THE EVOLVING SYSTEMS VIEW OF TRANSPORTATION: IMPLICATIONS FOR POLICY

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INTRODUCTION

Systems Thinkers

Transportation systems are intricately interwoven with nearly every facet of human activities, from work and production, to leisure and consumption, supporting a worldwide flow of goods, and linking societies. As these large technical systems become a pervasive and integral constituent of modern society, the manner in which human forces perceive, analyze and attempt to shape the development of these systems becomes increasingly complex, and increasingly important. One of the core concerns of this paper relates to "the role that networks of knowledge-based experts – epistemic communities – play in articulating the cause-and-effect relationships of complex problems, helping [actors] identify their interest, framing the issues for collective debate, proposing specific policies, and identifying salient points for negotiation" (Haas, 1992). While the precise definition of the term "epistemic communities" is the subject of continuing discussion, for the present purposes it can be taken to refer to a group of practitioners, scientists or engineers, who share a common set of methodologies, techniques and other forms of knowledge.[1]

Purpose

The purpose of this current paper is to survey the nature of these epistemic communities within the field of transportation systems, in order to identify certain persistent patterns as well as evident shifts in the systems view of transportation. The motivation behind this is the hypothesis that the systems framework for understanding a system has a significant impact on the manner in which modeling, design, planning and policymaking is carried out within that field. The ultimate question being addressed in this exercise can be stated as the following: *How has the "systems thinking" changed over time with regard to transportation systems and can one observe related changes in the transportation planning and policy processes?*

Methodology

In order to examine the concepts, models and techniques that have been used by transportation system analysts, trained in university programs in transportation studies, this study will briefly review some of the core literature used in the field (Hay, 1978; Lieb, 1978; Manheim, 1979; Haefner, 1986; Lieb, 1994[2]; Sussman, 2000). The literature reviewed here provides a representation of the past three decades of general introductory textbooks aimed at the graduate level. This is intended to provide a glimpse of the progression of the systems framework, as is generally accepted by the relevant epistemic community and codified in textbooks. In the course of the review, I hope to extract certain patterns in systems thinking, while also attempting to identify areas of fundamental shifts in thinking about the nature of systems. While all modes and scale of transportation systems will be considered here, examples will primarily be drawn from urban transportation systems.

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[1] As further elaborated by Haas (1992), members of an epistemic community often foster a "shared way of knowing; have shared patterns of reasoning; have a policy project drawing on shared values, shared causal beliefs, and the use of shared discursive practices; and have a shared commitment to the application and production of knowledge."

[2] The edition of the textbook used as an example here is the first edition (Lieb, 1978). While there is a fourth edition (Lieb, 1994) there appear to be few revisions to the essential structure of the presentation of transportation systems. Most of the changes take the form of updated data and overviews of events subsequent to the previous edition.

In attempting to describe the changing "systems view" in the field of transportation, the following types of questions should prove to be illustrative:

1. How is the transportation system *defined*?
    - What are the *components* and *boundaries* of the system?
    - What are considered important *factors*?
2. How is the system *modeled*, both qualitatively and quantitatively?
    - How can the system be changed – what are the *variables*?
    - What is the *behavior* of the system, and how will it respond to changes?
3. How is a transportation system *designed* and *planned*?
    - Who are the important "system builders?"[3]
4. How is *policy* made with regard to these systems?
    - What sets of attributes are used to *evaluate* the system?
    - Who are the *actors* involved in the decision process?
    - What does the policy *process* itself look like?

While this paper will focus upon the evolution of the more widely accepted systems views over time, where illustrative, I will use this background to explore potential departures from the more mainstream systems view. In particular, I hope to assess the potential relevance and utility of the growing set of concepts and methodologies being developed by researchers in the field of Complexity. However, before proposing avenues for the application of complexity-based ideas to problems in transportation, this exploration of the historical trends in systems thinking can perhaps provide a more solid base for understanding where complexity diverges from the traditional systems view. Moreover, it can help to illustrate in which ways the traditional systems approach in transportation may not be the appropriate framework for addressing some of the more intractable problems which transportation professionals have faced.

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[3] Thomas Hughes (1998) employs this term to describe the engineers that design systems.

DEFINING THE TRANSPORTATION SYSTEM

Drawing the Boundaries

One of the essential preliminary procedures in the framing of a system is the delineation of what does and does not constitute a part of the system. As stated previously, the underlying questions in this first stage of transportation analysis are the following. How is the transportation system defined? What are the components and boundaries of the system? What are considered the important factors?

Components and boundaries

In the first edition of his textbook, *Transportation*, Lieb (1978) clearly emphasizes the interdependence of the transportation system's development with urban development, as well as its role in the economic, social and political fabric of the metropolitan area.[4] Notwithstanding, he tends to delineate the transportation system itself as being comprised of the physical network and the vehicles operating on that network. For example, in measuring the "scope of the domestic transportation system," Lieb employs network route mileage and vehicle stock for various modes as the primary indicators of scope.

