An Agent Based Approach to Modeling the Behavior of Civil Infrastructure Systems

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Submitted To  
Engineering Systems Symposium  
March 29-31, 2004  
Tang Center, MIT

ABSTRACT  
Civil infrastructure systems – transportation, water and wastewater, utilities, communications – provide the foundation for economic growth and enhanced quality of life. The inherent complexity of infrastructure systems and the decision-making surrounding them can be formalized using complex systems theory. The models and tools we currently use for infrastructure management do not necessarily recognize this complex system behavior, but modeling system components as agents offers a mechanism to capture this behavior. This paper presents insights into network-level behavior of civil infrastructure systems using a simple simulation of pavement segments as agents.

INTRODUCTION  
Civil infrastructure systems – transportation, water and wastewater, utilities, communications – provide the foundation for economic growth and enhanced quality of life. The inherent complexity of infrastructure systems and the decision-making surrounding them can be formalized using complex systems theory. Complex systems are characterized by: 1) many agents or decision makers acting in parallel with dispersed control, 2) the presence of many organizational levels, 3) the ability of agents to adapt depending on the decisions made at other levels, and 4) the use of internal models to anticipate the future. Complex systems are also characterized by adaptive and emergent behavior at both the agent and system levels.

The models and tools we currently use for infrastructure management do not necessarily recognize this complex system behavior. Civil infrastructure systems exhibit interdependencies among the systems and the different influences and constraints on them, including the environment; the physical facilities themselves; and the financial, organizational, and political systems that govern them. Complex systems modeling can be used to understand and manage these interdependencies more effectively. Historically, we have used predictive models to support decision-making. In reality, however, such models are not always appropriate, as the decision-makers do not control the system and often are not able to intervene. For example,
improving existing infrastructure can involve many, separate units of government making decisions about investment, maintenance, financing, and pricing. At the same time, individual projects also involve large fixed costs that are irreversible, not transferable, and indivisible, resulting in increasing returns to scale and self-reinforcing behavior of decision-making.

Modeling system components as agents offers a mechanism to capture this behavior. We review the characteristics of infrastructure management decision-making agents in terms of the different types of agents, their roles, and their use of models, to better understand the interactions among agents. The hierarchical network of decision-makers includes many different types of agents, all of whom must be identified and whose interrelationships must be recognized when trying to understand the behavior of the system as a whole. Agent interactions that must be modeled include the time-dependent nature of some decisions (for example, program deadlines), the fact that some decision makers do not have access to critical pieces of information, and the many feedback loops in the decision-making process.

This paper presents insights into network-level behavior of civil infrastructure systems. First, we review the terminology used in complex systems theory and provide examples of how the concepts are relevant to infrastructure systems. We illustrate the limitations of deterministic models that do not capture the interdependencies through a series of simulations using a network of 1,000 pavement sections and various policies and deterioration models. We then introduce random behavior, interactions, and network constraints into our simulation to begin to understand the effect of the large number of different decision-making agents on the network. Finally, we draw on complex systems theory to understand why infrastructure is often neglected and deferral of maintenance is common. We demonstrate that complex systems theory provides a wider set of tools for solving infrastructure problems, with direct benefits to life cycle analysis and modeling of political considerations.

BACKGROUND

Infrastructure Management and Civil Systems

Infrastructure management allocates limited resources to address system deficiencies. This process, implemented as an infrastructure management system, provides a systematic approach to managing decaying transportation infrastructure and system improvement. These systems apply economics and engineering to understand the impacts of different maintenance, rehabilitation, reconstruction, and improvement projects over the life cycle of the specific facility or the entire network. Thus, they facilitate the prioritization of specific projects and the evaluation of different policy options. Pavement management systems (PMS), bridge management systems (BMS), and integrated asset management systems all use this approach (Haas et al., 1994; Roberts et al., 2003; USDOT, 1999).

For example, Pavement Management Systems (PMS) specifically focus on how best to distribute funds to maintain pavement segments in acceptable condition, as defined by the agency responsible. Steps in the process include data collection and system monitoring, impacts modeling, strategy selection, and strategy implementation and feedback (Haas et al., 1994). Network and project level pavement management systems have evolved over the past three decades as tools to assist in the management of pavements. These tools provide a well-organized inventory of pavements, including condition data, models to support condition prediction and performance assessment, tools for optimization and prioritization, and recognition of some regulatory and budgetary constraints. In project level pavement management systems, individual segments are identified and modeled separately, and system behavior is predicted based on
component behavior. For example, network pavement condition is forecast based on predictions of individual segment condition. This type of model is useful for project level pavement management, allowing the project manager to estimate costs and schedules. In reality, however, some segments may receive less traffic, or short segments may be rehabilitated because the contractor was at an adjoining site. This method of modeling fails to take into account the interactions between system components.

