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WMD Impact Modeling and Response

Topic: Modeling and Simulation

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Abstract:

Models to estimate the consequences of the Atmospheric Transport and Dispersion (ATD) of chemical, biological, radiological, or nuclear (CBRN) materials have been in development since the 1940s. Even so, limitations remain in the abilities of these models to be used in emergency situations (GAO, 2008). This paper describes our experiences in combining an optimization model we have developed for evacuation decision support with existing plume models, as well as geospatial tools and unique datasets, to provide an initial enhanced response modeling tool. The evacuation optimization model is described. A case study of a radiological event, its impacts, and implications for evacuation policy are described. Lessons learned from our experiences in integrating disparate tools and datasets are discussed.

Introduction

Models are used frequently in the literature to assess the resilience of systems to hazards, whether intentional, natural, or accidental. Models to estimate the consequences of the Atmospheric Transport and Dispersion (ATD) of chemical, biological, radiological, or nuclear (CBRN) materials have been in development since the 1940s. Even so, limitations remain in the abilities of these models to be used in emergency situations (GAO, 2008 and 2003). The purpose of this work is to enhance existing Chemical, Biological, Radiological, and Nuclear (CBRN) modeling tools to incorporate the ability to predict impact on critical infrastructures and provide decision support for evacuation response.

This research builds upon previous Noblis research and client projects in developing analysis tools with geospatial capabilities. For instance, the Telecommunications Infrastructure and Sensitivity Tool (TIST) is an interactive telecommunications critical infrastructure analysis tool which was developed for the National Communications System to address the government's need to maintain the ability to communicate during a crisis. It incorporates billing data from government telecommunications contracts to allow users to visualize agencies' telecommunications traffic inventories and perform critical infrastructure / sensitivity analysis in the event of disabled telecommunications carrier facilities. In addition, Noblis has conducted extensive geospatial architecture development using open source components through Noblis Research.

This research also builds upon Noblis research projects to integrate a network of commercial mobile radiation sensors through a Service Oriented Architecture (SOA). Sensor readings in this system are uploaded through a wireless network to a central repository, and a SOA provides automated common services to end users. The SOA can provide responders and decision makers with common access to critical information from a variety of sources and systems. One of the goals of this research is to demonstrate Atmospheric Transport and Dispersion models as user products utilizing the sensor data. The real-time sensor data can be leveraged to update modeling forecasts and support decision-making. Additional user products are developed in this research providing decision support for optimal evacuation modeling in response to a hazardous release incident. We also coordinate with other research efforts to demonstrate geospatial visualization of CBRN impact, so that government locations and telecommunications facilities in the estimated plume impact area can be visualized. The SOA, sensor platforms, and associated user products are depicted in Figure 1.

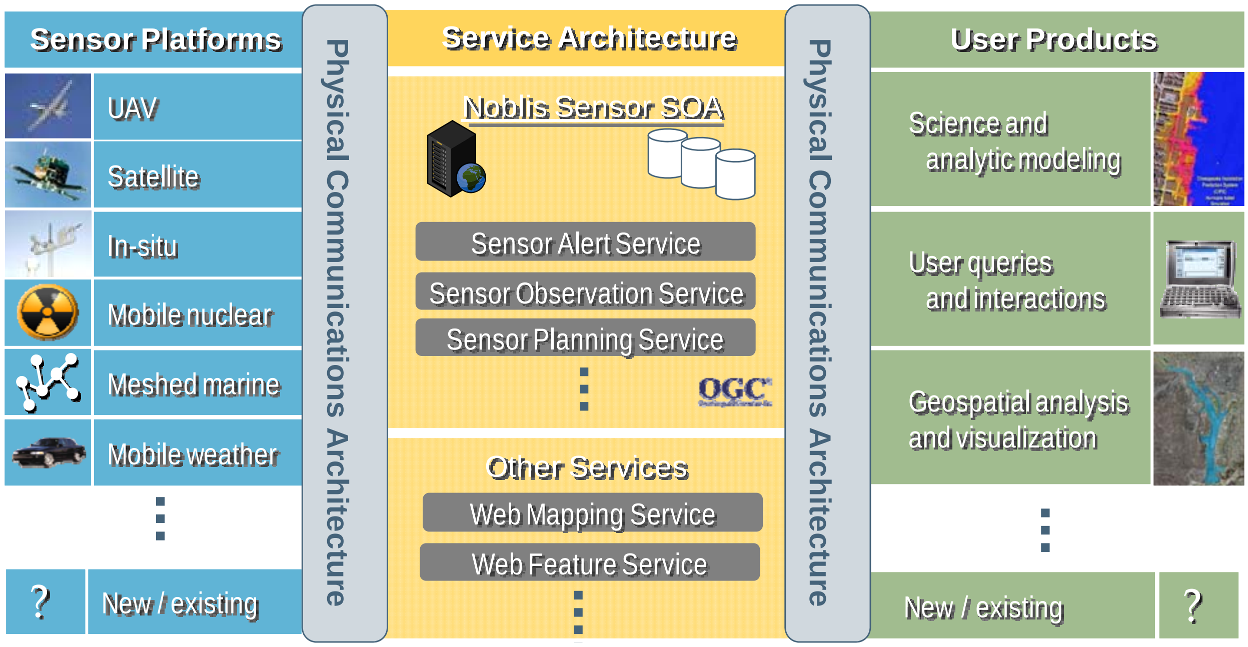

Figure 1. Noblis Sensor Network

Our focus in this paper is on the modeling-related User Products depicted in Figure 1. The basic elements of an Atmospheric Transport and Dispersion model, which is used to estimate contamination levels due to release of a hazardous material, are shown in Figure 2.

