Proximity to Public Transit in Boston 2022

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1 Abstract

Understanding the layout of a city's public transportation network yields numerous insights into the condition of its residents. This paper and its associated dashboard aim to evaluate macro, surface-level trends in the geography of Boston's MBTA system. It will also touch on some edge cases with respect to transit accessibility (i.e., the people that have no choice but to commute by train or bus). The analysis begins with a macro lens and breaks down the context necessary for an evaluation of microcosmic variables. After several dimensions of spatial analysis, it was found that Boston's rapid transit system lacks an even distribution of stations through the city, making movement difficult in the north-south direction. However, accounting for the MBTA bus network fills that void, resulting in a system of public transportation that is generally accessible.

2 Keywords

Rapid transit, MBTA, raster, kernel density estimation, coordinate reference system

3 Introduction and Research

The movement of people within a city is a major component of urban design, impacting the lifestyles of millions alongside the sensitive ecosystem of business, politics, and climate. Metropolitan areas are congested by nature, with the flow of residents often directed inwards. This is especially true of the United States, where infrastructure is designed to facilitate the circulation of people between suburbs and urban centers. Transit systems optimize this mechanism, generating movement in a single dimension–in and out of the city. Yet, this form of transportation assumes a lot about the lifestyle of metropolitan inhabitants; in particular, that they regularly commute to and from logistics centers, not between residential districts. With most jobs concentrated in major cities, it follows that transportation should facilitate that modality. However, the paradigm of American transportation is shifting to accommodate new styles of living and suburban development.

Studies have shown that more and more Americans are either working from home or commuting between suburbs, with the issue being that current systems of public transportation don't sustain those changes. A report by the Metropolitan Policy Program at Brookings indicates that suburban growth has contributed to a geographic expansion of job opportunities in recent decades, with fewer people commuting into major cities for work (Kneebone, 2013). As a result, a strain is being placed on inter-suburban infrastructure, stunting growth and generating waste. To travel between suburbs, residents are often forced along a circuitous route through the city center, creating unnecessary congestion and pollution. If one were to visualize the existing network of public transportation in most American cities, it would probably resemble this:

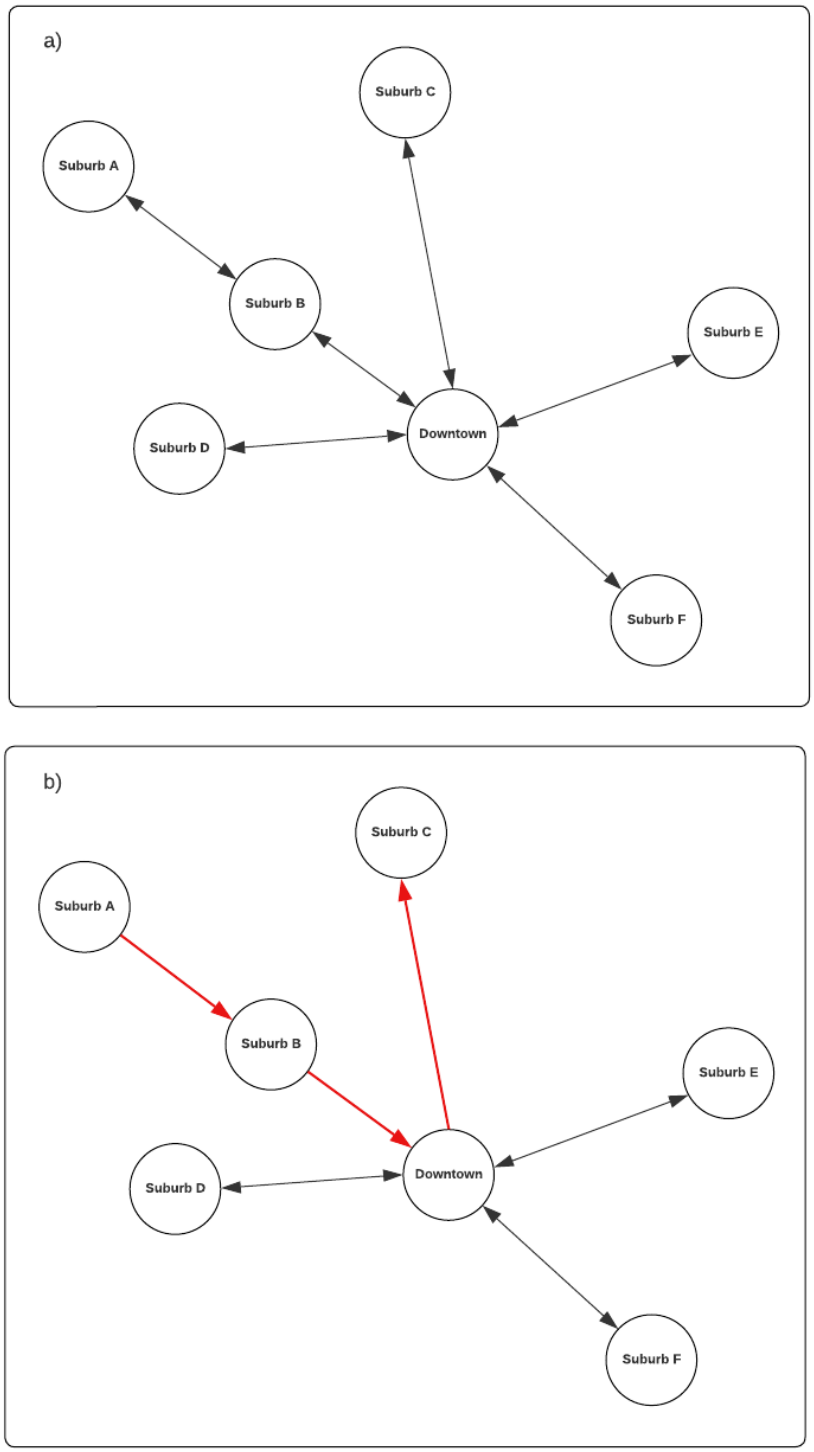


Figure I. Generalized illustration of movement within metro transit network. (a) Metro connections as a network. (b) The path from Suburb A to Suburb C.

In the diagram above, someone in Suburb A has to travel through Suburb B and the Downtown area to reach Suburb C. Clearly, a more direct path would be to travel from Suburb A to Suburb C (see Figure I(b)). The present route not only inconveniences the resident, but also places an unnecessary strain on the existing network, with all commuters, including those traveling between suburbs, forced into a dense urban area. At the same time, surface roads between the suburbs are likely to witness heavy traffic without the support of a high volume connection. Nonetheless, a majority of American transit networks are designed in this fashion, with many cities lacking adequate support for public transportation altogether. Though not included here, a map of any major subway network in the United States is likely to resemble the behavior demonstrated above.

With that in mind, it's obvious why few Americans choose to take public transportation. According to the Bureau of Transportation Statistics, a whopping 70% of Americans drive alone to work, with only 3% using public transportation (United States Department of Transportation, 2019). Considering that roughly 80% of the U.S. population lives in urban centers, that's a staggering number, requiring a dense network of roads and parking lots that require regular upkeep (United States Census Bureau, 2010). That means less available real estate and greenspace. It means additional public spending on top of already existing transit maintenance costs. Now consider the human toll, including avoidable car crashes and the pollution generated by this system–excess noise, greenhouse gas emissions, heat islands, etc.

Of course, it's difficult to adjust existing networks of public transportation to accommodate rapid urban advancements. It's far easier to construct roads, as they're cheaper and require less time to build. However, many Americans have no choice but to use the existing systems of public transportation; not everyone can afford or operate a vehicle. This results in socioeconomic disparities, with low-income residents limited to nearby occupations, lest they travel a far distance on foot or bike. Keep in mind that rapid transit systems (i.e., subways and light-rails) aren't specifically designed to transport people within a city–they're designed to transport people in and out of the city. This means limited lateral movement within an urban center, that is traveling from one end of the city to another; subways typically flow in one direction as this paper will attempt to demonstrate in part. Hence, social mobility is inextricably tied to one's place of residence–a shining example of the systems that continue to uphold racial and class-based discrimination in America.

