

Visualizing Complex Networks: Graph-Theoretic and Raster-Based Approach

Laurie A. Schintler, GMU

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Motivation for Research

- Analysis of Critical Infrastructure
 - Identification of Critical Nodes and Links
 - Understanding of Network Failures: Malicious or Unintentional
 - More specifically, to develop a methodology that can be used to identify potential vulnerabilities in critical infrastructure
 - "an acupuncture map of the country so we will know where to harden our protection...a map of all the interdependent telecom and IT networks, gas pipelines, railroad systems, and electric power lines" (Yasin 2002)
- Transportation Planning at the Operational Level
- Long-Term Transportation Planning
 - Capacity Expansion
 - Redesign of Transportation Networks

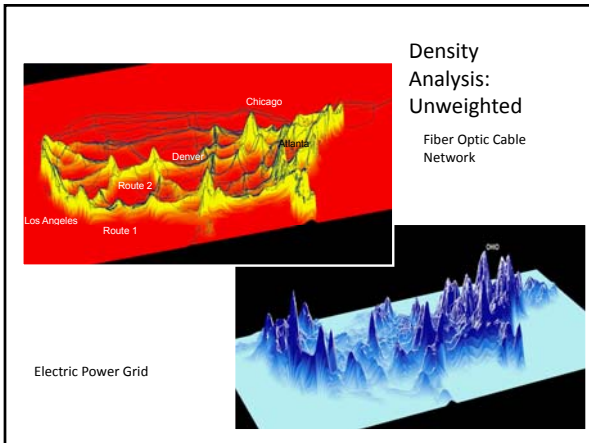
Complexity of Large-Scale Infrastructure Networks

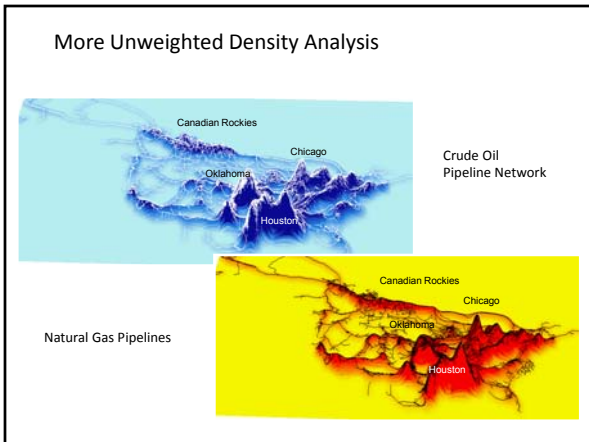
- Large Networks: links and Nodes
- Network Topology: Scale Free Networks
- Interdependencies and Cascading Failures: crude oil, refined products, electrical grid, road network
- Supply, Demand, Prices: Spatial Dimension
- Anticipatory Effects in the Market
- Multiple operators and owners of infrastructure

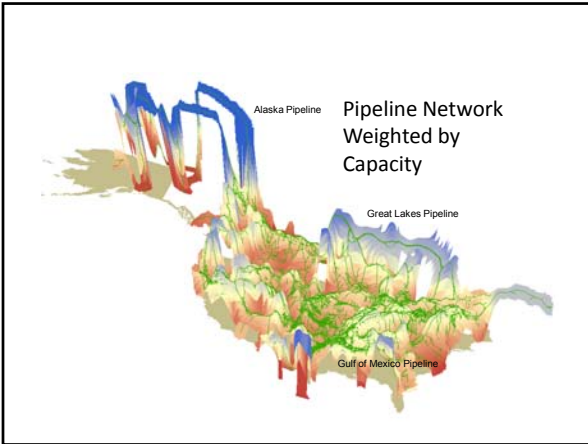


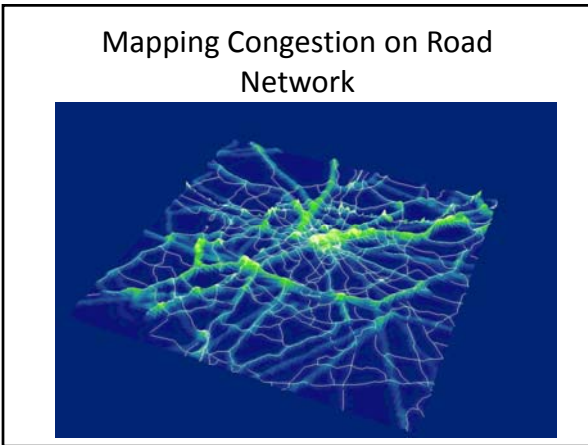
Identifying Critical Nodes/Links in Large, Complex Networks: Density Analysis

