ROBUSTNESS OF THE WASHINGTON DC METRO SYSTEM (WMATA)

Complex Network Analysis

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CONTENT

Context

Data & Implementations

Simulation

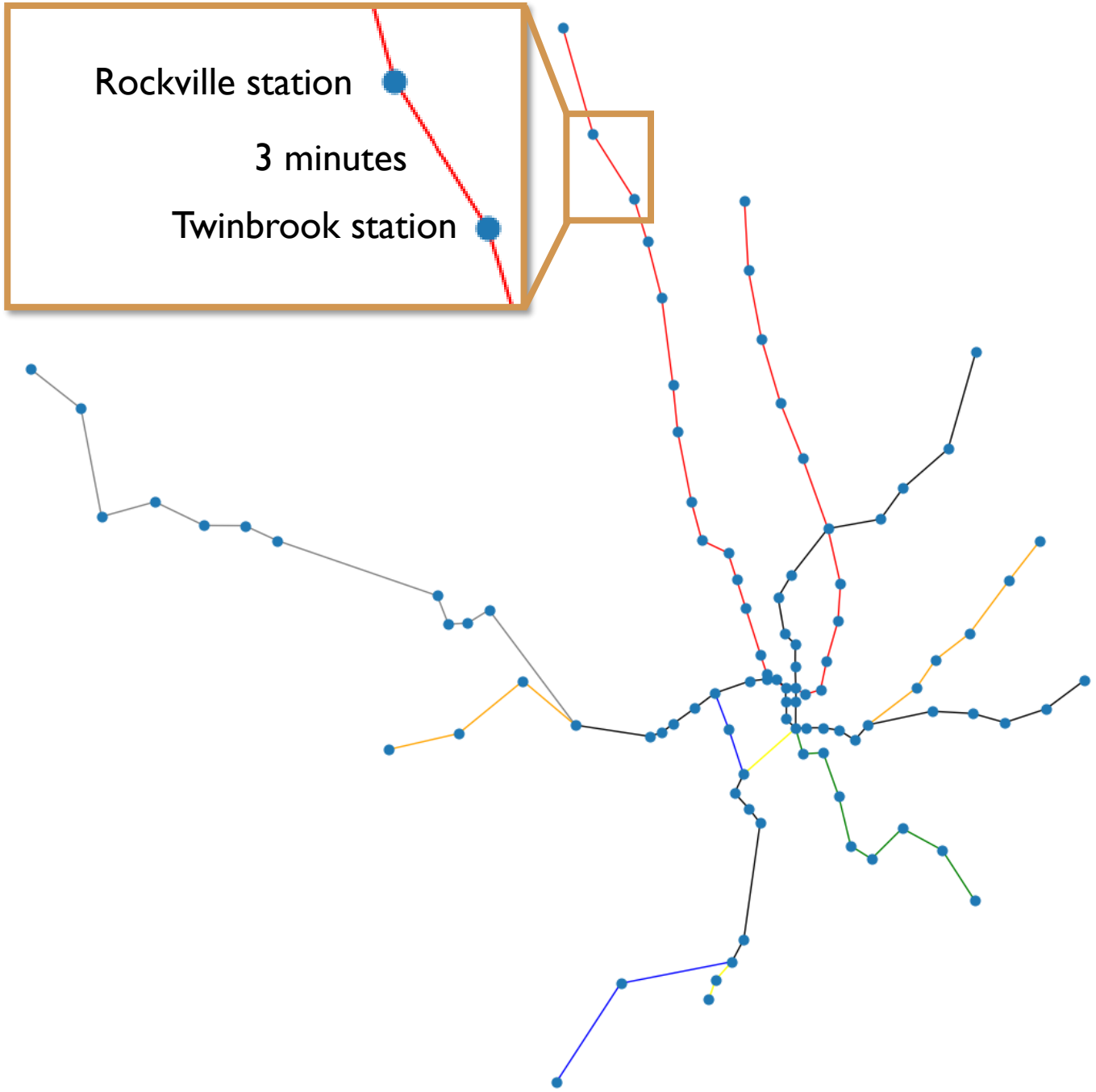
Analysis

Results

WASHINGTON METRO SYSTEM

Characteristics

- 97 metro stations (9 transfer stations)
- 6 metro lines
- 326,300 passengers per weekday (2022) – 3rd most in USA
- System length of 208 km (129 mi)



