Quantitative Assessment of Transportation Network Vulnerability with Dynamic Traffic Simulation Methods

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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

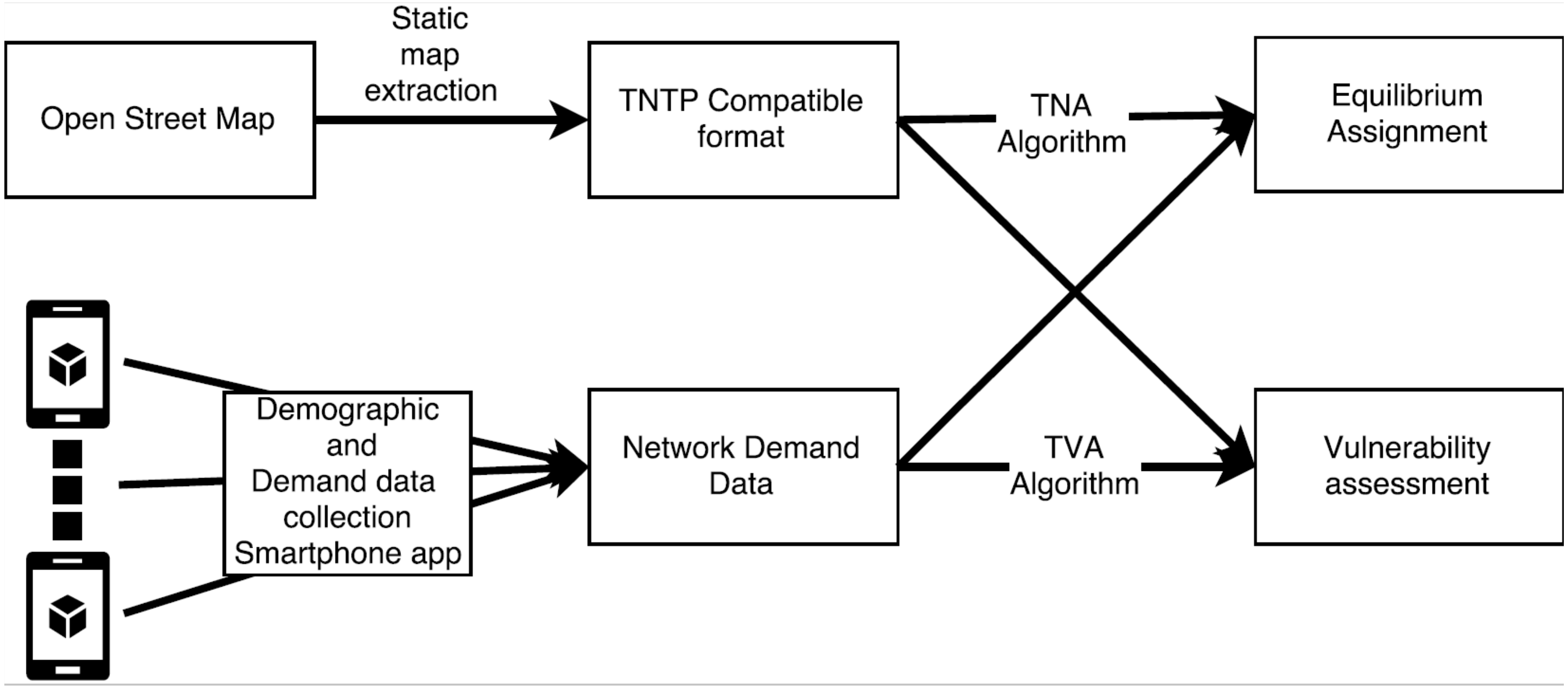
Dynamic Equilibrium (DE)