- Convert lines to points: polyline to point theme in GIS
- Use raster analysis to measure the density of the points
 - Unweighted or weighted by some attribute
- 3d maps of density help to highlight critical locations







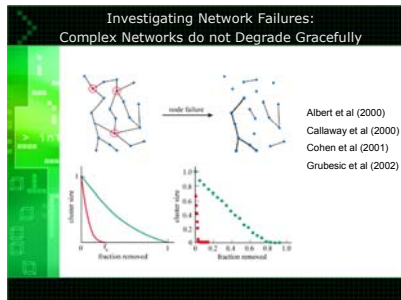


Disadvantages of Density Analysis

- Tends to highlight locations where there is a lot of infrastructure and redundancy as being critical
- Does not capture network topology

Identifying Critical Nodes/Links in Large, Complex Networks: Graph-Theoretic Density Analysis

Complex Network Theory



Graph-Theoretic Approaches

- Reed (1970) Indian airline, failure simulations, small network
- Erdos-Renyi – large networks, random (Poisson distribution))
- Albert (2000) – networks not random, Power law distribution, targeted attacks
- Critical Infrastructure - Grubestic (2003) major hub city removal, Gorman et. al. (2003)

Shortcomings of Approach

- Potential loss of geographic accuracy
- Challenges in identifying links and nodes
- Computational issues
- Difficulties in capturing network interdependencies – e.g., transportation and fiber optic cable
- Difficulties in capturing network failures
- Problems associated with “bad data”: e.g., discontinuities in road segments
- Visualization Issues

Grid-Based Approach to Vulnerability Mapping and Assessment

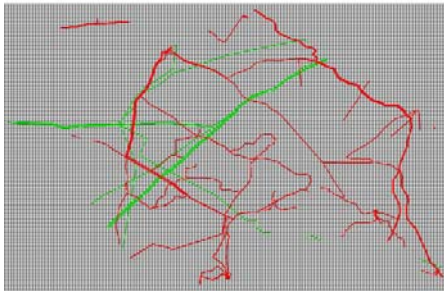
- Convert lines to points
- Overlay grid
- Assign attributes to grid cells – e.g., point density, capacity, etc.
- Map grid attributes
- Issue: Defining the grid dimensions

Adjacency Using Grid-Based Approach

1	2	3	4	5
6	7	8	9	10
11	12	13	14	15
16	17	18	19	20
21	22	23	24	25

Edge List
1, 7
7, 13
13, 19 9 17
19, 25
....

Grid Overlay for Prototype Networks



Selection of Criticality Index

- Betweenness: measures the degree to which a node is an intermediate location through indirect relationships connecting other nodes.
- Closeness: measures how close a node is to all other nodes based on the shortest paths between that node and all other nodes.
- In-Degree: measures the number of links that have direct connections to a node.
- Clustering Coefficient: measures the degree of small-world network local clustering of a node.
- Reachability: measures the extent to which a node can reach all other nodes in a fragmented