The decision-making process for infrastructure management is both bottom-up and top-down (Karaa, 1989). It is bottom-up in the sense that needs are generated from the component level, and it is top-down in the sense that budgets are dictated by high level decision-makers, often as part of the political process.

Traditionally, complex civil systems have been modeled using top-down techniques such as network level optimization (Hudson et al., 1997), input output analysis (Haines and Jiang, 2001), and system dynamics (de la Garza et al., 1998), or bottom-up simulation with little emphasis on interactions and interdependencies.

**Complex Systems Modeling**

Complex systems exhibit behavior that differs from the sum of the individual component behaviors. Bak (1996) also defines systems with large variability as complex. Infrastructure systems or projects at any scale – local, regional, state or national – do not function as isolated projects or segments, but rather as a network that serves to move people and goods from one place to another. They also exhibit significant variability in the types and volumes of traffic or usage, condition, the cost to maintain them, and their importance in terms of economic development, mobility, and quality of life. Complex systems theory can help to explain this variability and the sometimes unpredictable behavior of pavement networks.

Complex systems theory has been applied to systems ranging from biology (Resnick, 1994; Bonabeau et al., 1997) to the Nasdaq stock market (Bonabeau, 2002). Unlike physical systems (such as those studied in biology, physics, and geology), pavements respond to their environments in part because “human” agents make decisions. Therefore, we examine complex systems form the same perspective as economists (Arthur, 1999). Researchers use several different strategies for characterizing complex systems. In this section, we describe the attributes of complex systems and different approaches to modeling complex systems.

**Multiple Agents**

Complex systems are collections of inter-related elements in which the simple behaviors of the basic agents or elements combine in unprogrammed ways to produce sometimes unexpected results. In either case, these agents react to other agents and the environment in which they operate or function. In terms of agents, complex systems are characterized by (Holland, 1988): 1) many agents or decision-makers with dispersed control, 2) many organizational levels, 3) the ability of agents to adapt, and 4) the use of internal models to anticipate the future.

**Increasing Returns to Scale, and Self-Reinforcing and Adaptive Systems**

Complex systems often exhibit increasing returns to scale; these systems are also called “self-reinforcing” systems. Common properties of self-reinforcing systems are (Arthur, 1990; Arthur, 1999)

- The existence of multiple equilibria,
- Possible inefficiencies,
- Path dependence, and
• Lock-in.

Often, when a system is in equilibrium, or a “stable” state, we expect that any perturbation will die out over time, and the system will return to its original state. However, positive feedback leads to increasing returns to scale. Rather than the perturbation diminishing over time, its effects are reinforced, and the system ends in a different state than the one in which it started; the system moves to a new equilibrium. This equilibrium may or may not be an optimal state for the system. Path-dependence is the idea that early events can determine the state of a system at a much later date, and the sequence of events is important. “Lock-in” describes a state where a system cannot change to an alternate equilibrium without an external perturbation.

Self-reinforcing mechanisms can result from any one or combination of (Arthur, 1988)

• Large set-up or fixed costs, which yield increasing marginal profits,
• Learning effects, which lower costs and/or improve the product or method,
• Coordination effects, which make it profitable to follow or use an existing method or product, and
• Adaptive expectations, which enhance the belief of prevalence.

Adaptive systems respond to their environment over time. For example, biological communities respond to fewer food sources or food shortages, and other agents (including people) respond to new or uncertain information, to crowding, or market behavior (Bonabeau, 2002).

System States

Complex systems evolve to a state of self-organized criticality that can be described as on the edge of chaos. According to Bak and Chen (1991), the theory of self-organized criticality states that “...many composite systems naturally evolve to a critical state in which a minor event starts a chain reaction that can affect any number of elements in the system.” These “minor events” are especially important in path-dependent systems, including infrastructure development and management; this relationship is discussed below.