- 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

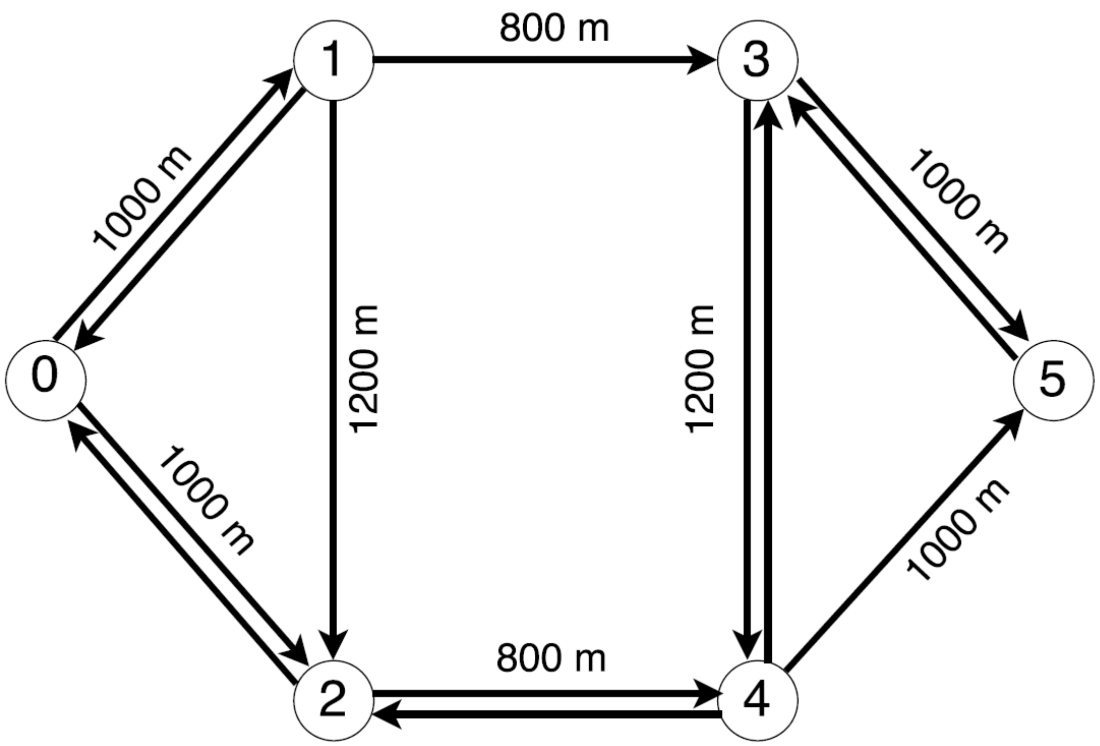

Open Street Map
Static
map
extraction
TNTP Compatible
format
TNA
Algorithm
Equilibrium
Assignment
Demographic
and
Demand data
collection
Smartphone app
Network Demand
Data
TVA
Algorithm
Vulnerability
assessment

Algorithm

Algorithm 1 Pseudo code for transportation network vulnerability assessment

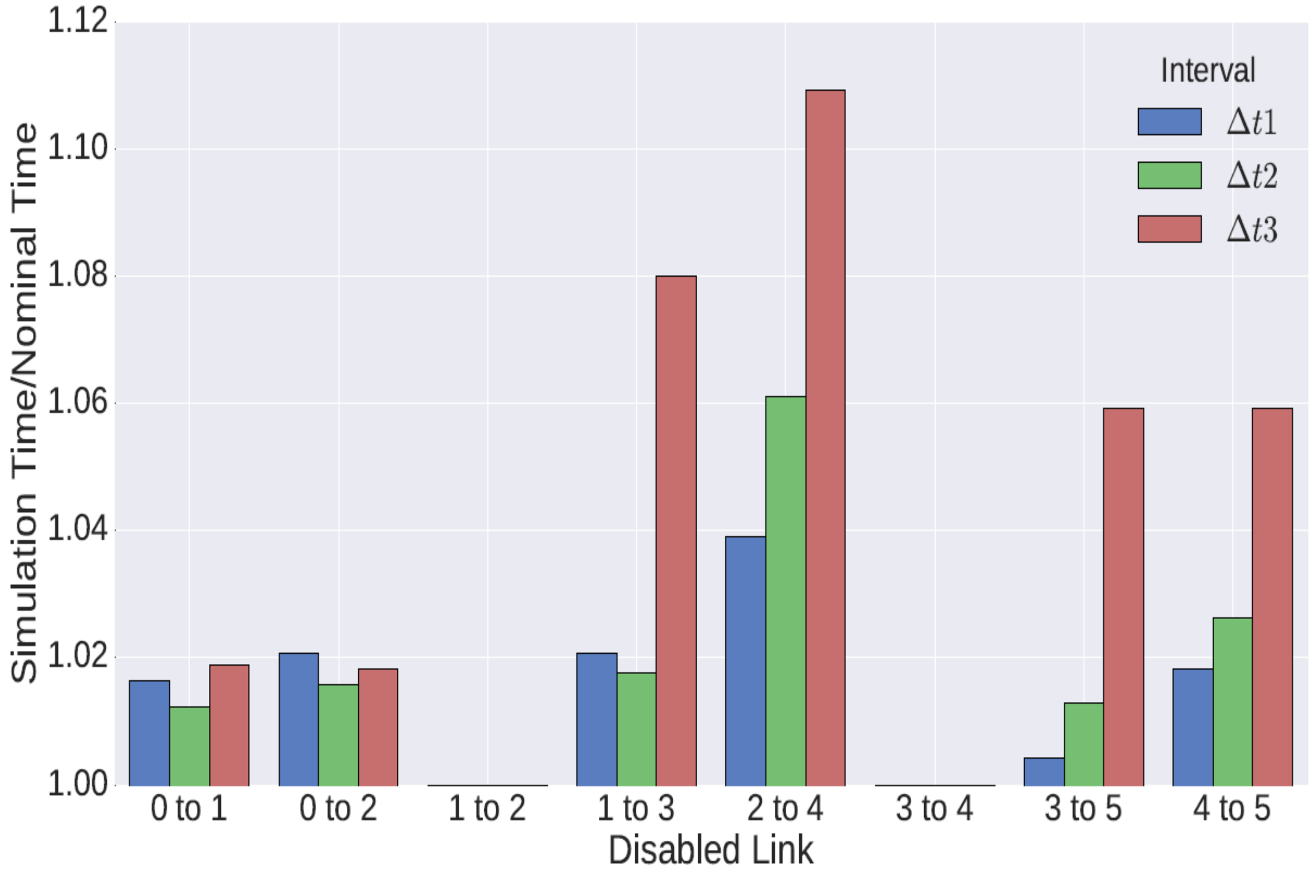
Require: Road network G with n nodes and e edges
Require: Traffic demand data $\mathbf{D}$
Require: Array of time intervals $\mathbf{T} = \langle \Delta t_1, \Delta t_2, \ldots, \Delta t_i, \ldots, \Delta t_k \rangle$
  $V_o =$ Run simulation without disabling links
  for Each edge $e \in G$ **do**
    for For each interval $\Delta t_i \in \mathbf{T}$ **do**
      $V_{e,i} =$ Run simulation, disabling edge e in time interval Δt_i
    end for
    $\Delta V_{e,i} = V_{e,i} / V_o$
  end for

