Dynamic Networks: Modeling Change in Environments Exposed to Risk

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ABSTRACT

Modeling the interaction between interdependent systems in dynamic environments represents a promising approach to enabling communities to assess and manage the recurring risk to which they are exposed. We frame the problem as a complex, adaptive system, examining the interaction between transportation and emergency response as a socio-technical system. Using methods of spatial and statistical analysis, we overlaid the engineered transportation system on the organizational emergency response system to identify the thresholds of fragility in each. We present a research design and preliminary results from a small-scale study conducted in the Pittsburgh Metropolitan Region that examined the interaction between the transportation and emergency response systems. These results informed the design of a Situational Assessment Module for emergency managers, currently under development at the University of Pittsburgh.

Keywords

Complex adaptive systems, socio-technical systems, modeling, small world networks.

RISK AND RESILIENCE IN PRACTICE

Managing the interaction between risk and resilience represents a continuing challenge for public managers who bear legal responsibility for protecting life, property and continuity of operations in metropolitan regions. This task has become increasingly critical as recent disasters – September 11, 2001; Sumatran Earthquake and Tsunami, 2004 and Hurricane Katrina, 2005 – have ratcheted up public expectations, attention, and allocation of resources for improving performance by governmental agencies in reducing vulnerability to extreme events. The focus on homeland security in U.S. national policy has raised substantive questions regarding the design of effective strategies for minimizing risk in complex environments. These strategies also need to maximize the capacity of public agencies to anticipate and respond to threats in timely and appropriate ways under uncertain conditions. The dynamic interaction between risk and resilience (Comfort, Boin and Demchak, forthcoming) is illustrated in the policy arena of managing critical infrastructure, such as transportation networks, communications networks, electrical, water, gas and sewage distribution systems. Continuity of operations in metropolitan regions requires reliable interaction among the technical systems that provide public services and the organizational systems that manage them. In continuing interaction, the two types of systems form a distinctive meta-system that encompasses both functions in a socio-technical system for managing critical infrastructure.

Socio-technical systems raise substantive questions of cognition and measurement for the types of dynamic interactions that occur within and among the component organizations in environments exposed to risk (Hutchins, 1995). Widely varying flux in the rate and direction of interactions among organizations affects the performance of agencies that need to coordinate their actions across disciplines and jurisdictions in rapid response to an unanticipated threat. This paper examines the problem of measuring inter-organizational performance in risk environments in the interdependent context of critical infrastructure. We address two research questions:

- What are the key characteristics and behaviors of a critical infrastructure system (e.g. failure patterns) for a metropolitan region operating under stress?

- What are the primary metrics of effective performance that characterize socio-technical systems operating in metropolitan regions at risk from extreme events?

These questions serve two functions. The findings will first assist in defining the parameters and processes for reducing risk, managing security, and maintaining continuity of operations for critical infrastructure systems in vulnerable metropolitan regions. The findings will also contribute to shaping the emerging policy field of socio-technical systems. The normal risks that characterize urban environments are compounded by the size, complexity, and density of expanding metropolitan regions. Designing improved measures for modeling and managing critical infrastructure systems is essential to managing risk in the world's megacities, and to developing the resilience to recover from damaging events when they do occur.

Previous efforts to model complex socio-technical systems and their dynamics have largely not been successful. This research uses the conceptual framework of complex adaptive systems to understand and analyze such systems. This approach provides an integrated framework that is essential in addressing the interdependencies that characterize socio-technical systems.

Under severe threat, the operational capacity of emergency organizations within a complex region suffers from spreading dysfunction that compounds failure and creates new dangers for vulnerable populations. The phenomenon of cascading failure has been observed and documented in reconnaissance studies following earthquakes (EERI reconnaissance reports, 1949-2003; Comfort, 1999), after action reports by public agencies, analyses of specific disaster events (Carley and Harrald, 1997; Quarantelli, 1992), and systematic reviews of disaster research (Mileti, 1999; Platt, 1999). Equally important is the spread of adaptive behavior as emergency organizations learn of the damaging event, take proactive measures to interrupt the spread of dysfunction, and reallocate resources to maintain community operations (Kauffman, 1993).