In large measure, a similar representation is reflected in Manheim (1979). Although, he provides a holistic description of what he terms the "total transportation system," his definition continues to differentiate to between the physical transportation system and the socioeconomic system. More specifically, Manheim's "total transportation system" is comprised of three different variables: the transportation system, the activity system (the pattern of social and economic activities), and the pattern of flows in the transportation system (origins, destinations, routes and volumes of goods and people moving through the system). Consequently, while he provides an illustration of the strong feedback loops between the three systems, the transportation system continues to remain conceptually separated from the socioeconomic activity system. The interrelationship between these three variables is illustrated in figure 1.

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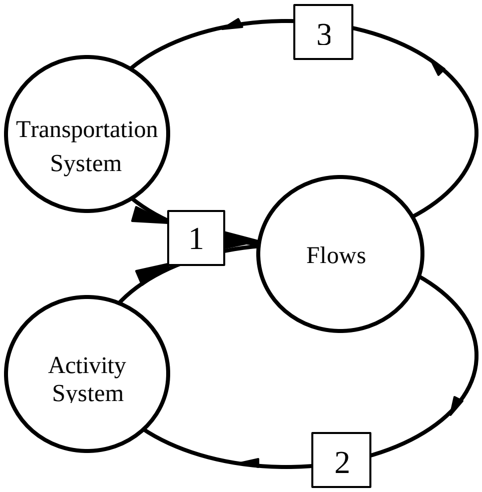
[4] While there have been several editions of this text, the fourth and more recent from 1994, the revisions and updating have primarily taken the form of additions of new information, without modifying the overall conceptual structure of the book. In the opinion of this writer, for this reason, the systems view presented in Lieb (1994) remains essentially the same as it was presented in the first edition of the book in 1978.

Figure 1: "Basic relations in the Total Transportation System"



Adapted from "Figure 1.1" in Manheim (1979)

Manheim (1979) identifies three types of relationships: 1) the current pattern of flows is determined by the transportation and activity systems, 2) the current flow pattern will cause changes over time in the activity system, and 3) the transportation system changes in response to actual or anticipated flows. While Manheim stresses the inclusion of all of these interrelationships for a complete transportation system analysis, the bulk of analysis in practice has tended to focus much less on the second of these variables, often taking the activity system as exogenously determined.

The scope of the definition of "transportation systems" has broadened during the past few decades. To a large extent, this broadening is due to the increasingly sophisticated analytical capabilities, which can handle more complex sets of variables. Moreover, the addition of many important variables in turn has a substantial impact on the methods of transportation analysis, planning and policymaking. As an example of this more inclusive drawing of boundaries, described in Sussman (2000, Chapter 2), the *internal* transportation system components include the following:

Table 1: Internal Transportation System Components

PHYSICAL COMPONENTS

Infrastructure
- Guideway
- Terminals
- Stations

Vehicles
Equipment
Power systems
Fuel
Control, communications and location systems

OPERATORS

Labor
Management
- Marketing
- Strategic Planning
- Operations
- Maintenance
- Information
- Operations research
- Administration

OPERATING PLANS

Schedule
Crew assignments
Flow distribution
Connection patterns
Cost/Level-of-Service Trade-off
Contingency Planning

Adapted from Sussman (2000)

This description emphasizes the increasing importance of two crucial components of the transportation system, specifically, *information* and *behavior*. First, with the growing number of potential applications of computer and information technology, the role of control, communications and location systems, and the information provided by these systems is increasingly perceived as an integral component of the physical system. Second, more focus seems to be placed upon the behavior of transportation systems. This behavior is guided by both the "operating plans," which specify the regular procedures of operation, as well as by the adaptive responses of "operators" (individual drivers, pilots or taxi dispatchers) and managers (in strategic planning, maintenance or marketing). Taken together, this represents the shift toward a more dynamic view of transportation systems, in which the behavior of the components within the transportation system is more extensively treated.

Linkages with other factors

While the interconnectedness between the transportation system and the socioeconomic factors with which it interacts has long been emphasized in the literature on transportation systems. Notwithstanding, for analytical purposes, the inherent difficulties in quantitatively modeling these complex linkages has necessarily led to a drawing of boundaries between the physical transportation structure and the broader socio-economic system in which that system is embedded. Therefore, although transportation has been conceptualized as a subsystem embedded in a larger socioeconomic system, it is "transportation as a *technological system* [that has been the] major frame of reference" for most analyses (Hay, 1978; author's italics).

Modeling the System

Probably the most important activity undertaken by a particular epistemic community, in this case transportation professionals, is the process of modeling systems, since this identifies and characterizes the cause-and-effect relationships of complex problems. First of all, as discussed above, the manner in which the system boundaries are drawn depends heavily upon the ability to actually model the system that is defined. Second, for the purposes of planning and policymaking, the model of a system's components and internal interactions will circumscribe the set of options available for changing that system. In this manner, the modeling method chosen shapes the answers to the questions: 1) How can the system be changed – what are the *variables?* 2) What is the *behavior* of the system, and how will it respond to changes? The predominant ways of structuring the analysis of transportation systems for the purposes of modeling has been to treat them as spatial networks over which there are flows of travelers and goods.