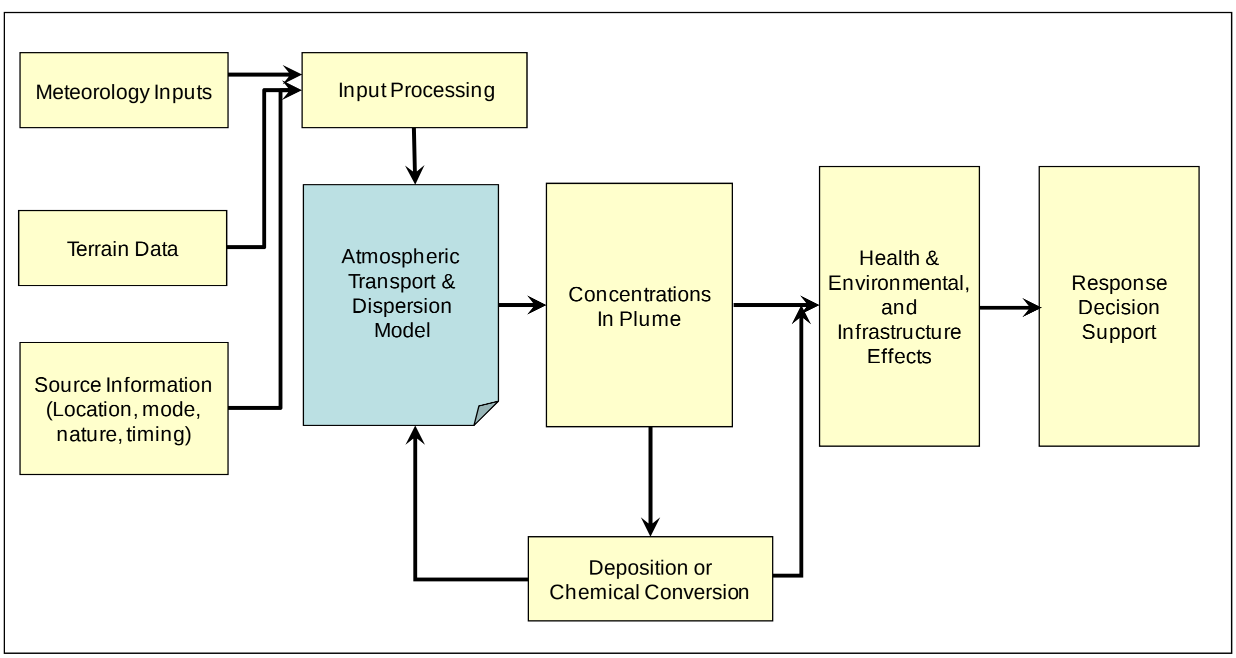

Figure 2. Basic Elements of an ATD Model, adapted from Noblis, 2008.

A comprehensive Atmospheric Transport and Dispersion model takes into account the material released, local topography, and meteorological data. The meteorological data can be obtained from mobile weather sensors or real-time feeds from national weather service web sites. Data on the local topography (e.g., from GIS databases) is also needed for ATD models. The data on the contaminant can come from CBRN sensors.

The atmospheric dispersion models produce estimates of the movement and concentration of contaminants over time. Effects on health can be estimated by consequence models. The estimated plume concentration and impacts can be further used in decision support response models. In addition to model use in direct response to an event, models can also be used in other phases of the emergency management cycle in conjunction with planning scenarios to include preparedness, mitigation, and recovery activities.

Review of existing tools and literature

Our research commenced with a review of the literature on existing Atmospheric Transport and Dispersion models estimating the area of contamination due to CBRN materials. One hundred forty-nine models were identified, including ATD models of particular agents which estimate where and in what concentration a contaminant may be present, consequence models which may extend the plume models to estimate human casualties, and integrated models which estimate dispersion for a broad range of CBRN hazardous materials. There are four main types of atmospheric transport and dispersion models, including 1) Gaussian plume or puff models, which are relatively simple models which run quickly and are fairly accurate in flat terrain, 2) Lagrangian models, which contain more detailed representations of dispersion, 3) Computational Fluid Dynamics (CFD) models which are simulations of complex flows especially present in urban areas, and 4) empirical urban models derived from field data (GAO, 2008). Borysiewicz and Borysiewicz (2006) provides an excellent survey of existing atmospheric transport and dispersion modeling tools for emergency management.

In addition to researching plume models to estimate geographic areas contaminated by hazardous materials, we also surveyed the literature in evacuation modeling, as a key goal of this effort is to integrate plume models of hazard contamination levels with response decision support capabilities. While more than thirty surface transportation modeling tools are available for evacuation modeling, most of the tools are designed for evacuation due to natural events such as hurricanes rather than more general vehicular evacuation to include man-made event scenarios such as hazardous materials or terrorist events. A major difference in these types of events is the amount of preparation time that is likely to be available. The modeling tools have varied levels of geographic scope, analysis precision, orientation for either planning or real-time decision support, and computational speed. The macro level models represent a large geographic area, but with reduced detail – modeling flows of traffic rather than individual vehicles – and reduced time sensitivity. Micro level models represent a certain segment of road rather than a large geographic area, but include detail on individual vehicles. The majority of the tools are geared toward long-term or operational planning rather than real-time decision support tools. Hardy and Wunderlich (2007) provides a thorough inventory and categorization of these tools. Hamacher and Tjandra

(2002) also surveys the evacuation modeling literature, focusing more on the macroscopic optimization-based model formulations than the micro-level simulation-based models.

In this paper we describe our work to enhance plume models by developing capabilities for response decision support and coordinating with a Noblis Sensor Network consisting of a Service Oriented Architecture, sensor data, and user products. A new user product, which is an initial evacuation model, is developed which interfaces with the plume model. The remainder of the paper describes our methodology, case study, a summary of results, lessons learned from the various tools and datasets that we worked with, and next steps.

Methodology

We selected an existing plume model from the 149 models that were identified, based on several factors: 1) its ability to model airborne dispersion of radioactive materials, which was desired for coordination and demonstration with Noblis radiation sensors, 2) model cost and availability, 3) model sponsorship by an appropriate federal agency, 4) model speed and portability, and 5) ability to process model output to create graphical depiction of contaminated area. The model Hotspot Health Physics Codes was selected based on these factors. Hotspot estimates the radiation effects due to the release of radioactive materials into the atmosphere, and was developed by Lawrence Livermore National Laboratory for emergency response usage. It is publicly available at no cost (see https://www-gs.llnl.gov/hotspot/index.htm). Many of the models of the dispersion of hazardous materials through the atmosphere are available only with government sponsorship.