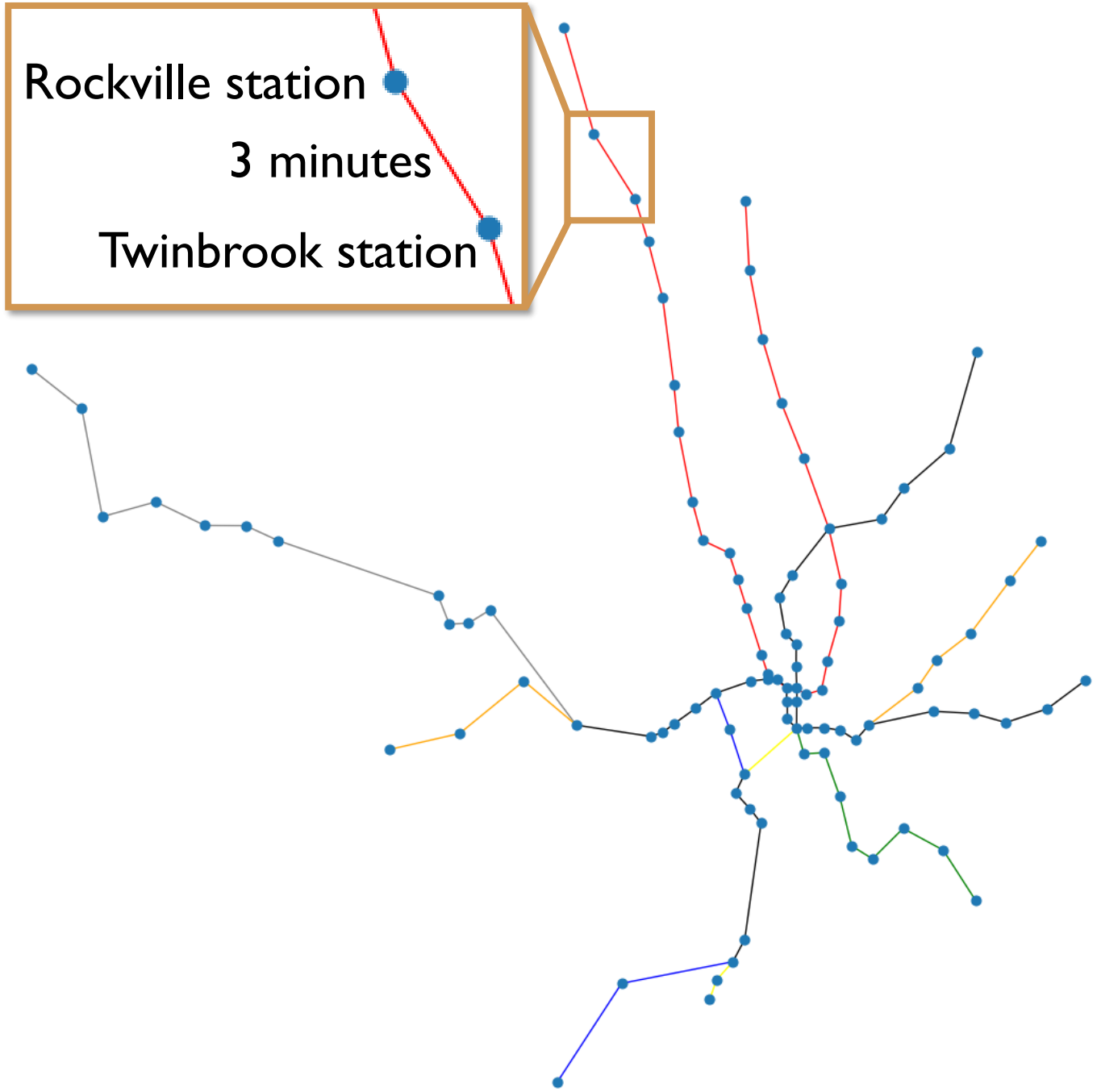
WASHINGTON METRO STATION

Characteristics

- 97 nodes - stations
- Edges: connects adjacent stations
- Weights: travel time (minutes) from station A to station B
- 2 graphs: directed and undirected
- 1 connected component

Data Used

- Station position (latitude and longitude)
- Travel time between stations
- Traffic data (2017 Women's day)



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DATA & IMPLEMENTATION

Data types

- CSV
- JSON via APIs

Tools

- API tool
  - Pull real-time transit data
- Pandas/Python
  - Data pre-processing
  - Simulations
- NetworkX
  - Graph implementation
  - Graph visualizations
  - Graph analysis
  - Useful libraries/functions

ROBUSTNESS/ SCALE-FREE NETWORKS

Important network properties in the context of transportation systems

- **Robustness**
  "the ability of a network to maintain a certain level of structural integrity and original functionality after nodes or edges experience random or deliberate attacks"

- **Scale-free network**
  "A Scale Free Network is one in which the distribution of links to nodes follows a power law. The power law means that the vast majority of nodes have very few connections, while a few important nodes (we call them Hubs) have a huge number of connections."