This paper will evaluate the geographic accessibility of public transportation in Boston, which has the oldest system of rapid transit in the United States. Alongside that, a dashboard has been created to communicate the spatial distribution of MBTA stations in a variety of contexts. Previously, it was difficult to find a visualization that demonstrated the global behavior of Boston's rapid transit system. The dashboard attempts to solve this by visually summarizing Boston's public transit system for a general audience, while maintaining geographic precision. It attempts to answer, in part, whether the city of Boston demonstrates any of the aforementioned phenomena, and if its system of public transportation should serve as an example for other cities. In other words, does Boston's system of rapid transit limit intra-city mobility, and is its location optimal for the general population? Answering these questions will provide some insight into the socioeconomic relations within Boston.

The prevailing sentiment in this area of research maintains that access to public transportation is a necessity for modern cities that wish to uphold a high standard of living. Public transportation has been shown to foster economic prosperity. A study conducted by the American Public Transportation Association indicated that investment in transit not only extends access to areas with high paying jobs, but directly contributes enough jobs to yield a 5 to 1 economic return (APTA 2020). Therefore, a spatial analysis of transit accessibility is also an analysis of job opportunities. By visualizing the spatial distribution of MBTA stations, one could in effect garner information about the availability of employment in the transportation sector for a particular region. This makes the dashboard an effective yet simple tool for mapping economic returns on transportation investments.

It should be noted, however, that conflicting reports indicate that regional economic growth would be largely unaffected by improvements to transportation alone. A study published by the Journal of Transport Geography posits that local variables have a far greater impact on economic trends and would likely drown out the effects felt by transit improvements (Banister et. al., 2001). In other words, the addition of new stations would be negligible from a macroeconomic perspective. Nevertheless, one could argue that this report is outdated and the motivation behind increased transit accessibility extends far beyond any marginal economic improvement; instead, improved accessibility is of ethnographic importance, ushering in opportunities for historically marginalized groups.

At the same time, reports have indicated that transportation infrastructure is shown to negatively impact the environment. While it's theoretically possible to mitigate the emission of CO_2 by replacing cars with trains, the construction of high-volume transportation networks would still contribute massively to ecological pollution (Achour et. al., 2016).. These mega projects would result in habitat fragmentation, a serious concern for the greater Boston area, which is home to numerous endangered species and wetlands. If transportation infrastructure encroached on sensitive wildlife habitats, it could threaten regional biodiversity (Massachusetts Department of Environmental Protection, 2022). An article published in the International Journal of Environmental Research and Public Health warns that the environmental challenges posed by transportation expansion could actually outweigh its benefits (Wang et. al., 2018). So, visualizing the distribution of existing transit networks also exposes some areas for environmental concern.

Nonetheless, improved transit has the potential to mitigate some of the systemic burdens placed on marginalized communities while deepening intercultural relations. This is demonstrated anecdotally by public transit expert Steven Higashide in his novel *Better Buses, Better Cities*. His work presents the need for reliable bus services in major cities, pointing to Boston's extensive bus network as an example of successful public transportation (Higashide, 2019). This is also communicated visually in this paper and the dashboard.

Based on this literature alone, it can be reasonably concluded that Boston is a case study when it comes to public transportation in the United States. This paper intends to develop the existing literature by contributing a series of spatial visualizations to the canon of Boston transit research. These visualizations aim to assist practitioners and the general public in their understanding of Boston's geography as it relates to the movement of people within the city.

4 Data and Methods

This analysis hinges on publicly available spatial datasets. Several different base maps were used for the Boston area. They were selected for their aesthetic and technical qualities, with the underlying goal being task-specific clarity. The primary base map used in this analysis comes from MassGIS Data: Municipalities. This dataset contains the "most accurate representation of Massachusetts' municipal boundaries" with coordinates generated from boundary marker surveys in the *Harbor and Lands Commission Town Boundary Atlas*. These coordinates were manually inputted by the MassGIS staff and converted into the NAD83 datum, opening up room for error. However, these coordinates were "double-checked," and any remaining errors are visually negligible for the sake of this analysis. The TOWNSSURVEY_POLY layer was used to generate the base map, with polygons representing the political boundaries of Massachusetts towns. The layer was filtered to only include geometries within Boston. A separate data layer from MassGIS Data: State Outlines was originally considered, but the data was from 1991 and proved difficult to use with the given resolution.

Another base map used regularly throughout this analysis comes from Analyze Boston and contains the geometries for Boston neighborhoods as approximated by 2020 Census block groups. The exact geometries for Boston neighborhoods cannot be directly extracted from the Decennial Census or the American Community Survey, as the U.S. Census Bureau does not recognize the political boundaries for Boston neighborhoods. Therefore, Census block group data was aggregated by Analyze Boston to generate passable polygons for Boston neighborhoods.

Other base maps were chosen for their stylistic qualities. This includes a map derived from Stamen Design map tiles using the ggmap library. It also includes a base map from CartoDB and another base map from Esri Leaflet. These are all used as separate canvases to display potions of the spatial analysis.

MBTA station coordinates were obtained through two MassGIS datasets: MBTA Rapid Transit and MBTA Bus Routes and Stops. The MBTA Rapid Transit layer is specific to subway system lines within the Boston metro area. The data is stored as both line and point geometries, representing stations in the Greater Boston area and the approximate railway lines between them. It was originally produced from United States Geological Survey transportation data, with regular updates being made, the most recent of which was in December of 2021. The other dataset, MBTA Bus Routes and Stops, represents all bus routes and stops in the Boston metro area. Data was generated using MBTA General Transit Feed Specification (GTFS) files. For this analysis, only the point data was extracted. These datasets form the bulk of data used throughout this project. Here's a sample of the Rapid Transit layer point data:

```
Projected CRS: NAD83 / Massachusetts Mainland
                    STATION  LINE TERMINUS                ROUTE                   geometry
1 Boston University Central GREEN        N B - Boston College POINT (232377.2 900023.9)
2              Amory Street GREEN        N B - Boston College POINT (231744.6 900123.8)
3            Babcock Street GREEN        N B - Boston College POINT (231314.9 900191.5)
4           Packards Corner GREEN        N B - Boston College   POINT (230877.6 900211)
5            Harvard Avenue GREEN        N B - Boston College   POINT (230402 900056.3)
6             Griggs Street GREEN        N B - Boston College POINT (230126.1 899878.3)
```

Figure II. Calling `head` on the MBTA Rapid Transit shapefile

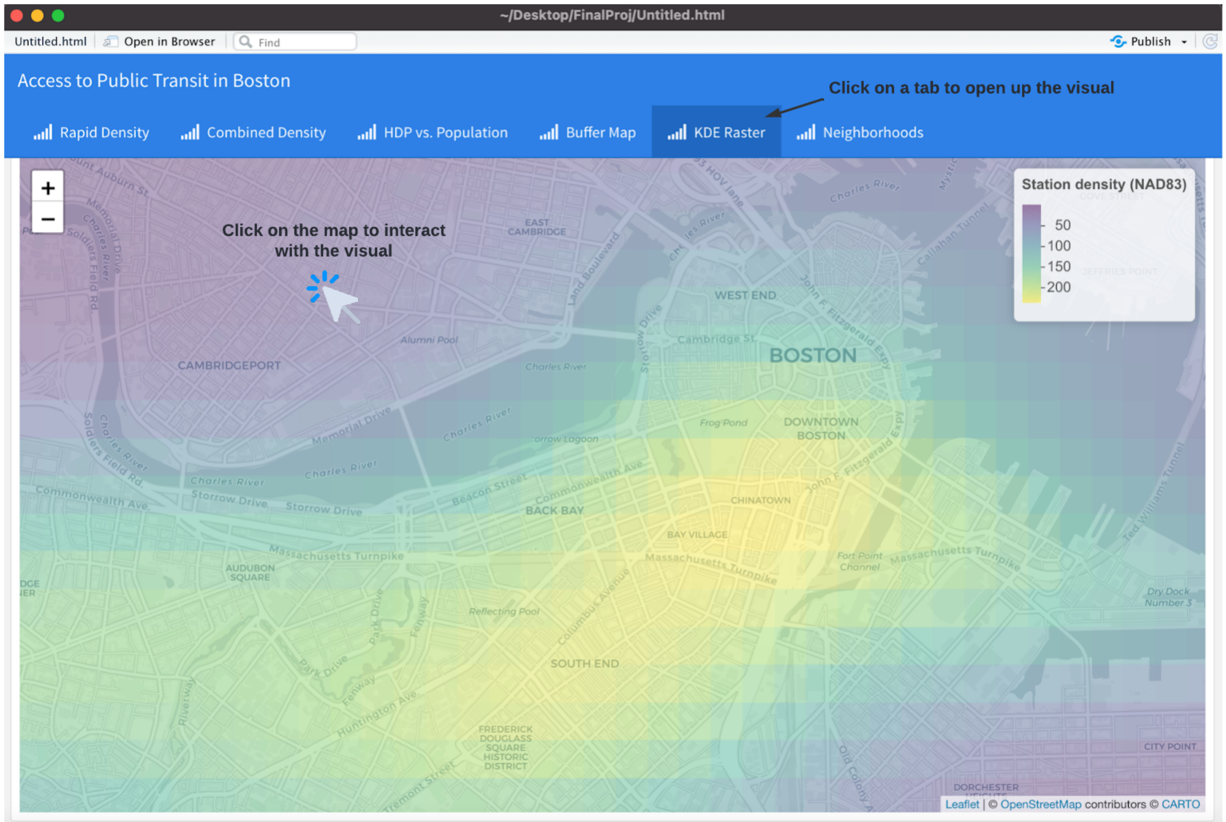
Notice that the original data is projected in a version of the NAD83 coordinate reference system (CRS). The NAD83 datum represents the standard of geometry data for North America. The Massachusetts Mainland variant is specific to onshore Massachusetts. All data extracted from MassGIS is stored in this format and was converted to NAD83 and WGS84 for experimentation and use with base maps:

