Public Transportation Resilience and Efficiency: A Case Study

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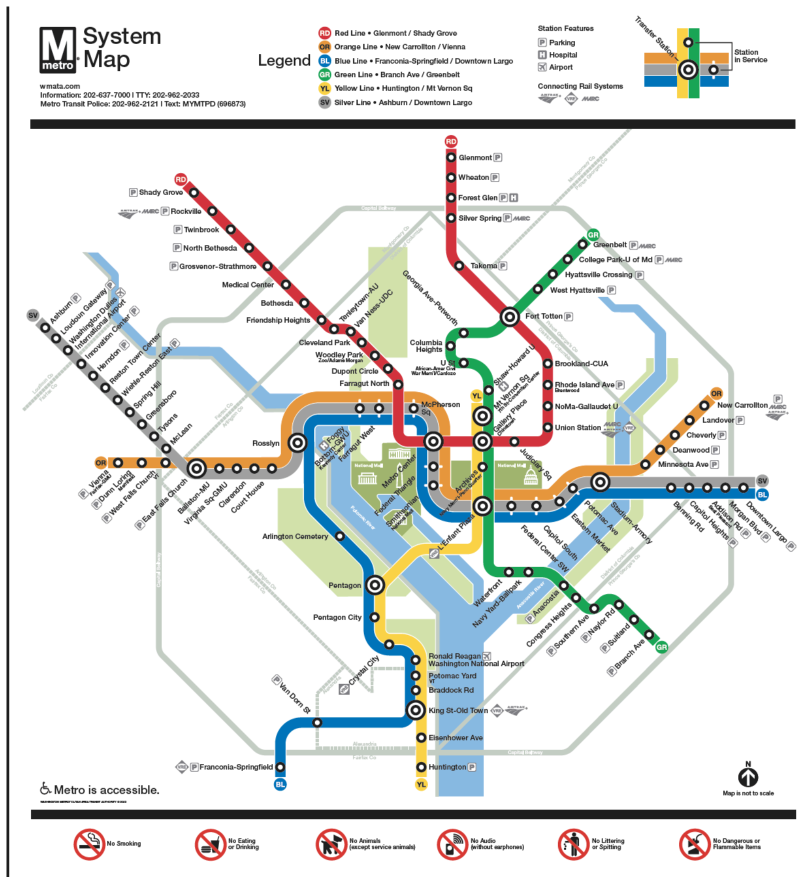
1. Introduction

With underground public transportation systems approaching status as old systems, there is a lot of work that goes into updating them to keep up with modern passenger behavior. Due to population growth, cities with older transportation systems now have much higher passenger demand than they did when the systems were first constructed (Liu). However, the problem of increased demand cannot be solved by simply increasing the frequency of trains running in the underground metro. This approach would fail to take into account the changing patterns and distributions of passenger movement from the time of the system's origin. After the COVID-19 pandemic in 2020, there have been significant changes in the way people use public transportation. There was an initial sharp decline in usage followed by a slow climb back up, but passenger use levels never reached pre-pandemic levels. In spring of 2022, ridership numbers recovered to about 62% of pre-pandemic levels (Paul and Taylor). This drop in ridership numbers was not uniform across entire systems as changing travel patterns differed between different neighborhoods based on different demographics (Paul and Taylor).

Given these changes, many public transportation networks structures should likely be reevaluated when looking at future changes. A major focus of public transportation planning is resilience to disruptions such as station closures or line closures. The most critical nodes in a public transit system for functioning of the system can be identified using centrality measures of the network (Stamos). Stations with high degrees are critical nodes in transit systems because they are important transfer points. Stations with high closeness centrality are also critical nodes for the system because passengers leaving from that station are able to reach other stations quickly (Stamos).

In this paper we will evaluate the structural properties and resilience of two different underground public transport systems: the DMV's WMATA Metro and Boston's MBTA T. These two systems serve cities of similar sizes but with different structures and approaches. The DC Metro serves 600,000 daily passengers on weekdays across 91 different stations (Truong, et. al). In 2016, 179 million trips were made on the DC Metro (Truoung, et. al). As seen in the map to the right (Destination DC) the system is made up of six different lines that extend into Maryland and Virginia and converge very close together in the middle of the city.