Networks

While the network structure seems to be the natural framework for a transportation system, it was not necessarily that obvious, at least in the case of urban transportation systems. Altshuler (1981) reflects that "traffic engineering in the 1920s and 1930s [paid] little attention to the benefits that might be gained by altering the geometric designs of existing streets." It is interesting to note that "the decade after World War II, however, was a period of rapid traffic engineering innovation…as traffic engineers achieved substantial increases in traffic flow by the widespread application of improved channelization techniques, one-way street systems, staggered traffic signals, street widening, parking restrictions, and intersection improvements" (Altshuler, 1981). Although this paper will not probe in detail the connections between the systems sciences used in military applications and those used in transportation engineering problems, the timing of the development of the network approach would certainly be consistent with the general spread of the systems approach from national defense to civil society (Hughes, 1998). This shift is probably best illustrated by Jay Forrester's *Urban Dynamics*, in which he employed the methods of system dynamics to explore the complexity and non-linearity of urban systems.

In *Introduction to Transportation Engineering and Planning*, Morlok succinctly summarizes the utility of analyzing transportation systems as networks. He describes a network as "a mathematical concept that can be applied to describe quantitatively transportation systems… and serves as a convenient means of arranging information on the characteristics of the various fixed facilities and the flows on them" (Morlok, 1978). Indeed, this systems view has been a powerful analytical structure for all types of transportation systems. By abstracting the system from the specific context in terms of location and modes, transportation analysts have been able to model network behavior and examine the changes in flows over the entire system as modifications are made to individual nodes and links within the network.

Flows

Conceptually linked to the network model of a transportation system is the idea of flows. Manheim (1979) notes the importance of flows in analyzing proposed changes in a transportation system.

> The core of any transportation problem is the prediction of changes in flows. There will usually be many other significant impacts as well, but predicting the changes in flows is an essential step (Manheim, 1979).

The gravity model represents a simplified but often good predictor of the average volume of flows between any two points, specified as a function of population at each point, and the distance. The basic model also provides a link between a transportation system and to the spatial distribution of population in that area. While the model has been expanded substantially to describe a complex system of linkages, and there have been several variations on the basic model, incorporating costs, as well as probabilities of trips between points, Haefner (1986) identifies two sources of criticism. First, the models fail to incorporate the possibility of new technological innovations or shifts in consumer preferences for travel. Second, the computations are "very mechanistic, forcing closure and allowing little room for logic in their operation" (Haefner, 1986).

From flows to individuals

While models such as the gravity model continue to provide valid and useful insights, the modeling of the demand for transportation services has progressed along several dimensions. First, as noted above, operators, including private automobile drivers, are now incorporated as internal components of the transportation system, whose behavior and decisions help determine the state of the system, rather than remaining as simply users of the system. Second, demand models have been increasingly disaggregated, as analysts develop more sophisticated understandings of user behavior. Third, the demand is understood to possess both a systematic and a random component of choice, thereby explicitly introducing demand stochasticity into the model. All of these trends have been developed within the set of models known as discrete choice analysis, which began to take shape in the 1970s.

In addition to the modeling advances associated with the disaggregation of the factors that generate demand for trips, models have also progressed from macroscopic simulations of traffic flows, to microscopic models that take into account the behavior of individual drivers and their interactions while on the network. As an indicator of this analytical shift from flows of vehicles to flows of individuals, one can point to changes in urban transportation planning. In the late 1960s, traffic engineers developed the concept of the exclusive bus lane. While this was driven by intensifying traffic congestion, and later by issues of air quality and energy use, Altshuler contends that "the bus lane represented a major turning points in the history of traffic engineering…. Now highway officials began to adopt the position that…the unit of analysis should be the person…[with] the aim of improved person flow" (Altshuler, 1981).

Taken together, these modeling advances have enabled analysts to move from a predominantly static to a more dynamic treatment of transportation systems. As will be discussed later, the next major step from static to more realistic dynamic models is to begin formulating models of adaptive systems. In this respect, it is important to note that the first of "30 Key Points" in Sussman (2000) states that: "People and organizations alter behavior based on transportation service expectations."

Building Systems

Closely intertwined with the methods and assumptions used for modeling the system, are the processes and steps by which the transportation system is *designed* and *planned*? In particular, how are alternative systems designs developed, and what are the variables and options available for changing existing systems or creating new systems. In this respect, it is also illustrative to question: who are the "system builders[5], and what role to they play?"

Beginning in the late 1960s, many analysts were arguing for the expanded utilization of the systems analysis framework for the urban transportation planning process (Catanese, 1972). This approach promised a more systematic and rational approach, "with assumptions made explicit, objectives and criteria clearly defined, and alternative courses of action compared in the light of their possible consequences" (Catanese, 1972). Although the process was recognized to be an iterative process, the basic approach entailed six stages: 1) problem formulation, 2) system structure, 3) quantitative approach, 4) development of alternatives, 5) evaluation of alternatives, and 6) interpretation. What will be argued here, is that the first three stages, which are related to way in which the system is defined and modeled, to a large extent, determine the alternatives that are developed.