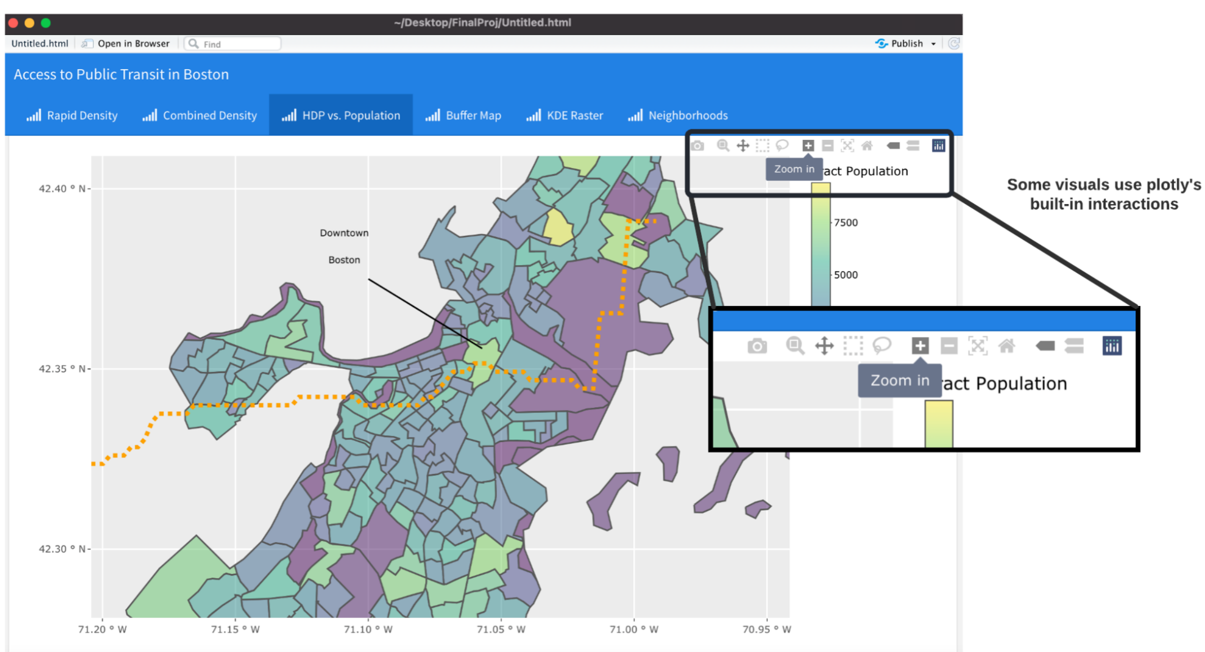
````
```{r}
## NAD83 / Massachusetts Mainland

# Extracting shapefile geometries into a separate data frame
t_sub_nodes_points <- as.data.frame(st_coordinates(st_geometry(t_sub_nodes)))
t_bus_stops_points <- as.data.frame(st_coordinates(st_geometry(t_bus_stops)))

t_sub_bus_points <- rbind(t_sub_nodes_points, t_bus_stops_points)

## WG84

# Conversion
t_sub_nodes_W84 <- st_transform(t_sub_nodes, st_crs(4326))
t_bus_stops_W84 <- st_transform(t_bus_stops, st_crs(4326))

# Extracting shapefile geometries into a separate data frame
t_sub_nodes_W84_points <- as.data.frame(st_coordinates(st_geometry(t_sub_nodes_W84)))
t_bus_stops_W84_points <- as.data.frame(st_coordinates(st_geometry(t_bus_stops_W84)))

t_sub_bus_W84_points <- rbind(t_sub_nodes_W84_points, t_bus_stops_W84_points)

## NAD83

# Conversion
t_sub_nodes_N83 <- st_transform(t_sub_nodes, st_crs(4269))
t_bus_stops_N83 <- st_transform(t_bus_stops, st_crs(4269))

# Extracting shapefile geometries into a separate data frame
t_sub_nodes_N83_points <- as.data.frame(st_coordinates(st_geometry(t_sub_nodes_N83)))
t_bus_stops_N83_points <- as.data.frame(st_coordinates(st_geometry(t_bus_stops_N83)))

t_sub_bus_N83_points <- rbind(t_sub_nodes_N83_points, t_bus_stops_N83_points)
```
````

Figure III. Code snippet demonstrating conversions between various coordinate reference systems for MBTA data

Any remaining data was obtained from the 2019 American Community Survey with the help of the TidyCensus library. This data contains the demographic and socioeconomic information used in this analysis. Data from the 2020 Census was not used, as the COVID-19 pandemic severely impacted the quality and interpretation of data for that year.

The data is summarized through a series of spatial visualizations that will be discussed in more detail throughout this report. The dashboard presents this information in a straightforward manner:


~/Desktop/FinalProj/Untitled.html
Untitled.html
Open in Browser
Find
Publish
Access to Public Transit in Boston
Click on a tab to open up the visual
Rapid Density
Combined Density
HDP vs. Population
Buffer Map
KDE Raster
Neighborhoods
Click on the map to interact with the visual
Station density (NAD83)
50
100
150
200
BOSTON
CAMBRIDGEPORT
EAST CAMBRIDGE
WEST END
DOWNTOWN BOSTON
CHINATOWN
BACK BAY
BAY VILLAGE
SOUTH END
AUDUBON SQUARE
FREDERICK DOUGLASS SQUARE HISTORIC DISTRICT
CITY POINT
DORCHESTER
Leaflet | © OpenStreetMap contributors © CARTO


~/Desktop/FinalProj/Untitled.html
Untitled.html
Open in Browser
Find
Publish
Access to Public Transit in Boston
Rapid Density
Combined Density
HDP vs. Population
Buffer Map
KDE Raster
Neighborhoods
Zoom in
act Population
7500
5000
Downtown
Boston
42.40 ° N
42.35 ° N
42.30 ° N
71.20 ° W
71.15 ° W
71.10 ° W
71.05 ° W
71.00 ° W
70.95 ° W
Some visuals use plotly's built-in interactions
Zoom in
act Population

5 Results and Spatial Analysis

The primary objective of the dashboard is to provide a comprehensive view of Boston's MBTA layout. A spatially accurate representation of Boston's rail and bus system can yield insights into a variety of research topics. This tool is meant to serve as an accessory to these studies, while remaining simple enough for a general audience. To achieve this, transit data had to be summarized in some meaningful fashion to highlight significant geographic features. This is what Boston's rapid transit system looks like without any processing:

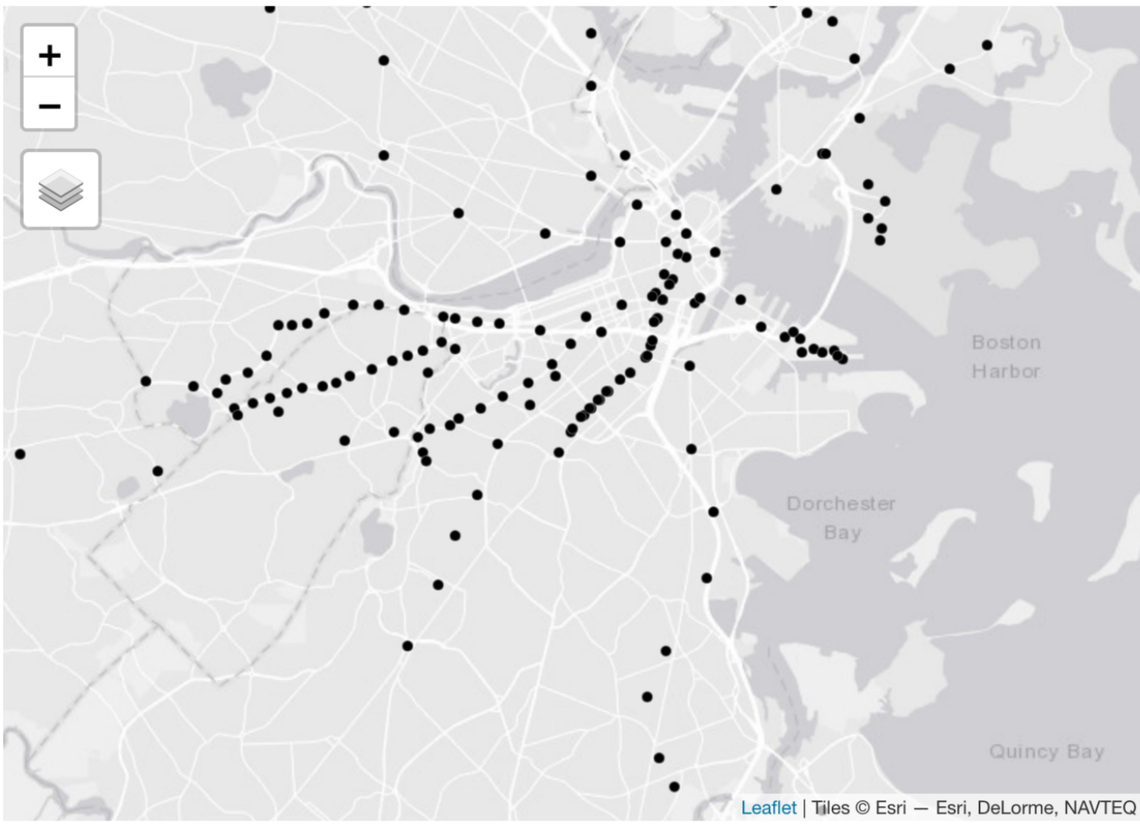


Figure IV. MBTA Rapid Transit (subway) stations

Here's a combination of MBTA bus stops and subway stations. Other modes of transit have been omitted, as their effect on the system as a whole is negligible (APTA, 21):

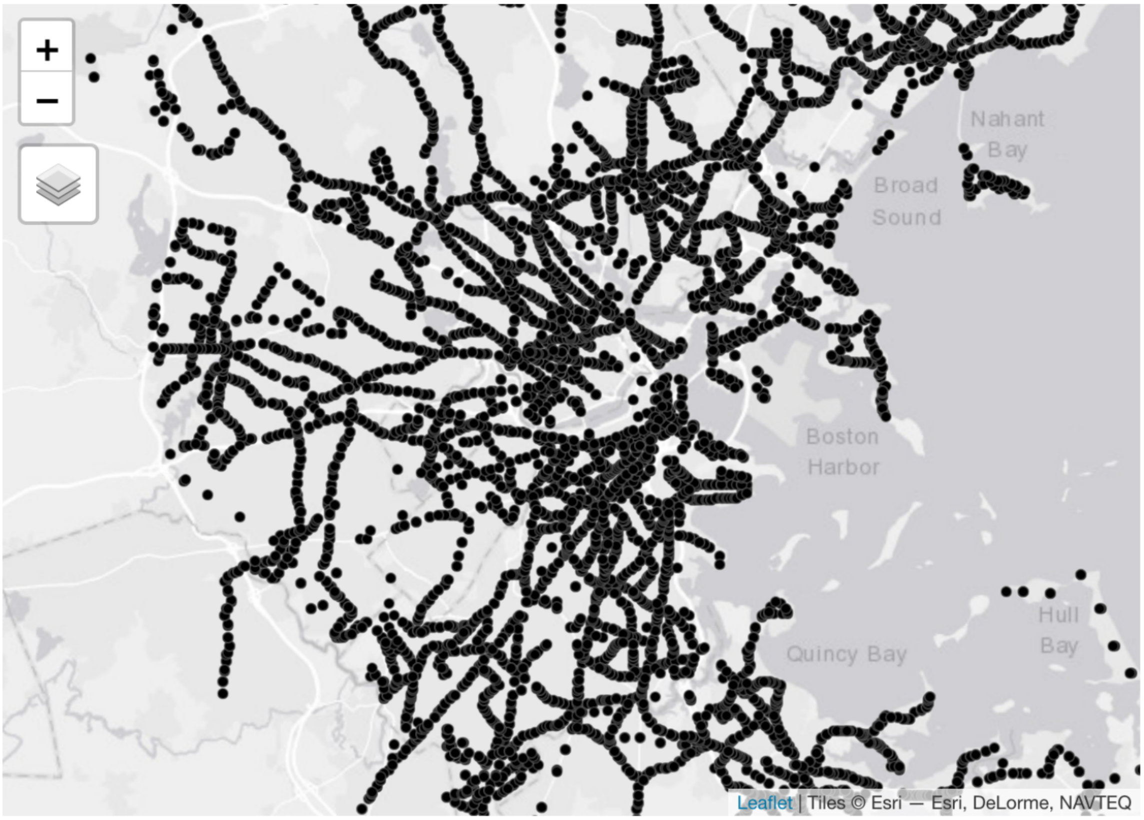


Figure V. MBTA Rapid Transit (subway) stations and bus stops

Clearly, it's difficult to extract meaningful information from this agglomeration of stations. The visuals communicate the exact location of each station, but don't provide any comprehensive information about the nature of the system as a whole. The dashboard attempts to solve this through raster analysis. It generates a density map of the point features to help analyze patterns in station locations. This was achieved using ggplot2's built in kernel-density-estimate function. Specifically, `stat_density_2d` was used to generate polygon contours representing different levels of station density. These polygons were filled by their respective density values, resulting in a heat map of MBTA stations in Boston:

