Transportation in the Critical Infrastructure: A Holistic Approach Using Systems Engineering Methodologies for Assessing Risk and Cost Impacts Due to Highway Disconnects

Gerard Ibarra, Jerrell Stracener, Stephen Szygenda, P.E.
Southern Methodist University

Introduction

The transportation sector of the CI is vital to the U.S. citizens' way of life and as well as how corporations do business. This CI is becoming more crucial to the US. This is because there are increases in the tonnage and value of goods moved, as well as rises in transportation costs and complexity. Furthermore, the US moves 67.2 percent of its goods measured in short tons using trucks (US DOT BTS 2004). Because of this, it is important to understand two more aspects. One, there is a plethora of geographical interdependencies (GIs) that affect the highways. Research papers and articles for the risk assessment and impact of highway disconnects do not include GIs. In fact, in terms of reliability, most of the risk stems from other variables. This includes time of travel, cell phone use, congestion, teen driving, accidents, road construction, rail, faulty bridges, and the transportation of hazardous material, to name a few (DOT NHTSA 1998; DOT FRA 2003; AAA 2005; Pasupathy, Ivan, and Ossenbruggen 2000). As of this article, the authors could not find any work incorporating GI into the risk assessment, analysis, and mitigation of the highways. Two, there are risks associated with the GIs. Other interdependencies also affecting the highways include logical and physical. Thus, understanding the importance the interdependencies have on highway networks, mainly the GIs, is the basis for this study.

Geographical Interdependencies

There are four types of interdependencies: physical, cyber, logical, and geographical (Rinaldi and Kelly 2001). Appendix 1 lists their definitions. All relate to the CIs and are highly interconnected and mutually dependent in complex ways. However, because the paper focuses on GIs as applied to the transportation CI, we begin with a definition followed by three examples.

GI is an element or system that is in proximity to the CIs. Figure 1 depicts the thirteen CIs. Any element that is physically next to a CI where a disruption of the element occurs might cause a negative effect on the CI is a GI. Thus, rail lines that transverse a highway is an example of a GI. The reason is if a disruption occurred on the rail line, such as a major hazardous spill, officials would close both rail line and highway. This closure affects the transportation CI in two ways. One is the abating of traffic and commerce on

the highway. The other is on the rail line. Furthermore, it is conceivable to state that the highway is a GI of the rail line. It works both ways. A second example of a GI is the power lines that cross over the highways. If a disruption occurs where the power lines snap over the highway; then the highway shuts down until the repairs are complete. In this case, there are two CIs affected. One is the movement of goods that pertains to the transportation CI. The other is the delivery of power that pertains mostly to the energy CI. Finally, there are also highway bridges that cross over rivers. If the river floods where the water goes over the highway, the highway becomes unusable and, hence, shutdown by authorities. Figure 2 illustrates the two of the three

Figure 1. Thirteen Critical Infrastructures

Figure 2. GIs: Rail and Water

GIs discussed. Not shown are the power lines. There are numerous other examples of GIs pertaining to highways.

Associating Risk with GIs

There is a myriad of GIs, each with a potential risk to the CI. Thus, to identify them all for a particular CI requires in-depth knowledge of all infrastructures. This is difficult and might be infeasible. However, there is a process to assist with the identification of GIs. It is hierarchical holographic modeling (HHM).

HHM is a general risk-identifying method evolving from the theory of scenario structuring (TTS). The TTS objective is to provide a unified perspective to risk analysis, where, by comparing multiple risk methods, affords a better understanding of the risks. HHM recognizes that most organizational systems are hierarchical in structure. Hence, the risk management of such systems must consider all these hierarchical structures (Kaplan, Haimes, and Garrick 2001). Consider a three-level work breakdown structure (WBS) for example. The top level is parent, while the next two levels are the children and grandchildren respectively. In the same manner, consider the transportation CI of a highway network. The infrastructure is the parent. The thirteen CIs are the children. Each CI has a grandchild. For the transportation CI, the grandchildren are the five modes of transportation. These modes include air, highway, pipeline, rail, and water. Moreover, the grandchildren of transportation CI have other children below them. They include the four interdependencies of the infrastructure. Succinctly for the transportation CI, the infrastructure is the parent, the thirteen CIs are the children, the five modes are the grandchildren, and children of the grandchildren are the interdependencies. The WBS is the organizational system and the children and grandchildren are the hierarchical structures. Note that it is infeasible to represent with a single model all the important and critical aspects of a complex system (Haimes, Kaplan, and Lambert 2002; Morgan et al. 2000). On the other hand, HHM has the ability to model intricate relationships among various subsystems. It facilitates the evaluation of subsystems' risks and their effects to the risks of the total system. HHM exists because it provides various perspectives for risk analysis of complex systems (Haimes, Kaplan, and Lambert 2002).

In short, HHM is a tool for analyzing the risk of systems. It is versatile. It also allows for defining risk of large and complex systems more readily. Thus, the HHM proves adaptable to identifying risk in the highway networks in terms of physical, cyber, logical, and geographical interdependencies. Appendix 2 depicts an example of the HHM, where rail lines are the GIs.

Other Interdependencies

Briefly, there are two other interdependencies used as variables in the model: physical and logical. These help quantify the risk of disconnects on the highways.

Physical interdependencies are those infrastructures that rely on one another (Rinaldi, Peerenboom, and Kelly 2001). The result or output of one depends on the other. In the transportation CI, for example, companies move goods on the highway networks. The goods are anything from fuel to food. If an accident occurs on the highway, then the accident may abate the flow of goods. The delay of these goods affects the CIs for food and energy. Fuel does not reach its destination on time, causing some shortages. Hence, the highway infrastructure is the medium in the transportation CI that provides the food and fuel to consumers. In short, the state of one infrastructure affects another and vice versa.