ATTACK TYPES

Random (failures)

- Nodes or edges are pick arbitrarily (at random)

Targeted (attacks)

- Nodes or edges are picked based on system properties:
  - Station location
  - Number of lines station serves
  - Line capacity
- Nodes or edges are picked based on network properties:
  - E.g., centrality measures

TRAFFIC SIMULATION

1. Simulate destination of each passenger, given their entry to the system

   Over 1M passengers

2. Determine path of each passenger, based on shortest path

3. Simulate all traffic, calculate:

   Total and average trip time

   Total and average number of stops

4. Attack the system
   1. Single attacks
   2. Nested attacks (of the same type)

ANALYSIS OF WHOLE NETWORK

Density: 0.021

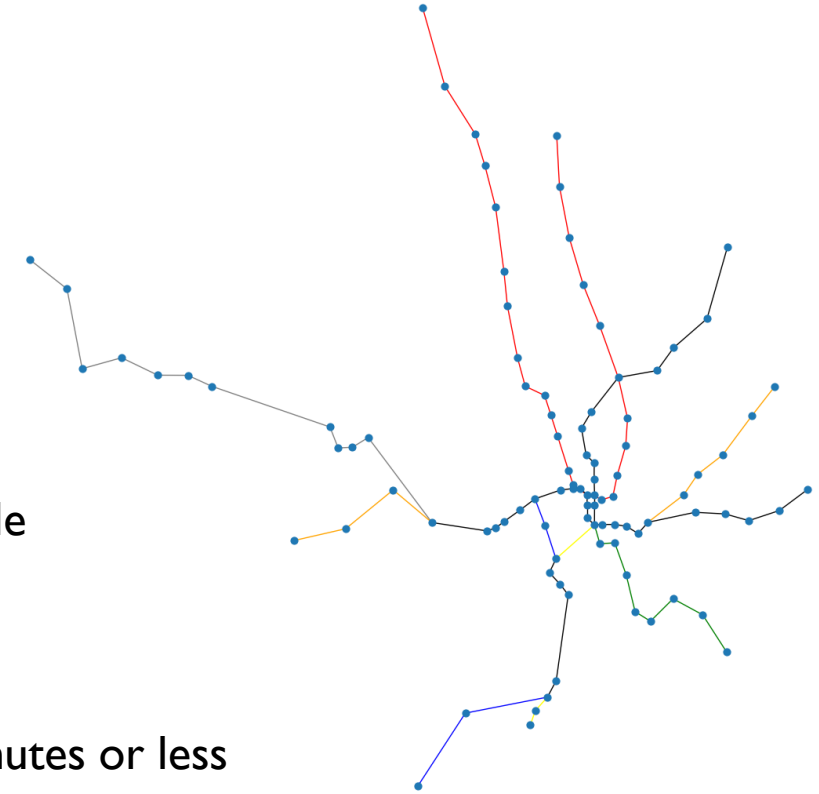
- Relatively sparse
- 2.1% of the stations have direct connections between them

For commuters:

- ➢ could make it more difficult for commuters to travel quickly and efficiently between different stations
- ➢ make the system easier to navigate, since there are fewer possible routes to choose from

Diameter: 34 minutes

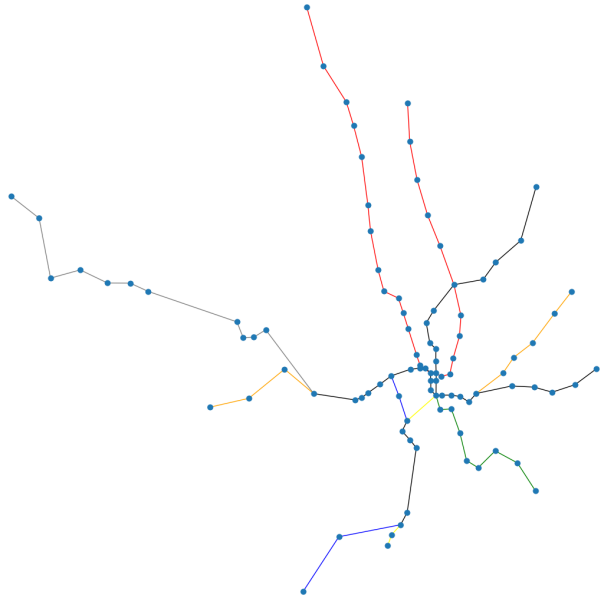
- longest possible journey time between any two stations is 34 minutes or less