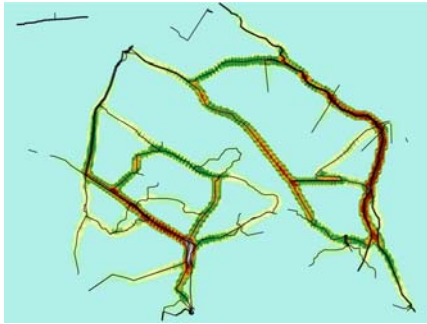
SOCIAL NETWORK ANALYSIS

Network Criticality Using Betweenness Index

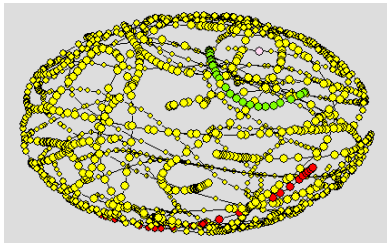


Note: Color scale in terms of criticality – white, red, orange, green, tan, blue

Network Failure and Redistribution of Criticality

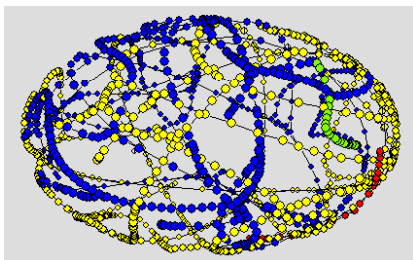


Visualization of Network Structure and Balkanization: Initial Network



Visualization Software: Pajek

Visualization of Network Topology and Balkanization After Failure

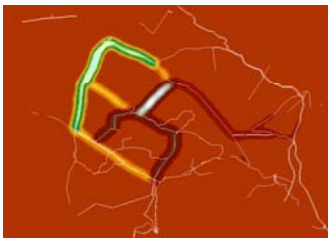


Mitigation Strategy Using Existing Right-of-Way



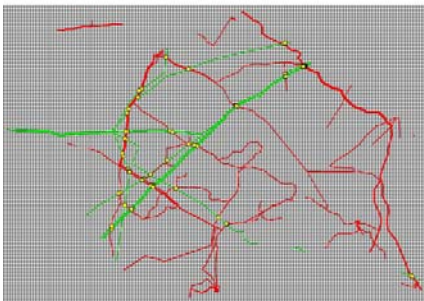
Note: Aggregate measure of betweenness declines with link addition

Redistribution of Traffic After Link Addition



Note: White and dark red indicates greatest positive change in betweenness

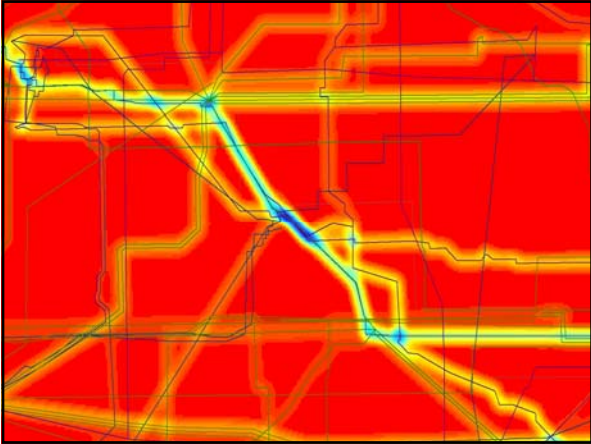
Grid Overlay for Prototype Networks: Capturing Interdependencies