Logical interdependencies on the other hand are two infrastructures that are interdependent when the state of one depends on the other via a mechanism that is not a physical, cyber or geographical connection (Rinaldi, Peerenboom, and Kelly 2001). In the transportation CI, with more traffic flow on the highways, there are more chances of an accident. The greater the chance of an accident, the more likely disconnects occur. Rush hour is a good example. Individuals use their vehicles to travel to and from work. As long as fuel prices remain stagnant, they continue to travel by themselves. However, if the price of fuel increases dramatically, then they may consider car pooling or even taking mass transit (*Dallas Business Journal* 2005). This affects the traffic flow on the highways by reducing the number of vehicles. The logical connection to congestion on the highways is fuel prices.

Objective

The objective of this paper is to provide city and government officials with a methodology for estimating the impact disconnects have on the highway network. Impacts are the costs and risks. A model of the Houston highway network is used to illustrate the application of the methodology. Results from the model aid with the allocation of resources. They also help with the risk mitigation analysis and the decision-making process.

Analysis Process

The development of the model uses an SE approach. This ensures consideration for the system versus a single entity within the system. The approach addresses the nuances of the system. These include the requirements and constraints. Each official has a different perspective of what is and is not important. Nuances also include the geographical, physical, and logical interdependencies of the highway network. Recall that the interdependencies are elements

affecting other CIs. In short, the SE approach provides the framework for the methodology for developing a model. This allows assessing the impact that disconnects have on the highway network.

Using an SE Approach

The first step in development of the model is to *define* the requirements, constraints, and resources. The second step is to *construct* a WBS. A WBS is a lucid platform for viewing the required items and understanding the processes of the model. It ensures consideration for the requirements, constraints, and resources. The third step is to *perform* functional analysis. It offers a perspicuous understanding of the system. This ensures that various components and other SoS are part of the analysis. The fourth step is to *determine* variables for measuring performance of the system. This helps identify how changes in the parameters alter the output of the system. This model includes cost and risk. Finally, *develop* a mathematical model from steps three and four. This helps determine the effects that disconnects have on the highways. Figure 3 shows the flow chart of the process.

Figure 3. SE Flow Chart Approach

Requirements

There are four main requirements for the model. Although they vary by customer, resources, and importance, the requirements are the building blocks for the model. They are listed in Table 1. The constraint portion of the process provides further details of the model.

Constraints and Limits

There are various constraints and limits pertaining to the model. They stem from the requirements. Five components make up these constraints and limits. First is the makeup of the network. Second is the cost of accidents and highway reconstruction due to an explosion. Third is the use of HHM almost exclusively for its risk identification process.

Table 1. Functional Requirements

#	Requirement
1.0	The model shall represent the Houston highway network.
1.1	The network shall consist of all highways inside Beltway 8.
1.2	The network shall include highways surrounding the Port of Houston.
1.3	The network shall include any highway entering the Houston International Airport.
2.0	The model shall mathematically relate disconnects to cost and risk.
3.0	The methodology shall be capable of being used in other metropolitan cities.
3.1	The methodology shall have a systematic procedure outlining its processes.
4.0	The model shall include performance measurements.
4.1	The model shall include the cost of accidents and highway construction due to an explosion as one of its output variables for measuring performance.
4.2	The model shall include the risks of the GI of the rail lines as one of its output variables for measuring performance.

Fourth is the limiting of the risks to the GIs and a single logical byproduct of the rail lines. It also limits the model to the flow of traffic on the highway network as a physical interdependency. It does not use the six dimensions of infrastructure interdependencies (Rinaldi, Peerenboom, and Kelly 2001). Lastly is the sole use of the designer for the quantitative risk analysis (QRA). This is because of the limiting resources. Particularly, the model does not incorporate the opinions of experts regarding the effects of accidents and highway construction due to an explosion.

Makeup of Network. The model represents the highways of a city as an undirected network $G = (N, L)$. The node set N corresponds to the set of highway intersections and transfer points. The *bidirectional* link (i, j) represents the segment of highway connecting intersections/transfer points i and j . Figure 4 depicts a partial network representation of the highway system for Houston, Texas.

Figure 4. Partial $G(N, A)$ Network for Houston

Incidentally, there are four general constraints to this methodology. One, it applies only to major metropolitan cities with highway networks. Two, the networks must consist of at least two links. Three, the network resides within the geographical area of the city. Fourth, the network is in a steady state condition.

This paper also limits the makeup of the network. There are five items: peak traffic hours, highway accidents, construction costs due to an explosion, rail lines, and HHM. Please refer to Appendix 1 for definitions on cities, highways, geographical area, steady state conditions, and peak hours.

Costs. The model uses cost for determining the impact to the system. Costs consist of highway reconstruction as well as injuries because of accidents. *Both elements assume explosions cause the incidents.* No costs associated with queuing, delay to the market, spoilage, loss of tourism, late delivery penalties, operational changes, or any other cost incurring factors, are currently part of the model. The model estimates the cost to reconstruct the disconnected links on the highway. The model also estimates the cost of accidents based on the number of people injured and their severity as well.

HHM. Another limit to the model is its use of HHM. The model uses it almost exclusively. HHM is an approach that allows the user to identify all risks in a system such that the risks are either joint or disjoint (Kaplan, Haimes, and Garrick 2001). The model presented here uses a combination of the analysis in Haimes, Kaplan, and Lambert's (2002) and Dean's (1993) work. This model also lacks Bayesian analysis. Bayesian helps in identifying the probability of scenarios occurring. A scenario could be anything from an accident to a terrorist act within the highway transportation network.

Geographical Interdependencies. GI is an element or system that is in proximity to the CIs. A disruption in

this element negatively affects the CIs. To have a better understanding of the interdependencies that affect the CIs, use the six dimensions of the infrastructure interdependencies (Rinaldi, Peerenboom, and Kelly 2001). However, the use of these dimensions is beyond the scope of this model. The model limits the GIs to rail lines and a single logical interdependency byproduct from the rail lines. No other GIs—such as power lines, manufacturing plants, and power facilities, to name a few—are part of the analysis. However, the model does use traffic flow as one of the many physical interdependencies within the network.