Emergent Behavior

The lack of centralized control that is characteristic of complex systems leads us to expect the behavior of these systems to be random. However, sometimes patterns emerge, or the population or system behaves in a manner that is counter-intuitive. Traffic jams, crowds, ants, and termites demonstrate emergent behavior. That is, the behavior of the system could not necessarily be predicted by simply examining the component behaviors.

Interconnectedness

Little (2002) points out that the reason we care so much about the “hardware” in a complex system is not because of the facilities in and of themselves, but rather because of the services they provide. He also observes that we have tended to focus on “first-order” effects of failures, because these are safety related and obvious. However, the ever-increasing interconnectedness of our different infrastructure systems suggests that we should focus on “secondary and tertiary effects” as well.

Agent-based Modeling

Agent-based modeling has been one approach to complex systems simulation. In agent-based modeling, system components are represented by agents with particular characteristics and the abilities to interact and adapt. Kikuchi et al. (2002) focus on agent-based modeling of transportation systems. They summarize the qualities of an agent based on the literature as “autonomy,” “social ability,” “responsiveness,” “pro-activeness,” and “learning ability.” Their literature review showed that most transportation-related applications of agent-based modeling
were to vehicle or pedestrian flow. Additional applications cited included Intelligent Transportation Systems, aircraft arrivals at an airport, travel behavior, vehicle routing, and land-use patterns.

Kikuchi et al. (2002) describe the fact that “…the individual agents do not make the globally optimal decisions” as a limitation of agent-based modeling. It is a limitation if we are trying to determine a globally optimal state. If, however, we are trying to gain a better understanding of the system dynamics (in order to identify appropriate intervention points, for example), this becomes a strength rather than a limitation.

INFRASTRUCTURE AS A COMPLEX SYSTEM

Complex system models explicitly model the behavior of the components from the bottom up. Most importantly, complex systems models capture the interactions among the components and with the environment. The end result is a representation of an emergent system in a state of self-organized criticality.

Many authors have characterized our civil infrastructure as a complex adaptive system (Amin, 2002; Heller, 2001; Little, 2002, Rinaldi et al, 2001). Chaker (2001) focuses on what he terms “disaster resiliency” of transportation systems. Specifically, he describes the transportation infrastructure as “complex, multiply connected networks of nodes and links.” He points out that “interaction among different modes of transport can affect the actual vulnerability of transportation systems,” for example, where modes intersect, or where modes act in parallel or in series. Because utilities often follow transportation rights of way, a utility failure can also have significant consequences for a transportation network. Chaker further observes that the redundancy of links on a system and the ability to substitute use of one mode for another can lessen the severity of the impact; service continues at reduced levels. Although he focused on “hazards,” many of Chaker’s observations apply equally well to failures due to deterioration or neglect of facilities and are transferable from infrastructure in general to pavements in particular. The following section explores how the concepts of complex systems apply to pavements.

To illustrate the application of complex systems concepts to civil systems we explore their application to a network of pavement segments. Most public works and transportation agencies manage a network of pavements that functions as a complex system. In this section, we investigate the concept of multiple agents as it relates to pavement management decisions from the perspective of Holland’s (1988) characteristics of complex systems. We then look at the applicability of Arthur’s (1990, 1999) characterization of complex systems in terms of increasing returns to scale and emergent behavior as it relates to pavement management decision-making. The discussion focuses on a pavement network, its managers and users, and the political decision-makers who influence its performance. We hypothesize that the network and decision-makers are, in fact, a complex system.

The Influence of Multiple Agents

As agents represent the elements of adaptive and emergent behavior, we review the characteristics of pavement management decision-making agents in terms of the different agents, their roles, and their use of models, to better understand the interactions among agents.

Many Agents or Decision-makers With Dispersed Control

For a pavement network, the agents or decision-makers include the pavements themselves, users, maintenance crews, maintenance engineers, capital improvement decision-makers, and
legislators. Control is dispersed not only geographically, but also temporally, and behavior involves not only decision-making, but also the engineering behavior of materials and the physical environment (such as soil conditions, temperature and precipitation). This also means that some decisions are made over and over again (such as whether to fill cracks), while others are non-recurring decisions (such as whether to rehabilitate a segment). The actions of the agents and the interactions between them produce the environment in which decisions are made.

Two different groups of agents or decision-makers interact with the environment in different ways. Users cause the system to deteriorate by traveling on it. System owners and system operators make maintenance and rehabilitation decisions that can improve the system or elements.

