Risk Analysis for the Security of VDOT Smart Traffic Centers

Erik Bond, Tony Colavito, Tiffany Luong, and George Park, *University of Virginia Capstone Team*
Yacov Haimes and Joost Santos*, Faculty Advisors*

Abstract—**This paper assesses risks related to hurricane and pandemic scenarios and evaluates risk management alternatives to enhance preparedness, response, and recovery capabilities of the Commonwealth of Virginia. Such disasters could potentially disrupt the operations of critical transportation infrastructure systems. Virginia Department of Transportation (VDOT) manages Virginia's highway infrastructure through its five high-technology communications hubs called Smart Traffic Centers (STCs). STCs are staffed by transportation engineers, who monitor traffic flow, provide traveler information, and manage incidents. In the event of incidents, STC operators dispatch roadside assistance and post warnings to motorists via variable messaging signs and public radio advisories.**

Transportation system failures further compound a disaster's devastating economic, physical, and social consequences. A hurricane makes roads inaccessible, resulting in the inability of the general workforce to commute. Since STCs enable workforce mobility, the hurricane's effects are magnified should the STC itself be impacted. The STC's physical structure is vulnerable to high winds and flooding, which may disconnect its power supply, disable communications, or damage essential equipment. A pandemic, on the other hand, can impact the health and availability of STC employees, who require specialized training and experience with intelligent transportation systems.

It is critical for the STCs to develop continuity of operations (COOP) plans. Such plans identify and detail specific procedures for maintaining essential functions in the event of a disaster. The Virginia Information Technology Agency (VITA) and Virginia Department of Emergency Management (VDEM) require STCs to comply with COOP standards and other security policies.

The project team employed risk-based methodologies to assist the STCs in achieving compliance. In particular, this paper discusses four case studies featuring the development and application of: (i) probabilistic risk analysis tools (e.g., data mining, regression analysis, and Monte Carlo simulation using incident databases), (ii) a dynamic recovery analysis model aided by geographic information systems (GIS) to predict the ripple effects of disasters across multiple sectors, and (iii) multi-criteria tradeoff analysis to evaluate the efficacy of risk management solutions. The results and findings from this research will contribute to Virginia's preparedness planning for managing disasters.

I. INTRODUCTION

A. *What is the problem?*

Hurricanes and pandemics are extreme events that have devastating consequences. In particular, they have the potential to disrupt the operations of Virginia's critical transportation infrastructure. VDOT manages Virginia's highway infrastructure through its five regional high-technology operations centers, or STCs, which are located in Hampton Roads, Northern Virginia, Richmond, Salem, and Staunton.

A hurricane or a pandemic may debilitate essential STC resources and impede their ability to fully maintain and restore safety-critical transportation functions. High winds and flooding from hurricanes may damage the STC's field equipment, such as roadside video cameras, vehicle detectors, and variable messaging signs as well as control room assets such as video monitors, control stations, and archived data. In addition, a hurricane threatens loss of electric power and communications. On the other hand, a widespread illness, known as a pandemic, threatens the health and availability of employees, who require technical knowledge of intelligent transportation systems. This can disrupt the continuity of critical STC functions.

B. *Why is the problem important?*

The immense physical, economic, and social consequences caused by recent disasters have prompted federal, state, and local agencies to develop policies for preparedness and recovery. The Homeland Security Council developed the National Response Plan (NRP), recognizing the need for a systemic approach to domestic incident management [1]. At the state level, Governor Tim Kaine's Executive Order 44 (EO44) mandates that state agencies develop risk management plans to provide essential services during large-scale emergencies. Because of state and federal policies that require investigation of threats to infrastructure functionality, it is critical for Virginia's STCs to perform COOP planning. A COOP plan details specific management strategies to maintain STC operations, such as a failover capability, a backup generator, or a call tree for essential employees. In addition to EO44, VDEM published a COOP Planning Manual requiring STCs and other critical infrastructure agencies to meet compliance standards.

