Evacuation Route Planning

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Sponsors: NSF, USDOD, MnDOT

Outline

- Motivation
- Problem Statement
- Why is the problem hard?
- Related Work
- Proposed Approach
- Evaluation
- Conclusion and Future works

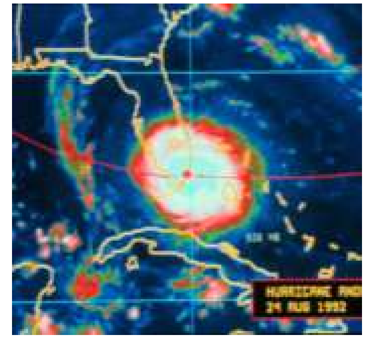
Large Scale Evacuation due Natural Events

Hurricane: Andrews, Rita

- Traffic congestions on all highways
    - E.g. 100-mile congestion (TX)
- Great confusions and chaos

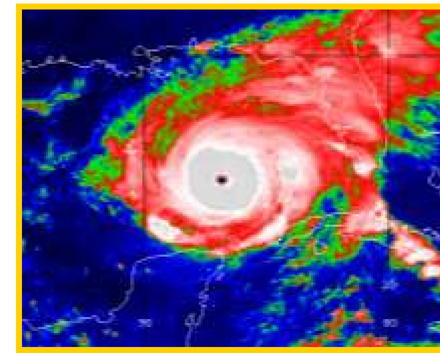
"We packed up Morgan City residents to evacuate in the a.m. on the day that Andrew hit coastal Louisiana, but in early afternoon the majority came back home. **The traffic was so bad that they couldn't get through Lafayette**."
Mayor Tim Mott, Morgan City, Louisiana
(http://i49south.com/hurricane.htm)

Florida, Lousiana (Andrew, 1992)



(National Weather Services)

Houston (Rita, 2005)



(National Weather Services)

(www.washingtonpost.com)

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 ?

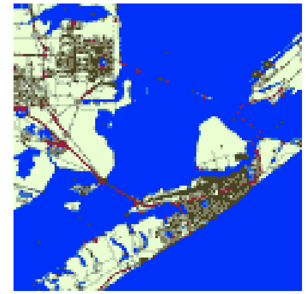
PLANNING SCENARIOS
Executive Summaries

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

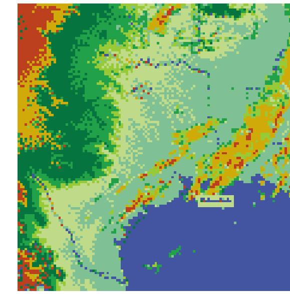
The Homeland Security Council

David Howe, Senior Director for Response and Planning

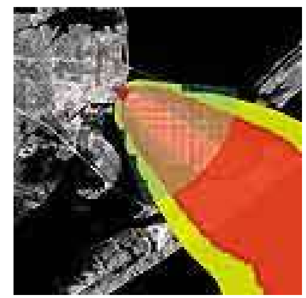
July 2004



Base Map

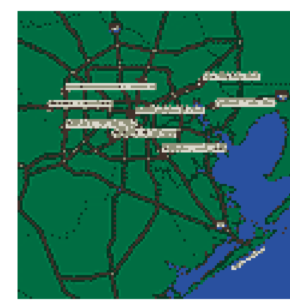


Weather Data



Plume Dispersion

Demographics Information

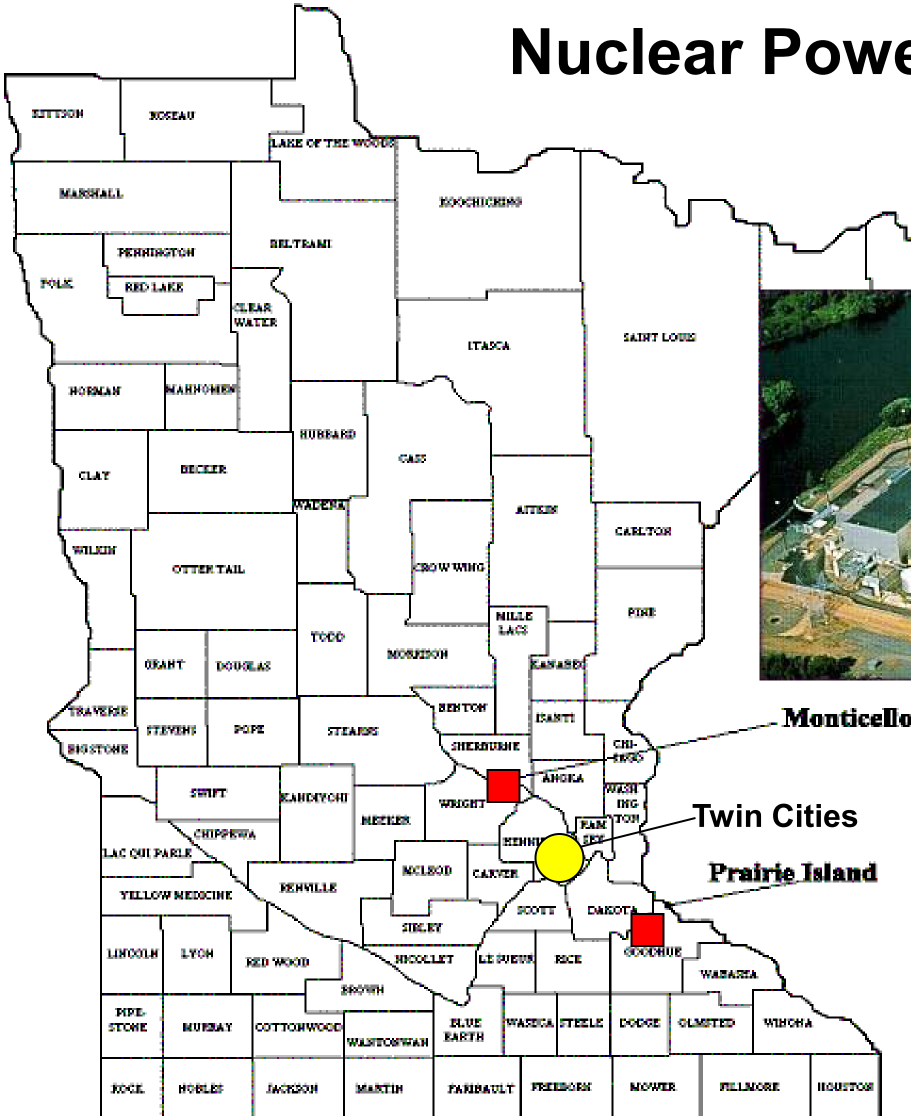


Transportation Networks

(Images from www.fortune.com)

Preparedness for Industrial Accidents, e.g. Nuclear Power Plants

Nuclear Power Plants in Minnesota



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
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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

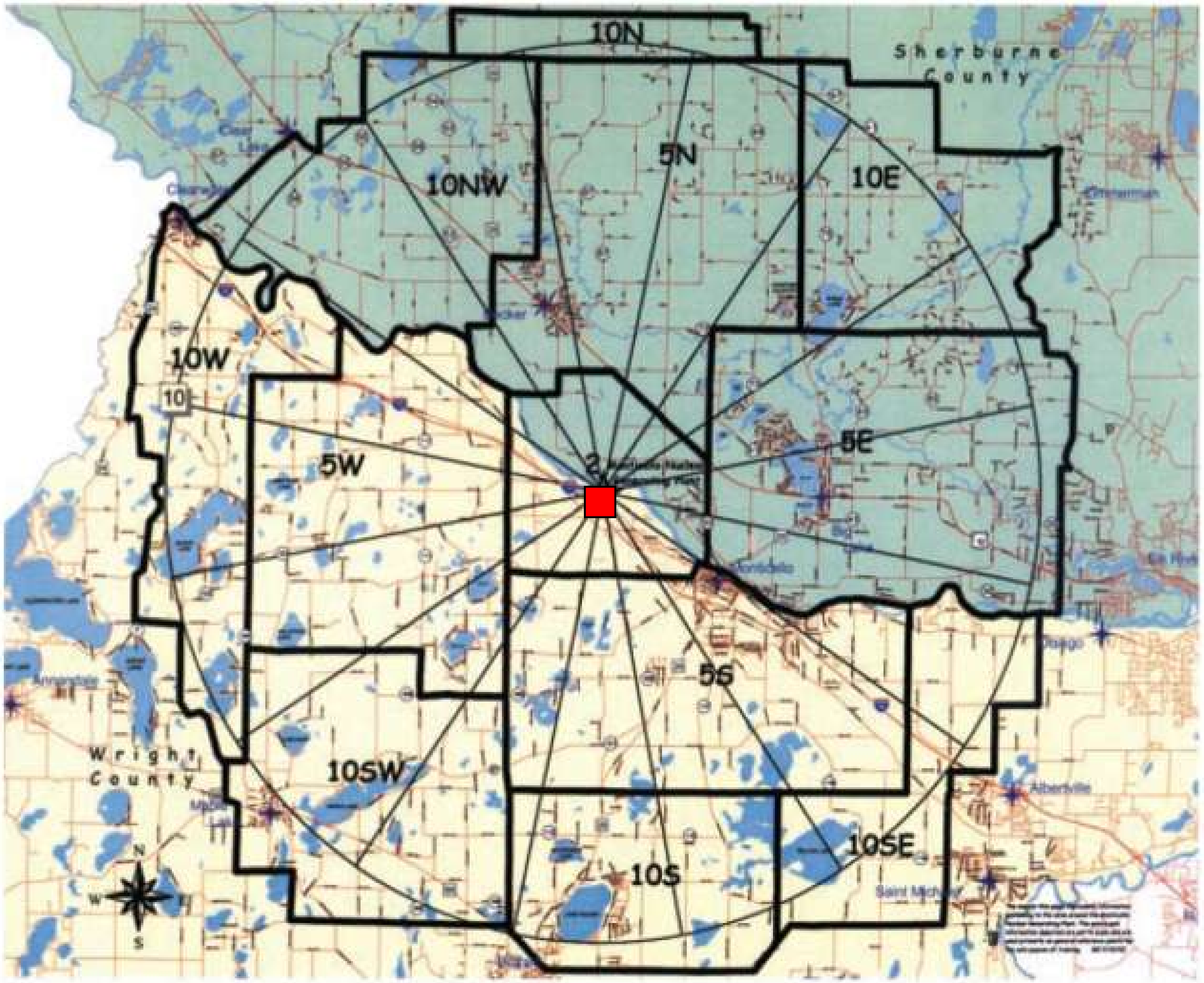
- Why minimize evacuation time?
  - Reduce exposure to evacuees
  - Since harm due to many hazards increase with exposure time!

- 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.



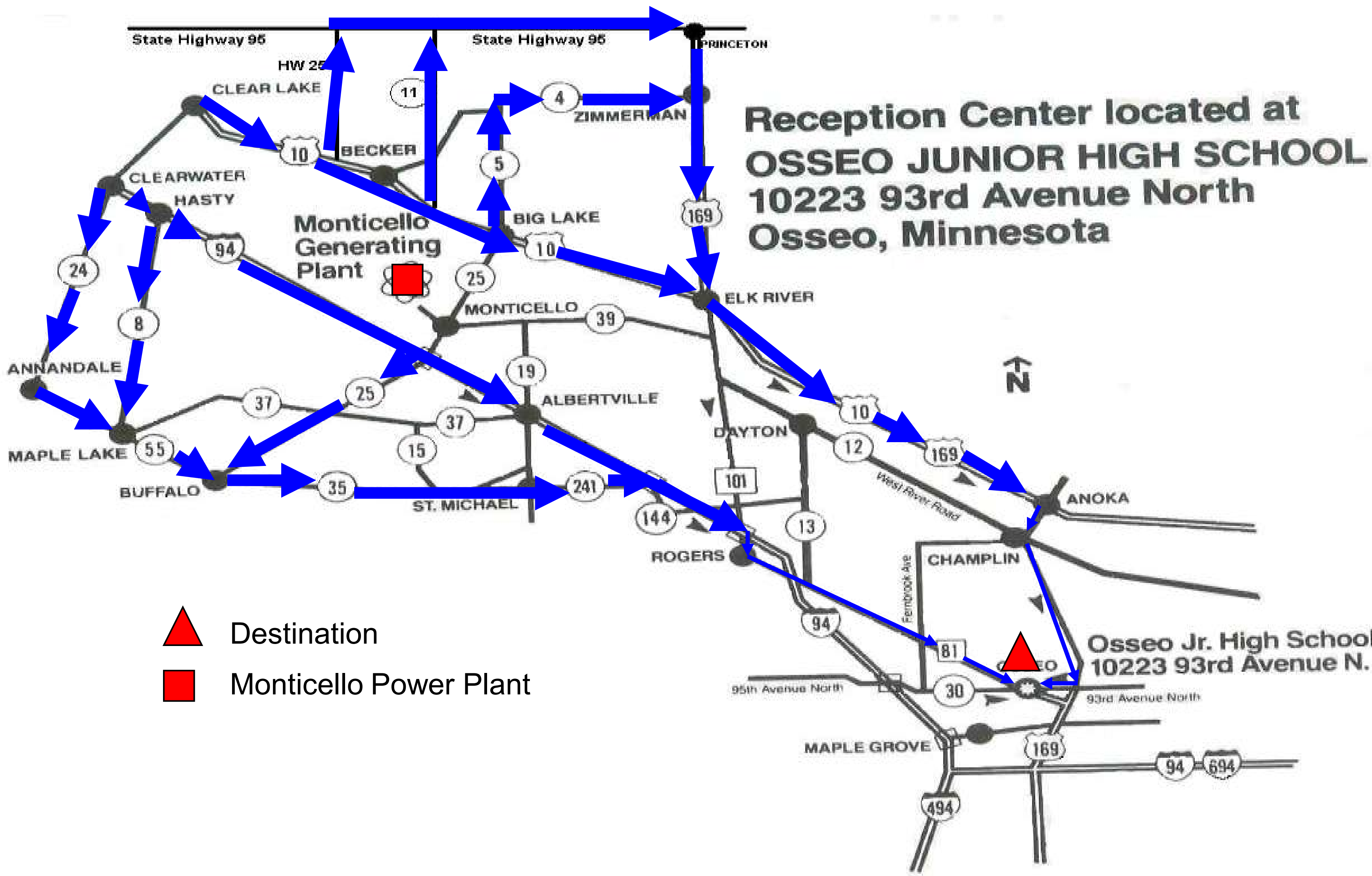
Monticello EPZ

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

Ex. 1 Output: Evacuation Routes (Handcrafted)



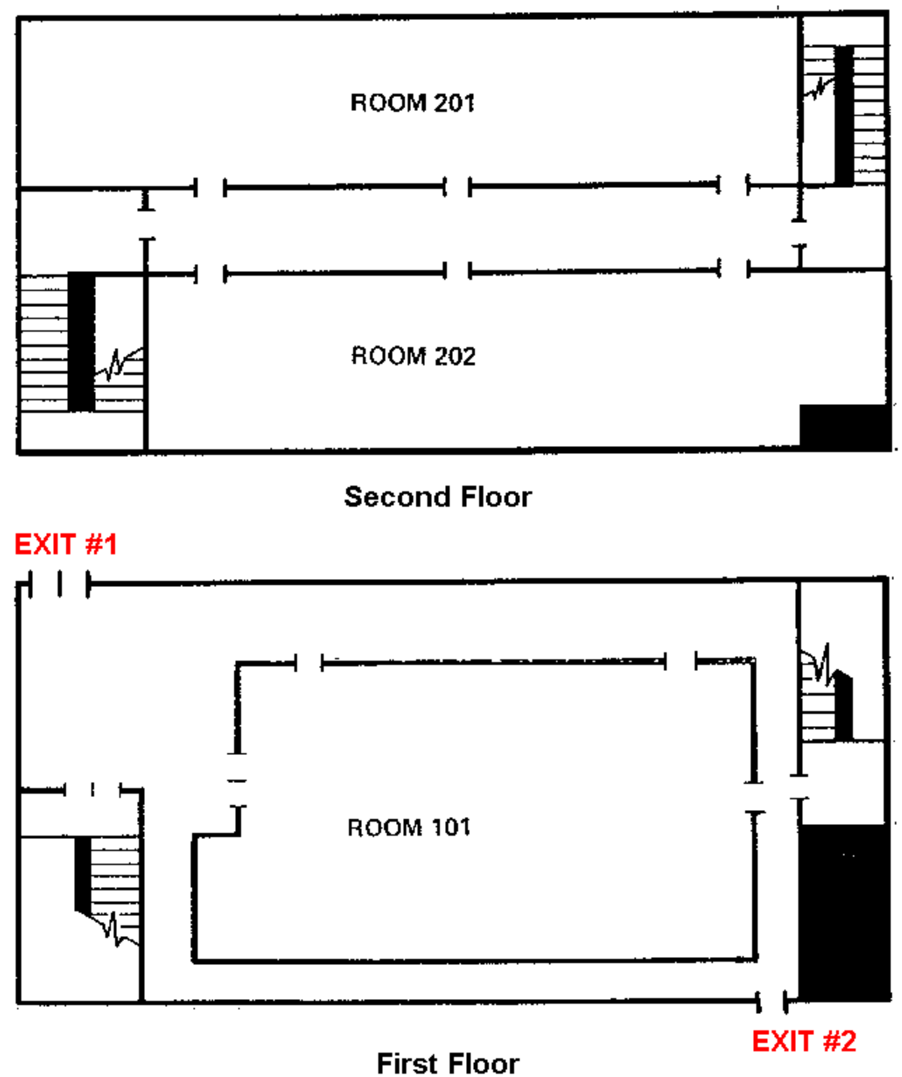
Destination

Monticello Power Plant

Example 2: A Building floor plan

Two-story building:

- Two staircases
- Two exits on first floor



(Building floor map from EVACNET User Manual)

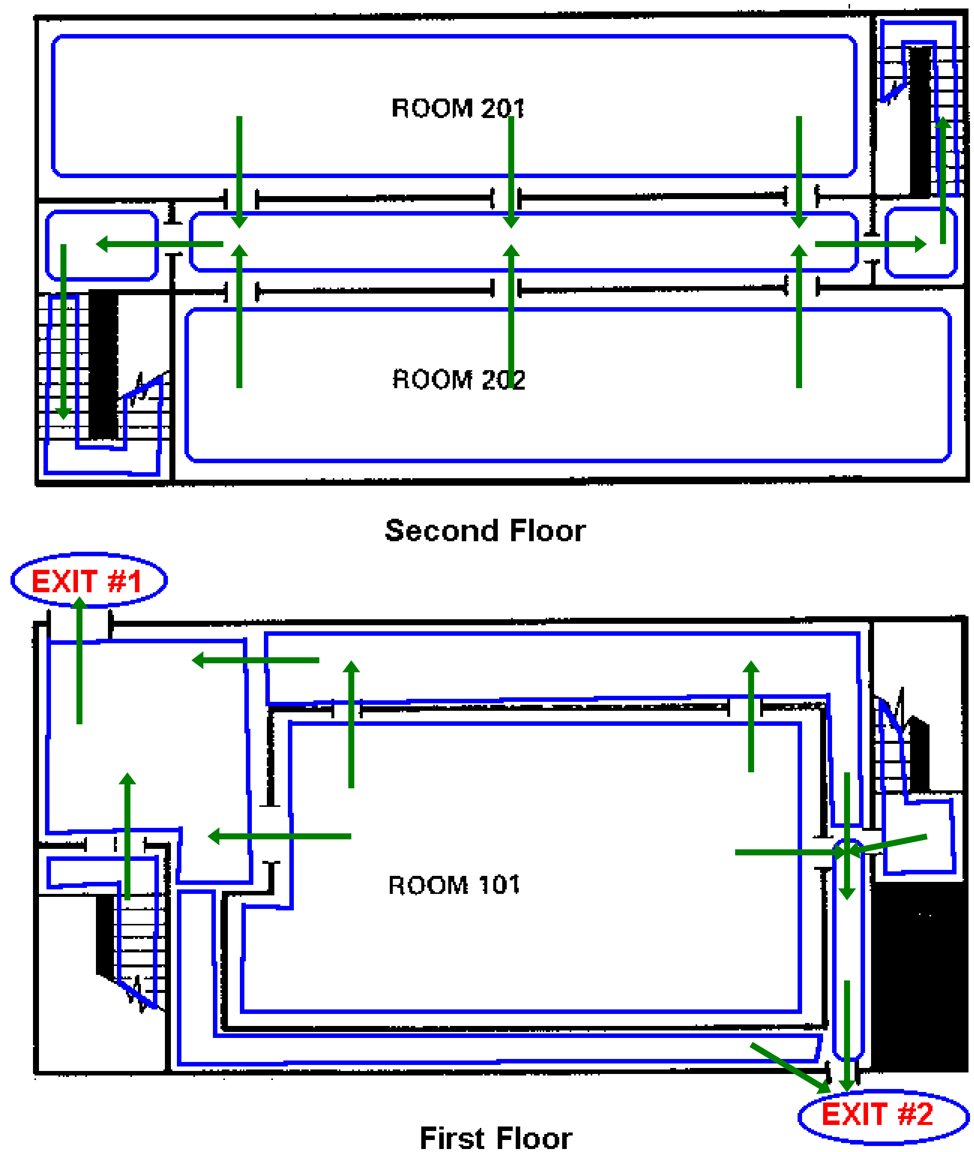
Example 2: Node and Edge Definition

Nodes:

Each room, hallway, staircase, etc.