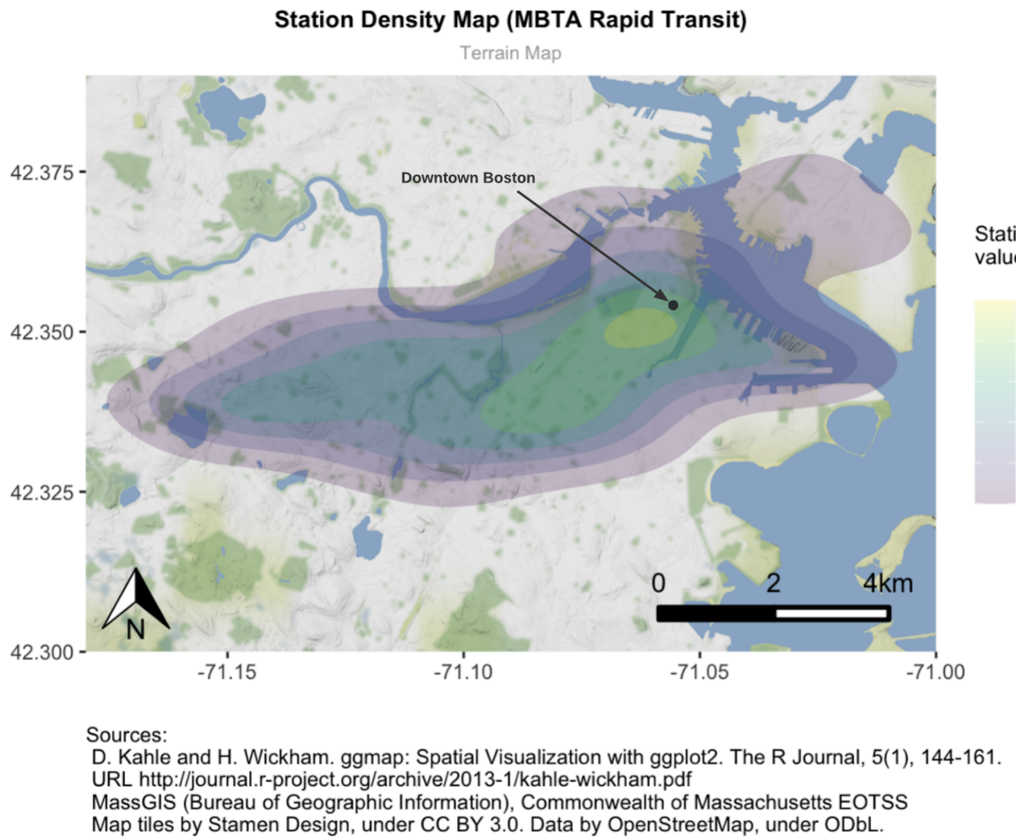
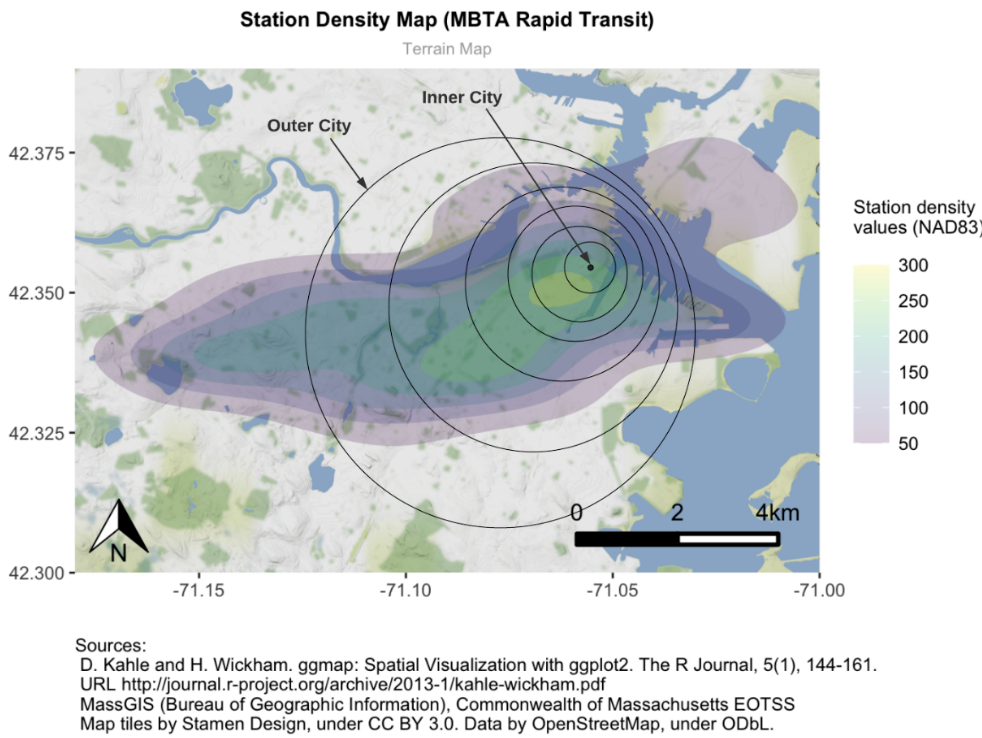


Figure VI. Density map for MBTA Rapid Transit (subway) stations

Compared to previous maps, this visual communicates more information about the behavior of the system as a whole. It's clear that the distribution of subway stations runs latitudinally, with the highest concentration of stations Downtown. This is consistent with the behavior discussed earlier in the research, which maintained that transit systems in United States are explicitly designed to move people in and out of the city.

a)



b)

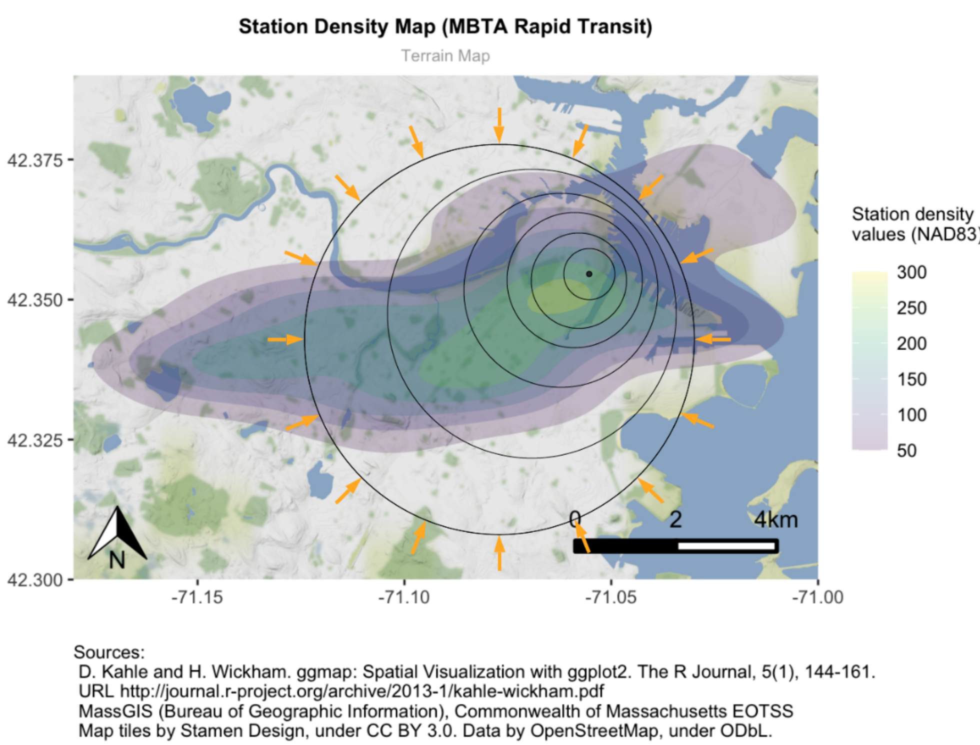
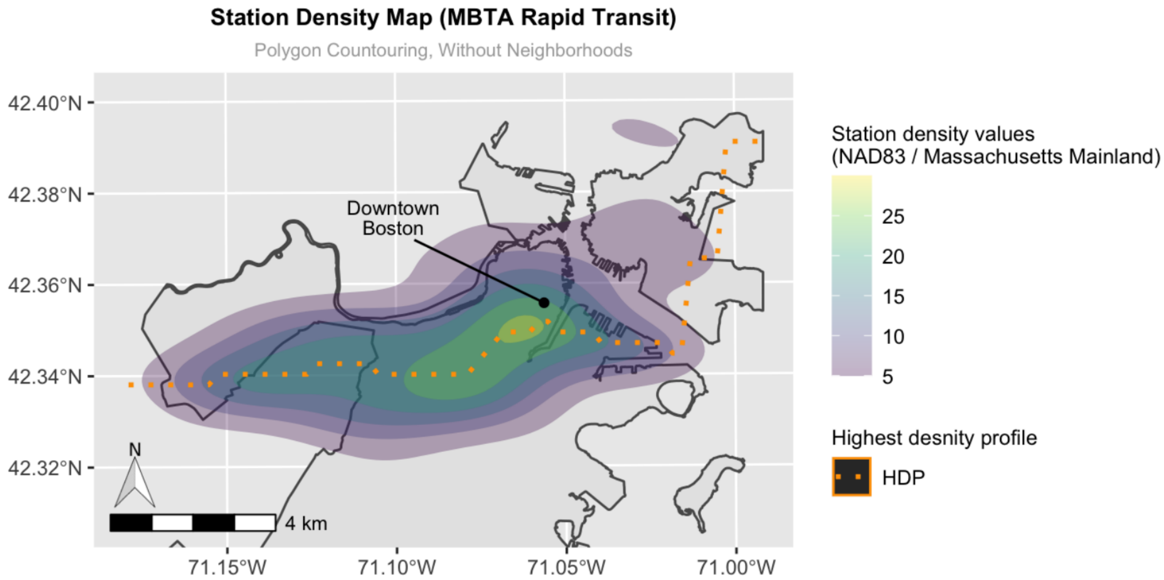


Figure VII. Density map for MBTA Rapid Transit stations. (a) Annotations for inner and outer city layers. (b) Stations are condensed around the city center.