Manuscript received April 13, 2007. This work was supported in part by the Virginia Department of Transportation and the Virginia Transportation Research Council.

Erik Bond, Tony Colavito, Tiffany Luong, George Park, Yacov Haimes, and Joost Santos are with the Systems and Information Engineering Department, University of Virginia, Charlottesville, VA 22904 (respectively: ejb8c@virginia.edu, apc5k@virginia.edu, tkl3m@virginia.edu, gmp2b@virginia.edu, yyh4f@virginia.edu, jrs8e@virginia.edu).

C. *What has been done so far and by whom?*

While it is not the primary aim of this paper to provide a comprehensive review of existing tools, guidelines, and regulatory policies for disaster management, it is worth noting several representative works that serve as a motivation for the research. Disaster preparedness and recovery studies have emerged increasingly in light of recent terrorist events and natural disasters. Examples of studies that feature the importance of quantifying economic impacts (and risk in general) include those of the Government Accountability Office for the 9/11 terrorist attack [2], Anderson et al. for the 2003 Northeast blackout [3], VDEM for an *ex post* analysis of a hurricane [4], and Meltzer et al. for forecasting pandemic effects [5]. Homeland Presidential Directive (HSPD) 5 calls for an all-hazards approach for preparing the nation against disruptive events, preventing the occurrence of consequences, and ensuring efficient response and recovery [6]. Hurricane and pandemic scenarios have been identified as two of the 15 planning scenarios within the NRP [1]. HSPD-7 [7] has identified 17 sectors as the critical infrastructures and key resources, which are further discussed in the National Infrastructure Protection Plan [8]. Despite the large volume of pertinent literature, significant gaps remain for addressing disaster preparedness and recovery.

II. GOALS AND OBJECTIVES

A. *Project Objectives*

The goal of this research is to analyze the impacts of disasters on the STCs, using principles of risk assessment and risk management. This research will assist the transportation agencies in developing COOP plans in compliance with EO44. Using a variety of risk-based tools and methods, the objectives of the research are as follows:

1. Analyze the current state of STC operations and preparedness during catastrophic events.
2. Design and perform case studies to assess transportation risk scenarios and evaluate risk management alternatives.
3. Provide recommendations to VDOT to enhance emergency preparedness and recovery capabilities.

B. *Project Deliverables*

The project team conducted four case studies, two for a hurricane and two for a pandemic. These case studies serve as a repeatable methodology, which can be extended to other disasters identified in the NRP. The findings of this project will be presented to VDOT officials and STC managers to enhance their preparedness and recovery capabilities for such events.

III. METHODOLOGY

Probabilistic Risk Analysis (PRA) is a general methodology for answering the triplet of questions proposed by Kaplan and Garrick: (i) what can go wrong? (ii) what is the likelihood? and (iii) what are the consequences? [9] A suite of PRA tools generates probability density functions (PDFs) for normal STC operations, called *baseline* scenario, and disrupted operations, called *disaster* scenario. The PDFs, when compared, quantify the effects of a hurricane or pandemic.

The project team quantified baseline operations by performing site visits, touring the control rooms, and conducting interviews with the facility managers to better understand operations and supporting technologies. In addition, the team was given access to large-scale VDOT incident databases.

Using the information gathered, the project team conducted case studies on two particular events, hurricane and pandemic. These case studies provide a framework for assessing the baseline scenario and how these operations can be affected. PDFs were developed to reflect the uncertainties in risk parameters, facilitated by curve-fitting and Monte Carlo simulation software. GIS was used to identify the spatial distribution of risks and a dynamic recovery analysis tool was used to predict the ripple effects of a disaster across interdependent sectors. To maintain STC continuity in the aftermath of disasters, the team performed multi-objective tradeoff analysis. This was guided by Haimes' triplet of risk management questions [10]: (i) what can be done and what options are available? (ii) what are the tradeoffs in terms of costs, benefits, and risks? and (iii) what are the impacts of current decisions on future options?