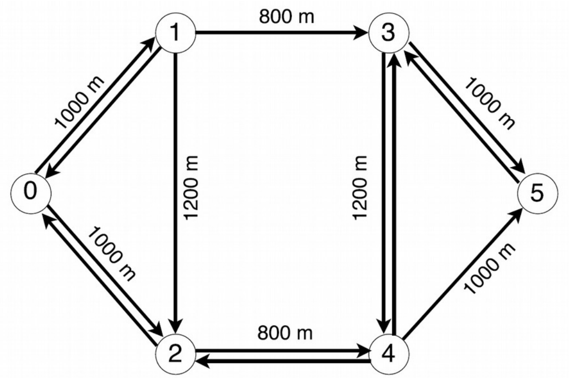
Illustration



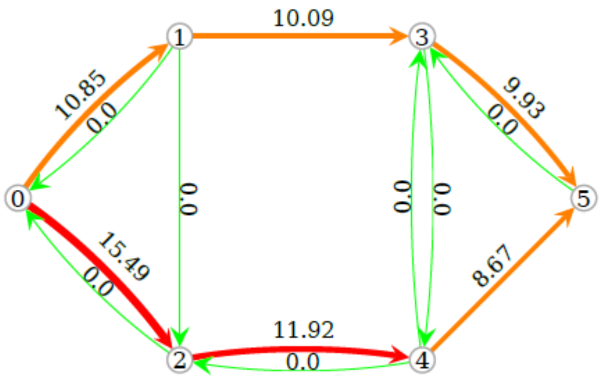
- Network Structure
  - 6 Nodes
  - 13 Links
- Speed Limit
  - 30 miles/hour
- Time intervals
  - Δt_1 = 0 – 500 sec
  - Δt_2 = 500 – 1000 sec
  - Δt_3 = 1000 – 1500 sec
- 500 vehicles depart node zero
- Destination is node five

Results

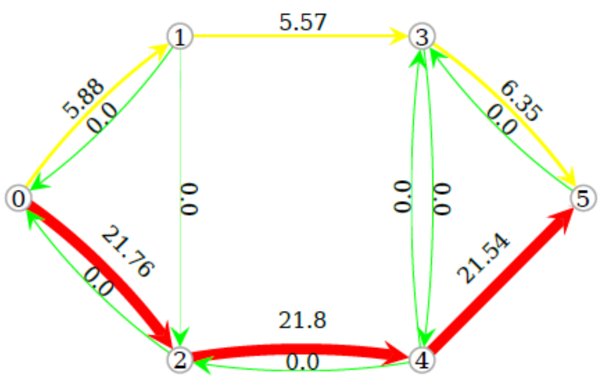

1.12
1.10
1.08
1.06
1.04
1.02
1.00
Simulation Time/Nominal Time
Interval
Δt1
Δt2
Δt3
0 to 1
0 to 2
1 to 2
1 to 3
2 to 4
3 to 4
3 to 5
4 to 5
Disabled Link


