Networks of Urban Vulnerability

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Sponsor: Lockheed Martin Advanced Technology Laboratories (ATL)

Urban Vulnerability

Purpose & Background

Cities are undergoing a growth in complexity as its urban systems rapidly emerge as intimately connected networks. This leaves them with increasing uncertainties related to disruptive impacts.

Measure, Identify and Visualize

- ➢ Level of Disruption and Vulnerability Characteristics
- ➢ Synergistic Effects arising from Multiple Disruptions

"the whole is greater than the sum of its parts".

Context: New York City Subway system

End Goal:

- ➔ Support Municipal Governments and Associated Entities in their efforts to Mitigate Exposure to Loss experienced by City Residents.

Context

New York City Subway system

Relevant

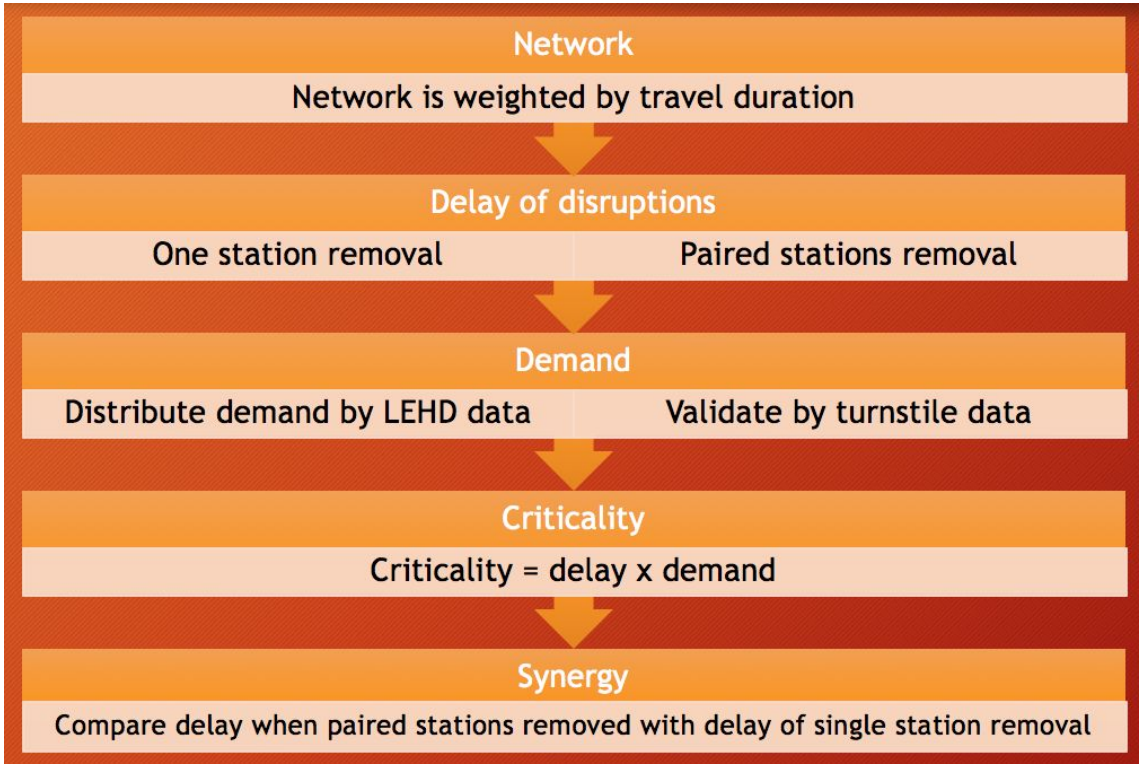
- Significant Complexity and Interconnectedness
  - 472 Stations
  - Possible Routes are Exponential in Scale
  - Connections to Other Modes

Purposeful

- Vulnerable to Considerable Social and Economic Loss
  - 5.7 million Passengers / Day (7th Largest in the world)
  - Overlaid by NYC's 27,888 residents / mile (1st in the U.S.)
  - Surrounded by 266 Skyscrapers (2nd in the world)

> Focus on Morning Rush-Hour Commute

Methodology Flow



Network Model

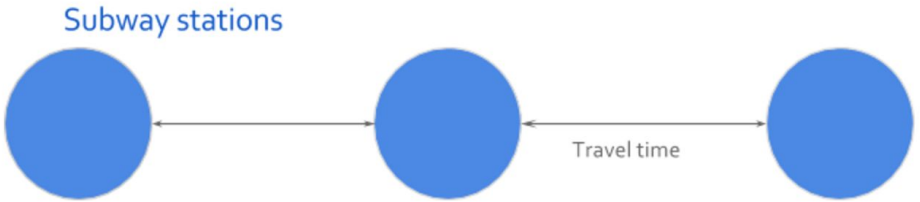
Motivation: simple network with travel time as edge does not account for transfer and waiting time.

The subway system is modeled as a directed network, weighted by time.

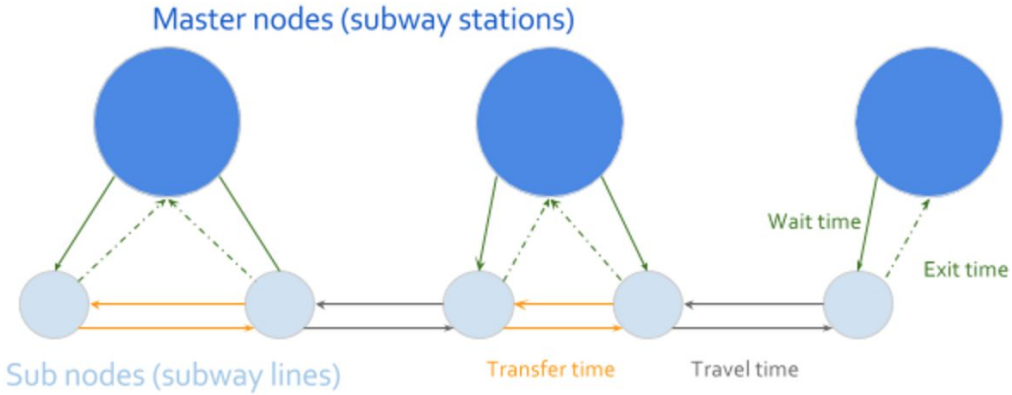
Nodes:
1) stations (master nodes)
2)lines within each station (sub nodes).

Edges:
1) travel
2) transfer
3) wait time

Simple Network

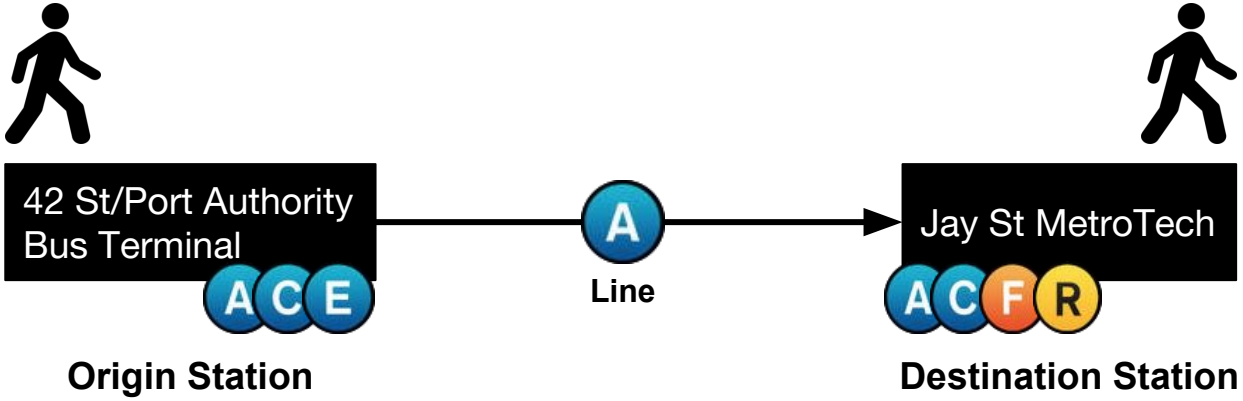


Our Network



Subway travel
(with no line change)

Travelling from -
- **42 St/Port Authority Station to**
- **Jay St MetroTech Station**



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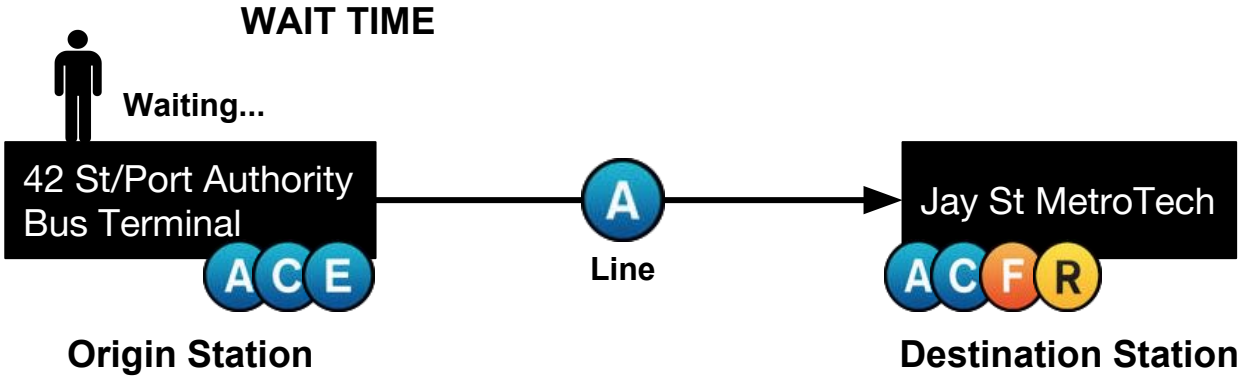

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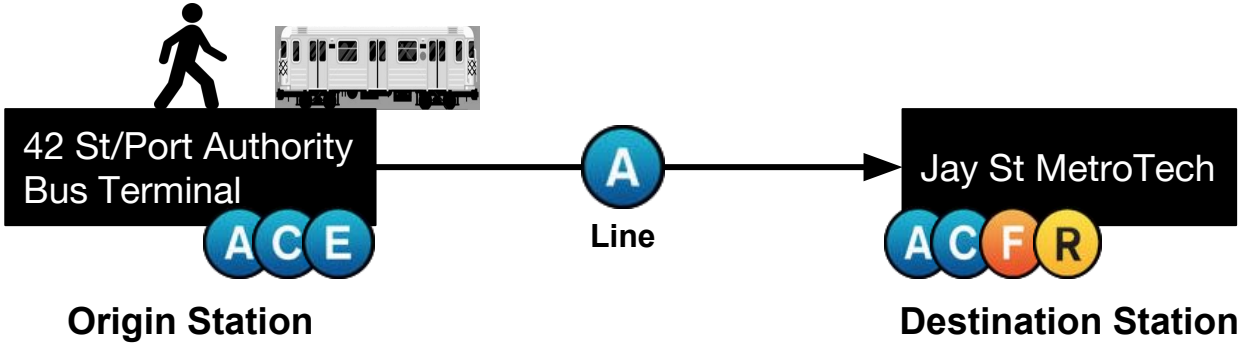

