Evacuation Route Planning

Shashi Shekhar
McKnight Distinguished University Professor
Faculty of Computer Sc. and Eng.
University of Minnesota (UM)
www.cs.umn.edu/~shekhar

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Ack.: Dr. Q. Lu (MSR), Dr. Ms. B. George (Oracle), Dr. S. Kim (ESRI)
Sponsors: NSF, USDOD, MnDOT
Outline

- Motivation
- Problem Statement
- Why is the problem hard?
- Related Work
- Proposed Approach
- Evaluation
- Conclusion and Future works
Large Scale Evacuation due Natural Events

Hurricane: Andrews, Rita
- Traffic congestions on all highways
  - E.g. 100-mile congestion (TX)
- Great confusions and chaos

"We packed up Morgan City residents to evacuate in the a.m. on the day that Andrew hit coastal Louisiana, but in early afternoon the majority came back home. The traffic was so bad that they couldn’t get through Lafayette."
Mayor Tim Mott, Morgan City, Louisiana
( http://i49south.com/hurricane.htm )

Florida, Lousiana (Andrew, 1992)
( National Weather Services)

Houston (Rita, 2005)
( National Weather Services)

I-45 out of Houston
( FEMA.gov)
Homeland Defense & Evacuation Scenarios

- Preparation of response to an attack
- Plan evacuation routes and schedules
- Help public officials to make important decisions
- Guide affected population to safety
- Reverse Evacuation: Mass vaccinations?

PLANNING SCENARIOS
Executive Summaries

Created for Use in National, Federal, State, and Local Homeland Security Preparedness Activities

The Homeland Security Council
David Howe, Senior Director for Response and Planning

July 2004

(Base Map) (Weather Data) (Plume Dispersion) (Demographics Information) (Transportation Networks)

(Images from www.fortune.com)
Preparedness for Industrial Accidents, e.g. Nuclear Power Plants

Nuclear Power Plants in Minnesota

Monticello
Prairie Island
Twin Cities
Who cares about evacuation planning?

- **Goal** - minimize loss of life and/or harm to public
  - First Responders
    - Which routes minimize evacuation time?
      - Respond to unanticipated events, e.g. Bridge failure, Accidents
  - Policy Makers, Emergency Planners
    - What transportation mode to use during evacuation?
      - Example, Walking, Private vehicles, Public transportation, …
    - Which locations take unacceptably long to evacuate?
      - Should one enrich transportation network to reduce evacuation time?
    - Should contra-flow strategy be used?
      - Texas Governor called for contra-flow on second day!
    - Should one used phased evacuation?

- **Goal** – Reduce loss of productivity due to congestion
  - Football game, major conventions, … – move parking 1 mile away?
  - Long weekends – Fishing opener, July 4th - contra-flow (I-94 or Hwy 10)

*Plans are nothing; planning is everything.* -- **Dwight D. Eisenhower**
Outline

- Motivation
- Problem Statement
  - Input, Output
  - Objectives
  - Illustration
- Why is the problem hard?
- Related Work
- Proposed Approach
- Evaluation
- Conclusion and Future works
Problem Statement

Given
- A transportation network, a directed graph \( G = (N, E) \) with
  - Capacity constraint for each edge and node
  - Travel time for each edge
- Number of evacuees and their initial locations
- Evacuation destinations

Output
- Evacuation plan consisting of a set of origin-destination routes
  - and a scheduling of evacuees on each route.

Objective
- Minimize evacuation egress time
  - time from start of evacuation to last evacuee reaching a destination

Constraints
- Route scheduling should observe **capacity constraints** of network
- Reasonable computation time despite limited computer memory
- Capacity constraints and travel times are non-negative integers
- Evacuees start from and end up at nodes
A Note on Objective Functions

- Why minimize evacuation time?
  - Reduce exposure to evacuees
  - Since harm due to many hazards increase with exposure time!

- Why minimize computation time?
  - During Evacuation
    - Unanticipated events
      - Bridge Failure due to Katrina, 100-mile traffic jams due to Rita
      - Plan new evacuation routes to respond to events
      - Contra-flow based plan for Rita
  - During Planning
    - Explore a large number of scenarios Based on
      - Transportation Modes
      - Event location and time

*Plans are nothing; planning is everything.* -- Dwight D. Eisenhower
Example 1 Input: Nuclear Power Plant

Emergency Planning Zone (EPZ) is a 10-mile radius around the plant divided into sub areas.

<table>
<thead>
<tr>
<th>Subarea</th>
<th>Population</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>4,675</td>
</tr>
<tr>
<td>5N</td>
<td>3,994</td>
</tr>
<tr>
<td>5E</td>
<td>9,645</td>
</tr>
<tr>
<td>5S</td>
<td>6,749</td>
</tr>
<tr>
<td>5W</td>
<td>2,236</td>
</tr>
<tr>
<td>10N</td>
<td>391</td>
</tr>
<tr>
<td>10E</td>
<td>1,785</td>
</tr>
<tr>
<td>10SE</td>
<td>1,390</td>
</tr>
<tr>
<td>10S</td>
<td>4,616</td>
</tr>
<tr>
<td>10SW</td>
<td>3,408</td>
</tr>
<tr>
<td>10W</td>
<td>2,354</td>
</tr>
<tr>
<td>10NW</td>
<td>707</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>41,950</strong></td>
</tr>
</tbody>
</table>

Monticello EPZ

Estimate EPZ evacuation time:
- Summer/Winter (good weather): 3 hours, 30 minutes
- Winter (adverse weather): 5 hours, 40 minutes

Data source: Minnesota DPS & DHS
Web site: http://www.dps.state.mn.us
http://www.dhs.state.mn.us
Ex. 1 Output: Evacuation Routes (Handcrafted)

- Destination
- Monticello Power Plant

Reception Center located at
OSSEO JUNIOR HIGH SCHOOL
10223 93rd Avenue North
Osseo, Minnesota

Monticello Generating Plant

State Highway 95

CLEAR LAKE

BECKER

ZIMMERMAN

BIG LAKE

ELK RIVER

ALBERTVILLE

DAYTON

ROGERS

ANOKA

Osseo Jr. High School
10223 93rd Avenue N.
Example 2: A Building floor plan

Two-story building:
- Two staircases
- Two exits on first floor

(Building floor map from EVACNET User Manual)
Example 2: Node and Edge Definition

Nodes: Each room, hallway, staircase, etc.

Edges: Each available link between two nodes.
Example 2: Initial State

- Each node has:
  - **Maximum node capacity** (max. number of people the node can hold)
  - **Initial node occupancy** (number of people at the node)

- Each edge has:
  - **Maximum edge capacity** (max. number of people can travel through this edge simultaneously)
  - **Edge Travel time** (how long it takes to travel through this edge)
Example 2 Input: Evacuation Network with Evacuees

Node ID, Max Capacity (Initial Occupancy)

Max Capacity, Travel time

Node ID

Destination node

Example evacuation network with evacuees:

- **Dest #1**: N10, 30
  - N10 connects to N4, 8 with an edge of (3,3) and N6, 10 with an edge of (5,4) and N13 with an edge of (8,1).
  - N10 also connects to N8, 65 (15) with an edge of (6,4).

- **Dest #2**: N14
  - N14 connects to N11, 8 with an edge of (3,2)
  - N11 connects to N9, 25 with an edge of (6,4).
  - N9 connects to N2, 50 (5) with an edge of (7,1).
  - N2 connects to N3, 30 with an edge of (7,1) and N5, 6 with an edge of (3,4).
  - N3 connects to N1, 50 (10) with an edge of (3,3).