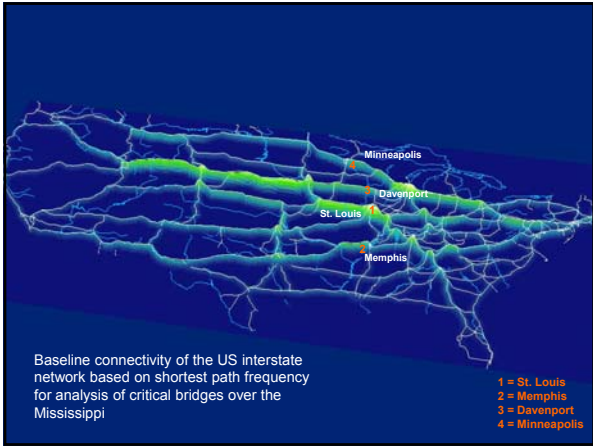


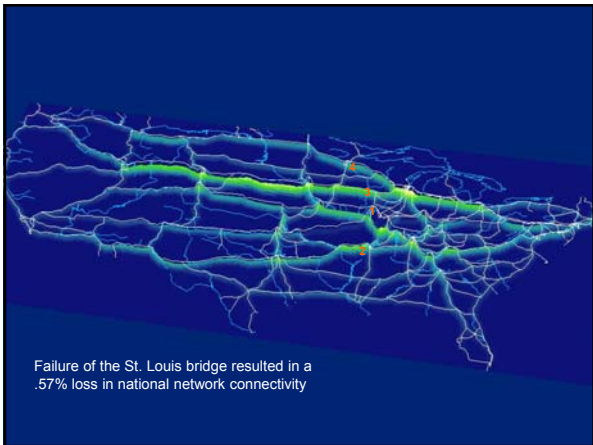
Conclusions

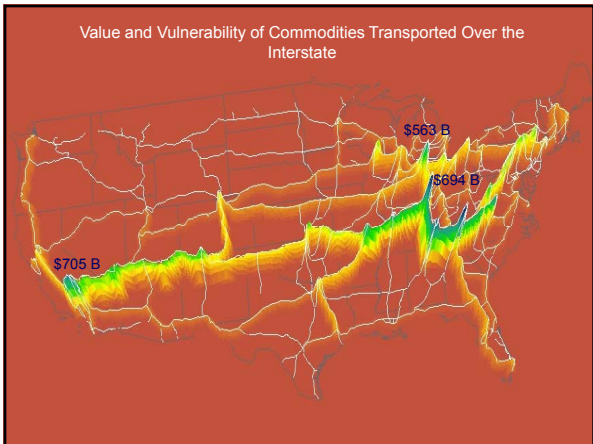
More complexities to incorporate into vulnerability analysis of large-scale networks

- Institutional
- Operational (dynamics)
- Environmental

Failure Simulation on Combined Infrastructure and 3d Visualization



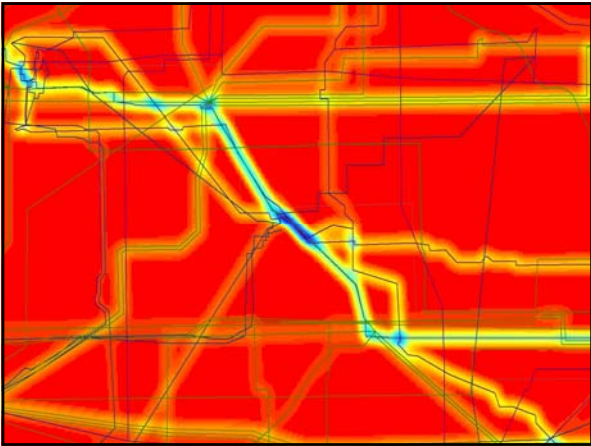




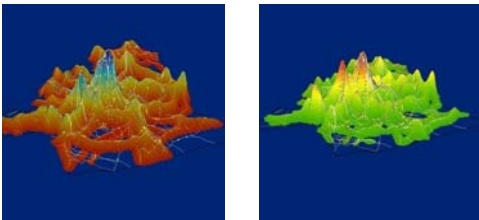






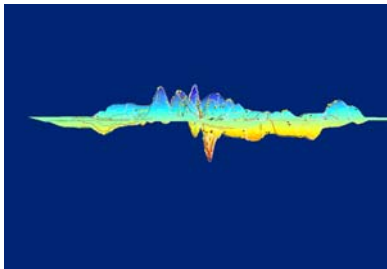


Charlotte Combined Infrastructure Before and After Failure



Note: Infrastructure includes road network, fiber optic cable, rail, gas pipeline and power transmission

Redistribution of Traffic in the Network



Note: this is based on changes in betweenness for each cell

Geographic Information Systems

- Transportation Networks (Simkowitz, 1989; Loukes and McLaughlin, 1991), Hazardous Materials Transportation
- Telecommunications – not from perspective of Security
 - (Moss and Townsend, 1997; Zook, 2000) Domain name registrations in UK
 - (Grubestic et. Al. 2004, 2002) Digital Divide
- Pipelines -National Pipeline Mapping System (DOT)
 - Route Optimization (Thorton and Buy, 2000)
 - Pipeline Safety (Porter and Parsons, 2000)
 - Threat Assessment (Nelson, 2002)
 - Emergency Response Planning (Marcotte, 2002)
- Shortcoming
 - Difficult to identify vulnerabilities when looking at map of infrastructure (absent data transformation)
