Accessibility-Based Analysis of Infrastructure Improvements to the Multimodal Western Corridor in Massachusetts

by

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Submitted to the Department of Civil and Environmental Engineering
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Abstract

MassDOT is in the planning stages of the Allston I-90 Interchange Improvement Project which, largely due to public participation, could evolve into a multimodal project involving replacing the structurally deficient highway interchange, providing enhanced bike and pedestrian connectivity, building a new West Station, and eventually introducing new passenger rail service using DMU's through Kendall to North Station. With the roadway network operating close to, at, or beyond its practical capacity, these changes could allow for a major modal shift to transit for commuters from the largely residential western suburbs to multiple high growth areas in Boston, including Kendall, Downtown, the Innovation District, and Longwood Medical Center. Growth in these areas is currently occurring in the absence of viable transportation options, rather than because of them, and additional options will need to be provided if future growth in the area is to be sustained.

This thesis assumes an optimistic view of continued development by continuing to project high job growth and related transportation demand in the Western Corridor to the year 2030. This includes identifying the mode shift that would be necessary to accommodate this future and designing the service characteristics of the system required to support this shift. These forecasts are considered in the context of other major infrastructure projects and the regional economic impacts they have had.

With sufficient investment in new and existing transportation infrastructure in the Western Corridor, including all-electronic tolling on the turnpike, off-ramp reconfiguration, increased frequency on commuter rail, new DMU service on the Grand Junction, and supplementary bus connections throughout the region, it will be possible to sustain high job and residential growth in the Boston area. Without these improvements, particularly those on the transit side, industries and individuals may see reduced accessibility to workers, jobs, and services and may therefore choose to move elsewhere. It is important to factor in these greater regional economic impacts when reviewing the true value of potential improvements to the transportation system.

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Chapter 1 – Introduction

The Boston area is growing. While in the past, growth in the area could be accommodated by the historic transit system as well as by the auto network, both networks are now running close to, at, or over capacity during peak hours. In order for projected growth to occur and not be constrained by an inadequate transportation network, improvements to the system need to be made because growth in demand is exceeding transportation capacity. Otherwise, roadway congestion and transit vehicle overcrowding will impose increased discomfort to commuters, accessibility to jobs and workers will decline, and economic growth will be constrained.

Infrastructure projects require a large upfront cost, with benefits lagging years behind in an unpredictable and perhaps very different future, making it challenging to justify these projects to taxpayers. It can also be difficult to quantify all the varying benefits that can ripple through society, including avoiding the cost of what would occur if nothing is done to improve transportation capacity. This challenge is studied in the Boston area in the context of improvements to the I-90 Turnpike and parallel commuter rail and other transit service now being considered in Allston. If improvements are made, particularly to improve transit capacity, current levels of service for auto travelers in the corridor could be maintained and additional demand could be satisfied by transit. If sufficient transit improvements are not made, auto traffic volumes will approach capacity, resulting in unstable flow and reduced capacity. This could increase commuter dissatisfaction, reduce the economic attractiveness of the region, and constrain the amount of development that is now occurring in existing growth nodes and could continue to occur in new areas in the future.

1.1 Background and Methodology

To compare future potential investments in transportation capacity and measure their potential impact, this thesis will employ an accessibility-based analysis to evaluate possible transportation improvement scenarios. Accessibility is defined as the number of jobs or workers than can be accessed from a home or job site within a certain travel time threshold. This measure is used to capture the economic and societal impacts of location choice by integrating not just travel time but also the number of opportunities that can be reached within a particular travel time (Ducas, 2011). This will capture the impacts of both additional congestion in the network and additional jobs and housing in the area. Further effort will be taken to disentangle these two impacts to better understand the types of changes that should be made in order to accommodate alternative potential futures.

This analysis will be applied to the transit and auto networks. The primary challenge facing the auto system is restoring a physical state of good repair to the aging infrastructure. Because few changes can or should be made to increase the capacity of the auto network, the only way to avoid further congestion on roadways will be to encourage some existing and new travelers to use alternate modes. Capacity constraints on a highway cause flow to be nonlinear, with density and travel speed ranges that can be difficult to predict and lead to reduced throughput. Free flow travel on the turnpike will not be possible during peak hours, nor is this necessarily desirable. But by preventing travel speeds from dropping from the 30 to 40 mile per hour range into the completely unstable 10 to 20 mile per hour range, satisfactory conditions and capacity could be maintained for adequate service for those who choose to travel by private vehicle.

An effort currently being planned by MassDOT to address structural deficiencies in a highway interchange could be developed to address these transportation network constraints. This project is the Allston Interchange Improvement Project, and while it was originally conceptualized as just a highway project, it has evolved in the planning stages into a multi-modal transportation project (MassDOT, 2014). This development could lead to better transit service in the Western Corridor, as will be discussed in the second chapter. If implemented in full, this project could help restore roadway flow to more stable conditions, improve transit frequency and reliability, alleviate growth constraints for commuters from the residential Western Corridor to high growth areas in and near Downtown Boston, and eventually support a new high accessibility growth node to complement these existing areas. This project is used to test the methodology in this thesis, particularly since the State of Massachusetts may have additional data on accessibility available in future years that could fit in with this framework for future project analysis.

This thesis will also look at changes in travel times and incorporate these results into the accessibility calculations. This is done in order to disentangle the two large-scale changes that will be occurring – job growth and congestion intensification. Accessibility is an insightful measure for comparison, but is best when considered alongside other methods that can provide additional understanding into the reasons behind the trends that are detected.

1.2 Objectives and Framework

Instead of the reactionary transit planning policy seen traditionally, this thesis intends to explore a methodology where anticipated problems are addressed before they become critical. This includes anticipating demand reaching the capacity constraints of a system while congestion is still at a manageable level. This is expected to better utilize existing resources in the long-run, because as networks become less efficient they also become less cost effective. Therefore, the timing of infrastructure improvement projects is very important, as these projects can be much more effective if they are implemented before the problems they are trying to solve have been exacerbated or have led to catastrophic consequences, as well as before construction costs have increased further, as they tend to outpace inflation.

This is illustrated by designing a system based not solely on demand, but by considering what capacity is possible. First, the limiting constraints of the transit and highway networks will be calculated. This allows alternative possible transit investments to be designed. Then, these systems must be compared to traveler preferences on mode choice in order to determine whether they will be sufficient to encourage the appropriate behavioral change. The final step will be to go back and calculate whether this level of transit usage will be enough to accommodate growth in the area and successfully bring turnpike traffic congestion down to levels that can maintain throughput capacity. If this is not possible, other changes to the auto network such as tolling, parking pricing, and parking restrictions will be suggested.

Real world projects are often constrained to looking at the world as it currently is and assuming it is likely to remain that way. Research offers the flexibility to test potential scenarios associated to specific trends – such as lower auto mode share, shifting residential patterns, more frequent transit service on new modes – in order to project a new future. The work in this thesis will assume high growth in the Boston area, particularly in certain existing and proposed job-dense areas, and attempt to design a transportation system that could sustain this growth. While this level of growth is possible it is not guaranteed, as it is much more likely to occur if it is not stunted by a lack of viable transportation options.

1.3 Thesis Organization

This thesis is organized into seven chapters including this introduction. Chapter two introduces the project area in which MassDOT is in the preliminary stages of the highway interchange improvement project that will integrate multi-modal components. This chapter analyzes the opportunities and challenges facing the transportation corridor this interchange serves and the communities along it.

The third chapter looks at a recently completed large infrastructure project, The Central Artery and Tunnel Project. In this chapter, projections made in the environmental review process can now be compared to actual conditions in order to provide insights on how accessibility by road and transit was affected by this project.

Chapter four discusses the literature on mode choice. Because a modal shift to transit will be necessary to accommodate projected growth in the area, this chapter looks at why travelers, particularly commuters, make the modal choices we have observed.

The fifth chapter takes a look at the past, analyzing the trends in demographics and transportation demand in order to create the framework and provide the expectations for future changes.

These future changes are further explored in chapter six where an accessibility-based analysis is conducted, so that potential improvements to the transportation network are analyzed and compared.

The seventh and final chapter will present the design of the multi-modal transportation system that would be sufficient to address the network and demographic changes explored in the previous chapters. This chapter will also provide recommendations on how similar methods can be used to analyze other infrastructure improvement projects in the future, before summarizing the findings of this thesis and suggesting future work.

Chapter 2 – Western Corridor Characteristics and Transportation Constraints

This chapter describes the current conditions of the area under analysis and the constraints facing its existing and potential transportation network. The area referred to as the Western Corridor runs about 50 miles mostly east-west from Downtown Boston through Allston, Newton, and suburban communities out to Worcester. By car, the corridor is served by the I-90 Turnpike, the eastern-most portion of the interstate highway that traverses the country from Seattle to Boston and charges a distance-based toll within the state of Massachusetts. The Western Corridor is also served by the Worcester/Framingham commuter rail line with 24 weekday trips in each direction (Massachusetts Bay Transit Authority, 2015). There is also some service provided through this corridor by the MBTA Green Line light rail system and nine overlapping commuter bus routes on the turnpike. Auto drivers can also take parallel routes on roads such as State Route 9, Nonantum Road, and Soldier's Field Road for parts of the corridor.

This corridor is important because it provides service from largely residential areas west of Boston to high growth employment areas in and near Downtown Boston, as highlighted in the map shown in Figure 2.1. These employment areas are expected to continue growing, despite constraints to employee access due to congested conditions on the turnpike and due to infrastructure restrictions that limit the expansion of service on commuter rail. Because the turnpike cannot accommodate additional traffic and will not be expanded to do so, the best option for moving a growing number of commuters through the Western Corridor is to encourage a modal shift of existing and new commuters to an enhanced and expanded transit network, which will be possible due to infrastructure improvements in the area referred to in Figure 2.1 as West Station. These changes could relieve the current single track bottleneck in the area, and allow for a new rail link from West Station through Kendall to North Station, possible due to new federal regulations on the use of Diesel Multiple Units (DMU) on corridors shared with freight rail. This link could also be expanded along existing commuter rail lines further into the Western Corridor. Additionally, there is potential for increased capacity on the Riverside branch of the Green Line and additional express buses on the turnpike to provide additional transit capacity in the corridor.

The chapter will begin by providing the context for why additional transportation demand is expected in the Western Corridor before introducing the constraints and opportunities for meeting this demand across the possible modes. Chapter 6 will elaborate further on whether these ideas could be successful.

Figure 2.1: Boston high growth employment areas (yellow) and Western Corridor transportation

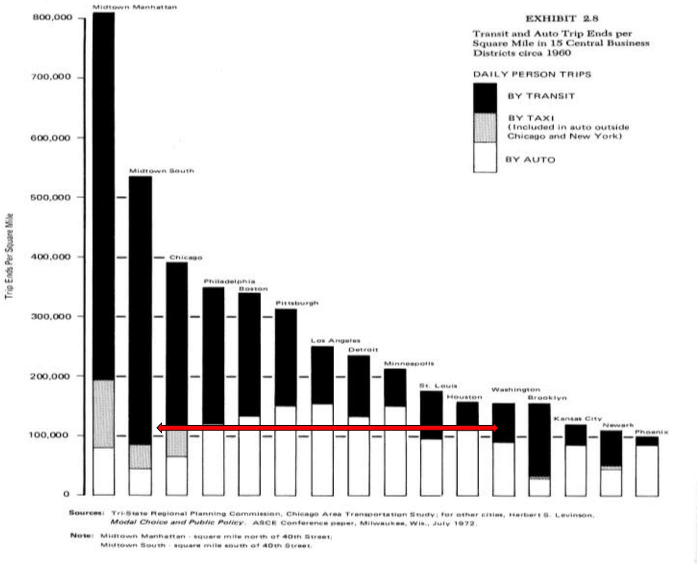
2.1 High Growth Employment Areas

The Boston economy is growing, and the transportation network is nearing the capacity to adequately serve the corresponding growth in travel demand. There are a few areas in particular whose growth is outpacing that of Boston as a whole, such as Longwood Medical Center, Kendall Square, the Innovation District, Logan Airport, and the Financial District and Back Bay in Downtown Boston. There is also potential for a new growth node at Allston near West Station. Some of these have traditionally been employment centers while others are newer. All lie within a reasonable distance of the I-90 Turnpike as it weaves through Boston and have a level of transit access such that service from the Western Corridor via the Framingham/Worcester commuter rail line is possible, directly or with a single transfer.

Kendall Square lies adjacent to MIT's campus and is a booming computer and biomedical technology center. This area benefits greatly from agglomeration effects of being close to MIT's and Harvard's campuses as well as many medical centers such as Massachusetts General Hospital and the Longwood Medical Center. Kendall is experiencing high growth in high-income jobs in biotech and other technology industries. High-income job growth will in turn increase the number of lower-income jobs to supplement the developing area. Correspondingly high residential growth has not occurred. According to the US Census, from 2000 to 2010 the number of households in the city of Cambridge increased just 3%, from 42,615 to 44,032 (U.S. Census Bureau, 2000; U.S. Census Bureau, 2010). This trend is expected to continue so many of these future employees will need to travel to their jobs (generally during peak hours) and the number of home-based work trips to Kendall is expected to increase.

The most direct transit option to Kendall is the Red Line, which is currently operating at capacity during the peak. Improvements to the signaling system could decrease headways to as low as 2 minutes, supporting more than double the capacity if sufficient vehicles are acquired. Arterial streets are also at capacity during peak hours and will not be able to adequately accommodate all additional users if growth happens as expected. Even if job growth is less than expected (as it may be if transportation constraints are not adequately addressed or if a large industry shift occurs), changes to the transit network through Cambridge could improve accessibility for residents from the west to travel to North Station, better linking the greater transit network of the Boston area and encouraging additional users to shift their travel mode to transit.

Zupan's historical analysis of the relationship between transportation modes and land use density demonstrated that high density development is not possible with auto usage alone (Zupan & Pushkarev, 1977). As the number of trip ends per square mile exceeds a certain threshold, the density of vehicles on the roadway and the amount of parking required is not sustainable and thus change in modal split between auto and other modes is required. Zupan and Pushkarev made this observation by comparing the number of daily person trips by auto across cities in the United States, and seeing that they did not exceed a rough threshold regardless of the density of the city. Boston had already exceeded this threshold in 1977 when the book was originally published, and today areas like Kendall and the Innovation District have even higher transportation demand, with approximately 350,000 and 340,000 trip ends per square mile, respectively, in the most dense centers of development (VHB, 2015; Fay, Spofford & Thorndike, 2015). If full build-out projections are realized, growth in Kendall and the Innovation District is estimated to increase these values to 460,000 and 530,000, respectively.



Sources: Tri-State Regional Planning Commission, Chicago Area Transportation Study; for other cities, Herbert S. Levinson, *Modal Choice and Public Policy*. ASCE Conference paper, Milwaukee, Wis., July 1972.

Note: Midtown Manhattan - square mile north of 40th Street.
Midtown South - square mile south of 40th Street.

Figure 2.2: High-density land use is possible due to transit usage (Zupan & Pushkarev, 1977)

Despite recent periods of worldwide recession, the change in the number of jobs in the metropolitan area has been net positive over the past 25 years (Executive Office of Labor and Workforce Development, 2016). Figure 2.3 includes jobs in all industries and in all locations in the Boston-Cambridge-Newton Metropolitan Area. Because this growth is expected to continue, so is the number of trip ends per mile, especially since the growth will be concentrated in certain industries and at certain high density locations. It will require increasing transit usage to sustain that development.

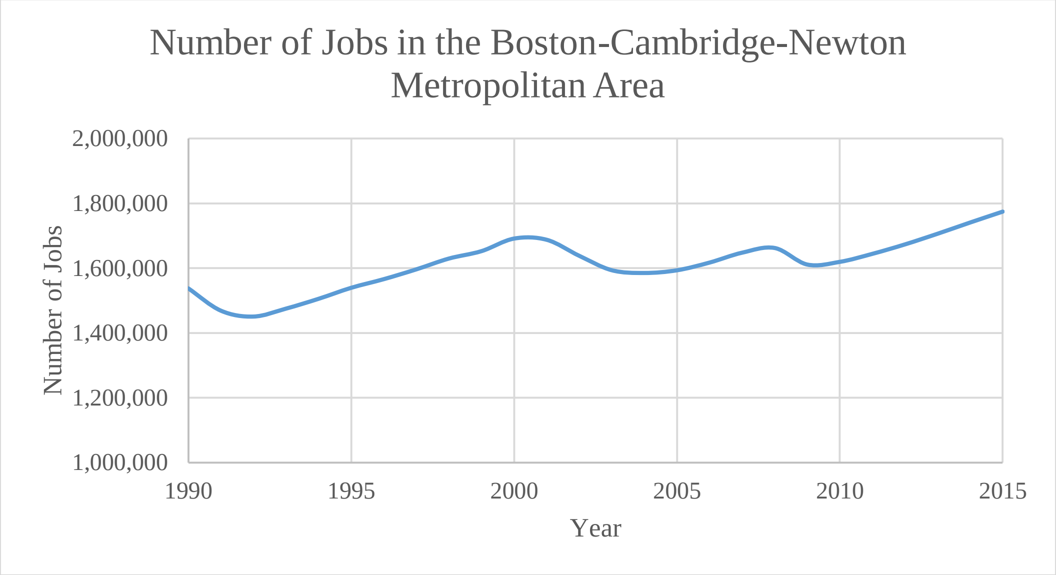


Figure 2.3: Change in number of jobs in the Boston metropolitan area (Executive Office of Labor and Workforce Development, 2016)

When looking just at high-growth industries in high-growth areas, the increase is much more significant. The number of jobs in the Innovation District increased from 28,800 to 36,500 from 2000 to 2013, an increase of 7,700 jobs, or 27% (VHB, 2015), higher than the overall increase of 3% in the city of Boston and 1% for the metropolitan area. The number of jobs in the Innovation District is expected to increase another 63% of current values by 2035, to 59,430 jobs. Concentrated growth is a larger issue from a transportation perspective because it places more strain on lower-capacity infrastructure such as off-ramps as well as larger-capacity infrastructure such as the main thoroughfare or highway. Longwood Medical Center is another example of concentrated job density and growth, as it already employs 45,200 people with an average of 1,100 new jobs per year (MASCO Area Planning, 2012). In Kendall, the majority of job growth has been in industries categorized as “Professional and Technical Services” which, when separated from total jobs or service jobs as in the following figure, shows substantially higher growth in the past decade than both total jobs and “Accommodation and Food Services” (United States Department of Labor, 2016).