0
1
2
3
4
5
800 m
800 m
1000 m
1000 m
1000 m
1000 m
1200 m
1200 m

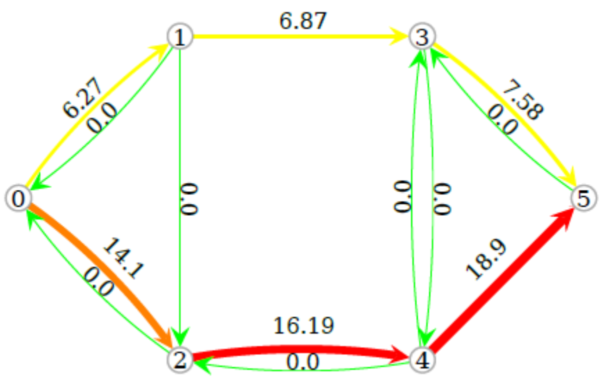
Vehicle Densities



(a) Time interval Δt_1



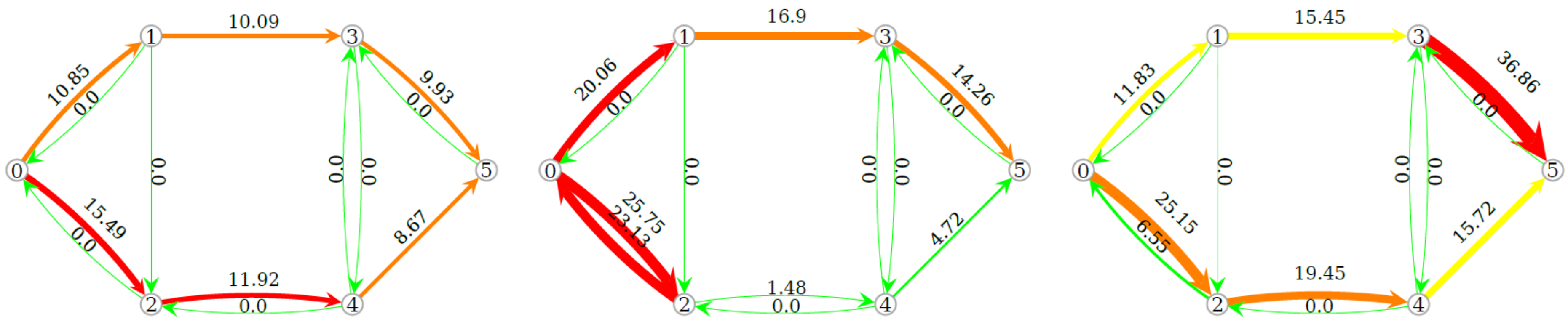
(b) Time interval Δt_2



(c) Time interval Δt_3

Fully functioning network

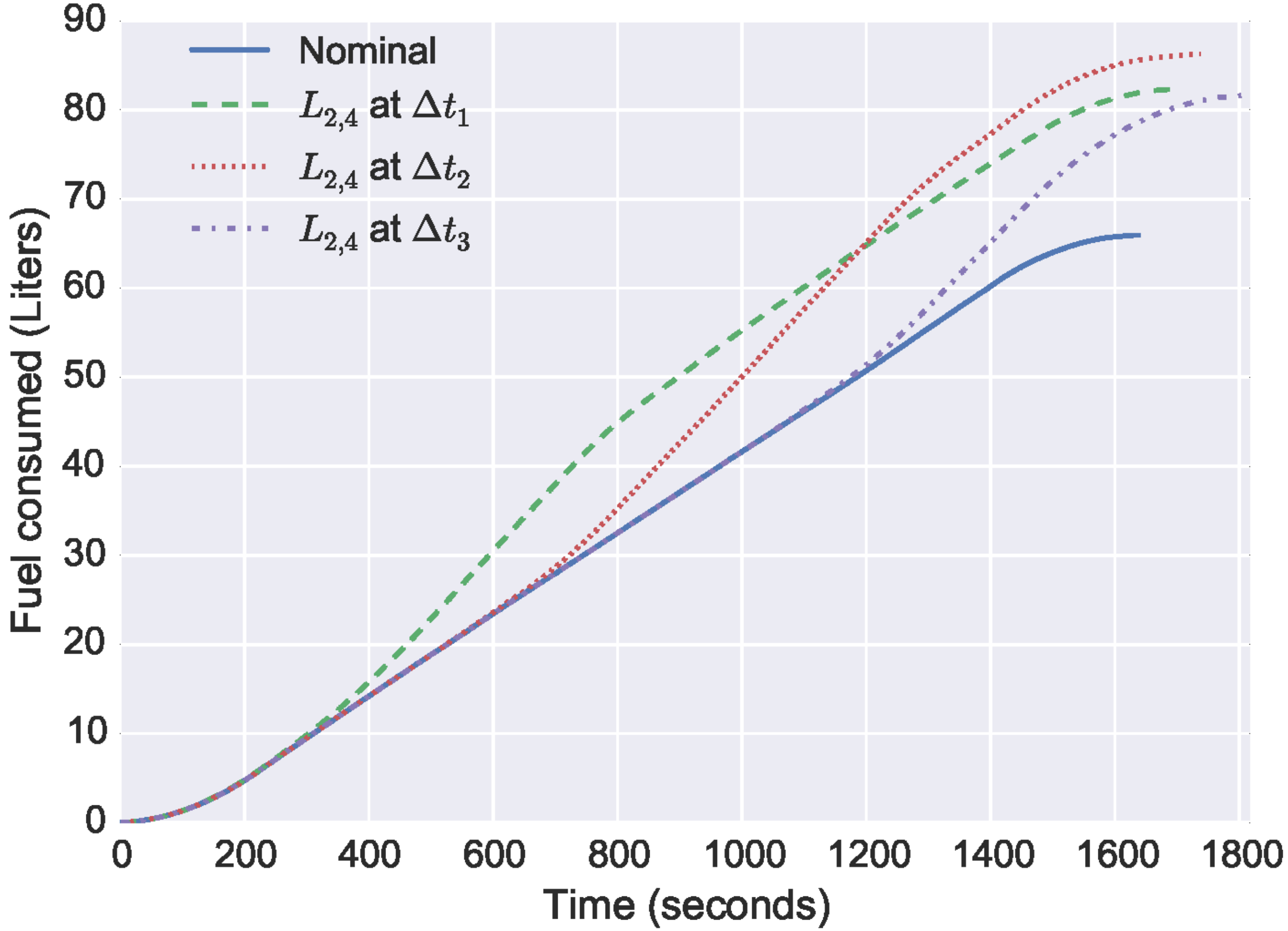
Vehicle Densities (2)