Risk Analysis. There are many risk hazards associated with the highways. It is infeasible to assess and rank them all. Hence, the model considers qualitative judgment for some risk outcomes. Furthermore, the QRA uses the perspective of the modeler and not the experts of each respective field viewed. For instance, the modeler provides a value in assessing the risk of an explosion. The modeler estimates the area damaged by the explosion on the highway.

Resources

The available resources for this study are time, software, and people.

Work Breakdown Structure

Once the user identifies the requirements, constraints, and resources, he/she should use a WBS to develop the mathematical model for the system. The WBS provides an executive overview of the processes and data requirements. It helps scope the model while providing direction at the same time. The WBS is a tool for beginning the problem, addressing various portions of it, and refraining from losing site of the objective. Appendix 3 shows a high-level WBS for the model.

Functional Analysis

The functional analysis portion of the SE process forces the user to learn more about the system and its interdependencies. It takes the major parts of the sub-components of the system and breaks them down further. Some of the sub-components are SoS. The overall analysis provides users with a clear and perspicacious understanding of the system. This understanding allows the designer to build a more robust model. Appendix 4 illustrates the functional flow block diagram (FFBD) for the risks associated with the GIs of highways.

Variables

There are two main output variables used for analyzing the performance of the highway system. Cost is the first. This enables city and government leaders to look at the system from a cost perspective. There are two main components.

One is the flow of vehicles on the highways. The other is the location where disconnects occur. Sensitivity analysis, incorporating the two components, allows the model to rank the most vulnerable links in terms of costs. The second variable is risk. This allows the officials to consider risk in their decision-making process. There are four components to this risk. The first is the GI. The model considers the risk of rail lines affecting the highways. That is, it considers their proximity to the highways. The second is traffic flow. The model shows how increases in traffic flow affect the risk of the system. The third is the commodity flow. The more flow of goods on the highway links, the greater the risks for those links. The last component is the nodes of the highways. A disconnect at a node affects traffic movement in at least two directions. Hence, any changes in these variables and their parameters alter the performance of the system.

Mathematical Model

The mathematical model represents the performance of the network. It initially uses the two main output variables, cost and risk. Secondly, it combines the two variables through weights and scales to yield a score. The latter provides an overall rating of the network. Figure 5 illustrates the process of the model.

City and government leaders understand the importance of costs. It has merit. Risk on the other hand, is subjective. What one leader construes as an extreme risk, another may not. The model corrects these risk discrepancies. The model accepts input from various individuals. These include experts and city officials, for example. Doing so prevents large variations in risk definitions and severity. Note, however, that only the designer provided input into the model. This view reduces the accuracy of the model.

Finally, the model combines both variables to form a single output score per link. The output easily allows ranking the impacts of cost and risks on links due to disconnects.

Estimating Cost

The first algorithm determines the cost of disconnects in the network. There are two types of costs due to an explosion: accidents and construction to restore the highway.

Cost of Accidents. The National Highway Council (NHC) has costs estimates for all types of accidents (NHC 2004). It breaks them down by severity, including fatality. For instance, the cost for a fatality is \$1,120,000, which includes lost income; medical, administrative and vehicle expenses; and uninsured employer costs. If three deaths occur, the total cost is three times the fatality figure plus or minus the prescribed rounding. Thus, the cost for three deaths is \$3.5 million. Note that further details on estimating vehicle injuries are available from the Department of Transportation (DOT). The average cost of a non-fatal accident, on the other hand, is \$45,000. This considers extremes of the accidents from fender benders to rollovers. However, the accidents are not fatal. To calculate the costs, use Equations 1–4.

$$K = Q/V \quad (1)$$

$$Bomb_{kill} = K \cdot Area_{kill} \cdot Lanes \cdot Indvi / veh \quad (2)$$

$$Bomb_{inj} = K \cdot Area_{inj} \cdot Lanes \cdot Indvi / veh \quad (3)$$

$$Cost_{Accident} = Bomb_{kill} \cdot Cost_{Fatal} + Bomb_{inj} \cdot Cost_{Inj} \quad (4)$$

In Equation 1, K is the density, Q is the flow per hour, and V is the miles per hour. Hence, to calculate the density, the analyst must first determine the flow and speed. To determine the flow, obtain a *traffic map* from the respective DOT. The traffic map indicates the average flow of vehicles per day. Convert the average flow per day to hourly flow. Use one of the three time slots—*peak*, *normal*, and *other hour*—to categorize the hourly flows. This permits further analysis based on the time of day. This paper considers peak hours only, however. Depending on the city, this accounts

Figure 5. Model Process

for a combined 10 to 20 percent of the total traffic flow, based on the respective traffic map and analysts. If the traffic flow on a link is 200,000 vehicles per day, then the hourly flow for that link is $[(200,000 \text{ vehicles per day}) \cdot (0.20)] / (6 \text{ hours per day}) = 6,667 \text{ vehicles per hour}$. If traffic counts per hour are available, then use them instead. On the other hand, to determine the average speed during rush hour, use the national average of 13.7 miles per hour defined by the DOT Federal Highway Administration (FHA). For accurate results in reference to the city, contact the local state agencies.

In Equations 2 and 3, $Area_{kill}$ and $Area_{inj}$ represents the area that an explosion kills and injures individuals respectively. The designer assumes that an explosion kills everyone within a 40-foot radius while everyone 100 feet outside the kill radius is injured. In addition, the parameter, $Lanes$, is the number of lanes on the highway section. Typically, there are six total. Finally, $Indiv/veh$ is the average number of individuals per vehicle. The model uses 1.25, based on rush hours samples.

Listed below is an example of the cost for an explosion on one of the links of the highway. It uses the provided data and Equations 5–8.