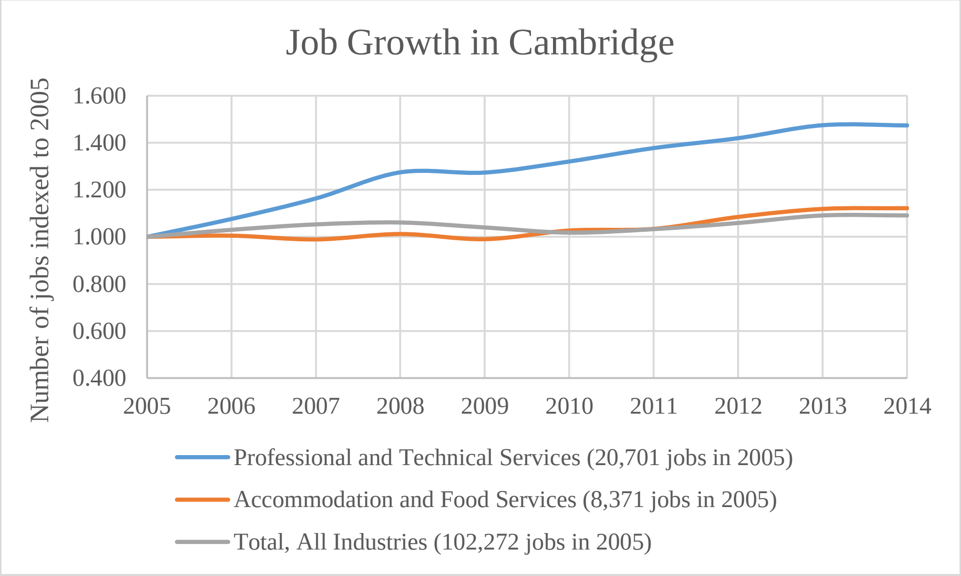
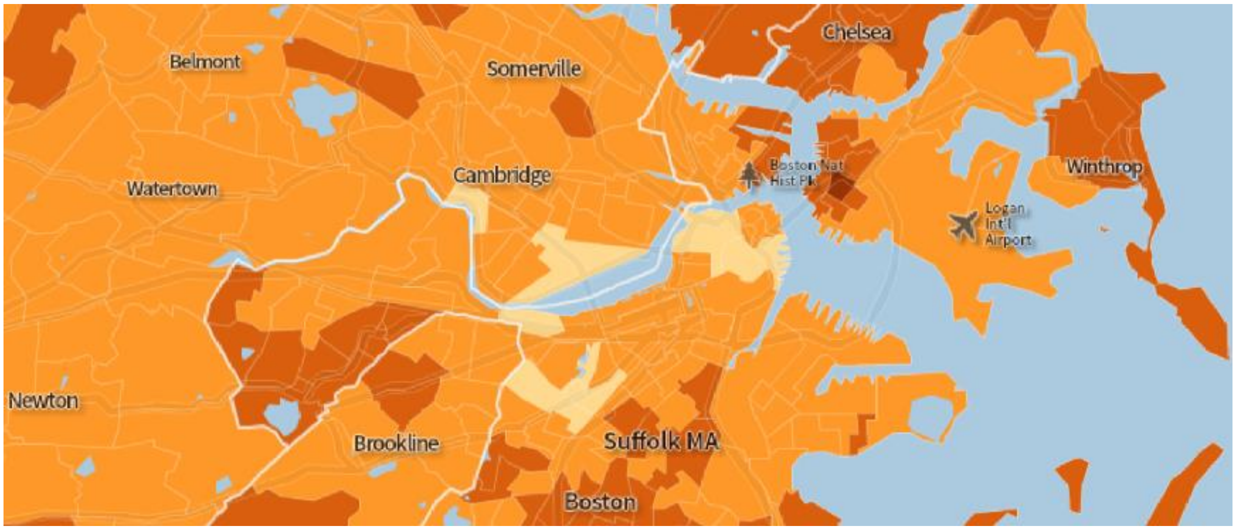


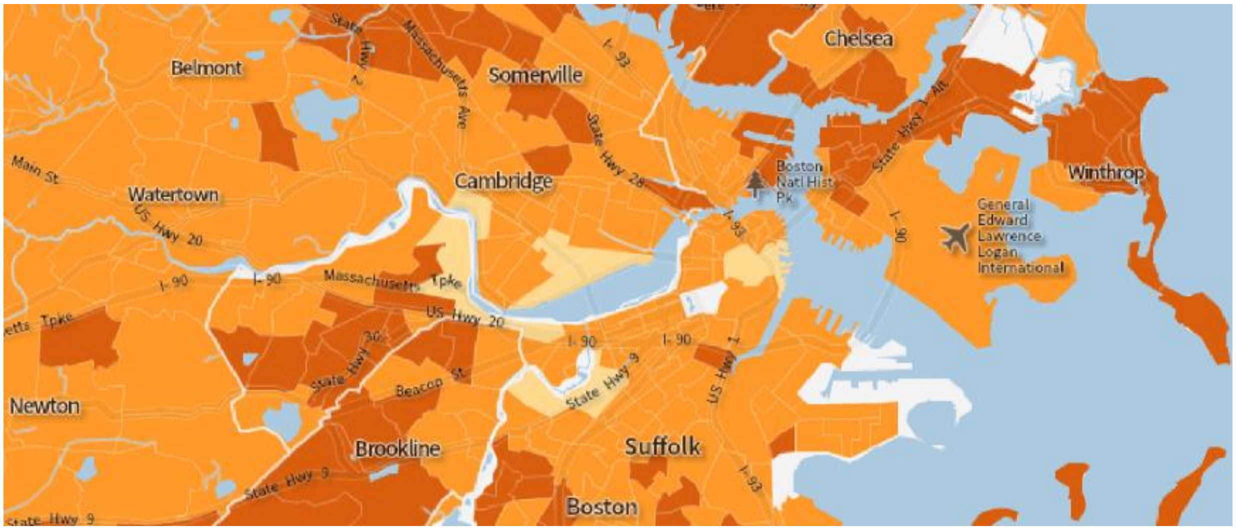
Figure 2.4: Change in number of jobs in Cambridge, MA over the past decade (United States Department of Labor, 2016)

Because of this job growth and relatively few infrastructure investments to help accommodate it, commuting times have been increasing over the same period. The following plots show the average commute time to a destination across all modes for the years 1990, 2000, and 2013. From 1990 to 2000, the Central Artery and Tunnel project helped mitigate increases to the average auto commute time in north Boston, but commute times outside of that area increased noticeably. It appears that between 2000 and 2013 capacity on the expanded Central Artery began to be reached again and average commute times across all modes increased relatively consistently across all of Boston. These trends will be analyzed further by mode in Chapter 4.

(a) 1990 Census



(b) 2000 Census



(c) 2013 ACS (areas in white are those for which no data could be found)

Scale:

Figure 2.5: Historic average commute time to work shown at the destination (U.S. Census Bureau, 2016)

2.2 Residential Suburbs

It has been difficult for residential growth in desirable locations to keep pace with employment growth. This has led to substantial increases in housing prices near job centers, and as a result many employees have had to move further away from their jobs, thereby placing additional strain on the transportation network with their longer daily commutes. For some, it is a preference to live in a less urban area but for many it is a choice made purely due to financial constraints (Ralph, Taylor, Blumenberg, Brown, & Voulgaris, 2016). Some commuters live as far as Worcester, but most remain within a more reasonable distance to Boston. Another reason for this distribution is two-income families where the job location constraints of both earners must be considered. The following figure pinpoints median sale prices of homes in communities along the Western Corridor where employees could move instead of living in Downtown Boston or Cambridge. Proximity to Boston is not the only factor for high home prices, as there is a ring around the Route 128 corridor with higher home prices, due to the size of the homes, quality of schools, and the appeal of suburban living. However, sale price per square foot shows a clearer gradient of decreasing unit cost from downtown outwards.

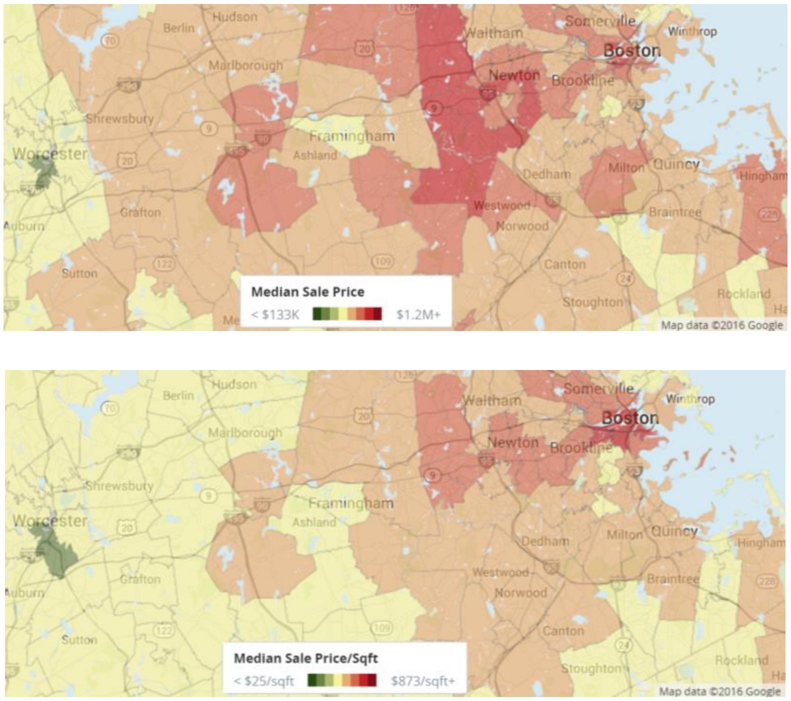


Figure 2.6: Home prices in the Western Corridor (Trulia, 2016)

According to a survey done as part of a City of Cambridge Incentive Zoning Nexus Study published in early 2015, the majority of new employees in Cambridge do not demand housing within the city of Cambridge (Murphy, 2015). This study asked participants whether after accepting a job offer in Cambridge they looked for housing in Cambridge and either moved there or did not, due just to the cost of housing. The question was phrased this way in order to capture not just those who live and work in the same city, but also those who want to, but were unable to do so due to financial constraints. The responses are summarized by employee industry in Table 2.1.

Table 2.1: Results of survey conducted in September and October 2014 (Murphy, 2015)

Tenant Use/Industry	Percentage of New Employees Desiring Cambridge Housing
Research and Development	11.3%
Office	13.3%
Educational Institutions	26.5%
Retail, Restaurant, and Hotel	12.3%

Employees at educational institutions were the most likely to desire housing within the city at 26.5%, while those in all other industries were roughly equally likely to desire housing within the city, with around 11 to 13 percent of new Cambridge employees demanding housing in Cambridge. This distinction between industries is important, because much of the new employment in Kendall is expected to be research and development or office, rather than educational institutions, meaning that it is expected that a higher percentage of future Cambridge employees will live outside the city (especially when the increasing cost of living in Cambridge is considered) and they will likely have a longer commute, generating a larger strain on transportation infrastructure during peak hours.

Currently around 47% of Cambridge employees are also Cambridge residents, though this is likely so high due to the large number of undergraduate and graduate students in the city. Also partially due to the large student population, around 25% of people working in Cambridge walk to work, meaning they have a very low impact on the transportation network compared to other types of commuters. This is also expected to change, both because of local housing constraints and a shift in employment character from educational institutions to high-tech research and development and office jobs. However, if alumni of the educational institutions are those taking the jobs in the research and development fields, this change may be moderated.

Many Red Line commuters travelling within Cambridge or from other urban areas such as Somerville do so partially due to the lower relative cost of living near places like Porter and Davis Squares than places like Kendall Square. Additional transit service along the Grand Junction could greatly benefit these types of commuters by providing additional living options along transit, allowing them to live in areas like Allston with a similar transit commute. These types of commuters are hypothesized to be the same type of people attracted to the new types of jobs in Kendall Square, so this change could have a large impact on the future commuting profile of the area.

While suburbs in the Western Corridor are close in distance to employment centers in Boston, they are often much further from a travel-time perspective. One example is Kendall Square and the residential Newtonville community in Newton, only 7.5 miles and around 16 minutes apart by car under free-flow conditions (Google Maps, 2016). However, this can take somewhere between 25 and 50 minutes by car during peak hours, which is both significantly longer and significantly more variable. Travel by transit requires at least one transfer, likely in downtown Boston, and will take around 45 minutes to an hour. With a better connection through West Station, travel time by transit could be competitive with or faster than travel by car, especially during peak hours, with in-vehicle time of around 15 minutes plus time spent accessing stations on both ends.

When studying the future of the Western Corridor from an accessibility standpoint, a different picture appears than for that of the downtown core and other high job growth destinations. Since accessibility measures not just travel time but the number of jobs that can be reached within this time, an increase in congestion can have a huge impact on the accessibility of an origin. Because of this, without improvements to the transportation network, Western Corridor communities are likely to see lower accessibility to jobs despite economic growth in the region.

2.3 Roadway Capacity Constraints

The Massachusetts I-90 Turnpike is one of just two interstate highways serving Downtown Boston, the other being I-93 which serves commuters from the north and from the south. Because of the high desire for travel from the western suburbs to job areas in and near downtown, demand on the turnpike has exceeded capacity for years, and as a result the turnpike has been operating at capacity during peak hours and the duration of the congested peak has increased. Congestion is also observed during off-peak times, not just for temporary reasons such as construction and lane closures but also because demand can genuinely exceed capacity during the off-peak (Boston Regional Metropolitan Planning Organization, 2012).

The turnpike has two lanes in either direction outside of the Boston metropolitan area which grow into three lanes just before the turnpike enters Newton. There are three lanes for most of the turnpike's journey through Boston, with the exception of four lanes between the Newton Corner and Prudential/Copley exits and two lanes in the Ted Williams Tunnel. Highway lanes are assumed to have a maximum capacity of around 2,000 vehicles per lane per hour, which can vary due to a variety of factors including driver behavior, weather, vehicle mix (of cars and trucks as well as locals and those less familiar with the road), and level of congestion (TRB National Cooperative Highway Research Program, 1999). Ideally, a highway will operate at somewhere under 1,500 vehicles per lane per hour, a level at which consistent travel movement can be maintained, but continuous flow at lower speeds is also possible for higher traffic volumes (Homburger, Hall, Reilly, & Sullivan, 2007). This corresponds with the theory behind the Fundamental Diagram of Traffic Engineering, simplified by the Greenshields Model in Figure 2.7, which demonstrates the relationship between traffic density (vehicles per unit length on a roadway) and traffic flow (vehicles per hour passing a reference point). The first range of the plot represents free flow conditions and, as the density of vehicles on a road increases and speed is maintained, flow increases. However, beyond the peak flow point, flow begins to decrease despite the increase in the number of vehicles on the road due to unstable flow which leads to a decrease in traffic speeds, and the relationship becomes less predictable, as demonstrated by the grey lines. This also corresponds to the range of values for speed, flow, and density in Table 2.2, which shows the peak flow point beyond which conditions become unstable, as demonstrated by the growing error bars.

Table 2.2: Highway level of service definitions and corresponding flow and density ranges (Homburger, Hall, Reilly, & Sullivan, 2007)

LOS	Speed Range (mph)	Flow Range (veh./hour/lane)	Density Range (veh./mile/lane)
A	Over 60	Under 700	Under 12
B	57-60	700-1,100	12-20
C	54-57	1,100-1,550	20-30
D	46-54	1,550-1,850	30-42
E	30-46	1,850-2,000	42-67
F	Under 30	Unstable	67-Maximum

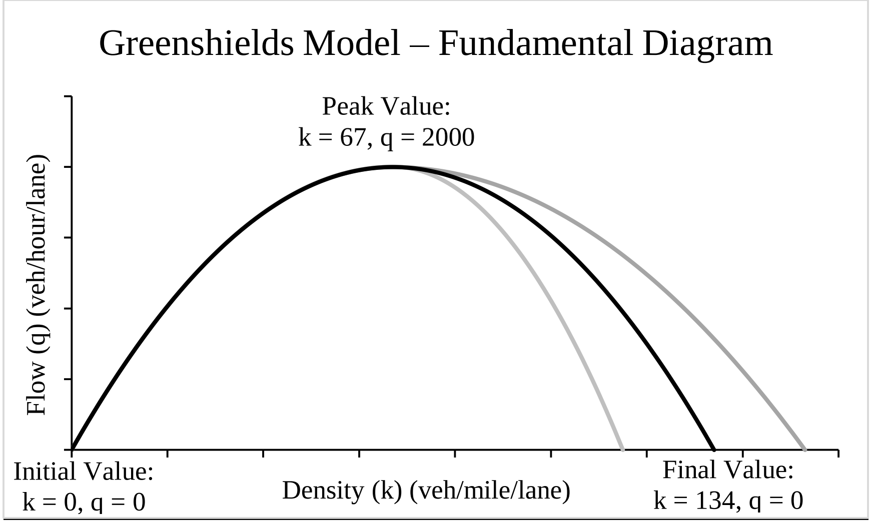


Figure 2.7: Greenshields Model – Fundamental Diagram (Odoni, 2014)

Travel demand on the I-90 Turnpike has greatly exceed this optimal density level during peak hours, effectively decreasing the capacity of the road when it is needed most. Figures 2.8 and 2.9 show average daily traffic volumes in each direction over the past three decades (Boston Regional Metropolitan Planning Organization, 2012). Traffic volumes have been consistently increasing and are particularly high in the Allston Interchange through the exit that leads to Cambridge and the growing job center in Kendall Square. Overall, daily capacity exceeds daily demand, but there are periods during the day when demand exceeds capacity due to peaking behavior. Traffic volumes are presented through the Allston Interchange because major infrastructure improvements are currently being proposed for this area, as will be discussed further in Section 2.5.

Figure 2.8: Average Daily Traffic Volumes – Eastbound

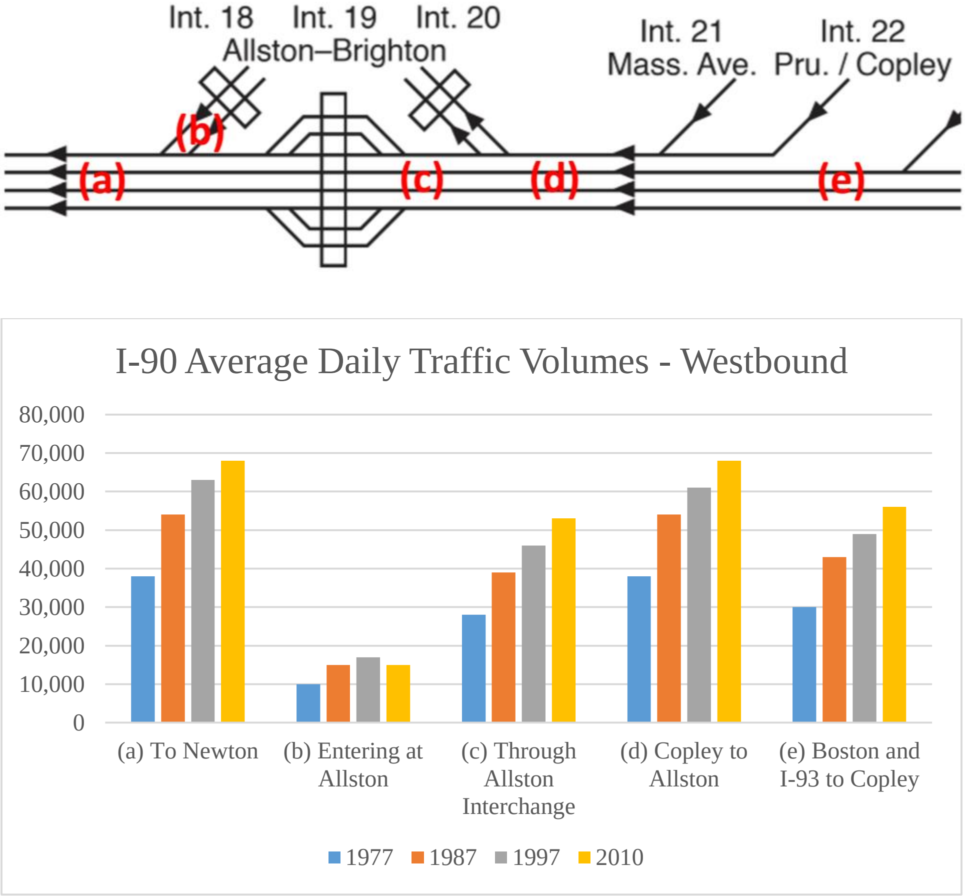


Figure 2.9: Average Daily Traffic Volumes – Westbound

As mentioned, demand exceeds capacity on the roadway during peak hours and thus traffic volumes are at capacity under slow-moving, congested conditions during this time. Traffic volumes during peak hours, as measured by MassDOT, are presented in Figures 2.10 and 2.11 (Boston Regional Metropolitan Planning Organization, 2012). The peaks are defined as 6 am to 10 am and 3 pm to 7 pm. In theory, capacity through this area is around 8,000 vehicles per hour assuming each of the four lanes has a capacity of 2,000 vehicles per hour. Actual capacity is likely more complicated due to the toll booths in the interchange, which cause complicated weaving between lanes as vehicles enter and exit as well as a variable amount of additional time to queue and make a payment, either in cash or electronically, at the booth. Traffic volumes do not reach the theoretical maximum value during any hours of the AM and PM peaks, likely due to the impact of congested travel speeds and conditions. Travel volumes are highest inbound in the morning and outbound in the evening, which makes sense given traditional patterns of travel from residential suburbs to the job-dense city, though travel in the reverse-commute direction is also significant. Overall, around 31-34% of all daily traffic passes through each location in the peak-direction and 19-26% of all daily traffic passes through each location during the peak in the reverse-commute direction. This is during four hours, or 17%, of the day. Peaking behavior is higher in the morning than in the evening. Traffic volumes are distributed approximately equally across the peak but with the “peak of the peak”, or the orange and grey bars in each figure, recording slightly higher traffic volumes than the “shoulders of the peak” in blue and yellow.

