factors | 0.5 |
| Surface of each cell | 63,000 m$^2$ (~ 16 acres) |
| Maximum electricity use | 1,332.0 |
| Minimum electricity use | 555.0 |
| Share of power generation (natural gas, coal, oil, municipal waste) | 0.25 each |
| $CO_2$, $SO_2$ and $NO_X$ from natural gas (g/kWh) | 514.82, 0.05, 0.77 |
| $CO_2$, $SO_2$ and $NO_X$ from coal (g/kWh) | 1020.12, 5.9, 2.72 |
| $CO_2$, $SO_2$ and $NO_X$ from oil (g/kWh) | 758.4, 5.44, 1.81 |
| $CO_2$, $SO_2$ and $NO_X$ from municipal waste (g/kWh) | 1355.33, 0.36, 2.45 |
| Farm consumption (undefined units) | 100 |

| | |
|---|---|
| Farm Pollution Coefficient (undefined units) | 1.0 |
| Fuel efficiency (mi/gal) | 30.0 |
| VOC from fuel use (g/gal) | 4.63 |
| CO from fuel use (g/gal) | 123.58 |
| $NO_X$ from fuel use (g/gal) | 6.16 |
| PM from fuel use (g/gal) | 0.74 |
| $SO_X$ from fuel use (g/gal) | 1.90 |
| $CH_4$ from fuel use (g/gal) | 1.88 |
| $N_2O$ from fuel use (g/gal) | 0.63 |
| $CO_2$ from fuel use (g/gal) | 8744.61 |

**Table 3. Aggregate values for electricity use, fuel use and $CO_2$ emissions**
(modified from Zellner et al. 2008)

| Scenario | Residents | Electricity kWh) | Fuel (gal) | $CO_2$ (Tn) | $CO_2$/res (Tn/res) | FI* |
|---|---|---|---|---|---|---|
| **Default scenario (5 roundtrips/week)** | **199000** | **1.33E+09** | **1.23E+10** | **1.09E+08** | **5.45E+02** | 5 |
| Minimum density zoning | 19900 | 3.18E+08 | 6.08E+09 | 5.34E+07 | 2.68E+03 | 16 |
| Concentric zoning | 199000 | 2.58E+09 | 4.76E+10 | 4.19E+08 | 2.10E+03 | 2 |
| Good central schools | 199000 | 1.33E+09 | 1.22E+10 | 1.08E+08 | 5.41E+02 | 5 |
| Good peripheral schools | 199000 | 1.33E+09 | 5.92E+10 | 5.19E+08 | 2.61E+03 | 2 |
| Three roundtrips/week | 199000 | 1.33E+09 | 7.29E+09 | 6.49E+07 | 3.26E+02 | 16 |
| Four roundtrips/week | 199000 | 1.33E+09 | 9.74E+09 | 8.64E+07 | 4.34E+02 | variable |

* Fisher Information

### *(b) Fisher Information*

The results of the Fisher information analysis suggest there are significant differences in the dynamic order of some scenarios. Moreover, scenarios can be grouped according to their impact on the sustainability of the system. In one extreme, the scenarios with minimum density zoning and fewer round-trips per week result in highly ordered systems, with consistently high values of FI. This is because of the sharp difference in the number of residents (a factor of ten) between the scenarios. With a low population, the minimum density scenario has low environmental stress, and is quite static with respect to consumption and system interactions. The lack of activity in the minimum density zoning scenario manifests in a system with high FI, and therefore a stable and highly ordered system. Although the spatial pattern of development is different when commuting trips are reduced, the overall emissions are restricted; thus the similarity among these scenarios.

In the other extreme, the scenarios with concentric zoning and good peripheral school produce consistently low FI values over time, indicating the system has low dynamic order. This is not surprising, since these scenarios produce the most dispersed urbanization patterns, encouraging long commutes and lower densities of development.