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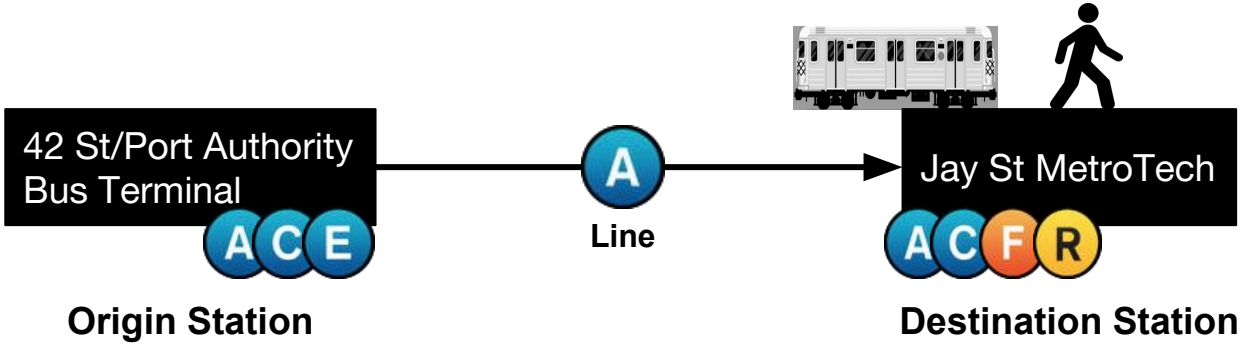

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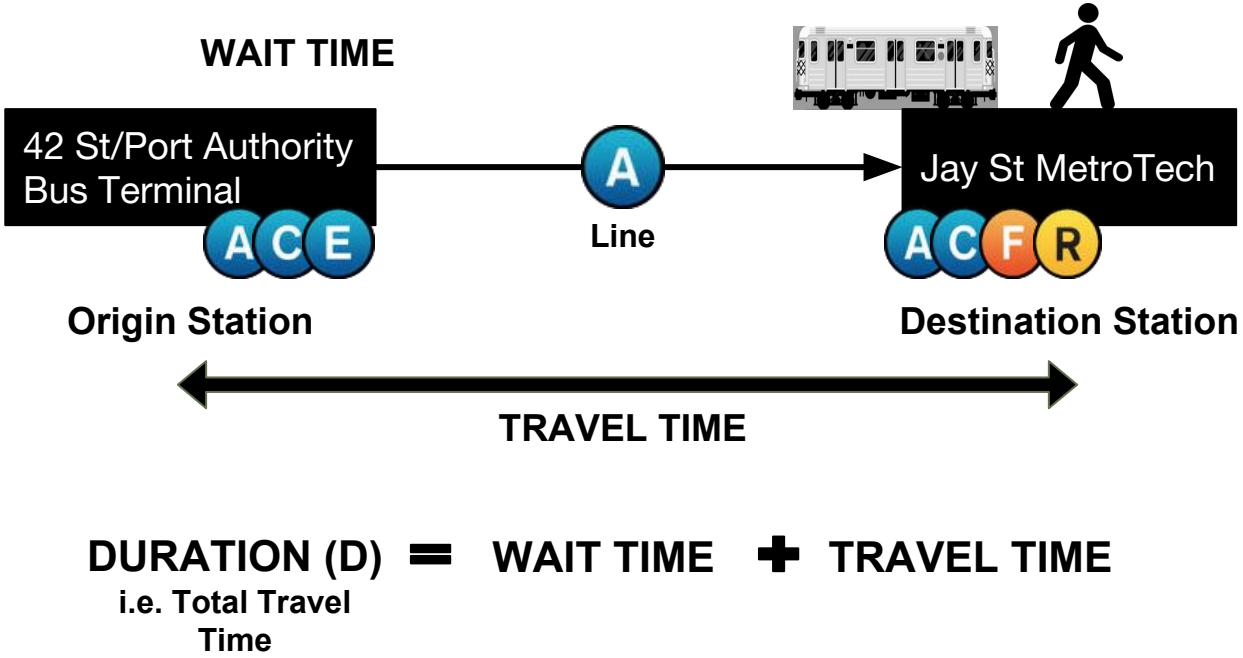

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(with transfer)

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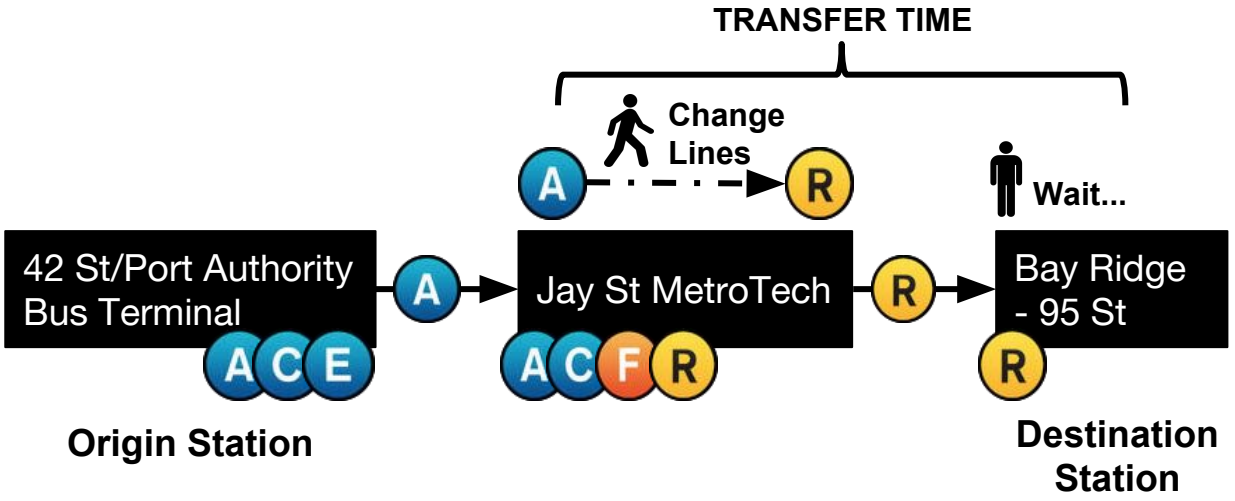

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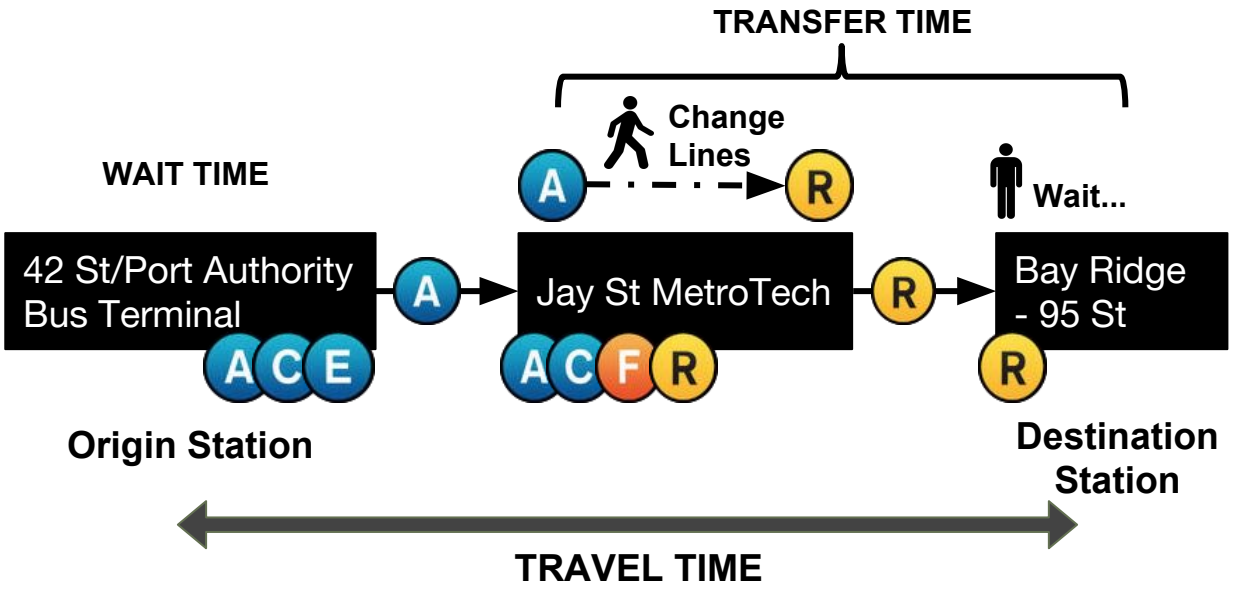

DURATION (D) i.e. Total Travel Time = **WAIT TIME** + **TRANSFER TIME** + **TRAVEL TIME**

Network Model

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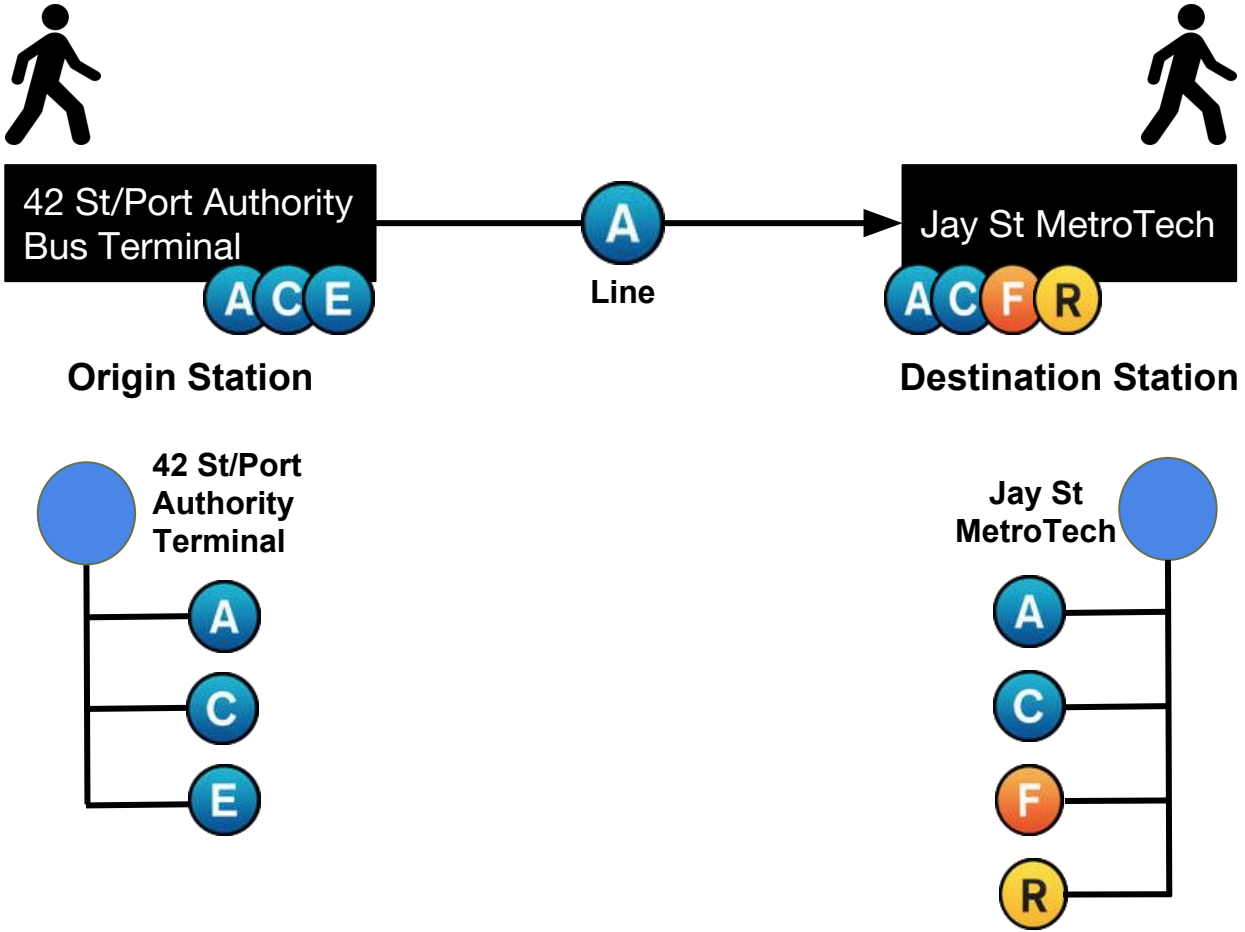