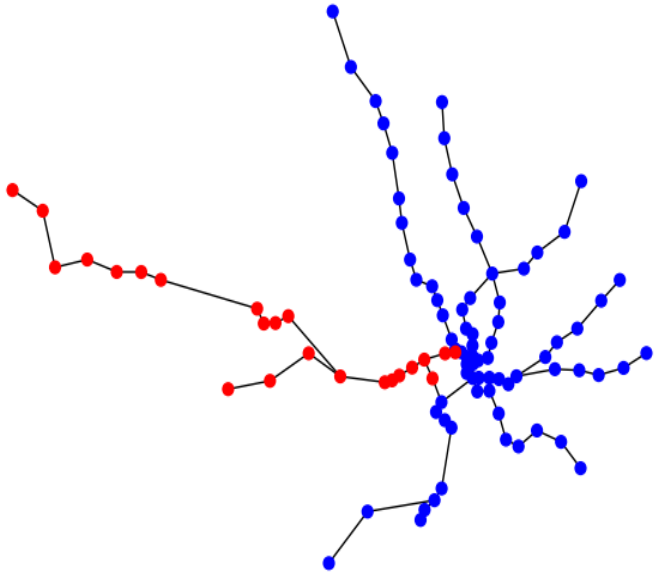


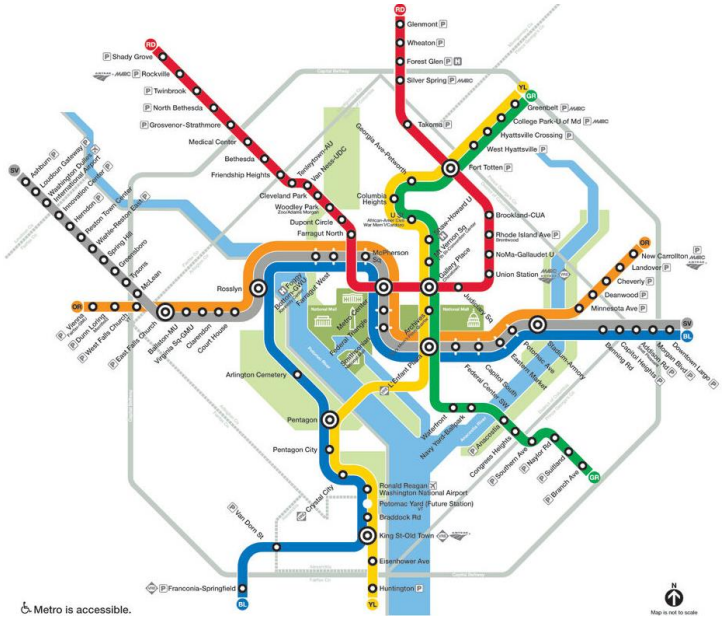
ANALYSIS OF WHOLE NETWORK

Fiedler value : 0.016

- not be well-separated into distinct clusters or communities



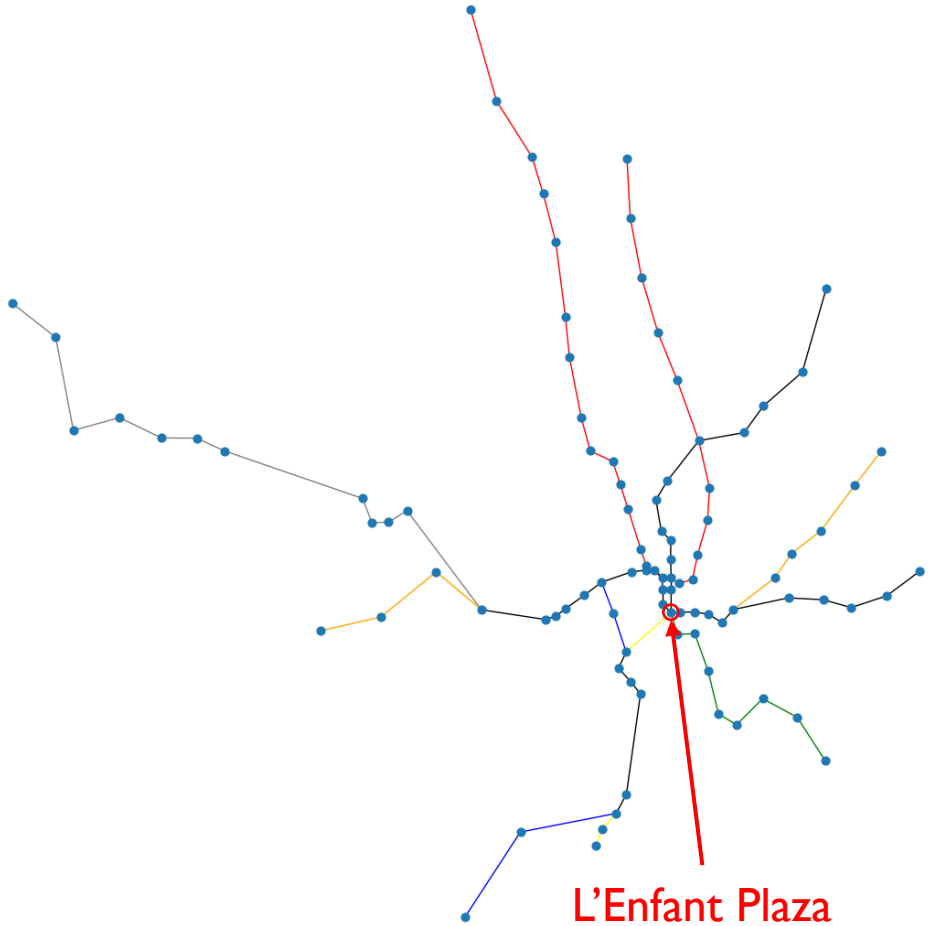




ANALYSIS OF WHOLE NETWORK

Centrality measures of the entire network:

1. Degree centrality : L'Enfant Plaza
2. Eigenvector centrality : L'Enfant Plaza
3. Betweenness centrality : L'Enfant Plaza
4. Closeness centrality : L'Enfant Plaza