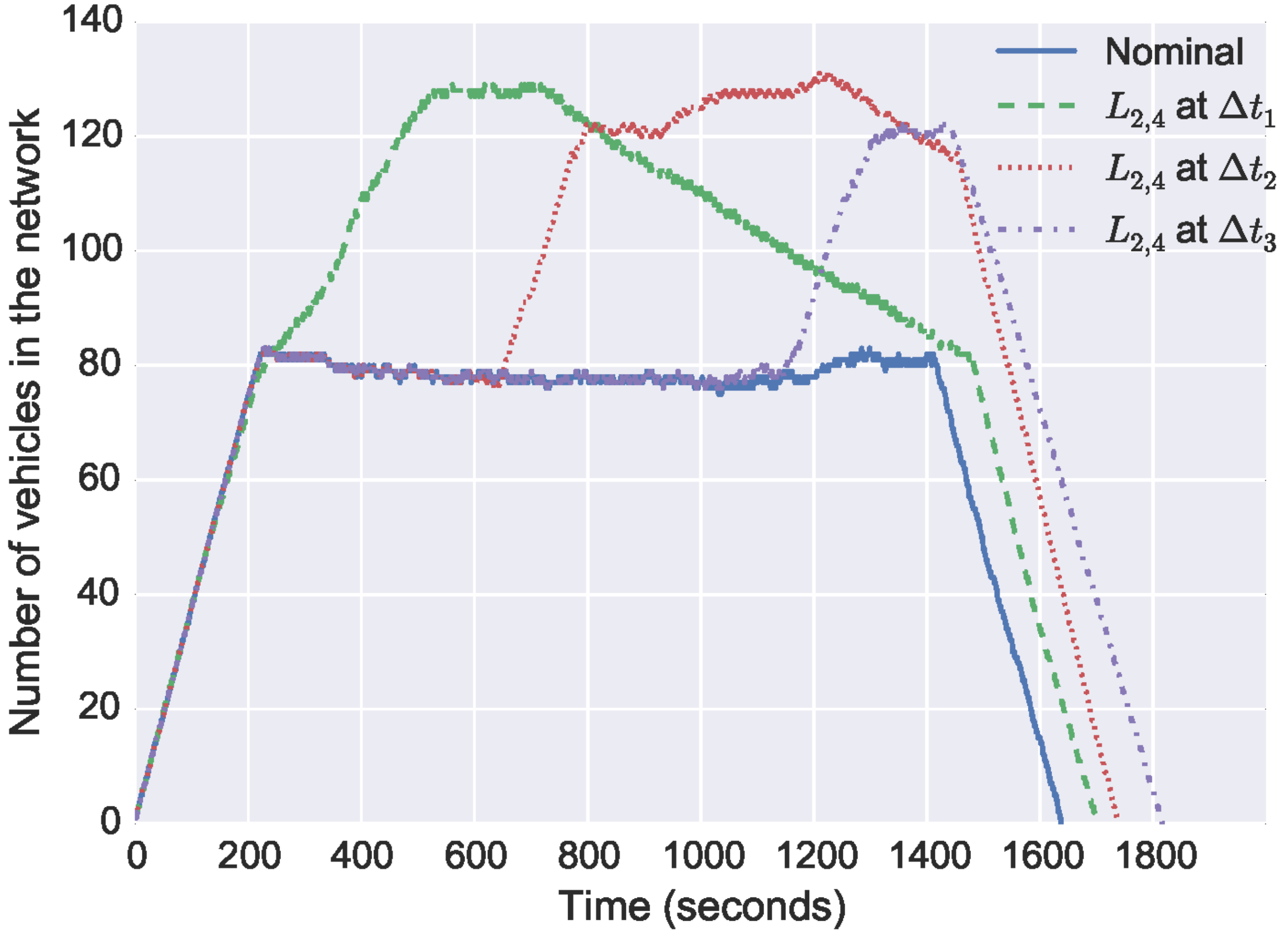
(a) Time interval Δt_1 (b) Time interval Δt_2 (c) Time interval Δt_3