Edges:

Each available link between two nodes.



Example 2: Initial State

- **Each node has:**

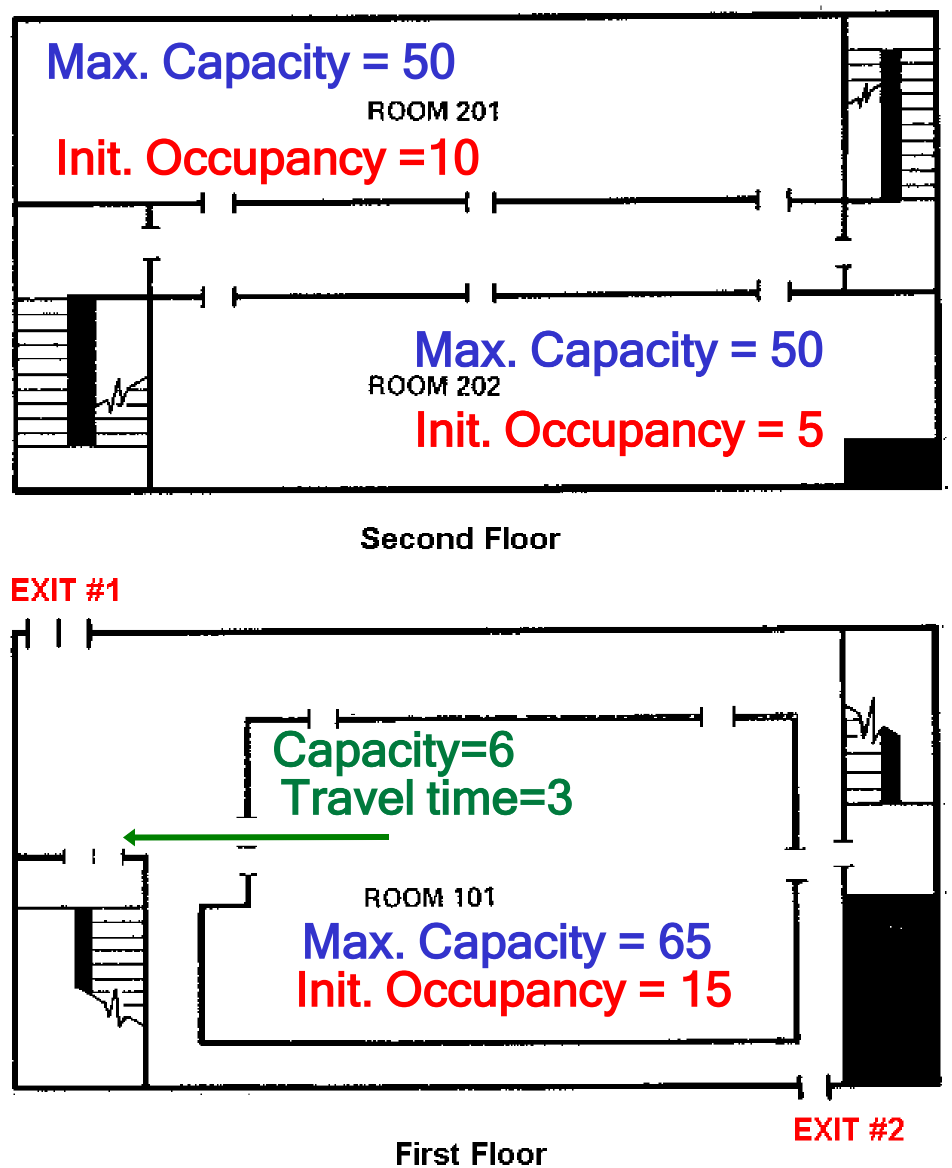
Maximum node capacity
(max. number of people the node can hold)

Initial node occupancy
(number of people at the node)

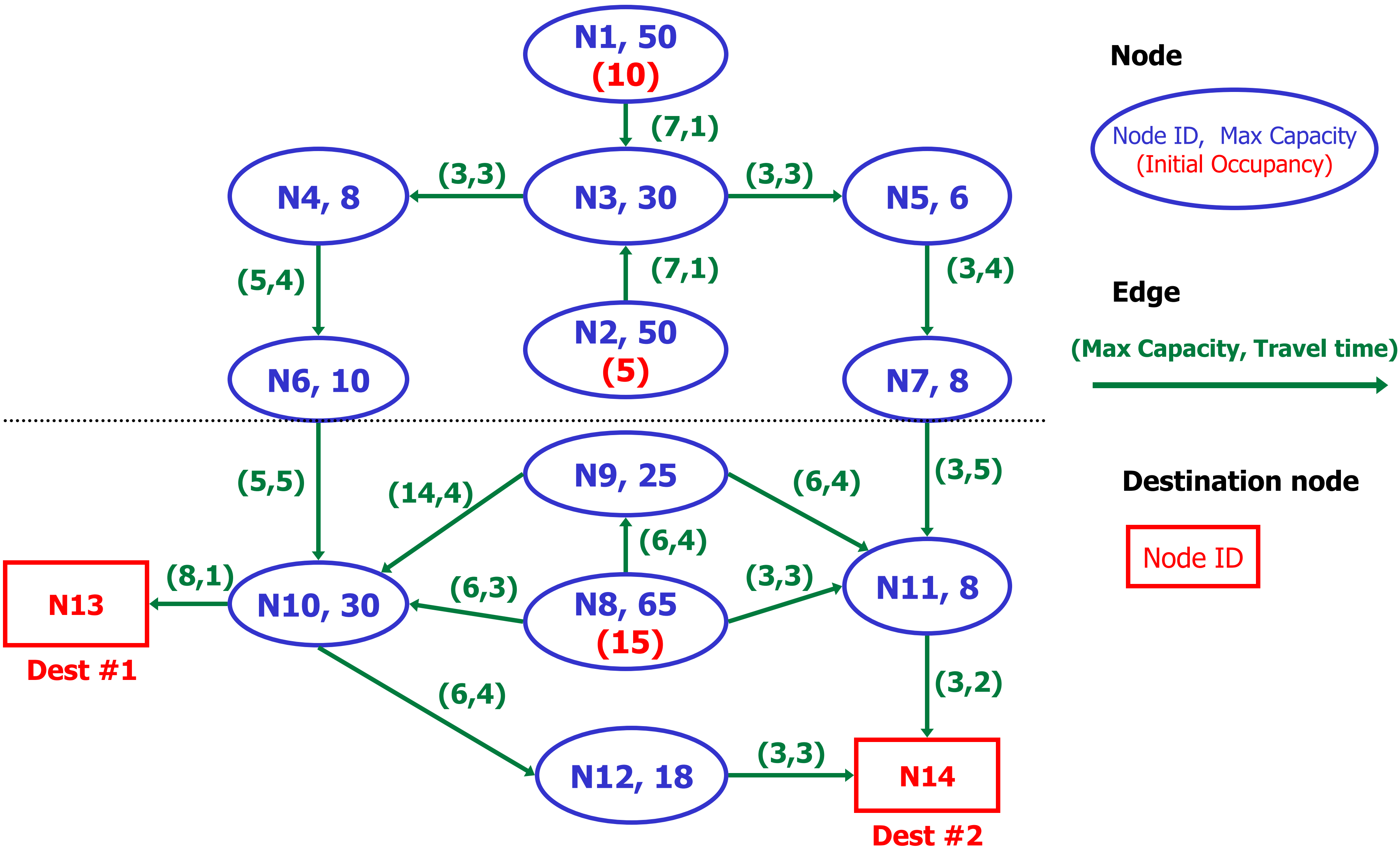
- **Each edge has:**

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



Example Output : Evacuation Plan & Schedule

Example Evacuation Plan:

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

Group of Evacuee			Route with Schedule	Dest. Time
ID	Source	No. of Evacuees		
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E	N1	3	N1(T0)-N3(T2)-N4(T5)-N6(T9)-N10(T14)-N13	15
F	N1	1	N1(T0)-N3(T1)-N5(T4)-N7(T8)-N11(T13)-N14	15
G	N2	2	N2(T0)-N3(T1)-N5(T4)-N7(T8)-N11(T13)-N14	15
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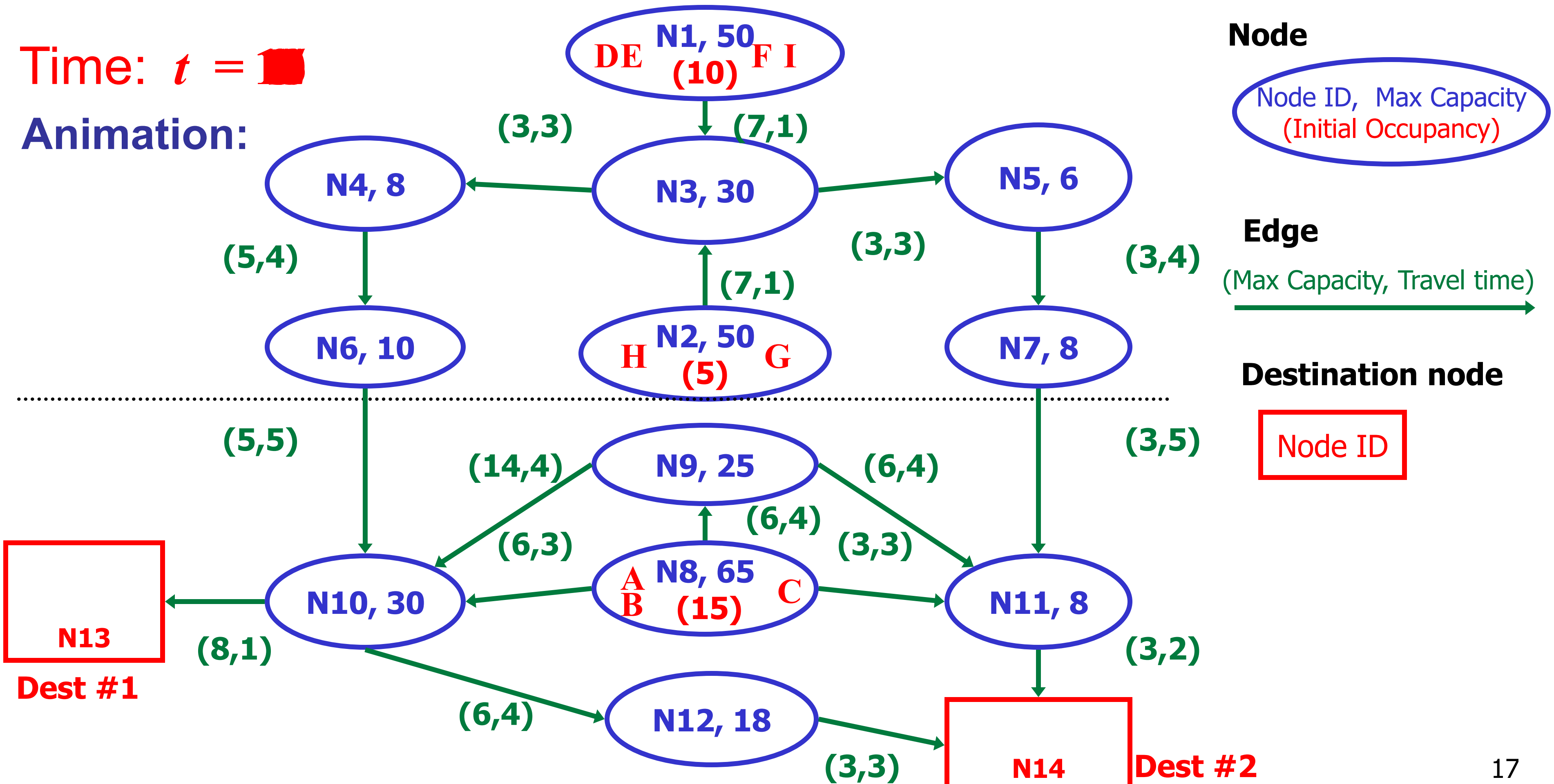
I	N1	3	N1(T1)-N3(T2)-N5(T5)-N7(T9)-N11(T14)-N14	16

Time: t =

Animation:



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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?
  - When to evacuate? Which routes? Modes? Shelters? Phased evacuation?
  - 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

OR = Population / (Bottleneck Capacity of Transport Network)

If (OR <=1)

{ shortest path algorithms, e.g. A* }

Else if (OR → infinity)

{ Min-cut max-flow problem }

Else { Computationally hard problem ! }

B. Spatio-temporal Networks

- Violate stationary assumption
  - behind shortest path algorithms, e.g. A*, Dijktra'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-ignorant Approach

- Simple shortest path computation, e.g. A*, Dijktra'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!

Number of Nodes	50	500	5,000	50,000
EVACNET Running Time	0.1 min	2.5 min	108 min	> 5 days

C. Transportation Science: Dynamic Traffic Assignment

- Game Theory: Wardrop Equilibrium, e.g. DYNASMART (FHWA), DYNAMIT(MIT)

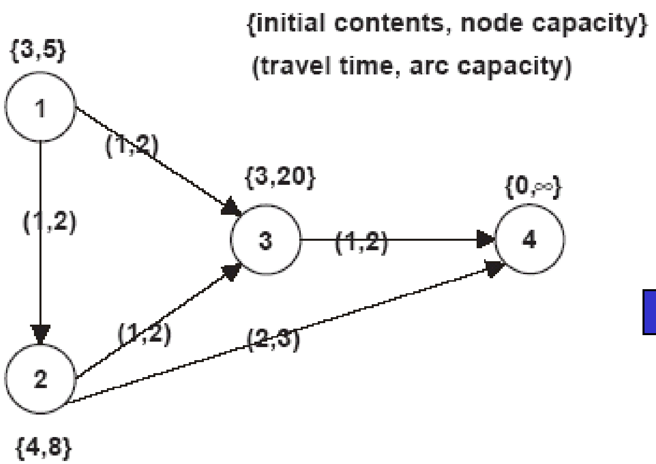
Limitation: Extremely high compute time

- Is Evacuation an equilibrium phenomena?

Time Expanded Graph

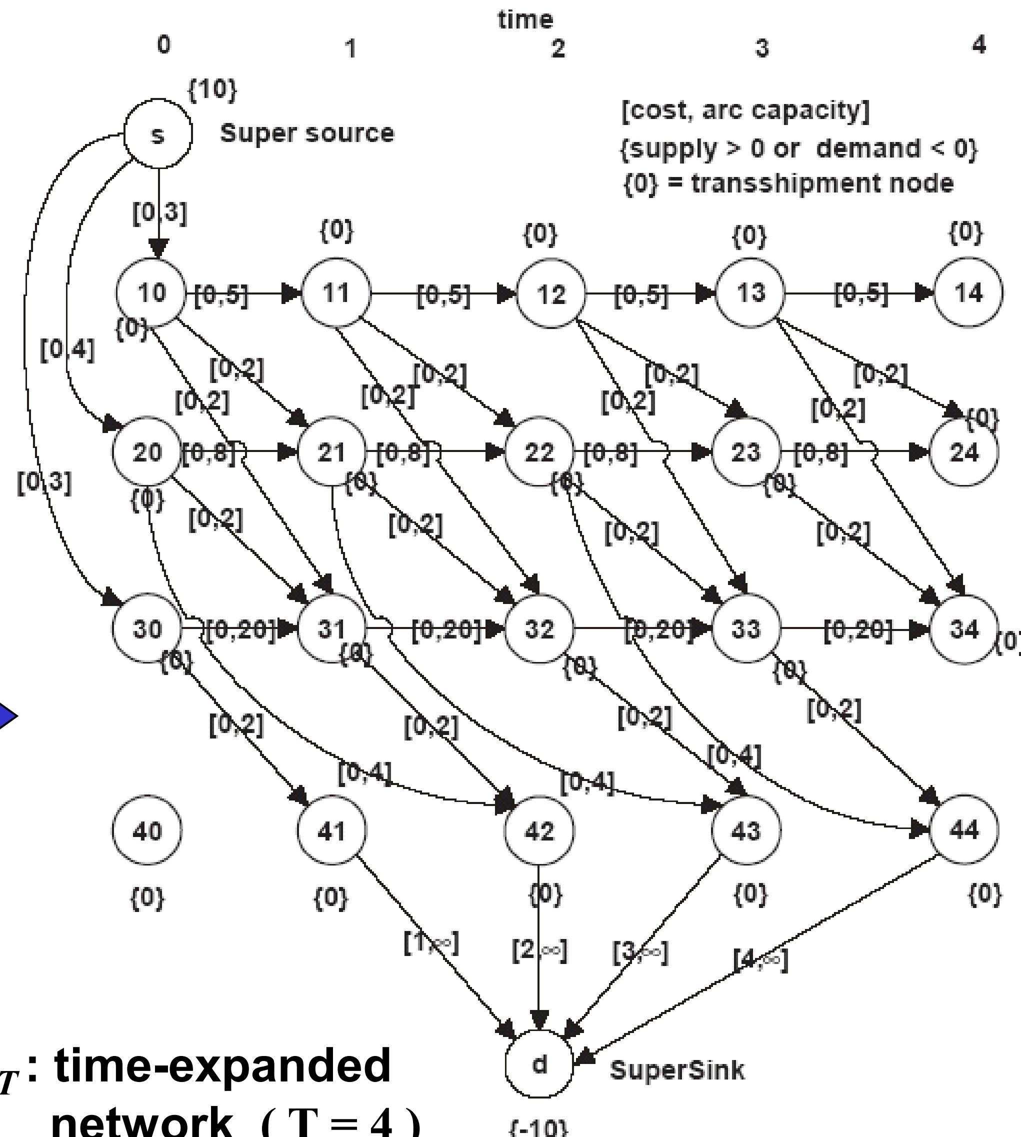
Step 1:

Convert evacuation network G into time-expanded network G_T with user provided time upper bound $\mathbf{T}$.