This research seeks to characterize the dual dynamic of cascading failure and informed adaptation within social and technical systems struck by disaster under different conditions of access to information, resources, and time. The research also explores the design of models for decision support to enable practicing managers to increase the efficiency and effectiveness of continuity in operations of critical infrastructure under the conditions of uncertainty and rapid change. The models seek to capture the interaction between risk and resilience (Wildavsky, 1988; Comfort, 1994) in disaster operations. While critical infrastructure includes different types of essential services, this research will focus on the interdependence between urban transportation systems and emergency response organizations.

This paper presents findings from a study of a section of the transportation system in the Pittsburgh Metropolitan Region as a case of critical infrastructure exposed to a range of extreme events.[1] It includes a preliminary set of metrics and a conceptual model of a socio-technical system for managing risk and maintaining resiliency in a metropolitan transportation system. Data on actual traffic loads for the regional transportation system needed to test the concept and build the computational model have been collected, and analysis of these data serve as the basis for developing the computational model. Still, initial observations of the performance of the regional transportation system under varying conditions of stress confirm the significance of the study. This research has three principal objectives:

- To identify a set of metrics that includes both the technical and organizational networks which characterize the operation of a regional transportation system

- To construct a model for simulating threats to the system – and conversely, patterns of adaptive response – under different conditions of risk and resilience

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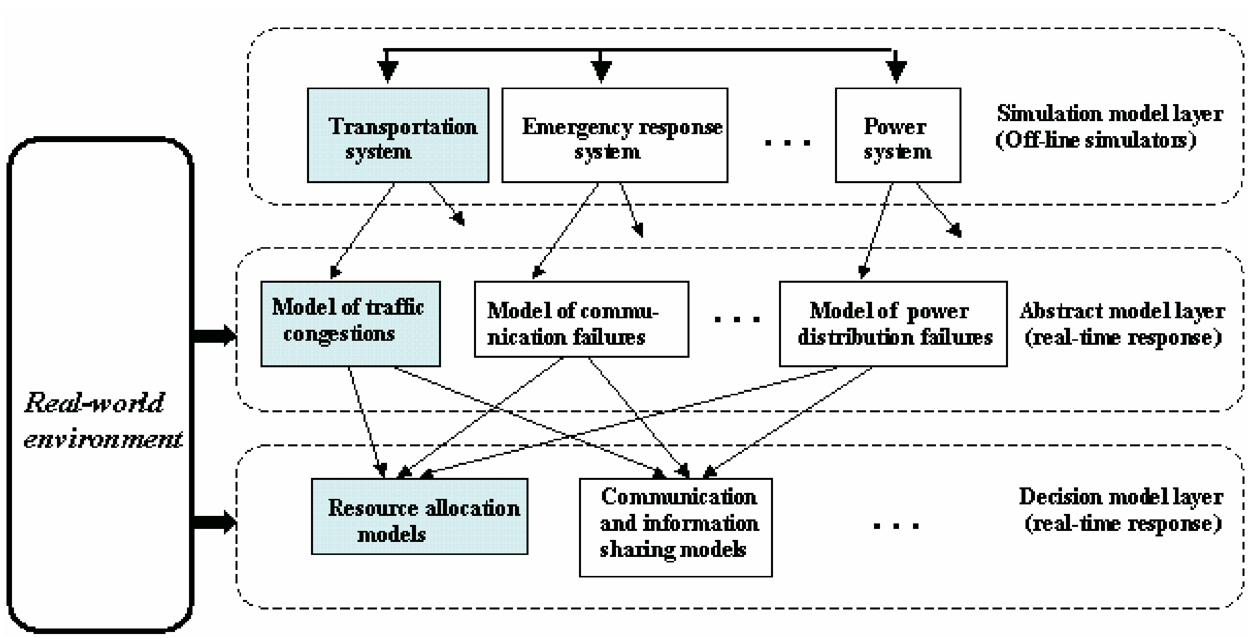
- To use the models to provide decision support to practicing managers, enabling them to increase the efficiency and effectiveness of managing risk to urban transportation systems

The basic concept is to calculate the rate of change in increasing demand from the environment exposed to risk against the decreasing capacity of the socio-technical response system under threat. The rate of change will enable us to identify the threshold point of failure for organizations operating within a disaster environment. Timely modeling of this rate of change will produce a real-time profile of gaps in performance that will enable managers with different responsibilities at different locations to take coordinated action to strengthen the regional system. This capacity would generate a self-organizing approach to the management of risk that would use local information to achieve a global goal. Timely modeling of the rate of change would also introduce a second dynamic, the system's informed adaptation to changed conditions that serves to interrupt the spread of dysfunction from the disaster event. It is the interaction between these two dynamics – spreading dysfunction and cascading adaptation – that measures the system's performance – or fragility – under threat.