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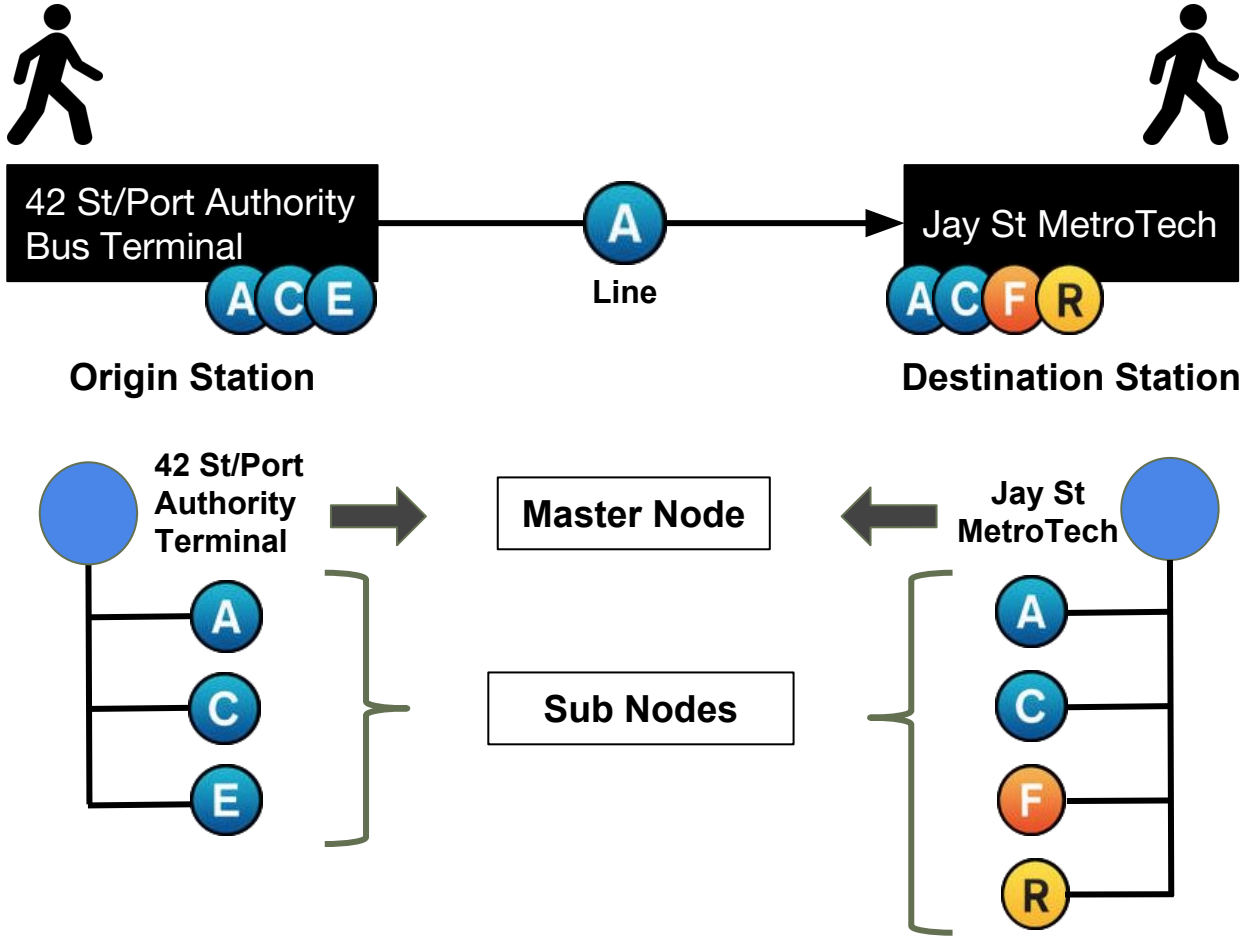

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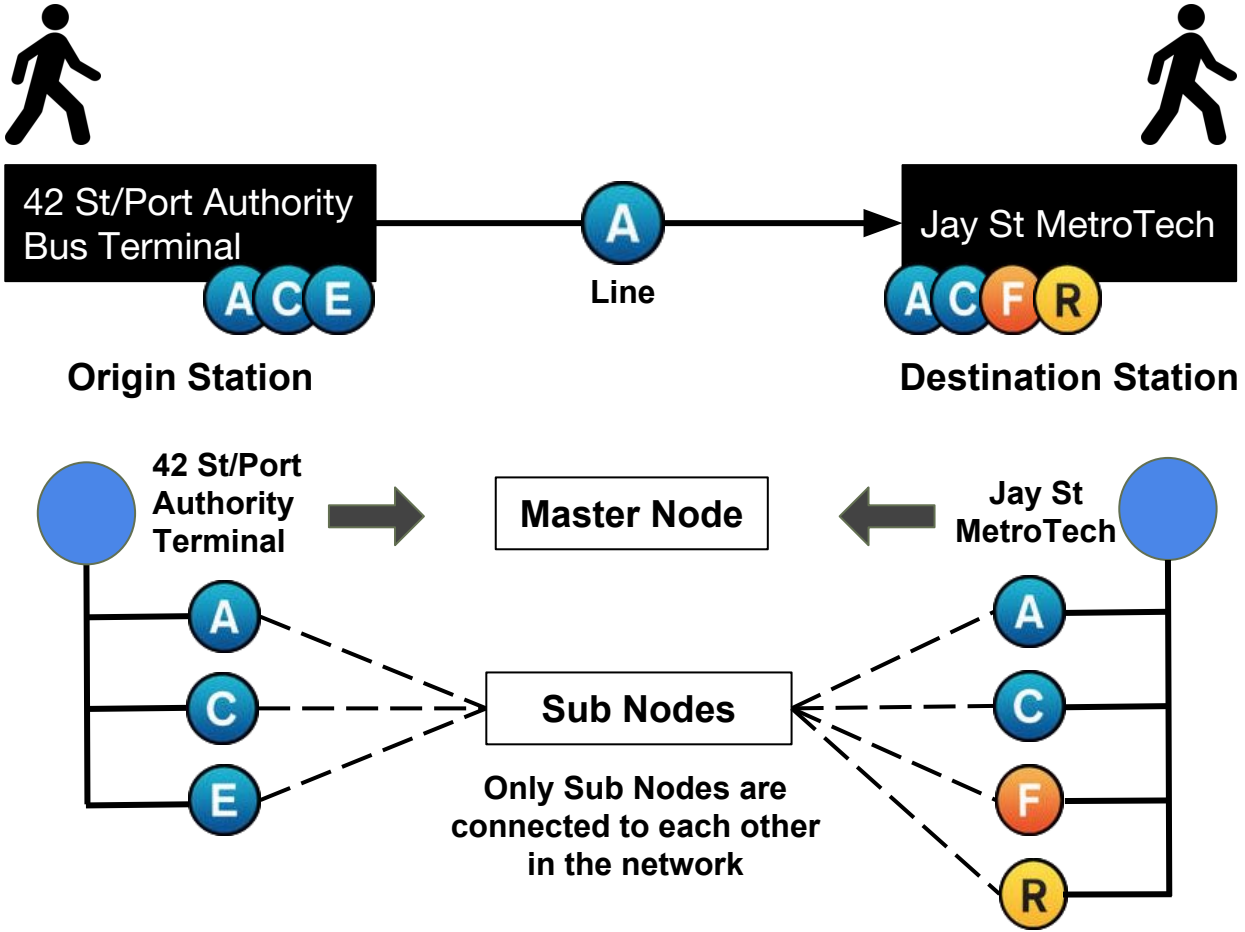
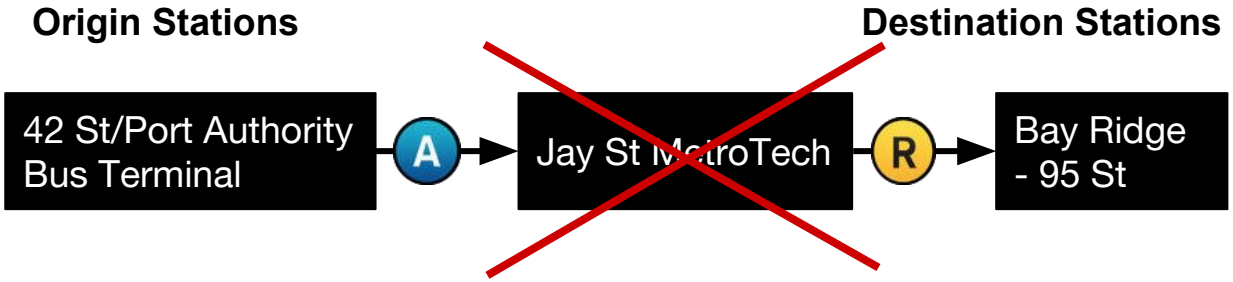


Subway travel
(with transfer) - Population and Delay Impact

Travelling from -
- **42 St/Port Authority Station to**
- **Jay St MetroTech Station**

1-Station Disruption



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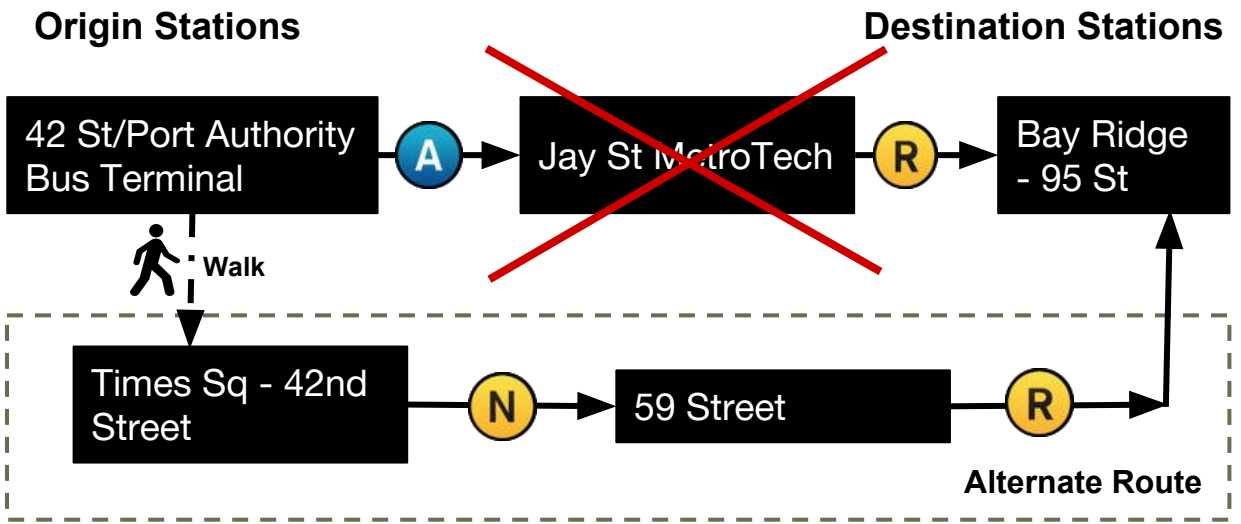