- **Nodes**:
  - N1: 50 (10)
  - N2: 50 (5)
  - N3: 30
  - N4: 8
  - N5: 6
  - N6: 10
  - N7: 8
  - N8: 65 (15)
  - N9: 25
  - N10: 30
  - N11: 8
  - N12: 18
  - N13
  - N14

- **Edges**:
  - (3,3), (3,4), (3,5), (3,2), (6,4), (6,3), (6,4), (6,4), (7,1), (7,1)
Example Evacuation Plan:

<table>
<thead>
<tr>
<th>ID</th>
<th>Source</th>
<th>No. of Evacuees</th>
<th>Route with Schedule</th>
<th>Dest. Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>N8</td>
<td>6</td>
<td>N8(T0)-N10(T3)-N13</td>
<td>4</td>
</tr>
<tr>
<td>B</td>
<td>N8</td>
<td>6</td>
<td>N8(T1)-N10(T4)-N13</td>
<td>5</td>
</tr>
<tr>
<td>C</td>
<td>N8</td>
<td>3</td>
<td>N8(T0)-N11(T3)-N14</td>
<td>5</td>
</tr>
<tr>
<td>D</td>
<td>N1</td>
<td>3</td>
<td>N1(T0)-N3(T1)-N4(T4)-N6(T8)-N10(T13)-N13</td>
<td>14</td>
</tr>
<tr>
<td>E</td>
<td>N1</td>
<td>3</td>
<td>N1(T0)-N3(T2)-N4(T5)-N6(T9)-N10(T14)-N13</td>
<td>15</td>
</tr>
<tr>
<td>F</td>
<td>N1</td>
<td>1</td>
<td>N1(T0)-N3(T1)-N5(T4)-N7(T8)-N11(T13)-N14</td>
<td>15</td>
</tr>
<tr>
<td>G</td>
<td>N2</td>
<td>2</td>
<td>N2(T0)-N3(T1)-N5(T4)-N7(T8)-N11(T13)-N14</td>
<td>15</td>
</tr>
<tr>
<td>H</td>
<td>N2</td>
<td>3</td>
<td>N2(T0)-N3(T3)-N4(T6)-N6(T10)-N10(T15)-N13</td>
<td>16</td>
</tr>
<tr>
<td>I</td>
<td>N1</td>
<td>3</td>
<td>N1(T1)-N3(T2)-N5(T5)-N7(T9)-N11(T14)-N14</td>
<td>16</td>
</tr>
</tbody>
</table>
Group of Evacuee

<table>
<thead>
<tr>
<th>ID</th>
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<th>Route with Schedule</th>
<th>Dest. Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>N8</td>
<td>6</td>
<td>N8(T0)-N10(T3)-N13</td>
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<tr>
<td>B</td>
<td>N8</td>
<td>6</td>
<td>N8(T1)-N10(T4)-N13</td>
<td>5</td>
</tr>
<tr>
<td>C</td>
<td>N8</td>
<td>3</td>
<td>N8(T0)-N11(T3)-N14</td>
<td>5</td>
</tr>
<tr>
<td>D</td>
<td>N1</td>
<td>3</td>
<td>N1(T0)-N3(T1)-N4(T4)-N6(T8)-N10(T13)-N13</td>
<td>14</td>
</tr>
<tr>
<td>E</td>
<td>N1</td>
<td>3</td>
<td>N1(T0)-N3(T2)-N4(T5)-N6(T9)-N10(T14)-N13</td>
<td>15</td>
</tr>
<tr>
<td>F</td>
<td>N1</td>
<td>1</td>
<td>N1(T0)-N3(T1)-N5(T4)-N7(T8)-N11(T13)-N14</td>
<td>15</td>
</tr>
<tr>
<td>G</td>
<td>N2</td>
<td>2</td>
<td>N2(T0)-N3(T1)-N5(T4)-N7(T8)-N11(T13)-N14</td>
<td>15</td>
</tr>
<tr>
<td>H</td>
<td>N2</td>
<td>3</td>
<td>N2(T0)-N3(T3)-N4(T6)-N6(T10)-N10(T15)-N13</td>
<td>16</td>
</tr>
<tr>
<td>I</td>
<td>N1</td>
<td>3</td>
<td>N1(T1)-N3(T2)-N5(T5)-N7(T9)-N11(T14)-N14</td>
<td>16</td>
</tr>
</tbody>
</table>

**Time: \( t = 10 \)**

**Animation:**

**Node**
- **Node ID, Max Capacity (Initial Occupancy)**
- **Edge**
  - (Max Capacity, Travel time)
  - **Destination node**
    - **Node ID**

**Dest #1**

**Dest #2**

**N13**

**N14**
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- Why is the problem hard?
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- Conclusion and Future works
Why is this problem hard?

- **Data Availability**
  - Estimating evacuee population, available transport capacity
  - Pedestrian data: walkway maps, link capacities based on width

- **Transportation**
  - Link capacity depends on traffic density
  - Modeling traffic control signals, ramp meters, contra-flow, …

- **Evacuee Behavior**
  - Unit of evacuation: Individual or Household
  - Heterogeneity: by physical ability, age, vehicle ownership, language, …

- **Policy Decisions**
  - How to gain public’s trust in plans? Will they comply?
  - Common good with awareness of winners and losers due to a decision

- **Science**
  - How does one evaluate an evacuation planning system?
Why is this problem hard computationally?

Intuition:
- Spread people over space and time
- Multiple paths + pipelining over those

A. Flow Networks

\[ \text{OR} = \frac{\text{Population}}{(\text{Bottleneck Capacity of Transport Network})} \]

If ( OR \( \leq 1 \) )
- \{ shortest path algorithms, e.g. A* \}
Else if ( OR \( \rightarrow \) infinity )
- \{ Min-cut max-flow problem \}
Else \{ Computationally hard problem ! \}

B. Spatio-temporal Networks

- Violate stationary assumption
  - behind shortest path algorithms, e.g. A*, Dijkstra’s
  - Optimal sub-structure and dynamic programming
Outline

- Motivation
- Problem Statement
- Why is the problem hard?
- Related Work
  - Operations Research Ideas
    - Time Expanded Graphs
    - Linear Programming
  - Limitations
- Proposed Approach
- Evaluation
- Conclusion and Future works
Summary of Related Works & Limitations

A. Capacity-ignorent Approach
   - Simple shortest path computation, e.g. A*, Dijkstra’s, etc.
   - e.g. EXIT89 (National Fire Protection Association)
   **Limitation**: Poor solution quality as evacuee population grows

B. Operations Research: Time-Expanded Graph + Linear Programming
   - Optimal solution, e.g. EVACNET (U. FL), Hoppe and Tardos (Cornell U).
   **Limitation**: High computational complexity => Does not scale to large problems
   - Users need to guess an upper bound on evacuation time
     Inaccurate guess => either no solution or increased computation cost!

<table>
<thead>
<tr>
<th>Number of Nodes</th>
<th>50</th>
<th>500</th>
<th>5,000</th>
<th>50,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>EVACNET Running Time</td>
<td>0.1 min</td>
<td>2.5 min</td>
<td>108 min</td>
<td>&gt; 5 days</td>
</tr>
</tbody>
</table>

C. Transportation Science: Dynamic Traffic Assignment
   - Game Theory: Wardrop Equilibrium, e.g. DYNASMART (FHWA), DYNAMIT(MIT)
   **Limitation**: Extremely high compute time
   - Is Evacuation an equilibrium phenomena?
Time Expanded Graph

Step 1:
Convert evacuation network $G$ into time-expanded network $G_T$ with user provided time upper bound $T$.