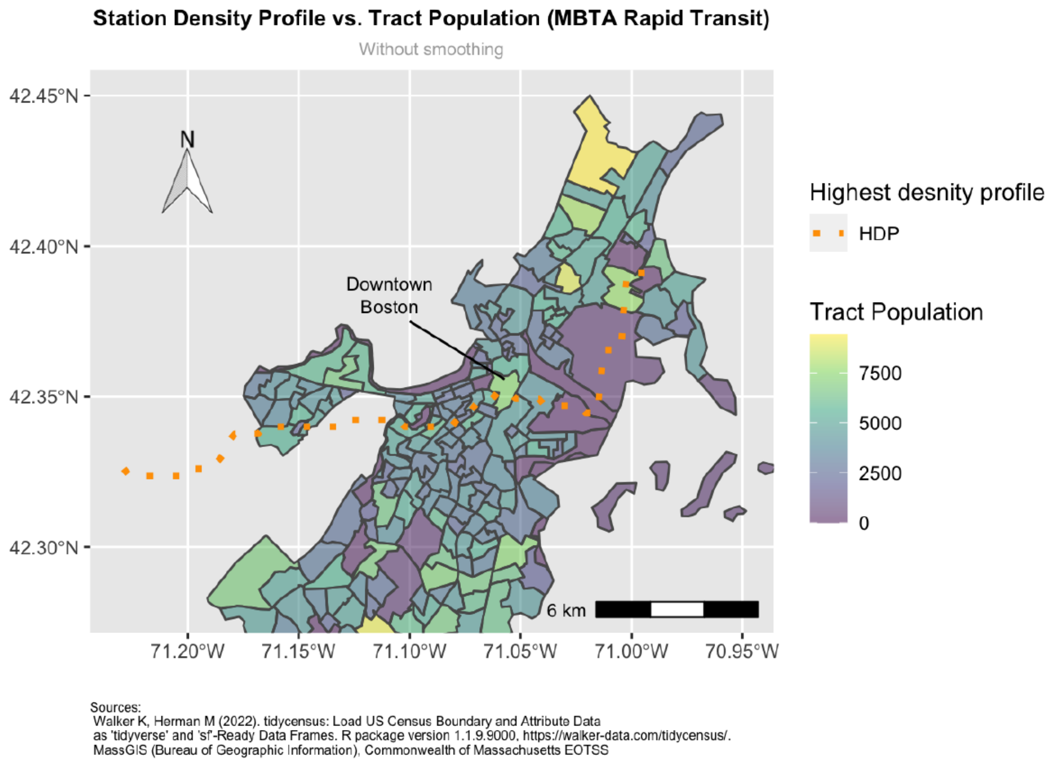
To get a better sense of the directional component, a high density profile was generated. This line represents the highest concentration of stations. The profile was generated by extracting the maximum density values at each latitude. It is shown in orange below:



Sources:
Walker K, Herman M (2022). tidycensus: Load US Census Boundary and Attribute Data as 'tidyverse' and 'sf'-Ready Data Frames. R package version 1.1.9.9000, https://walker-data.com/tidycensus/.
MassGIS (Bureau of Geographic Information), Commonwealth of Massachusetts EOTSS

Figure VIII. Density map for MBTA Rapid Transit (subway) stations and highest density profile.

The highest density profile visually confirms that rapid transit stations are concentrated along an east-west line. Consequently, using the subway to navigate North and South is inconvenient–one would likely end up Downtown before arriving at their final destination. This route should be familiar to anyone attempting to cross the Charles by train. Living too far from this line would mean limited access to rapid transit if any at all. Limited subway access means more congestion along roads. Of course, demand plays a significant role in this scenario: if fewer people wish to travel north and south, the problem is diminished. Other variables like median income, job distribution, and physical obstacles also come into play. From an objective standpoint, however, subway accessibility is limited to the profile above. To see how this line compares to the geographic distribution of Boston residents, a map of Census tracts filled by population can be generated:



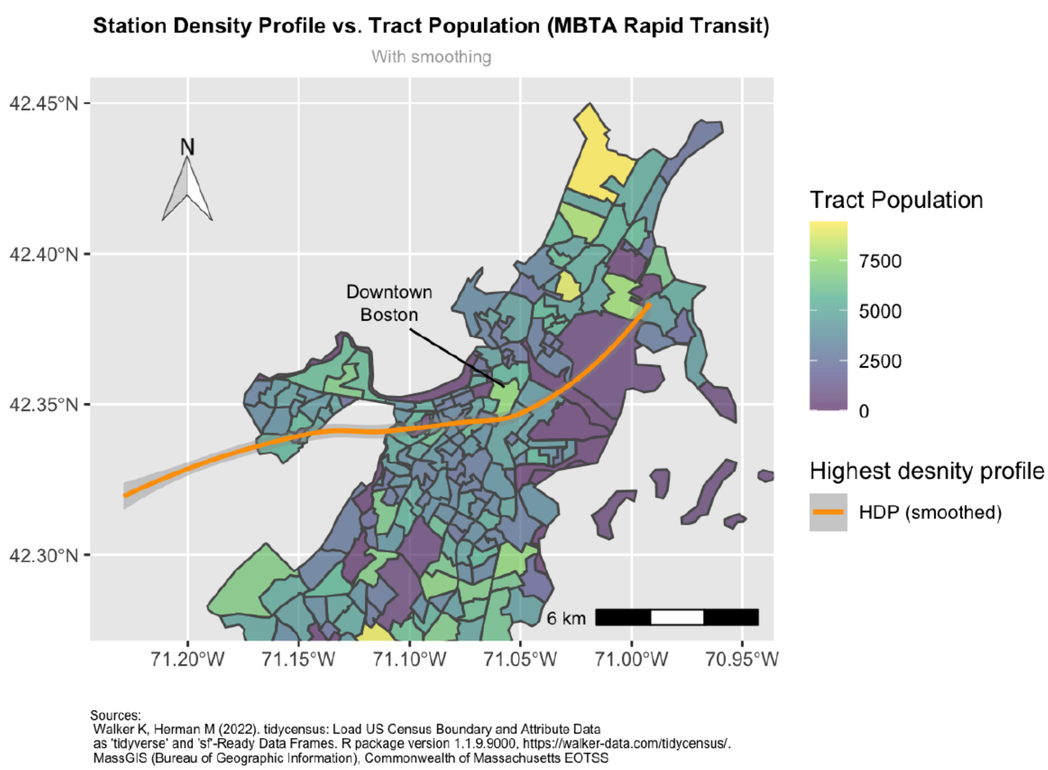


Figure IX. Highest density profile overlaid on Census tract populations.

