WMD Impact Modeling and Response

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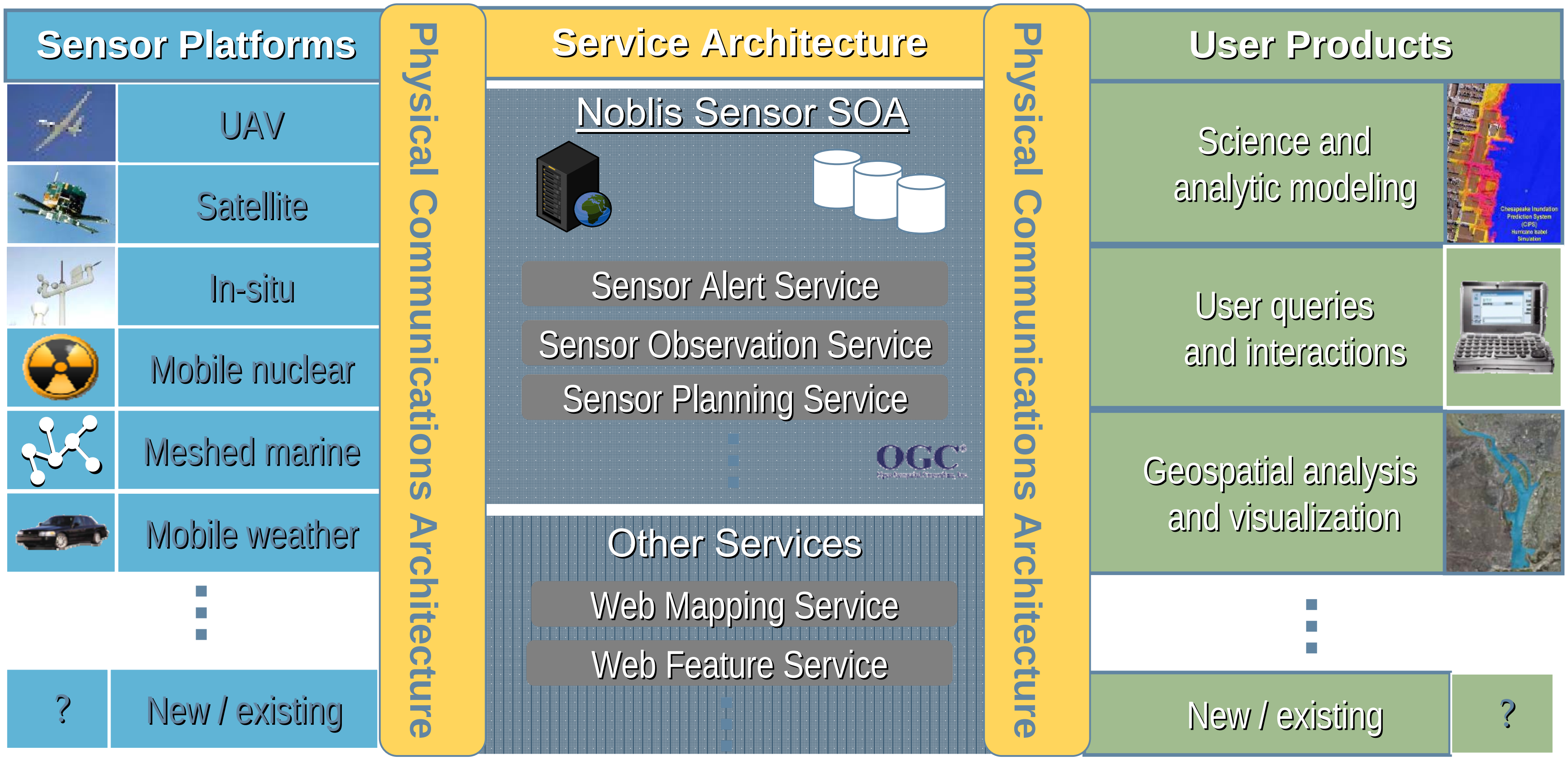
Abstract

- 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
  - 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

Motivation and Purpose

- Motivation
  - 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)
- Purpose
  - 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

Noblis Sensor Network



- Builds upon Noblis projects to integrate a network of commercial mobile radiation sensors through a Service Oriented Architecture (SOA)
- A goal of this research: to demonstrate ATD models as user products utilizing the sensor data

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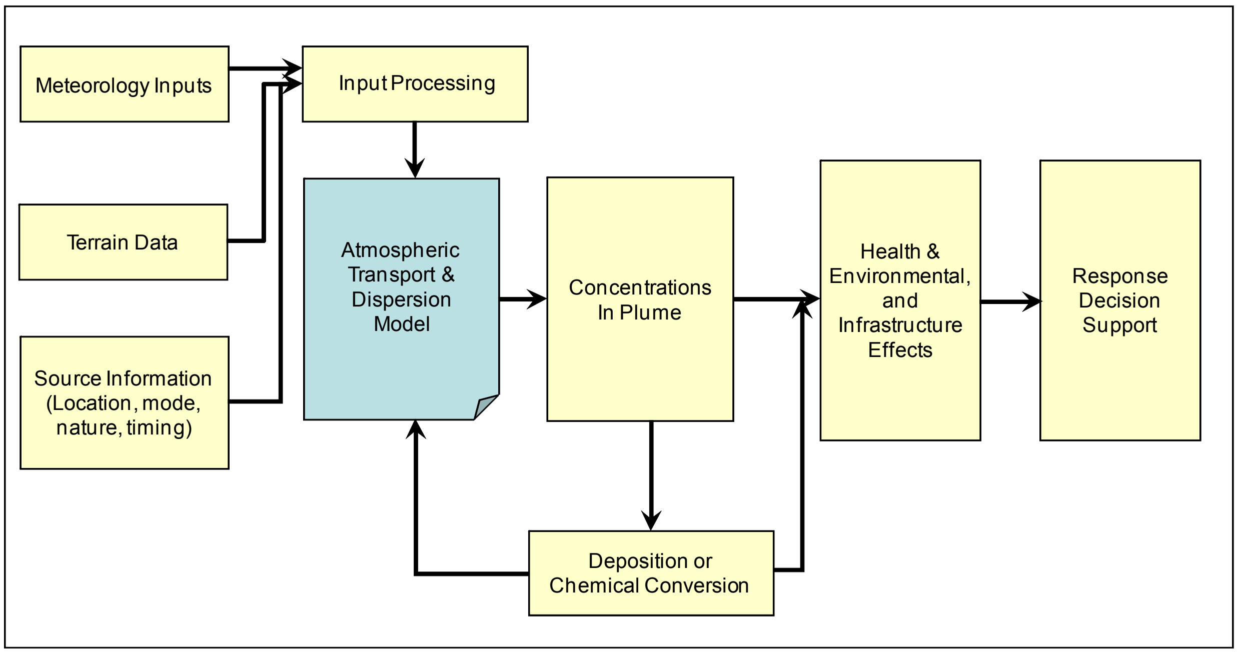
Basic Elements of an ATD Model