Link (2,4) disconnected at Δt_2

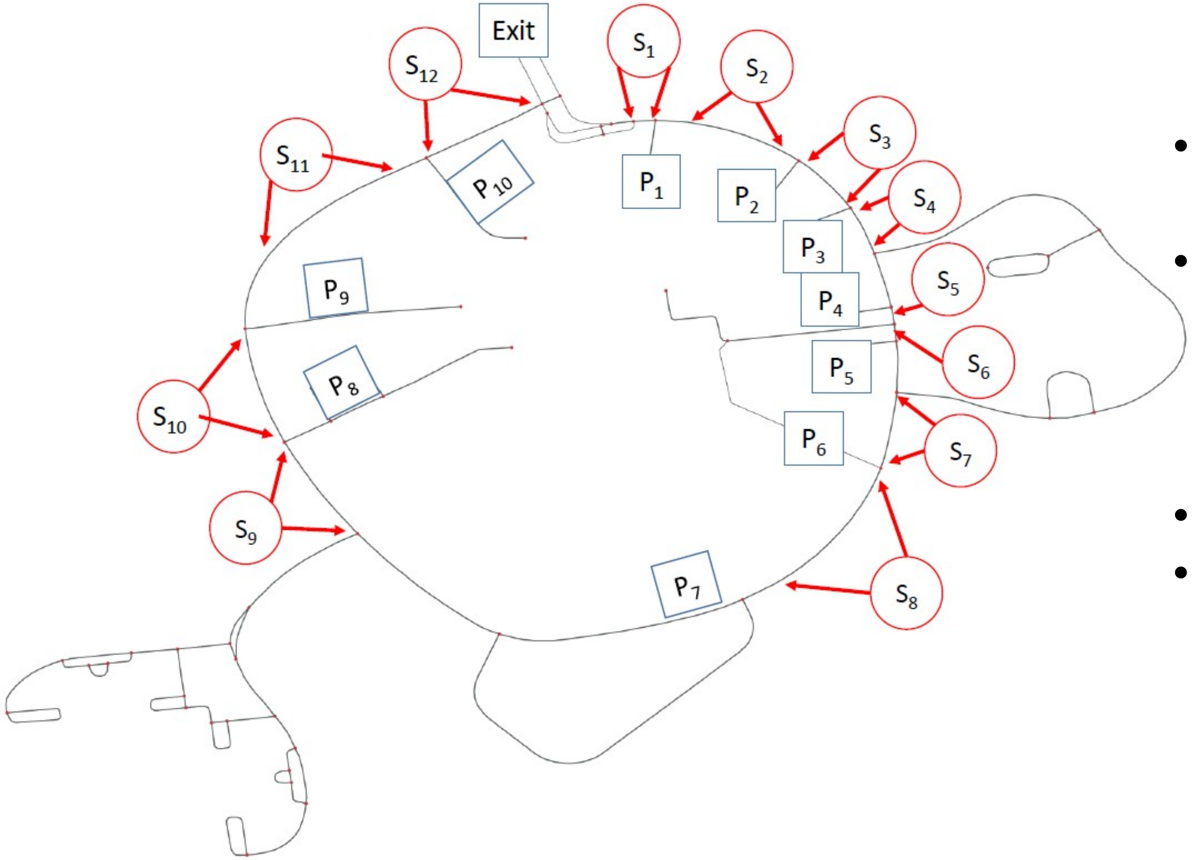
Total fuel consumed



Number of vehicles in the network

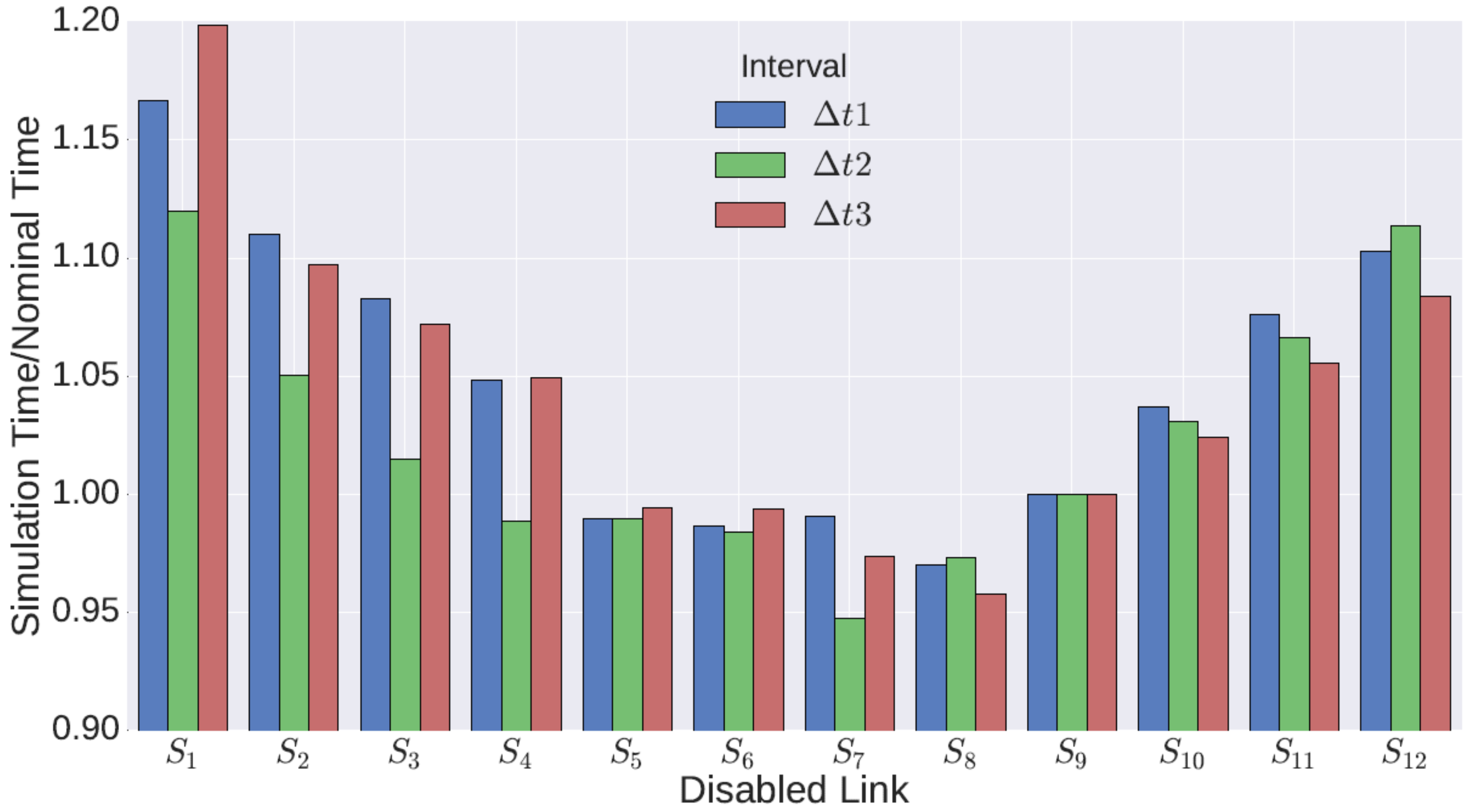


Small scale simulation UMass Dartmouth

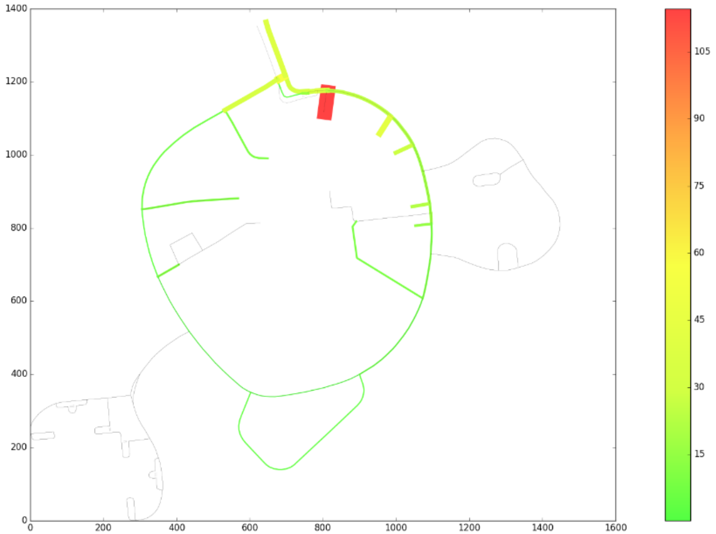