A goal of this work was to coordinate the selected plume model with other components of the Noblis Sensor Network. Data on the contaminant source term is required for any plume model, and the Noblis Sensor Network includes mobile nuclear and radiological sensors. A first step was to develop statistical models to estimate source term data required by the Hotspot model from the data collected by the radiation detectors. The SYNTHetic Gamma Ray Spectrometer (SYNTH) software was used to generate data to develop a model to predict curies of the radiological agent from the counts measured by the radiological sensors and the distance from the vehicular sensor to the source point. In addition, a simple regression model was first developed to estimate pounds of TNT used from the height of plume, based upon data from experimental runs of the HotSpot model.

The second step that was needed to coordinate the selected plume model with other components of the Noblis Sensor Network was to develop a script to read in the source (i.e., radiological element, number of curies, amount of explosives, etc.), terrain, and meteorological input data, and automate execution of the HotSpot plume model. The script then transforms the HotSpot end-state equivalent dosage contour output into multiple contours from time of detonation to end-state, then writes this output to a text file that can be input to the open source visualization program (QuantumGIS) used by the Noblis Sensor Network. This script was written in the perl programming language.

An initial demonstration was conducted of the Noblis Sensor Network on April 20, 2009, leveraging the Noblis Sensor SOA as part of a Radiological Dispersal Device (RDD) Response

System. Figure 1 depicts various types of sensors including nuclear, weather and marine sensors as part of the network; for this demonstration, only the nuclear / radiological sensors were utilized. Actual samples of Cs-137 were deployed at the Noblis facility in Falls Church, Virginia. The vehicular radiological detectors measured the radiation field strength, and the sensor readings were uploaded through a wireless network to the SOA central repository. The Sensor Alert Service provided user notifications that the sensor threshold was exceeded. Analysts utilized the sensor readings to employ the statistical models mentioned above to estimate the pounds of TNT and curies of Cs-137. Real-time government weather web sites were used for needed Hotspot model meteorological inputs. Upon model execution using the perl script, the forecasted Cs-137 plume for the next two hours were visualized using the QuantumGIS program, demonstrating two of the Sensor Network User Products (the ATD model and the geospatial visualization tools). The visualization of the plume over time was overlaid with the locations of various critical infrastructures, such as telecommunications facilities, government locations, schools, fire stations, and hospitals, and led to an assessment of the required time to evacuate key locations such as schools in the area.

The next phase of this research effort was to develop a decision support capability for optimal evacuation in response to a WMD attack in a densely-populated area. A linear program was formulated with the objective of maximizing the number of people evacuated from an affected "hot zone" in an allowable time. The "hot zone" is the contaminated region determined by the plume model. This model formulation is described in detail.

To analyze the region of interest, we first construct the graph $G = (V, E)$. The two principal zones of graph G are the "hot zone," in which individual are exposed to harmful agents, and the "safety zone," in which individuals are safe from deleterious effects of the WMD attack. The nodes in G represent the major intersections, which can be classified into three types:

- Evacuation nodes (V_e) → hot zone location with evacuees at time of detonation
- Destination nodes (V_d) → safe zone location
- Sink node (V_s) → artificial node to which all destination nodes are connected

The edges of G are the directed roadways between the nodes. The index sets of G are defined as follows:

$V_n = V_d \cup V_e \equiv$ set of all sites in region of interest

$V = V_n \cup V_s \equiv$ set of nodes in G

$E_n = \{(i, j) : i, j \in V_n\} \equiv$ set of directed edges in region of interest

$E_s = \{(j, s) : j \in V_d\} \equiv$ set of edges connecting each destination node to the sink node

$E = E_n \cup E_s \equiv$ set of directed edges in G

$M \equiv$ set of transportation modes (1 for bus, 2 for car, 3 for commuter rail)

The decision variables in our model are as follows:

$x_{ij}^{m} \equiv$ number of vehicles of type $m \in M$ to send from site i to site j in time T

$y_i \equiv$ number of individuals that cannot be evacuated from site i

The following input parameters in our model are defined:

$T \equiv$ required time to evacuate exposed individuals from hot zone

$u_{ij} \equiv$ maximum number of cars that can be sent from site i to site j in time T

$r_{ij} \equiv$ maximum number of commuter trains that can be sent from site i to site j in time T

$R \equiv$ throughput reduction factor for buses (i.e. decrease in throughput due to using larger vehicle)

$P_i \equiv$ number of individuals that are at evacuation site i at time of detonation

$b_i^m \equiv$ number of vehicles of mode m available at site i at time of detonation

$a^m \equiv$ average number of individuals that can occupy a single vehicle of mode m

The evacuation model that maximizes the number of people evacuated from the "hot zone" (denoted TH) in an allowable time T is formulated as follows:

$$\max_{x,y} TH = \sum_{i \in V_e} (P_i - y_i)$$

$$\sum_{j \in V} x_{ij}^m - \sum_{j \in V} x_{ji}^m = 0, \qquad \forall i \in V_d \qquad \text{(destination nodes)} \qquad (1)$$

$$\sum_{m \in M} a^m (x_{ij}^m - x_{ji}^m) = P_i - y_i, \qquad \forall i \in V_e \qquad \text{(evacuation nodes)} \qquad (2)$$

$$\sum_{i \in V_d} \sum_{m \in M} a^m x_{is}^m = \sum_{j \in V_e} (P_j - y_j) \qquad \text{(sink node)} \qquad (3)$$

$$\sum_{j \in V} x_{ij}^m \le b_i^m, \quad \forall \mathrm{i} \in \mathrm{V_e}, \forall \mathrm{m} \in \mathrm{M} \qquad (4)$$

$$y_i \le P_i, \quad \forall i \in V_e \qquad (5)$$

$$(1/R) x_{ij}^1 + x_{ij}^2 \le u_{ij}, \quad \forall (i,j) \in E_n \qquad (6)$$

$$x_{ij}^3 \le r_{ij}, \quad \forall (i,j) \in E_n \qquad (7)$$

Constraints (1), (2), and (3) are conservation of flow constraints; inflow is negative. Constraint (4) guarantees that vehicle availability is not exceeded. Constraint (5) is an excess demand constraint which ensures the number of evacuees is positive at all sites. Constraints (6) and (7) guarantee that road and rail capacity are not exceeded, respectively. The decision variables are the number of vehicles of each mode of transportation to send along a given route.