The default and the good central school scenarios show medium values for FI because they produce compact spatial patterns but, in contrast with the reduced trips scenarios, they generate greater emissions. Because of the central location of urbanization, however, these scenarios generate more orderly systems than in the concentric zoning and the peripheral good schools scenarios (i.e., higher FI values). Because residents are attracted to good schools and employment, when these are in the same locations, less fuel is consumed and less CO2 is emitted. Thus, the reduced volatility in the system is reflected in higher stability and dynamic order than in the peripheral schools scenario.

A comparison of the number of automobile trips taken during a week produced more interesting results, as shown in Figure 5. The three round-trips per week scenario results in high and constant FI, and therefore indicates a highly ordered and stable system. Once the number of automobile trips per week reaches four, the system undergoes a systemic transition in which the FI begins to oscillate in a dramatic fashion. This indicates a system that is very close to a regime change, which is fluctuating between two alternative dynamic regimes having high and low Fisher information, respectively. Note that in the default scenario, with five automobile trips per week, the system exhibits low FI with minor oscillations, which indicates the system has lost dynamic order but it is stable. While finding a simulation precisely at the point between two alternative dynamic regimes may have been fortuitous, the interpretation of the observed results seems to be robust because it follows the logic of the underlying theory. With more automobile trips, there is more fuel consumption and therefore more CO2 emissions. This transition from three to four to five automobile trips per week manifests in a dramatic shift from a highly ordered system to an oscillating period of transition and a shift to a less orderly system. This is what one would expect for a system that has gone through a regime change.

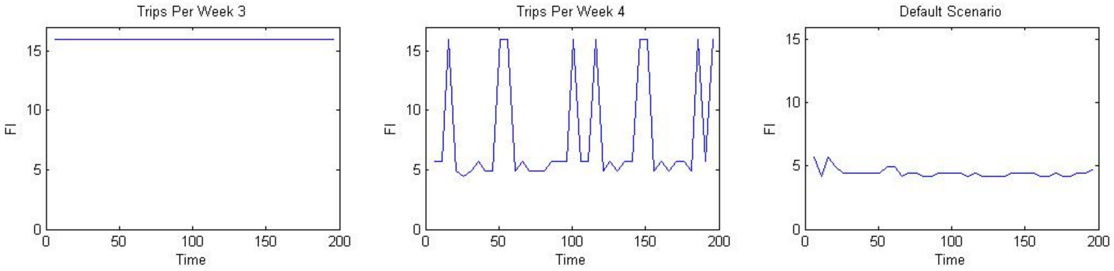


**Figure 5. Urban scenario results. Fisher Information for three, four, and five (default) roundtrips/week** (from Zellner et al. 2008)**.**

## Concluding remarks

In the context of the question posed earlier in reference to Figure 3 (are urban or suburban spaces more sustainable?), the answer suggested by this analysis is neither or perhaps both, i.e. it is the manner in which humans elect to meet their needs, in this case as defined by their educational and transportation needs, that determines the sustainability of the complete system. This paper has examined how small changes in behavior, land-use policies and investment in infrastructure may have significant impacts on environmental quality and long-term sustainability. The mechanisms relating sprawl and school development have only recently gained more attention (e.g., Norton, 2007), and promise to attract further research. A possible role for technology is in the possibility of telecommuting and reducing actual travel time; elimination of just one trip per week would greatly reduce both fuel consumption and pollution and stabilize the system. Those policies that induce residents to make such behavioral changes might offer considerable advantages over more rule-based approaches.

The relationship between urban form and environmental quality is not simple and varies with the scale of analysis. Combining agent-based modeling and information indexes can help scholars and policy-makers evaluate the common theoretical and practical assumptions about the sustainability, efficiency and equity of specific urban decisions, land-use patterns and their effects on energy use and air quality. This framework can be expanded to include newer information of the mechanisms currently represented, other environmental resources, such as water supply and quality, and other policy instruments, such as crime prevention, infrastructure investments and market-based instruments. In any case, the complexity of urban systems requires the review and adjustment of policy decisions on an ongoing basis. The framework presented in this paper facilitates policy adaptation as more knowledge is produced and as conditions of the metropolitan system change.

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