Forecasting and Planning

For the purposes of planning for investment in urban transportation, network flows have typically been projected as following well-specified patterns, usually with the forecast output matching existing statistical behavior for trip demand. The demand for urban transportation has been seen as roughly predictable enough to be forecast ten to twenty years into the future, so that urban transportation improvements could be undertaken in order to satisfy that future demand. These assumptions were in fact necessary, especially given the lumpy nature of investment in capacity expansion. Furthermore, the models relied heavily upon assumptions of travel market

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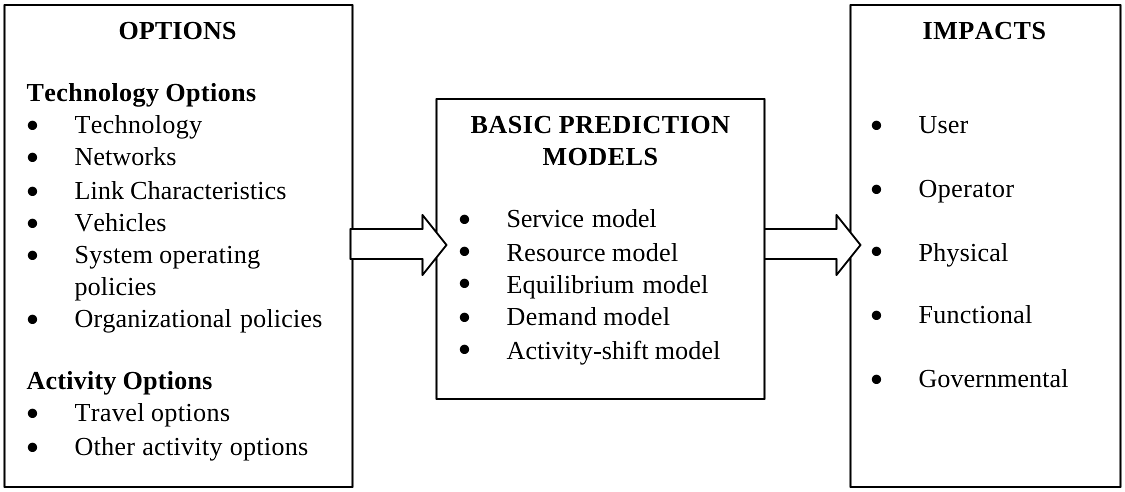
[5] Thomas Hughes (1998) employs this term to describe the engineers that design systems.

equilibrium between the volume of services demanded and provided. These assumptions of both a certain degree of predictability and linearity, while useful for such long-term planning as infrastructure investments, also have the effect of locking in a systems to a particular trajectory of development, and limiting less conventional planning options.

As noted in Haefner (1986), the effort involved in urban transportation planning can be roughly decomposed into a demand side and a supply and evaluation side. On the demand side, the analytical activities described above are important to provide a picture of the forecasted level of demand for travel ten to twenty years into the future. While on the supply side, the focus is on "which set of transportation improvements will best satisfy that demand" (Haefner, 1986). This viewpoint – building a transportation system that responds to mostly exogenous changes to the demand for transportation services – has implications for the planning process. Since this framework separates the demand-generating variables from the process of transportation system planning, it thereby restricts the set of options available to technology-related and operating variables.

A similar distinction between demand-side and supply-side options can be seen schematically in Manheim (1979). This diagram also illustrates the importance of the prediction models in specifying cause and effect relationships between options and impacts.

Figure 2. Basic Prediction Models for Transportation Options and their Impacts



Adapted from Figure 1.8 in Manheim (1979)

Manheim eloquently described the role of transportation system builders in the following manner. "*The challenge of transportation system analysis is to intervene, delicately and deliberately, in the complex fabric of a society to use transport effectively, in coordination with other public and private actions, to achieve the goals of that society*" (Manheim, 1979, author's italics). Notwithstanding, for operational purposes, the options or "decision variables" for that intervention, for designing transportation were typically much more blunt. The actual options, while subdivided into "transportation options" and "activity options," were almost entirely restricted to the transportation options such as network structure and system operating policies. In this sense, activity-system options, which relate to the drivers of aggregate demand for transportation, were perceived as exogenous for the purposes of system design.

Within the policy arena of urban transportation systems, some analysts suggested that at least until the early 1980s, the debate and analysis of policy options remained organized around *specific technologies and services*.

> “Analytic activities have tended overwhelmingly to focus on the appraisal, advocacy, and/or incremental adaptation of these technologies and services – which we term *preselected solutions* – rather than on laying bare the character of the problems generating demands for public action or on searching with a fresh eye for remedial strategies. Paramount among these preselected solutions have been highway and transit improvements, and policy discussions have typically proceeded as if these were the only options available for addressing sources of dissatisfaction with the urban transportation system” (Altshuler, 1981).

The question here is whether the particular systems view of urban transportation systems fostered lock-in to certain categories of systems solutions, by foreclosing the potential appraisal of options which dealt with factors not considered as integral or as manageable components of the system.

Managing the System

In building systems, engineers have increasingly focused on the control, communications and location system components. In this manner, there has been an expanded definition of which components of the physical system can be designed as variables in the system. As an example, beginning in the 1980’s, many transportation engineers began to conceptualize tools for dynamic traffic management, which enables network management in real time. Controls provide for more flexibility in the network, for example, through volume changes with reversible lanes or timing of flows at various points with ramp metering or signal timing.