IV. CASE STUDIES: HURRICANE

A hurricane can damage physical infrastructure, disrupt the flow of traffic, and lead to substantial economic loss. On September 19, 2003, Hurricane Isabel brought devastating damage to Virginia. Although it had weakened to a category one storm, the Commonwealth still sustained $625 million of damage and a death toll of 36 people [11, 12]. Furthermore, 90% of households and businesses lost electricity [13]. These power outages prevent traffic lights, interstate cameras, and variable messaging signs from functioning properly, making it difficult for the STC to perform its essential functions. In addition, VDOT closed the Midtown Tunnel for 28 days due to flooding [14]. Road debris, traffic light outages, and detours around the Midtown Tunnel caused congestion throughout the Hampton Roads region. These factors not only affected the workforce's ability to commute, but also made it difficult for businesses to ship and receive supplies. This example shows that in addition to physical damage, economic losses intensify the initial impact of a storm. The team performed two case studies featuring the Hampton Roads STC (HRSTC) and Staunton STC. The first assesses the inoperability and economic loss of specific industry sectors. The second proposes three alternative solutions to loss of electric power, which are evaluated by recovery time.

Case Study 1: Hurricane Risk Assessment for HRSTC

This case study assesses the inoperability and economic loss in Hampton Roads as a result of a hurricane.

Inoperability is the inability of an economic sector to deliver its baseline production level [3]. The team used two tools: Hazards U.S. Multi-Hazard (*HAZUS-MH*), the Federal Emergency Management Agency's GIS-based software tool, and the Dynamic Inoperability Input-Output Model (DIIM), a recovery assessment tool.

With *HAZUS-MH*, the team quantified the return period of category one and category two hurricanes. The Saffir-Simpson Scale classifies category one hurricanes as 74-95 mph wind speeds and category two hurricanes as 96-110 mph wind speeds. The map in Fig. 1 demonstrates the potential for each of these to return within 50 years.

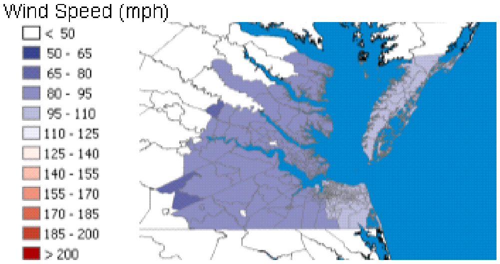

Fig. 1. Peak Wind Gusts over a 50-year Return Period

HAZUS-MH provided peak wind gust data for 10-year to 1,000-year return periods for each jurisdiction. By ranking these jurisdictions in each return period, the team found six regions that consistently had the highest predicted wind gusts: Accomack County, Chesapeake, Norfolk, Northampton, Portsmouth, and Virginia Beach.

Although Hurricane Isabel was technically a category one hurricane, its impact implies that it was closer to a category two storm [4]. The team studied the impacts of a category two hurricane using Hurricane Isabel as an analogous event. Isabel's effects helped estimate initial inoperability to the workforce, transportation, and electric power sectors. The DIIM projected the effect on all other sectors.

Following Isabel, almost the entire region lost power, people could not travel to work, and most businesses closed. Dominion Virginia Power reported that 1.8 million of its 2 million customers were without power, about 90% inoperability [13]. In the transportation sector, the Downtown Tunnel and Midtown Tunnel were closed due to flooding. Based on daily traffic volume statistics, the team estimated that transportation inoperability was about 40%. Consequently, the workforce suffered about 80% inoperability according to similar workforce studies [15].

From these estimates, the DIIM quantified inoperability and economic loss across all sectors. Fig. 2 shows the five most inoperable sectors and the time required for the sector to return to normalcy (e.g. 0% inoperability). The utilities sector is the most inoperable and recovers in approximately 24 days. Fig. 3 identifies the five sectors that suffer the most economic loss. Economic loss is measured in millions of dollars lost and days until recovery. The professional, scientific, and technical services sector bears the most loss, about $100-$120 million. The number of days until recovery for most sectors is 22-24 days.