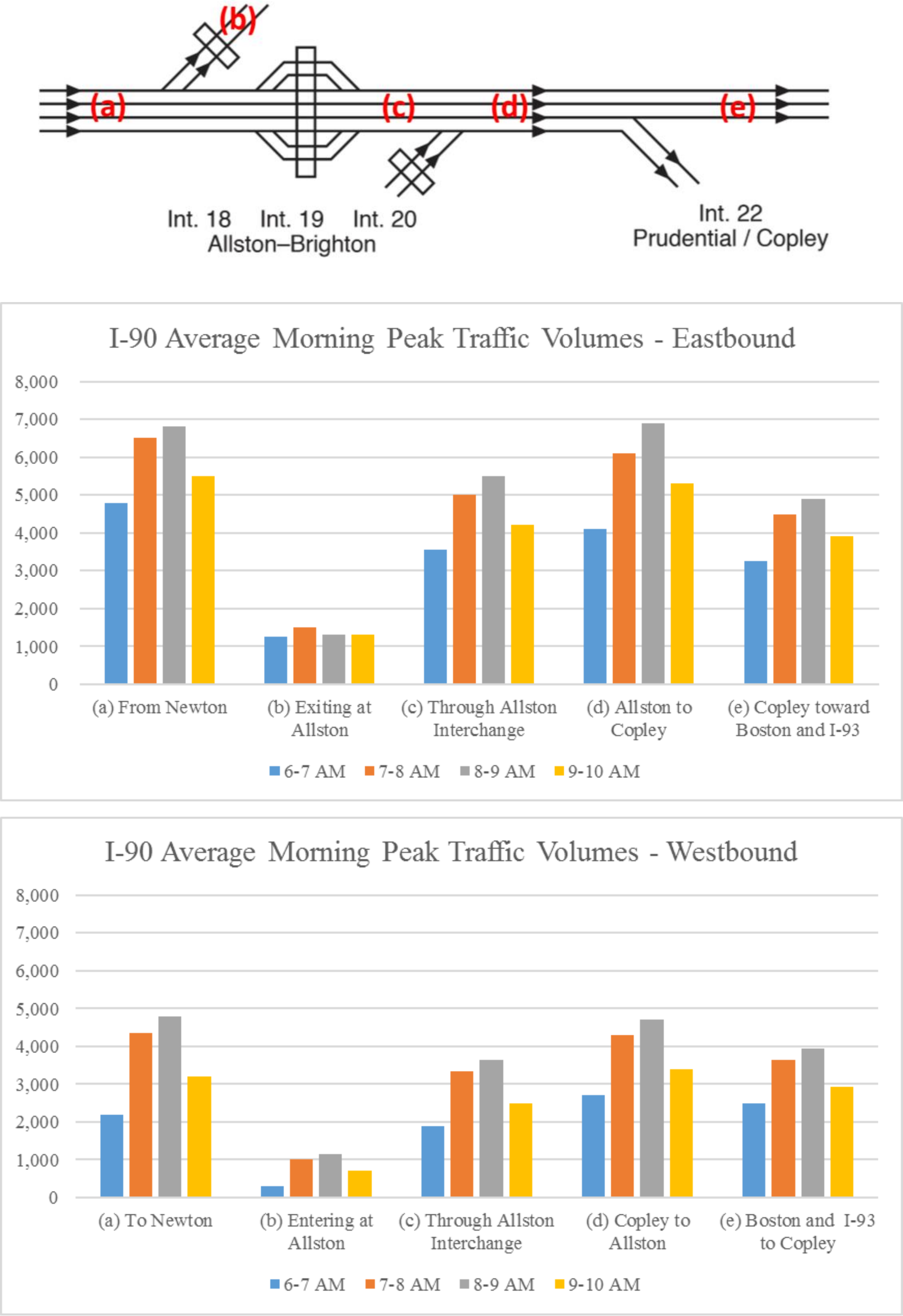


Figure 2.10: 2010 traffic volumes during AM peak

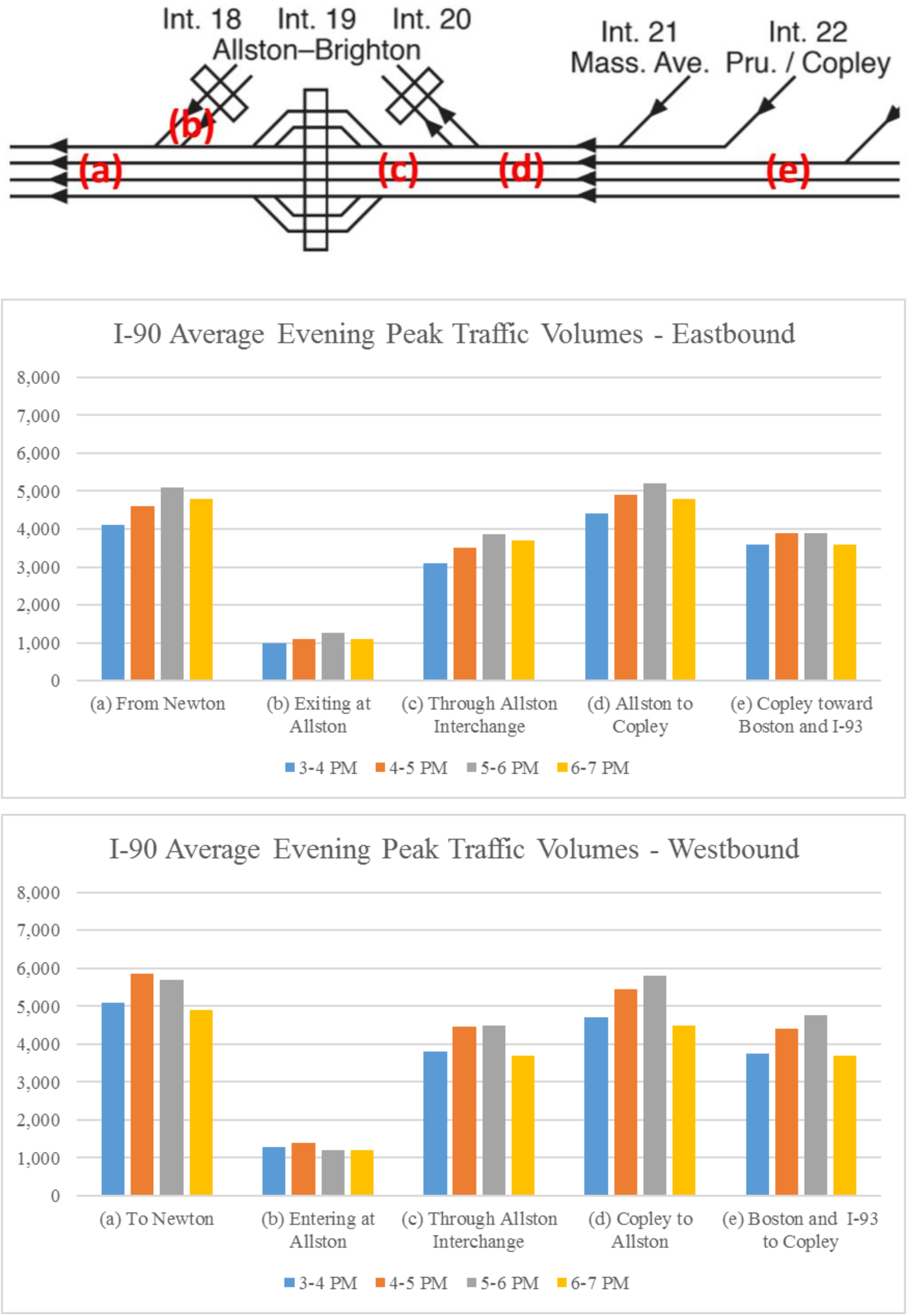


Figure 2.11: 2010 traffic volumes during PM peak

There are a variety of ways to measure traffic congestion since it is a somewhat subjective measure. These include roadway level-of-service classifications, as previously introduced in Table 2.2. Other methods include defining a travel time index as the ratio of peak to off-peak travel speeds, measuring the duration of the congested peak period, and calculating the number of “delay hours”, or extra travel time felt by users due to congestion. However, calculating an exact value for congestion is difficult because congested travel is inherently unstable. Since throughput decreases under high-volume conditions, demand is not always adequately measured by traffic volume. Demand beyond capacity splits into neighboring hours (or alternative paths), so during a time period such as 9-10 AM, actual travel demand may be below capacity but traffic volumes may still be high due to the presence of vehicles that would have liked to have traveled earlier but are still on the road due to the low travel speeds. Similarly, traffic volumes in the early morning hours such as 5 to 6 AM are likely higher than it would be if peak hours were not so congested as many commuters will choose to travel earlier and arrive at work before they are required to, in order to avoid congestion, shorten their time spent traveling, and lessen the frustration of their commute. This smooths traffic volumes from the peak into the "shoulders of the peak", as visualized in the following figure, where demand is defined as the original demand for travel during an hour and volume is defined as the actual number of vehicles that choose to or are able to travel during that time.

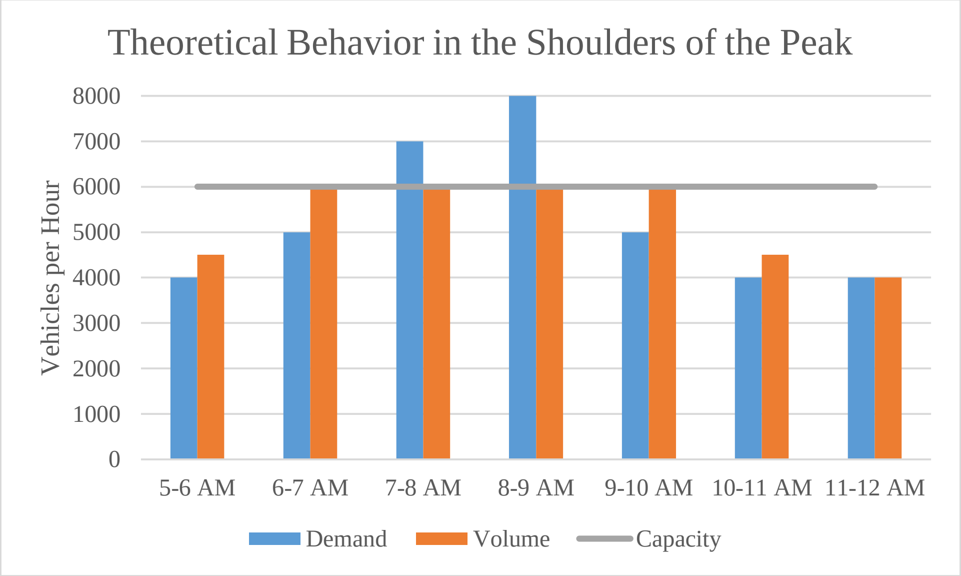


Figure 2.12: Theoretical visualization of peak and shoulder travel demand, volume, and capacity

Congestion also has an impact on driver behavior. Under high density conditions, drivers tend to be more cautious and may maintain large car spacing despite low travel speeds. Drivers, from the perspective of the roadway, do not have full information on the cause of the delay. Even as a road clears, drivers tend to maintain relatively low travel speeds with the expectation that they may need to suddenly slow down again later. Alternatively, they could become more aggressive in response to their frustration with travel conditions. Such changes in passenger behavior add to the instability of traffic conditions under periods of congestion. Travelers also begin to factor in reliability buffer time, and plan their trips based on the maximum amount of time they expect to take rather than the average due to the high level of variability in travel times under unstable conditions. Even when this leads to an early arrival, the perceived total travel time could still be considered the full reliability buffer time because this time is generally not spent optimally, as it would be if the user were not concerned about uncertainty in travel time and could plan their trip without this constraint.

The added cost of time and frustration, including unreliability in travel times, that comes with traveling during peak hours does encourage some users to shift their behavior to other time periods. Some cities have begun implementing strategies to further encourage users to shift driving behavior to the off-peak. This can potentially be achieved by implementing time-based tolling in order to allow users to weigh their travel value of time against the toll during the times in which they could travel, with discounts given for traveling outside of the peak hour. This is done in a variety of other systems, such as MTR in Hong Kong on the transit side and in the San Francisco/Oakland Bay Bridge in California on the roadway side. Time-based pricing does not completely eliminate congestion but it does influence some behavior, and is a relatively low-cost method of increasing the effective capacity of a highway or other transportation system, by better utilizing under-used capacity. It can also help dissuade users from avoiding the toll road during times when it would be socially optimal for them to use it, such as during the night when the alternative is traveling through a residential neighborhood. However, raising toll rates during peak hours to a level sufficient to influence behavior is likely not politically feasible in the short term in eastern Massachusetts. The toll rate from Framingham to the exit leading into Kendall Square in Cambridge currently totals $2.90 for the 19.5-mile journey, on the same order of magnitude as gasoline for most vehicles and minor compared to the cost of parking at the destination, which can run on the order of $6 just for the first half hour and up to $25 a day in parking facilities such as the One Kendall Square Garage. For this reason, it is unlikely that peak tolling will actually significantly modify behavior, though it may yield higher revenue for the state to meet its other goals.

In Massachusetts and in the United States as a whole, there is very little desire or feasibility to expand existing roads or build new highways, especially in dense urban areas. This has been the trend for decades as the negative externalities of highway expansion have been considered to outweigh the benefits of additional traffic capacity, particularly where this would come at the expense of displacing homes, businesses, and entire neighborhoods. Additionally, the sheer costs and disruption due to construction make it not a viable option, as the marginal cost to accommodate the peak of the peak is high. It is possible to work with these problems, such as during the Central Artery and Tunnel Project where capacity was added, and they were able to coordinate tunneling while the elevated structure was still operational and avoid taking residences and displacing jobs permanently. Still, the original decision was forced by a deteriorating viaduct structure. Building additional lanes for the turnpike or a high-capacity alternate route for Western

Corridor commuters is not considered a viable strategy to accommodate travel growth in the area. One option for highway expansion is in the existing right-of-way of the roadway, for example allowing use of the shoulder or breakdown lanes during peak hours, but this is only possible where this space has already been left available and has generally already been exhausted (as in the case of the Southeast Expressway).

One way to increase the throughput of people through a roadway without increasing roadway space or traffic volume is to increase the number of passengers per vehicle. In 2009, average vehicle occupancy for trips to and from work was 1.13, lower than 1.67 passengers per vehicle for trips of all purposes (Santos, McGuckin, Nakamoto, Gray, & Liss, 2011). Given that commute flows tend to be concentrated by time and space, there should be ample opportunity for carpooling with minimal inconvenience to the driver and passengers. Employers in job-dense areas with expensive parking can encourage carpooling by helping facilitate trip matching and offering parking incentives, such as a refund on the parking fee or a spot closer to the job site (or a spot at all in parking-sparse areas). The government can theoretically help encourage carpooling by offering lower or free tolls to carpoolers, though this can be hard to regulate and is likely to be ineffective since the cost and availability of parking at the destination is a much more dominant factor for commuters. A lane in the roadway could be dedicated exclusively to carpoolers, shielding them from the worst congestion, but this is likely not possible on the turnpike where there are only 3 lanes in each direction. Therefore, this research will not evaluate infrastructure improvements to encourage carpooling and assumes that employers will encourage carpooling at their job sites in the short-term.

With MassDOT moving to all-electronic tolling, there is some potential for improved traffic flow through the turnpike in certain areas, as users will no longer need to come to a stop and complete a cash transaction in order to pay their toll. However, this is not expected to have a significant impact on overall traffic conditions in the corridor. There are not very many toll booths and, more importantly, the cause of congestion on the turnpike is that demand exceeds capacity of the entire roadway rather than just of some bottlenecks, so fixing these bottlenecks is not expected to address the entirety of the congestion problem. Some additional throughput may be made possible through the Allston Interchange, due to the straightening of the highway allowing for higher speeds, and the potential reconfiguring of the off-ramps to permit better distribution to more of the urban network, with an exit onto Commonwealth Avenue and Beacon Street feeding more directly to Longwood and other areas.

Route 9 is an example of another road that serves the Western Corridor, even for longer distance trips, without charging a toll. According to a 2010 study, average travel speeds in 2005 were observed to be slower than those in 1996, at all but a few locations along this route (CMRPC, 2010). This has led to levels of service of C or D during peak hours, which the CTPS considers to be at or beyond practical capacity (CTPS, 2016). Some users may be using Route 9 in order to avoid the toll on the turnpike while others may be using this road in order to more conveniently reach their destination. Regardless of why users choose this route, it is clear it is also congested and cannot accommodate additional traffic growth, as was the case on the turnpike. In similar fashion, some drivers use Nonantum Road to bypass the toll, but this flow is joined by traffic from Greenough Boulevard and Fresh Pond Parkway, to overload the capacity of Solders Field Road and Memorial Drive, and so provides only modest turnpike relief for motorists with local Brighton destinations.

Given the lack of solutions to highway congestion available in the auto network, solutions to the congestion problem in the Western Corridor must be found in other modes where existing capacity is under-utilized or where expansion could be more feasible.

2.4 Transit Capacity Constraints

The western suburbs have historically been underserved by the transit network relative to suburbs to the north and the south of Boston, as is visualized in Figure 2.13. The key is calibrated to all areas in the United States, with Manhattan, New York being one of the only areas in the highest red category. While there are theoretical limits to transit capacity in the area, current service is well below these limits and there are many relatively inexpensive changes that could be made to vastly improve service and hopefully encourage a modal shift to transit.

