

A. T. Murray
T. H. Grubestic
Editors

Critical Infrastructure

Reliability
and Vulnerability

ADVANCES IN
SPATIAL SCIENCE



Springer

Advances in Spatial Science

Editorial Board

Manfred M. Fischer

Geoffrey J.D. Hewings

Peter Nijkamp

Folke Snickars (Coordinating Editor)

Titles in the Series

- G. Clarke and M. Madden (Eds.)*
Regional Science in Business
VIII, 363 pages. 2001. ISBN 978-3-540-41780-4
- M. M. Fischer and Y. Leung (Eds.)*
GeoComputational Modelling
XII, 279 pages. 2001. ISBN 978-3-540-41968-6
- M. M. Fischer and J. Fröhlich (Eds.)*
Knowledge, Complexity and Innovation Systems
XII, 477 pages. 2001. ISBN 978-3-540-41969-3
- M. M. Fischer, J. Revilla Diez and F. Snickars*
Metropolitan Innovation Systems
VIII, 270 pages. 2001. ISBN 978-3-540-41967-9
- L. Lundqvist and L.-G. Mattsson (Eds.)*
National Transport Models
VIII, 202 pages. 2002. ISBN 978-3-540-42426-0
- J. R. Cuadrado-Roura and M. Parellada (Eds.)*
Regional Convergence in the European Union
VIII, 368 pages. 2002. ISBN 978-3-540-43242-5
- G. J. D. Hewings, M. Sonis and D. Boyce (Eds.)*
Trade, Networks and Hierarchies
XI, 467 pages. 2002. ISBN 978-3-540-43087-2
- G. Atalik and M. M. Fischer (Eds.)*
Regional Development Reconsidered
X, 220 pages. 2002. ISBN 978-3-540-43610-2
- Z. J. Acs, H. L. F. de Groot and P. Nijkamp (Eds.)*
The Emergence of the Knowledge Economy
VII, 388 pages. 2002. ISBN 978-3-540-43722-2
- R. J. Stimson, R. R. Stough and B. H. Roberts*
Regional Economic Development
X, 397 pages. 2002. ISBN 978-3-540-43731-4
- S. Geertman and J. Stillwell (Eds.)*
Planning Support Systems in Practice
XII, 578 pages. 2003. ISBN 978-3-540-43719-2
- B. Fingleton (Ed.)*
European Regional Growth
VIII, 435 pages. 2003. ISBN 978-3-540-00366-3
- T. Puu*
Mathematical Location and Land Use Theory,
2nd Edition
X, 362 pages. 2003. ISBN 978-3-540-00931-3
- J. Bröcker, D. Dohse and R. Soltwedel (Eds.)*
Innovation Clusters
and Interregional Competition
VIII, 409 pages. 2003. ISBN 978-3-540-00999-3
- D. A. Griffith*
Spatial Autocorrelation and Spatial Filtering
XIV, 247 pages. 2003. ISBN 978-3-540-00932-0
- J. R. Roy*
Spatial Interaction Modelling
X, 239 pages. 2004. ISBN 978-3-540-20528-9
- M. Beuthe, V. Himanen, A. Reggiani
and L. Zamparini (Eds.)*
Transport Developments
and Innovations in an Evolving World
XIV, 346 pages. 2004. ISBN 978-3-540-00961-0
- Y. Okuyama and S. E. Chang (Eds.)*
Modeling Spatial
and Economic Impacts of Disasters
X, 323 pages. 2004. ISBN 978-3-540-21449-6
- L. Anselin, R.J.G.M. Florax and S. J. Rey*
Advances in Spatial Econometrics
XXII, 513 pages. 2004. ISBN 978-3-540-43729-1
- R.J.G.M. Florax and D. A. Plane (Eds.)*
Fifty Years of Regional Science
VIII, 400 pages. 2004. ISBN 978-3-540-22361-0
- D. Felsenstein and B.A. Portnov (Eds.)*
Regional Disparities in Small Countries
VI, 333 pages. 2005. ISBN 978-3-540-24303-8
- A. Reggiani and L.A. Schintler (Eds.)*
Methods and Models in Transport
and Telecommunications
XIII, 364 pages. 2005. ISBN 978-3-540-25859-9
- H.W. Richardson and C.-H.C. Bae (Eds.)*
Globalization and Urban Development
X, 321 pages. 2005. ISBN 978-3-540-22362-7
- G. Arbia*
Spatial Econometrics
XVII, 207 pages. 2006. ISBN 978-3-540-32304-4
- B. Johansson, C. Karlsson,
R. Stough (Eds.)*
The Emerging Digital Economy
X, 352 pages. 2006. ISBN 978-3-540-34487-2
- H. Westlund*
Social Capital in the Knowledge Economy
X, 212 pages. 2006. ISBN 978-3-540-35364-5
- A.E. Andersson, L. Pettersson,
U. Strömquist (Eds.)*
European Metropolitan Housing Markets
approx. 380 pages. 2007.
ISBN 978-3-540-69891-3

