VIRGINIA’S CRITICAL INFRASTRUCTURE PROTECTION:  
A STATEWIDE RISK ASSESSMENT STUDY

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ABSTRACT

This project, called the Capstone Project, serves the Virginia Department of Transportation (VDOT) by identifying and assessing risks resulting from willful hazards to the security of six critical transportation infrastructures. The project explores the specific vulnerabilities of each critical asset, in terms of structural design, system function, accessibility, and proximity to interdependent or separately critical assets. It also determines the asset’s interconnectedness with other systems in the infrastructure, and lastly recommends means for mitigating risk and improving emergency response and recovery (ERR) plans associated with the asset. A systems engineering approach involving risk assessment and management is applied. The project employs such techniques as Hierarchical Holographic Modeling (HHM), the Risk Filtering, Ranking, and Management (RFRM) method, and multi-objective tradeoff analysis. The result of risk analysis of each critical asset is a risk management plan which is designed to instill redundancy, robustness, and resilience in the transportation infrastructure.

INTRODUCTION

Background

Our client for the Capstone Project is the Virginia Transportation Research Counsel (VTRC), which is a research and development department in the Virginia Department of Transportation (VDOT). The main task is to identify and manage risks due to possible terrorist attacks to the surface transportation infrastructure of Virginia, which consists of highways, and over 13,000 bridges and eight tunnels.

Throughout the project, the Capstone Group, with the valuable inputs of VDOT experts, generated and investigated possible risk scenarios, and then filtered them according to their likelihoods and consequences. Thereafter, the group suggested ways to prevent or manage the damage resulting from terrorist attacks. The number of possible risk scenarios is infinite and is only limited by the imagination of the analysts. Therefore, not every scenario could be investigated in this project. Moreover, there is basically no way of guaranteeing full prevention of some known scenarios. The group suggested ways of obtaining “a safe system failure,” which assures that even in case of a complete failure the “relative” damage is minimized.

Objectives and Scope

The VTRC asked the Capstone Group to do the following:

I. Recommend a methodology to identify the most critical assets of VDOT.

II. Conduct case studies on the six predefined sites. The case studies should point out the most crucial vulnerabilities and suggest policy options to eliminate them.

Significance of the Study

Soon after the two airliners crashed into the Twin Towers of the World Trade Center, all the bridges and tunnels into Manhattan were shut down. With the attack on the Pentagon and the crash of a fourth plane...
in Pennsylvania, all the air traffic over the United States was suspended. The authorities made these decisions based on their emergency response plans. The tragic events of September 11th, 2001, showed us once more that terrorism is one of the biggest threats of our time, and not even the “most powerful” country in the world is safe from attacks. It is impossible to come up with measures to stop every possible terrorist act, but it is crucial to have policies and plans to handle major risk scenarios.

The Presidential Decision Directive 63 (PDD 63) [Clinton 1998] defines a critical asset as a “physical or cyber-based system essential to minimum operation of the economy and the government.” Highways, bridges, and tunnels are the veins of a country. Our daily lives as well as our military defense system depend on the full functionality of this critical infrastructure. Therefore, its protection is crucial.

**METHODOLOGICAL APPROACH**

The Capstone Group has followed the methodological framework for risk assessment and risk management developed by Professor Yacov Y. Haimes at the University of Virginia’s Center for Risk Management of Engineering Systems. Applied to large-scale systems such as surface transportation, the goals of the methodology are to:

- better understand the system, its elements, and their interdependencies,
- be able to point out vulnerabilities,
- develop policy options against these vulnerabilities, and
- filter, rank and recommend policy options.

**Risk Assessment Questions [Kaplan and Garrick 1981]**

The analyst starts out by asking the question, “What can go wrong?” The goal is to point out vulnerabilities that could jeopardize the integrity of the system. Model building and scenario generation help to answer this question.

Second, by asking, “What is the likelihood that it will go wrong?” and using probabilities, the analyst tries to quantify risk. Gathering as much expert opinion and factual data as possible, the analyst uses a probability density function (pdf) to calculate expected damage values.