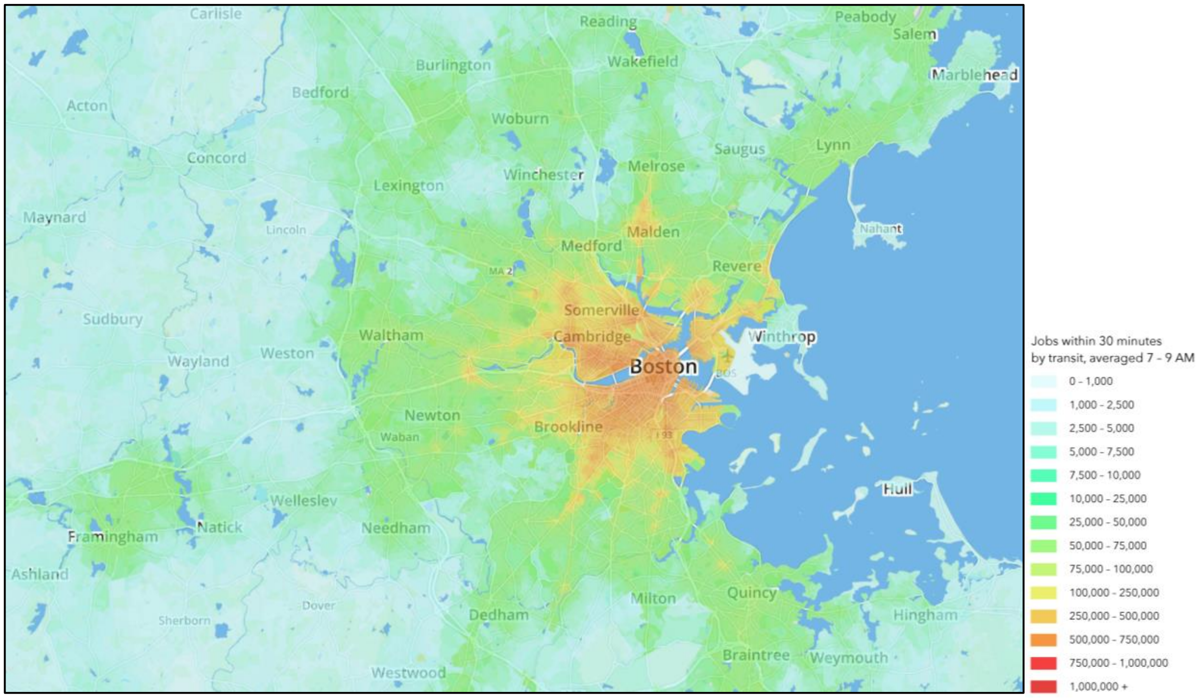


Figure 2.13: Accessibility to jobs by transit in the Boston metropolitan area (Owen & Levinson, 2014)

2.4.1 Current Transit Service

Current transit service, as measured by the number of vehicle trips per weekday, is summarized in the following table (Massachusetts Bay Transit Authority, 2015). The inbound peak is defined as 6 am to 9 am (start of service to 9 am for commuter rail) and the outbound peak is defined as 4 pm to 7 pm. Refer to Figure 2.1 for a geographic visualization of these services, which all travel through the Western Corridor, though some more directly than others relative to the turnpike.

Table 2.3: Number of weekday transit vehicle trips (Massachusetts Bay Transit Authority, 2015)

	Weekday		Peak	
	Inbound	Outbound	Inbound AM	Outbound PM
Commuter Rail	24	24	9	8
Green Line D	138	138	30	30
Turnpike Buses	223	214	111	94

The Worcester/Framingham commuter rail line utilizes six-car trains with a capacity of 100 to 150 passengers per train, leading to a full vehicle capacity of 600 to 900 passengers. The Green Line D Branch uses two-car trains with a capacity of 100 to 125 passengers per car, for a total capacity of 200 to 250 per train, and 2000 to 2500 passengers per hour (with 6 minute headways during peak hours) for this branch. Three-car trains are possible and have been used occasionally, which could increase train capacity to 300 to 375 passengers if more vehicles are introduced. New vehicles could also be introduced with higher capacity design. There are nine turnpike express bus routes. All routes run along the turnpike for at least part of their journey, some just to Brighton and others as far as Newton and Waltham. Each bus has a capacity of 40 to 70 passengers, depending on whether passengers are comfortable standing while traveling on the turnpike. Buses are currently well within capacity so passengers do not usually need to stand. Each route has between 10 and 50 scheduled trips per weekday, generally concentrated during peak hours.

For longer transit trips from the outer suburbs in the Western Corridor, the effective capacity is somewhere between seated capacity and standing crush capacity. While standing passengers will be able to board a specific trip, they may shift their future travel mode to auto, even on congested roads due to the higher relative comfort of sitting in a private vehicle. Ideally, users with long trips will have a seat for their entire inbound journey and at least part of their outbound journey and full capacity will only be reached at the peak load point near downtown with a mix of long and short commuters. With these assumptions, estimates of capacity are obtained from the MBTA Blue Book and are summarized in the following table (MBTA Service Planning Unit, 2010):

Table 2.4: Estimated Western Corridor transit capacity

	Weekday		Peak	
	Inbound	Outbound	Inbound AM	Outbound PM
Commuter Rail	14,400 – 21,600	14,400 – 21,600	5,400 – 8,100	4,800 – 7,200
Green Line D	27,600 – 34,500	27,600 – 34,500	6,000 – 7,500	6,000 – 7,500
Turnpike Buses	8,900 – 15,600	8,600 – 15,000	4,400 – 7,800	3,800 – 6,600
Total	**110,900–151,700**	**110,600–151,100**	**33,800 – 47,400**	**32,600 – 45,300**

Current transit ridership through the Western Corridor was also estimated using data provided in the MBTA Blue Book (MBTA Service Planning Unit, 2010). Total ridership on commuter rail and turnpike buses is considered in the Western Corridor, while for the Green Line D branch just boardings on the spur were considered to represent Western Corridor transit demand. Local behavior within Downtown Boston is not considered Western Corridor ridership, and as the capacity is considered at the load point approximately parallel to the Allston Interchange (between Longwood and Fenway), this should appropriately estimate just Western Corridor Green Line D branch demand relative to capacity and not demand and capacity for travel through other overlapping corridors. The AM peak is defined as 6am to 9am (start of service to 9am for commuter rail). Trips between 4pm and 7pm are considered the PM peak.

Table 2.5: Estimated current transit ridership through the Western Corridor

	Weekday		Peak	
	Inbound	Outbound	Inbound AM	Outbound PM
Commuter Rail	8,800	8,500	7,200	6,300
Green Line D	22,800	24,100	7,500	7,500
Turnpike Buses	4,500	4,100	2,200	1,800
Total	**36,100**	**36,700**	**16,900**	**15,600**

Demand is below capacity on existing vehicles, and the number of commuter rail and turnpike express vehicles is well below the theoretical maximum, so there is potential for increased transit service and usage in the Western Corridor. The Green Line D branch only barely serves Western Corridor demand, so if the Green Line isn’t considered mode share is 16% transit and 84% auto for travelers through the Western Corridor on the average weekday, comparing Table 2.5 to turnpike volumes from Section 2.3.

2.4.2 Constraints to Transit Service and Potential Solutions

Beacon Park Yard is a rail yard in Allston that was used for maintenance and freight transloading until 2013 when operations were moved out to Worcester. Due to a historical arrangement, the MBTA, and therefore the Framingham/Worcester line, only has access to a single track through Beacon Park Yard for an approximately 1.7-mile stretch between Yawkey and Newtonville stations (Central Transportation

Planning Staff, 2012). Assuming that, at a conservative speed of 40 miles per hour, it takes 3.4 minutes to clear this single-track section, this constraint caps the theoretical maximum capacity of the commuter rail line and any other potential service through the area to 17 trains per hour total in both directions, or a train approximately every seven minutes in each direction if distributed evenly. However, this single-track constraint will soon be lifted due to the closure of the rail yard and subsequent agreement to provide the MBTA with an additional track through the yard, eliminating this bottleneck to rail operations and the interdependency between schedules in opposing directions.

The currently scheduled minimum time between a train leaving Yawkey outbound toward Beacon Park Yard and a train entering Yawkey from Beacon Park Yard is 2 minutes (Massachusetts Bay Transit Authority, 2015). This occurs when an outbound train is scheduled to leave Yawkey at 6:51 PM and an inbound train is scheduled to enter Yawkey at 6:53 PM, near the end of the PM peak. The single-track constraint begins just about 1.0 miles outbound from Yawkey, so these two trains must be scheduled such that inbound train leaves the single-track area just before the outbound train reaches it. Other than that, and one other example where the time between an outbound and inbound train is 3 minutes, the single-track constraint does not seem to be an issue with regards to the currently scheduled 24 trains in each direction every weekday.

Unique among the MBTA Commuter Rail lines, the Framingham/Worcester line must share the tracks it runs on with freight railroad CSX. Historically, CSX controlled dispatching, so freight trains have often disrupted passenger service. However, in June 2015, the MBTA announced that they had completed acquisition of the CSX rail lines used for the Framingham/Worcester commuter rail service (Massachusetts Bay Transit Authority, 2015). This allows the MBTA to control dispatch and prioritize passenger rail over freight rail, effectively increasing the reliability of passenger rail in this corridor. Changing this priority, especially through the single-track constraint in Beacon Park Yard, has already greatly increased reliability on the commuter rail line.

Outside of Beacon Park Yard, there are a variety of additional constraints. Constraints going into Back Bay and South Station, including platform constraints that are being worked-on in a separate project, could limit the theoretical maximum capacity of the track space allocated to the Framingham/Worcester Line once it reaches downtown Boston. This problem is compounded by vehicle fleet constraints. One potential solution to address this problem is scheduling some trains to short-turn at various locations along the route, as it is already done on the outer end of the line, with some trains traveling to Framingham and others all the way out to Worcester. This could include ending some trains at Back Bay or at the new West Station, which must be balanced against the inconvenience it could create for some passengers who did not previously transfer but would now need to transfer in order to reach their final destination. However, it is an effective method to bypass vehicular capacity constraints if these arise as binding constraints that limit the maximum capacity of transit below what is desired. Based on the schematic shown in Figure 2.14, there are five tracks between Back Bay and South Station that the Framingham/Worcester track could use, but it must share this capacity with the NEC mainline from the South. Therefore, it should be assumed that there are only two tracks available, entering and leaving South Station, and likely two to three platforms available for use by the Framingham/Worcester line at South Station at any given time. The South Station Expansion Project will increase the amount of platform space at South Station, but it will not impact the number of tracks coming from Beacon Park Yard. Upgrading the interlocking as the tracks enter South Station is a component of the South Station project, now in the planning stages (MassDOT, 2014).

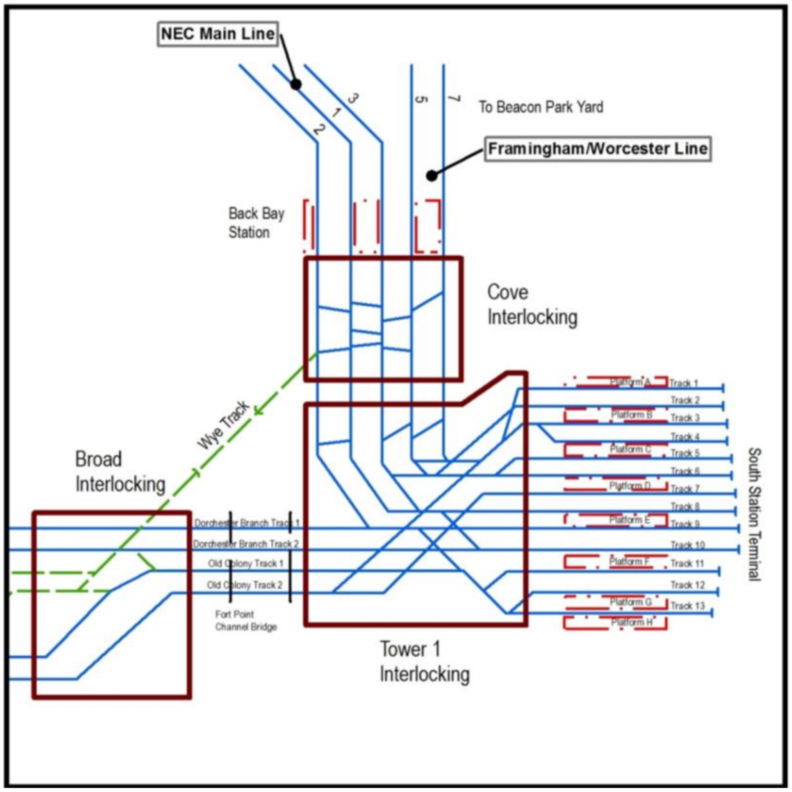


Figure 2.14: Schematic of South Station Terminal and Interlocking (MassDOT, 2014)

Many commuter rail stations along the Framingham/Worcester line, including those in Newton, have a single platform and thus cannot serve an inbound and outbound vehicle at the same time. It is assumed in this thesis that expanding these platforms such that both directions could simultaneously operate would be politically and financially feasible if future transit service in the area were to require dual platform use.

The MBTA Financing control board has voted to approve about half a billion dollars to install positive train control systems and modernize the interlocking and signaling system between Back Bay and

South Station. It should therefore be possible to improve frequency and throughput, but the platform capacity constraints at South Station are likely to remain, governing the effective maximum capacity, along with locomotive and coach constraints. Additional vehicles could be purchased, either for running longer or more frequent commuter rail, and/or to add DMU services.

On the bus side, there are nine bus routes that run on the turnpike. Five are considered Turnpike Express routes: 501, 502, 503, 504, and 505. The other four, 553, 554, 556, and 558, also have significant local service beyond their route on the turnpike. As these routes run along the turnpike for at least part of their journey, the buses must deal with congestion as they do not have a dedicated lane except at the Allston tolls. The five express bus routes operate peak service only (both directions in both peaks) and the other four have regular service throughout the day. Buses are currently running within capacity, so passengers do not usually need to stand. There are no infrastructure constraints limiting the expansion of these routes, beyond obtaining additional buses for the MBTA fleet as buses can travel on existing roads. Bus service could easily be enhanced on these roads if demand is known to exist, either by increasing frequency or by adding new routes, such as one directly from I-90 into the Seaport/Innovation District. Each bus would theoretically remove up to 70 cars from the road, which could better utilize the existing roadway capacity. This is if cars are assumed to have 1 person per vehicle (the driver) while buses are at crush load. The average load in a car on a home based work trip is around 1.1-1.2 and the comfortable load in a bus is around 40, meaning that approximately 35 cars are likely to be removed from the roadways if an additional bus trip is added and the appropriate modal shift occurs.

With the addition of the new West Station, there are many opportunities for expansion of transit service in the Western Corridor. One is to expand rail service along the Grand Junction in Cambridge, as was looked at in the Grand Junction Transportation Feasibility Study done by the CTPS in 2012 (Central Transportation Planning Staff, 2012). The right-of-way in Cambridge is partially double-tracked, but predominately single-tracked. However, there is space in the right of way for a second track, where one does not currently exist. The benefit of adding this connection through Cambridge is that it could provide direct or single-transfer service from the Western Corridor to the high growth Kendall Square area, as well as to North Station, further providing additional options for transit commuters coming through the Western Corridor. This would provide a travel time advantage for Kendall passengers, and a bypass of the capacity constraints at South Station and Back Bay.

Bus options could also be expanded at West Station in order to better serve the last mile from West Station to job locations in Allston and beyond. The bus routes that currently travel closest to West Station are routes 64, 66, and 70, which provide service to Cambridge, Brighton, Brookline, Watertown, and beyond. A valuable addition would be a shuttle to Ruggles Station via the Longwood Medical Center. This could be a new MBTA route or an employee shuttle, as they are already quite common for service to Longwood. Boston University owns some of the land adjacent to West Station and has expressed resistance to allowing buses to travel through campus property. However, there are many alternate routes that could provide this connection instead. To Longwood, this includes a shuttle along the turnpike and exiting at Huntington Avenue, providing direct service, or a shuttle from the existing commuter rail stop at Yawkey rather than from West Station. For other destinations, bus connections could be provided on adjacent arterial roads near Beacon Park Yard such as Commonwealth Ave via Malvern Street.

West Station could serve as a transfer point for both bus and rail connections, as mentioned previously in this section, which could help alleviate congestion in rail corridors in Downtown Boston, specifically transfers at Park Street and South Station (to the Red Line) and track space near Back Bay in the direction of South Station. Another option is to terminate commuter rail service at West Station, where additional layover space will be made available, and run two shuttle DMU services to North Station via the Grand Junction and to South Station via Back Bay, or some variation thereof. DMU service could also be extended in the other direction, out to Auburndale via Newton and the new stops at Boston Landing and West Station. This would provide suburban commuters in these areas with express service to Kendall and North Station. The connections possible in downtown Boston after the addition of service along the Grand Junction are presented in Figure 2.15.

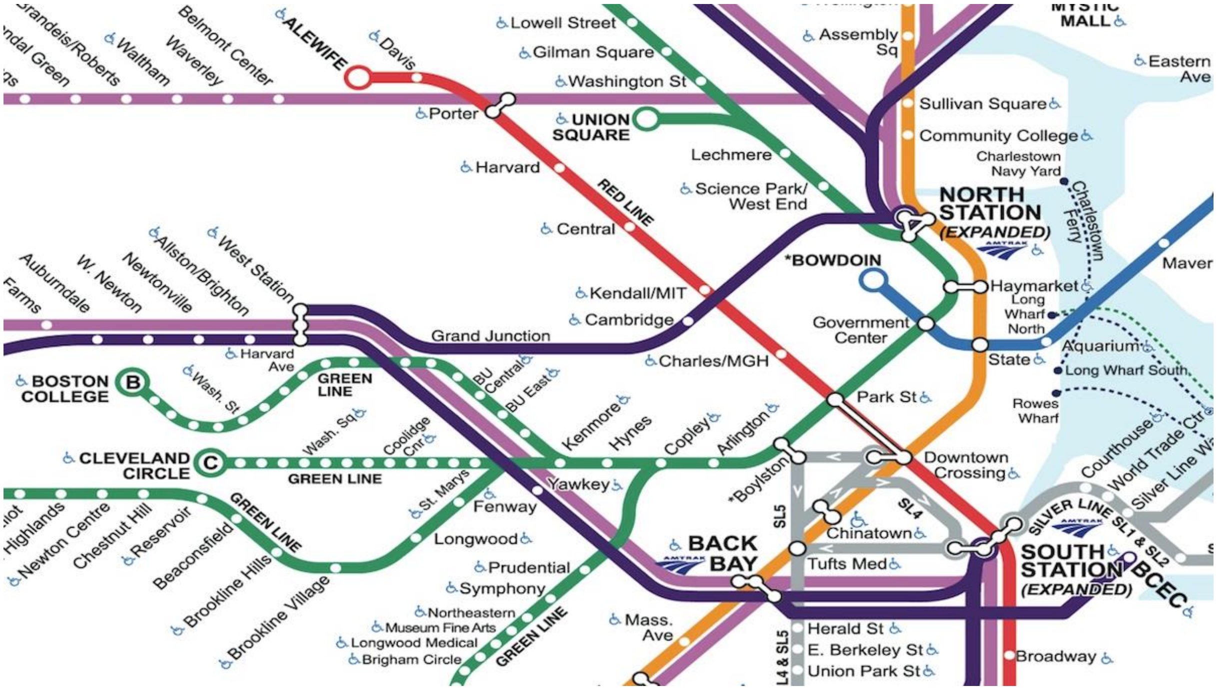


Figure 2.15: MassDOT’s vision for 2024, with Grand Junction service included (MassDOT, 2014)

Though changes to transit service will need to be considered from a demand and operational standpoint, particularly to minimize the number of onerous transfers to passengers, promoting transfers at West Station could potentially be beneficial to the majority of users. Because riders place a larger time-cost while standing in a transit vehicle than they do while sitting, many commuter rail users may move back to their cars if they have a large probability of standing for their journey (Waters, 1992). However, they will be more likely to continue taking transit if they only need to stand for the final shuttle segment of their commute. This could allow the system to better utilize available capacity during peak hours, by scheduling sufficient capacity to fill commuter rail trains up to seated capacity and DMU shuttles closer to standing or "crush" capacity if adequate platform space is available at South Station to accommodate the maximum throughput.

Many of the existing constraints to transit service in the Western Corridor will soon be lifted as part of the Allston Interchange project is put into service, which will be further explored in Section 2.5. Because of this, there is much potential for increased transit service in the area and for a modal shift to transit. In order to encourage this shift, existing and new options must become more frequent, more expansive, and generally more attractive to users, since theoretically "choice" transit users may switch back to using their personal cars if transit options seem inconvenient or unsatisfactory. However, because that would result in increasing auto volume beyond capacity and result in unstable flow, investment in transit options would provide an additional benefit to auto drivers even if they remain on the turnpike if sufficient trips can be attracted to transit.