Interaction rules will be extracted from the detailed characterization of the systems under evaluation and used to develop a second layer of models that simulate patterns of traffic congestion for the transportation system and communication failures for the emergency response system. These models will provide three specific benefits. First, the models will represent an abstract version of real-time response strategies for practicing decision makers. Second, the models will illustrate different options for action under different conditions, and will enable decision makers to estimate personnel, time, and resources more efficiently. Finally, the models will allow decision makers to make rapid calculation of priorities for action or allocation of resources based on actual reports of damage to the system. Figure 1 shows a diagram of the data collection, modeling, and inference processes that would provide real-time decision support to practicing managers in response to threats to a metropolitan transportation system.



(Comfort, Hauskrecht and Lin, 2004).

Figure 1. Models of the Rapid Response Emergency System

To develop computational models of a real-world environment that provide valid information to practicing managers for real-time decision support requires a complex set of monitoring and reasoning processes. Given the complexity of the real-world environment, the models are designed to abstract the critical points of interaction within each subsystem, as well as critical points of interaction between subsystems. We use a multi-step approach that first characterizes the actual structure and performance of the transportation and emergency response systems, and then develops detailed models of these systems based on data from the responsible organizations.

DESIGN AND IMPLEMENTATION OF THE STUDY

This research is an exploratory effort to design and develop a dynamic model to assess the consequences of a disaster event upon a metropolitan transportation system, and estimate the capacity of that system to withstand damage under different conditions of threat, access to information, availability of resources, and time. Some components of the research are currently in progress at the IISIS Lab, University of Pittsburgh; others are still under development. This paper presents the design for modeling the interactions of one component of critical infrastructure, a transportation system, with an organizational network, the emergency response system in a sub-region of Pittsburgh.

The challenge is to model a socio-technical system for disaster response reliably. Previously, social and technical infrastructure systems have been modeled independently. Technical networks have been represented spatially as an interconnected system of nodes and links (Ortauzar and Willumsen, 1990). Social networks have been described by a similar framework of interaction among organizations, tasks, and knowledge sources (Carley and Prietula, 1994; Wasserman and Faust, 1994). The interaction between the two types of infrastructure – social and technical – is critical in terms of assessing the vulnerability of a metropolitan region to disaster, and conversely, the robustness of its capacity to continue operations under threat.

We employ a recent advance in network research, specifically, the "small world" network model, to model both types of infrastructure. To employ this model, an infrastructure is represented in a "graph" that consists of vertices and edges, where a vertex represents a junction and an edge represents a linkage. The "small world" model was first proposed by Watts and Strogatz (1998), and was further developed by Watts (1999, 2003). The model explains how a small chain of acquaintances can connect any two people by tracking their interactions. In assessing infrastructure vulnerability, the concept of *topological robustness* from such research is useful. This concept implies that the *topology* or the *form* of an infrastructure also determines its vulnerability. Currently, there is no analytical solution to estimate the vulnerability of networks other than idealized networks such as small world or scale free networks. Numerical simulation offers a means to obtain the fragility characteristics of an infrastructure.

This exploratory research is being conducted in phases. First, we are developing a generic set of measures to characterize the socio-technical infrastructure for emergency response operations involving threats to transportation, based on the Pittsburgh Metropolitan Region. This region has a complex technical network of transportation lines and an equally complex organizational network of emergency response organizations that create an interdependent system for managing risk to transportation operations. Both types of infrastructure – technical and organizational – are being modeled using a generic set of measures of performance based on a limited section of this transportation system. In developing these measures, we build on prior work done by L. Comfort in emergency management, J-S Lin in infrastructure characterization, and M. Hauskrecht in stochastic modeling of traffic congestion.

Second, we are using this characterization of the socio-technical transportation infrastructure for the Pittsburgh Metro Region to build a simulation framework to simulate the impact of different types of disaster on the regional transportation system under different conditions of threat, access to information, availability of resources, and time stress. This process is currently under development in the IISIS Laboratory, as a Situational Assessment Module (SAM).