Keep in mind that these maps are not representative of population density in Boston. Instead, they demonstrate population on a tract-by-tract basis. Some noticeable outliers are larger tracts and the Boston Logan Airport, where few people live but many stations converge. Aside from that, the population distribution in central Boston is fairly even. Notice, however, that a considerable number of people live north and south of the highest density profile. Those attempting to commute into the city from areas like Roxbury and Dorchester are generally limited to a single subway line, assuming they're willing to walk far enough. While public transit isn't completely inaccessible, greater walking distances form an obstacle for sections of Boston's population. The density map effectively communicates the severity of this obstacle, but a buffer map would allow for a more accurate (although noisy) representation of station accessibility in terms of average walking distance. The U.S. Department of Transportation estimates that the average individual is willing to walk around 0.25 miles to a transit stop (U.S. Department of Transportation, 2013). Here, a map shows that distance as a buffer around each MBTA subway station:

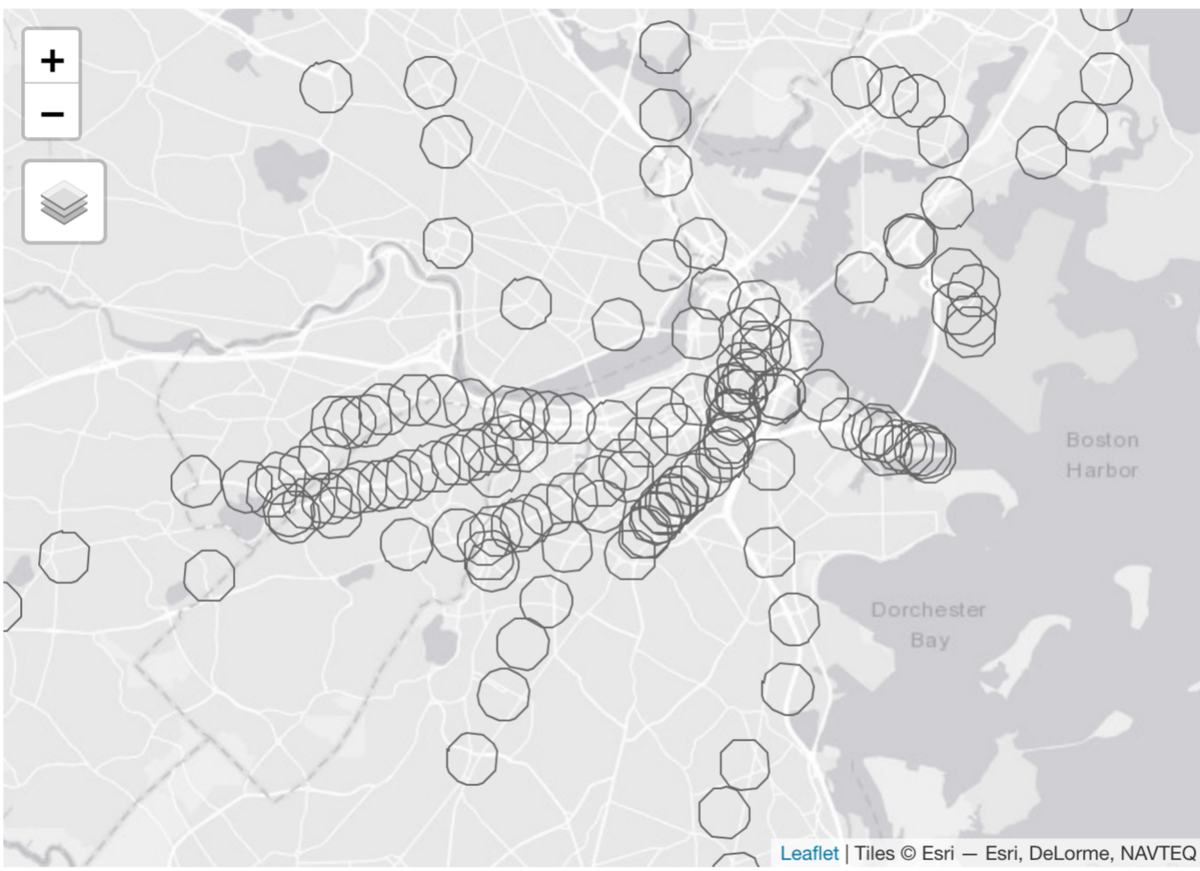


Figure X. Rapid transit buffer map (each buffer has a radius of 0.25 miles or 804.672 meters)

From this view, there are clearly areas of Boston that lack immediate access to rapid transit, particularly East Roxbury and Dorchester. It should be noted, though, that Boston's network is relatively well-designed, with lines fanning out in all directions. From this visual, it is also clear that certain areas have fewer stations, but that doesn't necessarily mean that they lack subway access altogether. That's one of the weaknesses of the density map; it overgeneralizes the directional component of the rapid transit system by ignoring areas with less dense stations. Hence, the buffer map provides a better picture of the real-world access to subway stations. One could look at this map and determine if they're within walking distance of an MBTA station, which is why it has been included in the dashboard. It should also be noted that a commuter rail line runs through the seemingly vacant area of Dorchester.

Another way of visualizing station accessibility by region is to fill each Boston neighborhood by the number of rapid transit stations it contains:

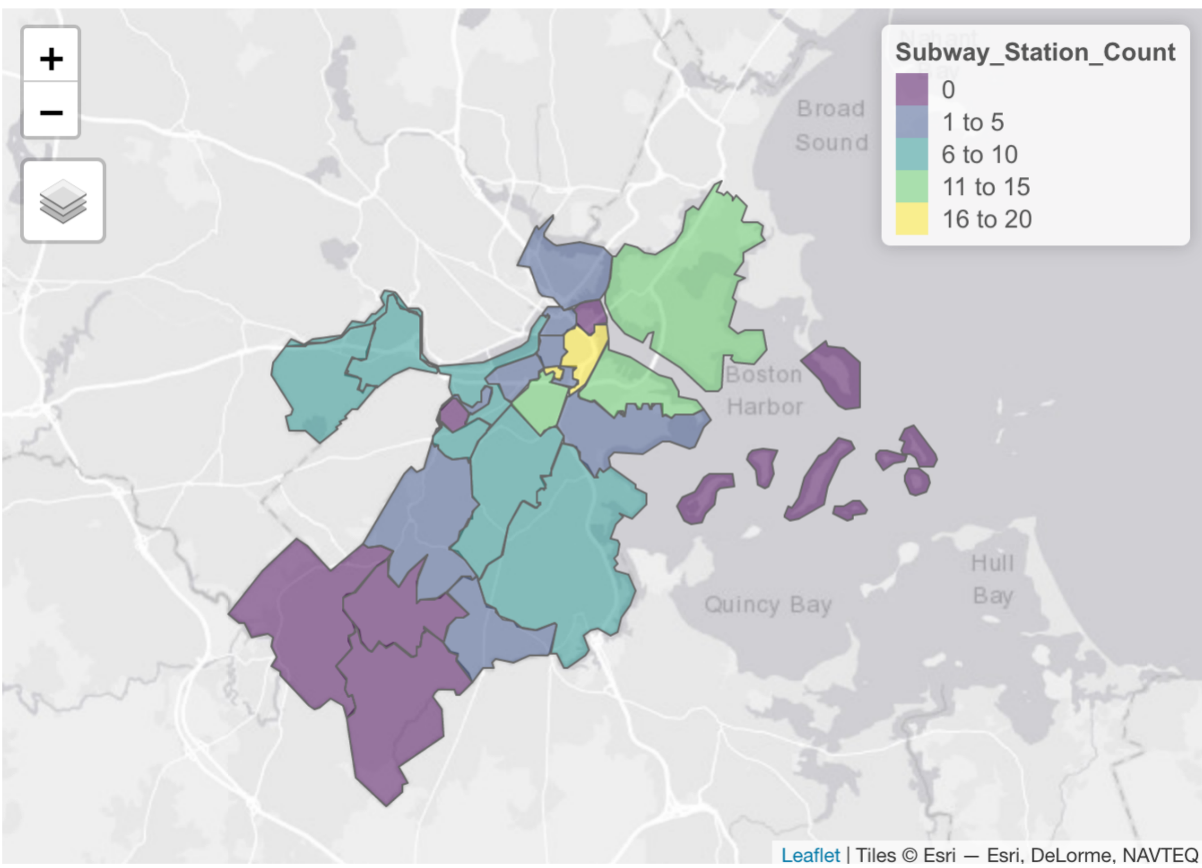


Figure XI. Rapid transit stations by neighborhood.