The Boston T has five lines (Blue, Orange, Red, Green, and Silver) although the Silver is actually a bus line with gated entries and does not go underground (Boston Discovery

Guide). The T has an average weekday ridership of just under 800,000 riders in 2024 across 153 stops (MBTA). As seen in the map below (Boston Discovery Guide), the T lines move in mostly straight lines across the city with most entering from the suburbs and exiting back into the suburbs .

In this analysis we will compare the two systems on resilience and efficiency while addressing the following research questions: How do properties of metro systems vary across cities? What are common structural patterns across metro networks? Which nodes and links are most critical to service continuity? What are the most significant bottlenecks?

2. Methods

2.1 Graph construction

To begin the comparison of the WMATA metro system in the DMV and the MBTA T underground system we first constructed NetworkX graph representations of each system. Using data from MassGIS (Bureau of Geographic Information) for the T and the DC Geographic Information System (via Maryland Transit) we isolated basic information about each stop on the network including coordinate location, station name, and lines that service the station. Each station was added as an individual node to the graph object by name with added attributes for position and lines. The MBTA T data contained information on stations along the Silver Line which we chose to exclude due to this line being an overground bus route instead of a rail line.

After adding the nodes for each network, we added edges to the graph object representing stations being connected via one or multiple train lines based on the provided maps of each respective transport system. In the Boston T system there is no overlap of multiple lines connecting the same two stations, but the WMATA Metro has significant overlap of certain lines covering the same route partially. To account for this difference in the characteristics of the edges, in the WMATA network graph we added weights to each edge representing the number of different lines that serve that path.

2.2 Basic metric calculation

After constructing graphs for each transit system we used these NetworkX graph objects to calculate some basic metrics to analyze and compare the structure of each system. These metrics included three centrality measures: degree centrality, betweenness centrality, and closeness centrality. Degree centrality is a measure of how many edges a node has, betweenness centrality is a measure of how often a node shows up in the shortest paths between nodes in the network, and closeness centrality is a measure of the average length of shortest paths to all other nodes. In addition to centrality measures we calculated the network diameter which is a measure of the longest path present in the Network.

2.3 Determining critical nodes

Using the calculations of centrality measures for each node, we evaluated which nodes had the highest of each type of centrality in the two networks. Using these rankings we determined the nodes that are most critical to the functioning of the network and compared the differing characteristics of critical nodes between the two different metro systems.