The final question in the risk assessment process is, “What are the consequences?” This requires quantifying the outcomes of the given risk scenarios in order to conduct a multiobjective trade-off analysis. Expert opinion is the main source of information for this phase [Crenshaw et al. 2001].


Having quantified the risk associated with the vulnerabilities and the consequences, the next task of the analyst is to come up with policy options to manage the risks. The first risk management question, “What can be done?” is similar to the first risk assessment question in that it tries to generate multiple policy options for any given threat. No single policy option alone would be foolproof in managing risk.

The next question, “What are the trade-offs?” tries to determine a means of choosing from the generated policy options. Calculations require information such as cost, percent effectiveness, and expected damage. The information then goes through a filter formed by probability distributions and Pareto-optimal graphs. The output gives the decision maker a visual representation of all the policy options with their respective trade-offs. Figure 1 is an example of a curve of Pareto-optimal policy options. The point labeled “Non-optimal” is an inferior policy since other policies exist that cost less and has a lower probability of failure. The policies along the line (Pareto curve) are Pareto-optimal policies. Each policy on this line offers an improvement in one objective at the expense of another. The selection of the policy to be implemented depends on the levels of cost and probability of failure that are acceptable to the decision maker(s).

Any recommendation should take future implications into account. The final question in the risk management phase, “What are the impacts of current decisions on future options?” helps the analyst make recommendations that do not create any complications or unintended severe risks in future system requirements [Crenshaw 2001]. The risk management phase offers options and action strategies for the most
critical sources of risks. Finally, it incorporates a review process to address missed items and improve the methodology. *Hierarchical Holographic Modeling* [Haimes 1981, 1998]

Hierarchical holographic modeling (HHM) is a graphical method that helps the analyst identify sources of risk. The model makes it easy to visualize the risk contributions of the subsystems within a large-scale system.

![Diagram](attachment:image.png)

**Figure 2.** General structure of Hierarchical Holographic Model

The diagram consists of subsystems and their sub-elements that together build up the main large-scale system. It also reveals and presents interdependencies between the elements very efficiently. HHM is a big help when generating risk scenarios. The analyst tries to find the vulnerabilities that would cause individual or multiple elements of the system/subsystems to fail. This brainstorming activity results in multiple risk scenarios that then proceed to the filtering phase.

For every system, multiple HHM diagrams can be built based on different perspectives and priorities. Therefore, the analyst has to get together with the client to agree on the diagram before starting with the study. *Risk Filtering, Ranking, and Management (RFRM)* [Haimes, Kaplan, and Lambert 2001]

The risk filtering, ranking, and management (RFRM) method captures all six risk assessment and management questions in a step-by-step procedure to identify, prioritize, assess, and manage multiple risk scenarios from different angles within a large-scale system. RFRM is comprised of an eight-phase process that uses qualitative and quantitative assessments to achieve a listing of the most important risks of a system. Phases I and II are interested in realizing and narrowing down the areas of risk in terms of the assessment. Phases III through V are concerned with the filtering and ranking of risks specific to the analysis. Phases VI creates risk management options, and phases VII and VIII check the methodology and get feedback, respectively.

**Phase I: Scenario Identification.** This phase is accomplished through the construction of a Hierarchical Holographic Model (HHM) (Haimes, 1991, 1998). The HHM can be described as a diagram that categorizes multiple perspectives of a system that encapsulates the gestalt of the sources of risk to the system. An HHM describes a series of ‘as planned scenarios’ that are represented by head nodes and sub-nodes for each perspective. Through the HHM, one can look at every source and point of risk within and outside the system.

**Phase II: Filtering on Scope, Decision Makers, and Time Domains.** This phase entails a process in which the entire set of risks are narrowed down into levels that the decision maker is more concerned with. Upon completion of this phase the analyst will have identified a more relevant subset of risk categories pertinent to the decision maker’s domain and interest.