- **Users.** System users function in two capacities. First, by deciding to travel on a specific segment, users contribute to the deterioration of that segment. Second, as voters and citizens, users can influence the decision-making process. Examples of this influence include voting for candidates or referenda that support infrastructure preservation or improvement, and taking part in the public participation process for specific projects or for setting goals and priorities for strategic improvement plans.

- **System owners and operators.** If we characterize decisions as 1) tactical, 2) operational, and 3) strategic, this group of agents or decision-makers functions at three different levels (Karaa, 1989).

  1) **Tactical decision-makers**
  Tactical decisions are day to day-to-day decisions related to the quality and extent of a repair to a particular segment. The maintenance crew and the maintenance foreman or equivalent decision-maker make the decisions. The actions of these decision-makers often are not recorded or communicated to other decision-makers in the organization. Any one action or decision is not likely to impact the condition of the infrastructure significantly, but over an extended period of time, these decisions will affect condition and life cycle costs.

  2) **Operational decision-makers**
  Operational decisions establish guidelines and policies that include frequency of maintenance and rehabilitation, and overall budgets. The maintenance engineer schedules the crew and argues for resources to maintain the physical assets.

  3) **Strategic decision-makers**
  Strategic decisions are made at the top tier of an organization and involve long-term planning and financing. The decision-makers include upper management and legislators. Examples of decisions include the allocation of resources for capital improvements and capital investments for infrastructure renewal. These decisions occur at all levels of government (local, state and federal). Furthermore, decision-makers are competing for resources to enhance mobility, improve quality of life, promote economic development, and preserve and improve the infrastructure.

The separation of maintenance and capital decision-making in many organizational structures illustrates the notion of dispersed control. In addition, the users make decisions independently from the owners/maintainers. For example, while the condition of a road may influence its use, the owners/maintainers cannot dictate a user’s preferred route to work.
Many Organizational Levels
The most commonly recognized organizational levels for infrastructure systems are local, state and federal. However, much of the decision-making is hierarchical. For example, a district engineer for a state Department of Transportation (DOT) depends on the budget from the central office. This budget, in turn, is determined by the allocation of funds to the state. The amount of money available for allocation depends on the health of the economy, tax rates, revenue streams, and other needs. Between these organizational levels is a complex decision-making hierarchy that is strongly influenced by the flow or absence of the flow of information.

Regulatory agencies at each of these levels also influence productivity and decision-making. For example, environmental regulations, work rules, material specifications (to qualify for federal funds), and requirements for public participation affect the nature and timing of projects.

The Ability of Agents to Adapt
The agents outlined above adapt to the condition of the infrastructure and the resources at their disposal. For example, a district engineer will respond to a reduction in budget by postponing projects or cutting back on “non-essential” activities. Engineers will also seek innovative technologies. As most pavement networks have a high level of redundancy, users can change routes if a particular segment is too rough or there is ongoing construction activity causing user delays.

The Use of Internal Models to Anticipate the Future
While all decision-makers construct internal models, the nature and sophistication of the models vary. For example, a user may be concerned about safety or damage to his or her vehicle on a rough road; a maintenance engineer may be interested in preserving the existing investment; and a locally elected official may be interested in the response of the voters. Each decision-maker or agent uses a different kind of model to make decisions about the impacts of current decisions. A field maintenance engineer may be trying to slow down the deterioration process through maintenance; a secretary of transportation may be trying to balance the budget. Neither decision-maker is explicitly thinking about user costs. The maintenance engineer will have internal deterioration models and a sense of the life cycle cost impacts for the agency. The secretary of transportation will use basic financial models, often without any explicit consideration of the long term cost impacts.

Increasing Returns to Scale
Self-reinforcing behavior and increasing returns to scale are most clearly seen in strategies involving disinvestments in pavements through deferred maintenance or rehabilitation, use of inferior materials or construction practices, lack of quality control, and heavy usage. Under increasing returns to scale, the greater the disinvestments, the worse the condition, and the greater the need for reinvestment. Alternatively, agents can respond by taking alternate routes, lowering expectations, trading off repair for preventative maintenance, and employing other strategies to avoid catastrophic failure.

The same state of disrepair can be achieved by using inferior materials or construction practices, deferring maintenance or rehabilitation, or increasing usage. Thus, multiple equilibria exist. Inefficiencies occur as costs shift from agencies to users, from one time period to the next, or from one location to another.