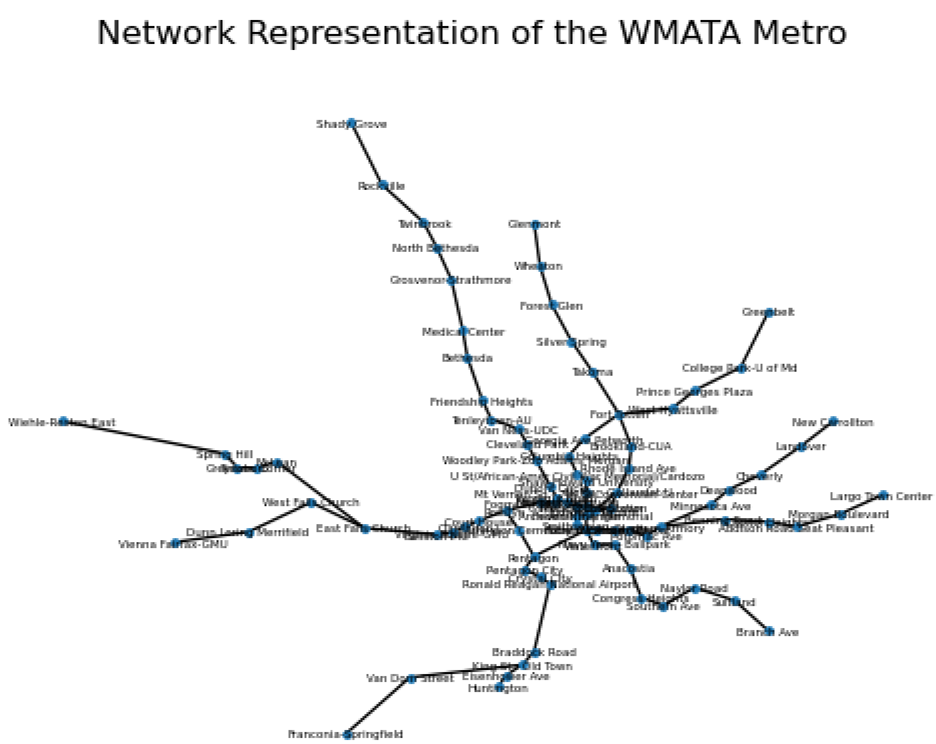
2.4 Determining busiest stations

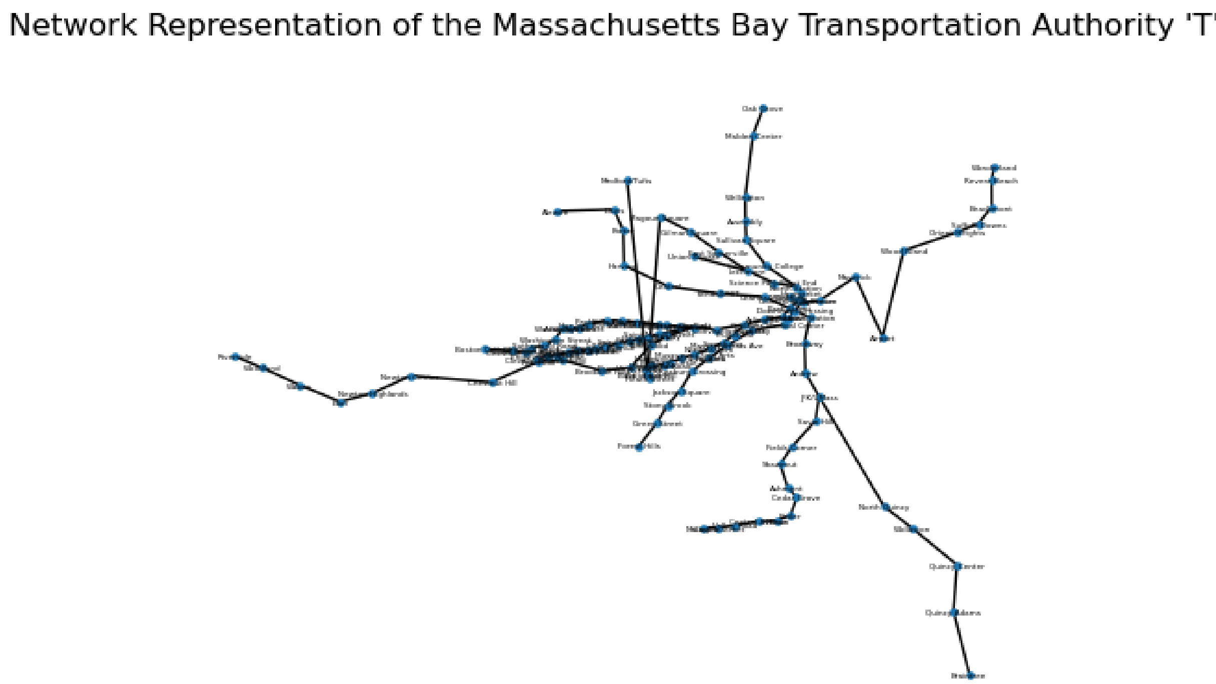
To evaluate ridership patterns in the networks we used data on the number of entries into each station from the WMATA Ridership Data Portal and MBTA Open Data Portal. The MBTA dataset had the total number of entries at each station broken up into half hour segments for each day in January through June of 2024. We aggregated and summarized the data to calculate the average daily passenger entries at each station for the six month period. The WMATA dataset had the average daily entries for all stations from January through June of 2024. It included values for tapped entries and untapped entries but we only considered tapped entries in the analysis because the MBTA data only accounts for tapped entries.

