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MODELING THE IMPACT OF INFRASTRUCTURE INTERDEPENDENCIES ON VIRGINIA’S HIGHWAY TRANSPORTATION SYSTEM

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ABSTRACT

This project seeks to address the Virginia Department of Transportation’s (VDOT) need to identify and manage the increasing number of interdependencies within its highway system. This study incorporates risk assessment and risk management methodologies in the analysis of four separate case studies involving VDOT assets. The results of this study provide insight not only as to how to manage the cascading effects of interdependent infrastructures within the individual case studies, but are applicable to the state of Virginia, as a whole. Management policies are recommended to unlock the interdependencies within the transportation system and thereby reduce the impact to the interdependencies following a transportation disruption.

1 INTRODUCTION

1.1 Background

The definition of a system implies that there are interdependencies. This project links the critical infrastructures which rely on the highway system to provide access. Due to the technological complexities, the interdependencies of the transportation system are not fully understood and mapped. This is especially true as to the risks that these interdependencies pose both to the highway system and the interdependent sectors themselves. For example, if there is a disruption to the highway system, whether accidental or intentional, transportation of raw materials and people may be impacted. This can have a large economic impact or even tragic consequences. Other systems such as communication networks and rail transportation may also be negatively impacted. Conversely, a power failure can cause interruptions to the highway system by creating more traffic or not allowing communication between highway operations systems.

These interdependencies were evident in July 2001, when a CSX freight train derailed in a Baltimore tunnel. The direct impact to the transportation system included the closure of the tunnel, which resulted in the cancellation and diversion of many freight trains. The transportation system was not the only system affected: There was an increase in demand for air and truck transport for the freight that could not be transported by train. There were higher manufacturing costs due to shipping delays and many local businesses suffered lost revenue due to street closures in the area. The telecommunications sector was affected: Damage to the fiber optic cables running through the tunnel. As a result, those in the Baltimore area lost cell phone service, and email service was disrupted along the entire Northeast corridor (Haimes et al. 2003). This example illustrates how the failure of one system can result in the failure of many systems surrounding it.

1.2 Scope

This study addresses the need to protect infrastructures in the highway transportation system against the risks posed by interdependencies of the transportation system. This goal was achieved through the use of risk assessment and risk management techniques to identify system vulnerabilities and the risks associated with those vulnerabilities. Four different case studies were conducted to provide a representative holistic view of the interdependency risks throughout the state of Virginia. These case studies included a study of two critical tunnels, a hospital, and a highway trucking route in the western part of the state. The case studies were selected to examine the impact on the interdependent sectors due to a transportation closure and to the transportation system as a result of a closure in an interdependent system. The focus for all case studies was on risk management, or finding ways to unlock the inter-
terdependencies of the highway system to reduce the risks associated with interdependencies.

This report is divided into five more sections: a description of risk assessment procedures; risk management protocol; the computer model; project findings; and, conclusions.

2 RISK ASSESSMENT

The critical facilities that depend on the Virginia transportation system provide an indeterminate source of risk to the highway system. In order to protect VDOT infrastructures, systems administrators must be prepared for potential failures in critical facilities outside of the highway system that can propagate into the highway system. Also, how failures in the highway system can cascade into other dependent facilities and systems. To minimize risk to the highway system, it is important to identify possible sources of failure within the transportation system through the risk assessment process. Risk assessment raises three important questions:

1) What can go wrong?
2) What is the likelihood that it would go wrong?
3) What are the consequences? (Kaplan and Garrick 1981).

The answers to these questions can help to measure the risks from interdependencies and allow system administrators to focus scarce resources on aspects of the transportation system that pose the greatest risk to surrounding infrastructures and systems.

2.1 Identification of Vulnerabilities

In order to identify the interdependencies of the system, the team created a Hierarchical Holographic Model (HHM) for the transportation system and the facilities it supports. Introduced in 1981 by Yacov Haimes, Ph.D., the HHM provides a holographic overview, thus enabling the user to identify all major sources of risk (Haimes 1998). Specifically, the HHM answers the first risk assessment question, “What can go wrong?” The team built the HHM through brainstorming, research and interviews with experts to determine what they believe has the greatest interconnectedness with their own system.

Once the information is gathered, the interconnectedness of the system components can be graphically depicted, which aids in the identification of present and potential risks, as seen in Figure 1. The head topics in the HHM include jurisdictional, intermodal, economic and user perspectives.

Research for the HHM was first done on the entire state of Virginia and then narrowed down to include only those subtopics specific to each case study. The team identified facilities that would be most impacted in the event of a terrorist attack. Depending on the HHM head topic, the team used different criteria to choose the facilities including the economic impact and the size of the facility. Both factors served as a measure of how large an impact a terrorist attack would have.

![Sample Hierarchical Holographic Model (HHM)](image)

Figure 1. Sample Hierarchical Holographic Model (HHM)

2.2 Threat Scenarios

In order to minimize the vulnerability of a critical infrastructure, stage one of the project was to assemble the case studies to identify the interdependencies and answer the three risk assessment questions. After identifying a number of critical facilities, a list of threat scenarios was brainstormed to ascertain potential case studies. Three individual case studies were chosen to represent the impact of a terrorist attack on a highway corridor, a tunnel and a hospital in different parts of Virginia.