- Individuals per vehicle = 1.25
- Flow on lane studied = 1,589
- Lanes on link studied = 6
- Speed = 13.7 MPH
- Disconnect explosion = 40ft
- Disconnect injuries = 100ft
- Cost / death ($Cost_{fatal}$) = \$1,120,000
- Cost / injury ($Cost_{inj}$) = \$45,500

$$K = \frac{1,589 \text{ veh} / \text{hr} / \text{lane}}{13.7 \text{ MPH}} \cdot \frac{1 \text{ mil}}{5,280 \text{ ft}} \quad (5)$$

$$K = 0.02197 \text{ veh} / \text{lane} \cdot \text{ft}$$

$$Bomb_{kill} = 0.02197 \text{ veh} / \text{lane} \cdot \text{ft} \cdot 40 \text{ ft} \cdot 6 \text{ lanes} \cdot 1.25 \text{ Indvi} / \text{veh} \quad (6)$$

$$Bomb_{kill} = 6.59 \text{ Indvi}$$

$$Bomb_{inj} = 0.02197 \text{ veh} / \text{lane} \cdot \text{ft} \cdot 100 \text{ ft} \cdot 6 \text{ lanes} \cdot 1.25 \text{ Indvi} / \text{veh} \quad (7)$$

$$Bomb_{inj} = 16.47 \text{ Indvi}$$

$$Cost_{Acc} = 6.59 \text{ Indvi} \cdot \$1.12M + 16.47 \text{ Indvi} \cdot \$45.5K \quad (8)$$

$$Cost_{Acc} = \$7,380,373$$

This shows the cost for an explosion on the defined link of the highway network. The cost is different for each link because the traffic flow and number of lanes are different. If the times change, the cost changes too. Traffic flow is directly proportional to the time of day.

Cost of Construction. To estimate the cost for construction, use an empirical approach. The steps are straightforward and reproducible for any region. First, obtain the specific highway construction cost for the respective city. A list is available from the DOT. Next, gather cost data in an electronic format for the past twelve months. The data must include the following items:

- Street and proximity of intersections
- Type of repair/construction—for example, grading, structures, base, surfacing, rail, and signage, to name a few
- The length of the repair
- The total repair costs

Categorize the data by the type of repair and highway. Do not use rural roads, city streets, farm to market paths, or other streets not defined as highways. The user must manually distinguish the highways from non-highways. Afterward, use a weighted average to determine the cost per mile, as depicted in Equation 9. Then estimate the length of repair of the highway given a disconnect. The designer assumes 0.10 mile per explosion. Hence, determine the construction costs based on the distance using the average cost for constructing the highway. The average cost for Dallas and Houston is \$3,686 per aerial foot based on highways with six total lanes. Equation 10 depicts the cost for construction.

$$C_{mi} = 1/n \sum_{i=1}^n Cc_i / D_i$$

$$C_{mi} = \text{Cost} / \text{Mile} \quad (9)$$

$$Cc_i = \text{Proj Const Cost}_i, i = 1, 2, \dots, n$$

$$D_i = \text{Distance}_i, i = 1, 2, \dots, n$$

$$n = \text{number of examined entries}, i$$

$$\text{Damage} = C_{mi} \cdot \text{Const Cost/ft} \quad (10)$$

Estimating Risks

The methodology uses HHM to determine the risks associated with the transportation CI due to an explosion. Because the CI is vast and complex, HHM allows the analyst to categorize the risk. Thus, the analyst reaches a point of interest and does further calculations based on that point. This includes QRA. Appendix 2 contains a high-level view of the HHM for the transportation CI. Note that this is a snippet of the associated risk for the transportation CI. To incorporate more risks requires further analysis, which is beyond the scope of this paper. However, it does represent a perspicuous view of the transportation CI for the highway network based on the GIs.

Based on the figure in Appendix 2, there are three risk entities. One entity estimates the risk of *rail lines* to the highway. It has four components. The first includes the proximity of the rail line to the nodes of the highway.

The second examines the proximity of the rail lines to each other. The rail lines must be close to the highway. The third considers the rail lines running parallel to the highway. The last component looks at the flow of commerce on the rail lines. The other entity is total *traffic flow* on the highways and at the nodes. The last entity is the amount and type of *traffic commerce* flowing on the highways and at the nodes.

Rail Lines. A GI is the rail lines adjacent to the highway network. This includes the rail lines in proximity to the nodes, other rail lines, and each other. In addition, the model incorporates the amount of commerce on the rail line. This is a logical interdependency and helps with determining the links affecting the network the most. That is, a rail line with heavy traffic and commerce is of a greater risk to the transportation CI than a rail line not commonly used.

Proximity to Nodes. First, a risk factor for the network is the rail lines that are in proximity to a node. This is important because the nodes have more traffic on them than links themselves. Recall that a node is the intersection of two or more highways. If a train runs off its track or experiences an explosion in one of its carts, then it affects the nodes. This effect is a physical interdependency (Rinaldi, Peerenboom, and Kelly 2001). It affects the transportation infrastructure of the highway. Furthermore, the rail line is a GI because of its location to the highway network. Hence, the closer a rail line to the node, the higher the risk. This is because a disaster, such as an explosion on the rail line, shuts down the node. Individuals using the highways that pass through this node can no longer traverse it.

To determine the risk the rail lines have on the nodes, obtain a map of the city. Ensure the map depicts the location of the rail lines. Next, number every node in the network. This helps identify what part of the network is most vulnerable. Do the same for the rail lines traversing the links. Then, develop a point system based on the proximity of the rail line to the node. Use hazardous material experts, the DOT, and other local agencies when possible, to determine the point system. The closer the rail lines to the node, the higher the risk. This model uses 0.50, 0.75 and 1.00 miles radii. Finally, construct a target zone with the defined radius. This helps with the efficiency of the analysis. Once these items are gathered, marked, identified, and constructed, place the target on the map over the rail line. Assign the appropriate value to the respective node. The closer the rail line is to the node, the higher the risk. Figure 6 illustrates an example.