ANALYSIS OF WHOLE NETWORK

Statistics on Simulation of whole Network

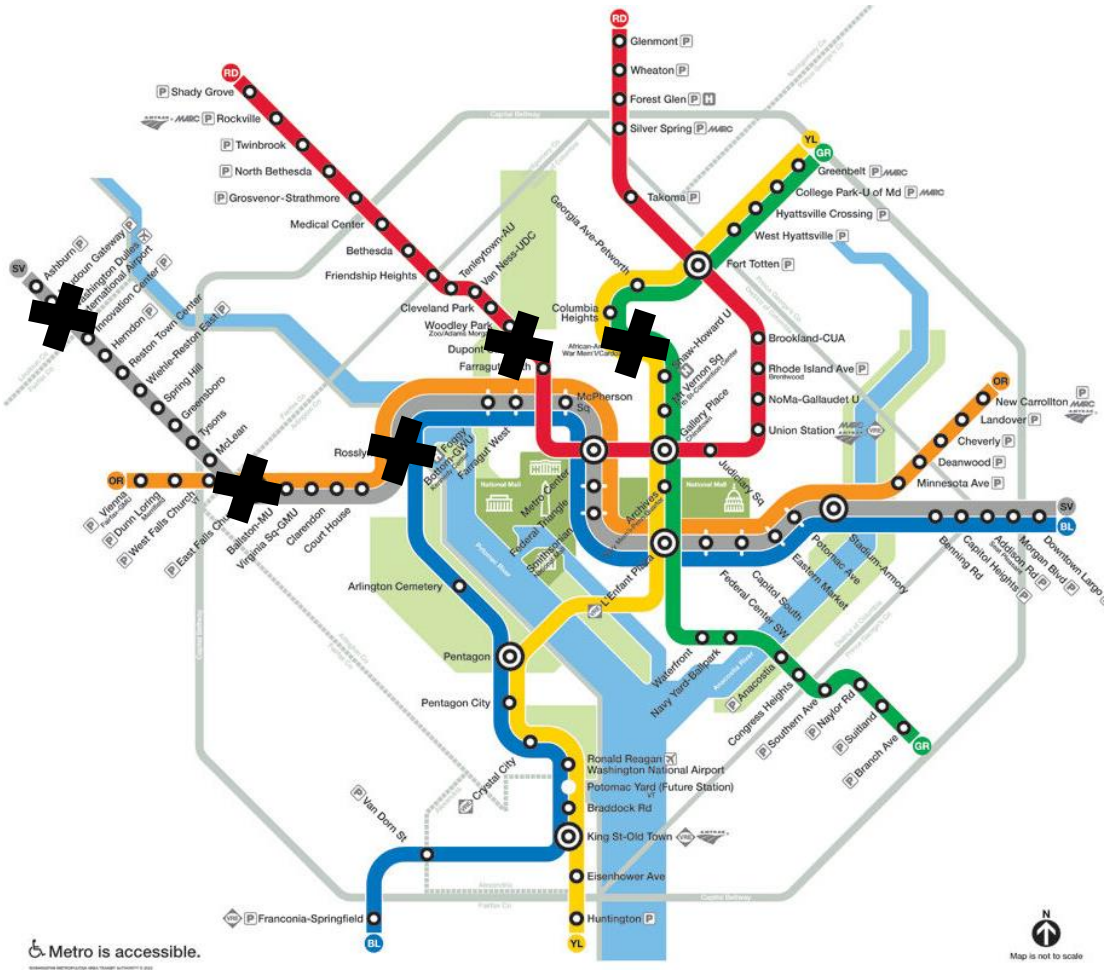
Baseline Scenario

Average Trip Time per Passenger (minutes)	Average Shortest Path Length (minutes)	Average Number of Stops per Passenger
26.3	12.49	10.9

ANALYSIS OF RANDOM ATTACK

Attacked stations

- Washington Dulles International Airport
- East Falls Church
- Rosslyn
- U Street/African-Amer Civil War Memorial/Cardozo
- Dupont Circle