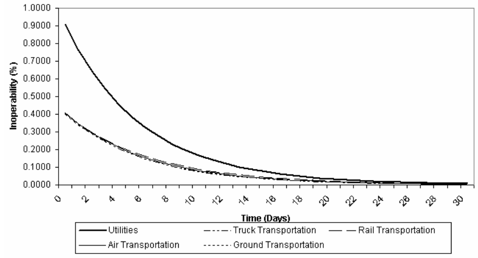

Fig. 2. Top Five Inoperable Sectors over a 30-day Recovery Period

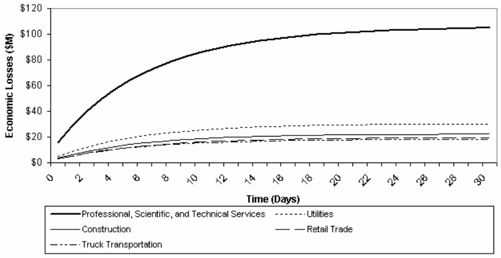

Fig. 3. Economic Loss of Top-5 Affected Sectors over 30-day Recovery

Case Study 2: Hurricane Risk Analysis for Staunton STC

This case study evaluates Staunton STC's backup plans for loss of power associated with a hurricane. Strong winds and flooding can cut off the power supply or damage critical equipment. If the STC's operations are disabled, then its incident response capability will be compromised.

Incident reports were collected for the week of September 20-26, 2002-2006, which includes the week of Hurricane Isabel. Four types of incidents were considered: abandoned vehicles, accidents, debris, and disabled vehicles. The sample from 2002 showed the highest number of reported incidents, 516, and the week of Hurricane Isabel in 2003 showed the fewest, with only 204. It was assumed that fewer incidents arose during Isabel because of decreased traffic flow. However, the average duration of incidents during Isabel was the highest, perhaps due to incapacity and delayed response at the STC.

Hurricane risk scenarios for the Staunton STC were identified using the Hierarchical Holographic Model (HHM). The HHM is a risk identification tool that encourages researchers to view the problem from various perspectives [16]. Three risk scenarios were identified: loss of power, loss of communications, and loss of facility. The team focused on managing loss of power. Three risk management options were developed for this scenario: (A) diesel generator, (B) alternate site, and (C) do nothing.

These risk management options were evaluated based on the time it takes the STC to recover to normalcy after a power outage, known as downtime. The STC seeks to minimize downtime because it effectively reduces incident response time. The downtime of operations was estimated through expert elicitation, specifically from STC employees.

A backup diesel generator was the most beneficial alternative. The downtime of operations can be less than 10 minutes. In addition, the generator can run as long as diesel fuel is available. Relying on an alternate site such as Salem STC was the second best alternative. The downtime of transferring operations is approximately 30 minutes. Lastly, if the STC chooses to do nothing, then it relies on first-hand witnesses to report incidents.

In addition to the downtime metric, other performance metrics can be analyzed simultaneously, such as implementation cost. Pareto optimality analysis determines the set of optimal solutions when faced with conflicting objectives, as seen in Case Study 4.

V. CASE STUDIES: PANDEMIC

Workforce unavailability hinders STC COOP because operations rely on technically trained operators. In a workforce debilitating disaster, such as the widespread outbreak of an infectious disease, workforce unavailability would interrupt traffic monitoring operations. Poor accident response leads to extended emergency response time, lack of warning messages to motorists, and traffic delays. Despite the pandemic threat, STCs do not protect their operations against workforce unavailability [17]. In addition, the VDEM COOP Planning Manual lacks focus on the necessary requirements to protect operations against workforce unavailability. The team performed two case studies on HRSTC. The first examines the increase in incident response duration using Hurricane Isabel as a surrogate event. The second examines the operator workload resulting from use of four alternative risk management solutions.