2.5 Allston I-90 Interchange Improvement Project

Originally completed during the expansion of the Massachusetts Turnpike to Downtown Boston in 1965, the I-90 Interchange in Allston is an elevated viaduct structure that is nearing the end of its functional lifespan and will need to be replaced in order to avoid becoming dangerously structurally deficient. Figure 2.16 shows the study area of this project, in green, taken from the first Task Force meeting for public input to the project (O'Dowd, 2014). This figure presents the turnpike interchange as it weaves through Allston and around Beacon Park Yard.

Figure 2.16: Project area for Allston Interchange Improvement Project (O'Dowd, 2014)

As indicated earlier, coinciding with the timing of this project, MassDOT intends to move completely to All-Electronic Tolling on the turnpike by the summer of 2016. This type of tolling does not require vehicles to slow down to a stop and perform a cash transaction, so it should improve traffic flow through toll booths on the turnpike. This includes the Allston Interchange, as it is currently a tolling station with both electronic and manual toll lanes. However, this improvement in traffic flow could actually be a problem as cars passing through at higher speeds must maneuver through the turn of the road around Beacon Park Yard and may have trouble doing so. This further justifies straightening the Allston Interchange.

Because of this, MassDOT has begun a project to straighten and modernize the Allston I-90 Interchange. Over time, this project has expanded to include transit improvements such as double-tracking commuter rail service through Beacon Park Yard and adding a new “West Station”. This station is planned for four tracks and two platforms, and while it will initially serve just the existing Worcester/Framingham commuter rail line, this leaves space for additional rail service in the future, in particular, higher frequency service to North Station via Kendall and South Station via Back Bay. There are also plans for bus, bike, and pedestrian connections to the station, though there will be no parking as this is considered an urban location. A drop-off area will be available for a “kiss-and-ride” facility. One hurdle is a 2009 law that requires all tolls collected from turnpike users to be spent exclusively on turnpike projects. Turnpike users likely benefit if turnpike congestion can be reduced when other users are able to use different modes and unstable auto traffic flow, which would otherwise occur, is avoided. MassDOT is looking into alternative ways to fund the transit, pedestrian, and bike infrastructure improvements as part of this project, in response to public participation and general political rhetoric having shifted away from “build more highways” to a more multi-modal approach, in order to gain local support for the project and make the most out of this unique infrastructure and place-making opportunity.

The Environmental Notification Form for the I-90 Allston Interchange Improvement Project was submitted in October 2014 and accepted by the Secretary of Energy and Environmental Affairs in December 2014. This document outlines the major components and potential challenges of the project at 5% conceptual design status, including scenario comparisons between urban and suburban interchange types, with urban being preferred, demonstrating how this project will likely continue to be treated. Much more detail, such as which of the specific scenarios will be pursued, will become available once the Draft Environmental Impact Report is published, likely in the fall of 2016. One update since the ENF was published is the added proposition of changing the highway interchange viaduct into an at-grade configuration, and instead raising the Grand Junction railway line. This idea was originally proposed by a member of the public and two at-grade alternatives and one viaduct alternative are now being prepared for the DEIR. All three options now include a four-track West Station, higher quality Grand Junction alignments, and a layover yard to improve capacity at South Station for Worcester branch operations.

2.6 Unique Challenges and Opportunities

The theme of multimodality in the planning process of the Allston I-90 Interchange Improvement Project provides a valuable opportunity to shape sustainable growth in the area beyond how transportation infrastructure projects have been treated in the past. In the context of high growth in the Boston area, this project has the potential to provide access to a growing number of commuters from the residential Western Corridor to areas in and near Downtown Boston. Focusing on this project in the context of improvements in accessibility is a valuable new method of analyzing infrastructure projects for improvements shifting the focus from the local community, into how transportation network changes can impact an entire region.

With MassDOT’s stated “GreenDOT” 2012 policy goal to triple non-auto mode share by 2030, the Western Corridor is a prime target as an untapped transit market. Mode share must include current users and future growth, making this policy goal even more ambitious. Preliminary results from 2014 indicate the correct trend toward non-auto mode share but not to a sufficient magnitude, so more innovative, larger-scale changes must be undertaken if MassDOT is to achieve its environmental policy goals.

As quantified in the MIT thesis “Productivity and Costs in the Transit Sector: The Impact of Baumol's Cost Disease”, project delays are a major contributor to the escalating costs of large infrastructure projects (Morales Sarriera, 2016). Costs rise due to rising construction costs, which tend to outpace inflation, and due to the cost of forgone benefits in the years the project should have been operational, but has yet to be completed. This is particularly true for systems currently operating above capacity, due to the externalities and inefficiencies inherent under congested operations. This is the case for enhancements to the Western Corridor transportation network and, if similar constraints can be anticipated in the future, could lead to better project planning and more cost-effective project implementation.

Another opportunity is to take advantage of the use of Diesel Multiple Units (DMU) on some freight corridors. DMUs can run on the same tracks as commuter rail and freight trains, but are self-propelled rather than requiring a locomotive. This allows them to accelerate and decelerate more quickly so they can better serve more stations closer together when compared to commuter rail trains. DMUs also provide a good amount of flexibility in service because the number of cars in a train is easily variable as each additional car provides an equivalent amount of power to run it. Trains used in the US must be FRA compliant, but beyond the purchase of the vehicles, construction of new stations, and installation of high capacity signaling systems, service can be implemented with relatively little infrastructure cost, as long as the right-of-way and tracks already in existence and underused are mobilized. The Grand Junction is currently only used about six times per day for vehicle rebalancing and occasional off-peak freight movement of the Chelsea Produce Market, so mixed traffic is not expected to be a significant issue against starting service. The MBTA has been considering adding this service in the Boston area by the 2024 planning horizon and has referred to it as the “Indigo Line”.

Chapter 3 – Comparison of Regional Model Predictions to Actual Conditions

The Central Artery and Tunnel Project, often referred to as the Big Dig, was a megaproject in the Boston area, many years in the making, that opened fully to traffic in 2006. This project involved rerouting the downtown portion of the I-93, then an elevated viaduct, into the Thomas P. O'Neill Jr. Tunnel in order to alleviate congestion and tie neighborhoods back together with a higher capacity roadway hidden from street view. The project also included extending the I-90 Turnpike to the Seaport/Innovation District and Boston Logan International Airport via the Ted Williams Tunnel, relocating that traffic from I-93 to relieve overcrowding, constructing the Leonard P. Zakim Bunker Hill Memorial Bridge to replace the Charlestown High Bridge over the Charles River, and creating the Rose Kennedy Greenway in the land formerly occupied by the Central Artery structure.

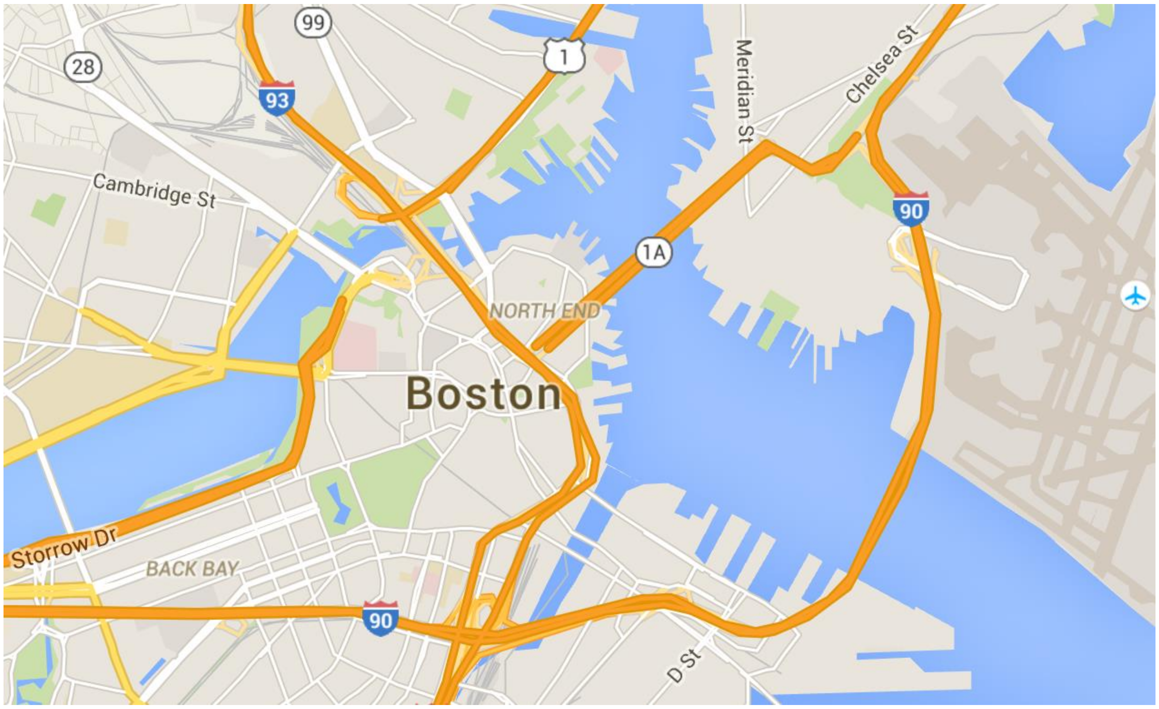


Figure 3.1: Site of I-90 and I-93 in Downtown Boston (Google, 2016)

Due to the timing of the project, projections made during the environmental review process in 1990, as part of the Final Supplemental Environmental Impact Statement (SFEIS) for a design year of 2010, can now be compared to actual conditions in 2010. Many factors, some more predictable than others, may have had a large impact on the accuracy of these projections. It is important to look back and consider how these varying factors could have been better integrated into the modeling and estimation process, in order to improve the accuracy of future predictions. Some transit projects which had been included in the original plans and the 2010 "Build" model network, including the Green Line extension, Blue Line to Red Line connector, and rolling stock replacement, were not completed by 2010. This may be the cause of some worsening of travel conditions in urban areas, even as conditions improved for the entire region. This analysis will consider the likely impact on accessibility once these projects are completed.

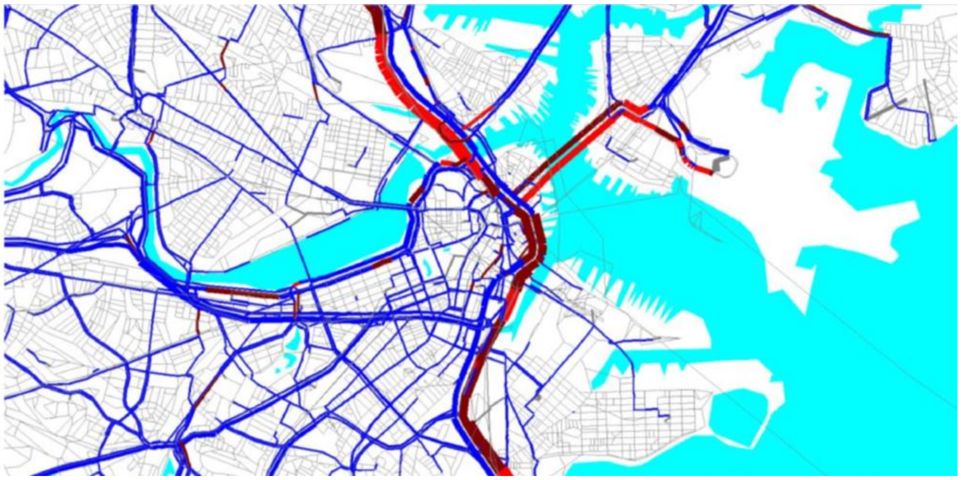
This exercise will provide insights on how greater economic and societal impacts can be better considered for future projects. The Allston Interchange Improvement Project introduced in Chapter 2 is a similar transportation infrastructure project, though with smaller scope, currently in its planning stages. Both projects are primarily designed to replacing a crumbling piece of infrastructure, although the Big Dig went further to change roadway capacity, and had a larger impact on auto travel time and connectivity of the network. Nevertheless, many similarities can be drawn and lessons can be learned from the earlier project in order to better execute the latter. There has been some discussion at public meetings about the accuracy of and assumptions behind current projections, as they will impact the eventual size and layout of arterial roads through nearby neighborhoods, which could impact the eventual use of these routes. Projects of this magnitude with network-level impacts should play an active role in shaping the way future travel demand is generated and satisfied rather than just accommodate the future projected to occur. This includes stabilizing auto network conditions and providing attractive transit options to encourage the use of multiple modes by allowing them to be attractive for purposes for which they will be most effective. The Big Dig had a larger impact on the auto network, by changing capacity, travel times, and connectivity, but the Allston Interchange Improvement Project could have a similar impact on the transportation network if transit elements are included fully. Other potential transportation network and place-making improvements to the Western Corridor that will be proposed in Chapter 7 also follow this narrative.

3.1 Transportation Network Impacts

Beyond the safety benefit of replacing deteriorating and potentially dangerous infrastructure, the most direct result of the Big Dig is its impact on a secondary problem it had evolved to be designed to solve – high congestion and inefficient routes in the transportation network within the downtown core. There were primarily positive impacts on auto traffic, with reduced auto congestion and economic growth being allowed to occur, although not exactly in the same way as was predicted in the 1990 projections. For example, some economic growth projected for Downtown occurred in the Innovation District or Kendall Square instead. Transit impacts were minimal, partially due to the delay of scheduled transit projects, resulting in minimal changes to the transit system.

3.1.1 Traffic Impacts

One primary purpose of the Central Artery and Tunnel Project was to improve the flow of traffic through Downtown Boston. The impact on road flows was explored in Peralta-Quirós (2013). Two figures, taken from this thesis, are reproduced below. They present road flows during the AM peak. Link thickness represents absolute volume, while the color represents the volume to capacity ratio. A blue road is one with a V/C ratio below 1.1, brown is between 1.1 to 1.5, and red is over 1.5. These figures show that congestion levels remained high even after the network improvements, but that there was some mitigation, particularly in the Callahan and Sumner Tunnels.



(a) Prior to Big Dig (1990)

(b) Completed Big Dig (2010)

Figure 3.2: Modeled road flows before and after the Big Dig (Peralta-Quirós, 2013)

Immediately after the project was completed, a study was done by the Economic Development Research Group to establish whether the desired impact on traffic had been achieved (Economic Development Research Group, Inc., 2006). Because this study was published in February 2006, it does not fully capture all the changes caused by the improvements, as behavior had not yet had the chance to fully stabilize. Instead, this study provides the results of similar levels of demand and travel times under the new infrastructure. With these assumptions in mind, the actual reductions in travel time are found to be on the same order of magnitude as the projected travel times forecasted in the SFEIS, as can be seen in the following table taken from that report.

Table 3.1: Comparison of VHT Changes with Original Projections (Economic Development Research Group, Inc., 2006)

Average Daily VHT on Expressways	Projected in EIS Document		
	No Build 2010	Build 2010	Reduction
Expressway Central Area*	27,154	15,848	42%
I-93/I-90 Interchange (S. End)*	8,611	5,858	32%
West End (Storrow Drive)*	2,251	1,206	46%
Total	**38,016**	**22,912**	**40%**
Average Daily VHT on Expressways	Actual		
	Pre-Opening 1995	Post-Opening 2004	Reduction
Central Artery*	23,758 *(13% lower)*	7,558 *(52% lower)*	68% *(64% higher)*
Tunnels (Airport & Ft.Pt Channel)*	14,330 *(66% higher)*	7,072 *(21% higher)*	51% *(58% higher)*
Storrow Drive at Leverett Circle*	1,120 *(50% lower)*	217 *(82% lower)*	81% *(74% higher)*
Total	**39,208 *(3% higher)***	**14,847 *(35% lower)***	**62% *(56% higher)***

The asterisks refer to a discussion on the limited comparability across these geographic areas, particularly how the tunnels are included. The Reduction column was added to allow for a comparison of the relative impact of the Big Dig, with the intent of helping remove external economic and demographic factors that cause both pre and post opening traffic volumes and congestion to be lower than projected (particularly due to the difference in years). The italic values in parenthesis were added to the second half of the table to express the percentage difference of actual values compared to projected. The measure of vehicle hours traveled (VHT) was used in the 1990 SFEIS to better predict air quality changes, compared to the more limited conclusions that could be drawn from vehicle miles traveled. Fortunately for this analysis, the measure of vehicle hours traveled also provides insight on improvements in accessibility because this measure incorporates travel time rather than travel distance.

The 1990 projections for 2010 are on the same order of magnitude as actual traffic values, with discrepancies partially due to the varying geographic boundaries (as the total discrepancy is lower than that of any subset). The reduction in vehicle hours traveled is likely higher than projected because these measurements were taken too soon after the project opened, and thus the expected induced demand due to the shorter travel times, in combination with the lack of transit improvements, had not yet fully had a chance to occur. This is especially true because the 1990 projections were based on full highway construction completion by 2000, providing almost ten years for traffic patterns to evolve by 2010. Instead, largely because of the 3.5-year delay and scope changes at the I-93 river crossing, construction was not completed until 2006.

A similar study was undertaken by the Central Transportation Planning Staff (CTPS) in 2014 (Peterson, 2014). This study is important because it was done by the very organization that made the projections in 1990. Their motivation was to verify the accuracy of their traffic and air quality projection techniques once actual results had become available. The traffic count comparison, included below, shows actual conditions consistent with projected – with actual counts slightly lower than projected on all but one segment, but by different magnitudes in different areas.

Table 3.2: Comparison of Traffic Projections from FSEIR and Recent Traffic Counts (Peterson, 2014)

Highway Segment	Projections	Traffic Counts[a]	Percent Difference
I-93 Northbound - I-90 On-Ramp to Gov't Center Off-Ramp	100,300	99,000	-1%
I-93 Northbound - Frontage On-Ramp to I-90 On-Ramp	84,600	77,500	-9%
I-93 Northbound - I-90 Off-Ramp to Mass. Avenue On-Ramp	54,000	52,000	-4%
I-93 Northbound - Southampton to Mass. Avenue	113,900	103,000	-11%
I-93 Northbound - North of Columbia Road	124,700	111,500	-12%
I-93 Southbound - Dewey Square Off-Ramp to barrel split	86,300	91,500	6%
I-93 Southbound - barrel converge to I-90 On-Ramp	82,300	74,500	-10%
I-93 Southbound - Albany On-Ramp to Mass. Avenue Off-Ramp	119,300	115,000	-4%
I-93 Southbound - Southampton to project limit	121,600	114,000	-7%
I-93 Southbound - South of Columbia Road	111,300	108,000	-3%
I-90 Westbound - Ted Williams Tunnel	47,300	40,500	-17%
I-90 Eastbound - Ted Williams Tunnel	51,200	42,000	-22%

[a] Annualization factor of 331 applied to convert annual results to daily results. Emissions from mobile sources only. FSEIR

According to later comments from the CTPS, there are a variety of reasons for the discrepancies between travel forecasts and reality. The regional model used for projections is driven by land use, demographics, and economic conditions, and it was assumed that growth at Logan Airport would be larger than it has been and that higher development would occur in the Seaport/Innovation District and on turnpike air-rights. This lower level of development could partially be due to the impact of construction and general increase of congestion on the turnpike, which lowered the improvement in accessibility to these potential growth areas over the course of project implementation as well as during the delay in construction completion. In general, the CTPS model is intended to work like this and, if anything, overestimate future traffic volumes in order to ensure that demand can be accommodated. Another reason demand was overestimated is that this report was used to calculate changes in air quality, and a conservative approach was used in order to ensure that improvements in air quality would be adequately accounted for in the planning process in order to protect public health and avoid over claiming benefits.

According to an article published in the Boston Globe in 2008, some suburban residents are concerned that the Big Dig actually created more congestion, just on roads leading up to the downtown rather than in the Central Artery (Murphy, 2008). This is certainly possible as the capacity of the Central Artery was greatly enhanced while other elements of the highway system stayed the same. However, these other roads were not and are still not as congested as the Central Artery was before construction.