The map shows nodes 23 and 24 as dark solid circles. The rail lines are solid thick lines represented by numbers 10, 11, 12, 16, and 17. The target has three circles with different radii. From the smallest to the largest circles, the radii are 0.50, 0.75, and 1.00 miles. The lines intersecting the cross and tangent to the circles are reference points.

Figure 6. Example of Analysis

This makes it easier to determine where the rail lines are with respect to the nodes. Thus, place the target directly over the rail line. This example shows rail line 10. Because node 23 is completely inside the first radius, rail line 10 has a high risk. It receives a high score. On the other hand, rail line 16 is outside the first zone and is almost outside the second. It receives a lower score than rail line 10. Finally, rail line 17 is completely outside of the target zone. It receives a very low score. This process continues until the analyst examines every rail line. To ensure consistency, the analyst must continuously refer to previous decisions on the risk values assigned. This helps keep the assignment in check. This is also part of the SE methodology for trade analysis.

To help provide a better risk estimate, use the following three items.

- Use an electronic map when performing the analysis. It makes it easier to modify the size of the target and its ranges, and node assignments. This helps with the “what-if scenarios.” Moreover, it facilitates the sharing of information.
- Refer to the website www.topozone.com for detail map information. The map distinctly shows the rail stations and their lines. In addition, refer to the websites <http://terrasserver.microsoft.com/> and www.terrasserver.com for a detailed aerial view of the city. The pictures illustrate a different perspective of the rail stations and their lines.
- Drive the city and make note of nodes and the GIs. Nothing is more lucid in understanding the GIs of the highway.

Proximity to Each Other

Another risk factor is the proximity of rail lines to each other with respect to the links and nodes of the network. The more lines closer to each other within proximity to the network, the greater the risk. For instance, two rail lines intersecting at a node causes more damage to the network than a single line with a disconnect crossing a link. There is a chance for a greater impact in the former. This is because

of the flow at the intersection of the line and node. Flow of goods on the lines also affects the likelihood of disconnects to the network. Lines with a high flow of goods on them entail more rail movement on the line. More movement means more chances for disconnects.

Referring back to Figure 6, rail line 10 has two other rail lines close to it. They are lines 11 and 16. Line 12 is the same as line 10 and thus not part of the evaluation. Line 11 is 0.50 and line 16 is 0.75 miles from line 10. The risk for line 10 is high and thus receives a high score. Conversely, line 11 in Figure 7 shows line 10 inside the 0.75-mile radius and line 16 at the 1.00-mile radius. Because of their proximities to line 11, line 11 is less vulnerable than 10. Hence, line 11 receives a lower risk score. Again, this process continues until the analyst examines every rail line.

Figure 7. Proximity to other Rail Lines

Parallel to Highways

Rail lines parallel to the highways affects the risk of the network. The lines provide a greater chance for disconnects. That is, a line running parallel to the highway for half a mile has a greater chance for disconnects because of the area covered by the line. If the line intersects the link, then the risk reduces to a point. There is less area coverage.

Referring to Figure 8, notice line 12 is parallel to the highway for some distance. On the other hand, line 11 intersects the link between 23 and 24. Therefore, line 12 is more vulnerable to the network than line 11 in terms of lines parallel to the highways.

Figure 8. Example of Rail Lines Parallel to the Highway

Commerce

Lastly, the flow of goods on the lines affects the chance of disconnects on the highways. Lines that have a high volume of goods on them mean there is typically more rail movement on the line. It also means there is a probability that the trains are longer. This is a coupling effect (Rinaldi, Peerenboom, and Kelly 2001). Coupling refers to how closely related the entities are to each other. In this case, the coupling effect refers to the number and length of time the trains run on the lines.

To determine the flow of goods on the rail lines, the analyst uses an empirical approach where two data sources are used. One is Union Pacific's (UP) allowable gross weight map. The other is the Commodity Flow Survey (CFS) from the US Census Bureau. Then the analyst combines the findings to estimate the flow.

First, use the gross weight map to determine where the rail lines lead and which set of tracks allows the most weight on them. Using the map in Figure 9 and the one in Appendix 5, the analyst determines the flow of commodities combining two methods. The first looks at the size and the number of rail lines of the destinations. For large movements, the analyst finds the major cities and depots. They include San Antonio, Dallas-Fort Worth, Texarkana, Shreveport, and Port Arthur. (Note other rail companies share the lines. These are not UP exclusive.) There are stops along the way however. While San Antonio, Dallas-Fort Worth, and Texarkana are obvious depots, Port Arthur and Shreveport are not. However, Shreveport is a major depot because it intersects lines from Dallas-Fort Worth, Pine Bluff, and Livonia. Port Arthur on the other hand has a water port thus making it a viable destination. On the lighter side of flow are destinations such as Highlands and Baytown. They have no major intersections and are towns. The next method looks at which lines allow the most weight on them. This premise is that lines with the heavier allowable weights entail more movement on them. Based on Figure 9, lines to San Antonio, Dallas-Fort Worth, Shreveport, and Port Arthur have the greatest capacity. On the other hand, the lowest is a single line to Baytown. The rest are in the middle.

Second, use the CFS. It contains detailed information regarding the movement of goods by metropolitan cities. Table 7 found in the CFS report (not depicted in this paper) shows the outbound shipment characteristics from an origin city. These characteristics are value, tons, and ton-miles. The table illustrates where most of the goods go, by state and large cities based on all modes of transportation. It does not break the information down by small cities, however. Hence, the Houston area, for example, ships 317,540,000 tons per year. Of that, 265,144 remain in Texas. Furthermore, 233,816 of the 265,144 remain in the Houston area. The rest goes between Austin-San Marcos, Dallas-Fort Worth, San Antonio, and the remainder of

Figure 9. Gross Weights on Rail Lines

Texas cities. Based on this information, Austin-San Marcos receives 741 while Dallas-Fort Worth gets 3,471,000 tons. San Antonio and the remainder of Texas receive 1,613 and 25,503,000 tons, respectively. The key item to note is where the flow moves outside of the Houston area. This data shows, for individual cities, that Dallas-Fort Worth receives most of the flow, while San Antonio and Austin-San Marcos come in second and third, respectively. Based on this, the model assumes the flow on the rail lines is similar to the total flow using all modes of transportation.