A linear programming solver is needed to solve the model. If there are fewer than 300 variables and 300 constraints, the student version of the AMPL Modeling Language is sufficient. For larger problems, a commercial LP solver is needed; the NEOS Server housed by Argonne National Laboratories provides some commercial solvers for use on their web site at no cost.

This model requires input data from various sources, including data on maximum throughput and average travel time on the roadways. This data was obtained from the Urban Congestion Report

(UCR) which is developed by Noblis personnel in support of the Department of Transportation Federal Highway Administration. The UCR data is available for 23 cities in the United States, and is a valuable source of detailed mobility and congestion data for sections of each city in 5-minute intervals since 2005. Maximum throughput for commuter rail can be obtained through published rail schedules. Vehicle availability data can be obtained possibly through Department of Transportation data, Census data, or first responders. The data on the number of people to evacuate can be obtained possibly through Census data or first responders. The hot zone boundaries and required evacuation time are estimated by the HOTSPOT model.

Given the required time T to evacuate the hot zone, we can determine the maximum number of vehicles u_{ij} that can be sent on the road between site i and site j in time T from the Urban Congestion Report (UCR) data. Since using a greater proportion of larger vehicles such as buses is expected to reduce vehicular throughput, we use a throughput reduction factor R to accurately reflect the reduction in throughput expected by using a greater proportion of buses. We express R as a proportion of the typical throughput such that $R \in (0, 1)$. The parameter r_{ij} gives a cap on commuter rail throughput and can be estimated from published rail schedules. The parameters P_i and b_i^m must be estimated by first responders at the commencement of the evacuation. We assume that each vehicle in the hot zone at the time of detonation is associated with exactly one evacuation site i such that $b = \sum_{i \in Ve, m \in M} b_i^m$ equals the total number of vehicles in the hot zone at the time of detonation. Finally, the parameter a^m represents an approximate average number of people that can be accommodated in a vehicle for mode $m \in M$. For instance, the choice of $a = 4$ would be an appropriate selection for an automobile.

Case Study – Chicago Radiological Dispersal Device Attack

An analysis was conducted of a scenario in which a Radiological Dispersal Device was detonated in Chicago, as a test scenario for the evacuation model. Detonation was assumed to take place at the Mount Sinai Hospital in Chicago. The RDD contained 150,000 Curies of Cs-137 and 100 pounds of the explosive TNT. Meteorological and terrain assumptions were made as follows: wind speed of 3.5 miles per hour coming out of the west, with 10 percent cloud cover, no precipitation, and city terrain.

The Hotspot model was run, using the perl script to automate model execution and output processing. Figure 3 shows the final Total Effective Dose Equivalent (TEDE) contour output in rem (roentgen equivalent, man) estimated by the model. The innermost contour represents a TEDE level of 1 rem, while the middle contour concentration is at least .1 rem, and the outermost contour corresponds to a TEDE of at least .01 rem. Ground deposition was also estimated by the model.

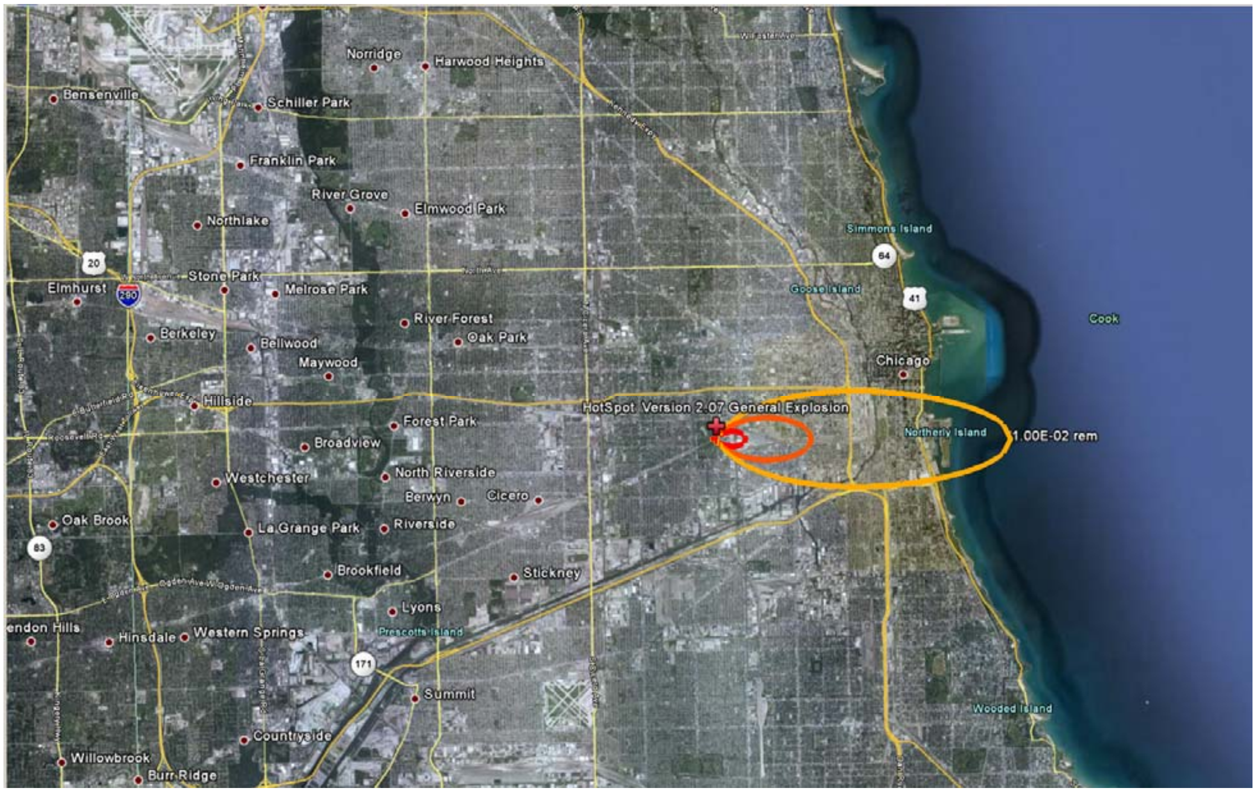

Figure 3. Chicago Case Study Final Equivalent Dosage Contours in rem

The roadway network for the Chicago area and associated throughput and average travel time on those roads was obtained from the Urban Congestion Report. Busy hours during nine dates in 2008 were selected for this case study. Figure 4 displays the graph structure which is a combination of evacuation nodes, destination nodes, and graph edges (a portion of which are shown in the figure). The evacuation nodes and destination nodes were determined by overlaying the hotzone, which is the region corresponding to the outermost final contour, onto the roadway network.