Also, a big aspect of the Big Dig was to change the flow of traffic, as demonstrated in Figure 3.3. The increase in route options to destinations such as Logan Airport could have helped offset the impact of added demand on arterial roads. Projects set to improve the transit system could also offset the impact. Therefore, it is not clear whether additional congestion on arterial roads is actually due to induced demand from the Big Dig or due to delayed implementation of transit projects or simply due to unrelated travel growth in the Boston area that would have happened regardless and would have led to even more congestion if no improvements had been made in downtown. Almost certainly, this increase in congestion could have been mitigated if transit had been expanded as planned.

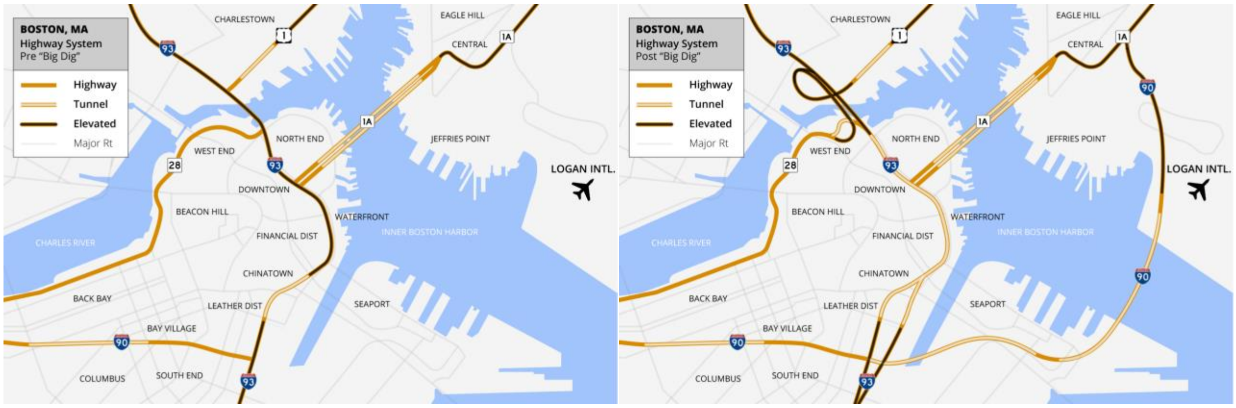


Figure 3.3: Traffic patterns in Downtown Boston before and after the Big Dig (Richard, 2015)

In general, it is impossible to know the full impact of a large infrastructure project right away, especially considering the new development that can be induced by the new accessibility provided. Users and systems begin to adapt, causing ripple effects that could impact behavior 50 or more years into the future. It is possible that all benefits of the Big Dig will not be realized for a long time, especially given that many planned transit projects are still ongoing or have yet to be started. In the case of the Big Dig, additional lanes did allow traffic to grow, though the amount of growth by 2010 was less than originally projected. However, as evident in recent reappearance of congestion, as described in Section 5.3, the remaining capacity on the Central Artery has been filled during peak hours by 2015, as was expected in the original projections. Without this project, traffic growth during the peak would not have been possible and this demand would have had to be accommodated elsewhere, either during the off-peak, on the (also congested) transit network, or with more roadway congestion and transit system crowding.

3.1.2 Transit Impacts

In conjunction with the roadway improvements, many enhancements to the transit system were planned within this same time scale. Many of these projects were simply necessary for the continued operation and expansion of the aging transit system to serve a growing metropolitan population. Their implementation was expected to complement the Central Artery and Tunnel Project in order to help mitigate the projected increase in vehicle miles traveled due to the added capacity of the new roadway, both to moderate levels of congestion and lower environmental impacts.

One of the more significant projects that has been completed is the construction of the Silver Line tunnels and the introduction of their service of four routes, including service to Logan Airport and Dudley Square. A regional bus terminal at South Station was also built. Expanded capacity on the Red and Orange Lines was facilitated by station lengthening in 1986, supporting an approximately 50% increase in capacity. However, many of the transit projects have not been completed as of 2016. The projects that were proposed, or planned, and have not yet been completed include:

- Extension of the Green Line into Somerville and Medford
- Connection of the Blue and Red Lines, currently 1500 feet apart in Downtown Boston
- Missing Silver Line link between South Station, Chinatown, Boylston Station, and Tufts New England Medical Center
- Urban Ring
- South Station bus terminal expansion
- South Station expansion (train platform space)
- Orange Line fleet replacement
- Overall bus fleet enhancement, including procurement and normal maintenance

With this in mind, an analysis of the transit side impacts of the Big Dig can be commenced. While not as detailed as the traffic projections, the Final Supplemental Environmental Impact Report does contain some projected estimates for transit usage in 2010. The following table is taken from the FSEIR of November 1990.

Table 3.3: Comparison of projected transit and auto trips to study area and Boston proper[1], 1987, 2010 Baseline, and 2010 Build (Massachusetts Department of Public Works, 1990)

	Transit Mode		Auto Mode	
	Trips[2]	Share (%)	Trips[2,3]	Share (%)
Study Area				
1987	354,020	33.4	705,951	66.6
2010 Baseline	464,742	34.3	888,901	65.7
2010 Proposed Action	463,777	34.3	889,866	65.7
Boston Proper[1]				
1987	248,615	39.0	389,408	61.0
2010 Baseline	302,144	38.2	489,420	61.8
2010 Proposed Action	301,932	38.1	489,661	61.9

[1] Area defined by Massachusetts Avenue, Charles River, Boston Harbor, and Fort Point Channel

[2] One-way trips to the study area

[3] Excludes intrazonal and Logan Airport trips, as well as HOV trips induced by Artery/Tunnel Project HOV Lanes

Source: Central Transportation Planning Staff

The issue with this data is that the study area is difficult to replicate using measurable, real-world data rather than estimates from the regional model. Origins or destinations of vehicles and passengers must be known in order to assign loads within the study area. This is much more difficult to obtain directly as it cannot be directly measured by simple traffic and ridership counts. A more involved approach could be used that either uses inferred origins and destinations in order to include just the relevant data or models desired results with these more easily measurable real-world data as inputs.

Because of these complications and possibly due to the fact that many Big Dig adjacent transit projects intended to encourage transit usage (and compensate for the negative impacts of the added auto capacity provided by the Big Dig) are not completed, or even initiated, the transit aspect of the demand side is not fully studied in either report. The CTPS report has a brief section on modal split, but as a comparison of running the regional model with and without some of the transit projects alongside the Central Artery and Tunnel, not as a comparison between projections and real world conditions. This analysis reports changes (as percentages) and not raw numbers, so it is difficult to determine where the data are from, and whether this corresponds to the projected estimates found in the FSEIR.

3.2. Impacts on Accessibility

The Central Artery and Tunnel Project provided new links in the highway network as well as added capacity in the downtown core. Because of these improvements, as well as job growth in the area, the number of jobs accessible to each location generally increased in the Boston area, showing up as green in the 4-step Cube Voyager model output of Figure 3.4. However, because there were no significant increases in roadway capacity outside of Downtown Boston, negative changes in accessibility did occur at some locations, particularly outside of the 495 outer belt. As projected by the Cube model run, congestion in the outer highway network outweighed the benefit of reduced congestion in the core and overall job growth for those with long commutes.

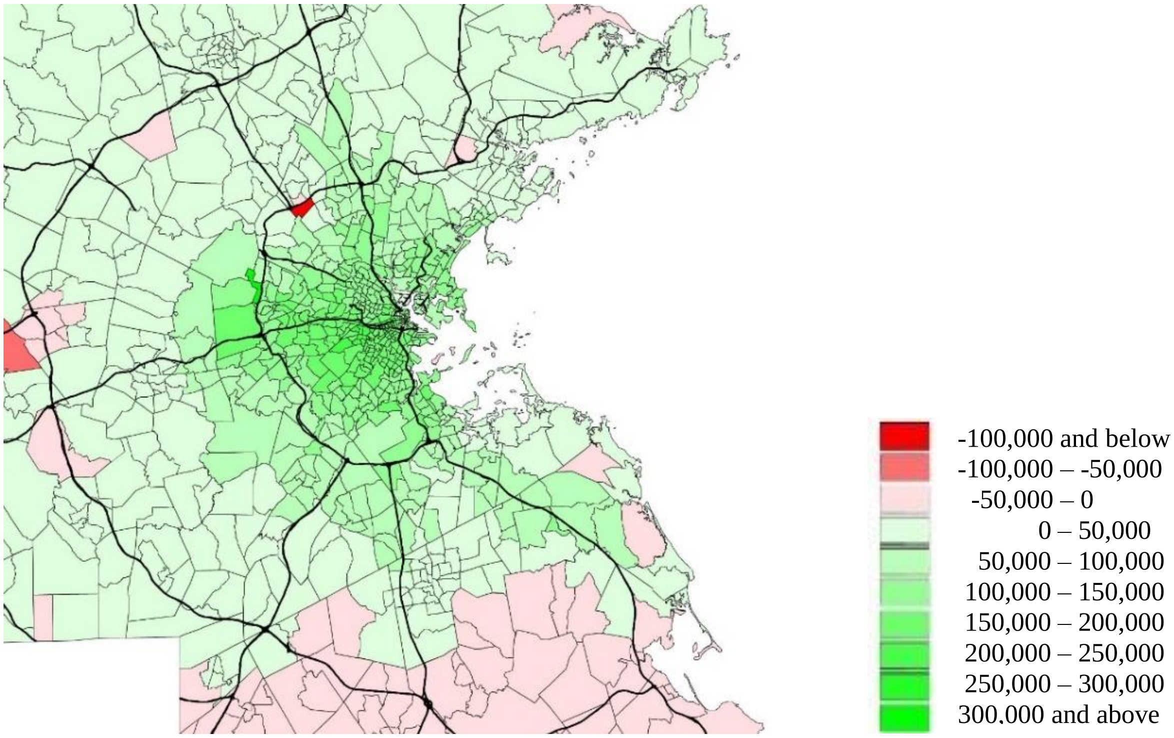


Figure 3.4: Changes in accessibility by auto to jobs for zones in the Boston area from 1990 to 2010

During this time, there is a less than 1% change in accessibility by transit to jobs at 80% of the zones in the Boston area. Where there are changes, either negative or positive, it is usually due to changes in attributes such as headways on existing services, and in a few cases, due to the transit infrastructure improvements that did occur and are outlined in the previous section. In the zones where there is a significant change in accessibility by transit, about 72% of the changes are positive and 28% are negative.

3.3 Wider Economic Impacts

Improved traffic speeds, higher capacity, and lower levels of congestion in the transportation network are just the beginning of the cascading impact a large infrastructure, such as the Central Artery and Tunnel Project, can have on a region. The economic benefits of a large infrastructure project can be vast and far-reaching, but are often hard to quantify. One example for the Big Dig is the multiplier effect due to the influx of federal money paid out to construction workers.

There are three observed stages of economic benefits of large infrastructure projects. The first is when construction is occurring and money is being spend locally on the project, multiplied by the additional money spent by construction workers and others who benefit financially in this stage. After construction has been completed, these benefits disappear and are replaced by operating and maintenance costs, which are significantly lower. However, the benefits to society then begin, as the infrastructure is used for its intended purpose. There are a variety of benefits in this stage, outlined in Figure 3.5, including those to individual users and to society as a whole.

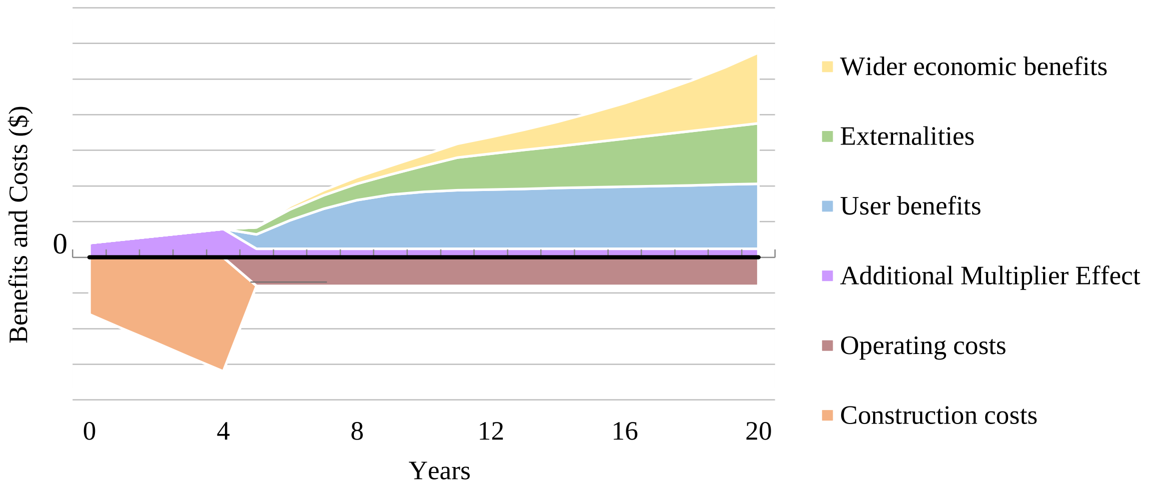


Figure 3.5: Theoretical “two-hump” trend of economic benefits of a large infrastructure project (Morales Sarriera, 2016)

For all transportation improvements, increased access to jobs and workers can provide additional opportunities for economic growth, ranging from the decrease in hours wasted in long unproductive commutes, to the better matching of jobs and workers possible when a larger pool is available. Companies also benefit from agglomeration by having easier access to each other and the additional resources such cooperation can provide. Many of these impacts may not be truly felt for years, as future decision makers and society continue to respond and adapt to the impact of infrastructure changes.

An often overlooked benefit of infrastructure projects is the cost of deferred maintenance or of doing nothing. Assuming an improvement project will need to happen at some point in the future in order to maintain a proper state of infrastructure, it is generally cheaper for it to occur as soon as possible. Yearly costs of maintenance are much higher for older structures than for newer ones, and while this cost is usually much lower compared to capital costs of new construction, it is still a benefit that can be accounted for in the short term. Similarly, with inflation, particularly in the construction industry (where prices tend to inflate faster than in other industries), capital costs are only going to increase if the project is deferred.

There is also the added cost of allowing a piece of infrastructure to serve beyond its useful capacity and effective lifecycle. This certainly means that maintenance and state of good repair through timely action is prudent, but it does not necessarily mean that every congested road should automatically be expanded. Certainly, there is often little realistic space or feasibility to significantly expand highway network capacity in an urban area. But anticipating roadway constraints and investing in alternative transit options and strategic road network improvements can help avoid or mitigate high congestion escalation as capacity limits are approached. Negative externalities of each improvement must be weighed against potential benefits in each case. However, it would be useful and efficient to anticipate corridors which are likely to see large increases in transportation demand in order to better serve these areas by increasing transit capacity and implementing strategic roadway improvements, before capacity constraint problems are reached or worsened.

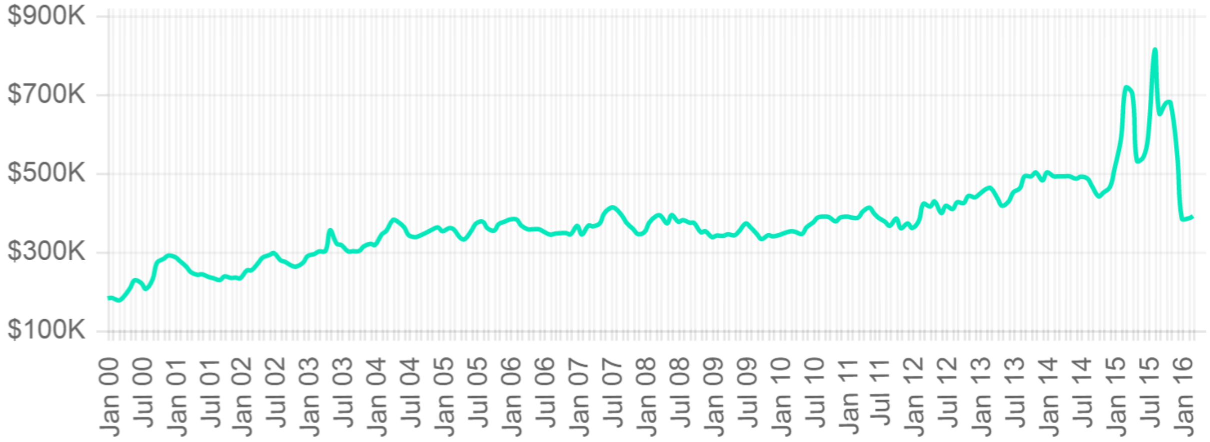
3.3.1. Real Estate Impacts

A supplementary report done by the Economic Development Research Group explores the real estate impacts of the Big Dig, including both land use changes and increased property values (Economic Development Research Group, 2006). Some examples include development on the land freed up by underground highways, increased property values in the area immediately surrounding the development (in this case, due to the removal of an eyesore), and changes in property values in the Greater Boston Area due to increased accessibility to services and jobs.

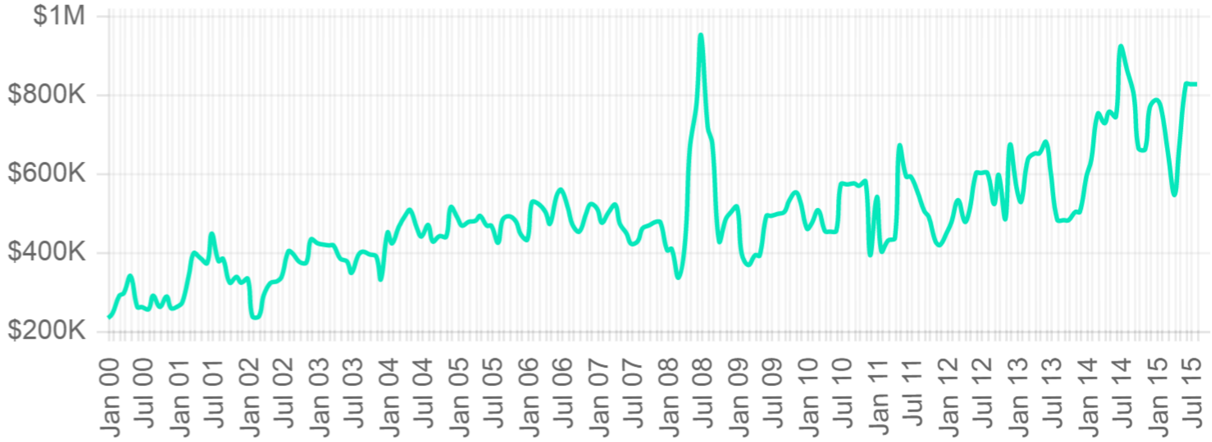
It is important to reconcile the difference between real estate impacts that occurred due to the changes in traffic flow and those that occurred due simply to place-making aspects of the project. This is particularly relevant when looking for lessons learned for other highway undergrounding projects in other cities, that may not have the same network-level impacts as the Central Artery and Tunnel project did. Many other projects maintain the same capacity (or even slightly reduced) and same routing patterns, with some modernizations; the main benefit lies in removing the loud, polluting road from public view by placing it at or below ground and creating a more livable area on the outside.

In the case of the Big Dig, it is hard to disentangle the network effects from the local livability aspects. One way to tease out the difference is by looking at different areas along the corridor where a highway was lowered underground and see whether changes in property values are correlated to whether a livability investment was made in that local area. For example, network-level effects are assumed to have benefited both the North End near Downtown and the area in South Boston around Fort Point Channel. However, the Rose Kennedy Greenway was only added in downtown. Therefore, it is expected that property values should have increased to a lesser degree south of Fort Point Channel if place-making creates a significant impact on property values. On the other hand, the connectivity of the Seaport Innovation District is improved somewhat more than the area that received the Greenway, because it has access to both the I-90 and I-93. For example, the recent decision by GE to move its headquarters to the Innovation District is almost certainly a response to the improved accessibility of the area, and will be a likely generator of further growth (Chesto, 2016).