Once the analyst estimates the flows, use the lines to determine the risk. Those lines with heavier flows on them have a greater likelihood of causing disconnects in the network. Therefore, define the risk scale based on the flow of goods. Assign the lines with the heaviest flow the greatest risk values. Compare the risk values of other destinations with each other to ensure consistency.

Summary of Rail Lines

Table 2 is the QRA for the rail lines, based on Figure 6. Because link (23, 24) shares two rail lines, 10 and 11, Table 2 reduces to Table 3. This table depicts QRA_i^R for one node and four links, where R represents rail lines and i is a counter. This table is one portion of the model. The model uses a scale and weighted factor to determine the QRA for each entity in the table.

First, the model uses a scale from one to ten to identify the risk for each entity. As the risks become greater, the scale approaches ten. The risk categories in Table 2 stem from the HHM found in Appendix 2. Look at rail line 10 in Figure 6; notice how close it is to node 23. Because of its proximity to the line, it receives a high number on the risk scale. That is, the risk for a disconnect based on the GI of the line is high. On the other hand, line 16 is furthest away from the node. Hence, it receives the lowest number on the risk scale. The analyst uses the same logic

Table 2. QRA with Multiple Links

i	Rail Line Num	Node w/Respt to Link	$k \rightarrow$				
			GI			Logical	
			Prox to Node 40%	Prox to Oth Rails 30%	Parallel to Hwy 10%	Flow 20%	
1	N/A	23-N/A	0.0	0.0	0.0	0.0	0.00
2	N/A	23-22,23	0.0	0.0	0.0	0.0	0.00
3	10	23-23,24	7.5	8.0	5.0	6.8	7.26
4	11	23-23,24	4.5	7.0	5.0	8.1	6.02
5	12	23-23,29	6.0	6.5	10.0	6.8	6.71
6	16	23-13,23	4.0	9.0	0.5	5.4	5.43

Table 3. QRA Combining Like Links

i	Node	Links	$k \rightarrow$				
			GI			Logical	
			Prox to Node 40%	Prox to Oth Rails 30%	Parallel to Hwy 10%	Flow 20%	
1	23		0.0	0.0	0.0	0.0	0.00
2		22, 23	0.0	0.0	0.0	0.0	0.00
3		23, 24	12.0	15.0	10.0	14.9	13.28
4		23, 29	4.5	7.0	5.0	8.1	6.02
5		13, 23	6.0	6.5	10.0	6.8	6.71

throughout the process of the model for each link, and for each GI. Then the analyst evaluates the flow. Recall that the flow is a logical interdependency. The more flow on the line, the greater the risk and, thus, the higher the scale number.

Second, the model uses a weighted number for each risk entity. The weights are a collaboration of officials and experts. The weights signify how much influence a particular entity has on the system. Furthermore, the weights must equal one. Hence, for proximity to the node, the weight is 40 percent. For proximity to other rail lines, parallel to the highways, and the flow on the lines, the weights are 30 percent, 10 percent and 20 percent, respectively. These weights are dynamic and change based on new information, experts identifying and reviewing the risk, or completion of failure mode and effects analysis (FMEA).

Once the analyst determines the risk, the algorithm of the model computes QRA_i^R for link based on the rail line. It takes the product sum of each risk category. The model uses Equation 11 to calculate QRA_i^R for each link. Below is an example for node 23, rail line number 10 in Table 2.

$$QRA_i^R = \sum_{k=1}^n Scale_{i,k} \cdot Factor_k$$

where $i = 3$ and $k = 1, 2, 3$, and 4

$$\therefore QRA_3^R = (7.5)(.4) + (8.0)(.3) + (5.0)(.1) + (6.8)(.2)$$

$$QRA_3^R = 7.26$$

Traffic Flow. To compute QRA_i^F for the network, where F represents the traffic flow, and i is a counter, use the highway traffic map of the respective district. The map contains the traffic flow for each link and node. The map is available from the respective DOT. The heavier the traffic flow is, the greater chance for risk. The risk pertains to accidents and deaths due to an explosion. If the model simulates a disconnect due to a terrorist act, such as an explosion, the node or link with the highest traffic flows has the highest rate of risk. Based on Figure 10, Table 4 illustrates the risk for one node and four links. Nodes 13 and 29 are not in the figure. The flow on the highways is during peak hours. Use Equation 12 to calculate QRA_i^F . The division by 100 normalizes the table between one and ten.

$$QRA_i^F = (Flow_i \cdot Factor_i) \div 100 \quad (12)$$

Figure 10. Traffic Flow for Node 23

Table 4. Traffic Flow Peak Hours

i	Node	Links	Physical Traffic Flow	Risk Factor	QRA_i^F
1	23		102.8	8.0	8.22
2		22, 23	57.2	6.0	3.43
3		23, 24	59.6	6.2	3.70
4		23, 29	42.5	5.0	2.13
5		13, 23	46.2	5.2	2.40

Traffic Commerce. The flow of commerce is a SoS for supply chain networks. It affects distribution centers (DC), inventory, labor, and multiple other costs indices, including

costs of goods. A disconnect on the highway network causes product delays, possible spoilage, and increased labor costs (Sheffi 2001). Hence, the risk assessment for this portion of the model considers the *movement of goods on the network*. Consider the amount, value, and hazardous goods and assign them a risk score. The sum score of risk for these three items help to qualify the risk assessment. Table 5 depicts QRA_i^C for the movement of goods, where C represents commodities/goods and i is a counter.