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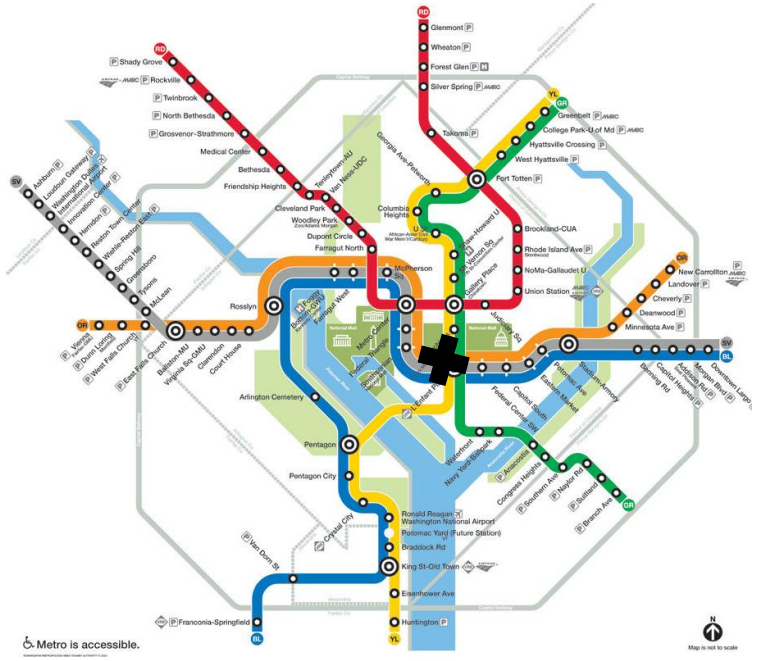
4. Closeness centrality : L'Enfant Plaza / Gallery Pl-Chinatown

Average Trip Time per Passenger (minutes)	Average Shortest Path Length (minutes)	Average Number of Stops per Passenger
35.1	41.84	10.97

ANALYSIS OF TARGETED ATTACK

Attacked station: L'Enfant Plaza



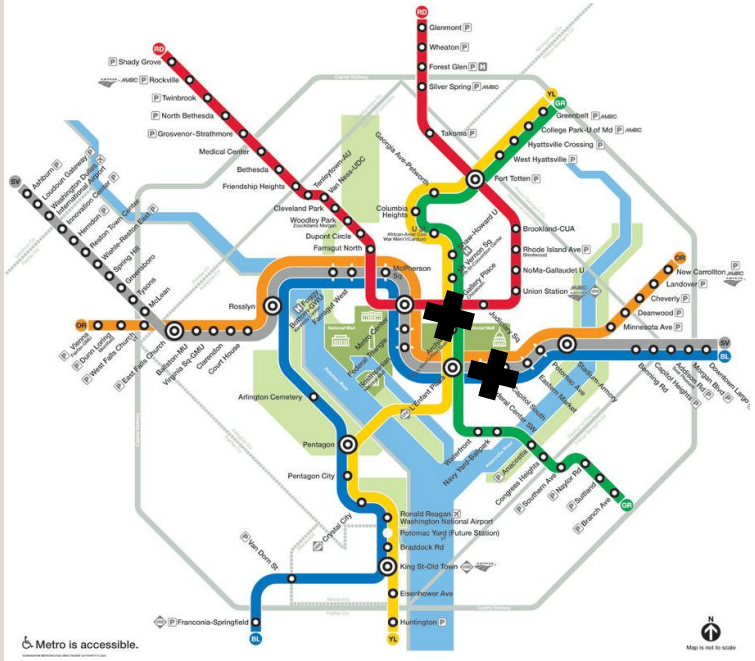
Centrality measures of the targeted network:

1. Degree centrality : Fort Totten, Gallery Pl-Chinatown, Metro Center
2. Eigenvector centrality : Metro Center
3. Betweenness centrality : Metro Center
4. Closeness centrality : Metro Center

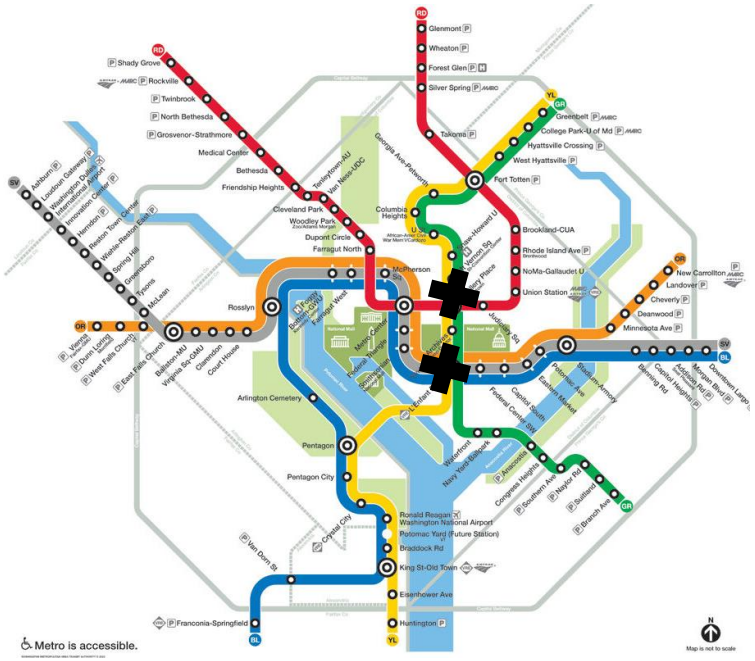
Average Trip Time per Passenger (minutes)	Average Shortest Path Length (minutes)	Average Number of Stops per Passenger
38.9	46.4	11.81

ANALYSIS OF SUCCESSIVE TARGETED ATTACK

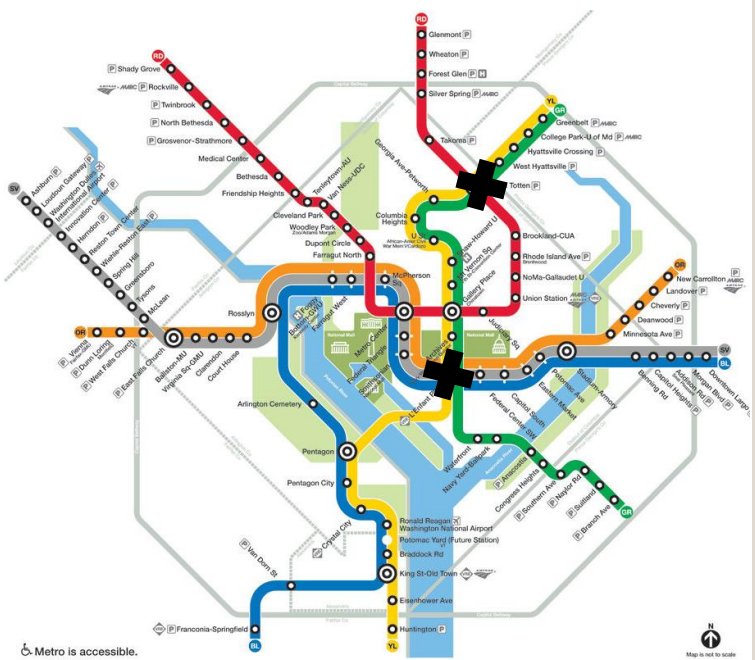
L'Enfant Plaza & Metro Center



L'Enfant Plaza & Gallery Pl-Chinatown



L'Enfant Plaza & Fort Totten



Average Trip Time per Passenger (minutes)	Average Shortest Path Length (minutes)	Average Number of Stops per Passenger
51.3	54.42	11.72