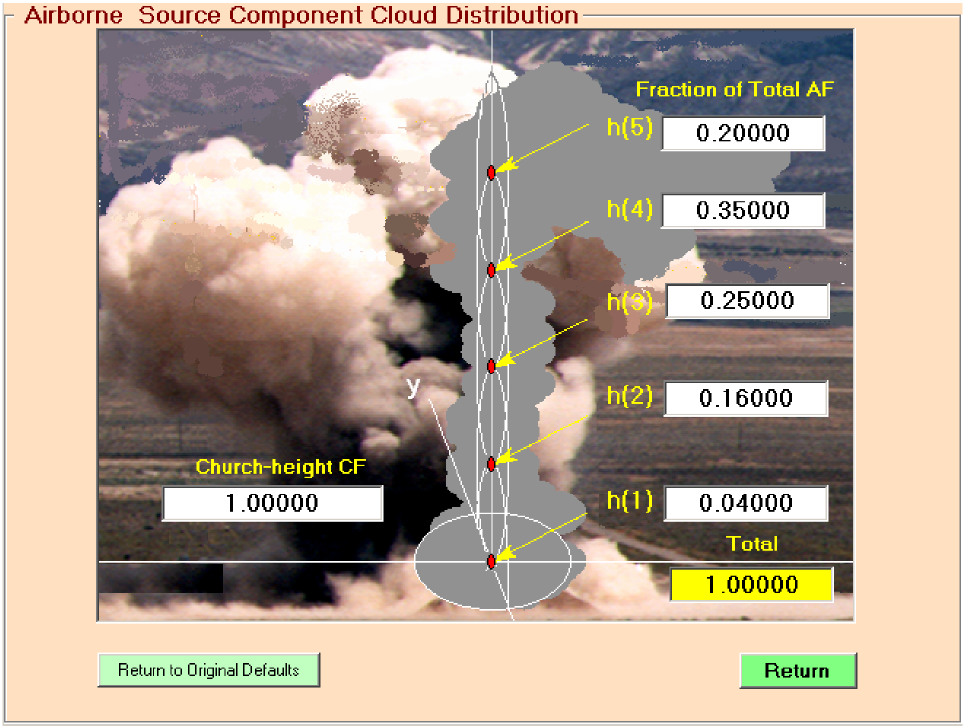


- ATD models produce estimates of the movement and concentration of contaminants over time
- Plume concentration and impact estimates can be further used in decision support response models
- Models can be used in all phases of the emergency management cycle: mitigation, preparedness, response, and recovery activities

Approach and Plume Model

- Approach: Develop capability to estimate impact of CBRNE events on critical infrastructures
  - Use existing plume models
  - Coordinate with existing Noblis critical infrastructure impact tools
- Plume Model Selection Criteria
  - Capability of model to analyze RDD attack scenario for demonstration by the Sensor Network team (Cs-137)
  - Ability to create graphical depiction of plume area
  - Model approved by government authority
  - Cost and availability

Selected Model: HOTSPOT



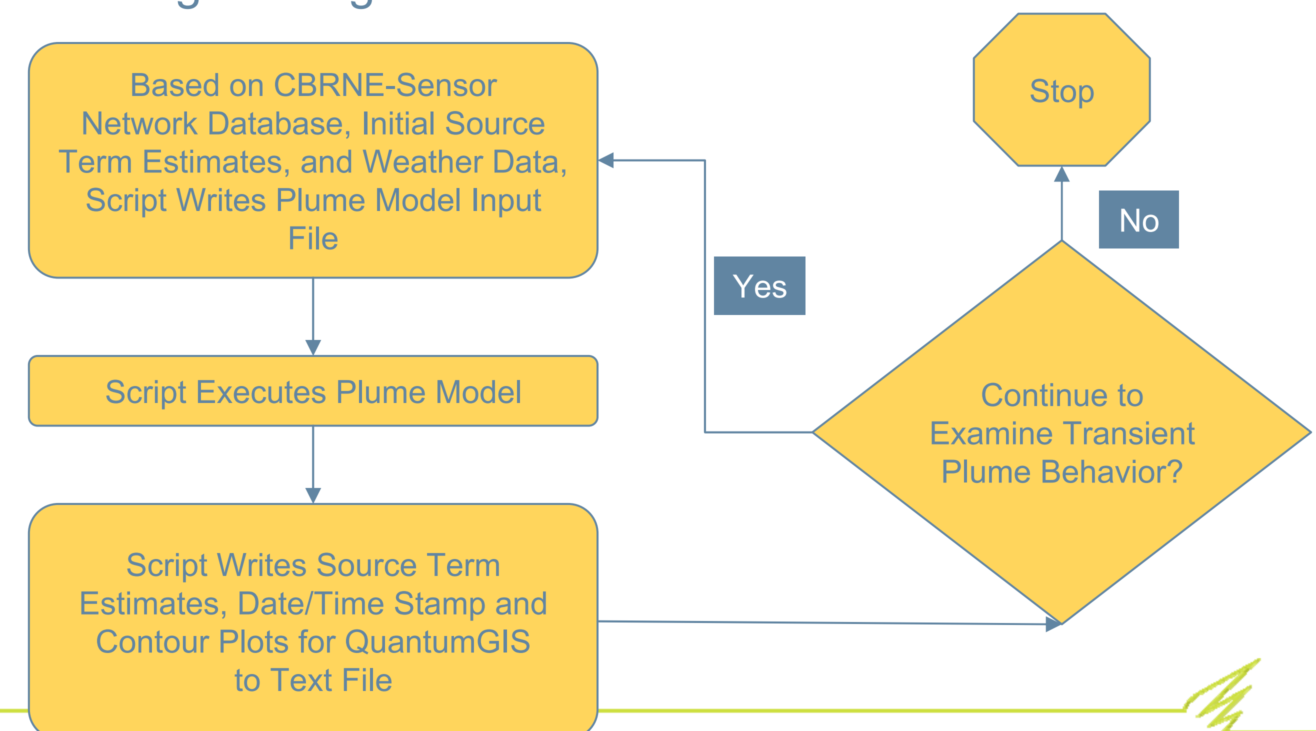
- Many (149) Atmospheric Transport and Dispersion (ATD) models were identified and evaluated