With the daily ridership data for each station we created a dictionary to map a ridership value to each node in the graph and added this value as an attribute to the node. With this attribute we were able to construct graph visualizations that showed the popularity of each station based on passenger entries using the size of the node on the graph. With these modified graphs we analyzed differences in ridership patterns between the two transit systems.

3. Results

3.1 Graph construction

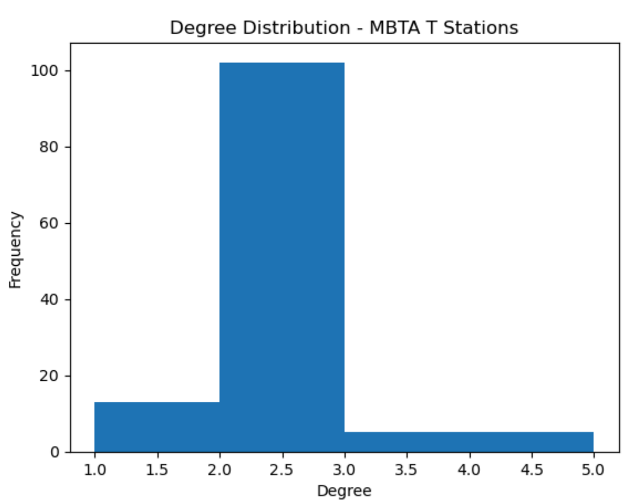


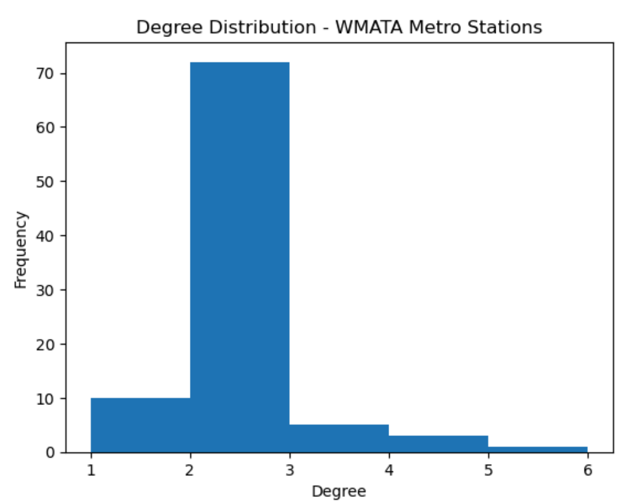


3.2 Basic metric calculation

3.2.1 Degree centrality

For the Boston T, the highest degree of any node was 4. The stop that had a degree of four is called Downtown Crossing which is a stop on the red and orange lines that is located near Boston Common and the Financial District. In the WMATA Metro system, the node with the highest degree is L’Enfant Plaza with a degree of 5. The green, yellow, blue, silver, and orange lines all run through L’Enfant Plaza and it is near the National Mall.