Crafting Policies

The systems view used in defining, modeling, planning and designing transportation systems, ultimately has a powerful impact on the policy making process. It not only frames the evaluation of the system – excluding certain factors as *external* to the system and highlighting some cause-effect relationships and at the expense of others – but also alters the process by which a final decision is reached with regard to one policy option or another.

Changing system evaluation

The definition of the system’s boundaries and components, the nature of its interaction with systems outside of those boundaries, and the internal dynamics between components, are critical to policymaking. The systems definition can determine what sets of attributes are used to *evaluate* the system. As the system’s view of the urban transportation system has changed, there has also been an expanded set of evaluative criteria for determining the ‘performance’ of the system. Whereas earlier, technical criteria and cost considerations were the dominant concerns, and therefore relatively easily dealt with using a systems analysis framework, as described above by Catanese (1972), in the post-WWII period a host of other concerns have become critical determinates of a system's perceived success or performance. For example, issues of environmental impacts, particularly air quality; preservation of ethnic, historic and neighborhood identity; safety; employment and job access; equity; and aesthetics have made the evaluation of systems incredibly complex.

Optimized or Negotiated Outcomes

As described in Haefner (1986), four broad classes of evaluative criteria have been used to assess the system: 1) economic analysis, 2) environmental impact, 3) citizen participation, and 4) implementation and financing trajectories. Haefner presents the problem of evaluating various proposed designs as being within the scope of optimization procedures, suggesting the value-matrix method as a "conceptual construct from which to develop interactions with the user and nonuser environmental impact perspective" (Haefner, 1986). This technique uses the assessments of various citizen groups to rank transportation alternatives, according to a value-weighted sum of the impact criteria, with different weights given to impacts such as air quality, noise or travel time. The option with the highest weighted sum would thus be the optimal alternative. However, this method of determining the weights for the values assigned to different systems criteria, in order to identify the "optimal" outcome would prove to be untenable.

Compounding the complexity of the many different variables used to evaluate a system, has been the increasing emphasis on citizen participation in transportation policy. Reaching an optimal design by no means guarantees that a consensus, or even a mandate for implementation, can be achieved. In the policymaking arena, beginning in the 1960s, there has been a trend toward more open and participatory processes. As the range of actors involved in the decision process expanded, the process of system evaluation and acceptance necessarily moved from finding an optimal solution to a negotiated solution. In this sense, Thomas Hughes' description of the Central Artery/Tunnel (CA/T) as a "postmodern" project is prototypical of this negotiated outcome.

> CA/T is not an elegantly reductionist endeavor; it is a messily complex embracing of contradictions…CA/T has been socially constructed, not technologically and economically determined (Hughes, 1998).

This description differs from the description of citizen participation and provided a decade earlier by Haefner, in which the engineering process remained distanced from the politics processes, which according to Hughes, shaped the final design of the CA/T.

> The engineer's job will be to fashion a set of transportation alternatives before and during the [public] hearing that has consensus to go forward for financing and implementation (Haefner, 1986).

Haefner represents the process of citizen participation as an iterative process of the transportation planner presenting the alternative designs to citizen groups for their acceptability and/or modifications. This process would be repeated at each stage from initial planning to final design and implementation, until a sufficient level of acceptance allowed progress to the next stage. Notwithstanding, it remains the responsibility of the transportation engineer to determine what are the technically feasible *alternatives*. The importance of this role of the transportation engineer not be understated, if there is validity to E.E. Schattschneider's proposition that "the definition of the alternatives is the supreme instrument of power" (quoted in Kingdon, 1994). For this reason, attention should be given to assess how the definition of these alternatives is shaped or, in some cases, even constrained by the mainstream systems approach to transportation design.

AN EMERGING TRANSPORTATION SYSTEMS FRAMEWORK - COMPLEXITY

The field of transportation systems in the post-WWII period has witnessed many advances and remarkable technological achievements, yet many of the messiest and most complex planning and policy problems with which analysis were grappling in the 1960s remain. For this reason, Manheim's statement continues to ring true, possibly with even greater emphasis today, as some transportation systems, such as those in developing megacities, are in precarious states with sometime debilitating problems of congestion and pollution. "*The challenge of transportation system analysis is to intervene, delicately and deliberately, in the complex fabric of a society to use transport effectively, in coordination with other public and private actions, to achieve the goals of that society*" (Manheim, 1979). Despite the technical, analytical and theoretical advances that the field has undergone, much of the traditional systems framework remains firmly in place. For many of these complex problems, assumptions about systems – such as rationality, equilibrium, homogeneity, perfect information, linearity, stability, and order – continue to hold. While this is a broad generalization for an extremely diverse and multidisciplinary field, these assumptions seem to form the underpinnings of most of the broadly-accepted theories and methodologies.

Applying Complexity Theory to Transportation?

Among the early groups of scientists working to develop theories of Complexity, many have found urban transportation systems to be an intriguing system to study through simulation modeling. Examples of these models can be found in Resnick (1994) and Casti (1997). However, for the purposes of planning, managing and policymaking with respect to transportation systems, the more relevant question is to what extent researchers and practitioners in transportation employ the complexity framework. Referring to Sussman (2000b), this work indicates that transportation systems are increasingly being examined in this framework:

> Transportation systems are complex, dynamic and internally interconnected as well as interconnected with other complex dynamic systems.
>
> They vary in space and time (at different scales for different components). Service is provided on complex network. Systems are stochastic in nature.
>
> Human decision-makers with complex decision calculi make choices that shape the transportation system. Modeling the entire system is almost unthinkable. Our challenge is to choose relevant subsystems and model them appropriately for the intended purpose, mindfully reflecting the boundary effects of the unmodeled components (Sussman, 2000b).