Demonstration of ATD Models Utilizing Sensor Data

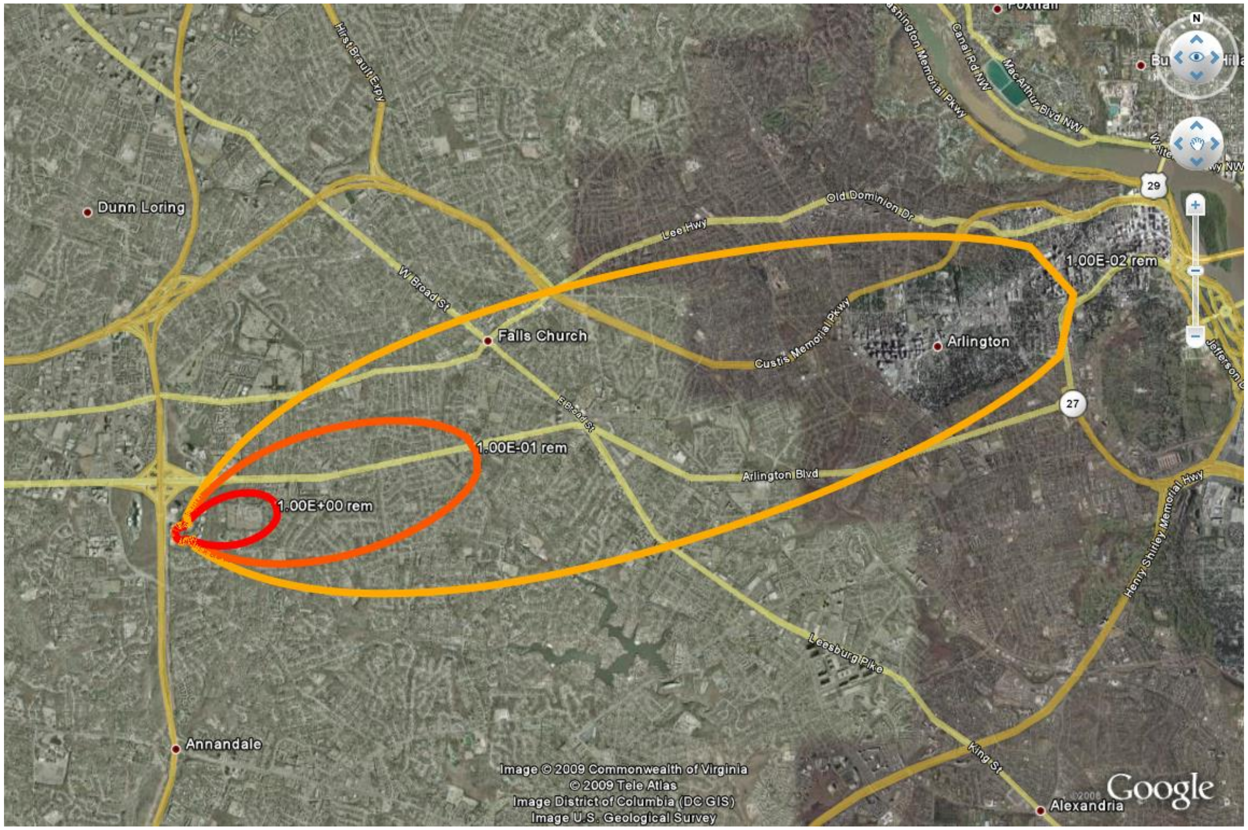
itial demonstration was conducted of the Noblis Sensor Network leveraging ie Noblis Sensor SOA as part of a Radiological Dispersal Device (RDD) esponse System

amples of Cs-137 were deployed at the Noblis facility in Falls Church, irginia; and the vehicular radiological detectors measured the radiation field trength and uploaded readings through a wireless network to SOA

igure shows WMD lodeling Flow:



Plume Model Sample Contour Plot



- Contours available for Total Effective Dose Equivalent (TEDE) in rem or for Ground Deposition (in $\mu Ci/m^2$)
- Movement of plume over time can be shown
- Also incorporated government location data and telecom facilities for demo

Optimal Evacuation Modeling

Evacuation Problem Statement

- Situation:
  - A densely-populated area is subjected to a WMD attack (chemical, biological, radiological, or nuclear)
  - Emergency responders must evacuate the affected area or “hot zone”
- Response decisions:
  - How to route traffic from the “hot zone” to the “safe zone”
  - How to utilize the following modes of transportation:
    - Personal cars
    - Commuter bus
    - Commuter rail

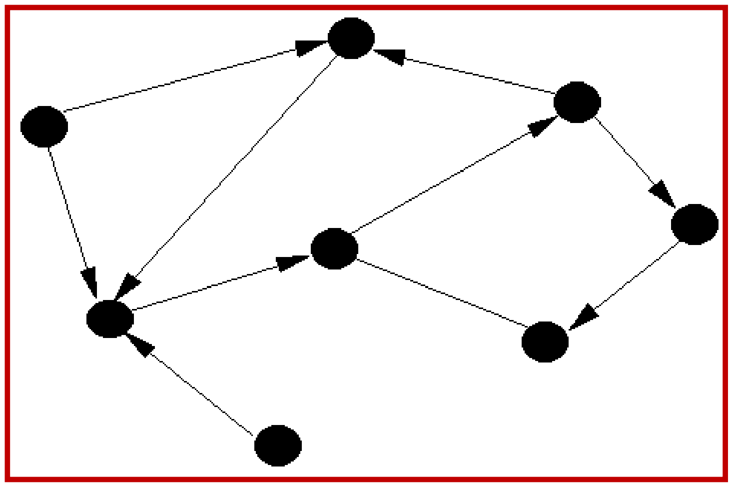
Evacuation Modeling Approach

- Linear programming (LP)/network programming formulation
  - Advantages: quick to solve (typically < 5 seconds), synthesis, sensitivity analysis
  - Disadvantages: potential for infeasibility, assumptions on form of constraints and objective function
- Required Input Data:
  - Maximum throughput (sources: Urban Congestion report (UCR) data, published rail schedules)
  - Average travel time (sources: UCR data, published rail schedules)
  - Vehicle availability (source: Census data, DOT data, first responders)
  - Number of people to evacuate (source: Census data, first responders)
  - Hot zone boundaries (source: HOTSPOT model estimated plume)
  - Required evacuation time (source: HOTSPOT model)

Evacuation Modeling Approach (cont.)

- Software requirements
  - **LP solver**: to solve model
    - If less than 300 variables and 300 constraints: student version of AMPL is sufficient
    - If more than 300 variables and 300 constraints: NEOS server or a commercial LP solver such as CPLEX
  - **Excel**: to manage input data
  - **GIS software** (e.g. Google Earth): to visualize model output

Model Description: Overview



Graph:

- Nodes: key intersections
  - Evacuation nodes (V_e) → hot zone location with evacuees after detonation
  - Destination nodes (V_d) → safe zone location
- Edges: roadways between intersections

Objective: maximize the number of people evacuated from the “hot zone” in an allowable time T

Decision variables: number of vehicles of each mode to send along a given route

Constraints:

- Road capacity
- Rail capacity
- Vehicle availability

Note: the value of T is determined using the HOTSPOT model

Case Study Scenario

Radiological Dispersal Device detonated in Chicago

- Mount Sinai Hospital
- 150,000 Curies of Cs-137; 100 pounds of TNT

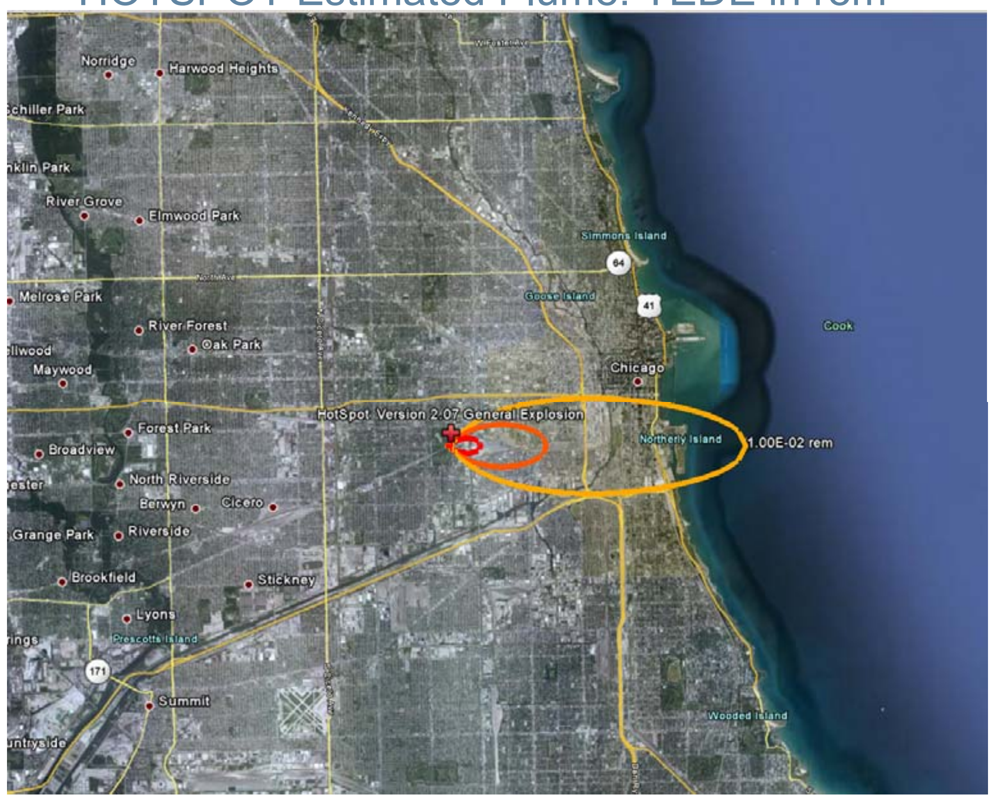
Meteorological and terrain assumptions:

- Wind speed/direction: 3.5 mph, W
- Cloud cover: 10 percent, no precipitation
- City terrain

Case Study Scenario (cont.)

- HOTSPOT Estimated Plume is shown
  - Final Total Effective Dose Equivalent (TEDE) in rem
  - Total elapsed time before the plume concentration dissipates to below threshold: 63.4 minutes

HOTSPOT Estimated Plume: TEDE in rem



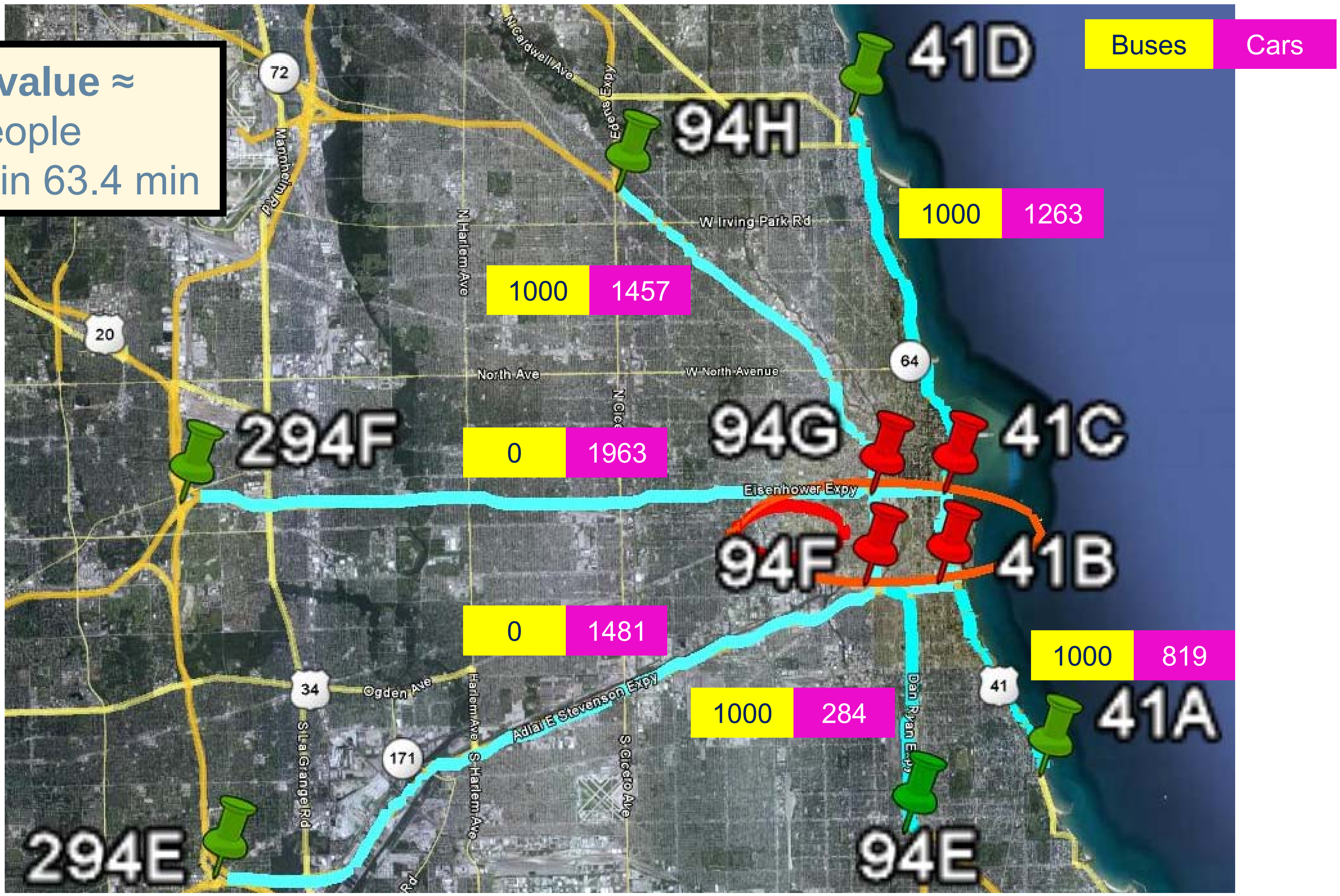
- Other evacuation inputs:
  - Resource Availability:
    - 4,000 buses
    - 50,000 cars
  - Number of evacuees = 500,000
  - Assumption: buses, cars, and evacuees are evenly distributed in hot zone
  - Maximum number of vehicles for each roadway segment came from the detailed UCR data