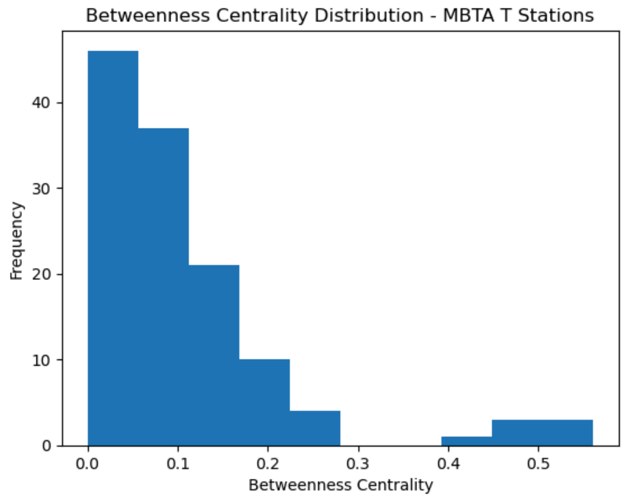


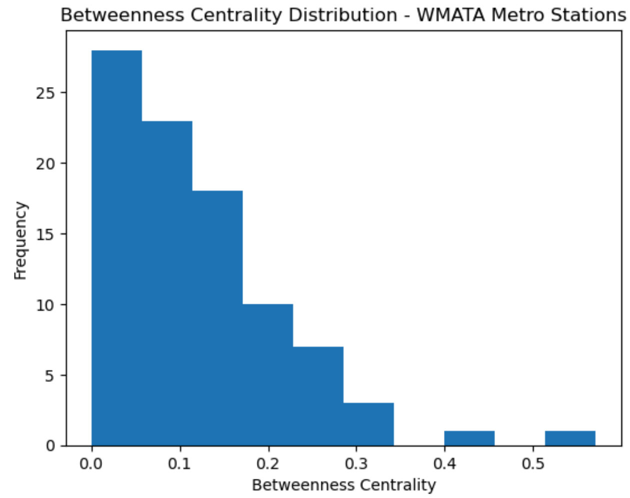


The above plots show the distribution of degrees for each of the stations in the network. For both DC and Boston, the vast majority of stations have a degree of two, meaning they are connected to one other station on either side. The second most frequent degree bin for both networks is one which encompasses the stations that are at the end of their lines. Each network has some stations with degrees higher than two, but these are more common in the DC Metro system which has a distribution that is slightly more skewed right than in Boston.

3.2.2 Betweenness Centrality

In Boston, the highest betweenness centrality value is 0.5611 at the Copley stop. The Copley stop is located centrally with the city of Boston and is the last stop on the green line before it splits into four different branches. In DC, the highest betweenness centrality value is 0.5710 at the L'Enfant Plaza stop. L'Enfant Plaza is the same stop that has the highest degree value of the DC Metro.

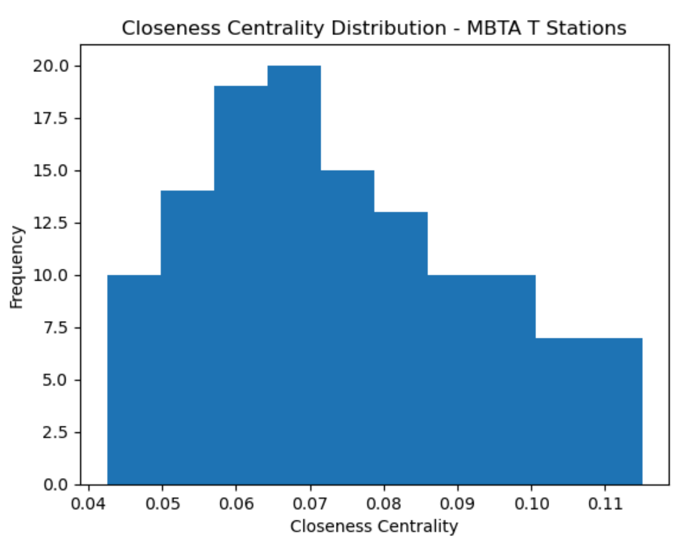


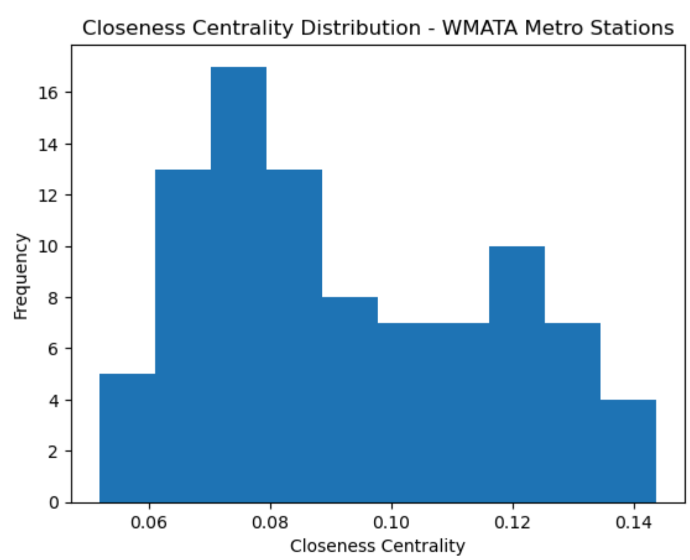


For both cities the betweenness centrality distribution is skewed to the right. Similar to the degree distribution, the WMATA Metro system has a slightly higher proportion of stops with higher values.