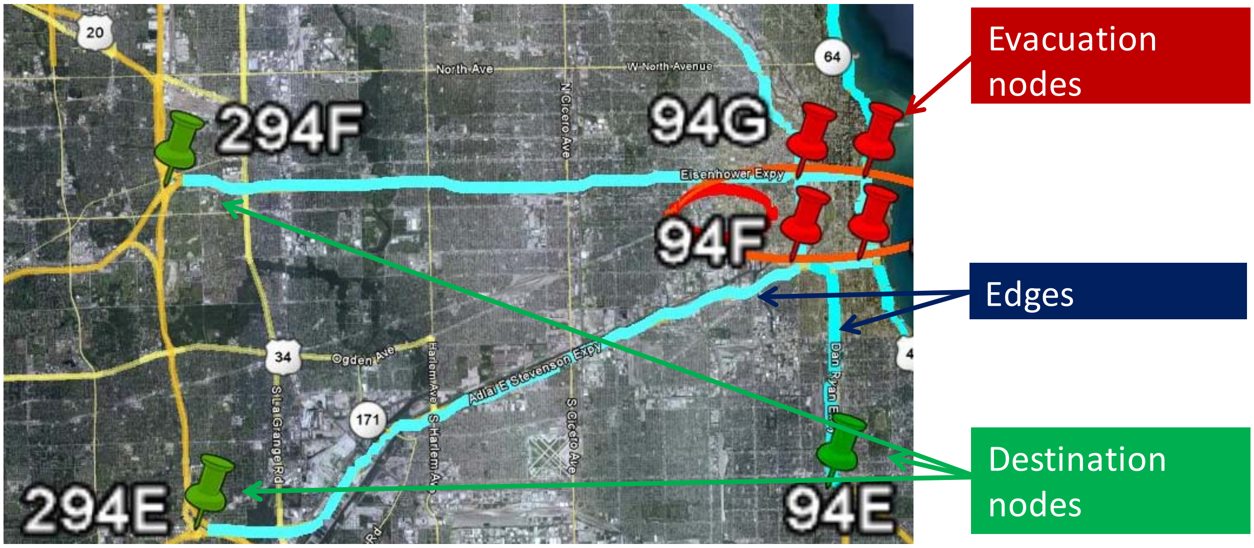

Figure 4. Chicago Case Study Graph Structure

The Hotspot model estimated that the total elapsed time before the plume concentration dissipates to below 1 rem Total Effective Dose Equivalent (TEDE) is 63.4 minutes, which was utilized as the required evacuation time parameter. We also assumed that buses, cars, and evacuees are evenly distributed in hot zone. Parameter values are as follows:

- Required evacuation time T = 63.4 minutes (estimated by the plume model)
- Maximum number of vehicles u_{ij} between nodes *i* and *j* during time T (from the UCR data for Chicago)
- Resource Availability:
  - 4,000 buses in the hot zone at the time of detonation
  - 50,000 cars in the hot zone at the time of detonation
  - Commuter rail was not included
- Number of evacuees = 500,000

While the evacuation time T was estimated by the plume model, and the maximum number of vehicles for each roadway segment came from the detailed UCR data, the remaining parameter values (resource availability and number of evacuees) were not scientifically estimated.

The optimization model was run, and results are depicted in Figure 5. Model results indicated that over 229,000 people could be evacuated during the required time, and routings resulting in this maximum throughput are given.