Under increasing returns to scale, complex systems also exhibit path dependence and lock-in. Arthur (1988) characterizes the path dependence in complex systems in terms of three attributes:
• Exploration or derivation of a particular equilibrium or solution requires a dynamic approach;
• Allocations or choices are influenced by the proportions of each alternative present; and
• End states may be influenced by small external events or perturbations, and therefore probability enters into the model.

In pavement networks, the path dependence is reinforced by the large initial investments involved, the learning effects as decision-makers discover that catastrophic failure will not occur, and the coordination effects of following past decision-making costs.

Lock-in also occurs when the pay-off (or additional losses) is reinforced by investing in the same technology. For this reason, whole states are committed to the same pavement design and materials. Similarly, budgets are set at a level to support crisis maintenance and repair, so there are never sufficient resources for rehabilitation or reconstruction, and the agency is locked into a strategy that focuses on repair.

Emergent Behavior

In the United States, pavement management has largely devolved to the local level, but many agents hierarchically control behavior through budgets and regulation. Furthermore, users simultaneously are demanding increased accountability of government, improved pavement performance, and tax cuts. The end result is the continued erosion of budgets and degradation of pavement condition. Deferred maintenance is the norm as local engineers adapt and innovate to ensure that pavements do not fail catastrophically. Occasionally, events (such as hurricanes or earthquakes) cause catastrophic failure, or the need for major rehabilitation on extensive portions of the network causes unacceptable levels of delay.

Interconnectedness

Pavements are interconnected through geography, the network connectivity of the roadway system, the hierarchical decision-making and funding process, the jurisdictional control of a specific area, and the fact that users do not identify with a particular segment but rather with a route between an origin and a destination. Pavements are also interconnected with other types of infrastructure and utilities, as water, wastewater, storm water, electricity, and communications are often co-located under the pavement or alongside the traveled way. There are also economies of scale in contracting long stretches of pavement for rehabilitation. At the same time, there are diseconomies of scale in terms of the disruption to users. Finally, different time periods are interconnected not only in terms of deferral but also in terms of the impact of specific activities over the life cycle.

Summary

Figure 1 illustrates the relationships among the pavement elements making a complex system. In the case of pavements, there are several different types of agents. The pavement segments themselves are “unintelligent” agents, and the many different types of decision-makers are “intelligent” agents. The challenge is to capture the interactions.
SIMULATION

We designed a bottom-up experiment to demonstrate how a pavement network behaves as a complex system. The model simulates the condition of a network of 1000 pavement segments over time in response to varying environmental conditions and maintenance and rehabilitation strategies. The simulation uses standard spreadsheet software (Microsoft Excel®).

Initially, all segments are assumed to have the same design, traffic, environment, deterioration rate, useful life, and maintenance actions performed. Segments start with randomly generated conditions; each segment is assigned a pavement condition index (PCI) value uniformly distributed between 20 and 95. This implies that a pavement will never be allowed to deteriorate below a PCI of 20, and a new pavement has a PCI 95. Rehabilitation is triggered at a PCI of 30; after rehabilitation, the PCI returns to 95. We also assume that the rehabilitation cost is the same for all segments and that the deterioration function is linear, with a life of 25 years.

Under these conditions, with an unlimited budget, in the steady state, the average pavement will have a PCI of 62.5, and the expenditures on maintenance and rehabilitation are constant. On average, 40 pavement segments will be rehabilitated each year.

Figure 1. Pavements as a Complex System

CHAOS/ CATASTROPHIC FAILURE

Complex Emergent Behavior of the System

SELF ORGANIZED CRITICALITY

Interaction

Environment

Users

Managers

Decision-Makers

Section 1 Behavior

Section 2 Behavior

Section n Behavior

Pavement Section 1

Pavement Section 2

...
In reality, a network of pavements is never that well behaved. In our example, with 1000 segments over 25 years, the theoretical equilibrium described above (represented in the figures by a dashed line) is not reached. Figure 2 shows the average PCI for each year; the scale is chosen to show the variation. The maximum average PCI in any year is approximately 64, while the minimum average PCI in any year is approximately 61. The average PCI over the 25 years is approximately 63. The small group and small time frames do not represent the infinite population and time horizon. Figure 3 shows the number of segments rehabilitated in each year. The average number of segments rehabilitated each year is 40, as expected.