$G :$ evacuation network with $n$ nodes  \( (n = 4) \)

$G_T :$ time-expanded network  \( (T = 4) \) with $N = n(T+1)$ nodes  \( (N = 20) \)

Step 2: Treat time-expanded network $G_T$ as a flow network and define the evacuation problem as a minimum cost flow problem on $G_T$:

$$\min \sum_{t=0}^{T} \sum_{i \in D} tx_{id}(t)$$

$$x_{si}(0) = q_i, \forall i \in S,$$

$$\sum_{t=0}^{T} \sum_{i \in D} x_{id}(t) = \sum_{j \in S} q_j,$$

$$(\text{minimize total evacuation time of all evacuees})$$

$$(\text{initial occupancy at source nodes at time 0})$$

$$(\text{all evacuees reach destination nodes by time T})$$

$$y_i(t + 1) - y_i(t) = \sum_{k \in \text{pred}(i)} x_{ki}(t - \lambda_{ki}) - \sum_{j \in \text{succ}(i)} x_{ij}(t),$$

$N$: set of nodes,
$S$: set of sources; $D$: set of destinations,
$q_i$: initial # of evacuees at source node $i$,
$x_{ij}(t)$: flow from node $i$ to $j$ at time $t$,
$y_i(t)$: # of evacuees stay at node $i$ at time $t$,
$a_i$: max. capacity of node $i$,
$b_{ij}$: max. capacity of arc from node $i$ to $j$.

Step 3: Solve above problem using minimum cost flow solvers.
e.g. NETFLO [Kennington and Helgason, 1980], RELAX-IV [Bertsekas and Tseng, 1994].
Based on *Triple Optimization Theorem* [Jarvis and Ratliff, 1982]:

Universal max. flow ⇔ Min. cost flow ⇒ Quickest flow

Example:

- Hoppe and Tardos (Cornell, 1994): ellipsoid method, theoretically polynomial time bounded: \(O(N^6), N = n(T+1)\), poor scalability to metropolitan road network.
- EVACNET (U. of Florida, 1993): designed for building evacuation, use NETFLO.

Summary:

- Produce optimal solution: minimize evacuation egress time.
- Suitable for problem with moderate size network and require optimal solution

Limitations:

- Require time-expanded network:
  - Duplicate network for each time unit → large memory requirement
  - Increased problem size: \(N = n(T+1)\) → high computational complexity
- Require user to estimated evacuation time upper bound \(T\):
  - Under-estimate → failure of finding a solution
  - Over-estimate → unnecessary storage and run-time
Outline

- Motivation
- Problem Statement
- Why is the problem hard?
- Related Work
- Proposed Approach
  - Time aggregated Graph
  - Capacity Constraint Route Planner
  - Dealing with non-stationary ST Networks
- Evaluation
- Conclusion and Future works
### Representation Challenge: Time-varying Networks

<table>
<thead>
<tr>
<th>Static</th>
<th>Time-Variant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Which is the shortest travel time path from downtown Minneapolis to airport?</td>
<td>Which is the shortest travel time path from downtown Minneapolis to airport at different times of a work day?</td>
</tr>
<tr>
<td>What is the capacity of Twin-Cities freeway network to evacuate downtown Minneapolis?</td>
<td>What is the capacity of Twin-Cities freeway network to evacuate downtown Minneapolis at different times in a work day?</td>
</tr>
</tbody>
</table>

“U.P.S. Embraces High-Tech Delivery Methods - *(by Claudia Deutsch)*  
The research at U.P.S. is paying off. Last year, it cut 28 million miles from truck routes — saving roughly three million gallons of fuel — in good part by *mapping routes that minimize left turns*”  
*New York Times* *(July 12, 2007)*
Representations of (Spatio-)temporal Networks

(1) **Snapshot Model** [Guting 04]

Node: \( N_i \)

Edge: Travel time

(2) **Time Expanded Graph (TEG)** [Ford 65]

- Holdover Edge
- Transfer Edges

(3) **Time Aggregated Graph (TAG)** [Our Approach]

Attributes aggregated over edges and nodes.

- \( m_1, \ldots, m_T \) - travel time at \( t=i \)
TAG vs. TEG: Theoretical Storage Cost Comparison

- Intuitively $\text{storage\_cost}(\text{TAG}) < \text{storage\_cost} (\text{TEG})$,
  (a) TAG does not replicate nodes and edges
  (b) TAG can use time-series compression when any property is invariant for some time-intervals

- Formally, if $k < (n+m+p)$ and $T \gg 1$.
  - Storage cost (TEG) = $O(nT + mT) + O(pT)$
  - Storage cost (TAG) = $O(n + m) + O(kT)$
  - Where $n =$ number of nodes
    - $m =$ number of edges
    - $T =$ length of time-series
    - $p =$ number of properties
    - $k =$ (eqv.) number of static properties $\leq p$

(*) All edge and node parameters might not display time-dependence.
TAG vs. TEG: Storage Cost Comparison

<table>
<thead>
<tr>
<th>Dataset</th>
<th># Nodes</th>
<th># Edges</th>
</tr>
</thead>
<tbody>
<tr>
<td>(MPLS - 1/2)</td>
<td>111</td>
<td>287</td>
</tr>
<tr>
<td>(MPLS - 1 mi)</td>
<td>277</td>
<td>674</td>
</tr>
<tr>
<td>(MPLS - 2 mi)</td>
<td>562</td>
<td>1443</td>
</tr>
<tr>
<td>(MPLS - 3 mi)</td>
<td>786</td>
<td>2106</td>
</tr>
</tbody>
</table>

Minneapolis CBD [1/2, 1, 2, 3 miles radii]

Trend: TAG better than TEG on storage overhead!
TEG vs. TAG

- **TEG has High Storage Overhead**
  - Redundancy of nodes across time-frames
  - Additional edges across time frames in TEG.

- **TEG => Computationally expensive Algorithms**
  - Increased Network size due to redundancy.

- **TEG => Inadequate support for modeling non-flow parameters on edges in TEG.**

- **TEG => Lack of physical independence of data**
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  - Capacity Constraint Route Planner
    - Dealing with non-stationary ST Networks
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Capacity Constrained Route Planning (CCRP)

- Time-series attributes

\[ Available\_Node\_Capacity\( (N_i, t) \) = \text{#additional evacuees that can stay at node } N_i \text{ at time } t \]

\[ Available\_Edge\_Capacity\( (N_i - N_j, t) \) = \text{#additional evacuees that may travel via edge } N_i - N_j \text{ at time } t \]

- Generalize shortest path algorithms to
  - Honor capacity constraints
  - Spread people over space and time

- Comparison with TEG+LP Approach
  - Faster and more scalable
  - Easier to use:
    - Does not require user provided time upper bound
    - Does not require post-processing to construct routes
  - Modular, i.e. can interface with transportation models
  - Determining link capacity as a function of occupancy
Psuedo-code for Capacity Constrained Route Planner (CCRP)

While (any source node has evacuees) do

Step 1: Find nearest pair (Source S, Destination D), based on current available capacity of nodes and edges.