Trends in the median sale price for all properties are presented in Figure 3.6 since January 2000. While there are fluctuations from year to year, general upward trends in median sale price are present in both locations. The jump in South Boston starting in mid-2015 corresponds to discussion about GE Headquarters moving to the area, which led to a time of instability. The jump in the North End in mid-2008 corresponds to the expected real estate impacts of the Big Dig, as this is about two years after construction was completed, allowing conditions to stabilize. Unfortunately, this is also around the same time as the Great Recession, so median prices quickly decreased before returning to a slow upward trend that continues to today.



(a) Changes in median sales price in South Boston



(b) Changes in median sales price in the North End

Figure 3.6: Changes in median sales price in (a) South Boston and (b) the North End for all properties (Trulia, Inc., 2016)

Many individual properties were examined using Boston's online Real Estate Assessments and Taxes tool to better understand these trends (The Assessing Department, 2015). In South Boston, the property at 20 Channel Center Street is right near Fort Point Channel, marked by the 1 marker in Figure 3.7. This property looks almost identical in 2007 and 2014, based on updated Google Maps Street View images. Across the street from this property in both cases are surface parking lots and other warehouses, so there have not been any place-making changes due to the Big Dig. This property is likely an old warehouse building that was converted into commercial offices or condos during this time. When it was zoned as industrial in 2009, its value was listed at $5.6 million. In 2015, as a commercial property, it is listed at $30.2 million. This growth far outpaced inflation over the six-year period. It is not exclusively due to the change in zoning, as a property at 51 Melcher Street (Figure 3.7, marker 2) rose in value from $4.1 million in 2013 to $28.5 million in 2016 despite no change in zoning or outward appearance. However, a property at 327 Summer Street (Figure 3.7, marker 3) also did not undergo a zoning change from 2009 to 2014, and also did not witness the same increase in value. Its price fluctuated during this time, starting at $2.6 million and ending at $2.5 million. It appears this building may be under construction so this could change in the coming years.

Figure 3.7: Locations of three analysis sites in the South Boston/Innovation District (Google, 2016)

It was not simply due to the Rose Kennedy Greenway replacing the elevated viaduct that property values increased in the area. While improvements to the aesthetics of the area did have an impact, better network connectivity and external changes in the economy brought increased property values to the real estate market all along the Big Dig corridor. Increased network capacity to many areas, most significantly the South Boston Innovation District, allowed job and residential growth to occur and place-making aspects made these areas desirable settings to live and work. Though growth did not necessarily occur because of these improvements, it would not have been able to occur without them. It would have been constrained by a lack of capacity to the high density job sites, as is being seen now as added capacity is being fully utilized, with congestion beginning to appear in the Ted Williams Tunnel and I-90, while the Red Line is operating at over-crowded levels during peak hours. In short, the network connective benefits are greater in the Seaport/Innovation District, while the aesthetic benefits are greater in downtown. However, the real estate value increases are similar, and not easily differentiated.

3.4 No-Build Scenario

If the Big Dig had not been completed, the Central Artery would have continued to be highly congested, both during peak hours and with an increase in the length of the congested peak, and flow through downtown would have continued to follow sub-optimal routes. Changes in accessibility from 1990 to 2010 under the no-build scenario would be much different than what actually occurred, especially considering some job growth in the area would still have happened. It is assumed in this analysis that the structural integrity of the elevated highway was restored, avoiding structural catastrophe, but that capacity and traffic flow improvements were not implemented. As projected in the EIR, this would have led to fewer vehicle miles traveled than the build scenario, but resulting in more vehicle hours traveled. Lower VMT is due to less induced demand and lower economic growth leading to less travel demand. However, higher VHT is due to this travel demand being served less efficiently, due primarily to higher congestion, and leading to longer travel times for the trips that are taken.

Table 3.4: Comparison of existing and projected VMT and VHT in study area (Massachusetts Department of Public Works, 1990)

	1987/88	2010 Baseline	2010 Proposed Action
VMT			
Daily	3,908,300	5,180,000	5,546,020
Annual	1,293.6 million	1,714.8 million	1,835.8 million
VHT			
Daily	278,000	485,700	418,400
Annual	92.0 million	160.7 million	138.5 million

Changes in accessibility from 1990 to 2010 are estimated using the Cube model, assuming the Central Artery & Tunnel Project was not completed but that some, but not all, socioeconomic changes still occurred. As compared to Figure 3.4, there are many more negative changes in accessibility, but still some positive changes, particularly within Route 128 where job growth was still expected to occur. Many of the changes are small, and conservative assumptions were made, so this alternative present scenario was not guaranteed, but should be considered possible given the high demand to capacity ratio already present in the system in 1990.

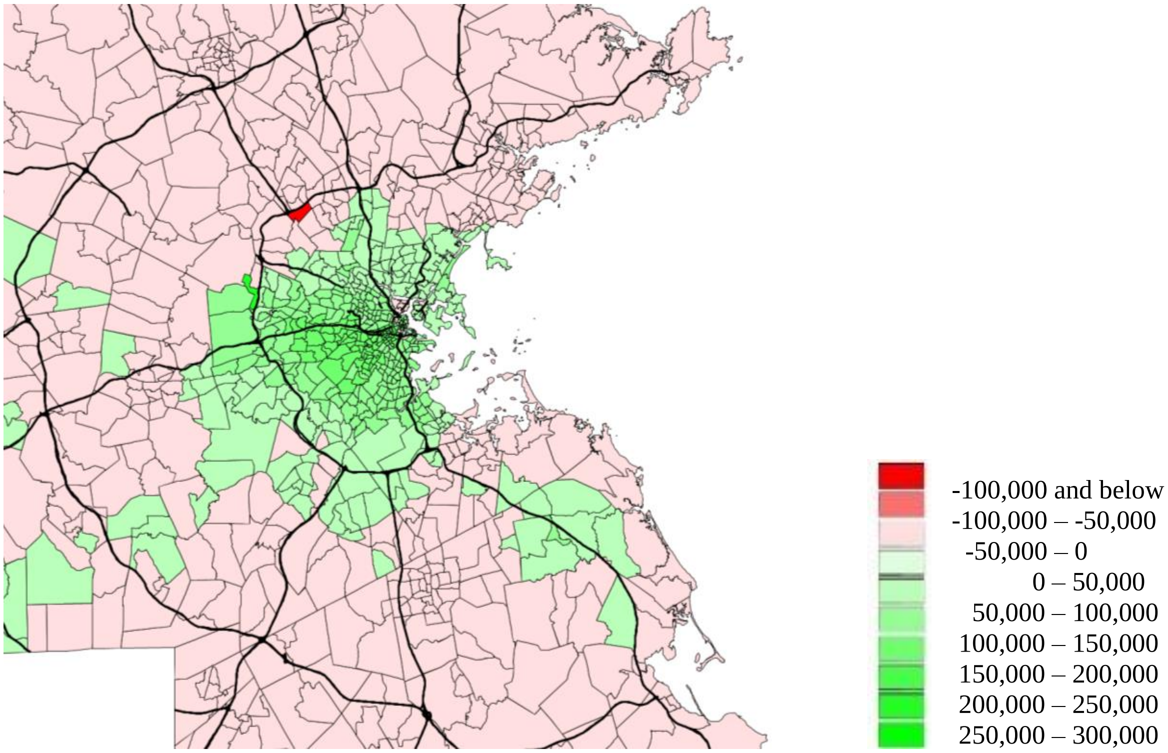


Figure 3.8: Changes in accessibility by auto to jobs from 1990 to 2010 under “no build” scenario

3.5 Lessons Learned for Future Projects

Because the CTPS is able to utilize their original model to judge past predictions, their forecasts are more robust and more applicable to real-world planning on future projects. However, we can mimic these results using the Cube Voyager model to establish what we would have predicted in 1990 and compare that to actual conditions in 2010 (Murga, 2015). From this preliminary analysis, it seems that predicted traffic volumes were slightly over-estimated but on the right order of magnitude and with a variation in differences on different roads and ramps. So a look at network-level impacts might be useful, since perhaps people are simply using the roads differently than expected. It may still be too close to opening to really gage the full impact of the project as the transit projects have not been completed and the roads have not been open long enough to fully impact land use, specifically due to uncertainty in fulfillment of the full project scope and because some changes in land use were likely to have occurred regardless.

While criticisms of the final price tag of the Big Dig have dominated press coverage, it is clear the project has provided massive benefits to the surrounding area. This lesson can be applied to smaller projects in other cities that have similar goals, particularly in the planning stages, when the scope is unclear and a retrospective look can provide insight on which aspects of a highway undergrounding or network change project are most effective. One example is the High Street cap over I-670 in Columbus, Ohio (National Transportation Enhancements Clearinghouse, 2005). The previously unsightly bridge that spanned the freeway was replaced by a 300-foot-wide structure with street-level retail, integrating with the surrounding streetscape and reconnecting Downtown Columbus with the Short North, a vibrant restaurant and cultural arts district. Despite the limited scope of the project, its impact on the walkability, economic activity, and aesthetics in the surrounding area have been immense. Similar projects to better integrate neighborhoods divided by urban freeways have been undertaken in Dallas, Texas, San Francisco, California, and Phoenix, Arizona (Klyde Warren Park, 2015; SF Gate, 2004; Weber, 2012).

The Allston I-90 Interchange Improvement Project has the opportunity to provide both transportation and place-making benefits to the surrounding area, as well as transportation network benefits to the entire regional area. However, the extent of these benefits will depend largely on how these projects are developed. When traffic projections for the Allston Interchange Improvement Project were presented at a public meeting in June 2015, many members of the public were concerned by the method of traffic projection, as it seemed to be more of an extrapolation of past trends rather than a well-reasoned account of what the transportation network is expected to be like including realistic capacity constraints. The CTPS model does take this into account more than the original, back-of-the-envelope calculations used in the preliminary planning process, by projecting traffic behavior from socioeconomic changes in the catchment area. However, since there is no room on the turnpike for this traffic to grow, it will simply not be able to accommodate any traffic growth without generating unstable flow that will result in lower throughput capacity. Thus, improvements to transit need to be considered in order to make up the gap between transportation demand and the constrained highway capacity supply, or otherwise accessibility is likely to actually worsen.

The Allston Interchange Improvement Project is being presented as a “multimodal transportation project” that should better integrate transit aspects along the way, rather than as an afterthought or as mitigation. Since West Station was announced near the beginning of the planning process, and has expanded in scope since, this seems likely. New roadway connections between the turnpike interchange and Commonwealth Avenue will reduce congestion on Cambridge Street, and improve access to Longwood. Ari Ofsevit’s plan to lower the highway viaduct, when considered in conjunction with the People’s Pike’s plan to extend the Paul Dudley White Bike Path, could allow for better bike and pedestrian connections. In particular, the expansion of the Charles River path and, more importantly, direct pedestrian connections over Beacon Park Yard will reconnect the neighborhoods of Upper and Lower Allston and have a significant place-making impact on the local neighborhood, as the Big Dig has on the North End and the Innovation/Seaport District.

There are a few network-level effects that could be anticipated from the Allston Interchange Improvement Project. Replacing the single-track constraint through Beacon Park Yard with the four-track West Station allows for the potential for more rail capacity through to Yawkey, Back Bay, and South Station. Signal modernization and vehicle purchases will be necessary to take advantage of this infrastructure improvement, which can then support improved travel time and increased throughput to Downtown, the Innovation District, and Back Bay. These are all areas where land use projections indicate that traffic demand will exceed capacity in the coming years. However, in order to accomplish this enhancement, vehicle and operation subsidy constraints must be dealt with. Providing more frequent service from West Station through Kendall to North Station will improve travel time and capacity for connections from the West, especially if this service is extended out to Route 128 in the planning horizon beyond 2025. Vehicle and operating budgetary constraints must again be dealt with, but this option provides the physical potential for the urban grid and for access to a new growth node in Allston. This growth node could be enhanced if the turnpike is lowered and decked rather than replaced by a viaduct, as this could provide an area four times the size of the Prudential Center for future development. These links will be further explored in Chapter 6.

Chapter 4 – Importance of Multi-Modality

The first two steps of the four-step model, trip generation and trip distribution, integrate socioeconomic factors that influence home, work, and other attraction locations, which in turn determine the amount and type of trips that will be taken. The third step of the four step model, mode choice, is when the physical characteristics of the transportation network are taken into account relative to the user socioeconomic profile and generated trips are split into different transportation modes, such as auto, transit (bus, rail, ferry, and variations thereof), walking, and biking. This chapter will mainly look at the split between auto and transit as these are more viable for commute trips through the Western Corridor rather than within communities along it. These auto and transit networks are susceptible to capacity constraints.

The I-90 Turnpike is at capacity during peak hours, so the best way to increase passenger throughput through the Western Corridor is to encourage a modal shift to transit or an increase in auto occupancy rates for commute trips that tend to occur during this time. Trips outside the peak are not part of the scope of this analysis since the turnpike tends to have excess capacity during the off-peak and because many suburban transit users, particularly those using park-and-ride facilities at commuter rail stations, may use their cars for essentially all of their other trips, but if these are not occurring on congested roads, they will not have a significant impact on growth constraints in the Western Corridor. Commute trips tend to be habitual, so a mode choice made once could have a lasting impact on the conditions of a network, especially if it results in a more permanent decision such as a change in the number of cars owned by a household. Employers can also have a strong influence on mode choice for commute trips of employees by choosing whether to provide and subsidize parking and transit benefits.

Transit is not a practical option for every commuter in the Western Corridor, due to the sparsity of the transit network stations in some suburban areas. However, many neighborhoods are served adequately by transit or could be with the proposed improvements at West Station, as well as the shuttle DMU service proposed along the Grand Junction, together with improved frequency on commuter rail, and better bus connections. Higher accessibility due to these improvements to the transit network are expected to encourage a modal shift to transit as commuters continue to make rational decisions on the best choice for their commute. This is particularly true, given that there will be no major increases in capacity in the highway network and scarcity and expense of parking will grow at employment destinations. The current situation during peak hours is one of unstable flow, reducing throughput, and increasing auto travel time and user stress. A high enough modal shift to transit could ease congestion on the turnpike, enough to stabilize auto travel times and network conditions, but this will require higher transit capacity and quality. Modal shift to transit in the context of overall travel demand growth in the area is expected to be necessary just to avoid pushing conditions further into the unstable traffic density range and preventing conditions from getting worse. Improving conditions will require more significant transit improvements.

In 2012, MassDOT announced a "GreenDOT" policy directive that included the ambitious goal of tripling non-auto mode share by 2030 (MassDOT, 2012). Since mode share is measured as a percentage of total users, if high employment growth occurs in the area as expected, this shift must more than triple the number of non-auto trips currently being taken. Furthermore, the goal is for the entire state of Massachusetts, but since non-auto mode share and the availability of transit options are currently highest in the Boston metropolitan area, much of the pressure to increase is on the Boston area network. In the Boston area, walking and bicycle use is growing, but these types of trips are attractive and possible only for short distances, and limits to the availability of affordable housing within a reasonable distance to job centers will limit the amount of growth in these modes, shifting an even greater growth burden onto transit. To achieve such high growth in transit mode share, the amount of employment growth in transit accessible areas must also grow disproportionally, as not all job locations are accessible by transit. In addition, much of the Boston area transit system is at capacity during peak hours, so very significant increases in transit capacity and comfort are required to support such job growth, and the climate change and economic policy objectives of the state.

Preliminary results from 2014 showed increasing transit usage, as measured by person miles traveled, as shown in Table 4.1 taken from the GreenDOT Status Update. This document presents transit growth only in miles traveled, while progress toward the mode shift goal will be measured by number of trips, regardless of length, on each mode. Growth will need to occur for trips of all lengths, but to achieve the mode shift goal with the smallest impact on capacity, it would be better if shorter trips grew more rapidly than longer trips, necessitating an even higher than three-fold increase in trips of this type.

Table 4.1: Person miles traveled on transit per year (MassDOT, 2014)

	2010	2012
Billion person miles	1.831	1.989
Person miles per capita	279	299

The Status Update document also discusses the difficulty of measuring walk and bike mode share, so results for these modes have not yet been published. Walk share in Boston and other dense cities such as Cambridge is significant and should be incorporated into future updates. Bike share, while small, is growing and may become significant.

Some proposed strategies to further increase non-auto mode share include "traveler education and encouragement", but given that many pieces of the system, particularly rapid transit, are at capacity during peak hours, actual changes to the design and operations of capacity and comfort on the system must be implemented if MassDOT is to achieve its mode shift goal and support its economic growth projections.

4.1 Factors that Impact Mode Choice

There are a variety of factors travelers take into account when planning their commute and other trips. The main determinant of mode choice is mode availability. If the trip between two points relatively far apart is not served by transit, while walking is not an option given the distance involved, there is no choice but to drive. But, if a user does not have access to a car or to parking at their destination, they will need to either take transit, not make the trip, get a ride from a friend, or take a taxi (which is only practical for infrequent trips).

There are many areas in the United States that have virtually no transit access, but the Boston metropolitan area is not one of them, especially for trips to downtown and when amenities such as park-and-rides can be used for trips beginning or ending in suburban locations.

If multiple modes are available and feasible for a trip, the next factor to be considered is the relative attractiveness of each mode. This includes raw travel time as well as conditions of travel. Both of these factors are strongly impacted by the volume to capacity ratio of the transportation network because congested conditions result in both slower travel times and less comfortable travel conditions, which leads to having to deal with stop-and-go traffic in a car or not getting a seat in a crowded transit vehicle.

A third factor is user preference. While this does play a role, the role is largely overstated in many cases. Separate studies in London, England and Trondheim, Norway studied the impact on mode choice of moving an office to a new location that happens to be more transit-accessible than the previous office location (Walker, Thomas, & Verplanken, 2015; Meland, 2002). In the first study, both locations were in outer London, but the second location had slightly better transit access, requiring a 7-minute walk from a rail station rather than 25 minutes at the first location, though both had equal parking access. In the second study, the offices were moved from an area 4 kilometers outside the city to the city center, and parking became more limited. Changes in mode share are displayed in Figures 4.1 and 4.2.