The team also created a scenario computer model, which will be discussed in more detail in later section 4. The model included the entire state of Virginia and conducted risk assessment in a similar way to the case studies.

2.3 Filtering of Threat Scenarios

At this point in the risk assessment process, the decision-maker is left with too many scenario issues to contemplate. The next project stage serves filter the pertinent subtopics and scenarios so that the decision-maker can focus effectively.

This step begins with qualitatively filtering the subtopics using an ordinal risk matrix. The matrix contains columns divided into five likelihood categories and rows with five or six consequence categories. An expert on the either the transportation system or the particular highway asset being studies is responsible for designating a subtopic’s
likelihood and consequence. Figure 2 provides an example risk matrix. Here, the subtopics placed in the upper right of the matrix are those that will require the most attention. Conversely, subtopics in the lower left of the matrix have the least severe risk and may be filtered out in later phases.

<table>
<thead>
<tr>
<th>Most Likely Effect</th>
<th>Likelihood</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Loss of Life</td>
<td></td>
</tr>
<tr>
<td>B. Long-term loss of mission</td>
<td></td>
</tr>
<tr>
<td>C. Short-term loss of mission</td>
<td></td>
</tr>
<tr>
<td>D. Loss of capability without loss of mission</td>
<td></td>
</tr>
<tr>
<td>E. No effect</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2. Example of Ordinal Risk Matrix

The next stage focuses on the scenarios’ ability to overcome a system’s main defense mechanisms: redundancy, resilience, and robustness. Within each of these three main topics of defenses lie eleven specific criteria:

1. Undetectability
2. Uncontrollability
3. Multiple paths to failure
4. Irreversibility
5. Duration of effects
6. Cascading effects
7. Operating environment
8. Wear and tear
9. Hardware/software/human/organizational
10. Complexity/emergent behaviors
11. Design immaturity (Haimes, Kaplan, and Lambert, 1998)

Each scenario should be assigned a rating of “high”, “medium”, or “low” with respect to the 11 criteria categories. Again, the filtering is qualitative in nature as it seeks to avoid quantitative measuring that will eventually take place in the next step.

The final phase in filtering is similar to the previous qualitative step, but implements a quantitative approach using a cardinal risk matrix. For example, a risk matrix in this stage might replace a previously rated scenario probability of “low” with a probability range of “0.001 < P < 0.01”. This final step is useful because of its quantitative nature. Because we now have real numbers, this phase allows for specific risk assessment that is easily confused when one is deciding between a “medium” and a “low” likelihood.

At this point in the filtering, a smaller, more manageable, number of scenarios is available for the risk management phase.

3 RISK MANAGEMENT

3.1 Evaluating Risk Management Options

In the next phase, attention turns to answering three questions:

- What can be done, and what options are available?
- What are the associated trade-offs in terms of costs, benefits, and risks?
- What are the impacts of current decisions on future management options? (Haimes 1998)

A list of possible solutions must be created to solve the first question. These options should focus on changes to the design or operation of the system that will prevent the risk from occurring and improve the response to the risk effectively. Specifically, risk options should be developed that relate to as many of the following six characteristics as possible:

1. Prevention
2. Detection
3. Hardening
4. Preparedness
5. Response
6. Recovery (Haimes 2002)

After a list of management options is created, one must turn to the second question: examining the trade-offs between cost, benefits, and risk. The first step requires estimating the cost for each of these possibilities. This cost estimate should come in the form of a triangular distribution to be derived from either a vendor or an expert’s opinion. The triangular distribution asks the expert to give a low cost, most likely cost, and a high cost estimate for the situation. From these numbers, an expected value for the cost may be generated.

Next, it is necessary to evaluate the benefit that each management option in terms of effectiveness to the system. The benefit will be in the form of the percentage of effectiveness the option provides. For the VDOT project, common effectiveness metrics will come in the form of the percentage of improvement in lives saved, dollars saved, and commuting time saved. The percentage of improvement is a necessary technique to compare across different metrics. For example, it becomes very difficult to implement one risk management technique over another by comparing a lost life with millions of saved dollars.
instead, the percent improvement provides a common measurement that eliminates the need for cross metric comparison. After each option is given its percentage of effectiveness, they will be ranked corresponding to this number so as to easily identify those options that have the most impact on the system.

3.2 Selecting Optimal Options

The next risk management step is to select management options based upon tradeoffs between options. This can be accomplished through Pareto-optimal graphs. Pareto optimal refers to any option that is non-inferior or efficient (Haimes, 1998). In the case of VDOT, this means selecting policies that minimize cost and maximize effectiveness (or minimize damage). An example of a Pareto-optimal graph is shown in Figure 3. The options shown along the frontier comprise the most effective options that minimized both the costs to VDOT and the damage to the sectors.

![Pareto Optimal Graph](image)

Figure 3. Sample Pareto Optimal Graph

Due to time constraints, this step was not completed by the research team. VDOT can perform these tasks and select the management options they feel will best serve the state of Virginia.