Step 2: Compute available flow on shortest route \( R(S,D) \)

\[
flow = \min \{ \text{number of current evacuees at } S , \quad \text{Available}_\text{Edge}_\text{Capacity}(\text{any edges on } R), \quad \text{Available}_\text{Node}_\text{Capacity}(\text{any nodes on } R) \}
\]

Step 3: Make reservation of capacity on route \( R \)

- Available capacity of each edge on \( R \) reduced by \( flow \)
- Available capacity of each incoming nodes on \( R \) reduced by \( flow \)

Summary:

- Each iteration generate route and schedule for one group of evacuee.
- Destination capacity constrains can be accommodated is needed
- Solution evacuation plan observes capacity constraints of network
- Wait at intermediate nodes addressed later non-stationary extension
Example Input: Evacuation Network with Evacuees

Node
- Node ID, Max Capacity
- Initial Occupancy

Edge
- Max Capacity, Travel time

Destination node
- Node ID

<table>
<thead>
<tr>
<th>Node ID</th>
<th>Max Capacity</th>
<th>Initial Occupancy</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1</td>
<td>50</td>
<td>(10)</td>
</tr>
<tr>
<td>N2</td>
<td>50</td>
<td>(5)</td>
</tr>
<tr>
<td>N3</td>
<td>30</td>
<td>(3,3)</td>
</tr>
<tr>
<td>N4</td>
<td>8</td>
<td>(3,3)</td>
</tr>
<tr>
<td>N5</td>
<td>6</td>
<td>(3,4)</td>
</tr>
<tr>
<td>N6</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>N7</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>N8</td>
<td>65</td>
<td>(15)</td>
</tr>
<tr>
<td>N9</td>
<td>25</td>
<td>(6,4)</td>
</tr>
<tr>
<td>N10</td>
<td>30</td>
<td>(6,3)</td>
</tr>
<tr>
<td>N11</td>
<td>8</td>
<td>(3,3)</td>
</tr>
<tr>
<td>N12</td>
<td>18</td>
<td>(3,3)</td>
</tr>
<tr>
<td>N13</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>N14</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Destinations:
- Dest #1
- Dest #2
CCRP Execution Trace

**Iteration: 1**

\( R \): (route with earliest destination arrival time)

- **Node:** N8 \( \rightarrow \) N10 \( \rightarrow \) N13
- **Start Time:** 0 \( \rightarrow \) 3 \( \rightarrow \) 4

Number of Evacuees on Route \( R \): 6

---

**Quickest route between source/destination pair:**

<table>
<thead>
<tr>
<th>Source</th>
<th>Destination</th>
<th>Dest. Arrival Time</th>
<th>No. of Evacuees</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1</td>
<td>N13</td>
<td>14</td>
<td>3</td>
</tr>
<tr>
<td>N1</td>
<td>N14</td>
<td>15</td>
<td>3</td>
</tr>
<tr>
<td>N2</td>
<td>N13</td>
<td>14</td>
<td>3</td>
</tr>
<tr>
<td>N2</td>
<td>N14</td>
<td>15</td>
<td>3</td>
</tr>
<tr>
<td>N8</td>
<td>N13</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>N8</td>
<td>N14</td>
<td>5</td>
<td>3</td>
</tr>
</tbody>
</table>

**Node:**

- Node ID, Max Capacity (Initial Occupancy)

**Edge:**

- (Max Capacity, Travel time)

**Edge reservation table:**

Each cell represents one time point (T0 \(-\) T15):

<table>
<thead>
<tr>
<th>T0</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
</tr>
</thead>
<tbody>
<tr>
<td>T4</td>
<td>T5</td>
<td>T6</td>
<td>T7</td>
</tr>
<tr>
<td>T8</td>
<td>T9</td>
<td>T10</td>
<td>T11</td>
</tr>
<tr>
<td>T12</td>
<td>T13</td>
<td>T14</td>
<td>T15</td>
</tr>
</tbody>
</table>

- e.g. Available edge capacity at time 3 is reduced to 5

---

**Quickest route between source/destination pair:**

- **Source:** N1
- **Destination:** N13
- **Dest. Arrival Time:** 14
- **No. of Evacuees:** 3

---

**Quickest route between source/destination pair:**

- **Source:** N2
- **Destination:** N13
- **Dest. Arrival Time:** 14
- **No. of Evacuees:** 3

---

**Quickest route between source/destination pair:**

- **Source:** N2
- **Destination:** N14
- **Dest. Arrival Time:** 15
- **No. of Evacuees:** 3

---

**Quickest route between source/destination pair:**

- **Source:** N8
- **Destination:** N13
- **Dest. Arrival Time:** 4
- **No. of Evacuees:** 6

---

**Quickest route between source/destination pair:**

- **Source:** N8
- **Destination:** N14
- **Dest. Arrival Time:** 5
- **No. of Evacuees:** 3

---

**Quickest route between source/destination pair:**

- **Source:** N10
- **Destination:** N13
- **Dest. Arrival Time:** 14
- **No. of Evacuees:** 3

---

**Quickest route between source/destination pair:**

- **Source:** N10
- **Destination:** N14
- **Dest. Arrival Time:** 15
- **No. of Evacuees:** 3

---

**Quickest route between source/destination pair:**

- **Source:** N11
- **Destination:** N13
- **Dest. Arrival Time:** 4
- **No. of Evacuees:** 6

---

**Quickest route between source/destination pair:**

- **Source:** N11
- **Destination:** N14
- **Dest. Arrival Time:** 5
- **No. of Evacuees:** 3

---

**Quickest route between source/destination pair:**

- **Source:** N12
- **Destination:** N13
- **Dest. Arrival Time:** 14
- **No. of Evacuees:** 3

---

**Quickest route between source/destination pair:**

- **Source:** N12
- **Destination:** N14
- **Dest. Arrival Time:** 15
- **No. of Evacuees:** 3

---

**Quickest route between source/destination pair:**

- **Source:** N13
- **Destination:** N10
- **Dest. Arrival Time:** 14
- **No. of Evacuees:** 3
CCRP Execution Trace

**Iteration: 2**

**R**: (route with earliest destination arrival time)

Node: N8, N10 → N13

Start Time: 1, 4, 5

Number of Evacuees on Route R: 6

Quickest route between source/destination pair:

<table>
<thead>
<tr>
<th>Source</th>
<th>Destination</th>
<th>Dest. Arrival Time</th>
<th>No. of Evacuees</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1</td>
<td>N13</td>
<td>14</td>
<td>3</td>
</tr>
<tr>
<td>N1</td>
<td>N14</td>
<td>15</td>
<td>3</td>
</tr>
<tr>
<td>N2</td>
<td>N13</td>
<td>14</td>
<td>3</td>
</tr>
<tr>
<td>N2</td>
<td>N14</td>
<td>15</td>
<td>3</td>
</tr>
<tr>
<td>N8</td>
<td>N13</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>N8</td>
<td>N14</td>
<td>5</td>
<td>3</td>
</tr>
</tbody>
</table>

Node:
- **Node ID, Max Capacity (Initial Occupancy)**
- **Edge**:
  - **Max Capacity, Travel time**

Edge reservation table:

Each cell represents one time point (T0 - T15):

- e.g. Available edge capacity at time 3 is reduced to 5

Dest #1

Dest #2
Iteration: 3

**R**: (route with earliest destination arrival time)

Node: N8 → N11 → N14

Start Time: 0 3 5

Number of Evacuees on Route R: 3

### Quickest route between source/destination pair:

<table>
<thead>
<tr>
<th>Source</th>
<th>Destination</th>
<th>Dest. Arrival Time</th>
<th>No. of Evacuees</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1</td>
<td>N13</td>
<td>14</td>
<td>3</td>
</tr>
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<td>3</td>
</tr>
<tr>
<td>N8</td>
<td>N14</td>
<td>5</td>
<td>3</td>
</tr>
</tbody>
</table>

**Node**

- **Node ID, Max Capacity (Initial Occupancy)**

**Edge**

- **(Max Capacity, Travel time)**

**Edge reservation table**

Each cell represents one time point (T0 - T15):

<table>
<thead>
<tr>
<th>T0</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
<th>T5</th>
<th>T6</th>
<th>T7</th>
<th>T8</th>
<th>T9</th>
<th>T10</th>
<th>T11</th>
<th>T12</th>
<th>T13</th>
<th>T14</th>
<th>T15</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>8</td>
<td>5</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
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<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
</tbody>
</table>

- Available edge capacity at time 3 is reduced to 5

**R**:

- **(route with earliest destination arrival time)**

- **Dest #1**: N13
- **Dest #2**: N14

**Quickest route between source/destination pair**

- N1 (50) → N2 (50) → N8 (65) → N10 (30) → N12 (18) → N14
- N1 (50) → N2 (50) → N8 (65) → N10 (30) → N11 (8) → N14
CCRP Execution Trace

Iteration: 4

R : (route with earliest destination arrival time)