Case Study Graph Structure

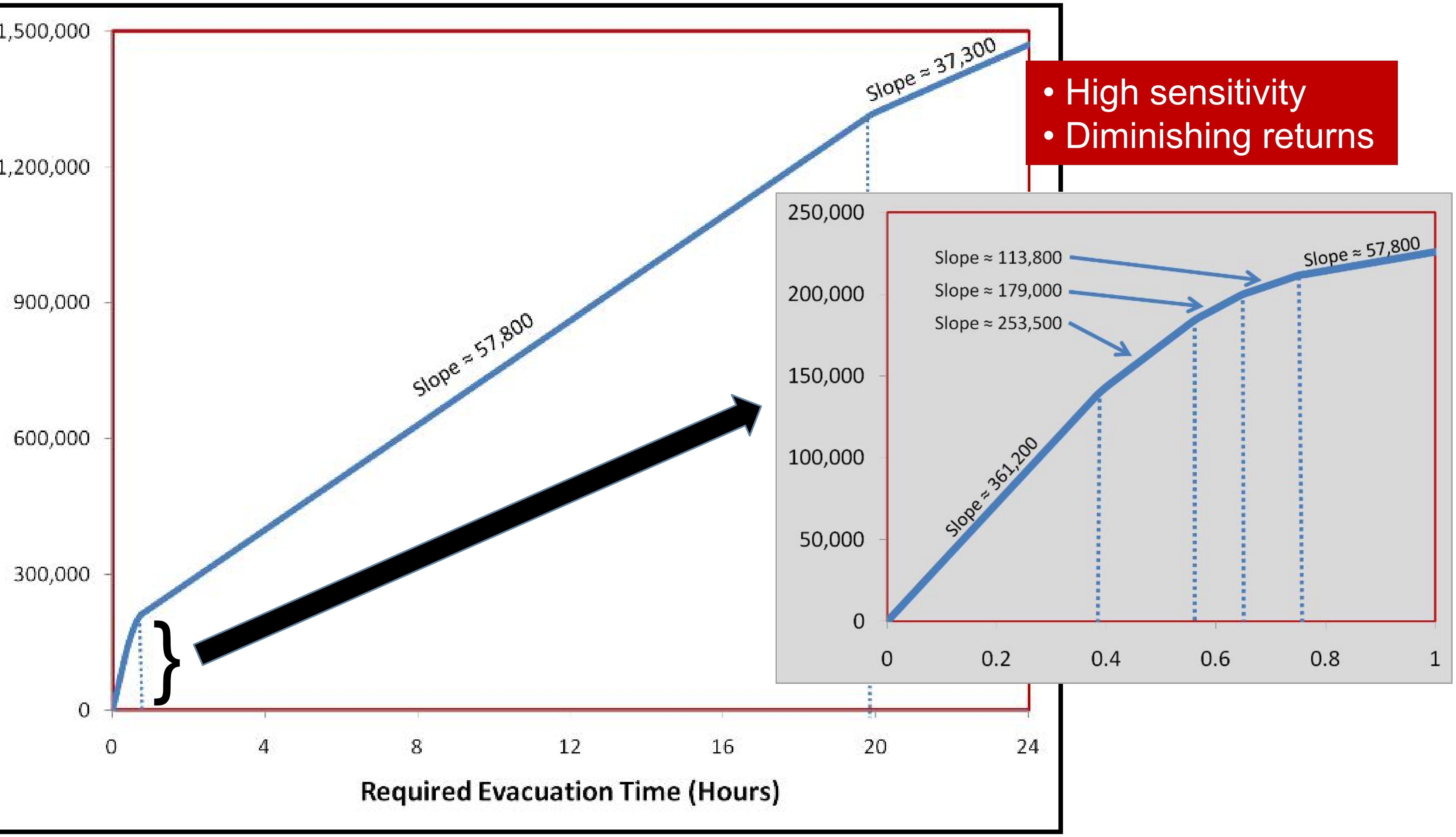
- The evacuation nodes and destination nodes were determined by overlaying the hot zone (region corresponding to the outermost final contour) onto the roadway network