Subway travel
(with transfer) - Population and Delay Impact

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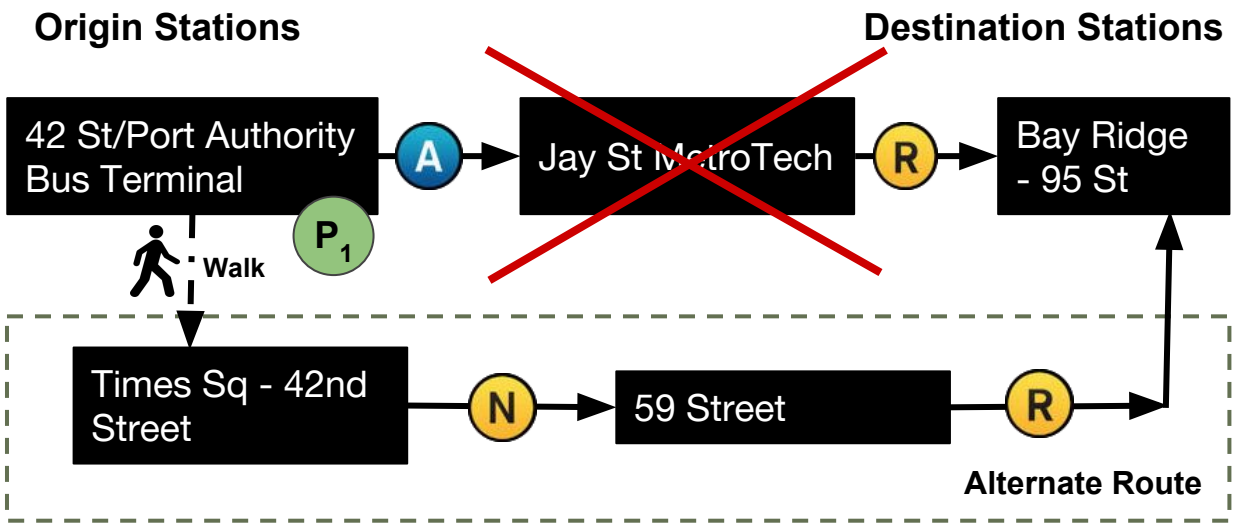
1-Station Disruption



P_1 = Passenger demand between the origin & destination stations.

D_1 = Delay caused due to station disruption.
Difference between the alternate and shortest travel routes.

$$\text{Criticality(Jay St MetroTech Station)} = P_1 \times D_1$$

Subway travel
(with transfer) - Population and Delay Impact

Travelling from -
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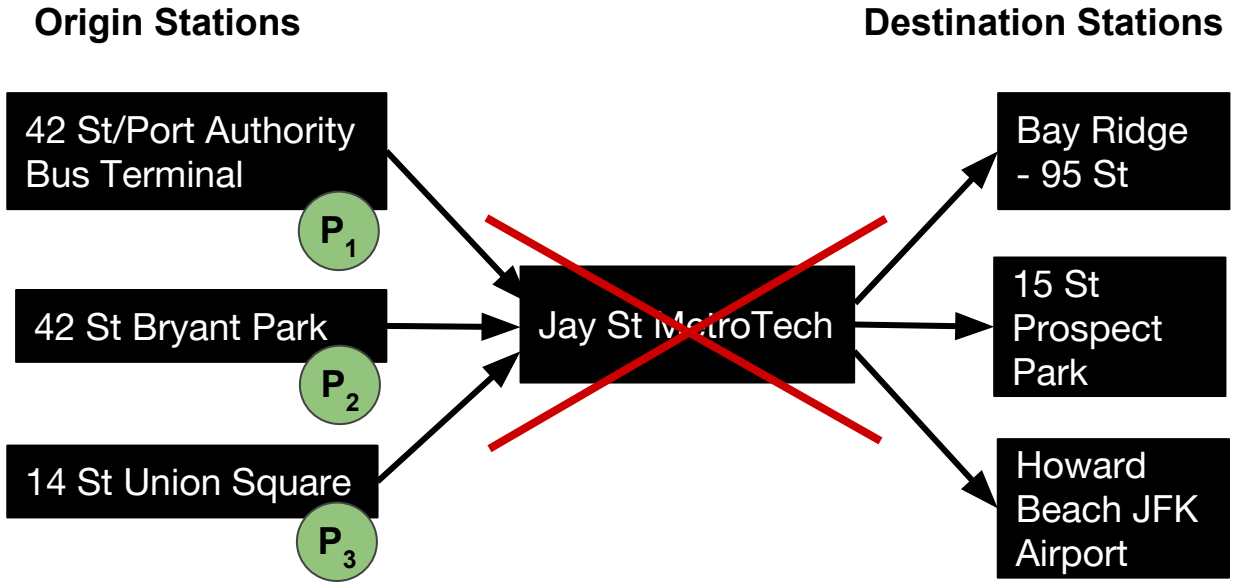
1-Station Disruption



Subway travel
(with transfer) - Population and Delay Impact

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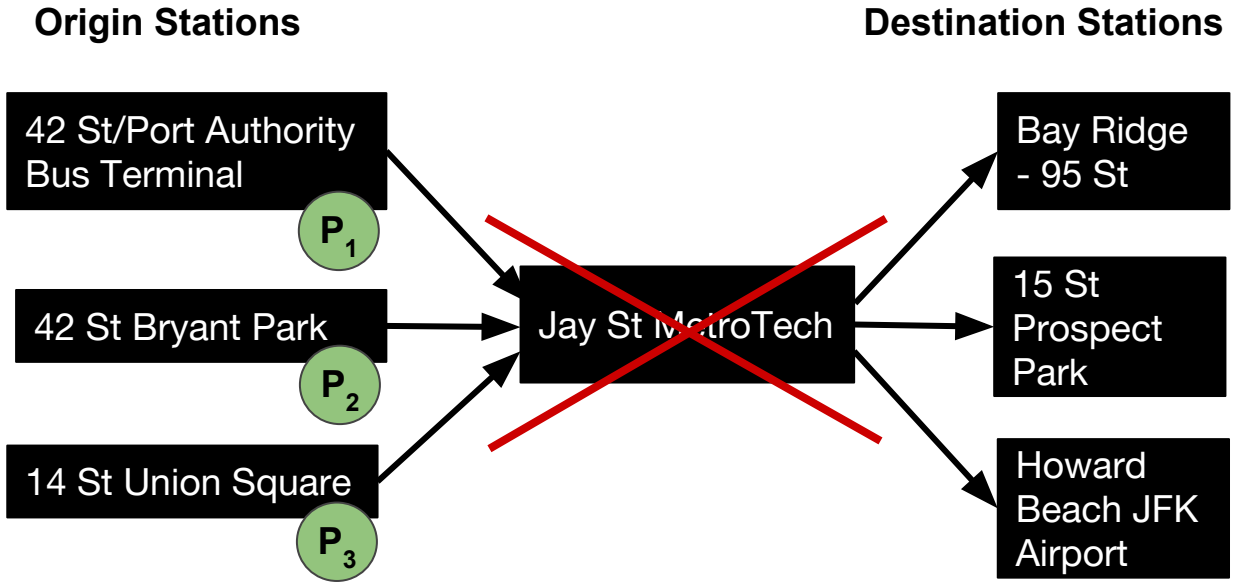


$$C(X) = \sum_{a,b} D_{a,b}(X) \times P(a,b)$$

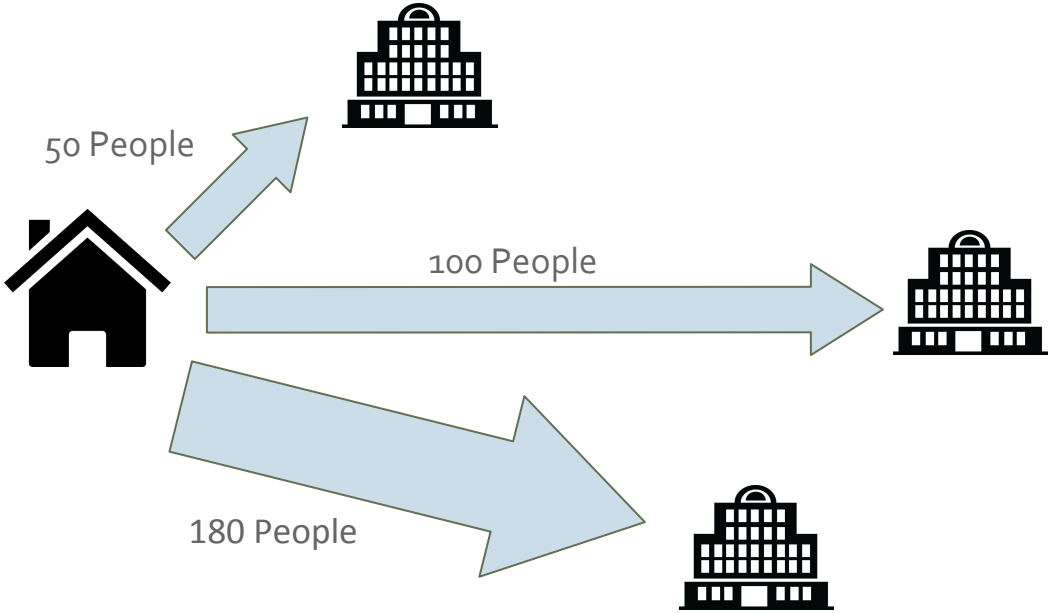
C = Node Criticality
X = Disrupted Station
D = Delay or Difference in Duration between all the a,b node pairs.
P = Passenger demand between a and b

Origin-Destination Passenger Flow

O-D data maps passenger flow to respective home and work Census Tracts.

We must determine which stations they use and which route they take.

Home-to-Work



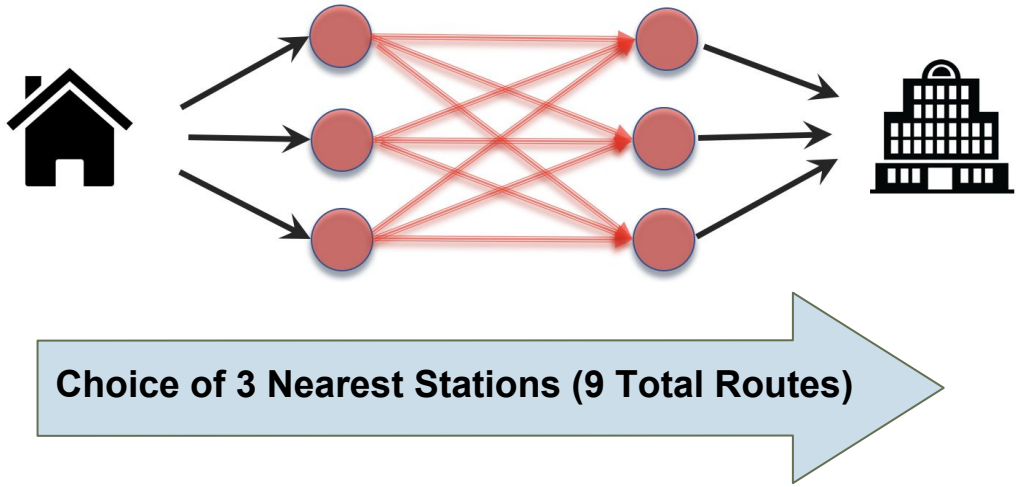
American Association of State Highway and Transportation Officials
AASHTO

- ➢ Home-to-Work Commuting by Transit Mode
- ➢ Based on Census Tracts
- ★ Need to map to Stations / Routes

Demand Allocation Model

We assume each commuter chooses of one of 3 of their closest stations which best suits their preference for shortest overall trip time while accounting for preferences in walking distance, onboard duration, and other, unobservable factors.