Node: N8 N3 N4 N6 N10 N13
Start Time: 0 1 4 8 13 14

Number of Evacuees on Route R: 3

Quickest route between source/destination pair:

<table>
<thead>
<tr>
<th>Source</th>
<th>Destination</th>
<th>Dest. Arrival Time</th>
<th>No. of Evacuees</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1</td>
<td>N13</td>
<td>14</td>
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<td>3</td>
</tr>
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</tr>
<tr>
<td>N2</td>
<td>N14</td>
<td>15</td>
<td>3</td>
</tr>
</tbody>
</table>

Node:

Node ID, Max Capacity (Initial Occupancy)

Edge:

(Max Capacity, Travel time)

Edge reservation table:

Each cell represents one time point (T0 - T15):

\[
\begin{array}{cccccc}
  & T0 & T1 & T2 & T3 & \\
\hline
T0 & 8 & 8 & 8 & 5 & \\
T1 & 8 & 8 & 8 & 8 & \\
T2 & 8 & 8 & 8 & 8 & \\
T3 & 8 & 8 & 8 & 8 & \\
\end{array}
\]

e.g. Available edge capacity at time 3 is reduced to 5
Iteration: 5

**R**: (route with earliest destination arrival time)

<table>
<thead>
<tr>
<th>Node</th>
<th>Start Time</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>N8</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>N3</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>N4</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>N6</td>
<td>9</td>
<td>14</td>
</tr>
<tr>
<td>N10</td>
<td>14</td>
<td>15</td>
</tr>
<tr>
<td>N13</td>
<td>15</td>
<td>15</td>
</tr>
</tbody>
</table>

Number of Evacuees on Route $R$: 3

Quickest route between source/destination pair:

<table>
<thead>
<tr>
<th>Source</th>
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<th>Dest. Arrival Time</th>
<th>No. of Evacuees</th>
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<tr>
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</tr>
<tr>
<td>N2</td>
<td>N14</td>
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<td>3</td>
</tr>
</tbody>
</table>

Node ID, Max Capacity (Initial Occupancy)

Max Capacity, Travel time

Edge reservation table:

Each cell represents one time point (T0 - T15):

*Available edge capacity at time 3 is reduced to 5*
Design Decision 1: Algorithm for Step 1 (1/2)

Step 1:
Finding route $R$ among routes between all (source, destination) pairs.

Three choices:

1. $n \times m$ single-source single-destination shortest path search: 1 per $(S_i, d_j)$ pair.

2. $n$ single-source all-destination shortest path search: 1 per source node.

3. One shortest path search:
   - Add super source node and super destination node to network.
   - One shortest path search from super source node to super destination node.

Choice: one shortest path search

Rationale: lower computational cost
Find Route $R$ with one Shortest Path Search:

If route $<S_0, S_x, \ldots, d_y, d_0>$ is the shortest route between $S_0$ and $d_0$, then $<S_x, \ldots, d_y>$ must be the shortest route $R$ between any (source, destination) pair.
Design Decision 2 – Choice of Shortest Path Algorithms

Shortest path algorithm for graph with non-negative edge length:

Three Choices:

1. Family of Dijkstra’s algorithm:
   Original Dijkstra’s algorithm: [Dijkstra, 1959].
   Survey of implementations: [Cherkassky, Goldberg and Radzik, 1993].
3. Hierarchical routing algorithm: [Shekhar, 1997], [Rundensteiner, 1998],

Choice: Dijkstra’s algorithm

Rationale:
• A* search: effectiveness of heuristic function deteriorate in later iterations of CCRP due to change of available capacity.
• Hierarchical routing: pre-computed shortest path between partitions no longer hold in later iterations of CCRP due to change of available capacity.
Capacity Constrained Route Planner (CCRP)

Input:
1) \( G(N,E) \): a graph \( G \) with a set of nodes \( N \) and a set of edges \( E \);
   Each node \( n \in N \) has two properties:
   - \( \text{Maximum Node Capacity}(n) \): non-negative integer
   - \( \text{Initial Node Occupancy}(n) \): non-negative integer
   Each edge \( e \in E \) has two properties:
   - \( \text{Maximum Edge Capacity}(e) \): non-negative integer
   - \( \text{Travel Time}(e) \): non-negative integer
2) \( S \): set of source nodes, \( S \subseteq N \);
3) \( D \): set of destination nodes, \( D \subseteq N \);

Output: Evacuation plan: Routes with schedules of evacuees on each route

Method:

Pre-process network: add super source node \( s_0 \) to network,
link \( s_0 \) to each source nodes with an edge which
\[ \text{Maximum Edge Capacity}() = \infty \text{ and Travel Time}() = 0; \] while any source node \( s \in S \) has evacuee do {
find route \( R < n_0, n_1, \ldots, n_k > \) with time schedule, such that \( R \) has the earliest
destination arrival time among routes between all \((s,d)\) pairs,
where \( s \in S, d \in D, n_0 = s, n_k = d \),
using one generalized shortest path search from super source \( s_0 \) to all destinations;
flow = \( \min( \text{number of evacuee still at source node } s, \text{Available Edge Capacity}(\text{all edges on route } R), \text{Available Node Capacity}(\text{all nodes from } n_1 \text{ to } n_{k-1} \text{ on route } R), \) \)
for \( i = 0 \) to \( k - 1 \) do {
\( t = \text{start time from node } n_i \text{ on route } R; \)
\( \text{Available Edge Capacity}(e_{n_i,n_{i+1}}, t) \text{ reduced by } flow; \)
\( \text{Available Node Capacity}(n_{i+1}, t + \text{Travel Time}(e_{n_i,n_{i+1}})) \text{ reduced by } flow; \)
}
Output evacuation plan;
Cost Model of CCRP

Number of iterations: \( O(p) \) \( p \) : number of evacuees
Each iteration generates one group of evacuees,
Upper bound of number of groups = number of evacuees

Cost for each iteration: ( \( n \): number nodes, \( m \): number of edges )

Step 1 - Find route \( R \) with one Dijkstra search:
  Dijkstra ( naïve implementation): \( O(n^2) \)
  Dijkstra ( with heap structure): \( O(m+n\log n) \)
  for sparse graphs (e.g. road network): \( m << n\log n \)
  Cost of Step 1: \( O(n\log n) \)

Step 2 - Compute flow amount on route \( R \) : \( O(1) \)
Step 3 - Make reservations on route \( R \) : \( O(n) \)

Step 1 is dominant.

CCRP cost model: \( O(p \ n\log n) \)
Performance Evaluation: Experiment Design

Goal:
1. Compare CCRP with LP minimum cost flow solver (e.g. NETFLO):
   - Solution Quality Measure: Evacuation egress time
   - Performance Measure: Run-time

2. Test effect of independent parameters on solution quality and performance:
   - Number of evacuees, number of source nodes, size of network (number of nodes).

Experiment Platform: CPU: Pentium 4 2GHz, RAM: 2GB, OS: Linux.
Performance Evaluation: Experiment Results 1

Experiment 1: Effect of Number of Evacuees

Setup: fixed network size = 5000 nodes, fixed number of source nodes = 2000 nodes, number of evacuees from 5,000 to 50,000.

- CCRP produces high quality solution, solution quality drops slightly as number of evacuees grows.
- Run-time of CCRP is less than 1/3 that of NETFLO.
- CCRP is scalable to the number of evacuees.
Performance Evaluation : Experiment Results 2

Experiment 2: Effect of Number of Source Nodes

Setup: fixed network size = 5000 nodes, fixed number of evacuees = 5000, number of source nodes from 1,000 to 4,000.