Alan T. Murray · Tony H. Grubescic
(Editors)

Critical Infrastructure

Reliability and Vulnerability

With 66 Figures
and 51 Tables

 Springer

Professor Alan T. Murray
The Ohio State University
Department of Geography
1036 Derby Hall
154 North Oval Mall
Columbus
Ohio 43210
USA
murray.308@osu.edu

Professor Tony H. Grubestic
Indiana University
Department of Geography
701 Kirkwood Ave
Student Building 120
Bloomington
Indiana 47405-7100
USA
tgrubesi@indiana.edu

Library of Congress Control Number: 2007921531

ISSN 1430-9602

ISBN 978-3-540-68055-0 Springer Berlin Heidelberg New York

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilm or in any other way, and storage in data banks. Duplication of this publication or parts thereof is permitted only under the provisions of the German Copyright Law of September 9, 1965, in its current version, and permission for use must always be obtained from Springer. Violations are liable to prosecution under the German Copyright Law.

Springer is a part of Springer Science+Business Media

springer.com

© Springer-Verlag Berlin Heidelberg 2007

The use of general descriptive names, registered names, trademarks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

Production: LE-TeX Jelonek, Schmidt & Vöckler GbR, Leipzig

Cover-design: WMX Design GmbH, Heidelberg

SPIN 11945567 88/3100YL - 5 4 3 2 1 0 Printed on acid-free paper

Preface

The aim of this text was to bring together differing geographic perspectives in modeling and analysis designed to highlight infrastructure weaknesses or plan for their protection. This began initially as the outgrowth of a series of lectures we organized for the Regional Science Association International conference in Seattle, Washington on November 10-13, 2004, and expanded substantially beyond this to include researchers in other disciplines and other countries. We are pleased with the final product and greatly appreciate the efforts of the contributors, referees, and the publisher.

January 2007

Alan Murray
Tony Grubestic

Table of Contents

	Preface.....	v
1	Overview of Reliability and Vulnerability in Critical Infrastructure.....	1
	Alan T. Murray and Tony H. Grubestic	
2	Transport Network Vulnerability: a Method for Diagnosis of Critical Locations in Transport Infrastructure Systems.....	9
	Michael A. P. Taylor and Glen M. D’Este	
3	A Framework for Vulnerability Assessment of Electric Power Systems.....	31
	Åke J. Holmgren	
4	Spatio-Temporal Models for Network Economic Loss Analysis Under Unscheduled Events: A Conceptual Design.....	57
	Jong Sung Lee and Tschangho John Kim	
5	Vulnerability: A Model-Based Case Study of the Road Network in Stockholm.....	81
	Katja Berdica and Lars-Göran Mattsson	
6	Survivability of Commercial Backbones with Peering: A Case Study of Korean Networks	107
	Morton E. O’Kelly and Hyun Kim	
7	Railway Capacity and Train Delay Relationships.....	129
	Lars-Göran Mattsson	
8	A Reliability-based User Equilibrium Model for Traffic Assignment.....	151
	William H.K. Lam, Ning Zhang and Hong K. Lo	
9	Reliability Analysis of Road Networks and Preplanning of Emergency Rescue Paths.....	173
	Yanyan Chen, Michael G.H. Bell and Ioannis Kaparias	

10	Continuity in Critical Network Infrastructures: Accounting for Nodal Disruptions	197
	Tony H. Grubestic, Alan T. Murray and Jessica N. Mefford	
11	Analysis of Facility Systems' Reliability when Subject To Attack or a Natural Disaster	221
	Richard Church and M. Paola Scaparra	
12	Bounding Network Interdiction Vulnerability Through Cutset Identification	243
	Timothy C. Matisziw, Alan T. Murray and Tony H. Grubestic	
13	Models for Reliable Supply Chain Network Design	257
	Lawrence V. Snyder, Mark S. Daskin	
14	Moving from Protection to Resiliency: A Path to Securing Critical Infrastructure	291
	Laurie Anne Schintler, Sean Gorman, Rajendra Kulkarni and Roger Stough	
	Index.....	309

1 Overview of Reliability and Vulnerability in Critical Infrastructure

Alan T. Murray¹, Tony H. Grubescic²

¹ Department of Geography, The Ohio State University, USA, Email: murray.308@osu.edu

² Department of Geography, Indiana University, USA, Email: tgrubesi@indiana.edu

1.1 Introduction

The concept of *interconnection* is an important one for a wide range of social, economic and political issues. Broadly defined, interconnection refers to a state of reciprocal connection. In this context, two or more interconnected entities can exchange ideas, currency, information and other valuable goods with each other, often for mutual benefit. For example, telecommunication backbone providers frequently interconnect at points of presence (POPs) or Internet exchanges (IXs) in order to accommodate peering relationships between large networks or to provide data transit for smaller systems. One obvious benefit accrued through this type of practice is extending the geographic reach of each backbone involved with the interconnection arrangement, providing access to new markets and potential customers. Over time, these interconnections can strengthen or decline, depending on the benefits acquired through interconnectivity. If the relationship between entities strengthens significantly, the condition of interdependency can emerge. In this context, the entities involved require the reliable operation of their interconnected partner(s) to function properly. If the relationship between entities weakens significantly, connections may be disbanded.