G : evacuation network

with n nodes ($n = 4$)



G_T : time-expanded network ($\mathbf{T} = 4$)

with $\mathbf{N} = n(\mathbf{T}+1)$ nodes ($\mathbf{N} = 20$)

(Source : H. Hamacher and S. Tjandra, "Mathematical Modeling of Evacuation Problems: A State of the Art". *Pedestrian and Evacuation Dynamics*, pp. 227-266, 2002.)

Linear Programming (2/3)

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 :

$$
\begin{aligned}
\min \quad & \sum_{t=0}^{T} \sum_{i \in D} t x_{id}(t) && \text{(minimize total evacuation time of all evacuees)} \\
x_{si}(0) &= q_i, \forall i \in S, && \text{(initial occupancy at source nodes at time } \mathbf{0}\text{)} \\
\sum_{t=0}^{T} \sum_{i \in D} x_{id}(t) &= \sum_{j \in S} q_j, && \text{(all evacuees reach destination nodes by time } \mathbf{T}\text{)} \\
y_i(t+1) - y_i(t) &= \sum_{k \in pred(i)} x_{ki}(t - \lambda_{ki}) - \sum_{j \in succ(i)} x_{ij}(t), \\
& \quad t = 0, \ldots, T; \; \forall i \in N \\
y_i(0) &= 0, \forall i \in N, \\
y_i(t) &= 0, \forall i \in D; t = 0, \ldots, T \\
0 \le y_i(t) &\le a_i, t = 1, \ldots, T; i \in N - D \\
0 \le x_{ij}(t) &\le b_{ij}, t = 0, \ldots, T - \lambda_{ij}; \forall (ij) \in A
\end{aligned}
$$

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].

Selected Insights ... (3/3)

- 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

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Representation Challenge: Time-varying Networks

Static	Time-Variant
Which is the shortest travel time path from downtown Minneapolis to airport?	Which is the shortest travel time path from downtown Minneapolis to airport at different times of a work day?
What is the capacity of Twin-Cities freeway network to evacuate downtown Minneapolis ?	What is the capacity of Twin-Cities freeway network to evacuate downtown Minneapolis at different times in a work day?

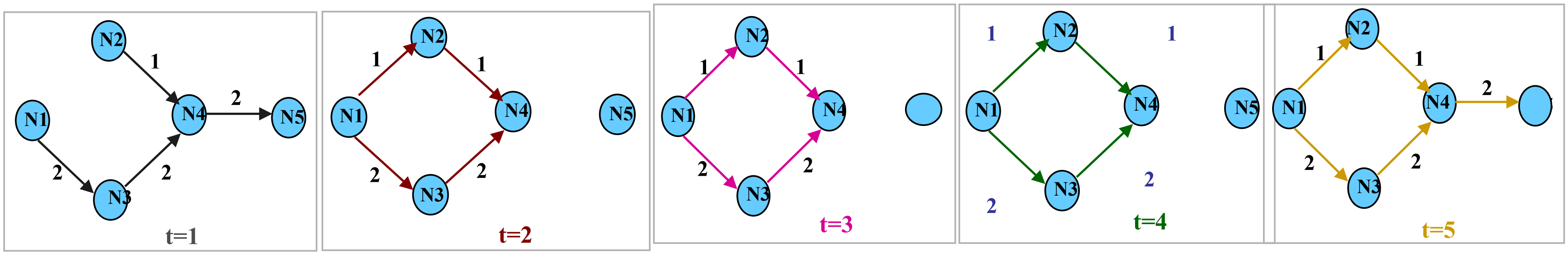
"U.P.S. Embraces High-Tech Delivery Methods - (*by Claudia Deutsch)*
The research at U.P.S. is paying off. Last year, it cut 28 million miles from truck routes — saving roughly three million gallons of fuel — in good part by *mapping routes that minimize left turns*"
- *New York Times* (July 12, 2007)

Representations of (Spatio-)temporal Networks

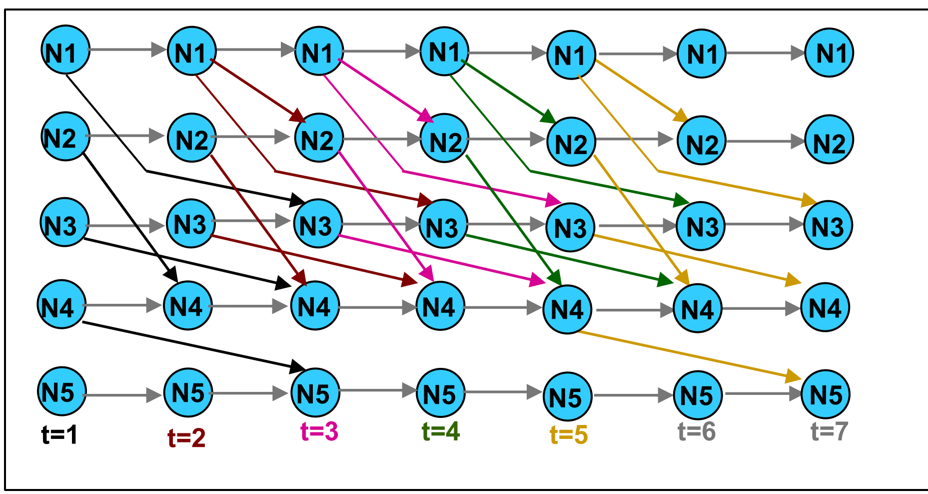
(1) Snapshot Model [Guting 04]

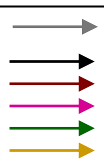
Node: 

Edge: 



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



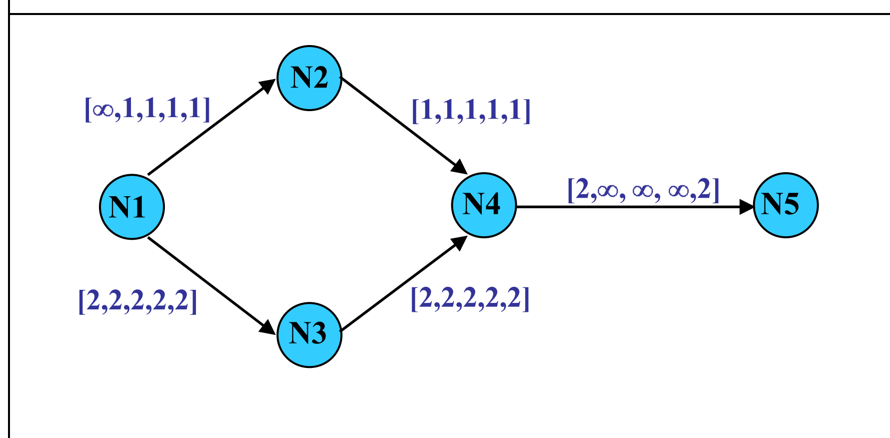


Holdover Edge

Transfer Edges

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

¤ Attributes aggregated over edges and nodes.



Edge $[m_1,\ldots,(m_T]$ → m_i- travel time at t=i

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TAG vs. TEG: Theoretical Storage Cost Comparison

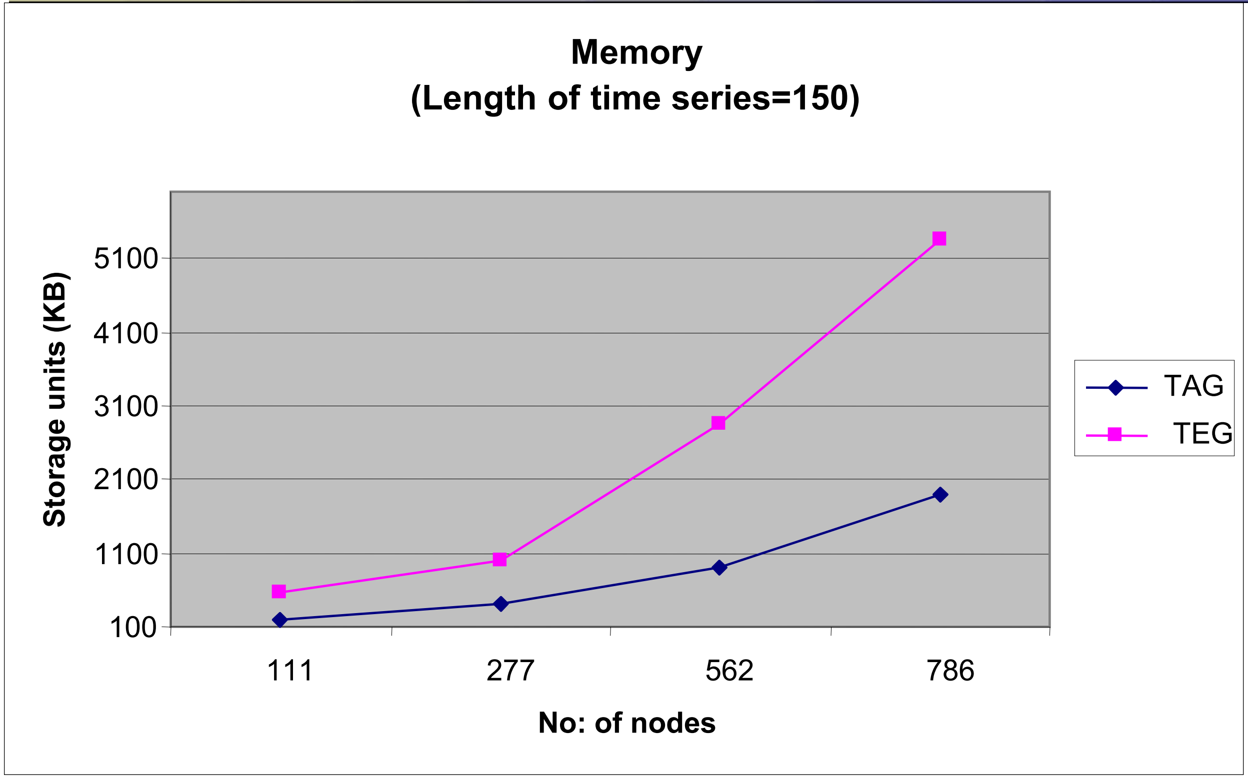
- Intuitively storage_cost(TAG) < storage_cost (TEG),
  (a) TAG does not replicate nodes and edges
  (b) TAG can use time-series compression when
  any property is invariant for some time-intervals

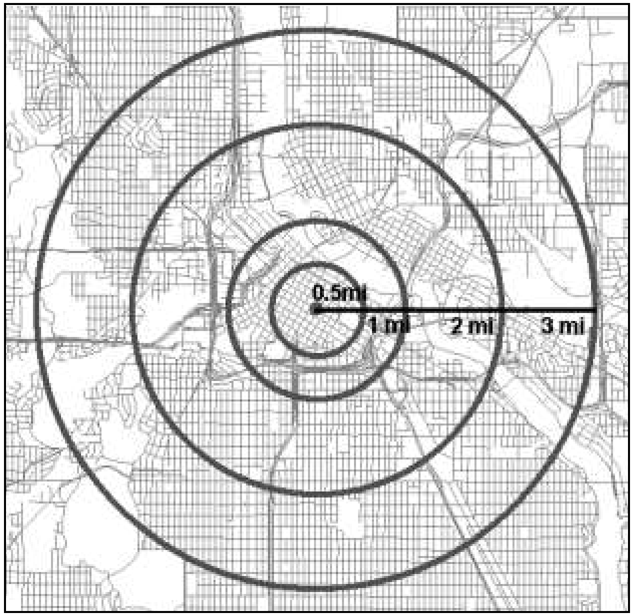
- Formally, if $k < (n+m+p)$ and $T >> 1$.
  - Storage cost (TEG) = $O(nT + mT) + O(pT)$
  - Storage cost (TAG) = $O(n + m) + O(kT)$
  - Where n = number of nodes
    - m = number of edges
    - T = length of time-series
    - p = number of properties
    - k = (eqv.) number of static properties <= p

(*) All edge and node parameters might not display time-dependence.

(**) D. Sawitski, Implicit Maximization of Flows over Time, Technical Report (R:01276), University of Dortmund, 2004.

TAG vs. TEG: Storage Cost Comparison





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

Trend: TAG better than TEG
on storage overhead!

Dataset	# Nodes	# Edges
(MPLS -1/2)	111	287
(MPLS -1 mi)	277	674
(MPLS - 2 mi)	562	1443
(MPLS - 3 mi)	786	2106

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 Constrained Route Planning (CCRP)

- Time-series attributes

  ***Available_Node_Capacity* (*Ni* , *t*)**

  = *#additional evacuees that can stay at* node *Ni* at time *t*

  ***Available_Edge_Capacity* (*Ni* -*Nj* , *t*)**

  = #additional evacuess that may travel via edge *Ni* -*Nj* 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 { number of current evacuees at S ,**
Available_Edge_Capacity**(any edges on R),**
Available_Node_Capacity**(any nodes on R) }**

Step 3: Make reservation of capacity on route ***R***

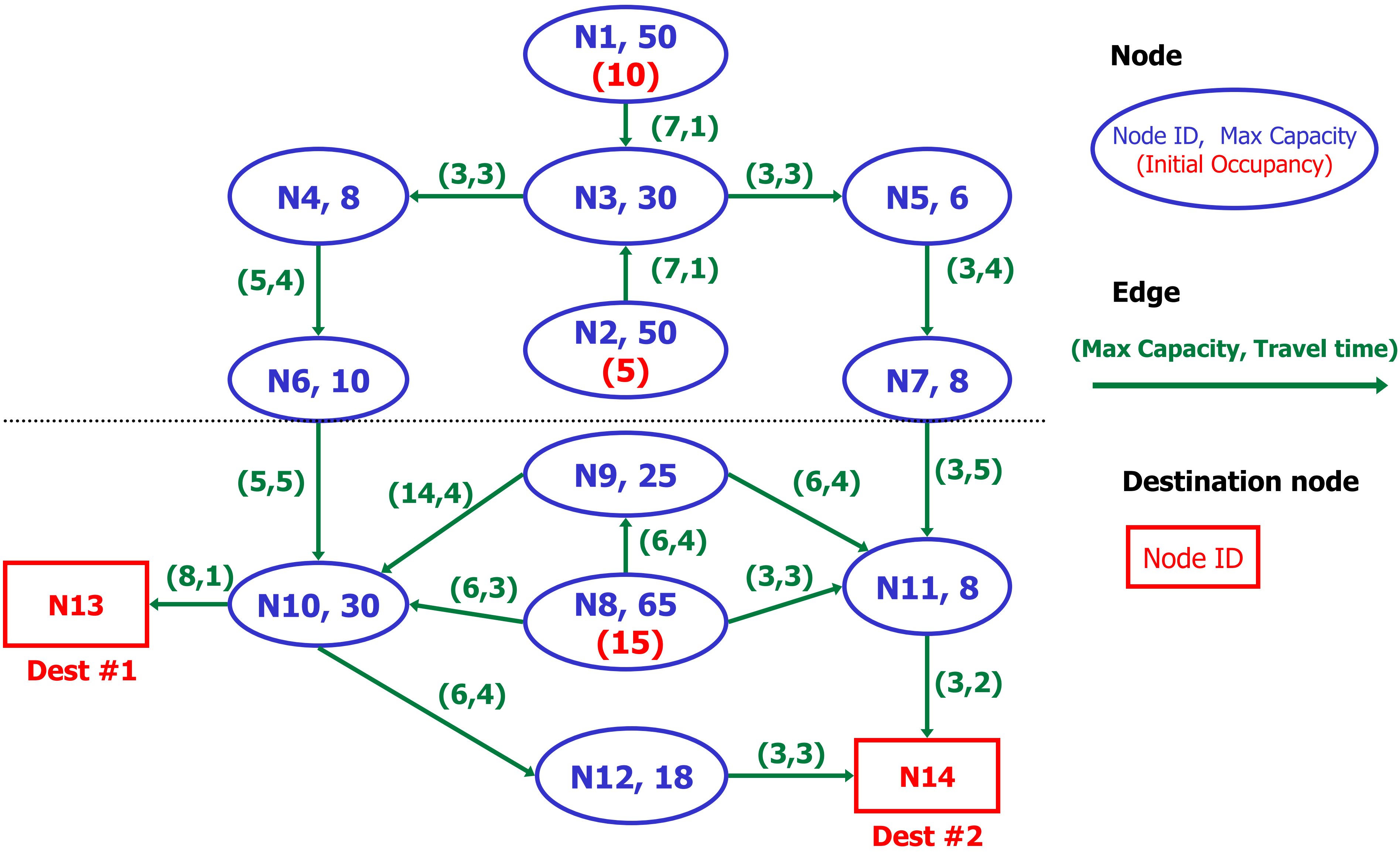
Available capacity of each edge on *R* reduced by *flow*

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



CCRP Execution Trace

Iteration: 1

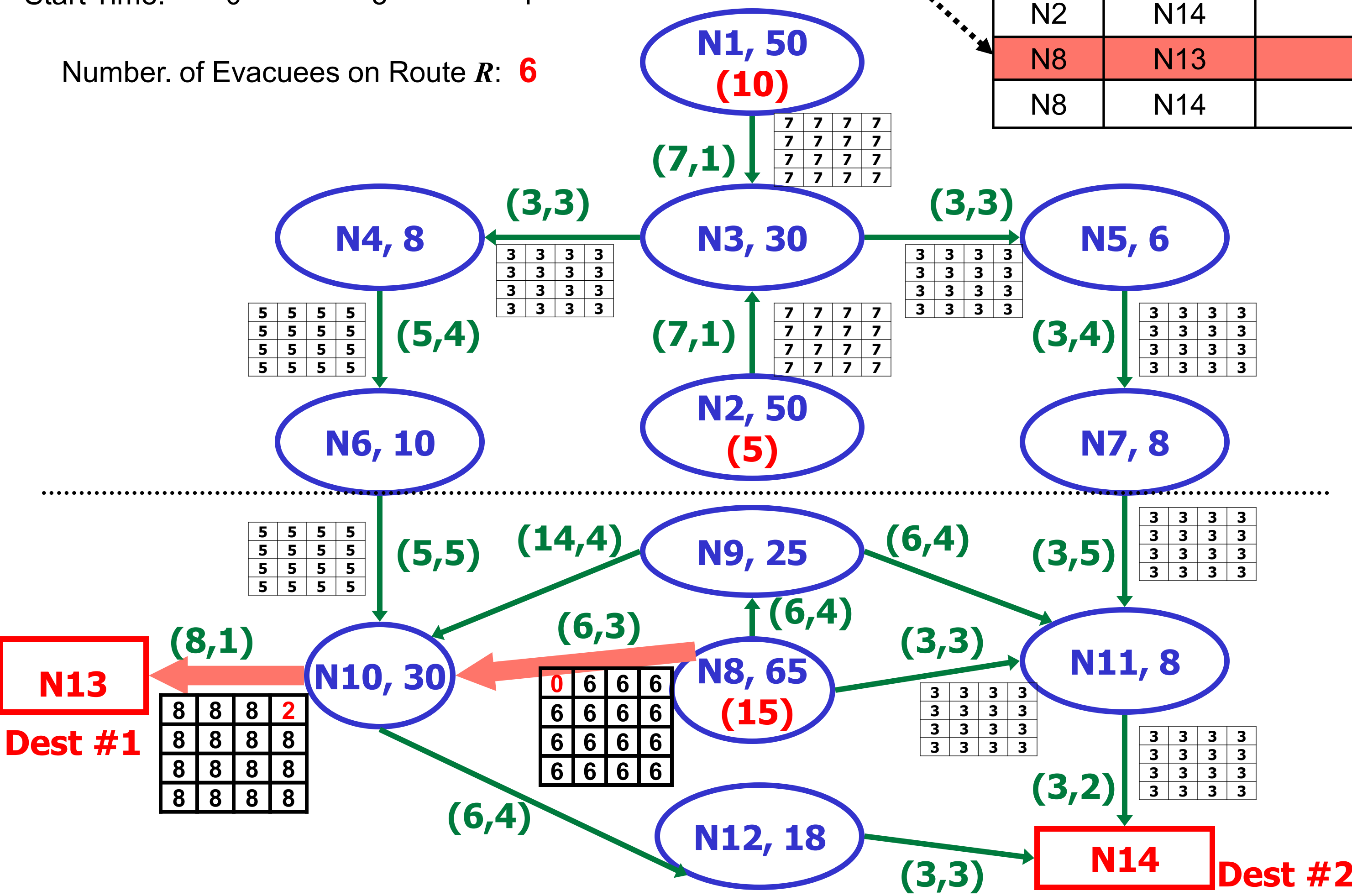
R : (route with earliest destination arrival time)