- CCRP produces high quality solution, solution quality not affected by number of source nodes.
- Run-time of CCRP is less than half of NETFLO.
- CCRP is scalable to the number of source nodes.
Performance Evaluation : Experiment Results 3

**Experiment 3: Effect of Network Size**

Setup: fixed number of evacuees = 5000, fixed number of source nodes = 10 nodes, number of nodes from 50 to 50,000.

- **CCRP** produces high quality solution, solution quality increases as network size grows.
- **Run-time of CCRP** is scalable to network size.

![Figure 1 Quality of solution](chart1.png)

![Figure 2 Run-time](chart2.png)
Outline

- Motivation
- Problem Statement
- Why is the problem hard?
- Related Work
- **Proposed Approach**
  - Time aggregated Graph
  - Capacity Constraint Route Planner
  - **Dealing with non-stationary networks**
- Evaluation
  - Computer Science – Theoretical, Experimental
  - Case Studies – Nuclear Power Plant, Homeland Security
- Conclusion and Future works
Summary: Routing in ST Networks

Predictable Future

Stationary

Special case (FIFO) SP-TAG, SP-TAG*, CapeCod

General Case

Non-stationary

Dijkstra’s, A*….

TEG: LP, Label-correcting
[Orda91, Kohler02, Pallotino98]

TAG: Transform to Stationary TAG

travel times → arrival times at end node → Min. arrival time series

Non-stationary TAG

Stationary TAG
Non-stationary Networks: Challenges

- Violation of optimal prefix property
  - Not all optimal paths show optimal prefix property.

- New and Alternate semantics

- Termination of the algorithm: an infinite non-negative cycle over time
Routing Algorithms - Sub-structure Optimality?

Find the *shortest path travel time* from N1 to N5 for start time $t = 1$.

Dijkstra’s: Reaches N5 at $t=8$.

**Total time** = 7

Optimal path: Reach N4 at $t=3$; Wait for $t=4$: Reach N5 at $t=6$

**Total time** = 5
Routing Algorithms and Spatio-temporal Networks

Limitations:

Label correcting algorithm over long time periods and large networks is computationally expensive.

LP algorithms are costly.
Related Work – Label Correcting Approach(*)

- Selection of node to expand is random.
- Algorithm terminates when no node gets updated.

Start time = 1; Start node : N1

Iteration 1: N1_1 selected
N1_2 = 2; N2_2 = 2; N3_3 = 3

Iteration 2: N2_2 selected
N2_3 = 3; N4_3 = 3

Iteration 3: N3_3 selected
N3_4 = 4; N4_5 = 5

...:

Iteration ..: N4_3 selected
N4_4 = 4; N5_8 = 8

Iteration ..: N4_4 selected
N4_5 = 5; N5_6 = 6

- Implementation used the Two-Q version \([O(n^2T^3(n+m))]\)

(*) Cherkassky 93, Zhan01, Ziliaskopoulos97
Proposed Approach – Key Idea

When start time is fixed, earliest arrival ⇒ least travel time (Shortest path)

Arrival Time Series Transformation (ATST) the network:

travel times → arrival times at end node → Min. arrival time series

Result is a Stationary TAG.

Greedy strategy (on cost of node, earliest arrival) works!!
**SP Algorithm in Non-FIFO Networks (NF-SP-TAG)**

**Greedy strategy on transformed TAG:**

- **Cost of a node = Arrival time at the node**
- **Expand the node with least cost.**
- **Update costs of adjacent nodes.**

Select Minimum \( \{\text{Cost of edge } ij\} \) \( t \geq \text{arrival at } i \)

**Trace of NF-SP-TAG Algorithm**

<table>
<thead>
<tr>
<th></th>
<th>N1</th>
<th>N2</th>
<th>N3</th>
<th>N4</th>
<th>N5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1</td>
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<tr>
<td>5</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>6</td>
</tr>
</tbody>
</table>
Routing Algorithms – New Semantics

Finding the shortest path from N1 to N5...

Start at \( t=1 \):
Shortest Path is **N1-N3-N4-N5**;
Travel time is 6 units.

Start at \( t=3 \):
Shortest Path is **N1-N2-N4-N5**;
Travel time is 4 units.

**Fixed Start Time Shortest Path**

**Least Travel Time (Best Start Time)**

**Shortest Path is dependent on start time!!**
Contributions (Broader Picture)

- Time Aggregated Graph (TAG)
- Routing Algorithms

<table>
<thead>
<tr>
<th></th>
<th>FIFO</th>
<th>Non-FIFO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed Start</td>
<td>(1) Greedy (SP-TAG)</td>
<td>(4) NF-SP-TAG</td>
</tr>
<tr>
<td>Time</td>
<td>(2) A* search (SP-TAG*)</td>
<td></td>
</tr>
<tr>
<td>Best Start</td>
<td>(3) Iterative A* search (TI-SP-TAG*)</td>
<td>(5) Label Correcting (BEST)</td>
</tr>
<tr>
<td>Time</td>
<td>(6) Iterative NF-SP-TAG</td>
<td></td>
</tr>
</tbody>
</table>
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  - Nuclear Power Plant
  - Homeland Security
- Conclusion and Future works
A Real Scenario: Montecillo Nuclear Power Plant

- **Affected Cities**: Monticello
- **Evacuation Destination**: University of Minnesota

Map showing the locations of Montecillo Power Plant, affected cities, and evacuation destination.
A Real Scenario: Monticello Emergency Planning Zone and Population

Emergency Planning Zone (EPZ) is a 10-mile radius around the plant divided into sub areas.

Monticello EPZ
Subarea Population
2  4,675
5N 3,994
5E 9,645
5S 6,749
5W 2,236
10N 391
10E 1,785
10SE 1,390
10S 4,616
10SW 3,408
10W 2,354
10NW 707
Total 41,950

Estimate EPZ evacuation time:
Summer/Winter (good weather): 3 hours, 30 minutes
Winter (adverse weather): 5 hours, 40 minutes

Data source: Minnesota DPS & DHS
Web site: http://www.dps.state.mn.us
http://www.dhs.state.mn.us
A Real Scenario: New Plan Routes

Experiment Result
Total evacuation time:
- Existing Plan: 268 min.
- New Plan: 162 min.

Congestion is likely in old plan near evacuation destination due to capacity constraints. Our plan has richer routes near destination to reduce congestion and total evacuation time.
Outline

- Motivation
- Problem Statement
- Why is the problem hard?
- Related Work
- Proposed Approach
- Evaluation Case Studies
  - Nuclear Power Plant
  - Homeland Security
    - (Note: use FoxTV clip)
- Conclusion and Future works
Case Study 2 - Metropolitan Wide Evacuation Planning

Mandate - DHS Requirement

Objectives

- Coordinate evacuation plans of individual communities
- Reduce conflicts across component plans
  - due to the use of common highways

Timeframe: January – November 2005
Advisory Board

MEMA/Hennepin Co. - Tim Turnbull, Judith Rue
Dakota Co. (MEMA) - David Gisch
Minneapolis Emergency Mgt. - Rocco Forte, Kristi Rollwagen
St. Paul Emergency Mgt. - Tim Butler
Minneapolis Fire - Ulie Seal
DPS HSEM - Kim Ketterhagen, Terri Smith
DPS Special Operations - Kent O’Grady
DPS State Patrol - Mark Peterson

Workshops

Over 100 participants from various local, state and federal govt.
Workshop Participants

Federal, State, County, City
Gerald Libbe, Federal Highway Administration (FHWA)
Katie Belmore, Representing Wisconsin Department of Transportation

Airports
George Condon, Metropolitan Airports Commission

Businesses
Chris Terzich, Minnesota Information Sharing and Analysis Center
Barry Gorelick, Minnesota Security Board

Communications and Public Information
Kevin Gutknecht, Mn/DOT
Lucy Kender, Mn/DOT
Andrew Terry, Mn/DOT