In fact, in *Introduction to Transportation Systems*, transportation is emphasized as prototypical of Complex, Large, Integrated, Open Systems (CLIOS). Although most of the literature linking transportation systems to the ideas of complexity theory focuses on urban transportation networks, typically in the form of agent-based modeling of individual drivers, the concept of CLIOS is extended to all transportation modes from freight transport, railroads, ocean shipping (Sussman, 2000a),

Modeling from the Bottom-up

One area in which one can clearly discern a link to the concepts of complexity theory is in simulations of urban transportation networks. In transportation modeling, many analysts have begun to apply the methods of agent-based modeling. The most notable of these models is an agent-based micro-simulation of urban traffic patterns called "TRANSIMS" (Transportation Analysis and Simulation System). The model was developed in the mid-1990s by researchers at Los Alamos National Laboratory, which is not surprising, given the lab's geographical and intellectual proximity to the Santa Fe Institute, the hub of the Complexity community. The model's developers describes the underlying philosophy of TRANSIMS as the following:

> Individual behaviors and their interactions, as constrained by the transportation system, generate the transportation system's performance. To effect that performance in a simulation, individual behavior must be modeled (Bush, 2000).

Because it is agent-based, the model simulates all entities of the traffic system – from travelers to traffic signals – as individual agents with specific rules of interaction (Nagel, et al, 2000). The movement of individuals is simulated in one-second time increments, with each individual vehicle moving across the cellular automaton grid cells of the transportation network. While the model breaks from other simulation models in terms of its extremely high level of disaggregation and adaptive interactions between individuals, many of the underlying concepts evolve quite naturally from the general analytical shift in transportation modeling that has occurred during the past decades. This shift includes a move from representing traffic as deterministic flows between fixed origins and destination to examining the internal dynamics and adaptive behaviors of heterogeneous agents moving on an uncertain landscape.

In terms of its quality, the model represents a richly detailed and overall accurate description of the traffic system of Albuquerque, New Mexico, the town for which the modeling technique was first applied.[6] In addition to recreating features of the actual system such as traffic jams, "the models has also been used with considerable success to test the effects of 'perturbations' of the system, such as new traffic light patterns or additional roads or bridges" (Gross and Strand, 2000). That said, as new systems modeling practices are developed, in determining the "quality" of a model, an important consideration is the purpose for which that model is constructed. Gross and Strand (2000) identify three types of uses for models:

- Predictive models – prediction the future states of a specific, real system,
- Explanatory models – elucidation of "essential" mechanisms, typically of a class of systems at a more general and/or idealized level,
- Heuristic models – invention and discovery of unknown emergent properties of some real or formal system.

In the case of the application of TRANSIMS to Albuquerque, its high degree of accuracy would enable its use as a *predictive model* for changes to the existing systems such as different operations procedures (signal timing) or altering the infrastructure itself (adding links to the

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[6] Other cities to which the TRANSIMS model has been applied include: Portland, Oregon and Dallas-Ft. Worth, Texas.

network). For longer term planning purposes, as opposed to more traditional forecasting-based methods, the use of simulation models such as TRANSIMS allows planners to play what Casti calls "what-if games" such as:

- What effect would a new bridge across the Rio Grande have on rush hour traffic?
- What if traffic were metered entering Interstate 25 and/or Interstate 40?
- How do the traffic-light patterns on Central Avenue (another major east-west artery) affect rush hour densities on the bridges? Casti (1997).

Despite the countless questions that can be asked with such a model, TRANSIMS' predictive quality is contingent upon the supply of vast amounts of data including origin-destination surveys, detailed demographics, and spatial distributions of household and employment locations. Given this highly data-intensive and context-specific modeling exercise, two questions arise. First, to what extent can more generic 'systems features' be extracted from the context of that system? This has important implications for the application of these models in a broader range of settings. For example, many of the world's most highly problematic urban transportation networks are in developing countries, where typically there is a dearth of the type of data needed for these agent-based models. A second and related question is: without the data needed to construct models for these regions, would there be any validity in transferring TRANSIMS to use as an *explanatory model* for cities such as New Delhi or Bogota? These systems may share many properties as a general class of systems. Yet, can one claim that the "essential mechanisms" are the same for these systems, when it is known that at the agent level, for example the private automobile or jitney driver, the agent-level "rules of interaction" (or "rules of the road") are quite different? The same argument applies to the concept of *heuristic models*, will the same emergence properties recur in different settings, or is the output of the model bound to its context?

Complexity and Control

On the modeling front substantial progress seems to have been made with the predictive properties of new agent-based simulation models performing as well as, if not better than, the more established models broadly based on network flow analysis. Furthermore, with regard to the explanatory properties of modeling, these agent-based models seem to be providing new insights as well by identifying the many of the micro-level decision rules that lead to unanticipated emergent properties. Nevertheless, despite the growing number of accurate and realistic simulations of transportation systems, it might be a chimera to expect that a high degree of control over the system can be exercised. "An algorithm that allows one to simulate the dynamics of a nonlinear system starting from a specific state does not necessarily allow one to control that system" (Lloyd, 1995). Controlling nonlinear systems remains an extremely difficult prospect for two reasons.