From Census Tracts to Routes:



Likely Choice Based on:

- Short Distance to Station
- Short Trip Duration
- Other Unobservable factors

$$P_i = \frac{\exp^{-\lambda_1 t_i - \lambda_2 d_i}}{\sum_j \exp^{-\lambda_1 t_i - \lambda_2 d_i}} P_{a,b}$$

Demand Allocation Model

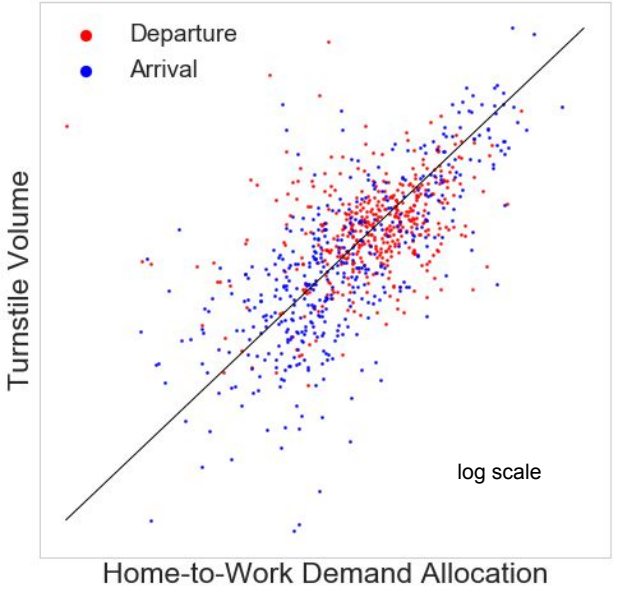
Model Selection & Parameter Fit

Fit / Validation

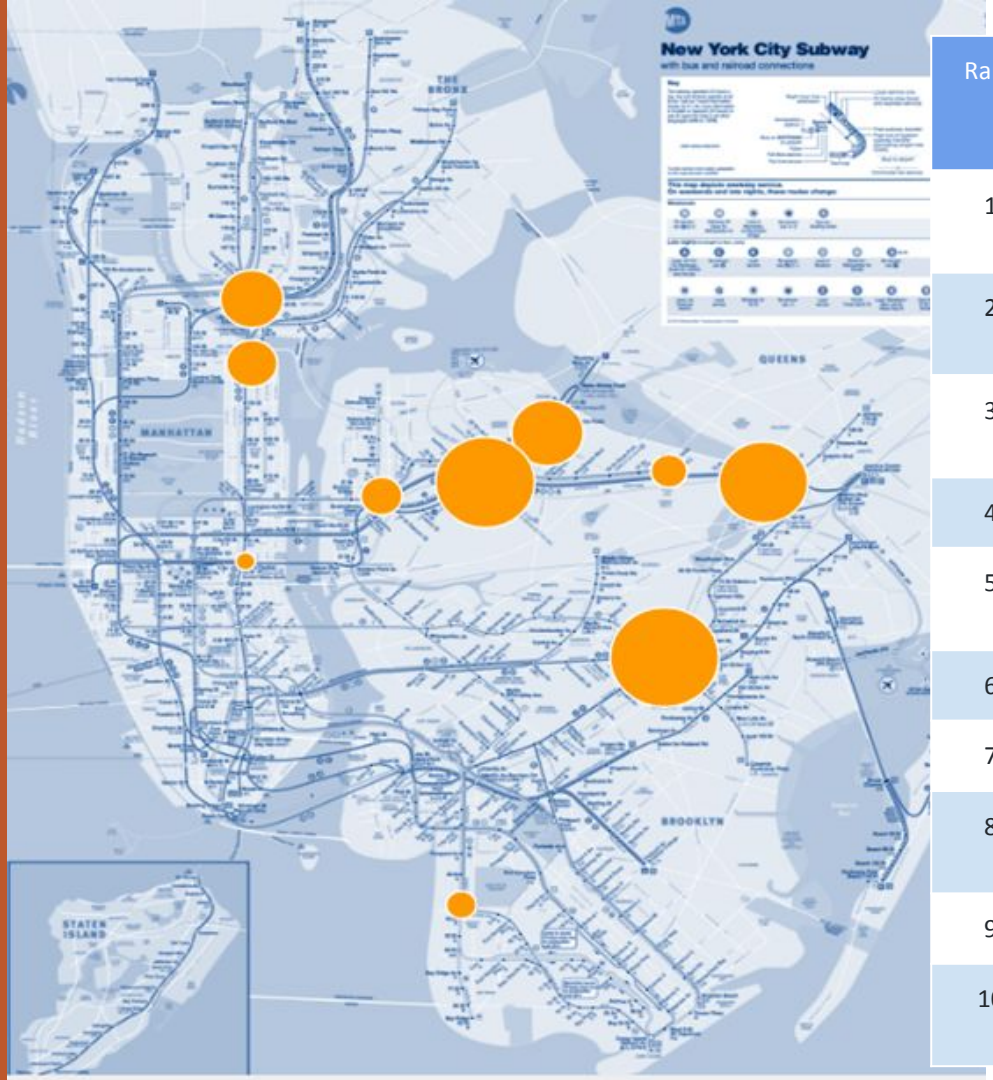
$$\sum_{station} (ODEntry_{station} - TnstEntry_{station})^2 + \sum_{station} (ODExit_{station} - TnstExit_{station})^2 \rightarrow min$$

SSR = .0069

Correlation Coefficient (Pearson):
Departures = .376
Arrivals = .728



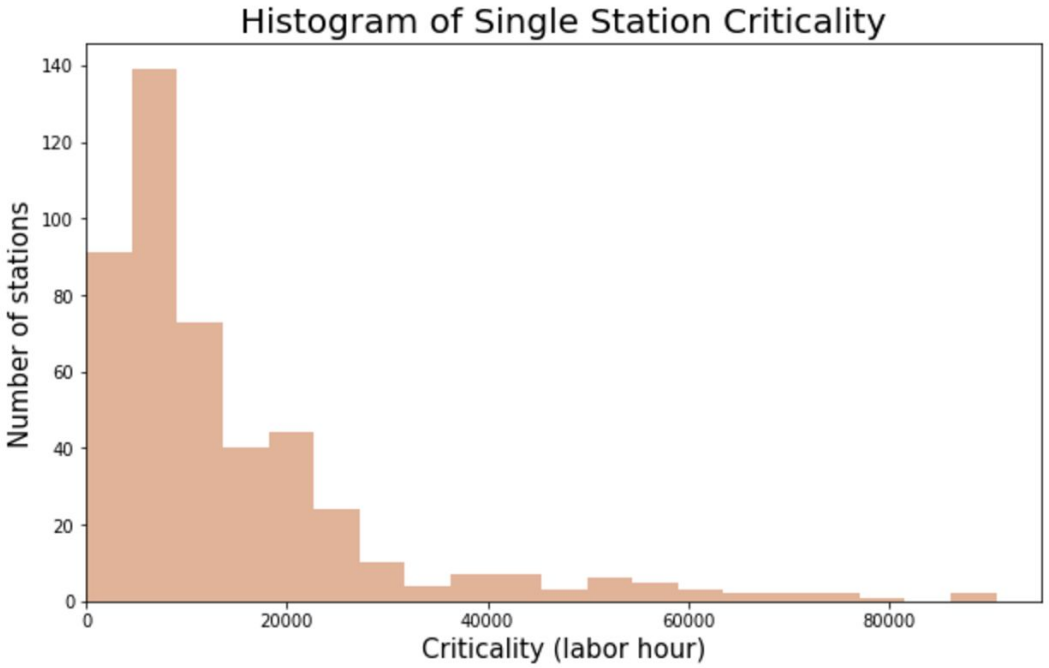
Findings: Single Station Criticality



Rank	Station	Delay (labor hour)
1	**Broadway Junction (A,C,J,L,Z)**	+90,668
2	**Jackson Heights - Roosevelt Avenue (E,F,M,R)**	+87,754
3	**Kew Gardens - Union Turnpike (E,F)**	+77,453
4	**Junction Blvd (7)**	+74902
5	**149 St - Grand Concourse (2,4,5)**	+73467
6	**125 St (4,5,6)**	+71193
7	**Queensboro Plaza (N,W,7)**	+69898
8	**Forest Hills - 71 Av (E,F,M,R)**	+66390
9	**36 St (D,N,R)**	+64838
10	**Grand Central - 42 St (S,4,5,6,7)**	+62119

Findings: Single Station Criticality

The distribution of criticality scores from single network disruptions skews to the low end.



Findings: paired criticality map

we calculated paired criticality for the most important pairs by

1) top 50 single station criticality,
2) stations which have more than 3 connected stations
3) stations have more than 2 lines going through

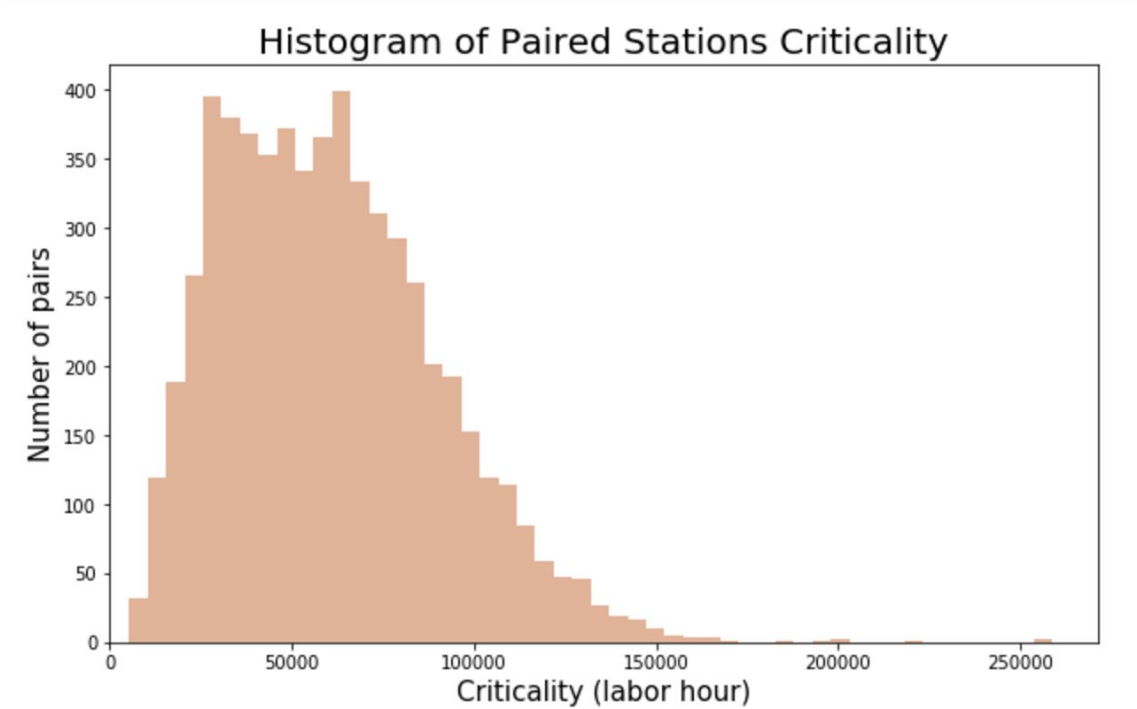
Altogether we will have 5565 pairs.