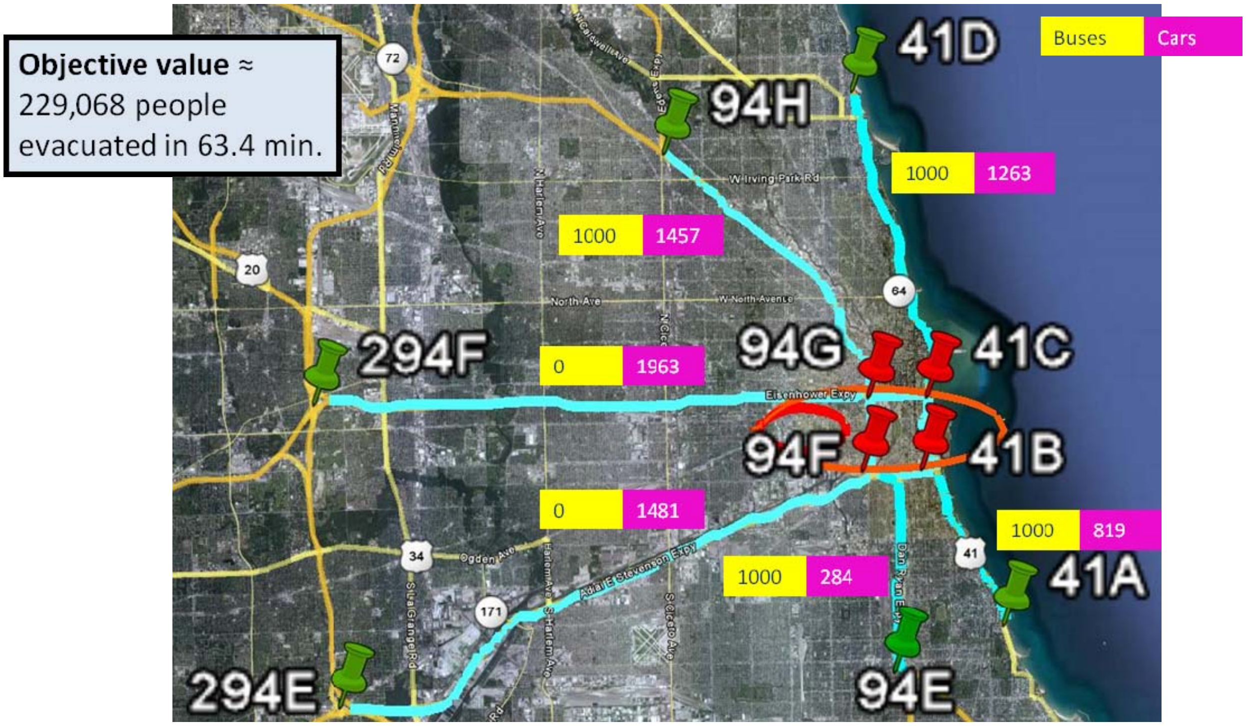

Figure 5: Chicago Case Study Model Solution

Since the model can be solved in a few seconds, extensive sensitivity analysis of the results to input parameters can be performed, which is a key strength of this linear programming formulation. Figure 6 shows the sensitivity of the total number that can be evacuated to the required evacuation time model parameter. This figure shows that total number that can be evacuated is highly sensitive to the required evacuation time, especially for required evacuation times less than one hour; there are diminishing returns to increasing this required time beyond about 50 minutes. The total number that can be evacuated is also highly sensitive to bus availability – see Figure 7. Returns from increased numbers of buses diminish only slightly with greater bus availability.

The number evacuated could also be greatly increased if the maximum edge throughput is augmented. Figure 8 displays this sensitivity on Highway 41 (roadway segments 41B-41A and 41C-41D), and Figure 9 shows throughput sensitivity levels for roadway segments 94F-94E and 94F-294E. In both cases, there are large potential returns at the current throughput levels. For roadway segments 94G-294F and 94G-94H (Figure 10), there are potential returns to increasing throughput at current throughput levels, but less than for the other segments.