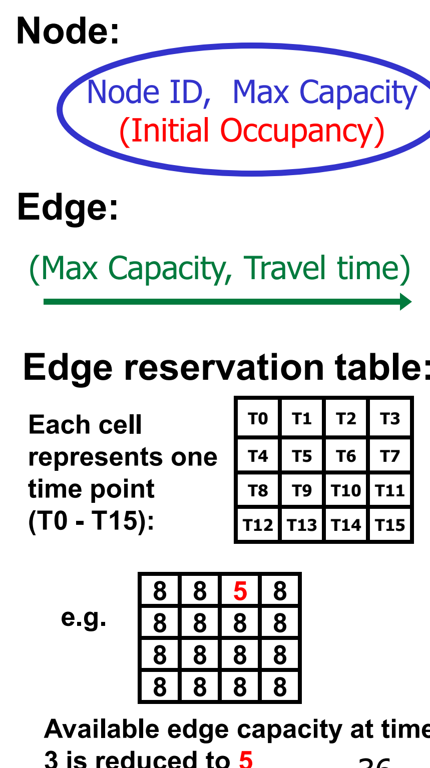
Node:	N8	→	N10	→	N13
Start Time:	0		3		4

Number. of Evacuees on Route ***R***: **6**

Quickest route between source/destination pair:

Source	Destination	Dest. Arrival Time	No. of Evacuees
N1	N13	14	3
N1	N14	15	3
N2	N13	14	3
N2	N14	15	3
N8	N13	4	6
N8	N14	5	3





CCRP Execution Trace

Iteration: 2

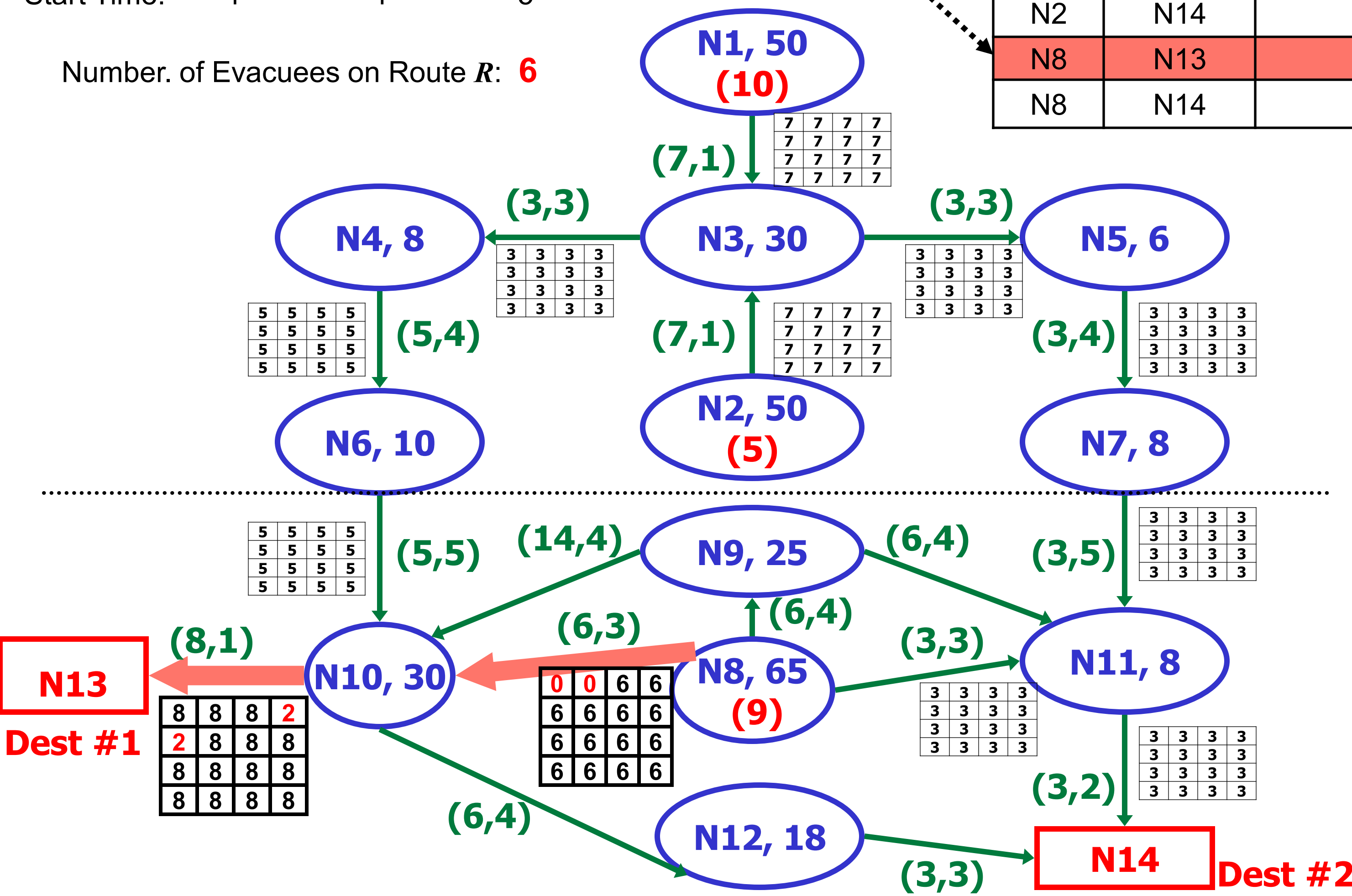
R : (route with earliest destination arrival time)

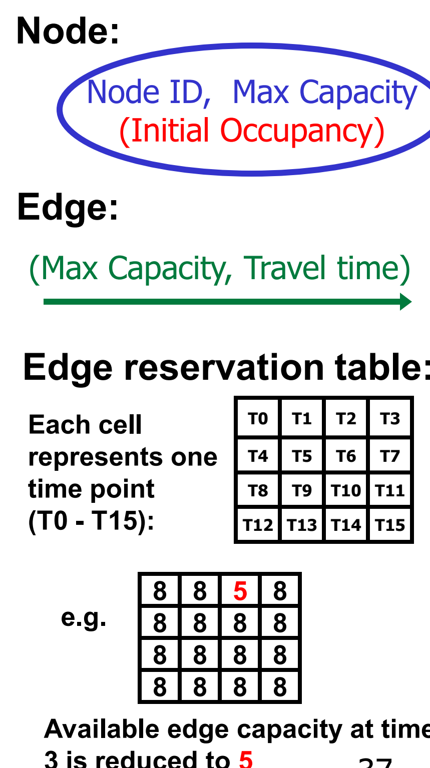
Node:	N8	→	N10	→	N13
Start Time:	1		4		5

Number. of Evacuees on Route *R*: **6**

Quickest route between source/destination pair:

Source	Destination	Dest. Arrival Time	No. of Evacuees
N1	N13	14	3
N1	N14	15	3
N2	N13	14	3
N2	N14	15	3
N8	N13	5	6
N8	N14	5	3





CCRP Execution Trace

Iteration: 3

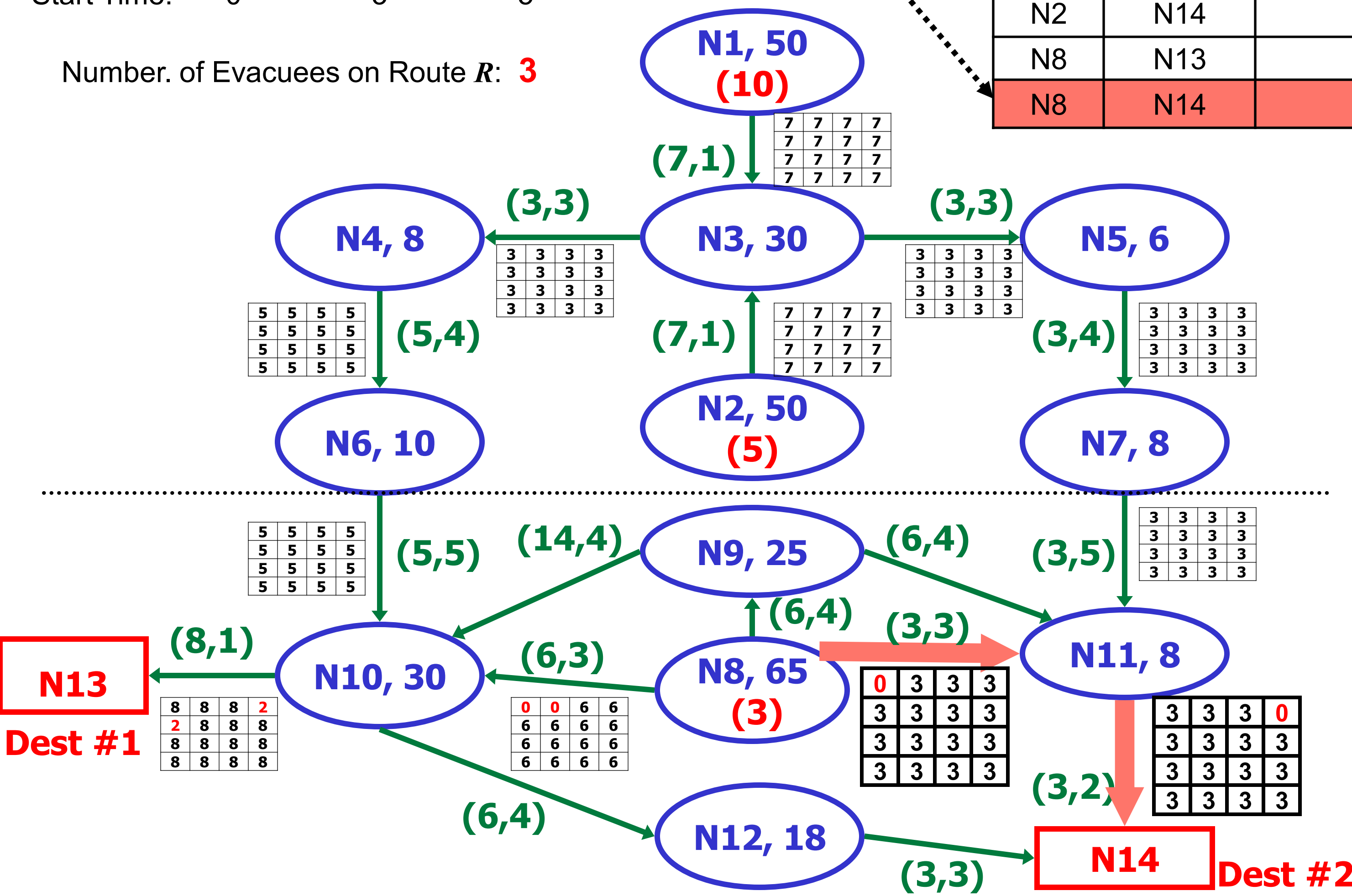
R : (route with earliest destination arrival time)

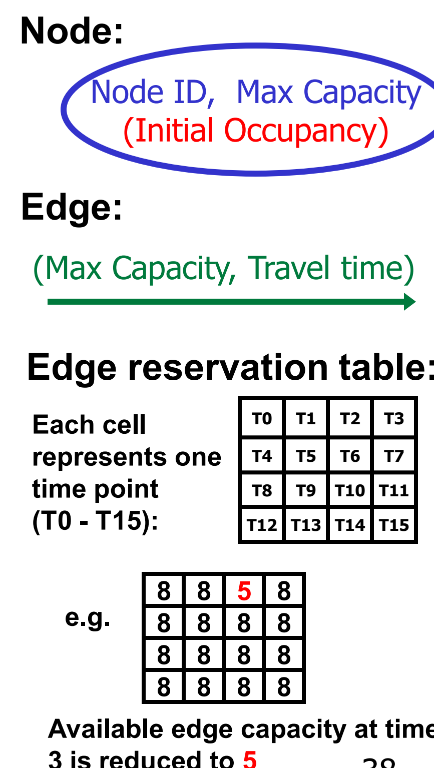
Node:	N8	N11	N14
Start Time:	0	3	5

Number. of Evacuees on Route *R*: **3**

Quickest route between source/destination pair:

Source	Destination	Dest. Arrival Time	No. of Evacuees
N1	N13	14	3
N1	N14	15	3
N2	N13	14	3
N2	N14	15	3
N8	N13	6	3
N8	N14	5	3





CCRP Execution Trace

Iteration: 4

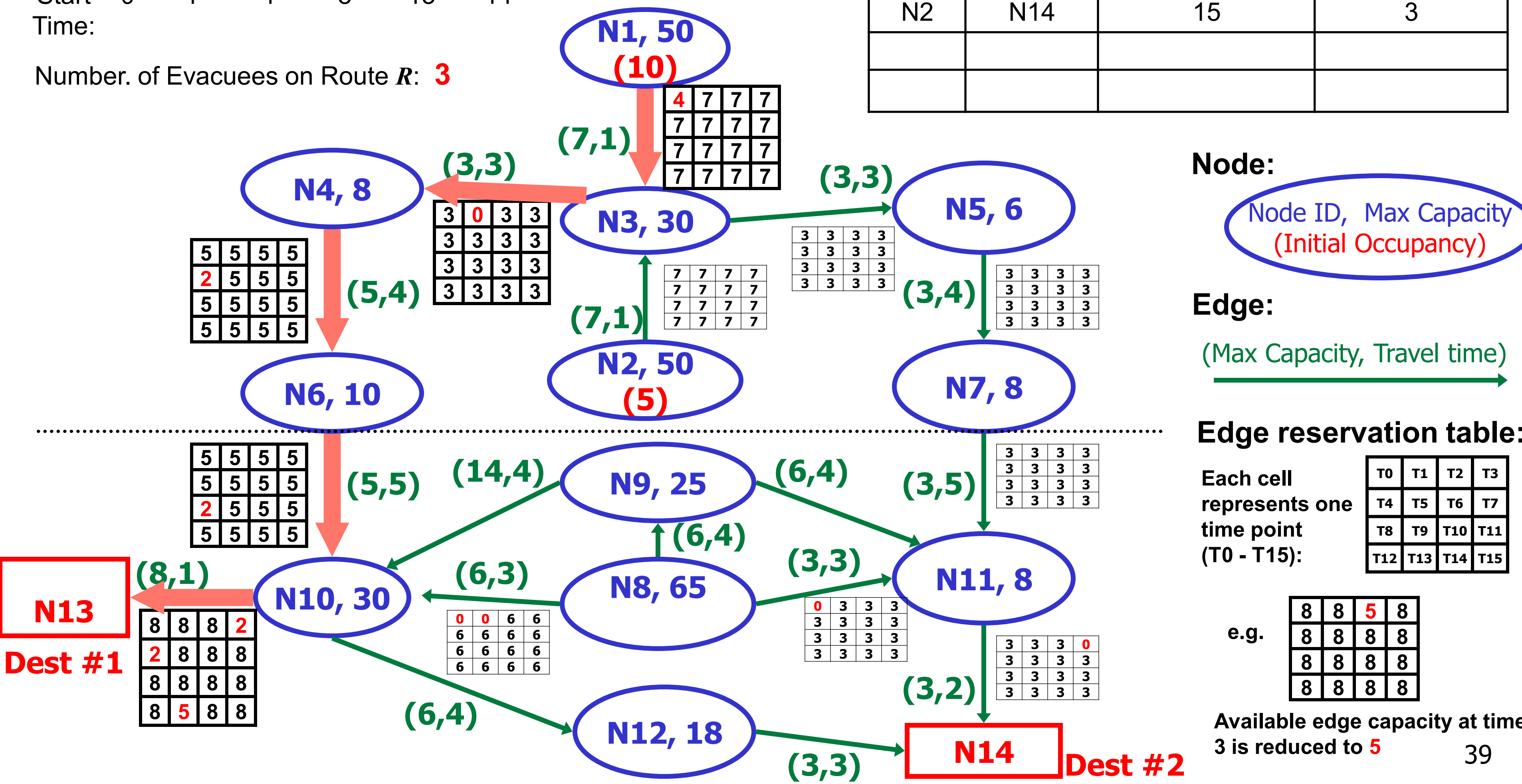
R : (route with earliest destination arrival time)

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:

Source	Destination	Dest. Arrival Time	No. of Evacuees
N1	N13	14	3
N1	N14	15	3
N2	N13	14	3
N2	N14	15	3



CCRP Execution Trace

Iteration: 5

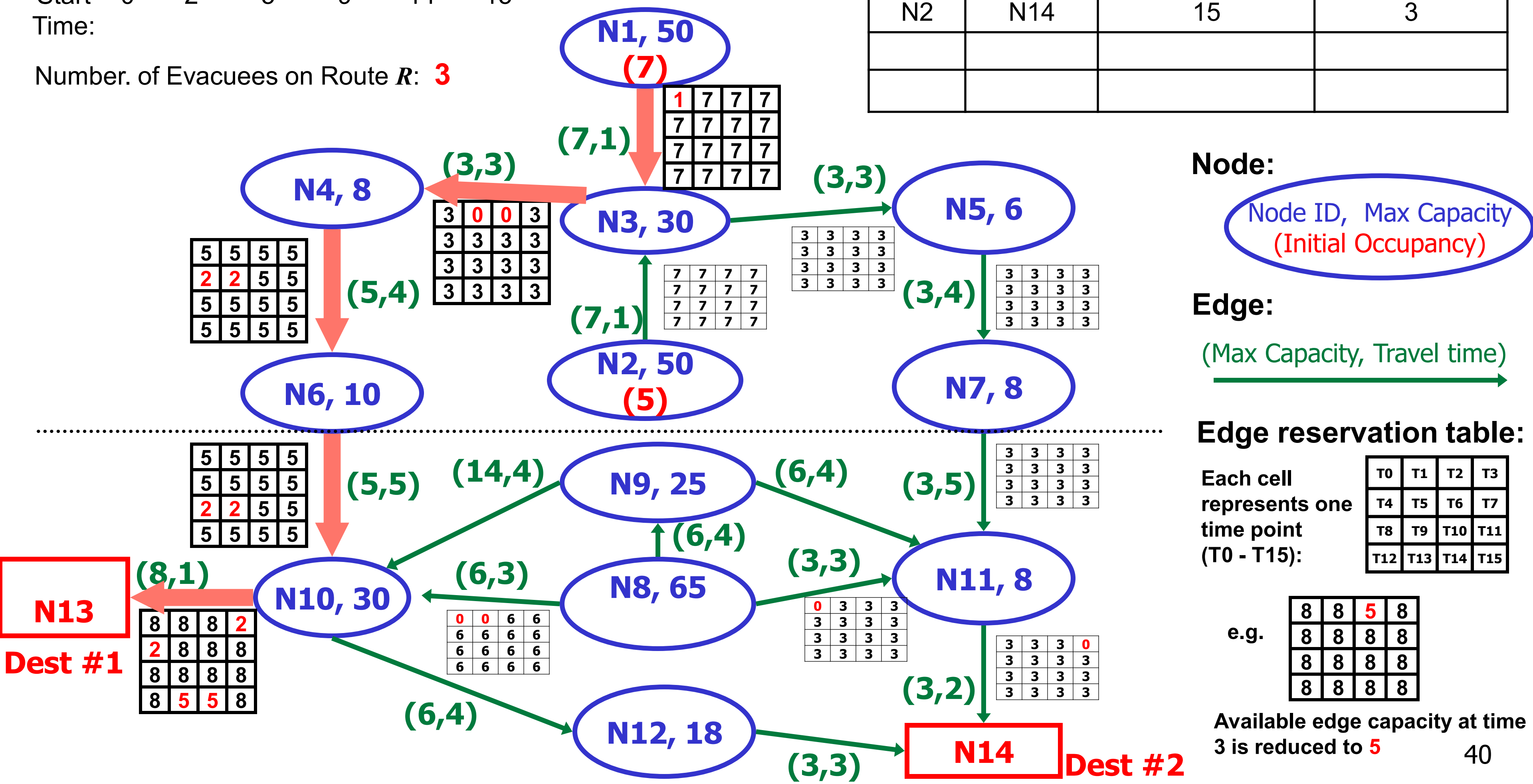
R : (route with earliest destination arrival time)