◆ paired criticality

Rank	Station 1	Station 2	Delay (labor hour)
1	Jackson Hts - Roosevelt Av (E,F,M,R)	Broadway Jct (A,C,J,L,Z)	258682.23
2	Jackson Hts - Roosevelt Av (E,F,M,R)	Queensboro Plaza (N,W,7)	255435.90
3	Broadway Jct (A,C,J,L,Z)	Forest Hills - 71 Av (E,F,M,R)	218867.80

Findings: Paired Station Criticality

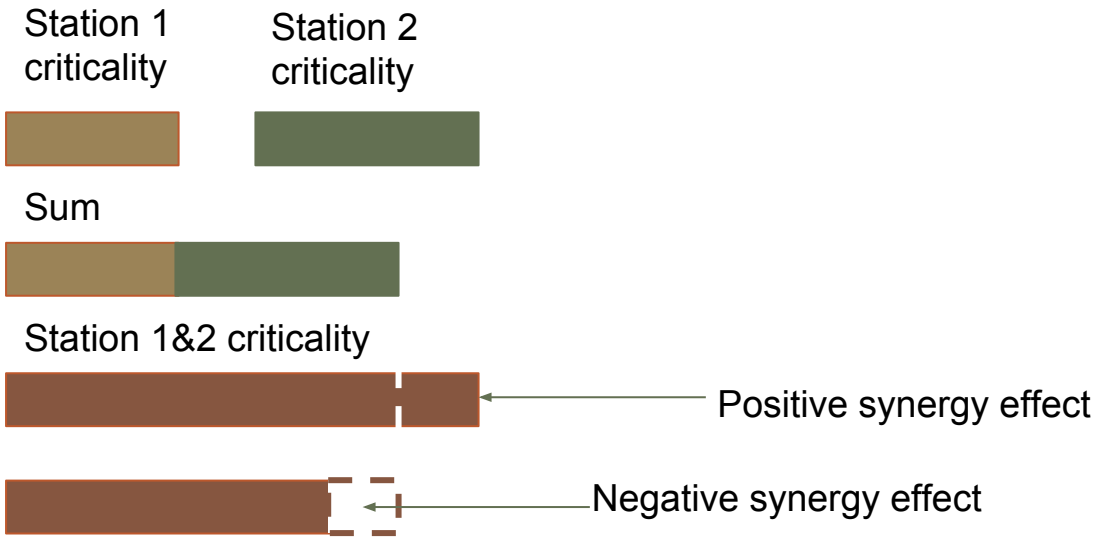
The distribution of paired simultaneous disruptions spreads out further to higher criticality values.



Findings: Synergy Effect

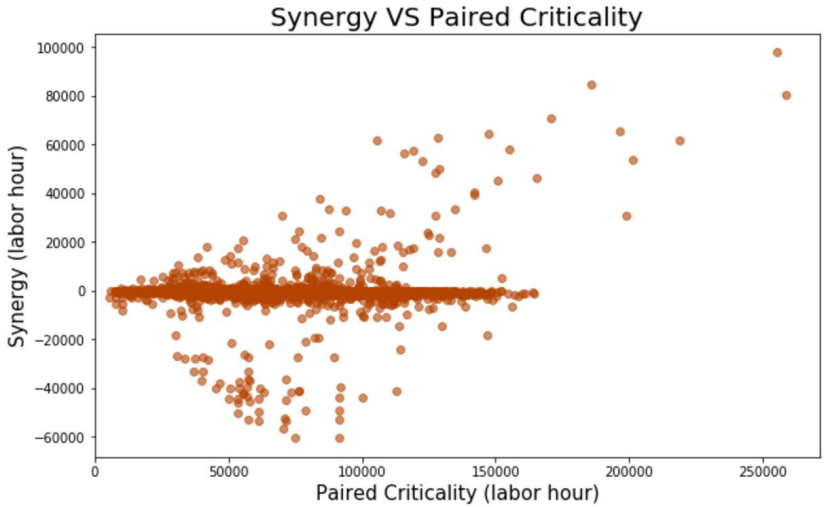
Definition of synergy

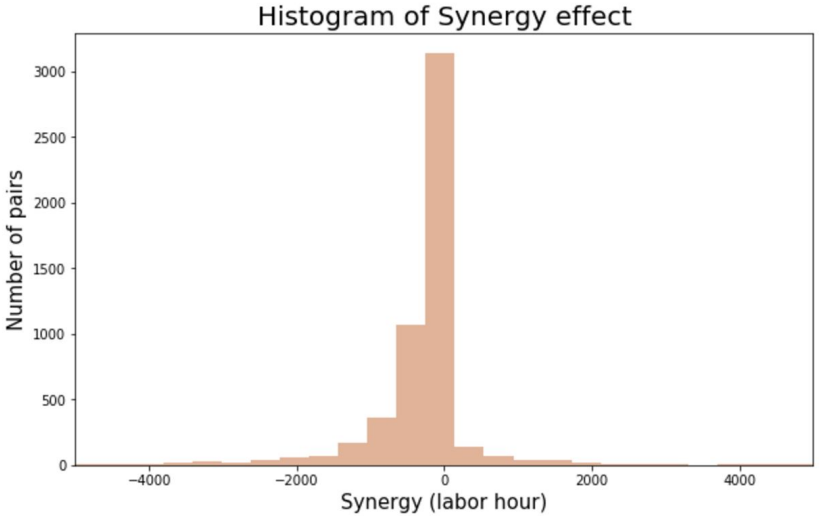
$$Synergy = C(x1, x2) - (C(x1) + C(x2))$$



Findings: Synergy

1. Out of 5565 pairs, 723 pairs have positive synergy effect and 4823 pairs negative
2. Synergy effects are mostly concentrated near 0
3. Synergy effect is tend to be positive when paired criticality is high

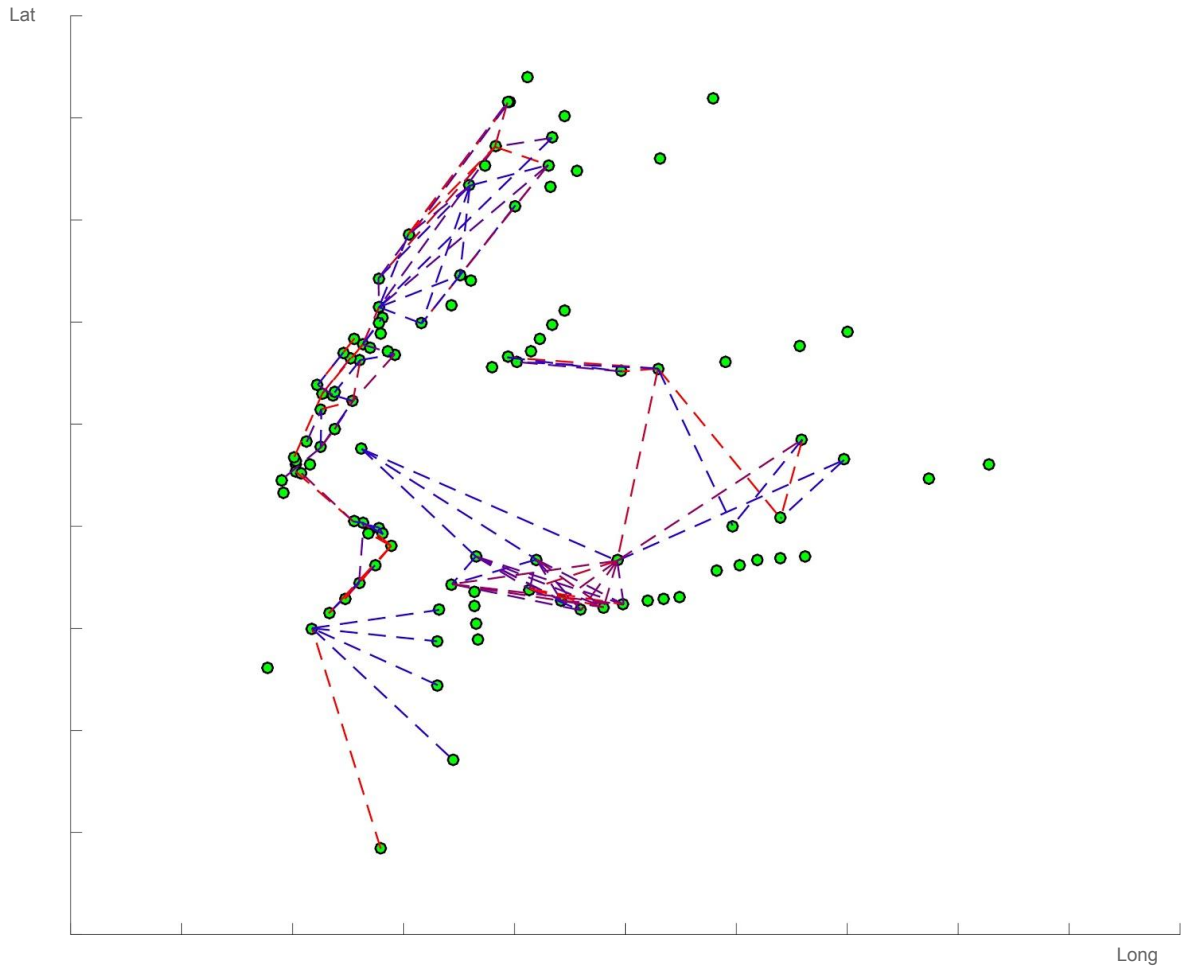




Positive Synergy Network

Positive links >10% go from blue to red depending on the synergy strength (all 20 links over 50% are red).

10-20%	
20-30%	
30-40%	
40-50%	
50%+	

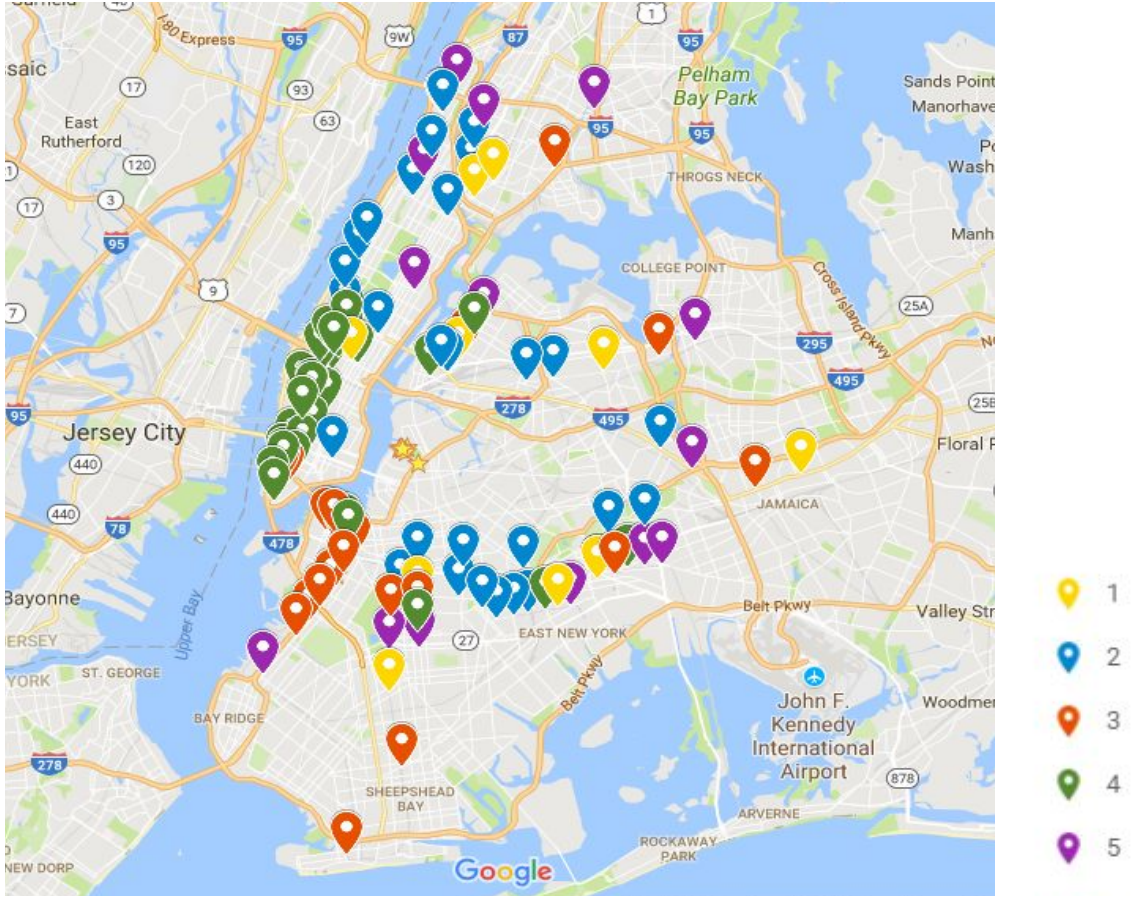


Community detection

5 communities detected based on highest positive synergy

Performed using Combo algorithm (1)