Dispatch
Keith Jacobson, Mn/DOT

Education
Bob Fischer, Minnesota Department of Education
Dick Guevremont, Minnesota Department of Education

Emergency Management
Bruce Wojack, Anoka County Emergency Management
Tim Walsh, Carver County Emergency Management
Jim Halstrom, Chisago County Emergency Management
David Gisch, Dakota County Emergency Preparedness
Tim O’Laughlin, Scott County Sheriff – Emergency Management
Tim Turnbull, Hennepin County Emergency Preparedness
Judith Rue, Hennepin County Emergency Preparedness
Rocco Forte, Minneapolis Fire Department – Emergency Preparedness
Kristi Rollwagen, Minneapolis Fire Department – Emergency Preparedness
William Hughes, Ramsey County Emergency Management and Homeland Security
Tim Butler, St. Paul Fire and Safety Services
Deb Paige, Washington County Emergency Management
Kim Ketterhagen, Department of Public Safety (DPS) HSEM
Sonia Pitt, Mn/DOT HSEM
Bob Vasek, Mn/DOT HSEM

Fire
Gary Sigfrinius, Forest Lake Fire Department

Health
Debrah Ehret, Minnesota Department of Health

Hospitals
Dan O’Laughlin, Metropolitan Hospital Compact

Human Services
Glenn Olson, Minnesota Department of Human Services

Law Enforcement
Brian Johnson, Hennepin County Sheriff
Jack Nelson, Metro Transit Police Department
David Indrehus, Metro Transit Police Department
Otto Wagenpfeil, Minneapolis Police Department
Kent O’Grady, Minnesota State Patrol
Mark Peterson, Minnesota State Patrol
Chuck Walerus, Minnesota State Patrol
Douglas Biehn, Ramsey County Sheriff’s Office
Mike Morehead, St. Paul Police

Maintenance and Operations
Beverly Farranher, Mn/DOT
Gary Workman, Mn/DOT
Robert Wryk, Mn/DOT

Military
Daniel Berg, Marine Safety Office St. Louis Planning Division
Eric Waage, Minnesota National Guard

Planning
Connie Kozlak, MetCouncil

Public Works
Bill Cordell, Wright County
Jim Gates, City of Bloomington
Jim Grube, Hennepin County
Bob Winter, Mn/DOT
Klara Fabry, City of Minneapolis
Mark Kennedy, City of Minneapolis
Gary Erickson, Hennepin County
Dan Schacht, Ramsey County

Safety
Thomas Cherney, Minnesota Department of Public Safety
Doug Thies, Mn/DOT

Security
Terri Smith, Minnesota Homeland Security Emergency Management
Paul Pettit, Transportation Security Administration

Transit
Dana Rude, Metro Mobility
Steve McLaird, MetroTransit
Christy Bailly, MetroTransit
David Simoneau, SouthWest Metro Transit

Traffic
Thomas Bowlin, City of Bloomington
Jon Wertjes, City of Minneapolis
Bernie Arseneau, Mn/DOT
Amr Jabr, Mn/DOT
Eil Kwon, Mn/DOT
Paul St. Martin, City of St. Paul

Trucking
John Hausladen, Minnesota Trucking Association

University
Dan JohnsonPowers,
University of Minnesota Emergency Management

Volunteer Organizations
Gene Borochoff, Minnesota Volunteer Organization active in Disaster
Metro Evacuation Plan

- Identify Stakeholders
- Establish Steering Committee
- Perform Inventory of Similar Efforts and Look at Federal Requirements
- Finalize Project Objectives
- Evacuation Route Modeling
- Evacuation Routes and Traffic Mgt. Strategies
  - Regional Coordination and Information Sharing
  - Agency Roles

Stakeholder Interviews and Workshops

Issues and Needs

Preparedness Process

Final Plan
1. TP+ (Tranplan) road network for Twin Cities Metro Area

   Source: Met Council TP+ dataset

   Summary:
   - Contain freeway and arterial roads with road capacity, travel time, road type, area type, number of lanes, etc.
   - Contain virtual nodes as population centroids for each TAZ.

   Limitation: No local roads (for pedestrian routes)

2. MnDOT Basemap

   Source: MnDOT Basemap website ([http://www.dot.state.mn.us/tda/basemap](http://www.dot.state.mn.us/tda/basemap))

   Summary: Contain all highway, arterial and local roads.

   Limitation: No road capacity or travel time.
Demographic Datasets

1. Night time population
   - Census 2000 data for Twin Cities Metro Area
   - Source: Met Council Datafinder (http://www.datafinder.org)
   - Summary: Census 2000 population and employment data for each TAZ.
   - Limitation: Data is 5 years old; day-time population is different.

2. Day-time Population
   - Employment Origin-Destination Dataset (Minnesota 2002)
     - Source: MN Dept. of Employment and Economic Development
     - Contain work origin-destination matrix for each Census block.
     - Need to aggregate data to TAZ level to obtain:
       - Employment Flow-Out: # of people leave each TAZ for work.
       - Employment Flow-In: # of people enter each TAZ for work.
   - Limitation: Coarse geo-coding => Omits 10% of workers
   - Does not include all travelers (e.g. students, shoppers, visitors).
Defining A Scenario

State Fairgrounds, Daytime, 1 Mile Src - 2 Mile Dst,

Evacuation Planning System for Twin Cities Metro Area
Step 2 of 3: Adjust Scenario Settings

Scenario Name:
User Defined Refinery

Evac Zone Adjustment
Source Radius: 1 mile
Destination Radius: 2 mile

Transportation Mode
Driving: 100%
Walking: 0%

Apply Parameters
(If some values of above parameters change, click 'Apply Parameters' button again.)
Rest Estimate value may decrease a little by applying parameters due to assignment.

Execute Planning Calculation
Run

Set source to 1 mile and destination to 2 mile
Click 'Apply Parameters' and wait for a while
If population estimate is shown, click 'run'.
Reviewing Resulting Evacuation Routes

State Fairgrounds, Daytime, 1 Mile Src - 2 Mile Dst,

Evacuation Planning System for Twin Cities Metro Area
Step 3 of 3: Evacuation Route Plan

- Web-based
  - Easy Installation
  - Easy Maintenance
  - Advanced Security

- Simple Interface
  - User friendly and intuitive

- Comparison on the fly
  - Changeable Zone Size
  - Day vs. Night Population
  - Driving vs. Pedestrian Mode
  - Capacity Adjustment

- Visualized routes

Scenario Name:
User Defined

Evacuation Radius
Src Radius: 1 mile
Dst Radius: 2 mile

Population Estimate
Original Estimate: 14431 (details)
Adjusted Estimate: 14431

Time of Day
Daytime

Analysis Result
Number of destinations: 45
Evacuation Time: 3 hr[s] 16 min

Results with routes
An Easy to Use Graphic User Interface

Evacuation Planning System for Twin Cities Metro Area
Step 3 of 3: Evacuation Route Plan

Scenario Name: User Defined

Evacuation Radius
Src Radius: 1.0 mile
Dst Radius: 1.0 mile

Population Estimate
Original Estimate: 19649 (details)
Adjusted Estimate: 1999
Time of Day: Daytime

Transportation Mode: Driving 100%
Capacity Adjust: 100%

Analysis Result
Number of destinations: 17
Evacuation Time: 0 hr(s) 14 min

Visualized routes

- Web-based
  - Easy Installation
  - Easy Maintenance
  - Advanced Security

- Simple Interface
  - User friendly and intuitive

- Comparison on the fly
  - Changeable Zone Size
  - Day vs. Night Population
  - Driving vs. Pedestrian Mode
  - Capacity Adjustment

- Visualized routes
Common Usage of the tool

- **Current Usage**: Compare options
  - Ex.: transportation modes
    - Walking may be better than driving for 1-mile scenarios
  - Ex.: Day-time and Night-time needs
    - Population is quite different

- **Potential Usage**: Identify bottleneck areas and links
  - Ex.: Large gathering places with sparse transportation network
  - Ex.: Bay bridge (San Francisco),

- **Potential**: Designing / refining transportation networks
  - Address evacuation bottlenecks
  - A quality of service for evacuation, e.g. 4 hour evacuation time
Finding: Pedestrians are faster than Vehicles!