Node:	N8	N3	N4	N6	N10	N13
Start Time:	0	2	5	9	14	15

Number. of Evacuees on Route *R*: 3

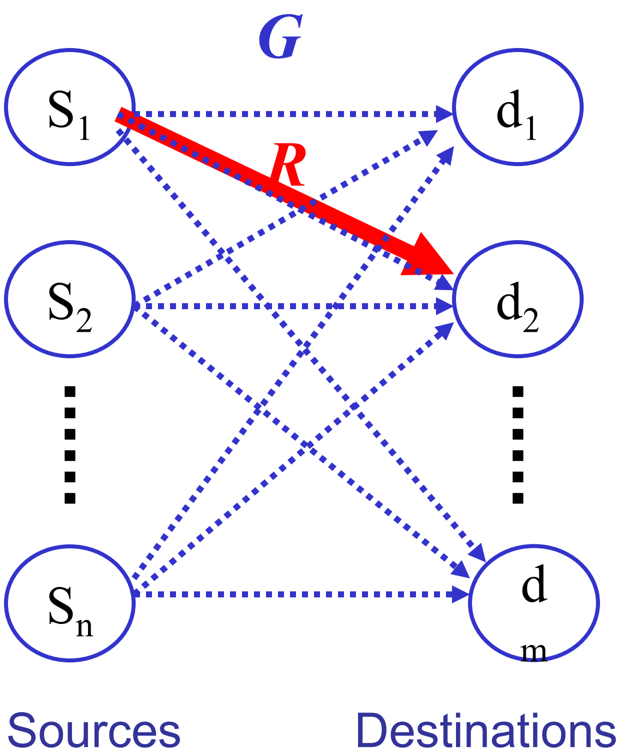
Quickest route between source/destination pair:

Source	Destination	Dest. Arrival Time	No. of Evacuees
N1	N13	15	3
N1	N14	15	3
N2	N13	15	3
N2	N14	15	3



Design Decision 1: Algorithm for Step 1 (1/2)

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



Three choices:

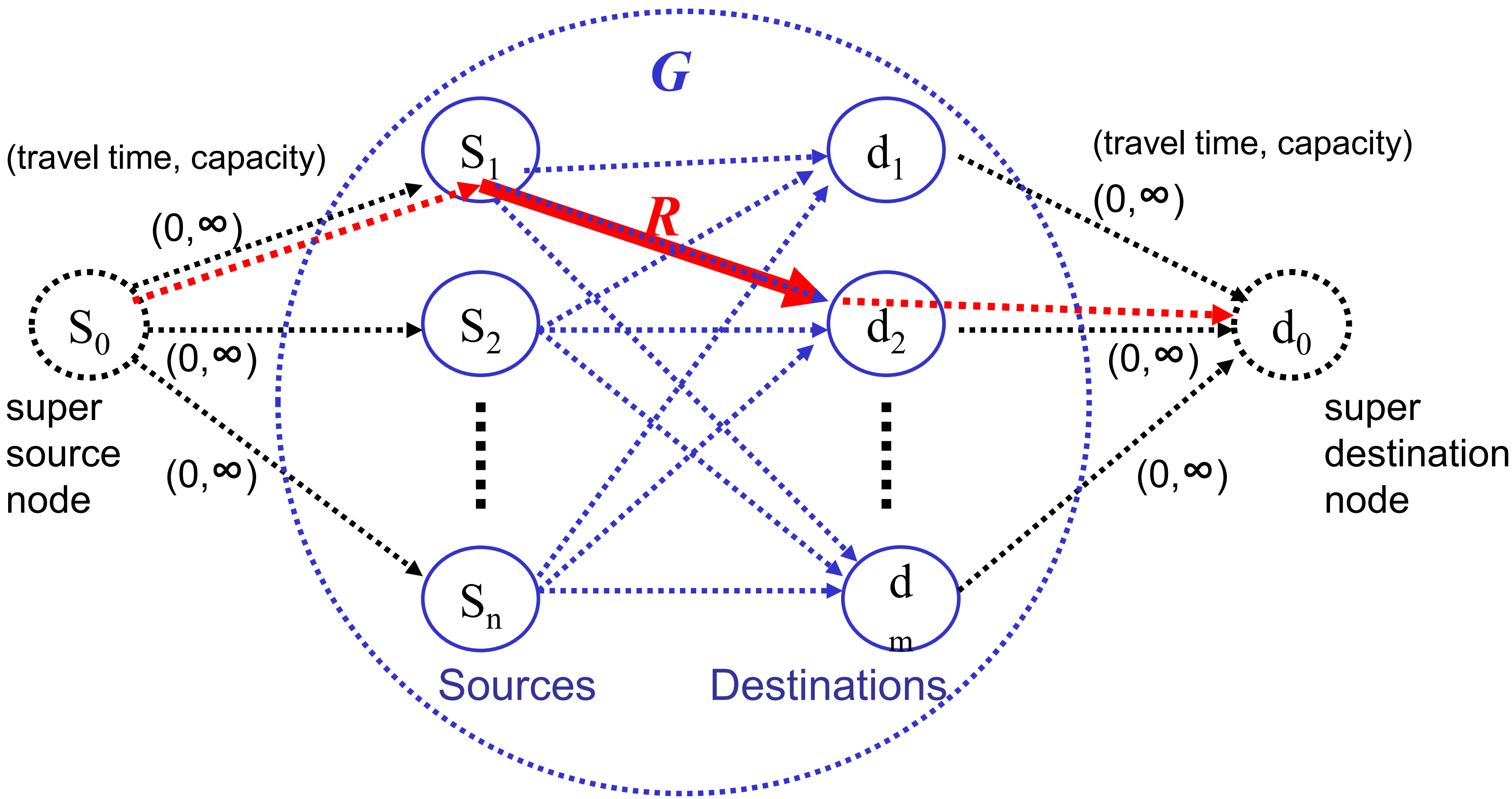
1. ***n*** x ***m*** single-source single-destination shortest path search: 1 per (S_i, d_j) pair.
2. ***n*** single-source all-destination shortest path search: 1 per source node.
3. One shortest path search:
   - Add super source node and super destination node to network.
   - One shortest path search from super source node to super destination node.

Choice: one shortest path search

Rationale: lower computational cost

Design Decision 1: Algorithm for Step 1 (2/2)

Finding Route ***R*** among routes between all (source, destination) pairs:



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].

2. A* search algorithm for shortest path: [Nilsson, 1980], [Goldberg, 2004].

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:
   $Maximum\_Node\_Capacity(n)$: non-negative integer
   $Initial\_Node\_Occupancy(n)$: non-negative integer
   Each edge $e \in E$ has two properties:
   $Maximum\_Edge\_Capacity(e)$: non-negative integer
   $Travel\_time(e)$: 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
  $Maximum\_Edge\_Capacity() = \infty$ and $Travel\_time() = 0$; (0)
while any source node $s \in S$ has evacuee do { (1)
  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;
    (2)
  $flow = \min($ number of evacuee still at source node s,
    $Available_Edge_Capacity($all edges on route $R)$,
    $Available_Node_Capacity($all nodes from n_1 to n_{k-1} on route $R)$,
  ); (3)
  for $i = 0$ to $k - 1$ do { (4)
    t =start time from node n_i on route R ; (5)
    $Available\_Edge\_Capacity(e_{n_i n_{i+1}}, t)$ reduced by $flow$; (6)
    $Available\_Node\_Capacity(n_{i+1}, t + Travel\_time(e_{n_i n_{i+1}}))$ reduced by $flow$; (7)
  } (8)
} (9)
Output evacuation plan; (10)

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): $O(m+nlogn)$

for sparse graphs (e.g. road network) : $m << nlogn$

Cost of Step 1: $O(nlogn)$

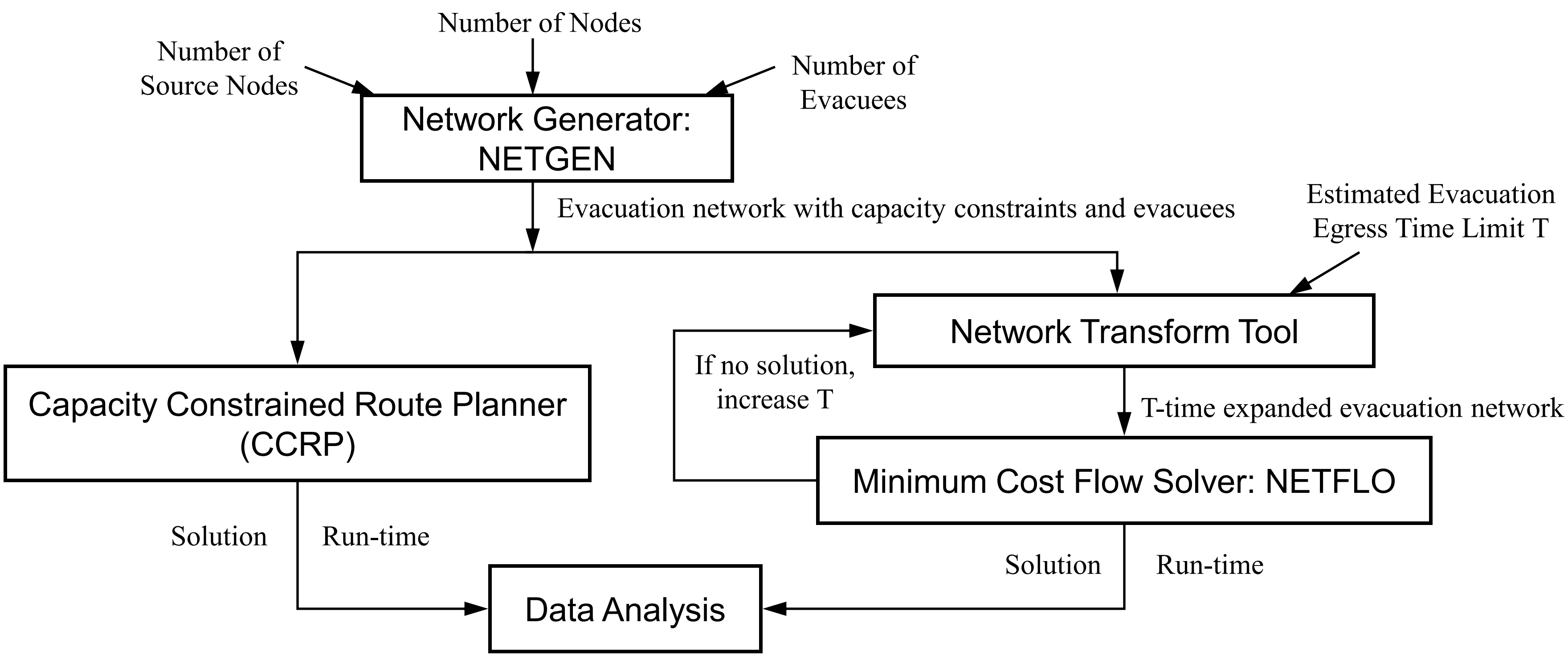
Step 2 - Compute flow amount on route R : $O(1)$

Step 3 - Make reservations on route R : $O(n)$

Step 1 is dominant.

CCRP cost model: $O(p \ nlogn)$

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.

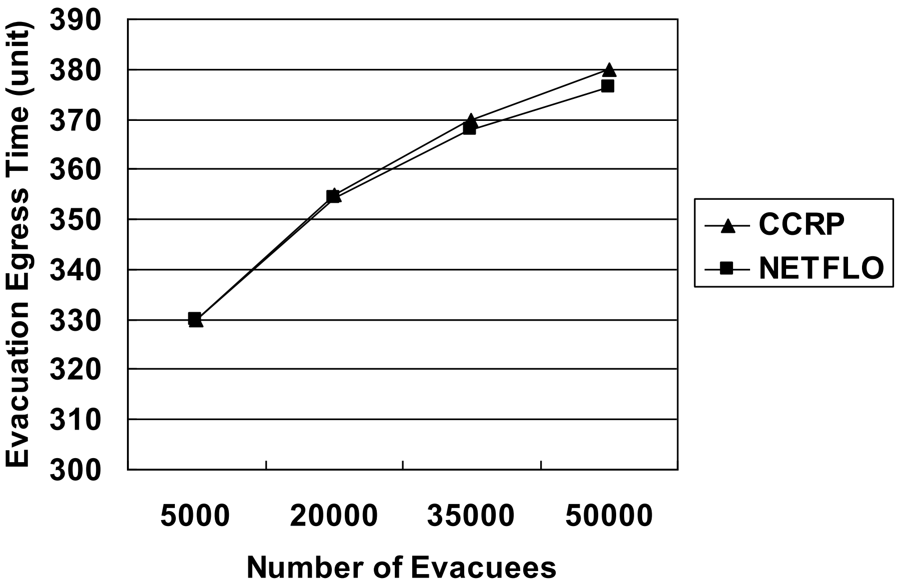


Figure 1 Quality of solution

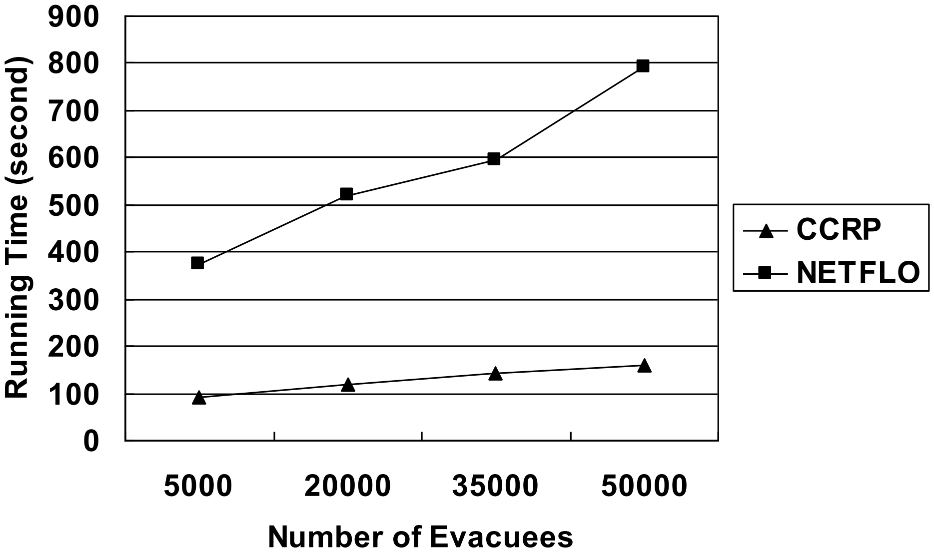


Figure 2 Run-time

- 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.

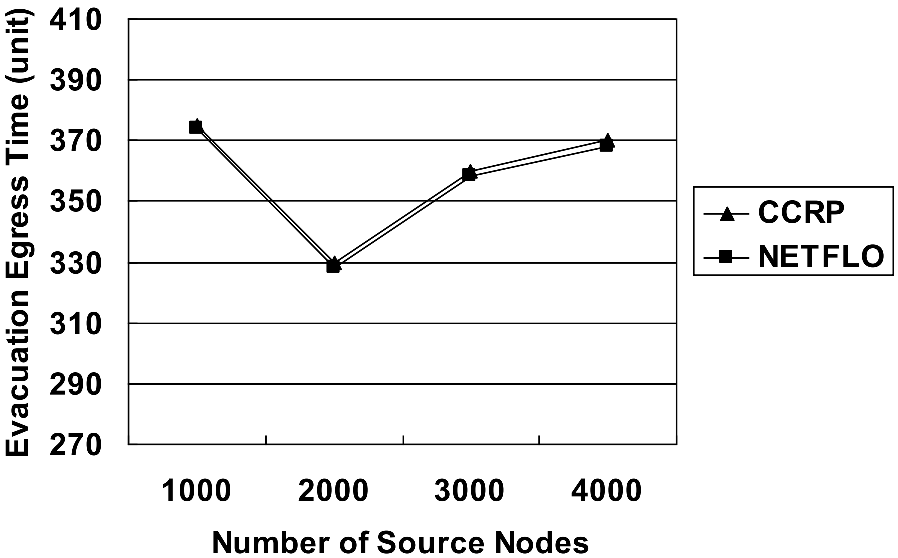


Figure 1 Quality of solution

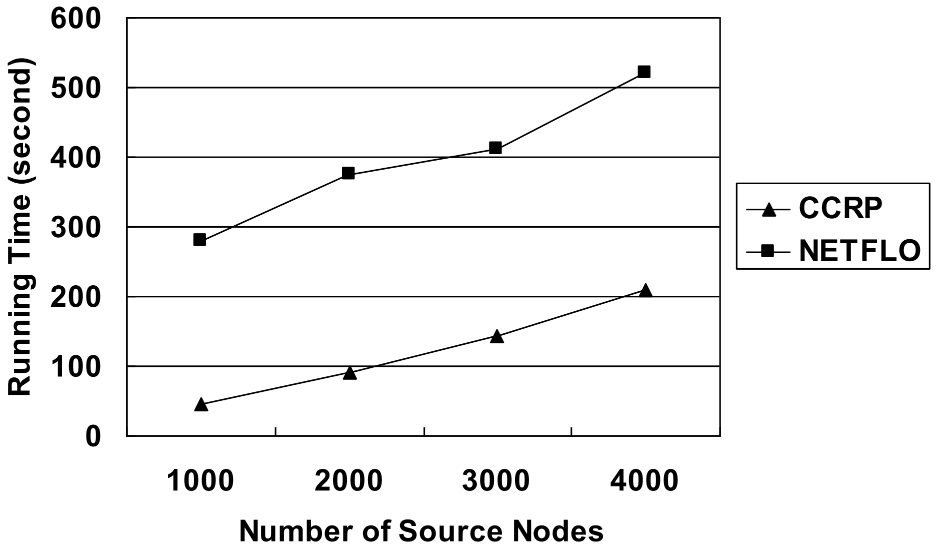


Figure 2 Run-time

- 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.