Case Study 3: Probabilistic Risk Analysis of a Pandemic

To begin risk assessment, this case study uses incident duration to measure a pandemic's disruption to STC operations. Duration is the amount of time in minutes from the moment an incident is reported to the moment it is resolved. In effect, this metric demonstrates the expediency with which employees operate.

Since a pandemic has not struck modern society, a pandemic's effect is uncertain. Therefore, the research team uses Hurricane Isabel as a surrogate event which simulates the effects on employee availability. During Isabel, transportation mobility hindered STC employee availability. Analogously, a pandemic's widespread illness threatens employee availability. Similar to Case Study 2, this case study uses incident reports from September 20-26, 2002-2006 (e.g. the week of Hurricane Isabel, 2003). This data enabled the team to create histograms of the duration metric for the baseline and disaster scenarios.

This study's PRA methodology formulates PDFs from the duration histograms and compares the baseline scenario with the disaster scenario. The team performed Monte Carlo simulation on the baseline and disaster scenario PDFs. This yields a function representing the difference in duration, called the delay function, which is depicted in Fig. 4 [18]. The delay function represents the marginal increase in incident duration resulting from a pandemic. Software programs (such as @Risk and BestFit) are used to simulate the delay values and fit a distribution.

A chi-square test indicates that the delay function is a log-logistic PDF with an expected delay of 0.74 minutes. This means that duration increases by about 44 seconds in a pandemic. Since an average week has about 880 incidents, the pandemic causes an additional 11 hours of delay. The added duration handicaps operations and can lead to additional risk scenarios.

Risk management examines analogous events and expert elicitation in order to develop and evaluate risk management alternatives. Each alternative is measured by reduction to risk and implementation cost. After developing several alternatives, expert judgment is elicited to evaluate each alternative's effectiveness. Experts provide pessimistic, most-likely, and optimistic estimates for each alternative, which is used to create a triangular distribution. Fig. 4 shows that Monte Carlo simulation is performed to multiply the triangular PDF with the baseline delay function. The simulated values derived from this process comprise the data points needed to generate the alternative delay function. The alternative delay function represents the incident duration improvement under the risk management alternative.

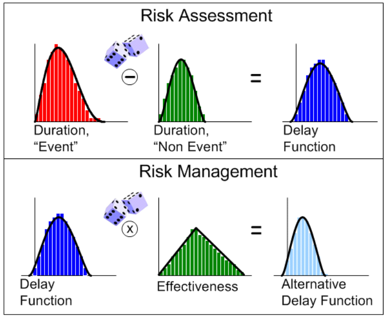

Fig. 4. Risk Assessment and Risk Management Framework for a Pandemic

The Pareto-optimal frontier (i.e., a flexible solution set) can be depicted graphically as cost versus expected marginal delay. The frontier provides decision makers with different organizational preferences and safety thresholds to allocate limited resources across competing agendas. Project sponsors will use the results to formulate policy recommendations for Virginia agencies. Case study 4 below performs multi-criteria evaluation of specific risk management solutions and shows how a Pareto-optimal frontier can be constructed and presented to policymakers.

Case Study 4: Workforce Productivity Analysis of HRSTC

Workforce unavailability due to a pandemic would "significantly handicap [an STC's] ability to perform core functions," including incident management [19]. This case study quantifies a pandemic's disruption by comparing operator workload, the ratio of incidents to available operators, in the baseline scenario to workload in a pandemic scenario. The objective of this case study is to analyze the costs and benefits of four potential solutions to the workforce unavailability problem:

1. *Do nothing*. Let the pandemic run its course. The Virginia Department of Health (VDH) anticipates that 10-25% of the workforce will be absent at any given time due to illness or caring for ill family members [20].
2. *Training a larger workforce*. Train and cross train personnel to perform operator functions. Consequently,

when a pandemic strikes and operators fall ill, a greater pool of personnel will be available for incident management.

