Quantitative Assessment of Transportation Network Vulnerability with Dynamic Traffic Simulation Methods

Venkateswaran Shekar and Lance Fiondella
Department of Electrical and Computer Engineering
University of Massachusetts Dartmouth

Samrat Chatterjee and Mahantesh Halappanavar
Pacific Northwest National Laboratory
Outline

• Motivation
• Equilibrium Assignment
  – Static and Dynamic
• Vulnerability Assessment Algorithm
  – Evacuation scenario illustration
• Conclusion
• Future Work
Motivation

• Continuing increase in city populations, criticality of transportation infrastructure is expected to increase
• Disaster planning, response, and recovery decision support systems
  – Often assume that transportation network is completely available
  – Unrealistic assumption may lead to strategy that is far from optimal
Static Traffic Assignment

• Previous transportation network vulnerability research has been performed in the context of static traffic models

• Simplified Assumptions
  – The travel times of each link on a route are added together to determine the route travel time
  – Inflow and Outflow of a link are equal
  – Congestion occurs if Volume-to-Capacity ratio (V/C) > 1.0
Dynamic Traffic Assignment

- Explicit modeling of traffic flow dynamics
  - Ensures direct linkage between travel time and congestion
- If link outflow is less than link inflow
  - Link density increases leading to congestion
  - Speed decreases leading to increase in link travel time
- Outflow may reduce due to
  - Merging
  - Weaving
  - Traffic signals
Dynamic Traffic Assignment

• Dynamic transportation models possess applications in
  – Congestion and vulnerability assessment
• Require two primary inputs
  – Static map characterizing network as graph composed of
    nodes and links
  – Dynamic (time-varying) network demand profile
Dynamic Equilibrium (DE)

• Travel demand is a function of time
• DE algorithms route existing demand within a network
  – Link outages disrupt this equilibrium necessitating rerouting
• Some disruptions increase overall travel time more significantly than others
Dynamic Equilibrium (2)

- Simple and systematic strategy to identify vulnerabilities in the dynamic transportation network
- *When and where* would a disabled link be most disruptive to the network?
- Results can inform how to prioritize time and location of defensive strategies
Framework

- Open Street Map
  - Static map extraction
  - TNTP Compatible format
- Network Demand Data
  - TNA Algorithm
  - TVA Algorithm
- Equilibrium Assignment
- Vulnerability assessment

- Demographic and Demand data collection
  - Smartphone app
Algorithm 1 Pseudo code for transportation network vulnerability assessment

Require: Road network $G$ with $n$ nodes and $e$ edges
Require: Traffic demand data $D$
Require: Array of time intervals $T = \langle \Delta t_1, \Delta t_2, \ldots, \Delta t_i, \ldots, \Delta t_k \rangle$

$V_o = \text{Run simulation without disabling links}$

for Each edge $e \in G$ do
    for Each interval $\Delta t_i \in T$ do
        $V_{e,i} = \text{Run simulation, disabling edge $e$ in time interval $\Delta t_i$}$
    end for
    $\Delta V_{e,i} = V_{e,i}/V_o$
end for
Illustration

- Network Structure
  - 6 Nodes
  - 13 Links
- Speed Limit
  - 30 miles/hour
- Time intervals
  - $\Delta t_1 = 0 – 500$ sec
  - $\Delta t_2 = 500 – 1000$ sec
  - $\Delta t_3 = 1000 – 1500$ sec
- 500 vehicles depart node zero
- Destination is node five
Results
Vehicle Densities

(a) Time interval $\Delta t_1$

(b) Time interval $\Delta t_2$

(c) Time interval $\Delta t_3$

Fully functioning network
Vehicle Densities (2)

Link (2,4) disconnected at $\Delta t_2$
Total fuel consumed

![Graph showing fuel consumption over time]

- **Nominal**
- $L_{2,4}$ at $\Delta t_1$
- $L_{2,4}$ at $\Delta t_2$
- $L_{2,4}$ at $\Delta t_3$
Number of vehicles in the network
Small scale simulation
UMass Dartmouth

- Speed Limit
  - 30 miles/hour
- Time intervals
  - $\Delta t_1 = 0 – 3000$ sec
  - $\Delta t_2 = 3000 – 6000$ sec
  - $\Delta t_3 = 6000 – 9000$ sec
- 4000 vehicles depart campus
- Destination is the exit node
UMassD Results

Simulation Time/Nominal Time

Interval
- $\Delta t1$
- $\Delta t2$
- $\Delta t3$

Disabled Link

$S_1$, $S_2$, $S_3$, $S_4$, $S_5$, $S_6$, $S_7$, $S_8$, $S_9$, $S_{10}$, $S_{11}$, $S_{12}$
UMassD S1 @ $\Delta t_3$ (Worst Case)
UMassD S7 @ $\Delta t_2$ (Best case)
Conclusion

• Developed quantitative method to identify vulnerabilities in the network
• Employed a microscopic road traffic simulator (SUMO) to compare a fully functioning network to a disrupted one
• Unlike static methods, the proposed work looks at the time varying nature of demand in addition to network structure
Future work

• Large scale simulations
  – NYC evacuation
  – Boston during normal operation
• Not feasible to disconnect all links
  – Social Network Analysis
  – Group betweeness centrality
  – Game Theory
• Incorporate dynamic plume models