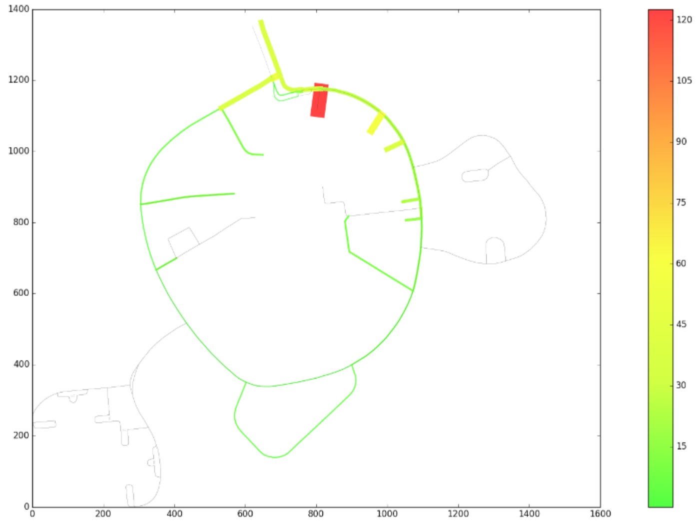
- Speed Limit
  - 30 miles/hour
- Time intervals
  - Δt_1 = 0 – 3000 sec
  - Δt_2 = 3000 – 6000 sec
  - Δt_3 = 6000 – 9000 sec
- 4000 vehicles depart campus
- Destination is the exit node