Third, we plan to use results from a set of simulated scenarios to develop probabilistic models of the spread of congestion in the transportation system due to a damaging event for the Pittsburgh region, as well as the cascade of proactive organizational measures taken to reduce the threat. This dynamic model will show the interaction between congestion in the transportation system due to disaster and self organization in the organizational system due to shared information. The model will specifically identify the threshold point of failure for the regional transportation system. This analysis will also identify the nodes and links within the socio-technical network that, if reinforced, would strengthen performance of the regional system and enable it to continue operations under different degrees of threat.

The results of this preliminary analysis will serve as the basis for designing a larger study of risk and resilience in the socio-technical transportation system of the Pittsburgh Metropolitan Region. In a larger study, we will convene a panel of experienced transportation and emergency managers from the region to assess the preliminary model in light of their expert knowledge of these patterns. This critical review will provide invaluable feedback regarding the reliability, robustness, and validity of the findings from the exploratory study. It will also serve as a guide to developing a strong, critical set of models for a larger, more comprehensive study of the performance of socio-technical systems under stress.

This analytical framework is intended to model the environment in which decisions to manage the tension between risk and resilience takes place. We identify major elements of the modeled environment, such as possible classes of threats, major resources required to mitigate those threats, major actors and their behavior rules, and the interaction among actors/agents and the environment. We build on prior research and a knowledge base that is under development for the Pittsburgh Metropolitan Region.[2] We are developing a simulation framework to investigate properties of the disaster response network and to determine adequate tools for policy design.

CHARACTERIZATION OF SOCIO-TECHNICAL INFRASTRUCTURE SYSTEMS

To model the fragility of an infrastructure, we rely on percolation theory (Peitgen, Jurgens and Saupe, 1992) in developing the necessary metrics. Percolation analysis is a study of the distribution of failure cluster size and phase transition. It provides a framework for developing quantitative measures for tracking when a system transitions from a stable phase to a failure phase. That is, a system reaches a critical point or a phase transition point when the failure cluster grows to an extent that the network is no longer connected. The general approach is to simulate a disaster, such as an earthquake, that causes damage over a large spatial area, and to determine whether the infrastructure of the area will maintain its operational capacity. This is defined as the ratio of the largest cluster formed by failure components to total components.

Modeling Vulnerability of Technical Infrastructure for Transportation

A preliminary study (Lin, 2003) carried out on the highway network around the Allegheny County, Pennsylvania. Figure 2 identified the original highway network that includes state maintained highways in the City of Pittsburgh. As a first step, only the part of highway that has daily traffic above 10,000 vehicles is investigated, which is shown in Figure 3. For practical application, more direct metrics are proposed (Lin, 2003).

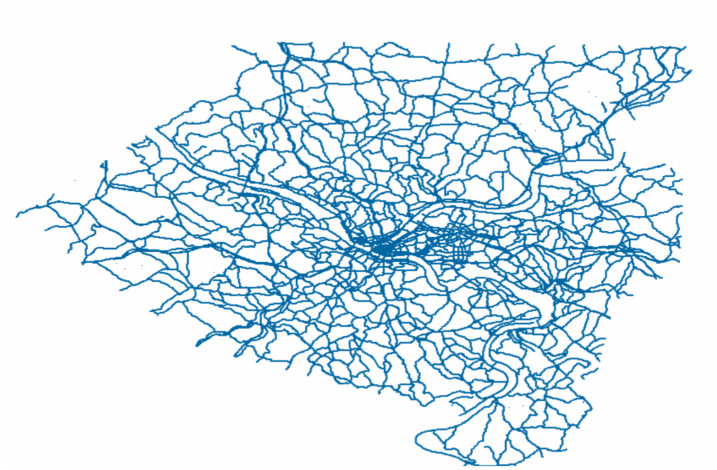


Figure 2. Highway Network around Pittsburgh

[2] *See* IISIS – An Interactive, Intelligent, Spatial Information System for Disaster Management, available at: http://www.iisis.pitt.edu/, last accessed March 15, 2008. Account name = demouser@pitt.edu; password = mypasswd.