3.2.3 Closeness Centrality

In Boston, the node with the highest closeness centrality is Park Street with a closeness centrality of 0.115. Park Street stop is a stop on the red and green lines that is located close near Boston Common and the main downtown area. In DC, the node with the highest closeness centrality is L'Enfant Plaza again with a closeness centrality value of 0.144.





The closeness centrality values are more evenly distributed than betweenness centrality and degree. The closeness centrality values for stations in DC trend slightly higher than the values for stations in Boston.

3.2.4 Network diameter

The network diameter for the MBTA T is 37 while having 125 nodes and 126 edges. The network diameter for the WMATA Metro is 28 while having 91 nodes and 93 edges.

3.3 Determining critical nodes

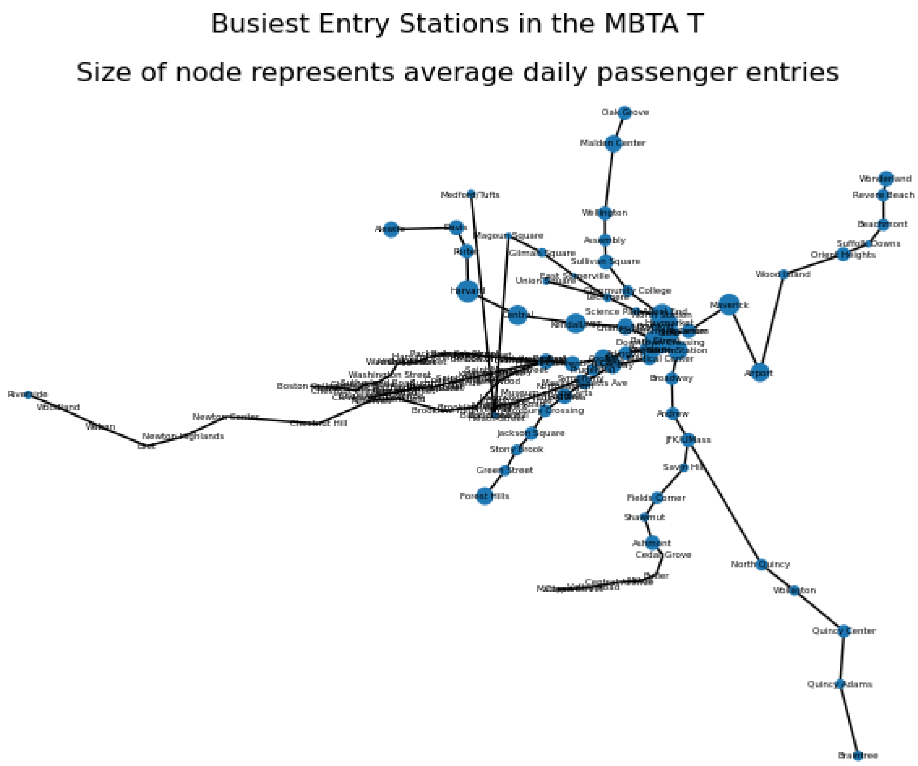
3.3.1 Boston (MBTA T)