3.3 Completing Risk Management Phase

All portions of the risk assessment and risk management processes should be reexamined to ensure no critical scenarios were overlooked at any step. Interviews with the client and other stakeholders will provide this feedback. Adjustments can then be made to the selected management options to include anything the stakeholders feel is essential to complete the risk management process.

Once management options are implemented, feedback should be received from site stakeholders and appropriate adjustments should be made to correct any potential unforeseen problems. However, because risk management options have yet to be implemented for this project, this step will be completed at a later date.

4 COMPUTER MODEL

As a complement to the case studies completed in the project, a computer model was created to enable future analysis on any VDOT interdependencies. This tool incorporates the risk assessment and risk management methodologies into a computer-based interface that will produce a case study of the VDOT employee’s choosing. Because it is easily completed without any prior knowledge of the risk techniques, the program can be used by all VDOT personnel.

Interaction with the model begins when the user enters the information about the asset they wish to study (Figure 4). With this initial information, the tool then guides the user through the process of identifying critical perspectives and scenarios related to the problem. Next, the tool assists with the qualitative and quantitative assessment of a scenario’s likelihood and consequences, while filtering scenarios throughout.

The interface then proceeds to risk management and follows the prior assessment steps (Section 3) to aid the user in generating risk management techniques and identifying their costs, benefits, and risk reduction. The output of the computer model consists of a list of the most critical risks to the system and the most effective management techniques to reduce these risks. The creation of this computer model provides an enduring tool that will enable the methodology to be used for many future decisions.

![Computer Model – Asset Selection Screen](image)

Figure 4. Computer Model – Asset Selection Screen

5 FINDINGS

Several conclusions were drawn during the risk assessment and risk management phases of the project.
During the risk assessment phase, the following conclusions were applicable to most of the case studies:

1. VDOT’s current risk management policies focus more on response and recovery than on prevention and preparedness.
2. Major impacts due to a highway’s inoperability were felt most heavily in the trucking and workforce sectors.
3. Major impacts to interdependent sectors were only felt for long-term closures.
4. Critical facilities must have excess stock of necessary supplies in case of a transportation failure.

Other specific risks were identified for each of the assets, however because they were unique to the site, they will not be discussed further.

From these identified impacts to the interdependent sectors, risk management options were created to unlock interdependencies and to respond to specific incidents. A sampling of these risk management options, organized by type, are as follows:

**Response:**
- Form emergency response teams that represent all interdependent sectors
- Ensure all emergency personnel have adequate two-way radio communication that can connect key agencies
- Ensure that alternate routes provide adequate capacity for overflow
- Provide redundancy in the system including parallel routes for rail and highway

**Unlocking Interdependencies:**
- Sending more truck freight through alternate forms of transportation, such as air or rail
- Overstocking critical facilities (e.g. hospitals) with necessary operational supplies
- Staggering work schedules during inoperability periods
- Provide workers with incentives to use alternate forms of transportation, such as buses or rail

These risk options cannot cover each individual case study. Thus, specific risk management options were created to identify specific risks at individual sites. For example, at Tunnel A, a management option to reduce communication and power lines running through the tunnel structure should be implemented.

While all findings were robust, several problems arose during the course of the research. First, assumptions and surrogate measures were used when security issues limited the quantity and quality of data. Second, research in this area is extremely limited and resources regarding interdependent sectors were not easily found. Thus risk assessment and risk management methodologies had to be varied on a case by case basis. Finally, administrators outside VDOT were not required or obligated to provide the team with information; this caused unequal distribution of data throughout the sectors.

### 6 CONCLUSIONS

There were many successes in both the risk assessment and risk management phases of the project. Many unknown interdependencies were identified as a result of our analysis. This was accomplished through the development of the HHM for the Commonwealth of Virginia. Extensive amounts of data were collected and cataloged for future use in the computer tool and for VDOT. A computer tool was also developed to aid VDOT in future interdependency analysis.

Although there were successes, several areas could be improved upon in future research. Limitations in data collection hindered our understanding of how interdependencies related to one another. Therefore, many assumptions were made when evaluating the risks to the sectors. For example, data regarding impact to commerce/trade was not available following the closure of a tunnel. As a result, inoperability data from the trucking sector was used to extrapolate and determine impacts to the commerce/trade sector. Problems also arose in identifying universal metrics between the examined sectors. Specifically, it was difficult to compare economic dollars with human lives lost.

Ultimately, the research will lead to a better transportation system in Virginia. The identification of the risks of interdependencies will minimize transportation delays, save lives, and reduce economic impact to the state of Virginia.

### REFERENCES


AUTHOR BIOGRAPHIES

Lisa Dryden is a 4th year Systems Engineering major from Williamsburg, VA. Her major contributions to the project were case studies of two critical tunnels. After graduation she will work as an information technology intern in Arlington, VA.

Matthew Haggerty is a 4th year Systems Engineering major from Newport News, VA. His major contribution to the project was creating a computer model to follow the risk assessment and risk management methodology. Next year, he will continue his studies as a graduate student in Systems Engineering at University of Virginia.

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