Table 5. QRA Goods Movement

		$k \longrightarrow$	1	2	3	
i	Node	Links	Physical HC Route 50%	Logical Cargo Value 30%	Physical Cargo Tonnage 20%	QRA_i^F
1	23		10	9.8	9.8	9.88
2		22, 23	10	5.0	5.0	7.50
3		23, 24	10	5.5	5.5	7.75
4		23, 29	0	4.0	4.0	2.00
5		13, 23	10	5.0	5.0	7.5

To address the risks for the tonnage and value of goods on the highway network, estimate their amount on the network for each link. The greater the tonnage and value of goods on the link are, the higher the risk score. To estimate the amount and value of goods, use a systematic approach. It is the same methodology for estimating the flow of goods on the rail lines given the CFS. Because the CFS also provides the value of goods, estimate the value of goods on the highway network as well. To solidify further the tonnage and value, use the traffic flow counts for the network. This illustrates which links have the most flow on them. Hence, the more tonnage and value of goods on the network, the higher the risks are. On the other hand, to estimate the risks for certified hazardous cargo (HC) routes, obtain a HC route list from the DOT. Simply, the risk is 10 for a HC route and 0 otherwise.

Overall, hazardous commodities have a higher risk than the value of the goods. However, the value of the goods is less important, but more than the amount moved. Thus, HC route receives a weighted value of 50 percent, while the other two receive 30 percent and 20 percent, respectively. Use Equation 13 to calculate QRA_i^C .

$$QRA_i^C = \sum_{k=1}^n Scale_{i,k} \cdot Factor_k \quad (13)$$

Network Performance. The second algorithm combines cost and risk to form an assessment of the respective node or link. It places both variables in the same field because cost and risk constitute a unit-less number. Table 6 shows the cost scales for Figure 10. Because both are unit-less numbers, they can be combined to form a

Table 6. Scale Based on Costs

i ↓	Node	Links	K =	Injuries	Deaths	(000)	Scale _i
1	23		0.03946	29.6	11.8	\$13,258	8.5
2		22, 23	0.02197	16.5	6.6	\$7,380	5.0
3		23, 24	0.02289	17.2	6.9	\$7,690	5.0
4		23, 29	0.01632	12.2	4.9	\$5,484	4.0
5		13, 23	0.01774	13.3	5.3	\$5,961	4.5

score. For example, the model has 60 percent as the weight of cost in terms of the system. The remaining 40 percent is in risk. Thus, the score for node 23 is 12.34. This score is a product sum, as defined by Equation 14. The score determines the magnitude of the impact for each node and link corresponding to the network. Table 7 illustrates the overall results assuming a complete disconnect in the respective node or link. Based on the information, link (23, 24) requires the most attention while link (23, 29), the least. Interestingly enough, node 23 is not the item with the highest risk, as one may expect. This goes to show that using a system's approach yields more meaningful results.

$$Score_i = \sum_{k=1}^n Cost_{i,k} \cdot Risk_k \quad (14)$$

Table 7. Score for Nodes and Links

$k \longrightarrow$		1	2		
i ↓	Node	Links	Cost 60%	Risk 40%	Score
1	23		8.5	18.1	12.34
2		22, 23	5.0	10.9	7.37
3		23, 24	5.0	24.7	12.89
4		23, 29	4.0	10.1	6.46
5		13, 23	4.5	16.6	9.34

Resource Allocation

The results from the model provide city and government officials with a basis for resource allocation. Officials would concentrate resources first at the nodes and links with the highest risk scores. In a critical infrastructure protection (CIP) example, suppose there is a terrorist threat. The threat involves the highway portion of the transportation CI. Only so many responders are available. Where do the officials assign the responders for reducing the severity of the threat? The model helps officials with the decision-making process. It helps them strategically place extra responders in the most crucial areas. Based on Table 6, the officials would start by placing responders at

link (23, 24). Then they would work down to link (23, 29). Responders are at least positioned to react immediately given any disconnect occurring. However, in a city where there are twenty-five nodes and forty links, only so many resources are available. In this case, leaders would target the top five areas and assign responders accordingly. This strategy places responders in the areas with the highest impact to the network. Officials could also increase the efficiency by placing responders close to those nodes and links with the highest risk scores. This allows responders to be in proximity to other nodes and links not in the top five. Because the coverage area increases, resource allocation is more efficient.

Risk Mitigation

The results could also assist officials with risk mitigation based on the nodes and links with the highest scores. Allocation of funds to the network could help abate risks. There are three examples for discussion. One, officials could purchase security cameras for installation at critical nodes and links. Proper agencies would then monitor them for unusual activity. Two, and more expensive, is to move geographical interdependencies away from the network. Power lines, for instance, could go under ground when traversing the network. This almost eliminates the risk of power lines causing disconnects on nodes or links. Three, based on the type of threat with resulting disconnects, agencies could move some of the traffic off the highways. This includes trucks with sensitive cargo. The movement reduces the number of vehicles on the network and, thus, chances of greater catastrophes.

Summary

This paper introduces a methodology for assessing the impact that highway disconnects have on metropolitan cities. It provides an example of a model. The model uses costs and risks as output variables. These variables are specific to three areas. One is the GIs of rail lines. Two is the logical interdependency byproduct of the rail lines. Three is the physical interdependencies of traffic flow on the highways. The example also shows one run from the model where it ranks the most crucial nodes and links. The paper then describes how officials could use the results from the model. That is, it helps them with the decision-making process for resource allocation and risk mitigation.

Future enhancements to this model should consider three areas. First, use experts in the risk identification and assessment of the highway network. This provides results that are more accurate. Second, include the six dimensions

of the infrastructure interdependencies. This makes the model more robust. Finally, adopt Bayesian analysis for the likelihood of threats. This provides better estimations from the model.

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Biography

Gerard Ibarra is a consultant in logistics and systems engineering. He is also an adjunct professor at Southern Methodist University (SMU) School of Engineering and at the University of Dallas Graduate School of Business. He has an M.S. in systems engineering and a B.S. in electrical engineering. He is doing research for SMU where he is focusing on systems engineering and transportation as related to the U.S. critical infrastructure while fulfilling his Ph.D. requirements.