Using simulation, we relax or impose various assumptions to approximate real world behavior. In each case, we relate the situation to the attributes of a complex system and describe the simulation results in terms of the overall network condition, the agency cost, and the user cost. The five scenarios we use are reduced funding, changing exogenous factors causing accelerated deterioration, changing technology to provide better information, uncertainty in inputs, and recognizing network connectivity. Table 1 summarizes the results of our analysis for these five scenarios, as described below.

Figure 2. Average PCI – Base Case
Figure 3. Number of Segments Rehabilitated – Base Case

Table 1. Simulation Results

<table>
<thead>
<tr>
<th>Case</th>
<th>Attribute/ Simulation</th>
<th>Many agents/decision-makers with dispersed control</th>
<th>Many organizational levels</th>
<th>Ability of agents to adapt</th>
<th>Internal models to anticipate the future</th>
<th>Condition</th>
<th>Agency cost</th>
<th>User costs</th>
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<tr>
<td>Reduced funding</td>
<td>One year deferral</td>
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<td>✔</td>
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<td></td>
<td>Lower trigger</td>
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<td></td>
<td>Budget cut</td>
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<tr>
<td>Changing exogenous factors</td>
<td>Accelerating deterioration rates</td>
<td>✔</td>
<td>✔</td>
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<td>✔</td>
<td>✔</td>
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<td></td>
<td>Traffic growth</td>
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<tr>
<td>Changing technology</td>
<td>Inspection data</td>
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<td>Feedback</td>
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<td>Uncertainty</td>
<td>Random failures – unlimited budget</td>
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<td>Random failures – constrained budget</td>
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<tr>
<td>Networked Segments</td>
<td>Opportunistic scheduling</td>
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Reduced Funding

We investigated the following scenarios and compared them to the base case as shown in Figures 4 and 5.

- Maintenance is deferred by 1 year, but the threshold for rehabilitation remains at 30. In this case, as expected, the average condition over time decreases (Figure 4). In the steady state, the amount of money spent will remain the same. Figure 5 shows a “phase shift” from the base case to the case of deferral by one year, as expected.

- The trigger condition for rehabilitation is lowered from 30 to 25 (which is similar to deferring maintenance by approximately 2 years). In this case, the average condition again declines (Figure 4), and in the steady state, the amount of money spent remains approximately the same (Figure 5).

- The number of segments rehabilitated in any one year is capped at a level below the steady state (in this example, 30 segments) and rehabilitation is performed by fixing the worst segments first. This is equivalent to capping the budget, since in this example costs remain the same for each segment. For example, the case where only 30 segments can be rehabilitated per year is equivalent to capping the budget at 25% below what is needed. As a result, in year 1, approximately 25% of the pavements that need to be rehabilitated are ignored. In year 2, the backlog is rehabilitated, leaving 50% of the pavements in need of rehabilitation in year 2 without action. Figure 5 shows that the network condition will deteriorate to failure over time, and Figure 6 shows constant expenditures at the value at which they are constrained.
Not surprisingly, reduced funding through deferral of rehabilitation, a lower trigger for rehabilitation, reduced levels of maintenance, or simply a budget reduction results in a lower overall condition and reduced agency costs, but higher user costs. At all organizational levels – federal, state or local – reduced funding for pavement preservation and improvement may occur. Users as voters can also choose not to support capital projects in their election of political decision-makers, or bond issues or referenda they support. The complex funding relationships between federal, state, and local government requiring various levels of matching funding illustrate both the many organizational levels and the dispersed decision-making.

Changing Exogenous Factors

The deterioration rate can vary as a result of a number of exogenous factors. In all cases of random deterioration rates (meaning rates are as likely to decline as they are to increase), the average network condition over time is constant, average expenditures over time are constant, and the system will be in equilibrium.

In our simulation of this scenario, we used a normal distribution. The mean of the distribution is (65/25) (pavements have an assumed life of 25 years, 65 is midway between the best condition, 95, and 30, the point that triggers rehabilitation – the deterioration curve remains linear) and the standard deviation is 0.2 (~90% of observations fall between 2 and 3). We modeled random deterioration rates across segments, random deterioration rates over time, and random deterioration rates across both segments and time (Figures 6 and 7).
Figure 6. Average PCI Over Time – Variable Deterioration Rates

Figure 7. Number of Segments Rehabilitated – Variable Deterioration Rates
Variations in deterioration rates occur because of deferred maintenance, traffic increases from one segment to another and over time, differences in initial construction quality, differences in environment, and truck weight increases. Most of these differences actually lead to accelerated deterioration, rather than both accelerated and slowed deterioration. With accelerated deterioration, the average network condition declines, and the agency and user costs increase.