First, while an agent-based simulation model may accurately and efficiently compute the consequences of a particular sequence of controls, it is a much more daunting computational task to begin with a "desired outcome" and find the particular sequence that drives the system to that outcome. For example, using TRANSIMS, one could quickly determine how the traffic-light patterns on Central Avenue affect rush hour densities on the bridges. Notwithstanding, if one were to specify a desired rush hour density for each bridge, one would then have to search through an exponentially large space of potential traffic-light patterns to identify which one was the solution. This type of problem falls in computational complexity class NP – for which "the problem of finding an adequate set of controls is hard" (Lloyd, 1995).

Second, even if found, the application of an "ideal" set of controls that leads to the desired outcome may not actually produce the anticipated state, due to the vast number of possible perturbations to the system. This is especially true with open system such as transportation, which remain subject not only to broader environmental fluctuations (i.e. weather) but also to the random components of the decision rules employed by the operators (i.e. automobile drivers).

Notwithstanding the technical challenges involved in this type of modeling, efficient network simulation is an important factor in the ability to work on dynamic traffic assignment in real time. "We have the ITS technologies that allow us to monitor flows in real-time, which allows us to deploy control strategies so that we can optimize how a system operates in real time" (Sussman, 2000a). The question is whether or not the optimal solution can be computed in real-time using these types of models; as noted above, this a problem of computational complexity class NP.

Viewing this problem through the lens of complexity theory, a different possible approach would involve an even greater decentralization of information to the individual agents, drivers and operators of vehicles. In this case, rather than centrally processing the information, in order to find an optimal real-time strategy for controlling network flows, using mandatory speed limits ramp-metering rates and routing instructions, the system would directly provide agents with that information. The clear hazard in this type of strategy, in which the *individual agents* adapt to information, rather than having the *system itself* response to that information, lies in the capricious nature of emergent systems. While the notion of adaptation might seem to indicate that the emergent behavior would eventually converge to more efficient network operation, there is really no guarantee that the system would necessarily be optimal. While the emergent state could be a smooth flow of traffic, with people quickly learning how to use information to choose the appropriate routes, speed or timing of travel, the emergent state follow a more destructive non-linear trajectory, with individual decisions leading perhaps to hyper-congestion and gridlock.

Perhaps one manner in which adaptation to a desired system state may be more quickly precipitated is through agent learning processes. Do drivers soon learn to recognize certain persistent patterns in the system, and make decisions that actually lead to a "better" system state? The question here is the relationship between *information* and *behavior* of agents. As noted by Lloyd (1995) dynamical systems can be viewed not just "as simply behaving, obeying the laws of physics," but also "as processing information: how systems get and use information determines how they behave." An agent's procedure for processing information will alter itself as it gains further information about the system – this learning process takes the form of agents modifying their predictions about the system, in response to whether their previous predictions were correct or not. For example, if a driver's strategy to avoid traffic actually puts that driver right in the middle of a traffic bottleneck, the strategy will probably be revised when a similar pattern arises in the future.

The Power of a Metaphor

Whether or not agent-based simulation modeling for transportation planning and management becomes widespread practice, there are still ways in which Complexity could impact the future evolution of transportation systems. While we have explored the *models* of Complexity, perhaps more influential is the systems paradigm imparted by the *metaphors* that are used to describe complex adaptive systems. Indeed, as noted by John Holland, one of the Santa Fe Institute's founders, models and metaphors provide many of the same functions. By abstracting from the actual phenomena being observed, models and metaphors can reveal the underlying mechanisms as well as the regularities and patterns in structure and behavior. Above all, they both "enable us to see new connections" (Holland, 1998). The intuitive nature of many of the metaphors employed to describe complex systems and their behavior implies that this complexity view of systems might take hold in the policy community.

Understanding the dynamics

For the purposes of strategy in industry, David Levy notes that the complexity paradigm, by rejecting the reliance upon "traditional reductionist framework" enables managers to understand that industries are dynamic, non-linear systems. He points to several implications of complexity theory for strategy (as quoted in Sussman, 2000b):

- Long-term planning is impossible
- Dramatic change can occur unexpectedly
- Complex systems exhibit patterns and short-term predictability
- Organizations can be tuned to be more innovative and adaptive

While Levy speaks to industry in this example, similar concepts are also valid in managing transportation systems. Two of the lessons of complex adaptive systems, which could be most useful to transportation decisionmakers and policymakers, relate to the ideas of 1) counterintuitive systems behavior, and 2) policy resistant systems. While this might not necessarily give policymakers a clear indication as to what types of specific policies would best overcome these problems, an appreciation of the dynamics could enable policymakers to recognize the potential for the unanticipated impacts of policies and lock-in to particular system patterns.