RESULTS & SUMMARY

Attack type	% increase in total trip time	Change in Average shortest path length (minutes)
Baseline (no attack)	0%	0
Random single (average)	9.86%	29.35
Targeted single	48.05%	33.91
Random 2x (average)	33.80%	32.11
Targeted 2x (average)	95.14%	41.93
Random 3x (average)	67.36%	37.31
Targeted 3x (average)	144.17%	59.11

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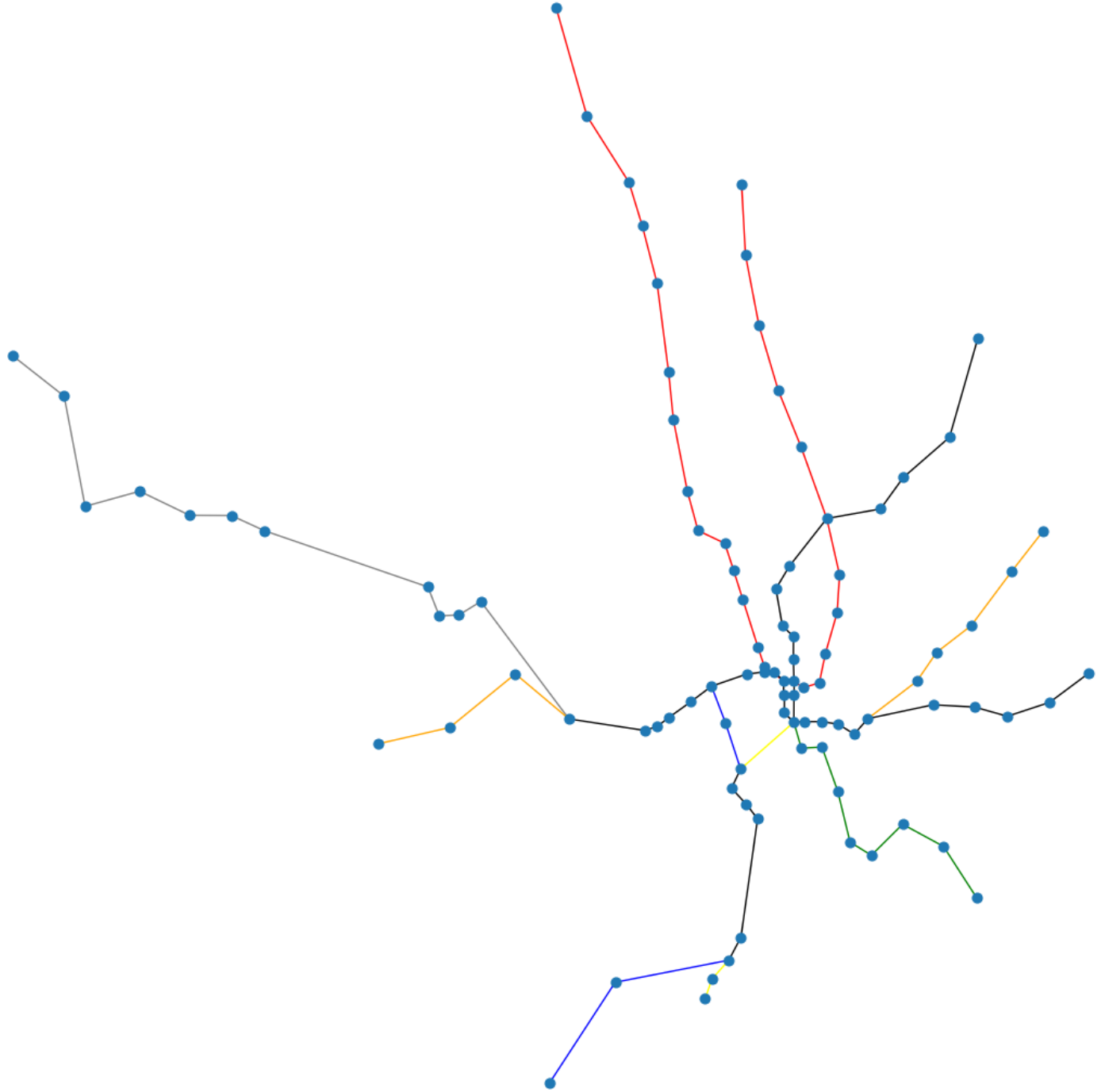
- Based on the average shortest path length, the network does not appear to be robust to either random failures or targeted attacks
- This does not follow the property of scale-free networks

THANK YOU!

Q/A



APPENDIX