Evacuation Model Solution

ective value ≈
,068 people
cuated in 63.4 min



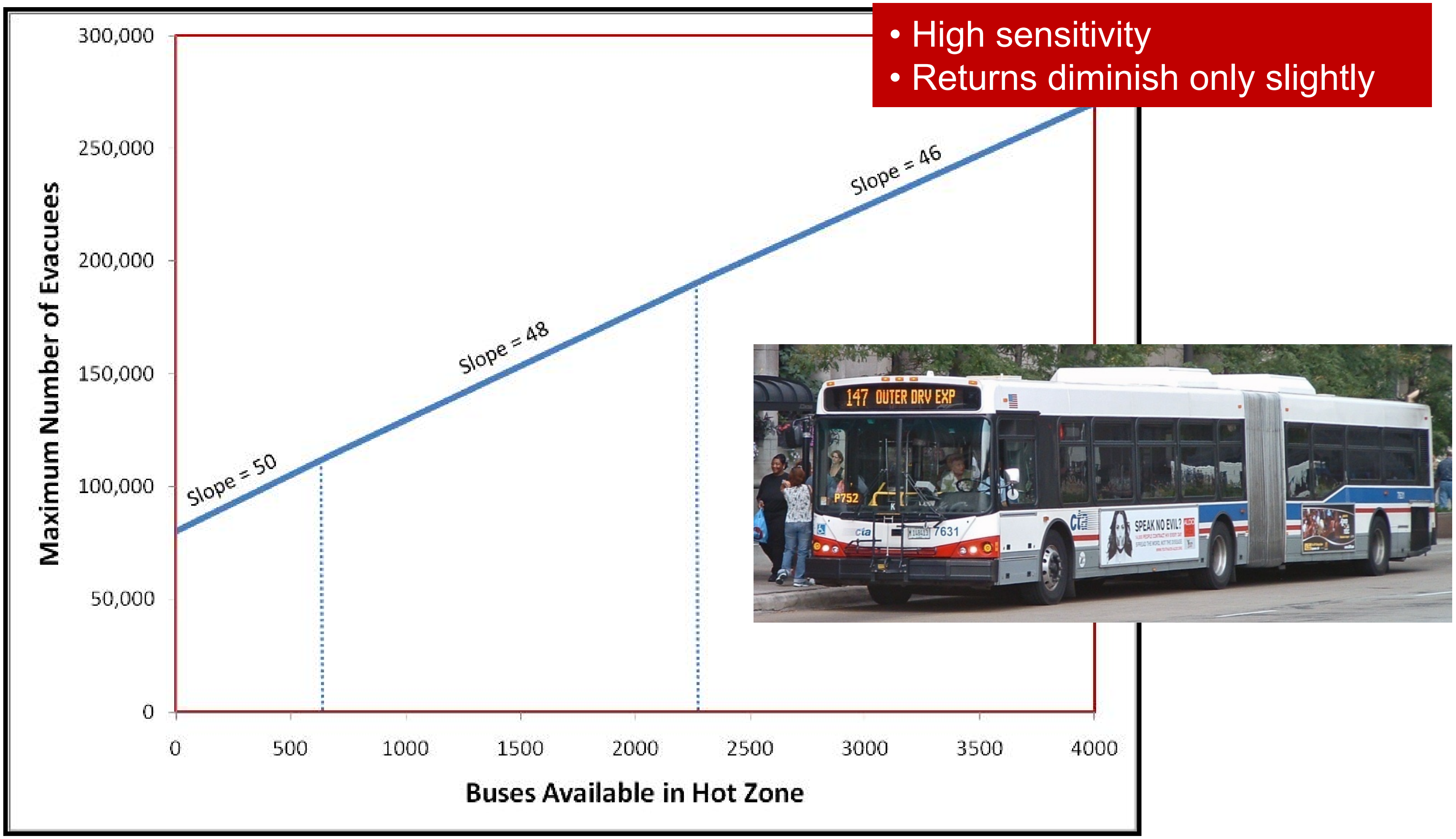
Sensitivity Analysis: Evacuation Time



- High sensitivity
- Diminishing returns

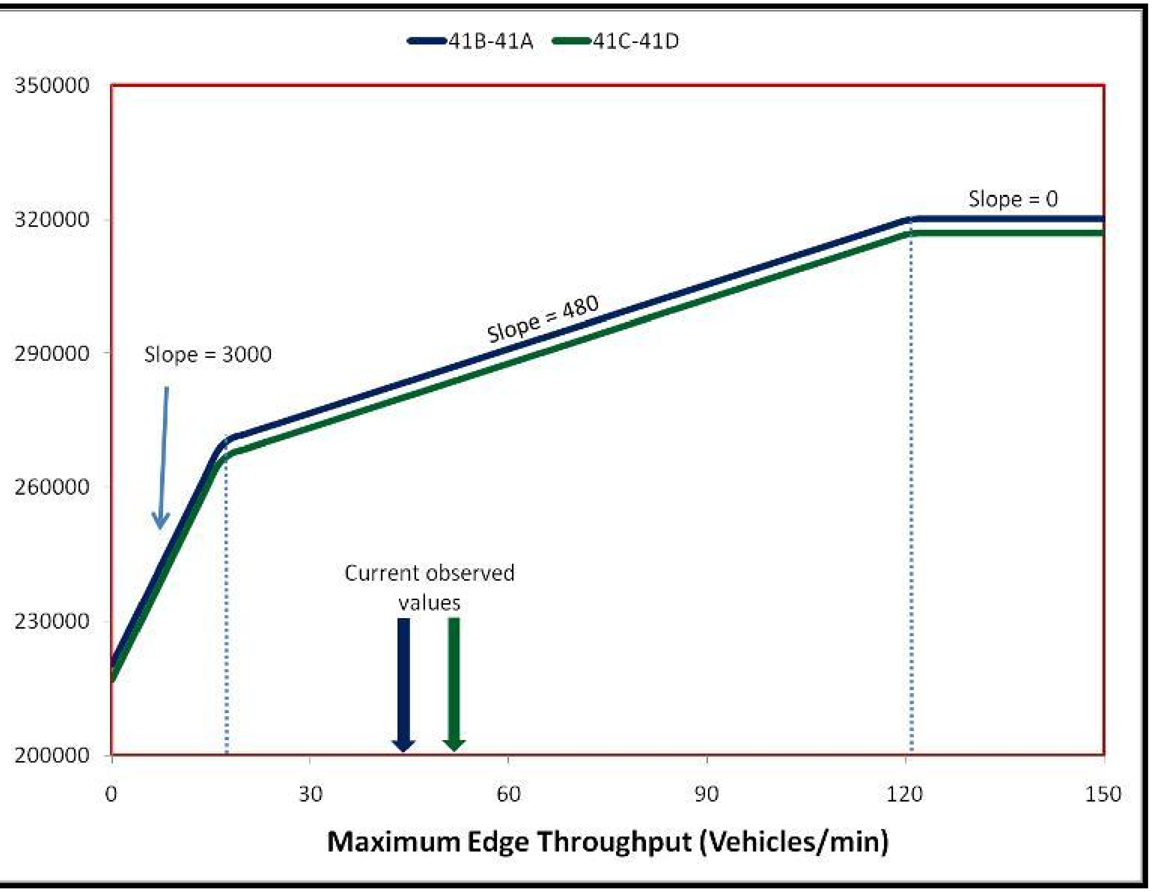
Sensitivity Analysis: Bus Availability

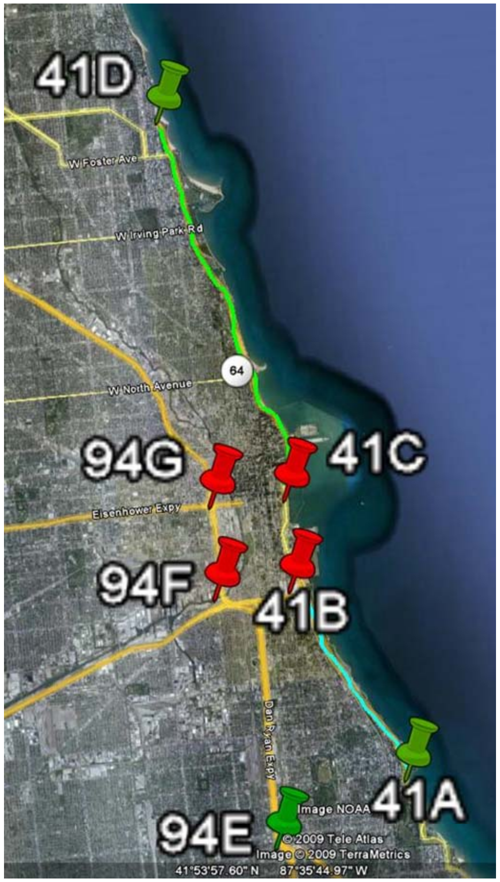
- High sensitivity
- Returns diminish only slightly