**Phase III: Ordinal Filtering and Ranking.** It is a process in which the set of categories developed in phase II can be reduced down even further. In this step, a risk matrix, that describes likelihood and consequence levels for sources of risk, is used. The matrix, similar to Figure 1, combines consequence and likelihood in Case-study sites in Virginia were chosen by VDOT experts. The sites consist of multiple types of assets:

- A command, control, and communications center
- A critical bridge
- Two critical bridge/tunnels
- An intersection of two major highways
- An intersection of a major highway and a vital, urban road

**Risk Filtering, Ranking, and Management**

Risk Filtering, Ranking, and Management, otherwise known as RFRM, is a methodology developed by Yacov Y. Haimes, Stan Kaplan, and James H. Lambert in order to identify, prioritize, assess, and manage multiple risk scenarios from different angles within a large-scale system. RFRM is comprised of an eight-phase process that uses qualitative and quantitative assessments to achieve a listing of the most important risks of a system. Phases I and II are interested in realizing and narrowing down the areas of risk in terms of the assessment. Phases III through V are concerned with the filtering and ranking of risks specific to the analysis. Phases VI creates risk management options, and phases VII and VIII check the methodology and get feedback, respectively.

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• three bridges
• two major interchange between critical interstate highways
• one bridge-tunnel
• a Smart Traffic Center

RESULTS

The risk assessment phase of the project identified the vulnerabilities and risks associated with each type of asset. Following are the possible risk scenarios that are applicable:

• Major bombing/missile attack
• Major accident
• Spill of hazardous materials
• Sabotage by way of biological, chemical, nuclear, or radiological weapons of mass destruction (WMD)
• Arson

The risk management phase of the project provided VDOT with options as to what could be done to protect the infrastructures against these possible risk scenarios. These options included the following recommendations for prevention and response:

• Secure facilities
  – Employ Intelligent Transportation Systems (ITS) for monitoring, deterrence, and rapid response
  – Secure facility access points with fences and punch-code locks when appropriate
  – Patrol the area
  – Restrict hazardous materials (HAZMAT) vehicles in some facilities
• Harden bridges by exploring new materials such as fiber-reinforced polymers (FRP)
• Create redundancy in design of bridges
  – Add additional piers and girders
• Access rapid bridge replacement technology
• Consider availability of material
• Plan detailed emergency response

CONCLUSIONS

The Critical Infrastructure Protection Capstone Project has provided VDOT with a methodology to: 1) recognize the interdependencies and interconnectedness of statewide transportation systems, 2) identify the vulnerabilities and risks associated with various types of surface transportation infrastructures in Virginia, and 3) evaluate risk management policy options by providing invaluable information to decision makers regarding the risks, costs, and benefits provided by any potential policy. Figure 1 below shows the costs and the expected value of damage of eight possible risk management options. This graph shows the multi-objective trade-off analysis conducted between two different objectives, minimizing cost and minimizing percent of inoperability. The Pareto-optimal frontier provides a method of identifying optimum policy options enabling management to decrease both the cost and risk of damage.

Figure 3. Multi-objective trade-off analysis

The above systemic risk assessment and risk management process allows decision makers to implement policies that will provide the most benefits to all users of the statewide systems. The potential impacts of implementing such policies will not only improve the protection of the critical infrastructures, but also military and government institutions, utilities, and human life within close proximity of those structures. The final deliverable of this project provides VDOT with a procedure for identifying risks and evaluating possible protective management policy options that can be applied to any critical transportation asset.

REFERENCES


BIOGRAPHIES

Lindsay Zulick is a fourth-year Systems Engineering major from Pittsburgh, PA, concentrating in management systems. Lindsay focused her efforts on the risk analysis of a critical bridge. She has accepted a job with KPMG in Washington, DC, where she will pursue information risk management.

Can Ozinci is a fourth-year Systems and Information Engineering major from Istanbul, Turkey. His area of concentration is in information systems. Can will be working for Capital One in Richmond as a data analyst.

Kimberly A. Stobbart is a fourth-year Systems Engineering major from Reading, PA, concentrating in management systems. Her major contribution to the project was a risk analysis of an interchange system. Kimberly has accepted a position with Lockheed Martin in Moorestown, NJ.

Matthew D. Singleton is a fourth-year Systems Engineering student from Pittsburgh, PA. On this project, Matthew focused on risk management of a critical bridge-tunnel system. Matthew has accepted a job with Honeywell as a financial consultant operating out of Minneapolis, MN.