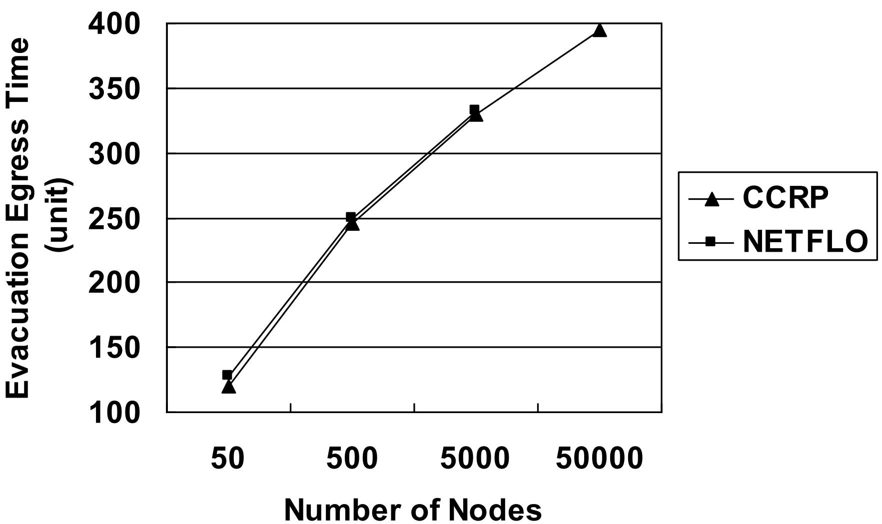
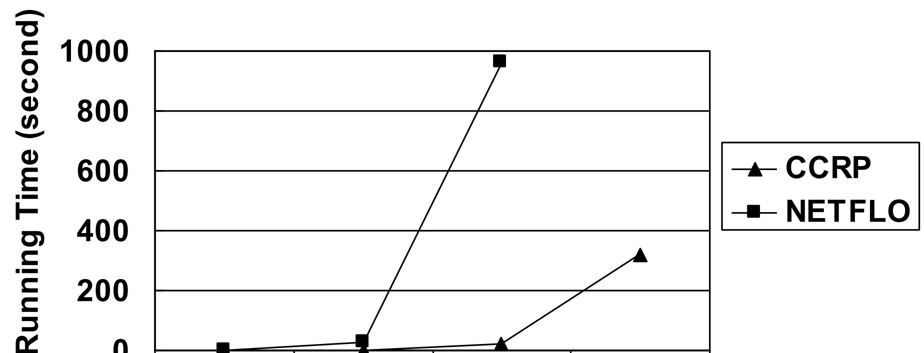


Figure 1 Quality of solution



	50	500	5000	50000
CCRP	0.1	1.5	23.1	316.4
NETFLO	0.3	25.5	962.2	

Number of Nodes

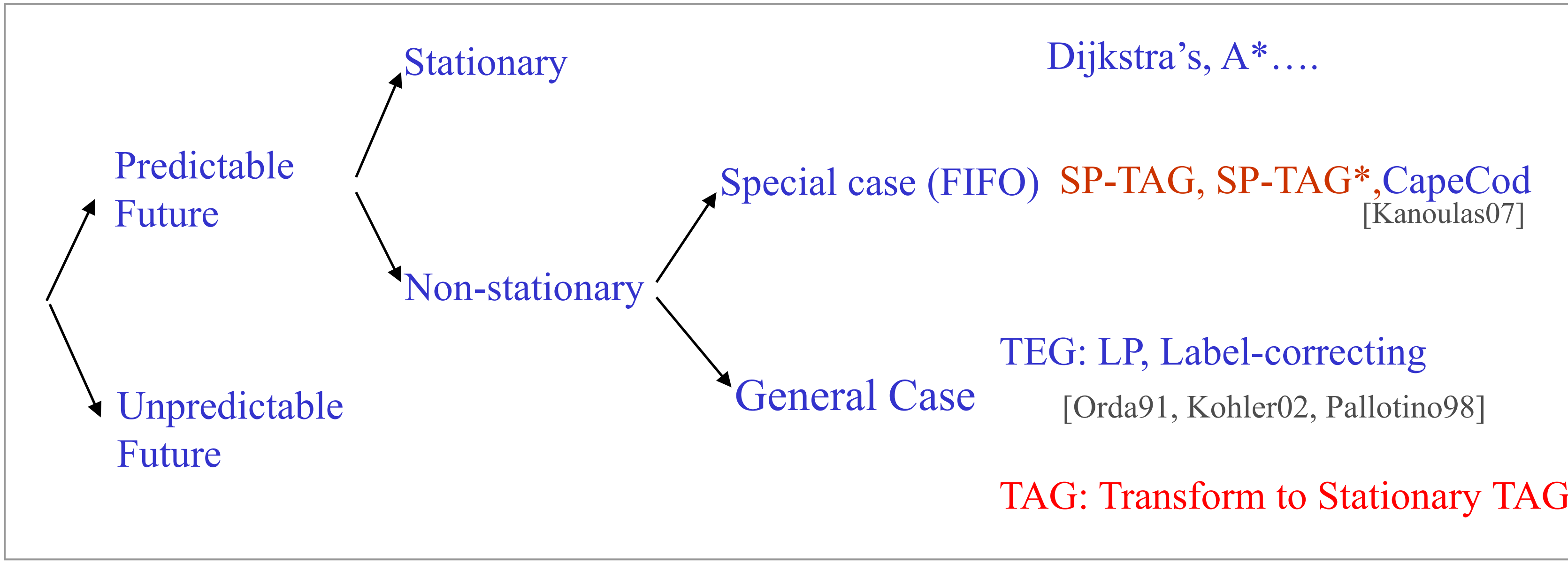
Figure 2 Run-time

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

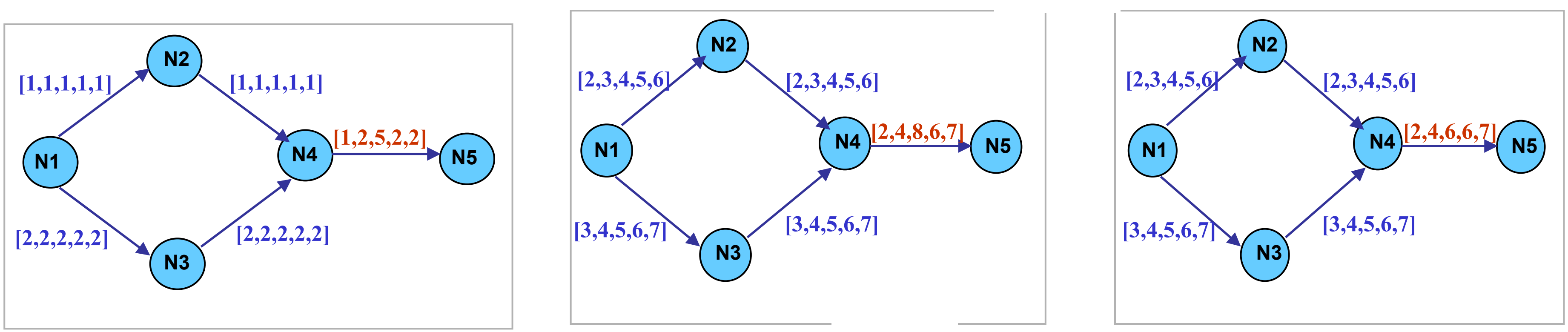
Outline

- 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



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



Non-stationary TAG → Stationary TAG

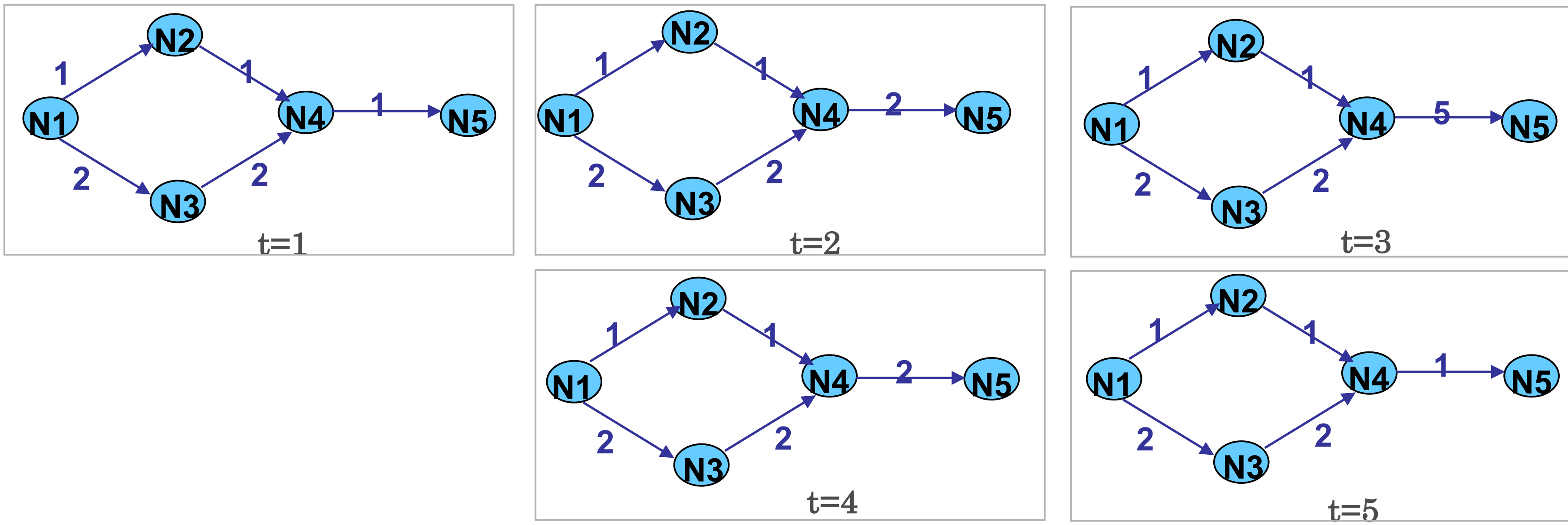
51

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.



	N1	N2	N3	N4	N5
1	~~1~~	∞	∞	∞	∞
2	1	~~2~~	3	∞	∞
3	1	2	~~3~~	3	∞
4	1	2	3	~~3~~	∞
5	1	2	3	3	8

Dijktra's: Reaches N5 at t=8.

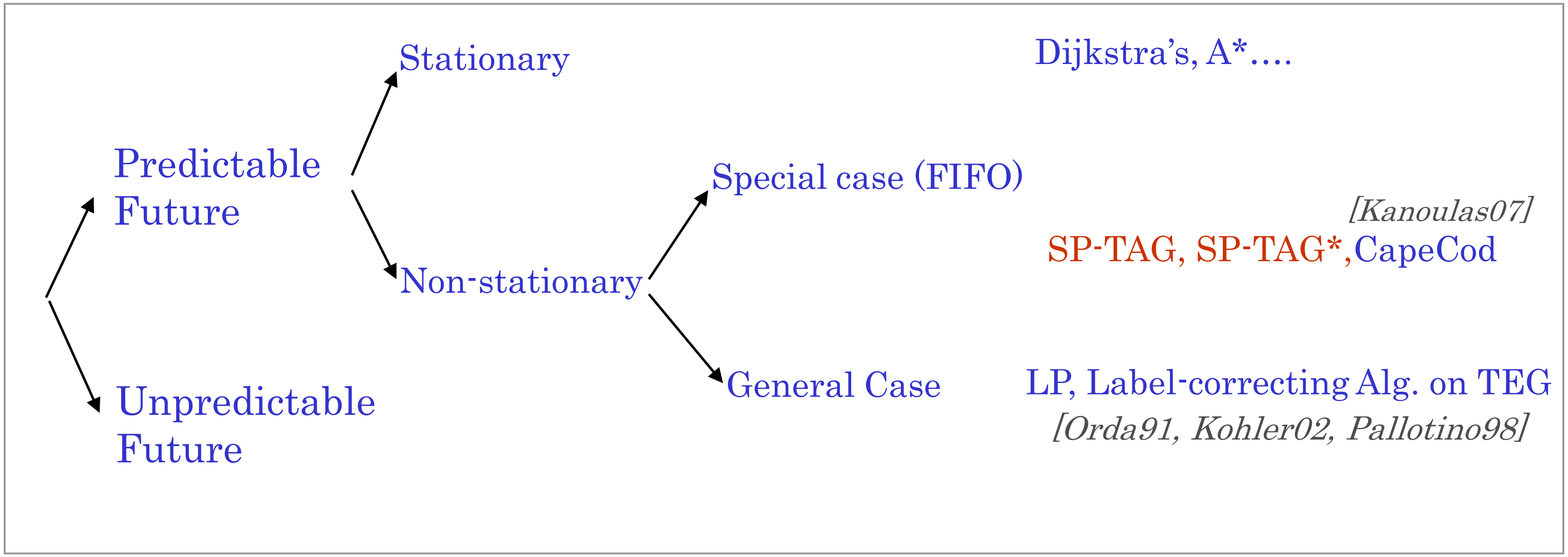
Total time = 7

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

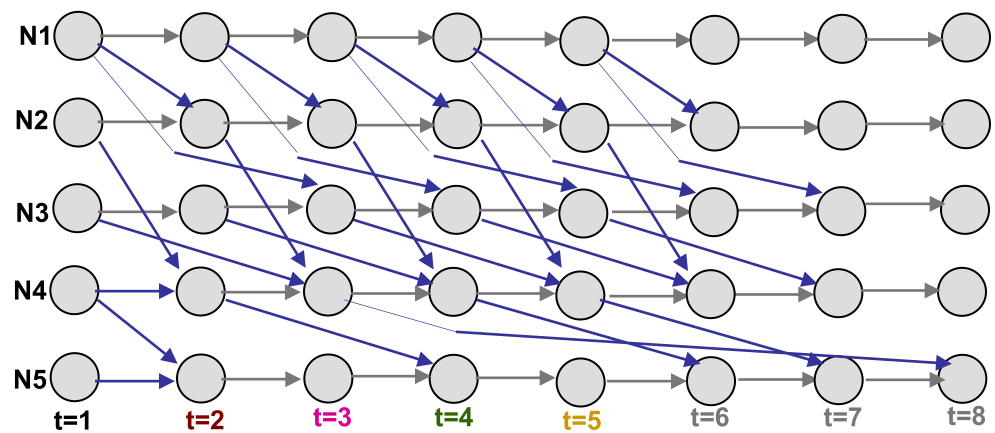
⋮

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($n^2T^3(n+m)$)]

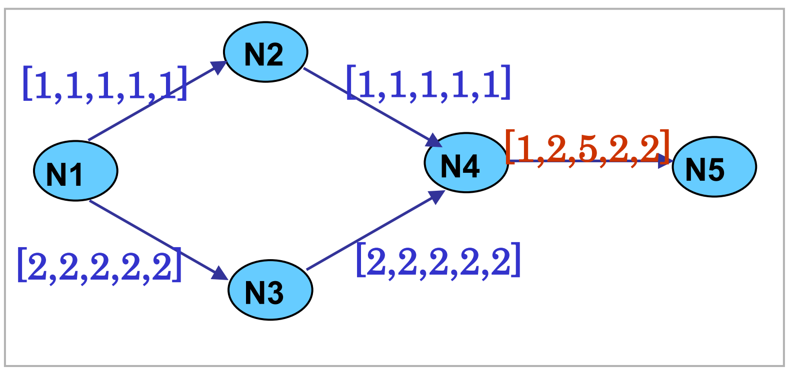
(*) *Cherkassky 93,Zhan01, Ziliaskopoulos97*

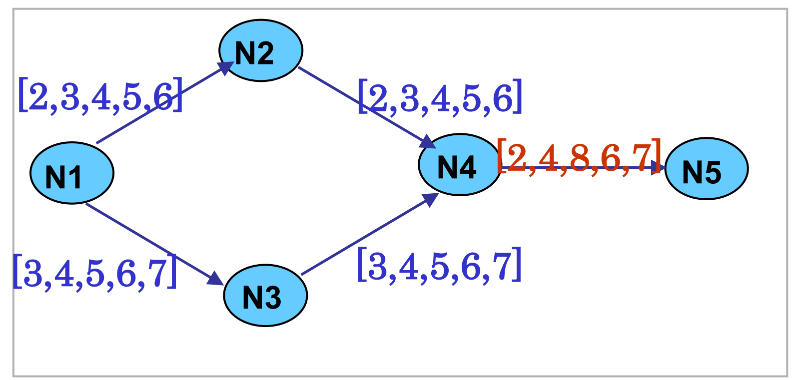
Proposed Approach – Key Idea

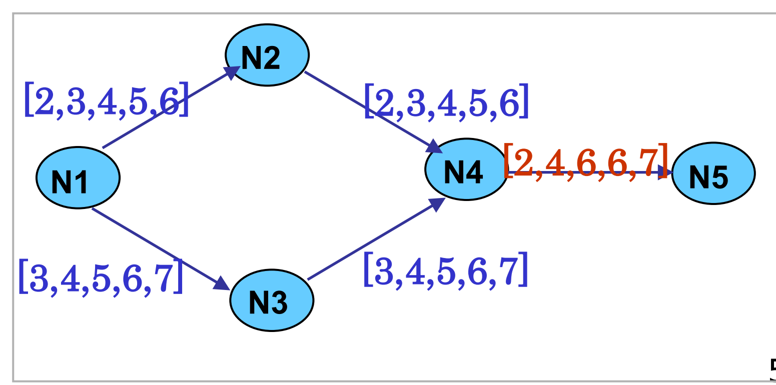
When start time is fixed, earliest arrival ⇒ least travel time (Shortest path)

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)

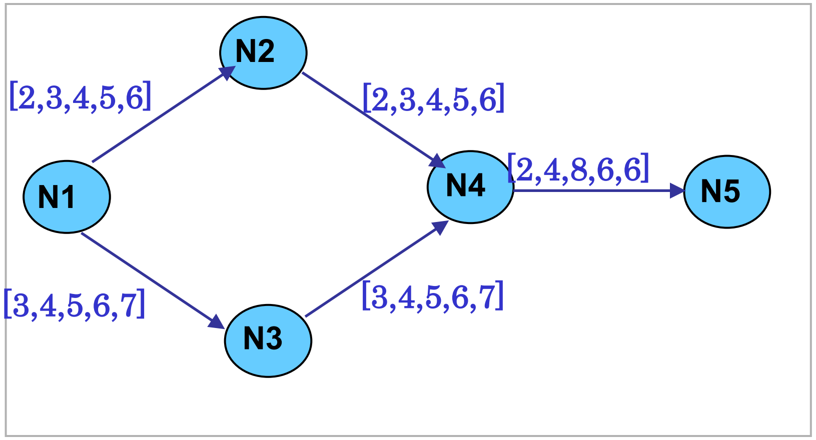
Greedy strategy on transformed TAG:

Cost of a node = Arrival time at the node

Expand the node with least cost.

Update costs of adjacent nodes.