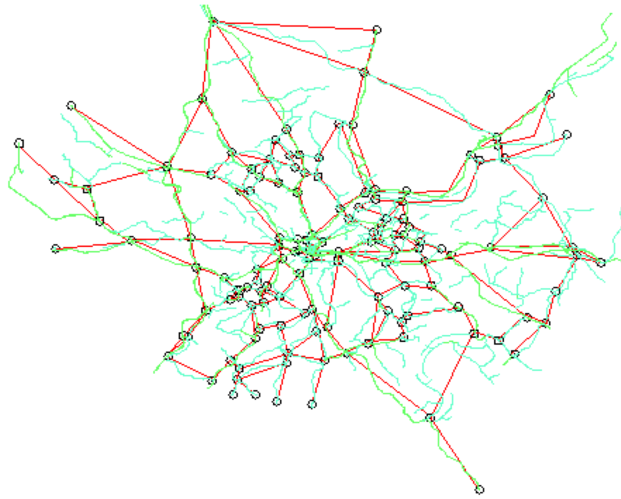


Figure 2. A Graph Derived from Allegheny Highway Network

The stressed diameter is defined as the longest distance to which any point can travel and the stressed characteristics path is the average distance that can be traveled. The current study is modeling the transportation system of the Pittsburgh Metropolitan Region along similar lines. The dynamic variable, used as an indicator or risk, will be the flow of traffic through the system. Data from actual traffic flows for a limited section of this transportation system have been collected with the assistance of the Pennsylvania Department of Transportation. The study also identifies the most significant vertices in this section, which upon their removal will cause the most damage to the transportation capacity for the Region.

Modeling Vulnerability of Organizational Infrastructure for Disaster Management

Similar analysis is being used to characterize the emergency response network that responds to disruptions in the selected area of the metropolitan transportation system. The emergency response organizations are being modeled as an organizational network (Prietula, Carley and Gasser, 1998; Carley, 2000), reflecting the existing emergency response system in the Pittsburgh Metropolitan Region. The vertices are the loci of authority for decision making within and among the organizations and jurisdictions. The edges are the laws, policies, and procedures that govern strategies of communication and action (Federal Emergency Management Agency, 2000; Allegheny County Emergency Management Agency, 2000). In addition, the cost of transactions (Williamson, 1975) in terms of time and resources required for response to actual incidents will be calculated as a measure of their capacity for action. The dynamic variable, used as an indicator of resilience, is the number of messages that flow through the network of emergency response organizations as they mobilize action in response to incidents of traffic congestion. A detailed study will identify the most significant vertices in this organizational communications system, which upon their removal, would cause the most damage to the emergency network's capacity for communication and coordination of response actions in the Region.

Modeling the Interaction between Social and Technical Infrastructure Systems

The second research question explores how the two types of infrastructure with different attributes interact, and what impact such interaction has on the operation of the regional transportation system, now defined as a socio-technical system exposed to risk, but with resources to demonstrate resilience under threat or heavy demand. Since both the transportation network and emergency response network are spatially distributed, we use spatial correlation as a means to determine how overlapping clusters of failure in the technical and organizational subsystems may adversely affect performance of the larger transportation system. That is, we will examine how patterns of clustering failure in traffic flow (a measure of risk) accelerate the deterioration of an organizational response system under stress. Conversely, we will investigate how the survival components remain connected to assess the resilience of the affected organizations to respond to the demand. This analysis will model the interaction between social and technical networks to enable disaster managers to enhance the performance of the regional infrastructure system under dynamic or threatening conditions.

Building the Simulation Framework

Our simulation framework will be built upon the socio-technical network as discussed. The simulation will address the propagation of failure when risk cumulates to disaster at any particular location. The simulation can be conducted once the interaction rules are determined. This critical step is, however, domain-dependent. This study will obtain the interaction rules through data gathering, survey of experienced managers, and pattern recognition.

Simulation of the Transportation Network

The study conducted a micro-traffic analysis that used small numbers of intersections surrounding a given vertex in our transportation graph. Different scenarios were examined to generate sufficient data for a local stochastic characterization and to train the congestion model. For the transportation system, data are gathered from agencies that monitor the flow of traffic on the roads, e.g., Pennsylvania Department of Transportation and Pennsylvania State Police. These data were used to extract interaction rules that represent recurring behavior of transportation and emergency response systems under different conditions of threat, access to information, resources, and time. For example, an interaction rule may state a relationship between speed of traffic and number of vehicles for roads with different capacities or lanes of traffic.

