On the traffic dynamics of urban network evacuations

Hani S. Mahmassani
On the traffic dynamics of urban network evacuations

“New Yorkers wait in traffic as they head into Manhattan from Brooklyn as the city continues to recover from superstorm Sandy.” – NBC News

ACKNOWLEDGMENTS

Ali Zockaie
Meead Saberi
Ömer Verbas
Simultaneous evacuation of all people during extreme events leads to premature congestion.

To delay the onset of congestion and to reduce its severity, two questions must be answered:

– Who should depart?
– When should they depart?
Focus of my talk

- Examine basic questions of network evacuation using a simple macroscopic approach.

- Bring recent insights from *macroscopic network flow theory* (NFD and dynamic properties) to the optimal evacuation problem, in particular with regard to *network reloading dynamics*.

- Explore the evolution of the network-wide traffic flow under different evacuation plans including different *temporal loading patterns*, different *spatial structures of the evacuation demand*, and varying *en-route traveler information*.

- Advance development of the network traffic flow theory of large-scale urban evacuations.
Network evacuation as a queuing process

- Server is the traffic network
- Evacuees arrive to receive service according to a spatial and temporal (departure) pattern
- Service rate is the throughput of the system, or rate at which users exit the system once they have reached their destinations.
Two Objectives

- Minimize Total Delay: \( \min K \)
- Minimize Evacuation Time: \( \min T \)

- \( \alpha \): Departure (loading) rate (veh/hr)
- \( D \): Total number of vehicles to be evacuated
- \( \beta \): Service (exit) rate (veh/hr)
- \( \beta = f(\alpha) \)
- \( M \): Maximum delay

\[ M = D/f(\alpha) - D/\alpha \]
How is the throughput (service rate) $\beta = f(\alpha)$ affected by the loading pattern $\alpha$?

- High loading rate induces premature flow breakdown.
- Recovery once breakdown occurs not likely $\Rightarrow$ severe inefficiency.
- Service rate also affected by spatial pattern, behavior and various traffic management schemes.
Two Objectives

- Minimize Total Delay: \( \min K \)
- Minimize Evacuation Time: \( \min T \)

- \( \alpha \): Departure (loading) rate \((\text{veh/hr})\)
- \( \beta \): Service (exit) rate \((\text{veh/hr})\)
- \( M \): Maximum delay

\[ M = D/f(\alpha) - D/\alpha \]
Formulation I

- Minimize Total Delay: \( \min K \)
  \[
  K = \frac{D}{2} \times \left[ \frac{D}{\beta} - \frac{D}{\alpha} \right] = \frac{D}{2} \times M
  \]

- Solution 1:
  \( f(\alpha) = \alpha \)

- Solution 2:
  \[
  \alpha = f(\alpha) \sqrt{\frac{df(\alpha)}{d\alpha}} \quad \text{s.t.} \quad f(\alpha) < \alpha
  \]
Formulation II

- Minimize Evacuation Time: $\min T$

\[ T = \frac{D}{f(\alpha)} \]

- This is equivalent to:

\[ \max f(\alpha) \quad \text{s.t.} \quad f(\alpha) \leq \alpha \]
The number of loading/unloading cycles $n$, 

- The maximum delay $M$:

$$M = \frac{D}{f(\alpha, u, n)} - \frac{D}{\alpha} - (n-1)u$$

- If $n=1$, the maximum delay $M$ equals to the previous case:

$$M = \frac{D}{f(\alpha, u, n)} - \frac{D}{\alpha}$$

- It can be shown that the total delay $K$ is still:

$$K = \frac{D}{2} \times M$$
Unloading-Reloading Hysteresis

- Two consecutive hysteresis loops of the morning and midday/afternoon loading-recovery cycles.
- Each cycle of network loading-recovery can cause formation of a hysteresis loop in the NFD.
- The network loading-recovery cycle in the morning often forms an incomplete hysteresis loop which is usually “unclosed” at the end of the morning recovery phase while the observed hysteresis loop in the afternoon is usually unclosed at the beginning of the loading phase.
Evidence from Portland, OR

Average Network Flow (vph)

Average Network Occupancy (%)

Initial loading
Reloading
Initial unloading
Series 4

April 29, 2011
Evidence from Portland, OR

April 29, 2011
Evidence from Chicago, IL

First cycle of loading-unloading

Second cycle of loading-unloading

August 4, 2009
Capacity drop type II is associated with the instability of network traffic when the network undergoes reloading (e.g. afternoon peak period) after an incomplete recovery from the initial loading (e.g. morning peak period). In some cases, this results in a lower capacity in the afternoon compared to the morning.
Extension to Partial Loading and Unloading

The number of loading/unloading cycles $n$,

- The maximum delay $M$:
  \[ M = \frac{D}{f(\alpha, u, n)} - \frac{D}{\alpha} - (n - 1)u \]

- If $n=1$, the maximum delay $M$ equals to the previous case:
  \[ M = \frac{D}{f(\alpha, u, n)} - \frac{D}{\alpha} \]

- It can be shown that the total delay $K$ is still:
  \[ K = \frac{D}{2} \times M \]
For both formulations, the questions are:

- How are we going to select
  - The departure rate $\alpha$,
  - The unloading duration $u$,
  - The number of loading/unloading cycles $n$,
  - So as to minimize the total delay $K$ and/or total evacuation time $T$?