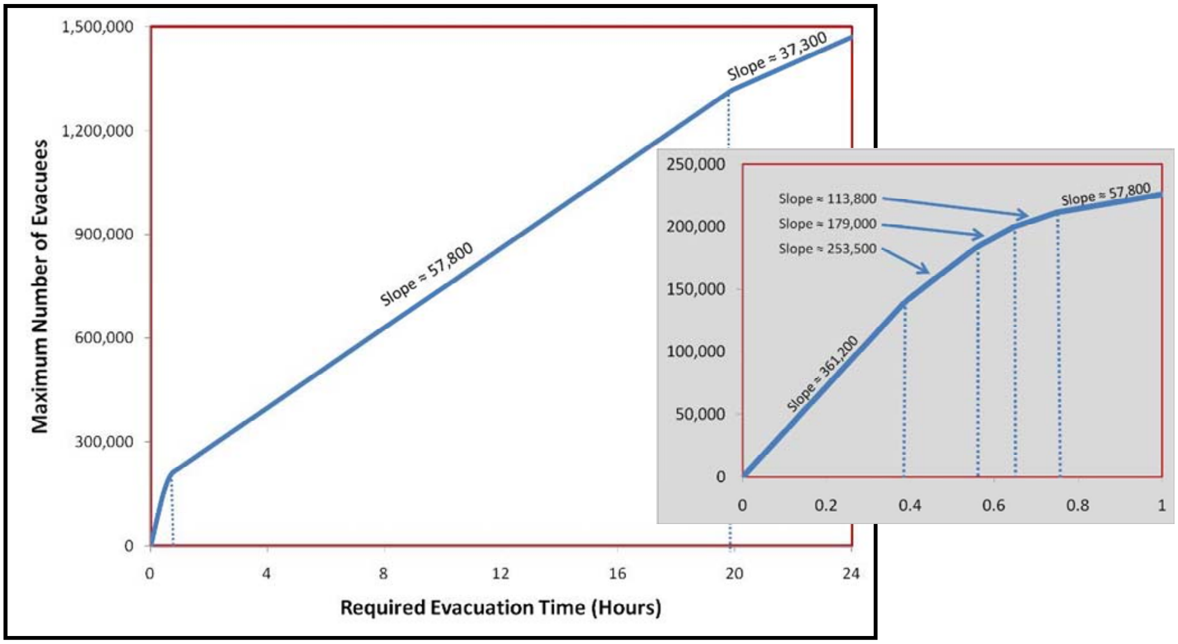

Figure 6: Sensitivity to Required Evacuation Time

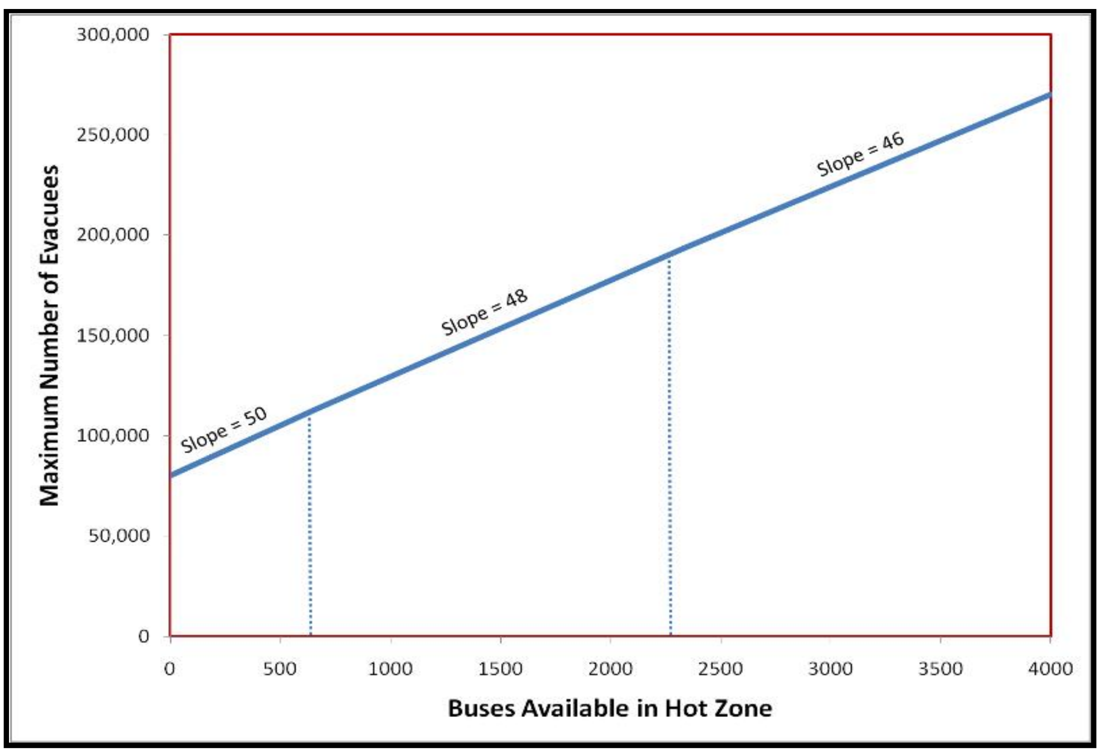

Figure 7: Sensitivity to Bus Availability

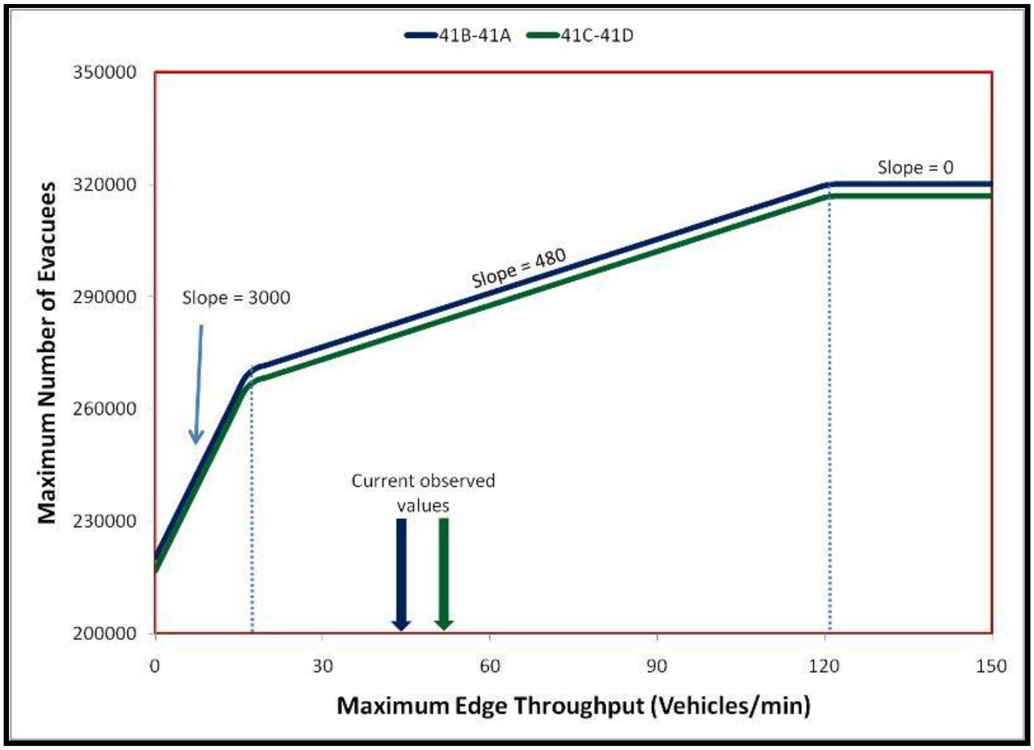

Figure 8: Sensitivity to Maximum Edge Throughput – 41A-41B and 41C-41D

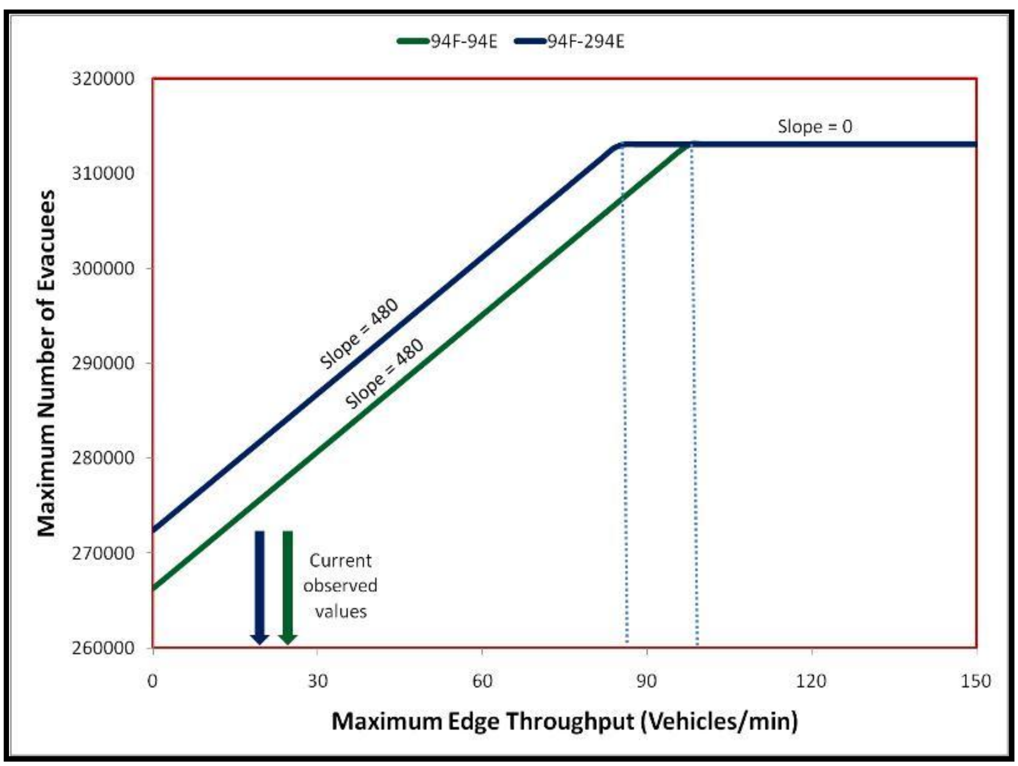

Figure 9: Sensitivity to Maximum Edge Throughput – 94F-94E and 94F-294E

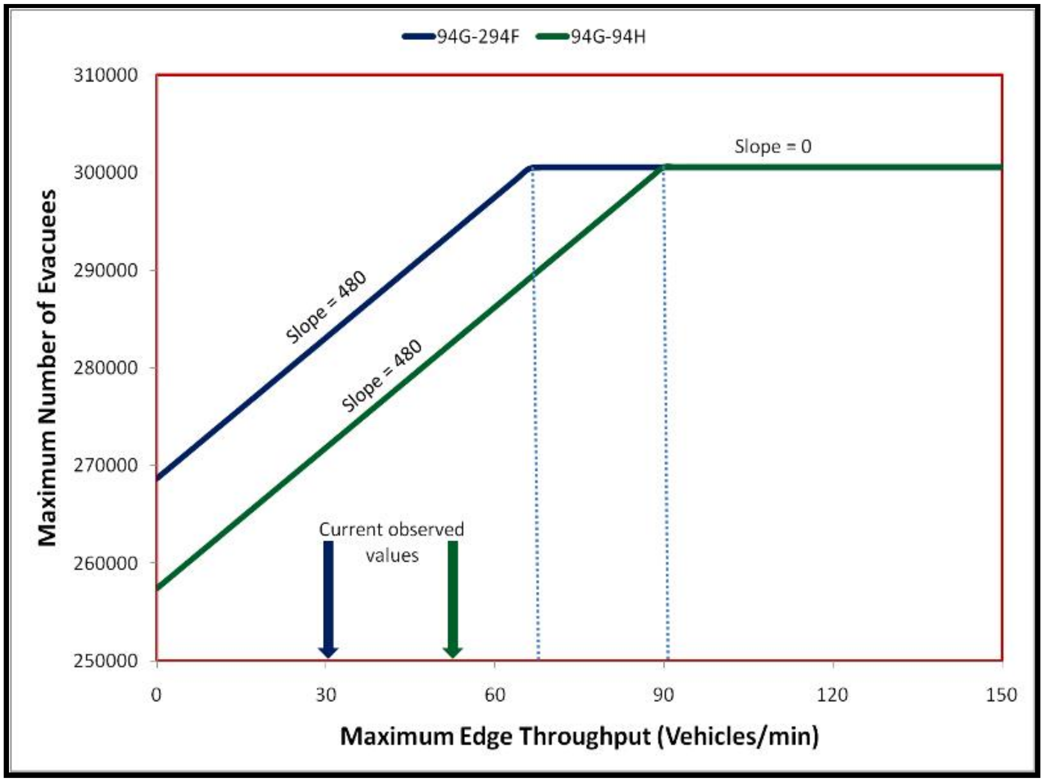

Figure 10: Sensitivity to Maximum Edge Throughput – 94G-294F and 94G-94H

We can make some general recommendations for policy from the evacuation model results, as well as real time routing guidelines during an emergency. This case study affecting the downtown Chicago area showed that bus service should be expanded, due to the large potential gains in number evacuated. Diminishing returns is a very minor factor. Additional buses should be utilized whenever possible, especially on routes with higher maximum throughput. Throughput should be increased (e.g., by adding lanes) especially on certain routes to boost the number that can be evacuated. However, diminishing returns is a factor.

Summary of Results

The key accomplishment of this research is the development of initial modeling and analysis capabilities in several areas: atmospheric transport and dispersion modeling, evacuation modeling, and geospatial analysis and visualization. In particular, we have brought an ATD model in-house and have developed additional models which allow us to estimate the needed source term data from Noblis sensor data, and integrate with Noblis tools to visualize impacts. A model to determine optimal routing and transportation modes for evacuation from an incident was also developed, utilizing highly detailed transportation data. The end result was a demonstration of an initial WMD planning and response system comprising mobile radiation detectors, integrated by an SOA, and including atmospheric transport and dispersion modeling, visualization including impacted government locations, and evacuation decision support user products.

Lessons Learned