Redefining the System

Clearly, transportation specialists have always had a keen appreciation of the complex interrelationships between the physical transportation system and its socioeconomic components. The transportation system have typically been seen an "embedded" in a broader socioeconomic fabric, however, for the purposes of designing both systems and policies there has remained a tendency to extract to the physical system as the object of design. There is agreement that the individual decisions of drivers, which are simultaneously operators and users of the system, impact both the current performance and the future development of that system. Yet, the tendency to for analysis and modeling the networks and flow patterns has led many planning activities to build in changes only on the technological system side, responding to the aggregate preferences and decisions of people using the systems.

By using the metaphor of co-evolution in biological systems, one may be better able to conceptualize the nature of the relationships between land-use, the environment, transportation systems, and the socioeconomic system. Could a greater appreciation of the role of individual agents lead to a greater acceptance of policies that focus on these demand-side issues (related to the "activity system" in Manheim's terminology), overcoming the problems identified by Altshuler?

> Measures entailing the direct regulation or consumer behavior or the imposition of selective price increases to influence consumer behavior have remained outside the realm of political acceptability….American politicians are drawn inexorably to technical and service innovations as a potential means of satisfying new public demands with minimal disruption to existing social arrangements and behavior patterns (Altshuler, 1981).

Similarly, could a conceptual expansion of the boundaries of the system foster organizational change within government, to lead to a greater integration of policy planning for land use, transportation and the environment?

An Emerging Framework for Transportation

Having laid out a brief, albeit hopefully indicative examination of the general trends in systems thinking for transportation, I will venture to speculate briefly about the principals that policies based on Complexity may begin to embody. To address the four questions presented at the beginning, this framework would encourage a shift in systems in terms of system 1) definition, 2) modeling, 3) designing and planning, and 4) policy-making. More specifically:

1. An expanded definition of the system will incorporate information and individual agent behavior in response to that information, as fundamental variables of the system.
   - The expanded boundaries will also promote greater integration with other system and policy domains such as land-use planning and environmental protection.
2. Computer-based simulation tools will serve as virtual experiments for long-term planning and provide real-time information to local decision-making agents.
3. More adaptive planning and design will rely less on forecasting and more on identification of good/bad emergent patterns
   - Systems would be modified by addressing not the emergent properties, but the underlying rules by which the individual agents interact.
4. Greater integration of different transportation modes will occur, focusing on the travelers rather than on the flow of particular modes
   - More open and participatory policy-making processes

Conflicting Systems Views - Air Transportation

Breaking from the consideration of urban transportation systems, I will sketch out an example of how two competing systems views could put the technological trajectory of air traffic control in civil aviation on one of two distinct paths.

Air traffic management is primarily ground-based, with "efficiency and safely obtained through the continuous, centralized control…and by the compliance to strict distance rules" (Gras, 1999). However, Gras argues that this current system of control may be unsustainable given burgeoning demand for air travel, increasing interactions between different national and regional air traffic management systems,[7] as system infrastructure constraints such as the number of airports and runways. While he does not explicitly invoke Complexity theory, his analysis invokes many of its core concepts.

> The future depends upon the balance between 'tight' and 'loose' coupling or on the level of determinism that can be maintained. Behind the apparent authoritarianism of centralization there may well be many hidden ways to change the rules (Gras, 1999).

As one of these ways to "change the rules" he also points to the idea of *free flight*, where more decision-making is delegated to the pilot, using airborne radar and anti-collision instruments and simple approach guidance. This would break from the more fully controlled flight with the "plane guided and regulated throughout the flight, compulsory routes with flight levels decided on the ground, and general flow control" (Gras, 1999). Currently, researchers at MIT are also developing communication tools that will help enable the development of this type of system.[8] Researchers at MIT have described free flight as "a system that more or less manages itself" (MIT, 2000). It is unsure to what extent the concept of free flight will be implemented. Nevertheless, this example illustrates the importance of the role of information networks, the way in which that information is processes and used by the system – in a centralized or dispersed manner – and the behavioral response of the system to that information.

Complex Policymaking

I have outlined some trends in how the epistemic community of transportation systems may begin to adopt many of the Complexity ideas and methodologies. Clearly a complexity view of transportation systems would impact policies, but in what manner? Some policy analysts have even begun to characterize the policy process using the concepts developed by complexity theorists. In the updated version of his book, which explores the nature of policymaking, Kingdon (1994) adds a new concluding chapter in which he identifies those facets of his model of the policy process that share many of the properties illuminated by complexity theory.

> First, they all find pattern and structure in very complicated, fluid and seemingly unpredictable phenomena… the structures emerge from local rules, rather than being imposed on high in some sense. Second, there is a residual randomness left after one identifies as much structure as one can, so that there is surprise and unpredictability…. Third, these models are historically contingent (Kingdon, 1994).

Since the development of these epistemic communities is in itself an emergent phenomenon, only history can judge the impact of complexity thinking on the field of transportation.

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[7] For example, the Central Flow Management Unit (CFMU) in Brussels is charged with the establishment and regulation of schedules for all European air space, including strategic planning (on the order of months and years) and tactical planning (on the order of hours) (Gras, 1999).

[8] For further information, see MIT's Center for Transportation Studies. "Trains and Planes and Cars, and People: Human/Machine Interaction in Transportation." Newsletter #41. web.mit.edu/cts/new/41/sheridan.html

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