Sensitivity Analysis

Large potential returns at current throughput levels





Sensitivity Analysis

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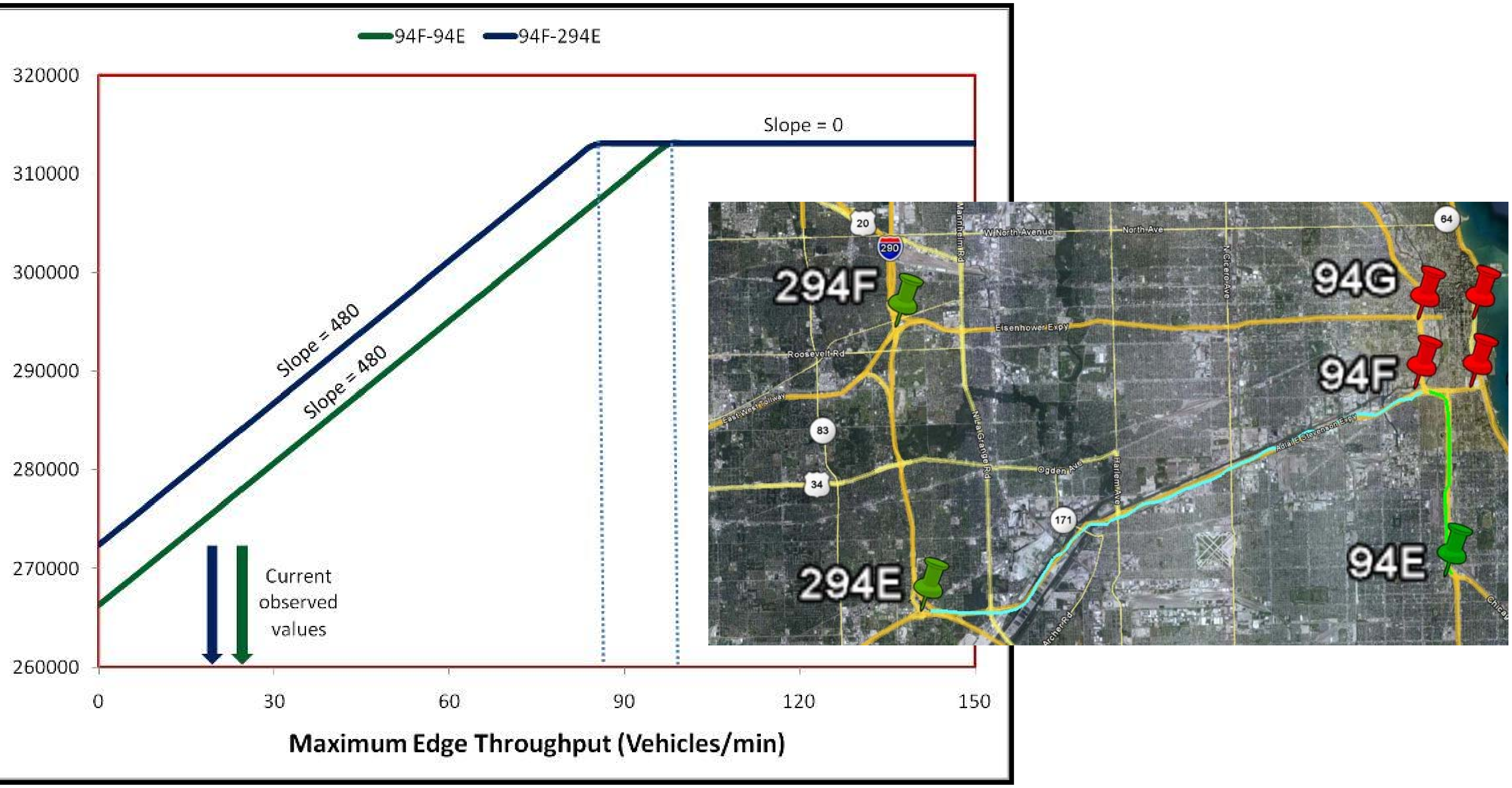
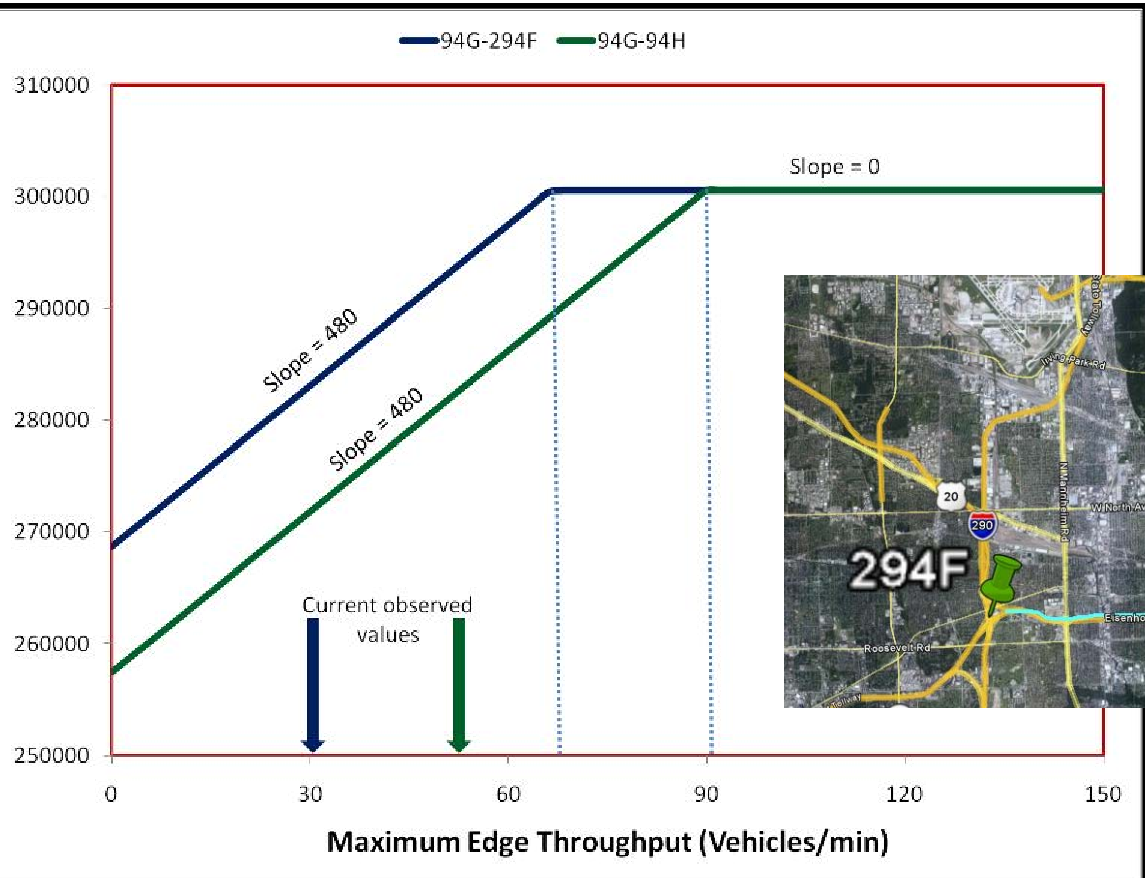
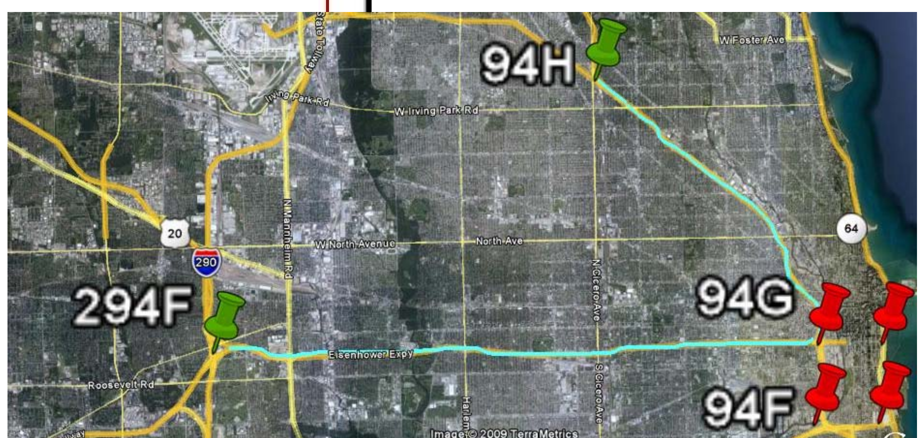


Sensitivity Analysis

Potential returns at current throughput levels (less than before)





General Evacuation Model Recommendations

Expansion of bus service
- Large potential gains in number evacuated
- “Diminishing returns” a very minor factor
- Utilization of buses:
  - Whenever possible
  - On routes with higher maximum throughput

Increase throughput (e.g. adding lanes) on certain routes
- For certain routes, increasing throughput can greatly improve objective
- “Diminishing returns” is a factor

Summary of Results

- Key accomplishment: development of initial modeling and analysis capabilities in several areas
  - Atmospheric transport and dispersion modeling
    - 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
  - Evacuation modeling
    - Developed linear program model to determine optimal routing and transportation modes for evacuation, utilizing highly detailed transportation data
- 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 and evacuation modeling