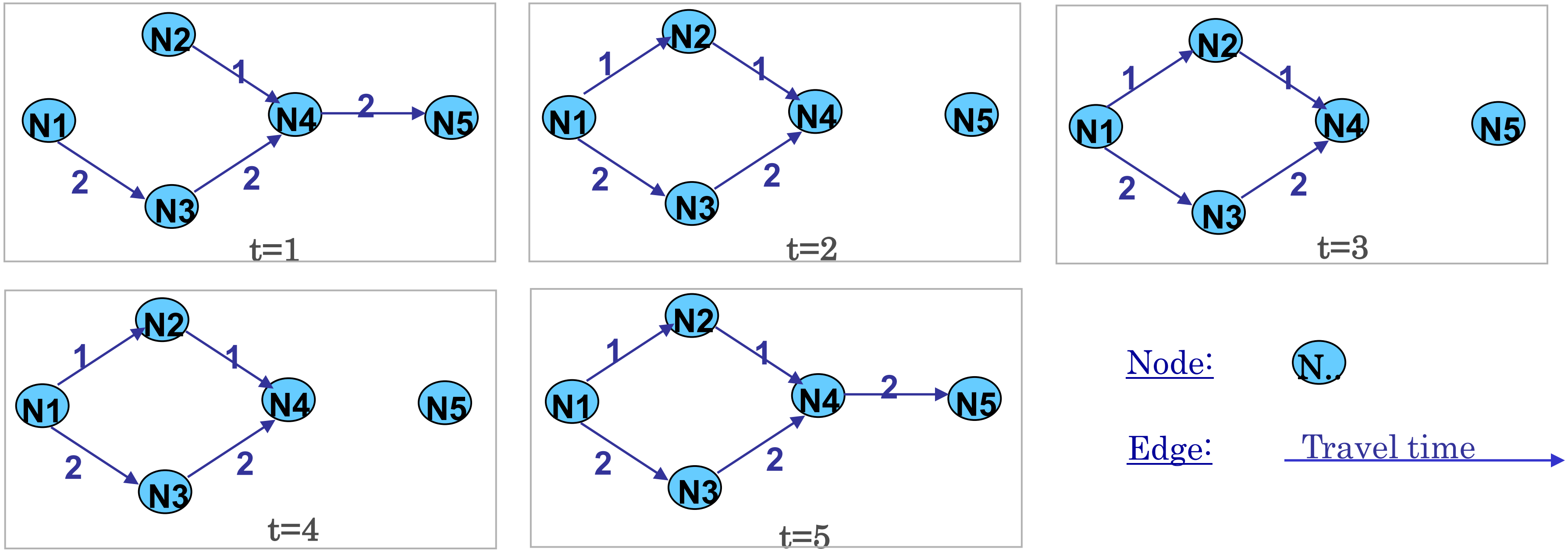
Select Minimum {Cost of edge ij}
$t \geq$ arrival at i



Trace of NF-SP-TAG Algorithm

	N1	N2	N3	N4	N5
1	~~1~~	∞	∞	∞	∞
2	1	~~2~~	3	∞	∞
3	1	2	~~3~~	3	∞
4	1	2	3	~~3~~	∞
5	1	2	3	3	6

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.

⇓

Fixed Start Time Shortest Path

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

⇓

Least Travel Time (Best Start Time)

Shortest Path is dependent on start time!!

Contributions (Broader Picture)

- Time Aggregated Graph (TAG)
- Routing Algorithms

	FIFO	Non-FIFO
Fixed Start Time	(1) Greedy (SP-TAG) (2) A* search (SP-TAG*)	(4) NF-SP-TAG
Best Start Time	(3) Iterative A* search (TI-SP-TAG*)	(5) Label Correcting (BEST) (6) Iterative NF-SP-TAG

Outline

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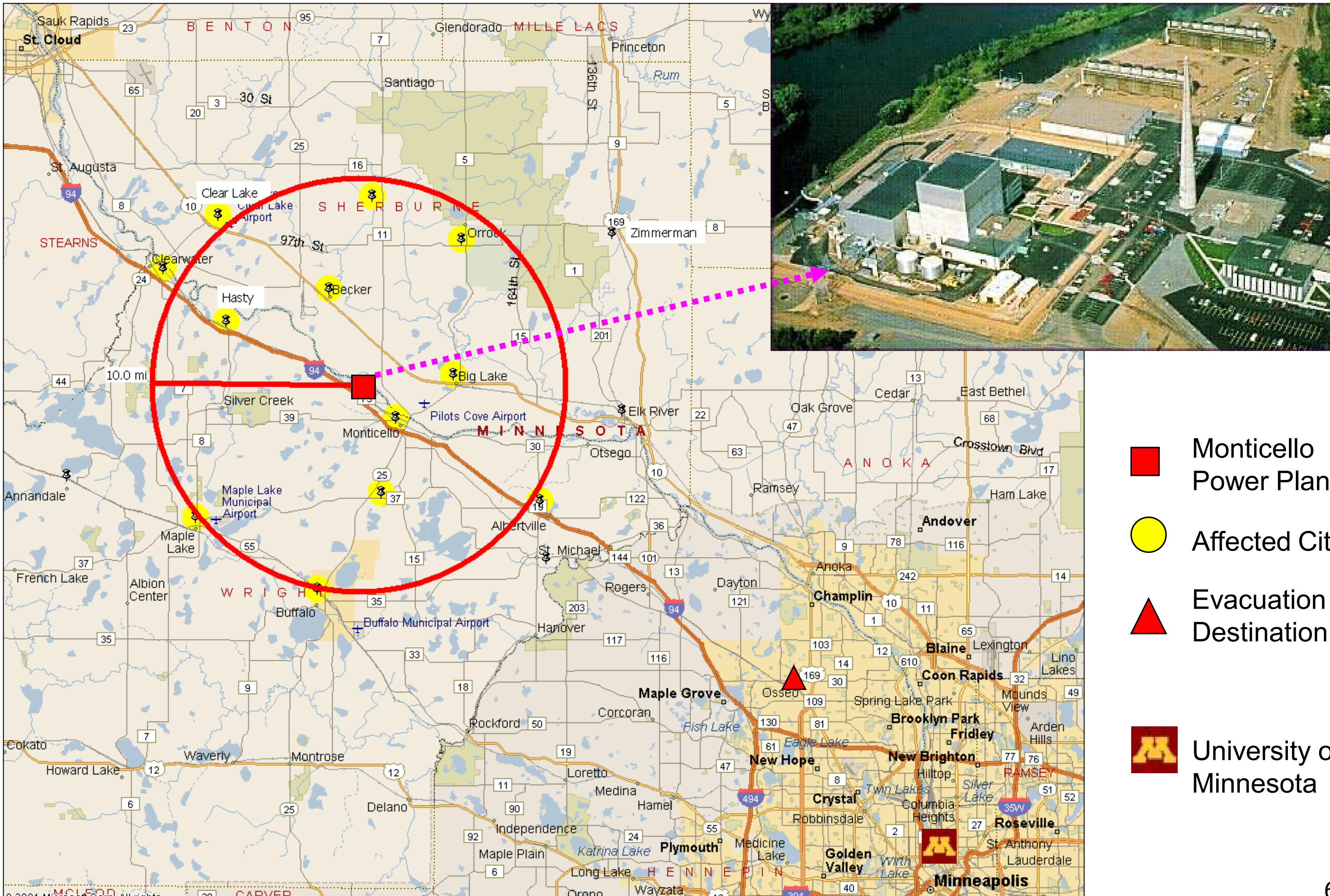
- Why is the problem hard?
- Related Work
- Proposed Approach
- Evaluation Case Studies
  - Nuclear Power Plant
  - Homeland Security
- Conclusion and Future works

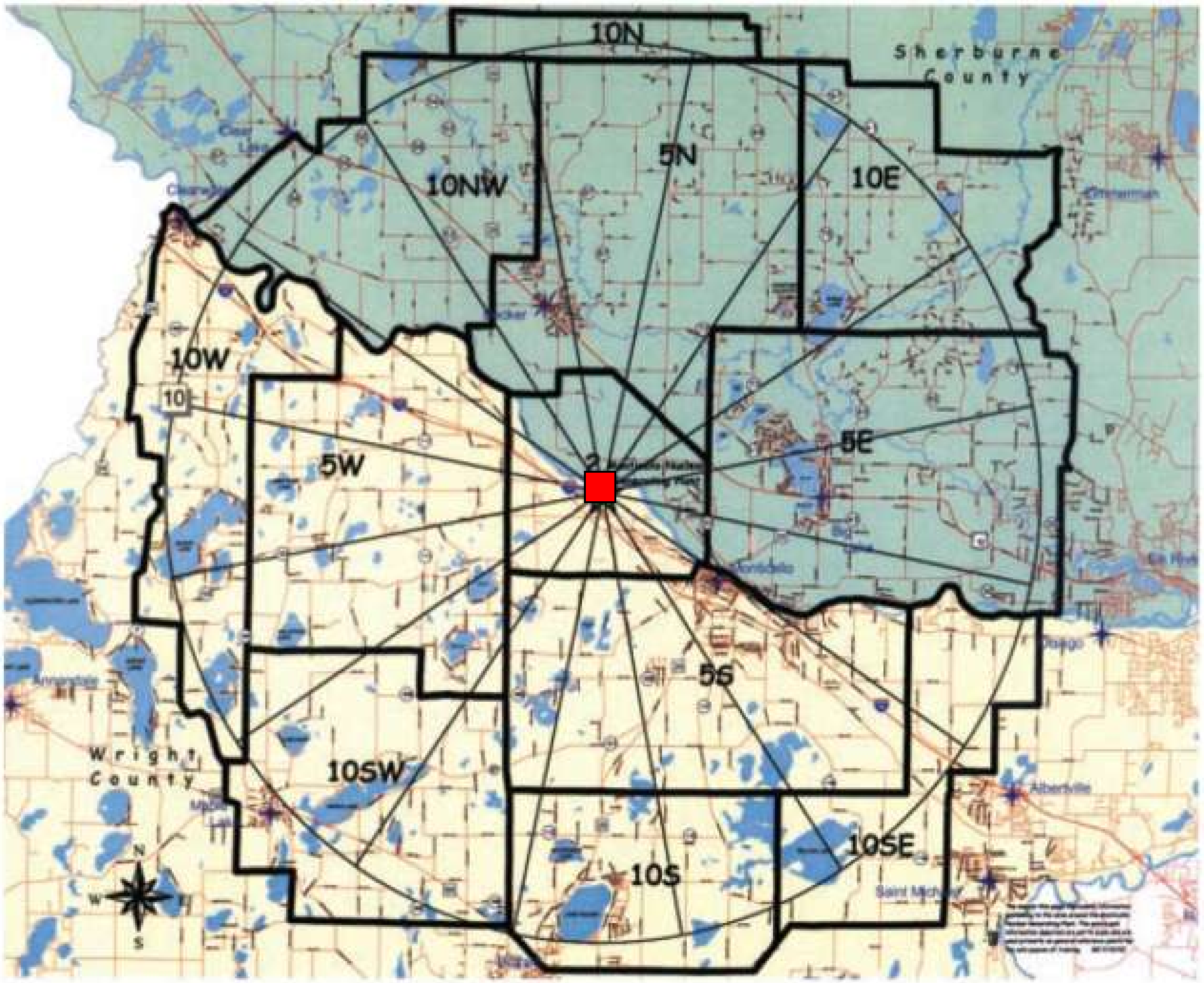
A Real Scenario: Montecillo Nuclear Power Plant



- Monticello Power Plant
- Affected Cities
- Evacuation Destination
- University of Minnesota

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

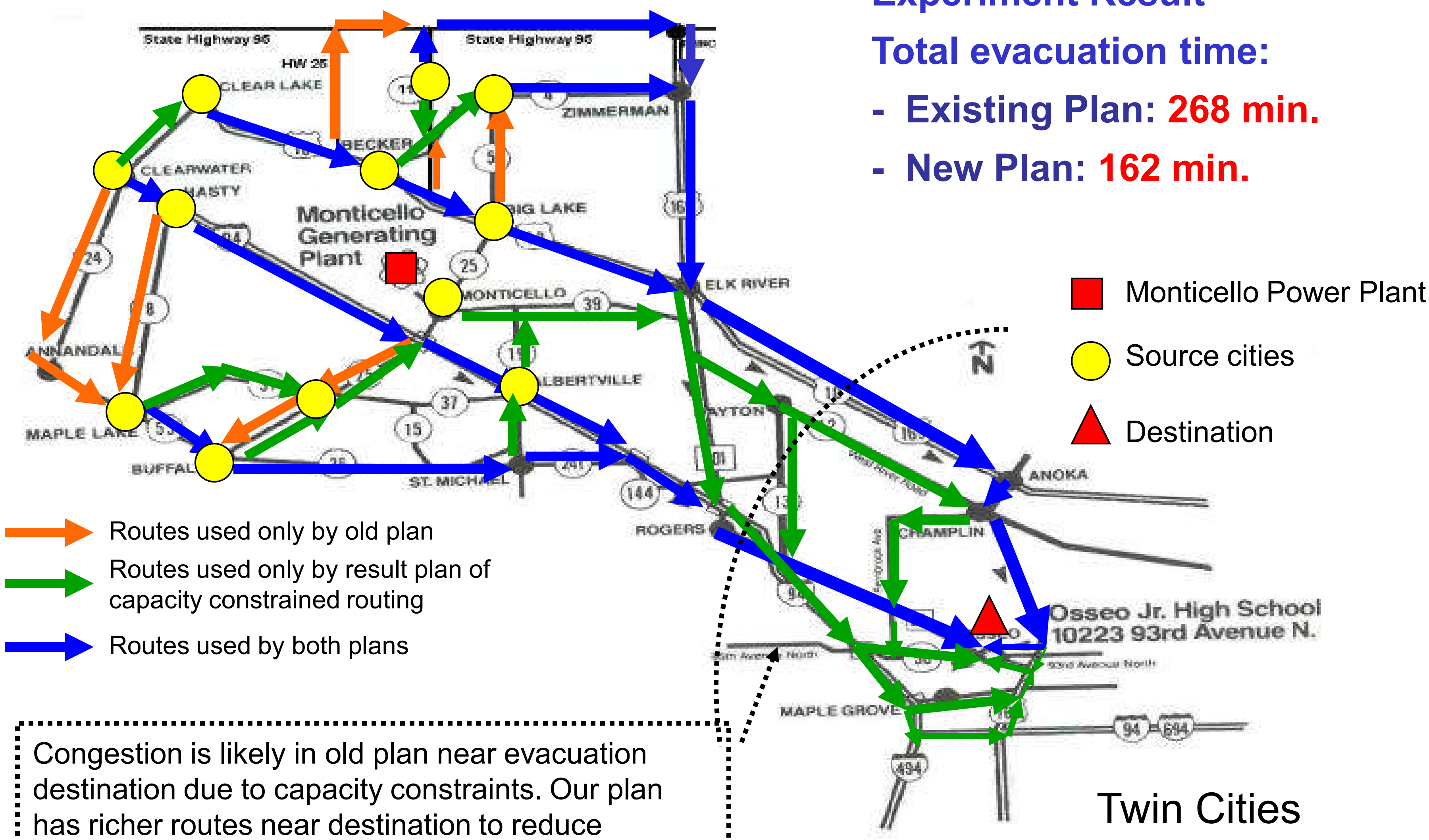
Data source: Minnesota DPS & DHS
Web site: http://www.dps.state.mn.us
http://www.dhs.state.mn.us

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


TWIN CITIES METRO EVACUATION PLAN

TECHNICAL MEMORANDUM #1

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Metropolitan Wide Evacuation Planning - 2

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 Liibbe, 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
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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
Debran 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 Walerius, Minnesota State Patrol
Douglas Biehn, Ramsey County Sheriff's Office
Mike Morehead, St. Paul Police

Maintenance and Operations
Beverly Farraher, 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
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University
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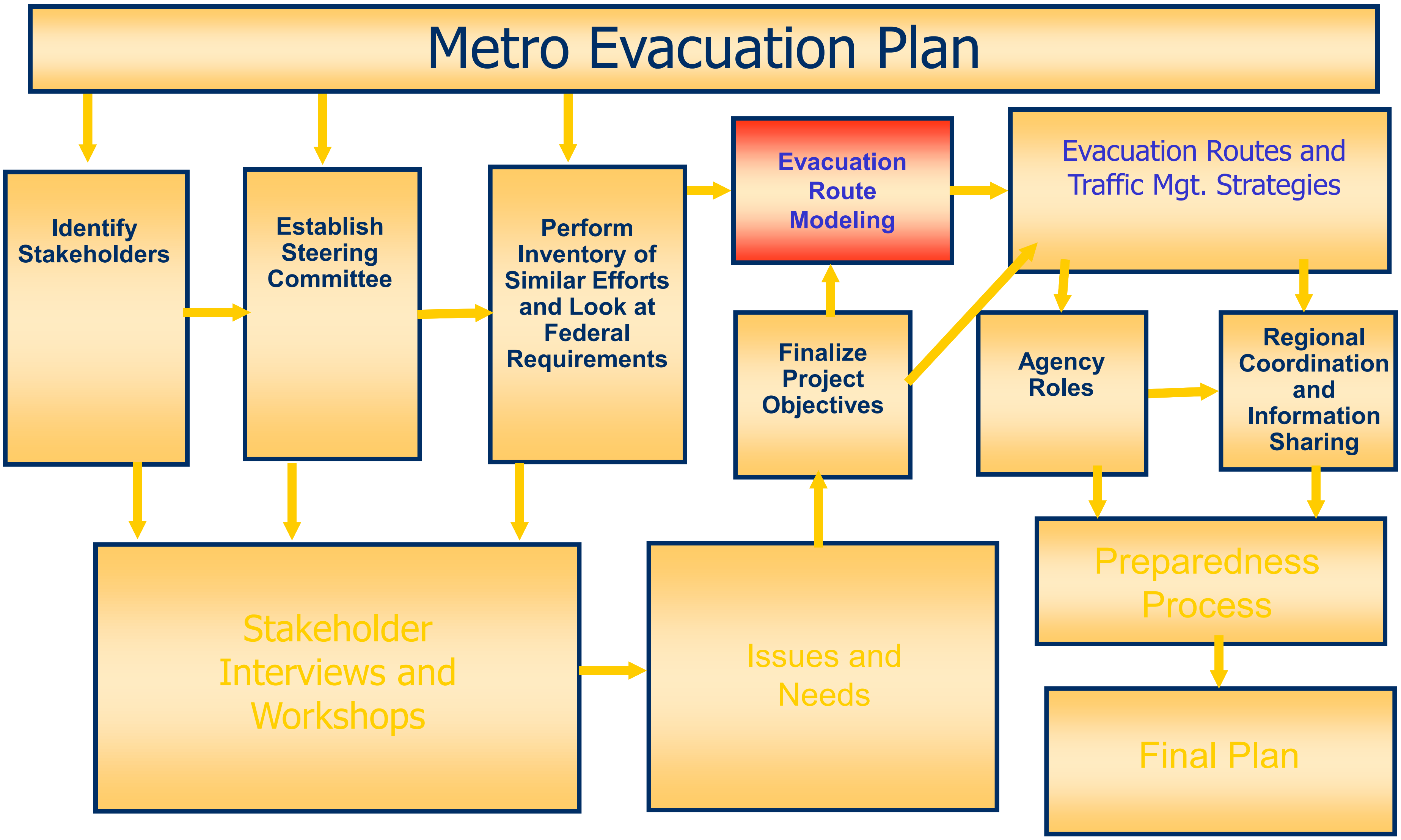
University of Minnesota Emergency Management

Volunteer Organizations
Gene Borochoff, MinnesotaVolunteer Organization active in Disaster

Task-structure



Road Networks

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)

   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 (go home)

Scenario Name:

User Defined Refinery

Evac. Zone Adjustment

Source Radius: 1 mile

Destination Radius: 2 mile

Population Adjustment

Original Estimate: 14431 (details)

Adjusted Estimate: 14431

Change time of day: ⦿ Daytime ○ Nighttime

Transportation Mode

Driving: 100 %

Walking: 0 %

Apply Parameters

(if some values of above parameters change, click 'Apply Parameters' button again.)

(Adjusted Estimate value may decrease a little after applying parameters due to assignment.)