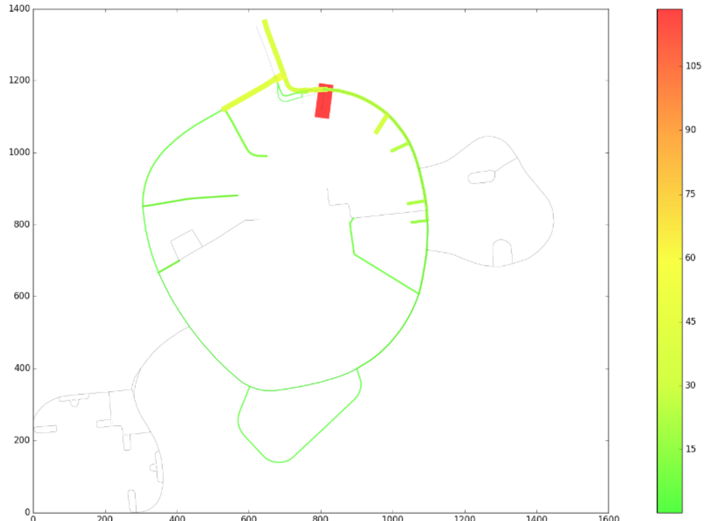
UMassD Results



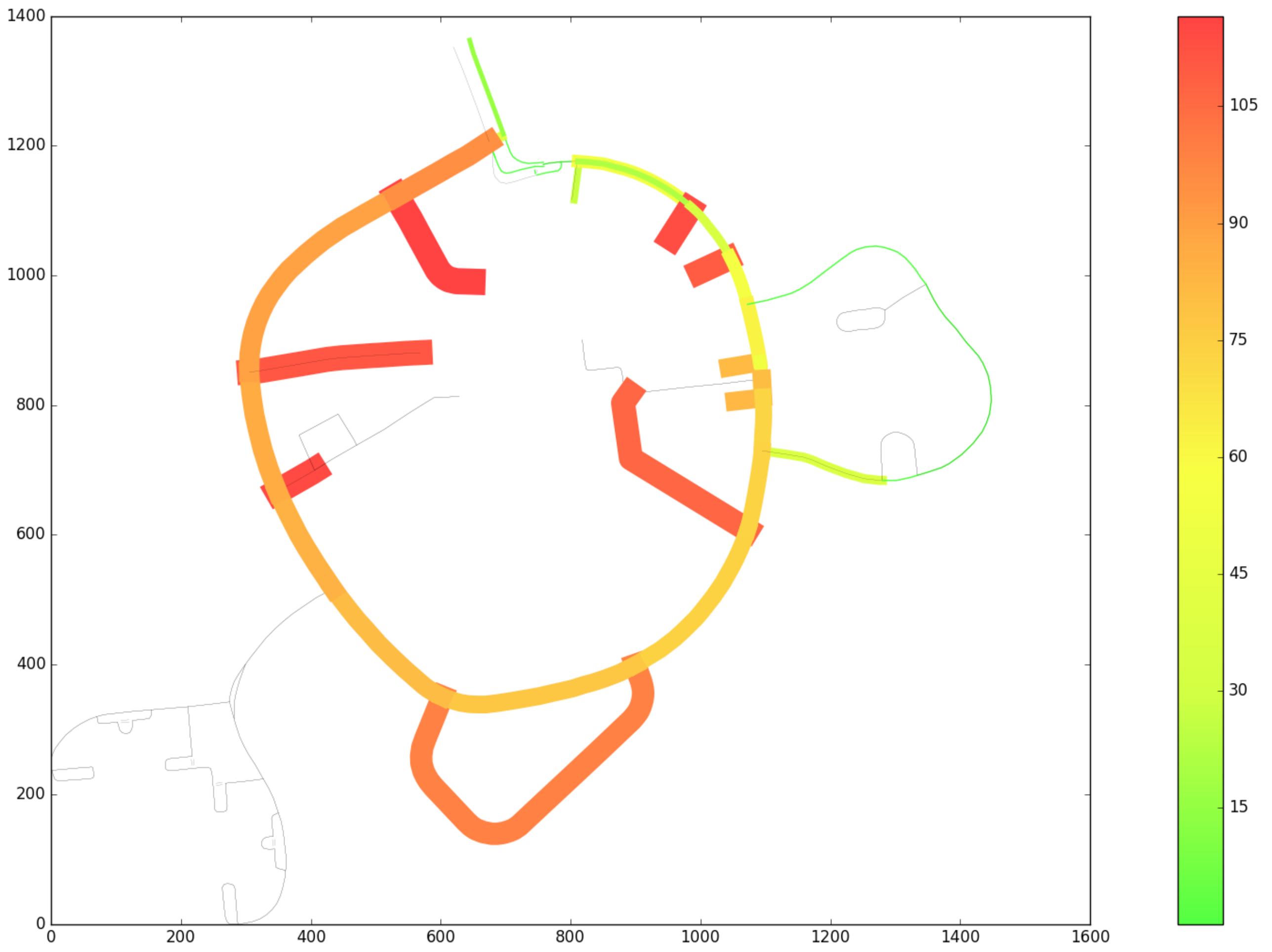
UMassD Nominal



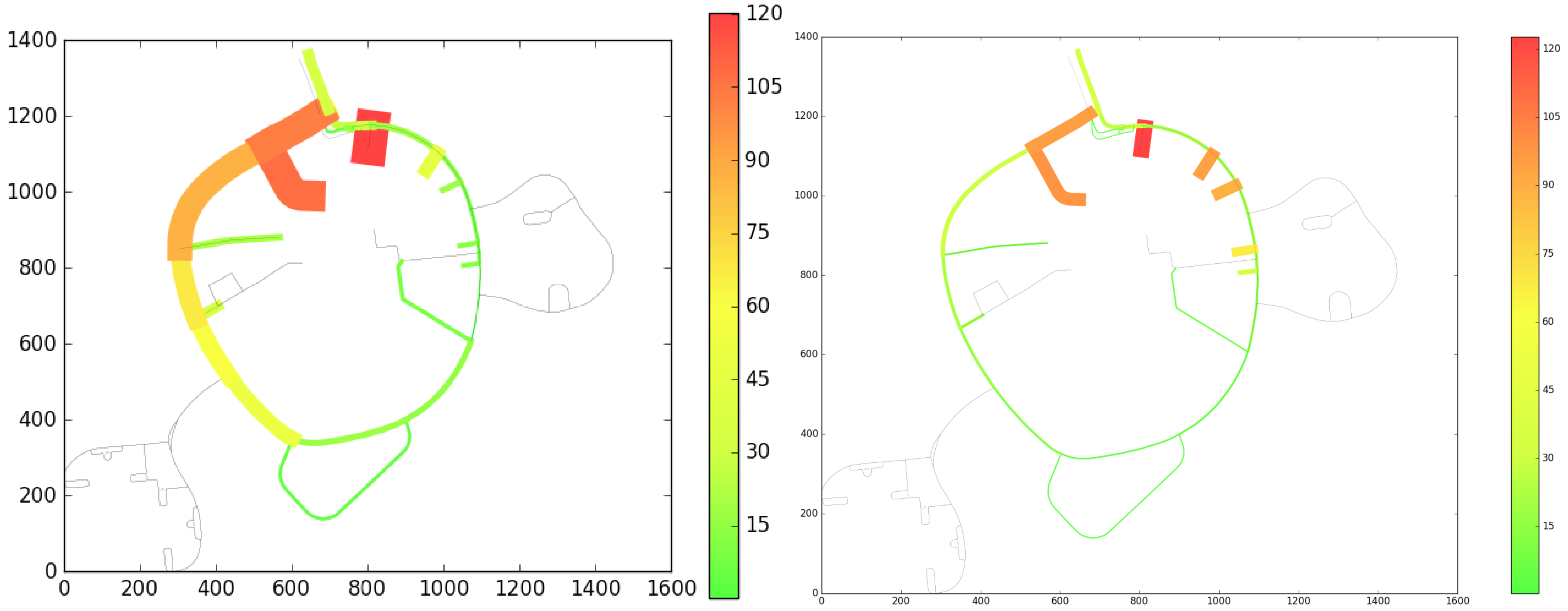




UMassD S1 @ Δt_3 (Worst Case)



UMassD S7 @ Δt_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