Lessons Learned

- Many sources of data and tools are required to model the impact of hazardous materials such as the RDD scenario from this study. Observations and insights from working with these datasets and tools were:
  - An alternate evacuation model to minimize evacuation time (rather than maximum number evacuated) was also formulated
    - Due to non-linearities in the model formulation, it appears that this model may not be suited to real-time decision support
  - Estimation of the contaminant source term parameters for the ATD model is not straightforward.
    - Model estimates of contaminant count per second readings should be calibrated versus the actual sensor readings.
  - Optimal placement of mobile sensors near the detonation point requires research

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Backup Slides

Model Description: Notation

- **Define the graph G = (V,E)**
- **Index Sets**:

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

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

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

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

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

Model Description: Notation

- **Decision Variables**:

$x_{ij}^m \equiv$ 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

- **Parameters:**

$T \equiv$ 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

Model Description: Objective Function

- **Objective**: maximize the number of people evacuated from the “hot zone” (denoted TH) in an allowable time T

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

Model Description: Constraints

- **Conservation of Flow Constraints**:

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

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

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

NOTE: Inflow is negative; inflow is negative

Model Description: Constraints

- **Vehicle Availability**:

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

- **Excess Demand:**

$$y_i \le P_i, \quad \forall i \in V_e$$

NOTE: ensures the number of evacuees is positive at all sites

- **Road Capacity:**

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

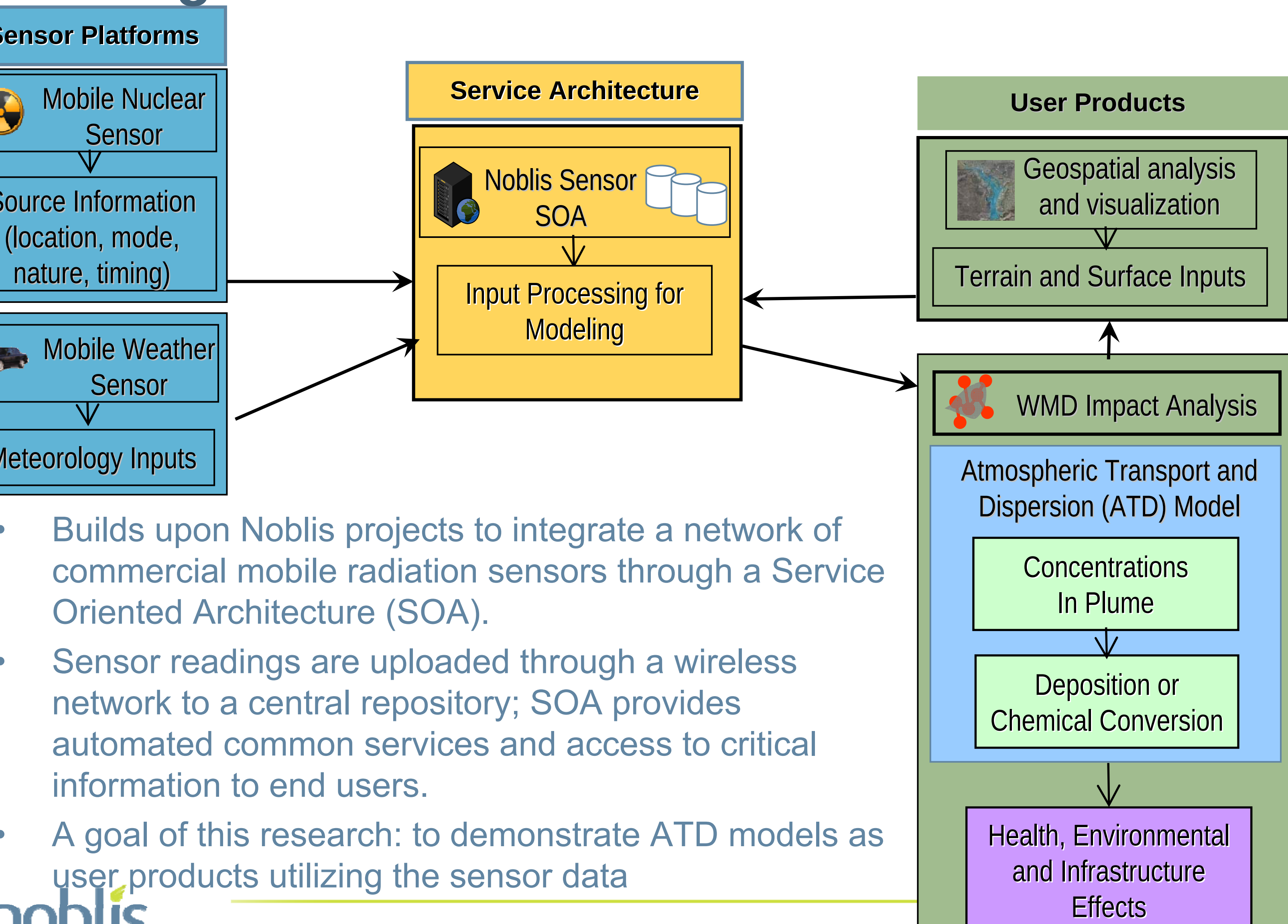
- **Rail Capacity:**

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

Possible Future Directions

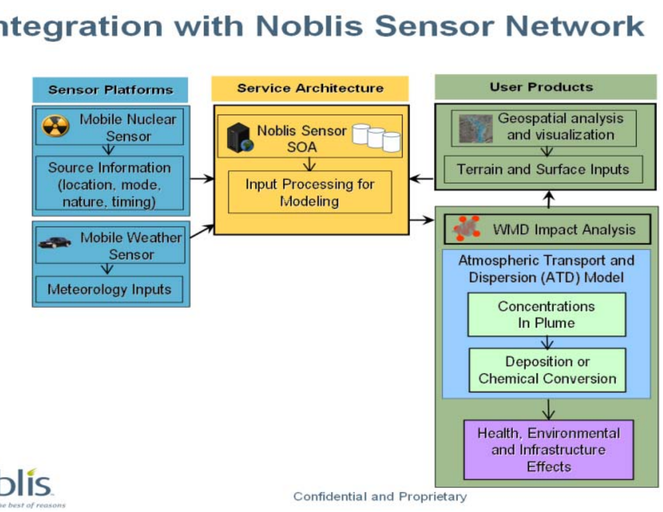
- Further develop a second model to minimize evacuation time given that all individuals in the hot zone must be evacuated
- Incorporate rail data into model
- Full solutions to other hypothetical attack scenarios and test another city (Houston, TX)
- Visualization tool to observe:
  - "Hot zone"
  - Flows on evacuation routes

Integration with Noblis Sensor Network



- Builds upon Noblis projects to integrate a network of commercial mobile radiation sensors through a Service Oriented Architecture (SOA).
- Sensor readings are uploaded through a wireless network to a central repository; SOA provides automated common services and access to critical information to end users.
- A goal of this research: to demonstrate ATD models as user products utilizing the sensor data

WMD Impact Modeling: BD View



Key Clients / Programs

- DHS: National Communications System (NCS) Operational Analysis Branch
- DTRA: HPAC Program
- FEMA Consequence Management Modeling

ness Development Objectives

monstrate early results of the A-based WMD Impact Modeling stem to DHS/NCS/OAB toward d of FY09

plore opportunities to merge pabilities with HPAC

plore opportunities within FEMA

Business Development Milestones

Nov 08: Introduced concept to NCS Technology & Programs Branch