3. *Remote operators*. Transfer essential STC functions to an alternate influenza-free work site such as an STC elsewhere in the Commonwealth. Operators at the alternate STC would perform incident management on the other STC's behalf [21].
4. *Immunization*. Operators are healthy and ready for work. Vaccines prevent illness among 70-90% of healthy adults, but, due to vaccine shortages, they will be available to only 75% of transportation employees [20], [22], [23].

The team employed three methods to estimate operator availability under each of the four solutions. These methods are investigation of literature, a workforce unavailability tool, and historical incident reports. Relevant literature investigated World Health Organization, Centers for Disease Control (CDC), and VDH reports to project a pandemic's severity. *FluWorkLoss*, a workforce unavailability tool developed by the CDC, quantifies a pandemic's impact on absenteeism [24]. The user inputs the pandemic's severity and population parameters such as population distribution by age and employment rate and the tool outputs the minimum, mode, and maximum number of workdays lost. The third method, historical data, consists of a sample of 1,910 incident reports from November 26 to December 10, 2006. They provide an estimate for the baseline number of incidents per day and number of operators on shift per day. These three methods combine to create PDFs for number of operators available under each solution. @Risk uses these inputs to calculate a PDF for incidents recorded per operator, or operator workload.

The multi-criteria tradeoff analysis process enables comparisons of the alternative strategies based on operator workload and cost metrics. Fig. 5 illustrates an example of comparing PDFs. Prior to the evaluation, it is important to simplify the resulting workload functions. The expected value of each distribution measures operator workload. Table 1 shows the mean operator workloads for the five scenarios and their associated relative costs. The baseline scenario has the lowest mean workload level and the do nothing solution has the highest. Immunization has the lowest workload of the alternative solutions. Implementation costs are also difficult to accurately quantify, hence multi-criteria evaluation uses available literature (e.g., [23, 25, 26]) to rank relative costs. Doing nothing has the lowest cost, followed by cross training operators, immunization, and remote control.

Table 1. Workload and cost rank for each scenario

Alternative Solution	Mean Operator Workload	% Increase Workload	Cost Rank
Baseline	17.3	0%	-
Do Nothing	19.1	11%	0
Training	18.2	5%	1
Remote	18.2	5%	3
Immunization	17.9	4%	2

Multi-criteria evaluation graphically compares the solutions based on their operator workload and cost in Fig. 6. Since HRSTC seeks to minimize both metrics, the ideal solution would have zero cost and zero increase in workload.

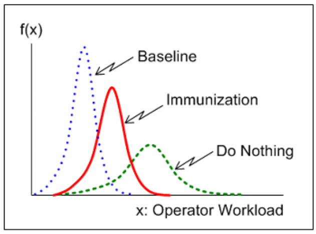

Fig. 5. Sample PDF comparisons

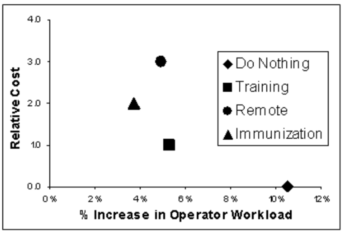

Fig. 6. Multi-criteria Evaluation

The alternative solutions create a solution space in which operator workload decreases with cost, hence there is no single optimal solution. A Pareto-optimal frontier is a set of solutions where an increase in the value of one metric will lead to a decrease in the value of another [10].

The pandemic training and immunization solutions are cost-effective because they provide benefits over the others in either operator workload or cost. Furthermore, the remote solution has a better operator workload than training, but training has a lower cost. However, the immunization solution dominates the remote solution. Immunization has lower cost and operator workload, therefore, a decision maker has no incentive to install remote capabilities. Multi-criteria evaluation enables HRSTC decision makers to visually compare each solution's tradeoffs and choose a solution within its budget. The methodology results in a flexible solution that provides a decision making tool for COOP planning and EO44 compliance for VDOT's STCs.