Execute Planning Calculation

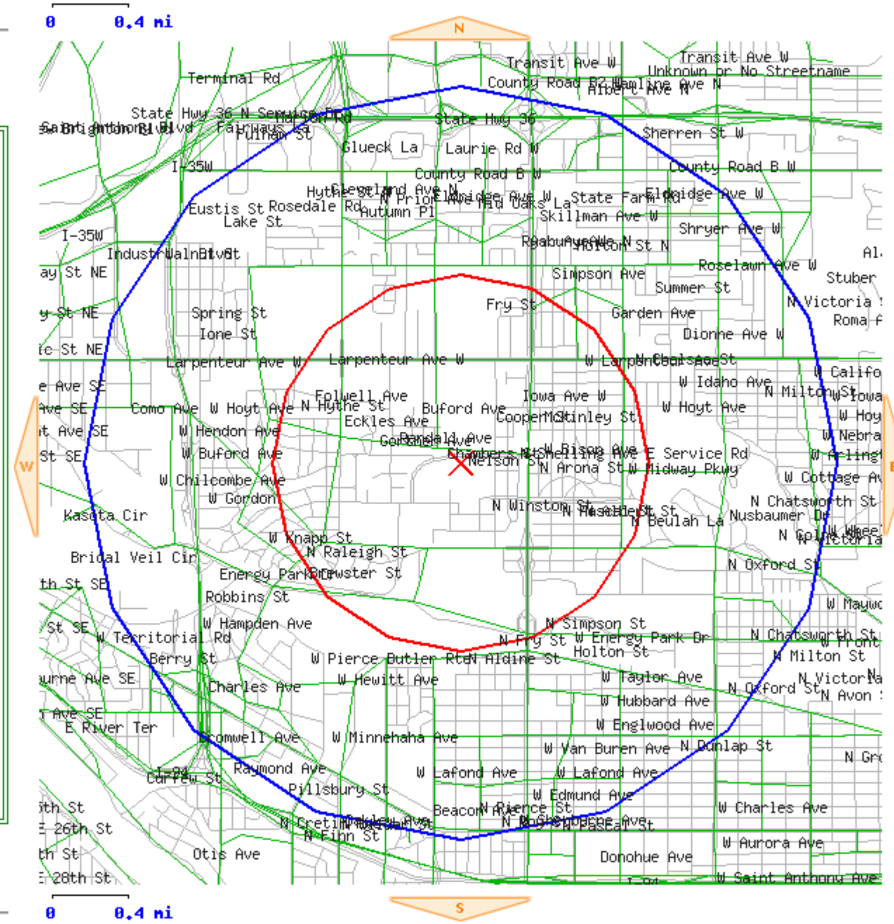
Run

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'.

Zoom In (x4) Zoom In (x2) Zoom Out (x2) Zoom Out (x4)



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 (go home)

Zoom In (x4) | Zoom In (x2) | Zoom Out (x2) | Zoom Out (x4)

Scenario Name:

User Defined

Evacuation Radius

Src Radius: 1 mile
Dst Radius: 2 mile

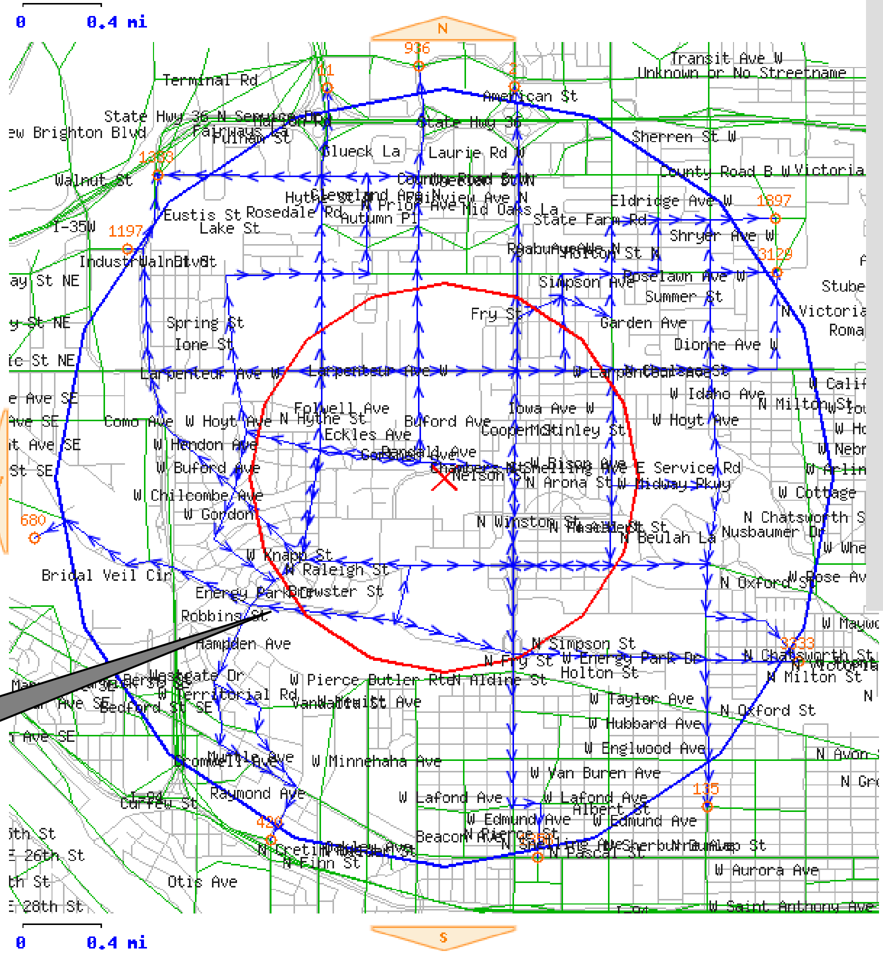
Population Estimate

Original Estimate: 14431 (details)
Adjusted Estimate: 14431

Time of Day: Daytime

Analysis Result

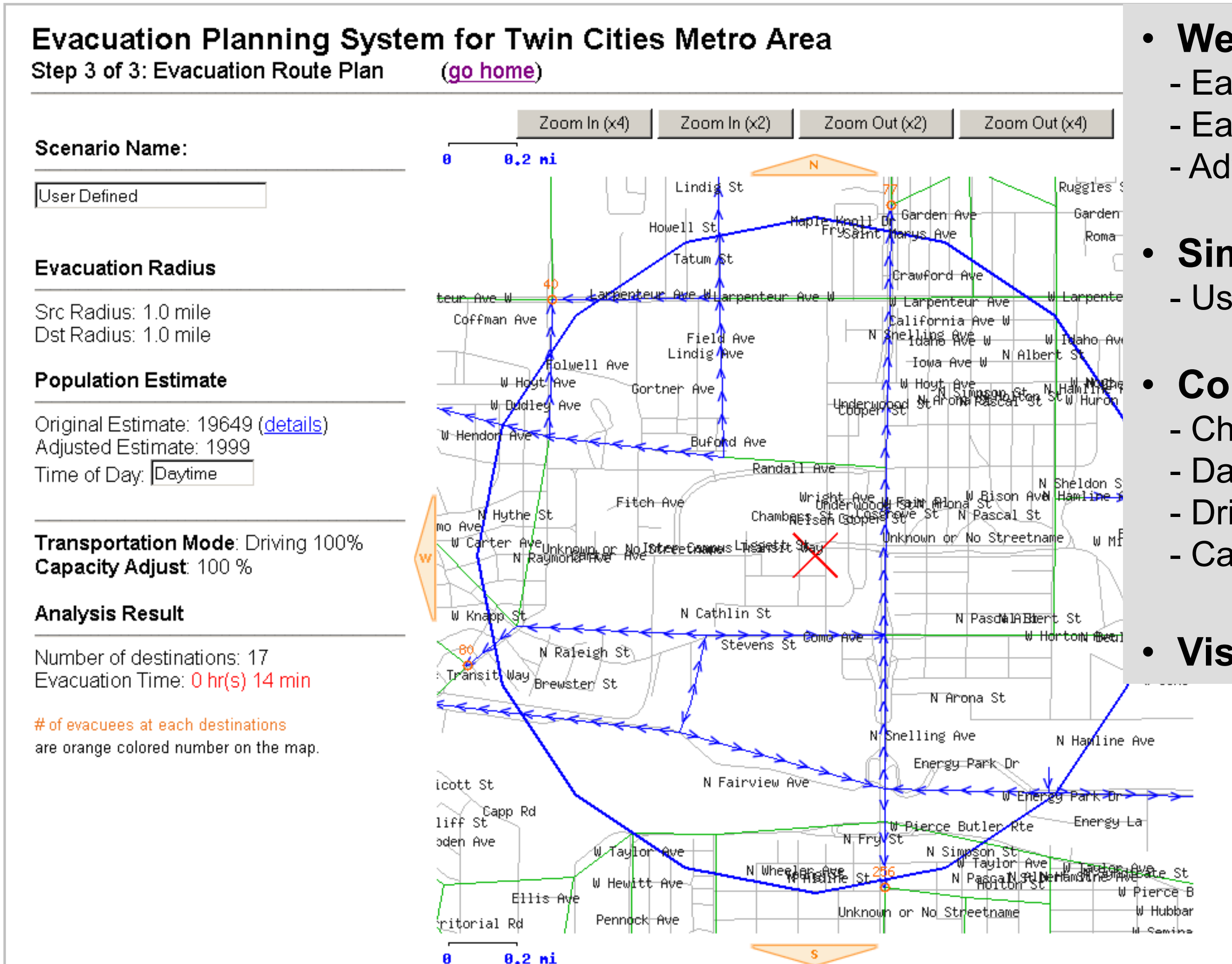
Number of destinations: 45
Evacuation Time: 3 hr(s) 16 min



Results with routes

- **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**

An Easy to Use Graphic User Interface



- **Web-based**
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  - Easy Maintenance
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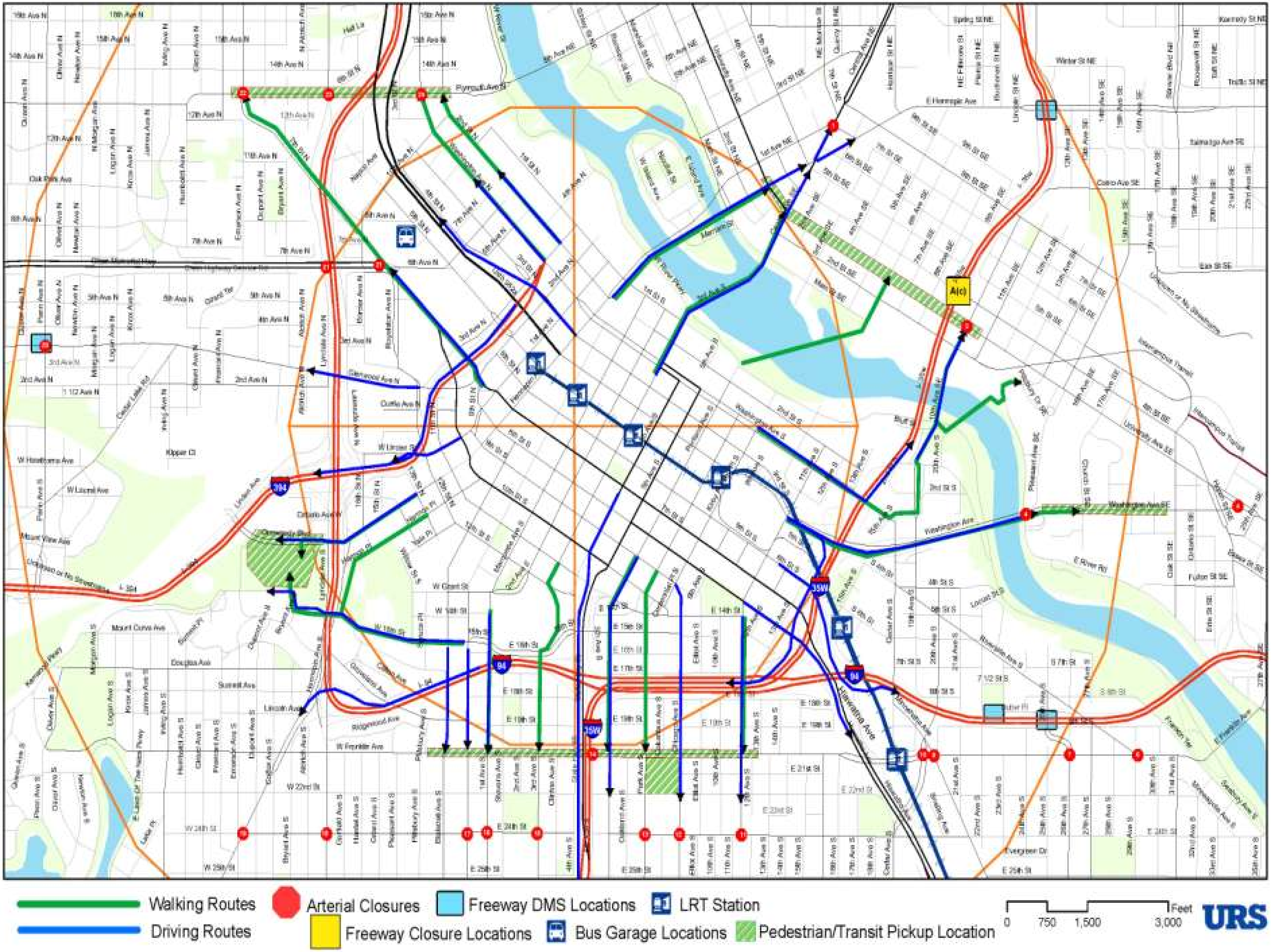


Walking Routes
Driving Routes
Arterial Closures
Freeway Closure Locations
Freeway DMS Locations
Bus Garage Locations
LRT Station
Pedestrian/Transit Pickup Location
0
750
1,500
3,000
Feet
URS

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

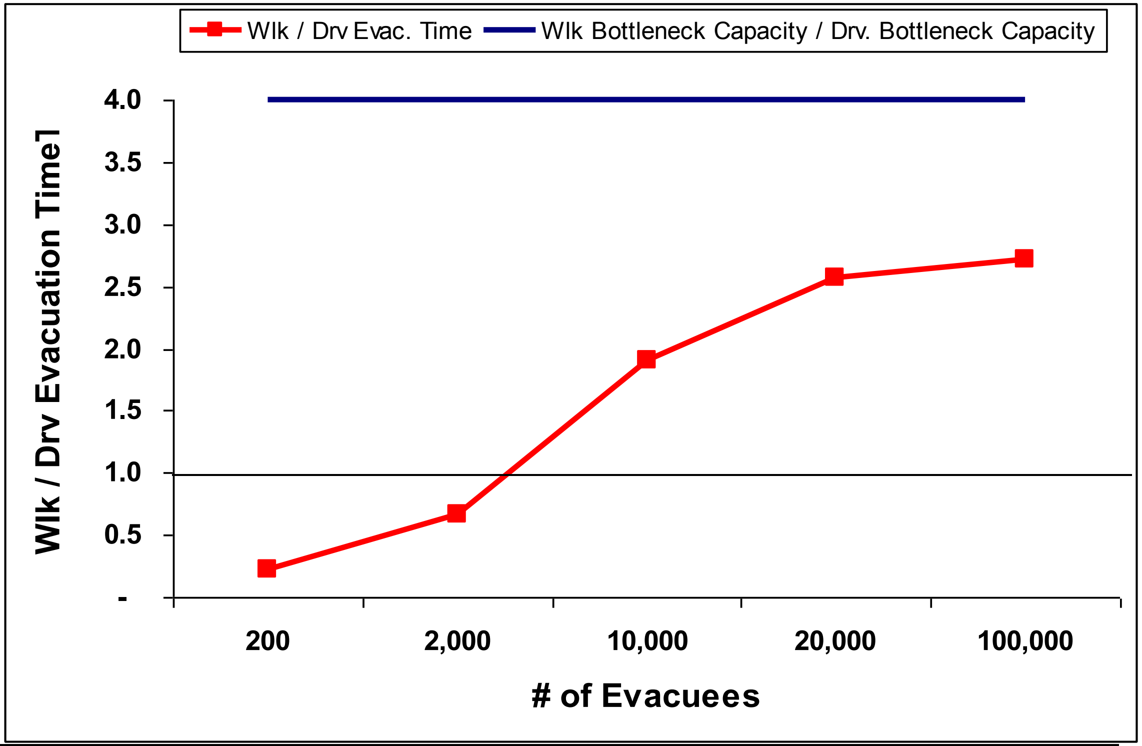
Finding: Pedestrians are faster than Vehicles!

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

Scenario	Population	Vehicle	Pedestrian	Ped / Veh
Scenario A	143,360	4 hr 45 min	1 hr 32 min	32%
Scenario B	83,143	2 hr 45 min	1 hr 04 min	39%
Scenario C	27,406	4 hr 27 min	1 hr 41 min	38%
Scenario D	50,995	3 hr 41 min	1 hr 20 min	36%
Scenario E	3,611	1 hr 21 min	0 hr 36 min	44%

Finding: Pedestrians are faster than Vehicles!

If number of evacuees > bottleneck capacity of network



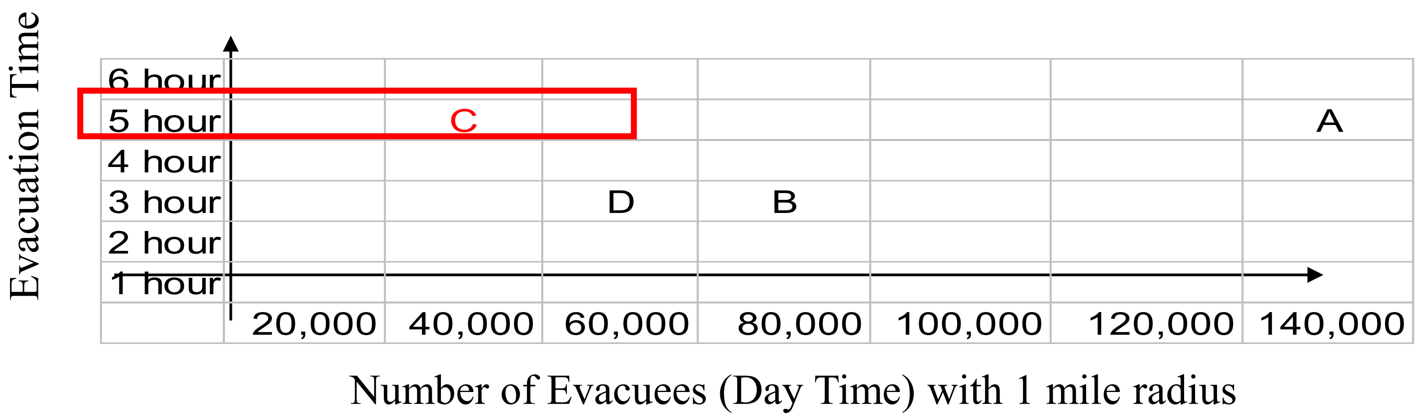
Small scenario –
1 mile radius circle
around State Fairground

# of Evacuees	200	2,000	10,000	20,000	100,000
Driving	4 min	14 min	57 min	108 min	535 min
Walking	18 min	21 min	30 min	42 min	197 min
Drv / Wlk	**0.22**	**0.67**	**1.90**	**2.57**	**2.72**

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

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 ?



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?
  - When to evacuate? Which routes? Modes? Shelters? Phased evacuation?
  - Common good with awareness of winners and losers due to a decision
- Science
  - How does one evaluate an evacuation planning system ?
  - How do we caliberate parameters?

Future Work

- Time-Variant Flow Network Questions

Static	Time-Variant
Which is the shortest travel time path from downtown Minneapolis to airport?	Which is the shortest travel time path from downtown Minneapolis to airport at different times of a work day?
What is the capacity of Twin-Cities freeway network to evacuate downtown Minneapolis ?	What is the capacity of Twin-Cities freeway network to evacuate downtown Minneapolis at different times in a work day?

- 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 4^{th} 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

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  - Coast Guard, FHWA, TSA, Mn National Guard, UMN
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  - 3 Fire Depts., 7 Law Enforcements

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Welcome to Computational Aspects of Geo-Informatics
ACM – SIG-Spatial
ACM Intl. Conference on GIS, November, 2009, Seattle
& Workshop on Computational Transportation Systmes
Symposium on Spatial and Temporal Databases, 2009, Denmark