1. Sobolevsky, S., Campari, R., Belyi, A. and Ratti, C., 2014. General optimization technique for high-quality community detection in complex networks. Physical Review E, 90(1), p.012811.

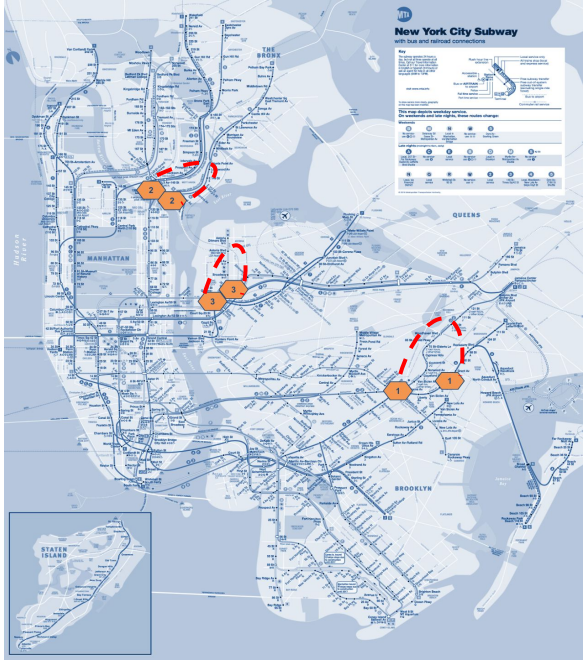


Findings: Maps of absolute synergy

absolute synergistic effect

Top 3 stations with positive absolute synergy

Rank	Station 1	Station 2	Additional Delay (labor hour)
1	Jackson Hts - Roosevelt Av (E,F,M,R)	Queensboro Plaza (N,W,7)	+97,782
2	Jackson Hts - Roosevelt Av (E,F,M,R)	Woodside - 61 St (7)	+84,639
3	Jackson Hts - Roosevelt Av (E,F,M,R)	Broadway Jct (A,C,J,L,Z)	+80,259

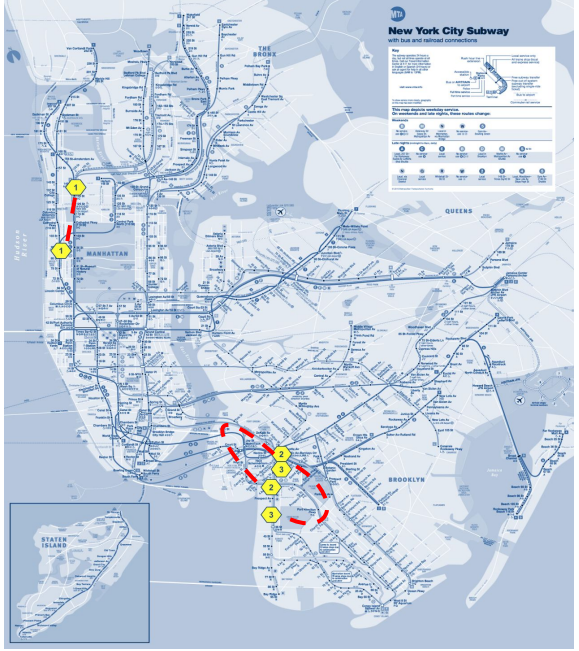


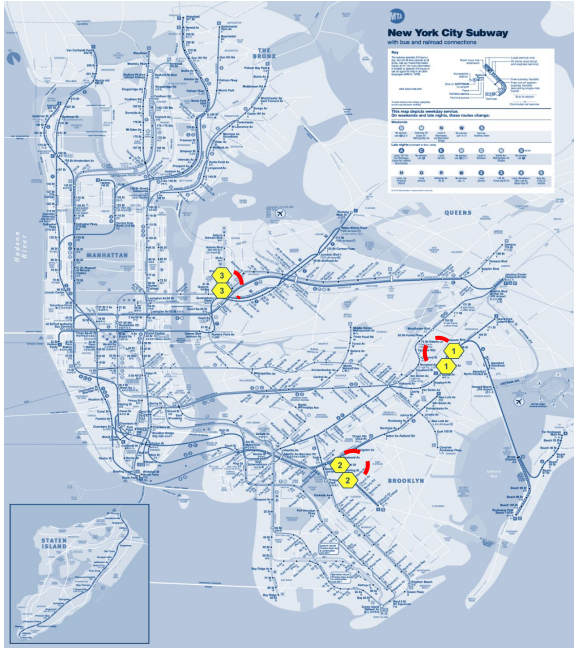
Top 3 stations with negative absolute synergy

Rank	Station 1	Station 2	Additional Delay (labor hour)
1	Broadway Jct (A,C,J,L,Z)	Euclid Av (A,C)	-60,338
2	149 St - Grand Concourse (2,4,5)	3 Av - 149 St (2,5)	-60,227
3	Queensboro Plaza (N,W,7)	39 Av (N,W)	-56,363

Findings: Maps of relative synergy

relative synergistic effect





Top 3 stations with positive relative synergy

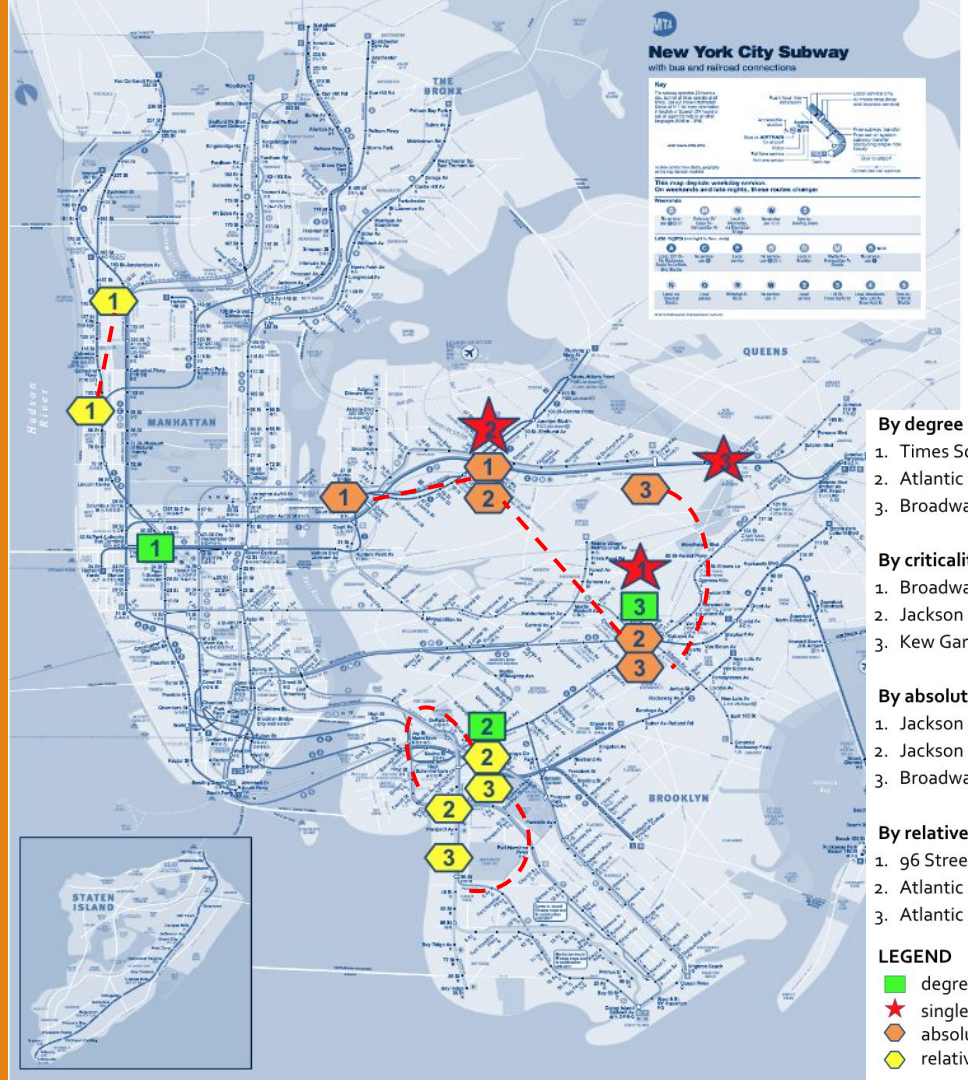
Rank	Station 1	Station 2	Additional Delay (labor hour)
1	96 St (1,2,3)	145 St (A,B,C,D)	+141.53%
2	Atlantic Av - Barclays Ctr (B,Q,2,3,4,5,LIRR)	9 St (F,G,R)	+95.73%
3	Atlantic Av - Barclays Ctr (B,Q,2,3,4,5,LIRR)	25 St (R)	+94.97%

Top 3 stations with negative relative synergy

Rank	Station 1	Station 2	Additional Delay (labor hour)
1	Grant Av (A)	80 St (A)	-48.24%
2	President St (2,5)	Sterling St (2,5)	-47.90%
3	39 Av (N,W)	36 Av (N,W)	--47.82%

Comparison of Criticality Metrics

We can observe that some of the stations appear in multiple categories, such as Broadway Junction, Jackson Heights/Roosevelt Avenue, Atlantic Avenue/Barclays Center, Forest Hills/71 Avenue.