**Uncertainty**

In addition to random changes in deterioration rates, pavements may fail catastrophically in response to sudden events, such as unusual weather. We investigated what would happen if a percentage of pavement segments failed suddenly each year. Under a scenario without budget constraints, average condition improves over time. This happened because we have assumed rehabilitation restores the pavement to “new” condition; therefore, if more segments fail and they are all rehabilitated, condition of the network improves. However, if the budget is limited, as is almost certain to be the case in the real world, network condition declines rapidly as a backlog is established and grows.

**Changing Technology**

New technology provides decision-makers with more and better information in the form of data from non-destructive testing, more frequent condition assessments, more consistent condition assessments, better access to historical data, and the ability to evaluate the efficacy and efficiency of past decisions. The overall condition of the pavement network will be better, but agency costs may actually go up as the agency is responding to the actual condition and investing in new technology. At the same time, user costs will go down. The complex systems behavior is evident in the adoption of the new technology and how it supports decision-making as local agencies seek approvals to explore the new technology.

**Networked Segments**

In reality the pavement segments form a network. This is important in terms of the disruptions users’ experience during rehabilitation, and savings from opportunistic scheduling and economies of scale. To simulate this, we assume our 1000 pavement segments represent a linear network. Adjacent segments that would require rehabilitation in the year following rehabilitation would be rehabilitated at the same time as the segment currently requiring rehabilitation. Not surprisingly, the average condition improved slightly, and average number of rehabilitations per year remained the same. Assuming that this strategy saves set-up costs for the project, significant savings can be realized.

**CONCLUSION**

This paper has reviewed the basic complex systems modeling concepts as they apply to pavement management systems. We have demonstrated that a pavement network behaves as a complex system, and that a series of complex interactions occur between the individual pavement segments and the hierarchical network of decision-makers. Based on similar observations and analysis, Little (2002) calls for research in the “modeling and simulation of interconnected complex infrastructures” and how “policies affecting one infrastructure may have unintended consequences in others, due to the linkages involved.” While we support this idea, we believe that pavements can benefit from some focused efforts to capture the interactions and interconnectedness relevant to pavement systems before tackling the larger infrastructure systems, especially when physical proximity of different types of infrastructure is relevant. Our simulations also demonstrate all the attributes of a complex system. Decisions made by different
stakeholders will impact the network, but rarely is the question asked: “What is best for the network?” Catastrophic failure tends not to occur because, unlike our simulation, agents adapt to respond to particularly poor conditions. In some cases agents will anticipate the need to respond based on internal models.

Based on our exploration of complex systems concepts and our simple simulation models, we have identified three areas that require attention:

1) Decision-makers as agents. The hierarchical network of decision-makers means that there are many different types of agents, all of whom must be identified and whose interrelationships must be recognized when trying to understand the behavior of the system as a whole. This includes recognition of the time dependent nature of some decisions (for example, program deadlines), the fact that some decision-makers do not have access to critical pieces of information, and the decision-making process has many feedback loops.

2) Time is an important dimension. Pavement related activities occur as both continuous and discrete events. We did not distinguish between these in our simulation. Catastrophic events and construction events are often both modeled as discrete events, but they occur on very different time scales.

3) Geography matters. Network connectivity means that connecting segments share the same traffic. Proximity also means that some cost savings can be achieved by working on neighboring segments at the same time.

The value of life cycle cost analysis, the importance of accounting for user costs, and the benefits of better data and information are well documented. However, in reality, the condition of civil infrastructure in the United States continues to decline, as evidenced by the American Society of Civil Engineers’ (ASCE) Report Card that gave infrastructure an unacceptable grade of D+ (ASCE, 2003). Infrastructure management systems serve as tools to leverage limited resources. Complex systems theory provides an explanation for the differences between what decision support systems tell us and what is observed in practice. Recognizing that infrastructure networks are also complex systems may provide an appropriate paradigm shift to change the nature of decision-making and ultimately improve the condition of pavements.
REFERENCES