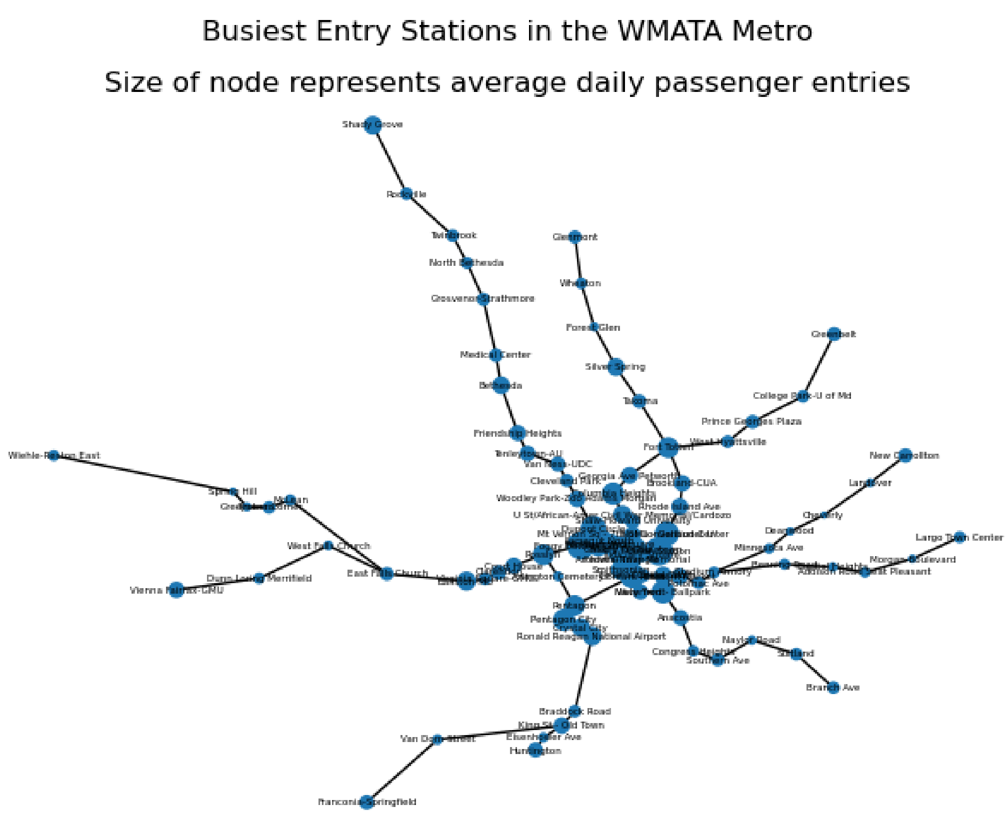
The stations with the three highest degree centrality values are Downtown Crossing, Government Center, and Kenmore. The stations with the three highest betweenness centrality values are Copley, Park Street, and Kenmore. The stations with the three highest closeness centrality values are Park Street, Boylston, and Arlington.

3.3.2. DC (WMATA Metro)

The stations with the three highest degree centrality values are L’Enfant Plaza, Fort Totten, and Metro Center. The stations with the three highest betweenness centrality values are L’Enfant Plaza, Metro Center, and Gallery Place. The stations with the three highest closeness centrality values are Gallery Place, Archives-Navy Memorial, and Metro Center.

3.4 Determining busiest stations





4. Conclusions

While serving similar population sizes, Boston and DC take different approaches to the most efficient way to organize a public transportation system. Based on the distributions of centrality measures we can conclude that the Boston “T” has more different critical stations spread throughout the city while the DC Metro puts a lot of weight on a couple of major hubs where multiple lines intersect. The Boston system does not have any stations with degrees higher than four, unlike the DC Metro’s L’Enfant Plaza and Metro Center stations which connect several lines and stations. For all three of the centrality measures looked at, L’Enfant had the highest value of all the stations in the DC Metro. In the Boston system, three different metro stations made up the group with highest centrality values. The three different high centrality stations in Boston (Copley, Park Street, and Downtown Crossing) are located somewhat near each other in busy parts of the city. This provides evidence to suggest that the Boston T is organized to have redundancy in busy areas by adding several critical stations.

The DC Metro takes a different approach to adding redundancy in busy areas. As stated above, the major hubs of the DC Metro system (L’Enfant Plaza, Metro Center, and Gallery Place) are at the intersections of several metro lines. The DC Metro system seems to add redundancy by having more trains moving in and out of the critical stations. As we can see in the map of the metro, there is a great deal of overlap between lines with most paths between stations being covered by more than one line. This approach could be used to minimize bottlenecking in the major hubs at the identified critical nodes.

Both Boston and DC seem to have added these above redundancies in the areas with the highest amount of passenger entries. Both cities have their busiest stations by passenger entry clustered in the main downtown of the city where the critical nodes are located. The stations that are located at the ends of lines in the suburbs have much fewer daily entries than the stations in the heart of the city. These patterns suggest that metro systems are not being used as much for commuters into the city as they are for people moving within the city. Going forward with line and station expansion projects, this should be taken into consideration.

5. References

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