Simulation of the Emergency Response Network

At this stage in our modeling of the organizational infrastructure that assists the decision process for an emergency management system, not all the components are represented in numerical data. For the emergency response network, data have been gathered from emergency plans, protocols and policies for emergency response, and collected from operations logs from previous incidents. We initially tracked the flow of information among the organizations engaged in emergency response operations. These measures include the number of messages sent, the direction of message flow, and urgency of need, according to priorities defined by emergency managers. These priorities are defined in Standard Operating Procedures for first responders and in the assignment codes used by 911 dispatch operators. They roughly reflect the categories of 1) protection of life; 2) protection of property; and 3) continuity of operations for the community. We used operations logs from previous incidents in the Pittsburgh Metropolitan region to establish the parameters of information flow among emergency response organizations in the selected study area, and use these parameters to simulate the search, exchange, and adaptive behavior of emergency response organizations for disasters of different magnitudes and duration.

For emergency response organizations, an interaction rule may state a relationship between distance from the incident and response time for emergency vehicles garaged at fixed locations, or number of calls received and actions taken for a fixed number of emergency personnel.

In this application of a complex systems framework to investigate decision making in disaster management, we introduce three concepts to simulate this process. First, a meta-agent is introduced. The meta-agent plays a role in coordination and control just as higher level organizations or executives do. Second, we adopt the Bayesian Network (BN) for the reasoning process of meta-agent. The BN allows us to model the conditions of incomplete information and uncertainty of human decision making.

Simultaneous Simulation of Social and Transportation Networks

Once the interaction rules for the “organizational infrastructure” and “physical infrastructure” are developed, we carry out percolation analysis on the coupled infrastructure. This analysis addresses two questions: 1) how can decision making related to disaster management be improved, given a predictive model of the underlying physical infrastructure; and 2) how can organizational decision processes be designed to minimize the impact of disaster events upon a stressed physical infrastructure? This analysis is necessarily preliminary, but it will provide insight and have implications for the research that follows.

DECISION-SUPPORT MODULE

This process of characterization of critical infrastructure, model building, and inference processes contribute to the goal of this research, a decision support module that will enable practicing managers to increase the efficiency and effectiveness of disaster operations under conditions of uncertainty and rapid change. The products of this research would be incorporated into the current prototype, Interactive, Intelligent, Spatial Information System (IISIS), a decision support system for emergency managers that has been developed at the University of Pittsburgh for hazardous materials management.[2] The IISIS prototype is a working distributed system, developed with the support and advice of practicing emergency managers in the Pittsburgh Metropolitan Region. Models from this research would extend the IISIS prototype for wider application to a range of hazard events in managing risk to transportation infrastructure.

CONCLUSIONS

The research presented above is still in progress; yet preliminary findings from the analysis conducted to date are summarized below. The proposed analytical framework shows strengths, but also weaknesses, primarily due to the limitations of the data available. We were able to obtain findings in the following three areas.

Fragility of the Transportation System

1. Based on the traffic flow data recorded by the PennDOT sensors, we found that the spatial correlation of traffic is strong over a large distance; that is, the stochastic dependence extends beyond the immediate neighboring sensors. This has an important implication for stochastic traffic modeling, which is crucial for the decision support needed for dispatching first responders.

2. Boundary effects are important in the development of failure metrics. We confined our study to Allegheny County and built an infrastructure network only within the county boundary. As a result, nodes on or near the county boundary give skewed small world parameters and metrics. This issue needs to be resolved for urban transportation systems.

3. The occurrence of accidents had the anticipated effect of slowing traffic. We documented the drop in speed of traffic following an accident from sensors monitoring the traffic.

4. Using the 911 data available for the City of Pittsburgh's Emergency Medical Services and Fire Department, both important components of the City's emergency response system, we found seasonal variation in response time. Performance was measured in two ways, the amount of time spent on scene, and response time. Response time was measured from the time that an emergency unit was dispatched to the scene of an accident to the time that the unit reported arrival on scene (on scene arrival time - dispatch entry time).

5. The severity of the accidents also had an impact on traffic, but the actual number of accidents classified as major, critical or severe that occurred during this time period was relatively low, 19 out of 330, or 5.75%.