Five scenarios in metropolitan area
Evacuation Zone Radius: 1 Mile circle, daytime

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Population</th>
<th>Vehicle</th>
<th>Pedestrian</th>
<th>Ped / Veh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario A</td>
<td>143,360</td>
<td>4 hr 45 min</td>
<td>1 hr 32 min</td>
<td>32%</td>
</tr>
<tr>
<td>Scenario B</td>
<td>83,143</td>
<td>2 hr 45 min</td>
<td>1 hr 04 min</td>
<td>39%</td>
</tr>
<tr>
<td>Scenario C</td>
<td>27,406</td>
<td>4 hr 27 min</td>
<td>1 hr 41 min</td>
<td>38%</td>
</tr>
<tr>
<td>Scenario D</td>
<td>50,995</td>
<td>3 hr 41 min</td>
<td>1 hr 20 min</td>
<td>36%</td>
</tr>
<tr>
<td>Scenario E</td>
<td>3,611</td>
<td>1 hr 21 min</td>
<td>0 hr 36 min</td>
<td>44%</td>
</tr>
</tbody>
</table>
Finding: Pedestrians are faster than Vehicles!

If number of evacuees > bottleneck capacity of network

<table>
<thead>
<tr>
<th># of Evacuees</th>
<th>200</th>
<th>2,000</th>
<th>10,000</th>
<th>20,000</th>
<th>100,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driving</td>
<td>4 min</td>
<td>14 min</td>
<td>57 min</td>
<td>108 min</td>
<td>535 min</td>
</tr>
<tr>
<td>Walking</td>
<td>18 min</td>
<td>21 min</td>
<td>30 min</td>
<td>42 min</td>
<td>197 min</td>
</tr>
<tr>
<td>Drv / Wlk</td>
<td>0.22</td>
<td>0.67</td>
<td>1.90</td>
<td>2.57</td>
<td>2.72</td>
</tr>
</tbody>
</table>

Driving / Walking Evacuation Time Ratio with regard to # of Evacuees

Small scenario – 1 mile radius circle around State Fairground
Key finding 2 – Finding hard to evacuate places!

- Scenario C is a difficult case
  - Same evacuation time as A, but one-fourth evacuees!
  - Consider enriching transportation network around C?

<table>
<thead>
<tr>
<th>Evacuation Time</th>
<th>Number of Evacuees (Day Time) with 1 mile radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 hour</td>
<td>20,000</td>
</tr>
<tr>
<td>5 hour</td>
<td>40,000</td>
</tr>
<tr>
<td>4 hour</td>
<td>60,000</td>
</tr>
<tr>
<td>3 hour</td>
<td>80,000</td>
</tr>
<tr>
<td>2 hour</td>
<td>100,000</td>
</tr>
<tr>
<td>1 hour</td>
<td>120,000</td>
</tr>
<tr>
<td></td>
<td>140,000</td>
</tr>
</tbody>
</table>
Outline

- Motivation
- Problem Statement
- Why is the problem hard?
- Related Work
- Proposed Approach
- Evaluation Case Studies
  - Nuclear Power Plant
  - Homeland Security
- Conclusion and Future works
Summary Messages

• Evacuation Planning is critical for homeland defense
• Existing methods can not handle large urban scenarios
  • Communities use hand-crafted evacuation plans
• New Methods from Our Research
  • Can produce evacuation plans for large urban area
  • Reduce total time to evacuate!
  • Improves current hand-crafted evacuation plans
  • Ideas somewhat tested in the field
Current Limitations & Future Work

- Evacuation time estimates
  - Approximate and optimistic
  - Assumptions about available capacity, speed, demand, etc.
  - No model for pedestrians, bikes, public transportation, etc.

- Quality of input data
  - Population and road network database age!
    - Ex.: Rosemount scenario – an old bridge in the roadmap!
  - Data availability
    - Pedestrian routes (links, capacities and speed)

- On-line editing capabilities
  - Taking out a link (e.g. New Orleans bridge flooding)!
Future Work Across Disciplines

- **Data Availability**
  - Estimating evacuee population, available transport capacity
  - Pedestrian data: walkway maps, link capacities based on width

- **Transportation**
  - Link capacity depends on traffic density
  - Modeling traffic control signals, ramp meters, contra-flow, …

- **Evacuee Behavior**
  - Unit of evacuation: Individual or Household
  - Heterogeneity: by physical ability, age, vehicle ownership, language, …

- **Policy Decisions**
  - How to gain public’s trust in plans? Will they comply?
  - Common good with awareness of winners and losers due to a decision

- **Science**
  - How does one evaluate an evacuation planning system?
  - How do we calibrate parameters?
Future Work

- **Time-Variant Flow Network Questions**

<table>
<thead>
<tr>
<th>Static</th>
<th>Time-Variant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Which is the shortest travel time path from downtown Minneapolis to airport?</td>
<td>Which is the shortest travel time path from downtown Minneapolis to airport at different times of a work day?</td>
</tr>
<tr>
<td>What is the capacity of Twin-Cities freeway network to evacuate downtown Minneapolis?</td>
<td>What is the capacity of Twin-Cities freeway network to evacuate downtown Minneapolis at different times in a work day?</td>
</tr>
</tbody>
</table>

- **New Routing Questions**
  - Best start time to minimize time spend on network
  - Account for delays at signals, rush hour, etc.

---

**The New York Times**

*U.P.S. Embraces High-Tech Delivery Methods (July 12, 2007)*

By Claudia H. Deutsch

“The research at U.P.S. is paying off. …….— saving roughly three million gallons of fuel in good part by mapping routes that minimize left turns.”
Technology Transfer …

• Help the nation in the critical area of evacuation planning!
  • Save lives and reduce injuries by reducing evacuation time
  • Reduce productivity loss due to congestion at events (e.g. conventions, professional sports, long weekends such as 4th of July, Memorial day, Fishing opener etc.)

• Mature the research results into tools for first responders
  • Help them use explore many evacuation scenarios
  • Help them compare alternate evacuation routes, transportation modes, etc.
  • Identify hot-spots (e.g. places which take too long to evacuate)
  • Improve transportation networks to address hot-spots

• Develop new scientific knowledge
  • When to use each mode (e.g. public transportation, pedestrian, SOVs)?
  • How to plan multi-modal evacuation routes and schedules?
  • How to model capacities, speed and flow-rate for public transportation, pedestrians?
  • Panic management
Acknowledgements

• **Sponsors**
  • NSF, AHPCRC, Army Research Lab.
  • CTS, MnDOT

• **Key Individuals**
  • Univ. of Minnesota - Sangho Kim, Qingsong Lu, and Betsy George
  • MnDOT - Sonia Pitt, Robert Vasek, Cathy Clark, Mike Sobolesky, Eil Kwon
  • URS - Daryl Taavola, Tait Swanson, Erik Seiberlich

• **Participating Organizations**
  • DPS, MEMA, Mpls./St. Paul Emergency Mgmt.
  • Dept. of Public Safety, DOE, DOH, DO Human Services
  • Coast Guard, FHWA, TSA, Mn National Guard, UMN
  • 9 Counties, 4 Cities, Metropolitan Council, Metro Transit
  • 3 Fire Depts., 7 Law Enforcements
Welcome to Computational Aspects of Geo-Informatics
ACM – SIG-Spatial
& Workshop on Computational Transportation Systems
Symposium on Spatial and Temporal Databases, 2009, Denmark

Thank you!