- How can we relate the service rate $\beta$ to the departure rate $\alpha$ and to the unloading duration $u$? In other words, what is $f(\alpha, u, n)$?

- Can we find an empirical relation via simulation?

- What are the characteristics of the traffic flow dynamics at the network level?
The Long Island Network

NETWORK PROPERTIES
- 1,431 zones
- 9,403 nodes
- 21,791 links

TWO SCENARIOS
- Evacuate the entire Eastern portion (Nassau, Suffolk)
- Evacuate all the coasts
Vehicles on the eastern origins try to go to the designated western portion of the island or leave the island:

- 30% try to go to the super destination connecting the nearby zones in Manhattan, Bronx, New Jersey, New York State.
- 70% try to go to the super destination connecting all the zones in Kings and Queens.

The total demand is around 1.08 million.

The eastbound lanes of the freeways are reversed westbound to provide additional capacity.
Evacuate the Coasts

- Vehicles on the coastal origins try to go to the designated safe locations on the inner parts of the island.
- All the destinations are connected to one super destination.
- The total demand is around 1.07 million.
Demand Structure

Normal day

Coastal evacuation

Eastern portion evacuation
Using Weather Responsive Traffic Simulation

- DYNASMART-P (Dynamic Network Assignment-Simulation Model for Advanced Roadway Telematics – Planning version)
  - Used to simulate the vehicular traffic and assign the individual vehicles to destinations and paths in a time-dependent manner.

- The specific version is capable of simulating the effect of weather (visibility, rain intensity, snow intensity) on traffic flow parameters.

A Demonstration Video via YouTube

An Offline Demonstration Video

1/14/2013
Numerical Results

- Effect of En-route Information on Output Rate,
- Effect of Departure Rate on Maximum Delay,
- Departure (Loading) Rate vs. Service (Exit) Rate,
  - Relation of Departure Rate and Throughput in Coastal Evacuation
- Average Travel Time and Evacuation Time for Different Demand Scenarios in Coastal Evacuation.
Effect of En-route Information on Output Rate

24 Hours Loading 0 Percent En-route

Cumulative Number of Vehicles

Simulation Time (min)

y = 158.17x
R² = 0.8692

Generation
Exit
Linear (Exit)
Effect of En-route Information on Output Rate

24 Hours Loading 50 Percent En-route

Cumulative Number of Vehicles vs. Simulation Time (min)

- Generation
- Exit
- Linear (Exit)

\[ y = 194.25x \]
\[ R^2 = 0.9237 \]
Effect of En-route Information on Output Rate

24 Hours Loading 75 Percent En-route

Cumulative Number of Vehicles

Simulation Time (min)

y = 258.15x
R² = 0.999

Generation
Exit
Linear (Exit)
Effect of En-route Information on Output Rate

24 Hours Loading 100 Percent En-route

Cumulative Number of Vehicles vs. Simulation Time (min)

- Generation
- Exit
- Linear (Exit)

\[ y = 258.71x \]

\[ R^2 = 0.9997 \]
Effect of Departure Rate on Maximum Delay

1 Hour Loading

Maximum Delay

Cumulative Number of Vehicles

Simulation Time (min)

$y = 261.33x$
$R^2 = 0.9998$

- Generation
- Exit
- Linear (Exit)
Effect of Departure Rate on Maximum Delay

4 Hours Loading

Maximum Delay

Cumulative Number of Vehicles

Simulation Time (min)

γ = 253.32x
R² = 0.999
Effect of Departure Rate on Maximum Delay

8 Hours Loading

Maximum Delay

Cumulative Number of Vehicles

0 100,000 200,000 300,000 400,000 500,000 600,000 700,000 800,000 900,000 1,000,000 1,100,000 1,200,000

Simulation Time (min)

0 600 1200 1800 2400 3000 3600

γ = 259.52x
R² = 0.9996

Generation
Exit
Linear (Exit)
Effect of Departure Rate on Maximum Delay

16 Hours Loading

Maximum Delay

Cumulative Number of Vehicles

Simulation Time (min)

\[ \gamma = 251.86x \]

\[ R^2 = 0.9993 \]
Effect of Departure Rate on Maximum Delay

24 Hours Loading

Maximum Delay

Cumulative Number of Vehicles

Simulation Time (min)

y = 258.15x
R² = 0.999

Generation
Exit
Linear (Exit)
Effect of Departure Rate on Maximum Delay

48 Hours Loading

Maximum Delay

Cumulative Number of Vehicles

Simulation Time (min)

\[ y = 268.33x \]

\[ R^2 = 0.9983 \]
Effect of Departure Rate on Maximum Delay

Three 16 Hours Loading with 4 Hours Unloading Interval in between

Maximum Delay

\[ y = 283.25x \]

\[ R^2 = 0.9991 \]
Coastal Evacuation

Average Output Rate
15,905 (veh/hr)