Dr. Jerrell Stracener is currently scholar in residence and systems engineering program director at SMU. He was the integrated logistics support program manager on military aircraft programs at Vought Aircraft Company/Northrop Grumman Corporation. Stracener is an elected Fellow of SAE and Associate Fellow of AIAA. Stracener received his Ph.D. and M.S. degrees in statistics from SMU.

Dr. Stephen Szygenda presently holds the Green Chair in Engineering at SMU. Previously, he has been the dean of engineering at SMU and the University of Alabama at Birmingham and Chair of the ECE Department at the University of Texas at Austin. He was the founder and president of a number of companies and a member of technical staff at Bell Laboratories. He received his M.S. and Ph.D. degrees from Northwestern University.

Appendix 1: Definitions

Best Link: The best link is similar to the worst link's concept. The difference is the best link is the link with the least negative influence on the network.

City Boundary: The city boundary typically consists of the city and its surrounding suburbs. The boundary is always outside of any interstate loop.

Cyber Interdependency: An infrastructure where its state depends on information transmitted through the information structure (Rinaldi, Peerenboom, and Kelly 2001).

Disconnects: Disconnects are the complete impediment of traffic flow on the links. They are bidirectional.

Geographical Area: It is the city boundary.

Geographical Interdependency: These are infrastructures where the local environment event can create state changes in all of them (Rinaldi Peerenboom, and Kelly 2001).

Highway: Highway, where tolls are inclusive, consists of multiple bidirectional lanes traveling at posted speed limits of 45 to 70 MPH. There are no traffic signals on the highway and dividers separate opposing lanes. The dividers typically are concrete barriers. Highways do not include their adjacent service roads.

Links: In a bidirectional highway system, links are the aggregated highway lanes in one direction connecting nodes. Links are only the highway lanes and are not streets or highway access roads.

Logical Interdependency: Two infrastructures that are interdependent when the state of one depends on the other via a mechanism that is not physical, cyber or geographical connection (Rinaldi, Peerenboom, and Kelly 2001).

Major Metropolitan Cities: Major cities are those with a population of at least 100,000 or more. They have suburbs that are adjacent to them making up a metropolitan area. Furthermore, the cities must contain at least two highways within the metropolitan area.

Movement of Goods: The movement of goods consists of moving items, such as food, raw materials, fuel, and other commodities, on the highways. The model limits the movement to large trucks. It does not include couriers that transport lab work, legal documents, and other small miscellaneous items. Typically, couriers move these items using small personal vehicles such as automobiles, pickup trucks, and vans.

Normal Traffic: Normal traffic hours are between 9 a.m. and 4 p.m. It also includes the hours from 5 a.m. to before 6 a.m. and after 7 p.m. up to 10 p.m. Traffic delays during these times are not as severe as those delays occurring during peak traffic hours.

Nodes: The nodes are the intersections of the highways. They are within the boundaries of the city.

Other Traffic: Other traffic hours are between 10 p.m. and 5 a.m. This traffic flow constitutes the lightest volume on the network. Traffic delays are at a minimum during these hours.

Peak Traffic: Peak traffic hours are those when the network experiences the heaviest traffic. There are two periods: from 6 p.m. to 9 a.m., and from 4 a.m. to 7 p.m. (Schrack and Lomax 2004).

Physical Interdependency: It is the state where two infrastructures physically depend on each other for their respective outputs (Rinaldi, Peerenboom, and Kelly 2001).

Snapshot of System: A snapshot of the system is the state of the network at any given time. It is not continuous where as time elapses, it changes the network.

Steady State: Steady state refers to the network operating under normal conditions. Traffic patterns are consistent. There are no outside forces, such as weather or accidents, affecting the network. Furthermore, steady state includes the current threat level for a terrorism attack.

System: System is the thirteen CIs of the U.S.

System of Systems: SoS is a subcomponent of the system. There could be multiple SoS. They could act alone as a system, and when aggregated with other subsystems, create an overall system. In addition, the SoS could include further subsystems of the SoS. The highway network is an SoS while the child and its parent is the transportation CI. The transportation CI is also a SoS and the child of the CI, the system.

Worst Link: The worst link is that highway section that negatively affects the system the most. The link creates the worst performance for the defined links of the network.

HHM
Hierarchical Holographic Modeling

Appendix 2: HHM

Work Breakdown Structure of the
Transportation CI Model

Appendix 3: WBS

Functional Flow Block Diagram for GIs of the Transportation CI of Highways

The map displays the state of Texas with its major cities and transportation networks. Two specific regions are highlighted with rectangular boxes:

- North Central Texas:** This box encompasses the Dallas-Fort Worth metropolitan area, including cities like Dallas, Fort Worth, and surrounding suburbs.
- South Central Texas:** This box encompasses the Houston metropolitan area, including the city of Houston and its immediate surroundings.

The map also shows other major Texas cities such as San Antonio, Austin, El Paso, and Dallas. Major highways (Interstates) are depicted as thick, solid lines, while other roads are shown as thinner lines. The Gulf of Mexico is visible to the east of the state.

AAA: American Automotive Association
BTS: Bureau of Transportation Statistics
CFS: Commodity Flow Survey
CI: Critical Infrastructure
CIP: Critical Infrastructure Protection
DC: Distribution Centers
DHS: Department of Homeland Security
DOT: Department of Transportation
FFBD: Functional Flow Block Diagram
FHA: Federal Highway Association
FMEA: Failure Mode and Effects Analysis
FRA: Federal Railroad Administration
GI: Geographical Interdependency
HC: Hazardous Cargo
HHM: Hierarchical Holographic Modeling
NHC: National Highway Council
NHTSA: National Highway Traffic Safety Administration
QRA: Quantitative Risk Analysis
SE: Systems Engineering
SoS: System of Systems
TTS: Theory of Scenario Structuring
UP: Union Pacific
U.S.: United States
WBS: Work Breakdown Structure