Once again, it's evident that the inner city contains far more stations to accommodate a higher density of people. Yet, those living further out from the city have a limited number of stations with some neighborhoods having no stations at all. To better visualize this, a graph can be drawn to represent the connections between Boston neighborhoods by subway. If a neighborhood contains any stations, one could assume that its residents are able to reach any other neighborhood that also contains stations. This network demonstrates the connections by subway line (i.e., the green line, orange line, etc.):

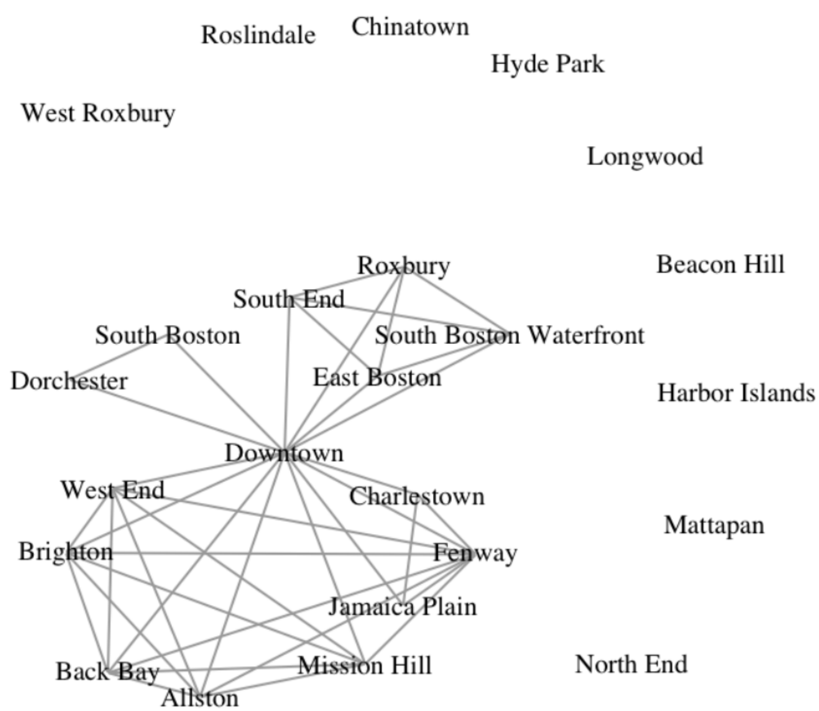
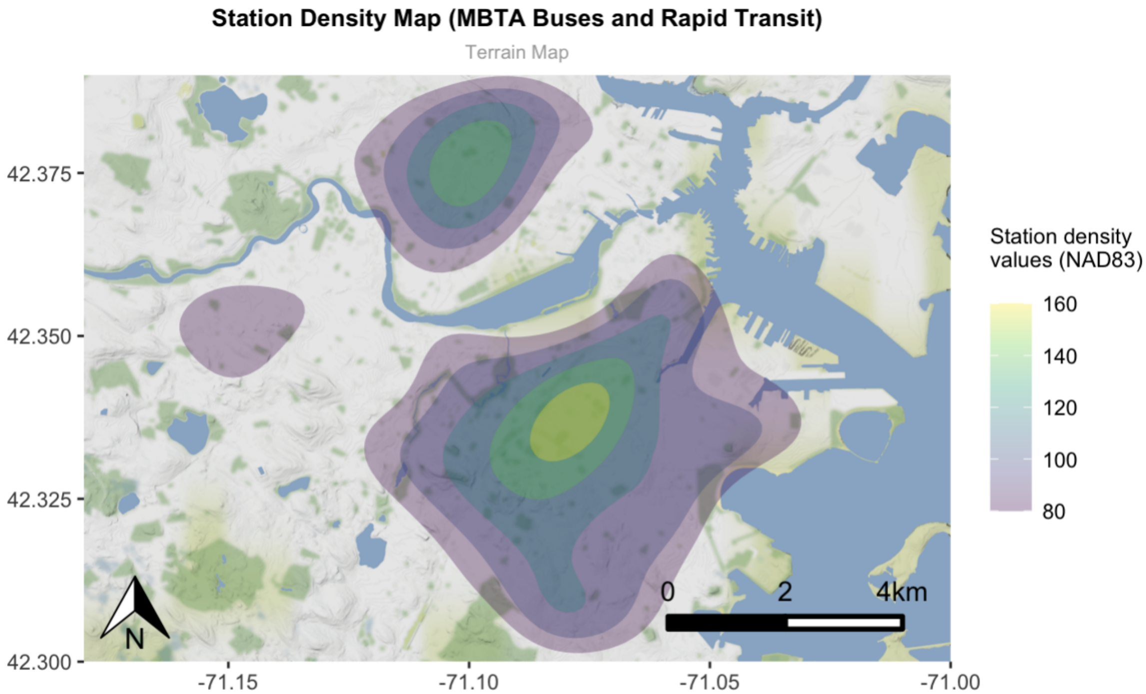


Figure XII. Neighborhoods connected by rapid transit lines.

This graph shows that a number of Boston neighborhoods completely lack rapid transit stations. Some of these neighborhoods are small enough to share stations with bordering neighborhoods. However, others such as West Roxbury have no stations in their immediate vicinity. These areas are connected via the commuter rail which has a lower frequency of trains, making regular travel by rail difficult.

Things change when accounting for Boston's bus network. The same methodology from before can be applied to a combination of bus and subway data. Another kernel density estimate was generated from the combined collection of stations:



Sources:
D. Kahle and H. Wickham. ggmap: Spatial Visualization with ggplot2. The R Journal, 5(1), 144-161.
URL http://journal.r-project.org/archive/2013-1/kahle-wickham.pdf
MassGIS (Bureau of Geographic Information), Commonwealth of Massachusetts EOTSS
Map tiles by Stamen Design, under CC BY 3.0. Data by OpenStreetMap, under ODbL.

Figure XII. Density map for MBTA Rapid Transit stations and bus stops.

Evidently, the distribution of transit access becomes much more even when buses are taken into account. In fact, the concentration of buses and subway stations seems to align closely with the geographic and political boundaries of Boston. There is also a high concentration of stations in Cambridge, allowing for movement North and South. Hence, traveling within the greater Boston area is fairly accessible from a geographic perspective. This result is consistent with the aforementioned claim by Steven Higashide that Boston's bus network is an example of equitable urban planning. It also demonstrates the potential for transit expansion in some of America's oldest, most populated cities. Urban planners managed to work around nearly 400 years of established infrastructure to provide modern public transportation to a majority of residents.

6 Discussion

The spatial analysis presented here and in the dashboard contributes an objective representation of Boston's MBTA layout. As discussed in the introduction, an analysis of station locations yields a number of useful insights for future research. The proximity of vulnerable communities to rapid transit stations can represent disparities in opportunities for social mobility. In other words, those facing low-income or other socio-political obstacles can be hampered financially by limited access to public transportation when it is a necessity. Demand for transit can also manifest itself within communities that physically cannot drive, such as disabled residents and the elderly. The station density map communicates the severity of limited transportation in a geographic sense. The dashboard allows its audience to interact with this visual and other representations of transit accessibility in an easy-to-digest manner. A typical map of the MBTA system lacks these features for the sake of simplicity.

The dashboard also conveys surface-level information about the environmental threat of high-volume transit networks in Boston. In particular, the visual analysis presents could be extended to monitor the proximity of transit to wildlife reserves and water. Overall, the dashboard is meant to serve as an all-purpose tool for researchers and locals. It solves the first step in any spatial analysis of Boston that's interested in evaluating the nature of station locations.

Arguably, Boston has one of the best public transportation networks in the United States. Its rapid transit system is designed to funnel high volumes of people into the city, while an extensive bus network accounts for inter-regional travel. The system fans out from the center of Boston in all directions with support for long-distance and short-distance travel.

7 Future Research

Time did not permit this analysis to go in-depth on some of the socioeconomic variables presented. It would be useful to model MBTA traffic, perhaps with a Poisson distribution, to visualize the actual movement of people at certain times of the day. Using principal component analysis and other dimensions of spatial analysis could also be worthwhile. In particular, more layers of Census data should be overlaid with the existing network visual. Other ethnographic and innovation topics could also be explored, such as the introduction of alternative fuels and the waste generated by stations that see little use. This analysis was also interested in exploring economies of scale within the transportation industry, but it was decided that the topic was outside of the scope of this analysis.

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