Eastern Portion Evacuation

Average Output Rate
14,747 (veh/hr)
Relation of Output Rate and Loading Rate in Coastal Evacuation

**Linear:**
\[ f(\alpha) = 0.1732 \alpha + 12133 \]
\[ R^2 = 0.9168 \]

**Linear w/o intercept:**
\[ f(\alpha) = 0.7192 \alpha \]
\[ R^2 = 0.8379 \]

**Second-degree polynomial:**
\[ f(\alpha) = -2E-05 \alpha^2 + 0.9029 \alpha + 4164.7 \]
\[ R^2 = 0.9775 \]

**Second-degree polynomial w/o intercept:**
\[ f(\alpha) = -2E-05 \alpha^2 + 1.2814 \alpha \]
\[ R^2 = 0.9612 \]
Effect of Departure Rate on Maximum Delay

Three 16 Hours Loading with 4 Hours Unloading Interval in between

Maximum Delay

Cumulative Number of Vehicles

Simulation Time (min)

\[ y = 283.25x \]

\[ R^2 = 0.9991 \]
A demand scenario in this case includes three times loading with two unloading periods in between.
(The numbers in parenthesis for each scenario are loading and unloading period durations in hours.)
A demand scenario in this case includes three times loading with two unloading periods in between.
(The numbers in parenthesis for each scenario are loading and unloading period durations in hours.)
A demand scenario in this case includes three times loading with two unloading periods in between.
(The numbers in parenthesis for each scenario are loading and unloading period durations in hours.)
Examine network properties under evacuation from perspective of macroscopic flow theory (NFD and dynamics).

Properties derived from NFD characterization are translated into insights for evacuation planning and design, in particular with regard to network reloading dynamics.

Explore the evolution of the network-wide traffic flow under different evacuation plans including different temporal loading patterns, different spatial structures of the evacuation demand, and varying en-route traveler information.

Develop the network traffic flow theory of large-scale evacuations.
Tamminga et al. (2011):

“As long as gridlock phenomena can be prevented, even significant levels of congestion do not necessarily have a negative impact on the evacuation time.”
Experimental Set up

Two different evacuation scenarios are designed:

- Coastal evacuation (1,067,718 vehicles)
- Eastern portion evacuation (1,091,210 vehicles)
Demand Structure

Normal day

Coastal evacuation

Eastern portion evacuation
NFDs with different loading durations (coastal)
NFDs with different loading durations (eastern)
Evolution of Network Gridlock
16-hr loading, coastal evacuation
Maximum network flow is decreasing as the loading duration increases. The drop in the maximum network flow should not be interpreted as a drop in the network capacity; rather, it reflects the reduction in demand loading peak.
When loading duration increases, the average network throughput remains roughly **constant** for the **coastal** evacuation case. For the **eastern** portion evacuation, the average network throughput **varies** due to extensive fluctuations and formation of a hysteresis loop.
Effects of loading duration (coastal)
Effects of loading duration (eastern)
Since the demand structure of the coastal evacuation is radial-shaped, it is expected that queues entering the safe destinations (evacuation shelters) also propagate radially. Therefore, what governs the network-wide trip completion rate is the discharge/exit rate of the bottlenecks at the destinations.

Results suggest that the structure of evacuation demand significantly affects the dynamics of the network traffic flow during evacuation. A radially-shaped structure helps network throughput to remain relatively constant and stable during both loading and recovery periods while a more elaborate structure causes formation of hysteresis loops and thus, network throughput drops during the recovery period compared to the loading period.
Loading a network in multiple phases could mitigate congestion and increase network throughput. Here, loading and unloading durations in each cycle are 16 hours and 4 hours, consecutively.
Results confirm the existence of the unloading-reloading hysteresis phenomenon and verify that if a network undergoes a near full recovery, the reloading path in the NFD follows almost the same path as in the initial loading.
Previous studies suggested a linear relationship between trip completion rate and network flow. However, under highly congested, or volatile conditions, that relation might break down. This occurs under disruptive conditions, and when the fraction of adaptive drivers is relatively large.
Effects of Adaptive Driving

Adaptive driving increases fluctuations in the NFD.

Adaptive driving reduces hysteresis and gridlock.

Adaptive driving increases network capacity.

Some instabilities in network flow were observed.

24 hour loading period
1. **Structure of the evacuation demand** can significantly affect network performance. A radial-shape structure resulted in a more stable network recovery compared to a directional (east-to-west) evacuation structure.

2. **Multiple cycles of loading and un-loading** with sufficient recovery time can improve performance of evacuation with regard to both trip completion rate (total evacuation time) and average delay of evacuees.

3. The linear relationship between average network flow and trip completion rate does not hold when a network is highly congested and under disruption, and sufficient number of adaptive drivers exist.

4. **Adaptive driving** also increases fluctuations in the NFD. However, it reduces hysteresis and gridlock while increasing network capacity.
THANK YOU

Questions?

masmah@northwestern.edu

Connect with NUTC

ICEM 2015 3rd International Conference on Evacuation Modeling and Management