6. Like the "small world" model, we built an "undirected" graph for a transportation network. Such a model dictates that traffic on all lanes and both directions is blocked when an edge, or route, failed. This limits the use of a percolation study to only large hazards. For most traffic incidents, the "undirected" graph would not be very useful and should be revised. In future study, we will instead use a "directed graph." Additional attributes will also be included. These attributes will include the number of traffic lanes in each direction, the capacity of the roadway, and the jurisdiction. A more sophisticated percolation model will also be built.

Fragility of the Organizational Response System

1. We found a complex series of interdependencies that characterized the ownership of the roads in the metropolitan transportation system and the legal responsibilities of the municipalities, county, and state agencies involved in emergency response operations.

2. The ownership of the roads in the metropolitan transportation system is often marked by jurisdictional boundaries, but not always. For example, a single road may travel through multiple jurisdictions, e.g. a state road becomes a county road and also traverses a municipality. In most instances, the responsibilities for maintaining the road falls to the higher jurisdiction, but access to these roads remains with the lower jurisdiction. For example, the state will maintain a state road, but the county or municipality must maintain the on- and off-ramps for the exits and entrances to the state-maintained road.

3. The interdependence of ownership and the financial costs of organizational response create a major problem in asymmetry of information that likely has an effect on organizational capacity for response. This problem will be explored in further research, specifically in simulating performance of the system under different conditions of access to the roadways and authority to engage in response operations.

4. Using the 911 data available for the City of Pittsburgh's Emergency Medical Services and Fire Department, both important components of the City's emergency response system, we found seasonal variation in response time. Performance was measured in two ways, the amount of time spent on scene, and response time. Response time was measured from the time that an emergency unit was dispatched to the scene of an accident to the time that the unit reported arrival on scene (on scene arrival time - dispatch entry time) over a total of 1806 observations.

Interaction between the Transportation and Emergency Response Systems

1. We found 330 cases of matched incidents – reported traffic accidents (identified from PennDOT data) to which emergency response units had been dispatched (identified from Allegheny County 911 data). In this process, we demonstrated that both datasets could be accessed and that it is possible to characterize the demand on the emergency response system from traffic accidents as well as the capacity of the existing emergency response system to meet that demand.

2. The analysis of matched incidents revealed that the burden of emergency response to traffic accidents reported by PennDOT fell primarily on the City of Pittsburgh, not on the municipalities traversed by the state-maintained highways. The reason for this distribution was the physical access to the freeway provided by the entrance and exit ramps. Even though the freeway ran through the geographic boundaries of small municipalities and the accidents occurred within their jurisdictions, the entrance and exit ramps closest to the Fort Pitt Tunnel were located within the jurisdiction of the City of Pittsburgh. Consequently, the County 911 dispatch system, basing their allocation decisions on speed of response, assigned the City of Pittsburgh emergency response teams consistently in terms of access to the freeway.

3. The analysis of the integrated traffic incident and emergency response data demonstrates that a regional system of emergency response to traffic accidents does operate within the Pittsburgh Metropolitan Region. This regional system shows that recurring interactions are largely between the state transportation agency (PennDOT) reporting the accidents, the Allegheny County 911 dispatch system assigning emergency response units, and the City of Pittsburgh emergency response units that are closest to the location of the accidents in terms of freeway access. The emergency response units of the smaller municipalities play a much lesser role in response to traffic accidents on the freeway, even if the accidents occur physically within their geographic boundaries.

4. The detailed analysis of the traffic flow in the study region documents that the primary cause of vulnerability in the transportation system of the Pittsburgh Metro Region is not traffic accidents, but rather recurring congestion caused by overloaded roadways. This finding points to a different set of policy strategies for relieving congestion that focus on the management of traffic and the provision of timely information to drivers that would allow them to adjust their driving patterns more efficiently to the actual capacity of the roadways.

5. These findings complement similar findings from another research project that analyzed data from the Pennsylvania Emergency Management Agency and led to the development of a mathematical model for measuring the degree of symmetry/asymmetry in information processes among organizational systems composed of diverse operating units. The model could be used to calculate the effect of asymmetry in information processes upon performance of the transportation system. Exploring this effect will be a major task in our continuing research.

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