There were several lessons learned from this research. Many sources of data and tools are required to model the impact of hazardous materials such as the RDD scenario from this study. We had access to several detailed datasets that contributed to this modeling effort, such as the Urban Congestion Report's maximum throughput and average travel time roadway data, mobile vehicular sensor data, and government telecommunications infrastructure data for impact visualization. Some of our observations and insights from working with these datasets and tools were:

1. An alternate evacuation model to minimize evacuation time (rather than maximum number evacuated) was also formulated, but due to non-linearities in the model formulation, it appears that this model may not be suited to real-time decision support.
2. Estimation of the contaminant source term parameters for the ATD model is not straightforward. As the estimates of the source term may be imprecise, due to the collection of sensor readings and necessary translation to model inputs, the model accuracy would likely be increased if the model estimates of contaminant count per second readings were calibrated versus the actual sensor readings, to converge to the best estimates about the nature of the source term.
3. Optimal placement of mobile sensors near the detonation point requires research. Initial research for this study indicated that the sensor readings may decrease in a quadratic rather than linear fashion with distance from detonation. Objects between the source and the sensor may block radioactive material. In addition, the sensor readings are sensitive to detector orientation.

Possible Future Directions

There are a number of possible future directions for this research. Further development could be performed on an alternate optimization model to minimize evacuation time given that all individuals in the hot zone must be evacuated. Tighter integration with the Noblis visualization tools could be developed to observe the optimal flow results on evacuation routes.

We would also like to obtain the flagship Hazard Prediction and Assessment Capability (HPAC) tool from Defense Threat Reduction Agency, due to its modeling capabilities across the range of CBRN threats, and integrate this with our evacuation optimization model. This would enable a broad set of hazard scenarios to be modeled, with implications for policy evaluated.

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