By degree centrality:
1. Times Square/42 Street
2. Atlantic Avenue/Barclays Center
3. Broadway Junction

By criticality after one-node removal:
1. Broadway Junction
2. Jackson Heights/Roosevelt Avenue
3. Kew Gardens/Union Turnpike

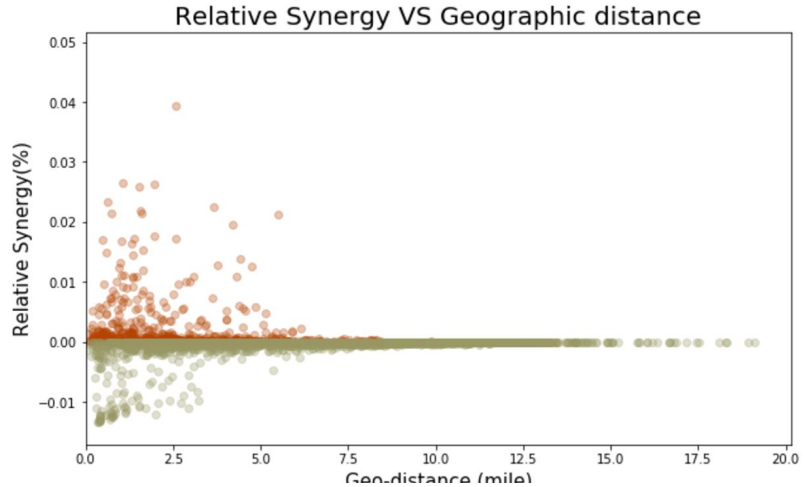
By absolute synergistic effect:
1. Jackson Hts/Roosevelt Av - Queensboro Plaza
2. Jackson Hts/Roosevelt Av - Broadway Jct
3. Broadway Junction - Forest Hills/71 Avenue

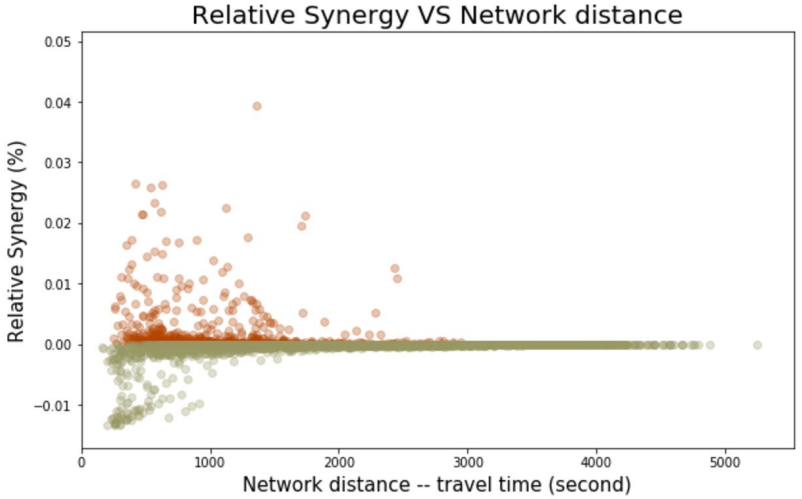
By relative synergistic effect:
1. 96 Street - 145 Street
2. Atlantic Avenue/Barclays Center - 9 St
3. Atlantic Avenue/Barclays Center - 25 st

LEGEND
- degree centrality
- single disruption criticality
- absolute synergistic effect
- relative synergistic effect

Findings: Synergy to Distance

1. When distance is far, the synergy effect tend to be zero
2. When distance is near, synergy effect is either highly positive or highly negative



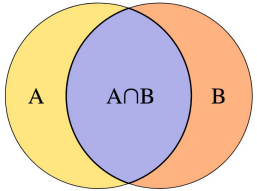


Findings: Synergy to Similarity

Explore correlation of similarity and synergy effect

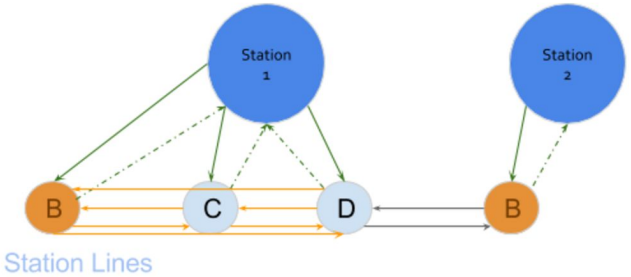
We employ concept of a Jaccard Similarity:

$$Similarity = \frac{A \cap B}{A \cup B}$$



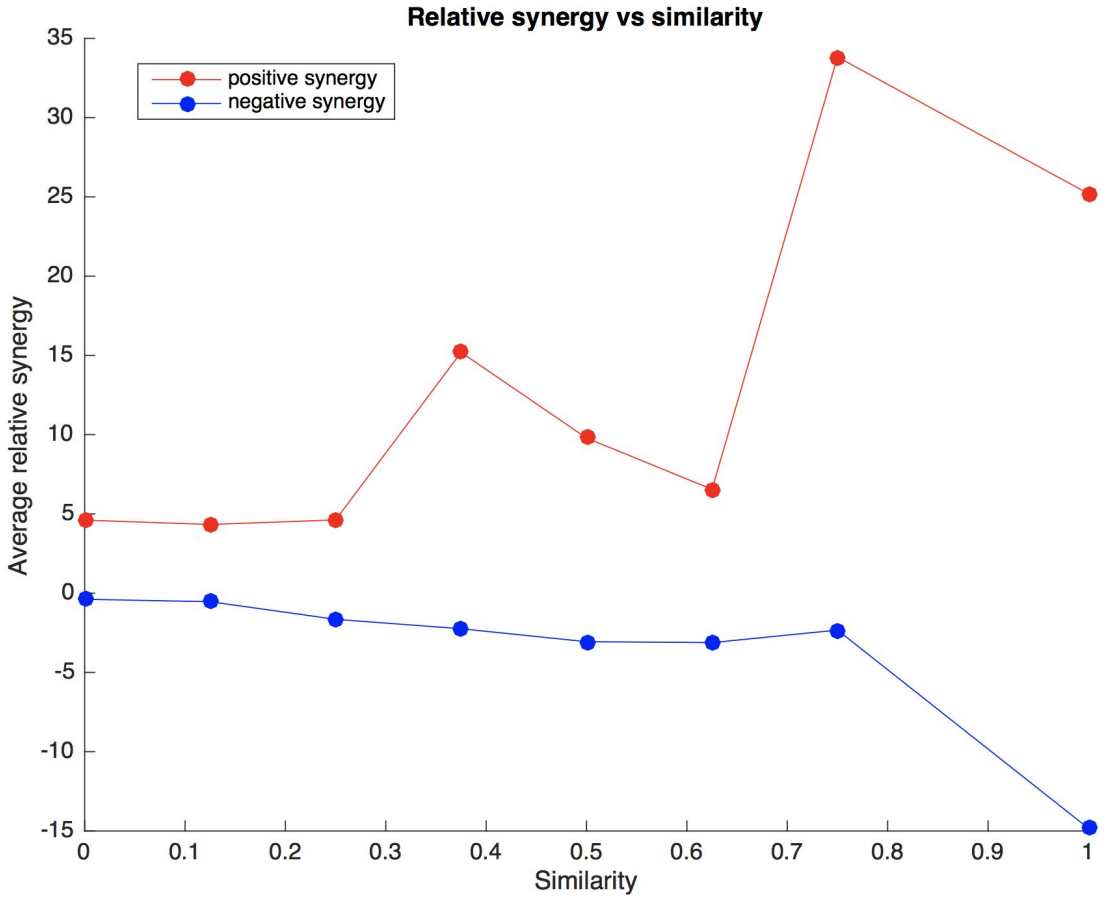
In our context,

Station 1 has **B,C,D** lines
Station 2 has **B** line,
then Similarity = 1/3



Findings: Synergy to Similarity

1. For negative relative synergy, the more similar two stations are, the more negative synergy effect is. Correlation value of -0.4436
2. However, there is no strong pattern for positive relative synergy. Correlation value of .2772
3. As similarity grows, average relative synergy tends to be more negative



Project Summary

Contributions:

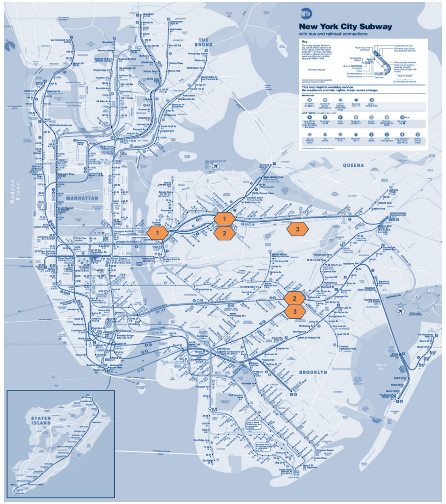
- Built subway system model that captures wait, transfer and travel times.
- Distributed demand between subway station pairs and validated distribution against real world ‘turnstile’ data
- Defined a methodology for assessing the criticality of single and paired disruptions
- Identified positive synergy in the network
- Identified patterns across positive and negative synergistic scenarios

Project Summary

Thoughts on Further Research…

- Real-time network and dynamic simulations
- Incorporate historic real-world events
- Incorporate other modes of transportation
- Explore alternative OD models and decision parameters

Thank You


New York City Subway
with bus and railroad connections
THE BRONX
MANHATTAN
QUEENS
BROOKLYN
STATEN ISLAND
1
1
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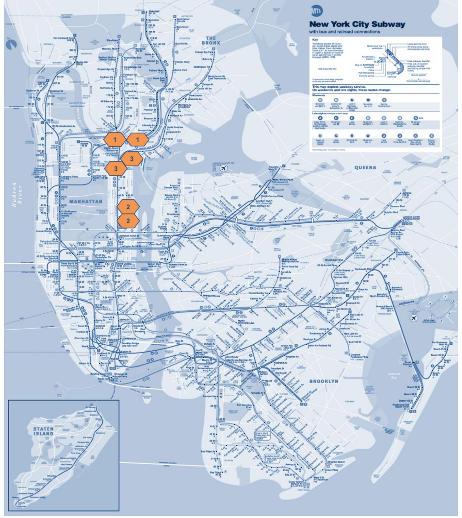
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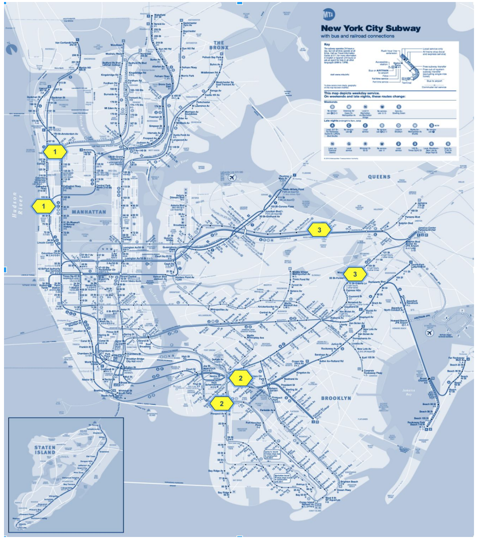
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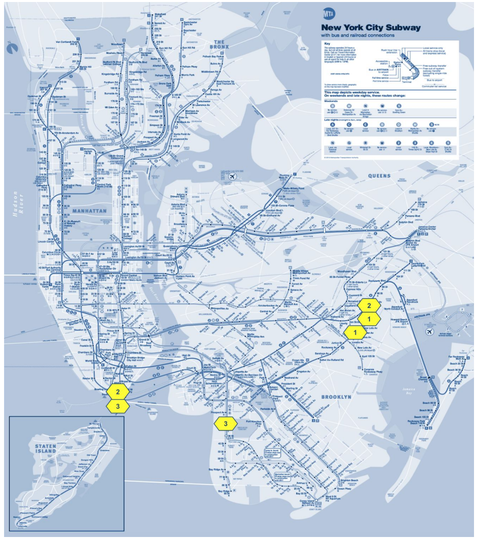
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Geographic to Network Distance

Network distance and geographic distance are highly correlated.