In recent years, the interdependencies of many infrastructure systems have increased dramatically. In the White House (2003) report titled “National Strategy for the Physical Protection of Critical Infrastructures and

Key Assets” problems associated with increased levels of interconnectivity between critical infrastructure systems are noted:

“the challenges and uncertainties presented by critical nodes and single-points-of-failure within infrastructures, as well as increasing interdependencies that exist among the various infrastructure sectors both nationally and internationally... are often difficult to identify and resolve, as are the cascading and cross-sector effects associated with their disruption” (White House 2003, pp. 33)

Perhaps the most notable problem with these increased levels of interdependencies is the potential for cascading failure across mutually dependent systems. Cascading failure occurs when an event triggering a collapse produces a series of secondary failures in interdependent infrastructures (Carreras et al. 2002; Little 2002; Albert et al., 2004; Talukdar et al. 2003; Houck et al. 2004). For example, if the electrical grid is significantly disrupted, it is likely that telecommunication services will also be disrupted. This, in fact, occurred during the massive electrical blackout in the Northeastern U.S. and portions of Canada in 2003 (Grubestic and Murray, 2006). Nearly 2,500 telecommunication networks were disrupted (*ibid*). Not surprisingly, with each disruption to a critical infrastructure system, accidental or otherwise, attempts are made to reevaluate the degree to which many of these engineered systems are able to maintain some type of operational continuity. The results of these evaluations are often used to fortify or protect existing systems, plan and construct newer, more resilient infrastructure, motivate new public policies regarding critical infrastructure and its expected performance and to help in the development of hazard mitigation plans.

1.2 Critical Infrastructure

Societal functions are highly dependent on networked systems in the developed world. Even the most basic day-to-day functions involve interaction with a variety of critical infrastructure systems. For example, millions of Americans utilize transportation infrastructure to get to work, school, or the local mall. Telecommunication infrastructure is used to maintain contact with family and friends, shop or perform financial transactions. Energy infrastructure is used to heat our homes, power local industries and deliver fuel to our automobiles. While these basic activities are relatively easy to comprehend, the magnitude of infrastructure use is less obvious. For instance, over 19 billion tons of freight valued at \$13 trillion dollars was moved through the multimodal transportation system and its associated networks in the United States during 2002 (USDOT, 2006). Where

telecommunication networks are concerned, U.S. backbone traffic exceeded 100 petabytes per month in 2002 (SVBJ, 2002). Assuming an average email is 25 kilobytes, this translates into 45,035,996,273 emails per month. Finally, the daily delivery capacity of the U.S. natural gas grid is 119 billion cubic feet, with yearly consumption estimated at 22.8 trillion cubic feet during 2002. Considering the degree to which industrialized societies are reliant on such critical infrastructure systems, their importance should not be underestimated. Moreover, because the operability of these systems can be vulnerable to disasters, accidents and intentional harm, there is a need to understand how critical infrastructure and its functionality might be impacted when subjected to disruption. Thus, there is a need to develop strategies for planning networked systems capable of surviving and performing under duress.

As a response to the growing threat of terrorism in the late 1990s, the U.S. federal government established the President's Commission on Critical Infrastructure Protection (E.O. 13010). This executive order defined "infrastructure" as (E.O. 13010):

The framework of interdependent networks and systems comprising identifiable industries, institutions (including people and procedures), and distribution capabilities that provide a reliable flow of products and services essential to the defense and economic security of the United States, the smooth functioning of government at all levels, and society as a whole.

More importantly, E.O. 13010 (1996) suggests that "...certain national infrastructures are so vital that their incapacity or destruction would have a debilitating impact on the defense or economic security of the United States." The concept of "vital" or "critical" infrastructure is important for establishing national security benchmarks. Basic inventories of critical infrastructure are often subdivided into sectors, and include (E.O. 13010, 1996; White House, 2003):

- telecommunications
- electrical power systems
- gas and oil storage
- transportation
- banking and finance
- water supply systems
- emergency services (including medical, police, fire, and rescue)
- continuity of government.

Similarly, a group of key assets were also highlighted:

- National Monuments and Icons
- Nuclear Power Plants