VI. Discussion

A disaster's characteristics, such as the duration, population affected, and severity, are uncertain. PRA helps to address uncertainty and quantify a disaster's characteristics using a suite of PRA tools. Here, the project team performed COOP planning for VDOT's STCs via four case studies using GIS-based spatial analysis, dynamic recovery modeling, data mining, expert elicitation, review of available literature, and Monte Carlo simulation. The case studies compare normal STC operations with those under a disaster scenario and demonstrate that the STCs are susceptible to catastrophic events. Case study 1 analyzed the potential inoperability and economic loss resulting from a category two hurricane. Case study 2 examined possible risk management options to maintain STC operations through a power outage scenario following a hurricane. Case study 3 investigated the potential increases in incident duration time in a pandemic based on a historical data from a comparable event. Case study 4 explored a pandemic's effect on workforce availability and consequently operator workload. The case studies and the supporting tools can be extended to the analysis of various risk scenarios to transportation and other critical infrastructure systems.

VII. Conclusions

The project team developed and applied risk analysis and systems engineering tools for Virginia's transportation and interdependent critical infrastructure systems. This underscores the importance of STC COOP planning for disaster preparedness and recovery. The tools are intended to aid the STCs in assessing risks imposed by a hurricane or a pandemic on transportation and their employees and to ultimately enhance the reliability of their operations.

The scope of the current effort focused on risk analysis of two major disasters in terms of their disruptions to the continuity of critical functions and availability of essential employees. Detailed feasibility studies are needed to further explore risk management solutions taking into account the presence of multiple stakeholders with different risk and benefit objectives. Our research intends to provide policymakers a repeatable framework and a set of tools for disaster preparedness and recovery. In combination with other tools (e.g., forecasting and agent-based simulation models), analysis can be customized to a wide array of disaster risk scenarios such as those identified in the Homeland Security Council's NRP.

ACKNOWLEDGMENTS

The project team would like to thank the following people and organizations for their continued support of our research project:

Sponsor: Virginia Department of Transportation (VDOT) *Steering Committee:* Murali Rao, Mary Clark, Steve Kelliher, Bill Kane, Dean Gustafson, Cathy McGhee, Mike Perfater, and Wayne Ferguson

Smart Traffic Centers Assisting with Research:
Hampton Roads STC: Facility Manager Stephany Hanshaw
Staunton STC: Elliott Asbury and Gary Sickler

University of Virginia Faculty and Students:
Yacov Haimes, Joost Santos, James Lambert, Kenneth Crowther, Kash Barker, Zhenyu Yan, Brett Dickey, Mark Orsi

REFERENCES

[1] D. Howe (2004). Homeland Security Council: planning scenarios [Online]. Available: http://www.voiceoffreedom.com/archives/ homeland security/15-attacks_the_hawiaa_disclosure.htm#Scenario %2010.

[2] Government Accountability Office (GAO), *Review of studies of the economic impact of the September 11, 2001 terrorist attacks on the World Trade Center.* Washington, DC: GAO, 2002.

[3] C.W Anderson, J.R. Santos, and Y.Y. Haimes. "A risk-based input-output methodology for measuring the effects of the August 2003 northeast blackout," *Economics Systems Research,* vol. 11, 2007.

[4] Virginia Department of Emergency Management. (2004). Hazard identification and risk assessment [Online]. Available: http://www. vdes.state.va.us/ library/plans/coveop/eopvol6/3.0%20HIRA.pdf

[5] M. I. Meltzer, N. J. Cox, and K. Fukuda, "The economic impact of pandemic influenza in the United States: priorities for intervention," *Emerging Infectious Diseases*, vol. 5, 1999, pp. 659-671.

[6] Homeland Security Presidential Directive-5 (HSPD-5). (2003). Management of domestic incidents [Online]. Available: http://www.whitehouse.gov/news/releases/2003/02/20030228-9.html

[7] HSPD-7. (2003). Critical infrastructure identification, prioritization, and protection [Online]. Available: http://www.whitehouse.gov/news /releases/2003/12/20031217-5.html

[8] Department of Homeland Security. (2006). National infrastructure protection plan [Online]. Available: http://www.dhs.gov/xlibrary/ assets/NIPP_Plan.pdf.

[9] S. Kaplan and B. J. Garrick, "On the quantitative definition of risk," *Risk Analysis*, vol. 1, 1981, pp. 11-27.

[10] Y.Y. Haimes, *Risk Modeling, Assessment, and Management*, 2nd ed. New York: John Wiley and Sons, Inc, 2004.

[11] VDEM. (2007). Virginia hurricane history [Online]. Available: http://www.vaemergency.com/newsroom/history/hurricane.cfm.

[12] C. M Smith and C.S. Graffeo (2005). Regional impact of Hurricane Isabel on emergency departments in coastal southeastern Virginia. *Academic Emergency Medicine,* vol. 12, 2005, pp. 1201-1205.

[13] Dominion Virginia Power. (2003). Dominion on target for completion of Hurricane Isabel restoration effort [Online]. Available: http://www.dom.com/news/elec2003/pr1003.jsp

[14] VDOT. (2003). Midtown tunnel has reopened [Online]. Available: http://www.virginiadot.org/news/newsrelease.asp?ID=HRO-0337

[15] P. Gordon, H.W. Richardson, and B. Davis, "Transport-related impacts of Northridge earthquake," *Journal of Transportation and Statistics,* vol. 1, 1998, pp. 21-36.

[16] Y.Y. Haimes, "Hierarchical holographic modeling," *IEEE Transactions on Systems, Man, and Cybernetics*, vol. 11, 1981, pp. 606-617.

[17] T. Kaine and M.M. Cline, Continuity of operations (COOP) planning manual, version 3. Virginia: Virginia Department of Emergency Management, 2006.

[18] D. Vose, "Monte Carlo risk analysis modeling," in V. Molak (Ed.), *Fundamentals of Risk Analysis and Risk Management,* New York: CRC Press, 1996, pp. 45.

[19] S. Hanshaw, Phone interview, March 21, 2007.

[20] Virginia Department of Health. (2006, March). Draft VDH pandemic influenza plan, *Emergency operations plan* [Online]. Available: www.vdh.virginia.gov/PandemicFlu/pdf/DRAFT_Virginia_Pandemic _Influenza_Plan.pdf.

[21] Virginia Department of Transportation, *Northwestern and Southwestern region smart traffic center's continuity of operations plan.*

[22] J. A. Wilde, J. A McMillan, J. Serwint, J. Butta, M. A. O'Riordan, and M. C. Steinhoff, "Effectiveness of influenza vaccine in health care professionals: A randomized trial," *JAMA*: *The Journal of the American Medical Association*, vol. 281, 1999, pp. 908-913.

[23] C. B. Bridges, W. W. Thompson, M. I. Meltzer, G. R. Reeve, W. J. Talamonti, N. J. Cox, "Effectiveness and cost-benefit of influenza vaccination of healthy working adults: A randomized controlled trial," *JAMA: The Journal of the American Medical Association*, vol. 284, 2000, pp. 1655-1663.

[24] P. Dhankhar, X. Zhang, M.I. Meltzer, C.B. Bridges. "FluWorkLoss: software to estimate the impact of an influenza pandemic on work day loss." Atlanta, GA: Centers for Disease Control and Prevention, U.S. Department of Health and Human Services, 2006.

[25] D. S. Campbell and M. H. Rumley, "Cost-effectiveness of the influenza vaccine in a healthy, working-age population," *Journal of occupational and environmental medicine/American College of Occupational and Environmental Medicine*, vol. 39, 1997, pp. 408-414.

[26] A. Schroeder, Final report: ITS implementation center: route 460 wireless network, Blacksburg, VA: The Center for ITS Implementation Research, 2006.