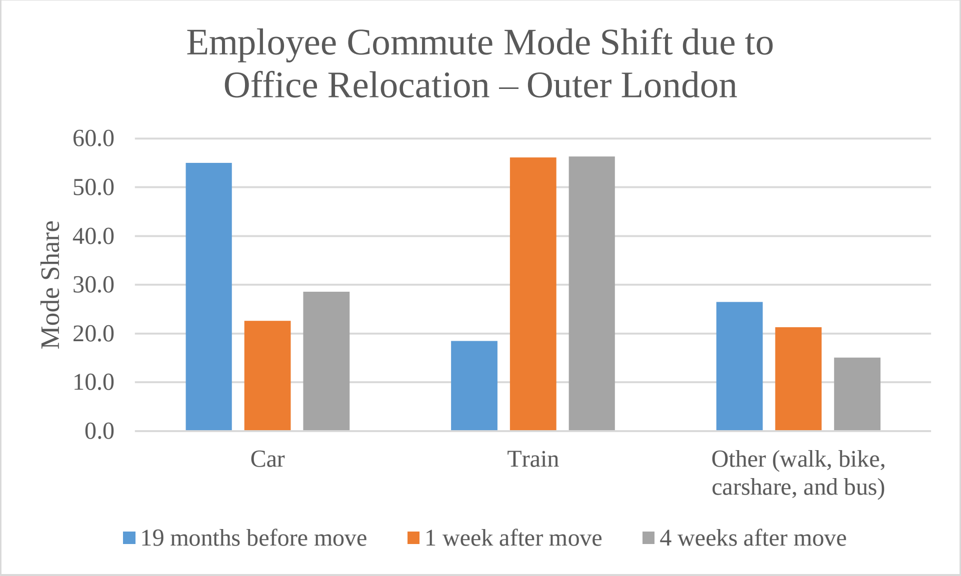


Figure 4.1: Employee Commute Mode Shift due to Office Relocation – Outer London. Note: the decrease in active mode use from week 1 to week 4 is likely because the study occurred in late fall

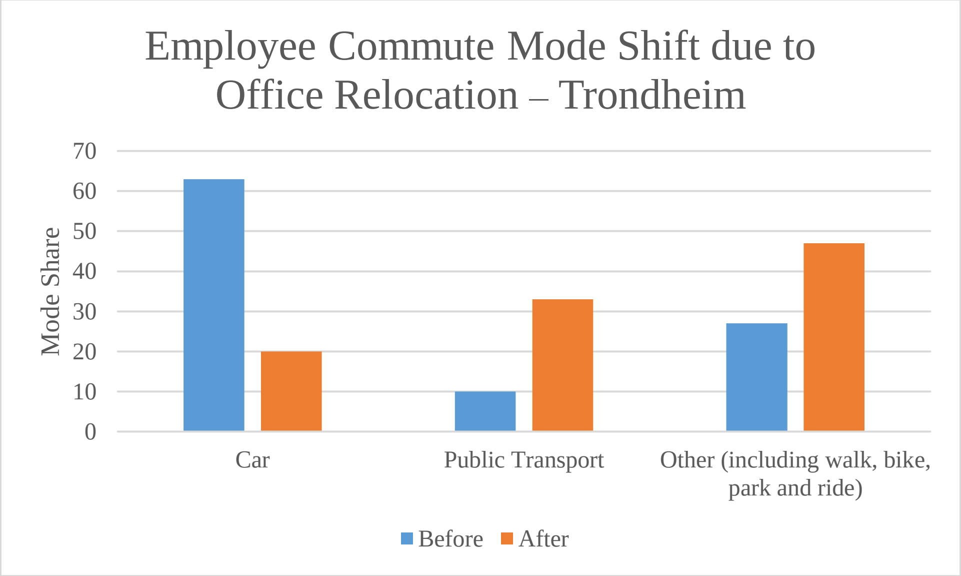


Figure 4.2: Employee Commute Mode Shift due to Office Relocation – Trondheim

While some commuters stayed with their original habits, or switched back after trying out a new mode, there was a significant modal shift in both cases as employees reevaluated their commute based on the new options and information. This suggests that most people are not “transit-people” or “auto-people” but rather that they make the best, most reasonable choice given the resources and options available to them for their commute. Because the same employees were surveyed through the relocation, they did not self-select and did not choose the job for its type of access to the transportation network. While people do value their time differently, and there may be some number of people who are tied to their commute mode, most are simply making a rational choice on how best to travel, given the options available to them. For example, many of those who did not shift to transit in the Trondheim and London studies likely thought about doing so, but did not due to bad transit access at their origin or simply because the auto network still served their needs better.

This has also been seen domestically in the United States, with Panasonic seeing transit mode share increase from 4% to 57% after moving from suburban Secaucus, New Jersey to downtown Newark (Jaffe, 2015). While the new North American headquarters is significantly more accessible by transit than the former, this remarkable change in mode shift was encouraged by increasing commuter transit benefits and raising parking prices from free to market rate.

These types of office location shifts in Trondheim, London, and New Jersey are similar to a shift from suburban office parks at Route 128 to Kendall. In Kendall, there is still a large auto mode share, as will be discussed in Section 5.3, but the transit mode share is significant enough to sustain the level of density in the area. Jobs are similar in these two locations, so while there may be some self-selection as people search for jobs nearest to where they want to live, this is likely not the determining factor that differentiates mode share in the two locations.

There is some evidence of shifting preferences for younger people, which may have an impact on peak travel conditions as this generation enters the workforce in larger numbers. For example, a study at the University of Michigan Transportation Institute found that while in 1983 91.8% of 20-24 year olds had a driver's license, in 2014 just 76.7% did (Sivak & Schoettle, 2016). The proportion of persons with a driver's license decreased over this same period for all age groups under 55 but at a consistently higher magnitude for younger age groups, ranging from a 47.0% decrease for 16 year olds to a 0.2% decrease for 50-54 year olds. There are a variety of potential reasons for this change in driver's license ownership, but the result is clear – a growing number of people do not find it necessary to obtain a driver's license and are therefore, at least temporarily, reliant on modes other than driving alone.

There is also growing pressure on employers to reduce parking availability because of increasing real estate prices and the cost of constructing parking structures. Surface lots have historically been practiced in urban areas due to the low costs of maintenance and high price people are willing to pay for parking in close proximity to their destination. However, more recently, with rising land values, surface lots have become prime spots for infield development. Demolition costs are negligible and construction can start as soon as possible. Since developers have a large incentive to increase density quickly in high growth areas in Boston, they are willing to offer large buyouts to existing land owners, beyond the value of owning a surface parking facility. Parking garages make better use of available land for parking, but they are about four times as expensive to construct per space, making the conversion significantly costly (Victoria Transport Policy Institute, 2016). There are a few examples in Boston, such as the Government Center Garage, where even existing garages have been considered for partial demolition in order to use the land for office or residential redevelopment (Logan, 2016). Less dramatically, in Kendall, there has been some exceptions to zoning requirements, allowing for higher density development without adding the same proportion of garage space. In general, in many high job density areas, office space has become more valuable than parking space and developers have begun looking at more innovative and multi-modal ways of serving transportation needs, not just for environmental policy reasons but for their own monetary self-interests.

Looking at the Boston area specifically, there is a large variation in mode share both between and within different corridors in the region. Figure 4.3, with major roads in white and rapid transit and commuter rail lines in grey, shows many trends in mode share variation along transportation corridors for residents in the area. Areas with higher transit mode share relative to auto mode share are in blue, while those with a lower ratio of transit mode share to auto mode share are in yellow or green. There are clusters of blue along rapid transit lines, particularly to the west along the Green Line, and commuter rail, for example far to the north in Salem. To the west along the Framingham/Worcester line and I-90 Turnpike, the transit to auto mode share ratio seems to fall in the mid-range of the area when the two paths directly overlap, but when they begin to diverge there is a distinct pattern of higher relative transit mode share directly along commuter rail and lower relative transit mode share directly along the turnpike. Corridors along the Lowell and Haverhill lines, which roughly follow I-93, have lower transit usage relative to auto usage than the Fitchburg line corridor, also slightly to the north but with a less direct alternate auto route. It is unclear whether areas have higher transit usage because people who are more transit oriented choose to live there due to the transit accessibility, or whether people living in these areas are simply responding to the options available to them and would be less likely to use transit if they lived in a less transit accessible area. An unpublished paper by Mikel Murga documented that auto ownership is much lower in transit served areas, suggesting that transit availability plays a large role, in any case. This all suggests that variations in accessibility between different areas can have a large impact on mode choice, which will be further explored in Sections 4.3 and 4.4.

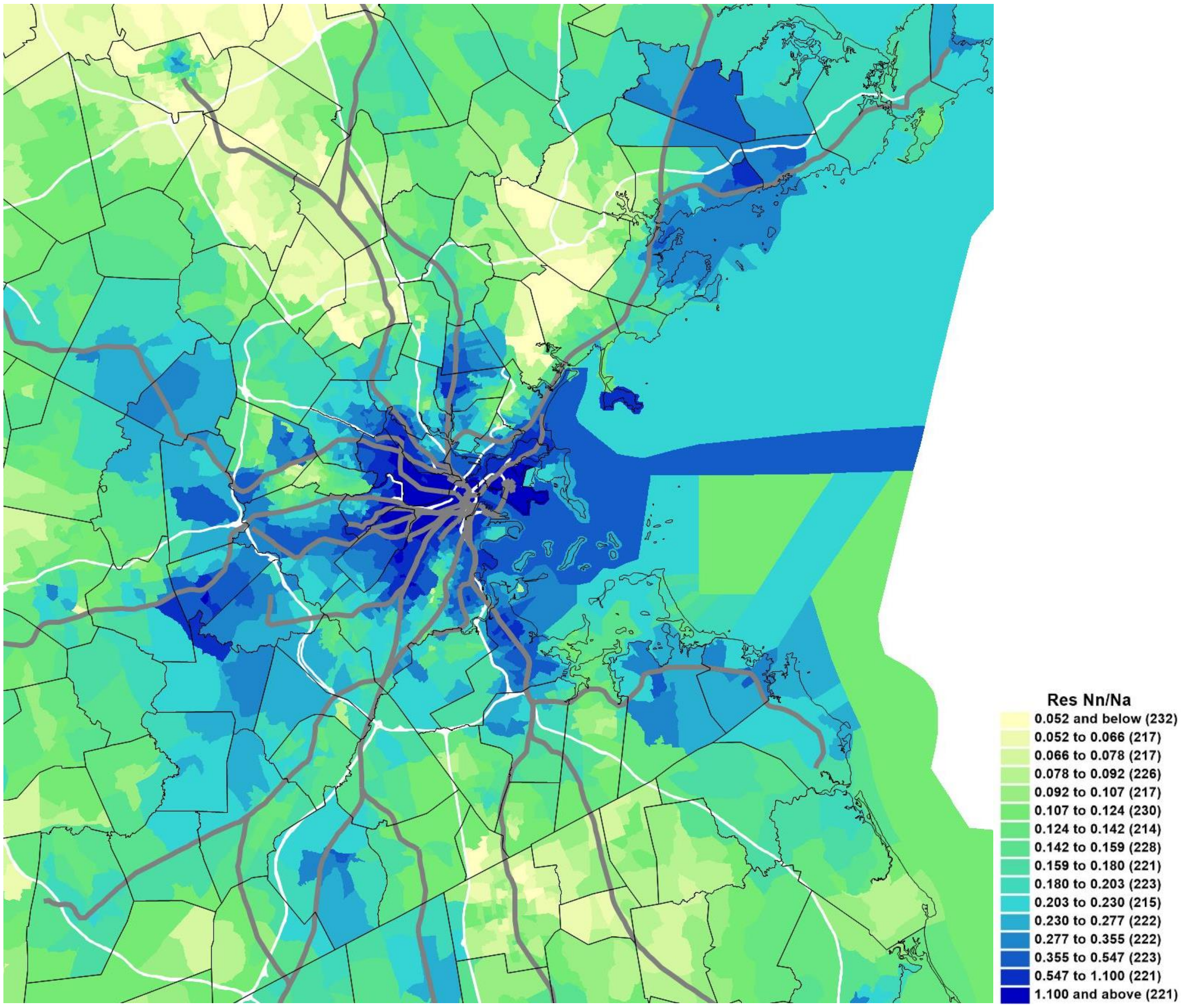


Figure 4.3: Ratio of non-auto mode share to auto mode share on the residential end

According to the 2013 TRB report "Commuting in America 2013: The National Report on Commuting Patterns and Trends", the average commuting travel time by private vehicle is significantly lower than that by any transit mode. Table 4.2 presents average travel time to work by commuters in the United States across all modes over the past three decades. The census data used in this analysis does not allow users to select more than one mode, so for multi-modal trips, such as bus-to-subway or car-to-rail, the total travel time is categorized in the longest modal stage of the trip.

Table 4.2: Average travel time to work by mode in the United States (American Association of State Highway and Transportation Officials, 2015)

Average Travel Time by Mode (minutes)			
Mode	**1990**	**2000**	**2010**
Private vehicle	N/A	24.7	24.6
Drive alone	21.1	24.1	24.2
2 people	24.0	27.1	26.8
3 people	28.6	30.9	31.0
4+ people	34.8	37.7	36.1
Bus	38.0	45.9	45.1
Subway	44.9	47.8	46.4
Railroad	58.5	70.6	69.4
Ferry	58.4	65.7	65.1
Taxi	17.2	20.1	18.6
Motorcycle	22.5	21.7	22.3
Bike and Walk	10.9	12.4	13.0
All	22.4	25.5	25.6

Travel times on all modes except motorcycle increased during the 1990 to 2000 time period. This can mainly be attributed to added congestion in the networks, as demand increased with few infrastructure improvements to accommodate it. Average trip distances also increased slightly during this time for a variety of reasons, which also caused average trip times to increase. Travel times tended to increase slightly during the 2000 to 2010 time period, but not across all modes due to many factors such as changes in transit service availability and demographic shifts among modes. Trips by private vehicle are consistently shorter on average across all time periods than trips by any public transit mode, implying varying values of time on each mode as well as characteristics of the networks themselves, such as car ownership and parking constraints. Bike and walk trips are relatively short on average, showing that active travel modes have relatively low travel time thresholds before additional modes begin to become more attractive. These results are for the entire United States but because some trends such as the long average commute by railroad may be due to regional trends, like the particularly long and common commuter rail journeys into New York City, data for just the Boston area is presented in Table 4.3, with similar results.

Table 4.3: Average travel time to work by mode in the Boston area for 2010 to 2014 (U.S. Census Bureau, 2010-2014)

Average Travel Time by Mode in Boston (minutes)	
Car, truck, or van	27.6
Drive alone	27.4
2 people	27.5
3+ people	33.3
Public transportation (excluding taxicab)	38.6
Bus or trolley bus	38.8
Streetcar or trolley car, subway or elevated	38.0
Railroad or ferryboat	45.5
Walked	14.9
Taxicab, motorcycle, bicycle, or other means	24.2
All	29.4

Because the average travel time varies by mode it may be useful to use different travel time thresholds when comparing the attractiveness of different modes. Users may perceive travel time by transit differently, since they may be able to do other productive tasks which they cannot do as an auto driver. However, this is highly dependent on the conditions of travel – a user will be much more satisfied on a 45-minute commuter rail journey if they are provided Wi-Fi or can rely on their phone for data, and can sit and begin their workday during the trip than if they must stand in crowded conditions and remain uncomfortable and unproductive. However, for a 10-minute travel time, these comfort differences are likely much less significant and may not have as large of an impact on future behavior.

Another important factor is travel time reliability. This is true for both the auto and the transit networks. Needing to buffer time to work in response to unstable traffic conditions or inconsistent transit vehicle arrival increases the effective travel time of a commute trip and may impact future behavior. Potential impacts could include shifting to a more reliable mode or shifting behavior within a mode by time or by route.

4.2 Discussion of Capacity Constraints by Mode

Capacity constraints for auto are complex to model, especially when relying on static assignments. As volume on a roadway reaches capacity, the density of vehicles increases and travel speeds begin to slow. This lowers the effective capacity on the roadway, further exacerbating the congestion under unstable conditions. Demand beyond capacity spills into later time periods, pushing traffic volumes into the shoulder of the peak. Consistent congestion during peak hours encourages some commuters with more flexible schedules to travel outside the peak during future travel, but this is not possible for most commuters and congestion will likely remain highest during peak commuting times, when demand is high, volume is close to or at capacity, travel speeds are slow, and travel times are further augmented by increasing reliability buffer time, as humans continue to adapt to degrading conditions. A downward spiral can result as capacity constraints lead to reduced throughput capacity and unstable flow.

It is equally complicated to integrate capacity constraints into transit models. The simplest approach is to set capacity as the stated capacity of each vehicle and assign passengers to trips taking into account the headway up until that threshold has been reached. However, passengers begin to feel capacity constraints below the stated threshold and may begin to feel impacts that shift their behavior before a vehicle has officially reached capacity. These impacts include increased dwell time at stations, due to the large number of boarding and alighting passengers and the interactions between them. There is also an increased possibility of denied boardings, which would cause a passenger's trip time to increase by at least the headway of the service. Passengers on a crowded vehicle experience high levels of discomfort, which is important because they may value their time differently, depending on how comfortable they are. Crowding is particularly relevant on commuter rail where users are likely not to accept a standing commute for trips more than a few miles long. For the journey inbound this is not a huge issue as those with longer journeys board first and will be able to find a seat, but for the outbound trip all passengers have equal probability of standing while the vehicle is at its maximum capacity. Commuter rail users are also more likely to own a car than urban transportation users, and can easily shift modes, thus losing them as transit users if conditions are not satisfactory, and parking is available and affordable at their destination. As explored in a 2014 MIT Transit Lab thesis, a better method to account for these externalities is to add a stop-based penalty to capture the effect of increased difficulty of boarding the vehicle and the likelihood of experiencing a denied boarding alongside a link-based penalty to capture the increasing level of discomfort of travel as well as the increased dwell times at stations due to difficulty in reaching the vehicle exit (Tuttle, 2014). This is one potential method to better model capacity constraints on transit.

4.3 Comparison of Current Accessibility by Mode

According to a study by the Accessibility Observatory at the University of Minnesota, in 2014 the Boston metropolitan area had the 6th highest accessibility to jobs by transit in the nation and the 9th highest accessibility to jobs by auto in the nation (Owen & Levinson, 2013; Owen & Levinson, 2014). The census-defined Boston-Cambridge-Newton metropolitan area is ranked 10th in population by the US Census Bureau (U.S. Census Bureau, 2010), so in comparison to other metropolitan areas it has slightly higher relative auto accessibility to jobs and much higher relative transit accessibility to jobs compared to similar areas, ranked in Table 4.4. This makes sense since it is an older, denser city with a historic and established transit system that played a role in shaping growth in the area. The high concentration of jobs in central areas allows for high transit accessibility due to the number of jobs within the catchment area of the hub of the system and multiple transit lines, but also for even higher absolute auto accessibility as downtown is also the hub of the freeway network and as a result, auto travel times remain lower than transit travel times despite congestion due to the single-stage, non-stop, door-to-door nature of the auto trip.

Table 4.4: Ranking of top US cities and metropolitan areas

Ranking	**Metro Area Population**	**Accessibility by Auto**	**Accessibility by Transit**
1	New York	Los Angeles	New York
2	Los Angeles	San Francisco	San Francisco
3	Chicago	New York	Los Angeles
4	Dallas	Chicago	Washington, D.C.
5	Houston	Minneapolis	Chicago
6	Washington, D.C.	San Jose	**Boston**
7	Philadelphia	Washington, D.C.	Philadelphia
8	Miami	Dallas	Seattle
9	Atlanta	**Boston**	Denver
10	**Boston**	Houston	San Jose

Within the Boston region, job sites are compared for their accessibility to workers as a measure of the attractiveness of each high-growth employment center. Accessibility is defined as the number of workers within a 60-minute travel time, under a time-decay function to weigh closer workers more favorably that will be introduced more fully in Section 6.1.2. Calibrated to real-world home-based work trips, this time-decay function does not decay for the first 23 minutes, as it is assumed that people have equal preference for short commute trips. It then decays until it reaches the final cutoff at the 60-minute mark (Peralta-Quirós, 2013). This function results in values for accessibility that are lower than the population of the metropolitan area due to this decay. Therefore, they should not be taken as an actual number of people and rather as a metric to compare areas with each other.

Table 4.5, sorted from highest to lowest ratio of transit accessibility to congested auto accessibility, provides values for accessibility for many growing job centers in the Boston area, as well as locations (in italics) that are traditionally more suburban and auto-oriented with some transit access. Congested travel is under AM peak conditions while free flow travel times are from the pre-assignment stage of the four-step model.

Table 4.5: Accessibility to workers at job destinations in the Boston area

Location	**Free Flow Auto**	**Congested Auto**	**Transit**	**Ratio**
Downtown	1,463,242	299,033	208,193	0.696
Innovation	1,463,772	294,840	113,230	0.384
Kendall	1,410,443	390,877	140,839	0.360
Longwood	1,400,103	412,395	122,099	0.296
Alewife	1,392,507	469,320	67,982	0.145
Logan	1,425,504	280,667	27,469	0.098
Allston	1,393,191	517,251	21,606	0.042
Quincy Adams	1,242,011	240,042	3,772	0.016
Waltham	1,327,101	484,929	6,700	0.014

Even congested auto accessibility is higher than transit accessibility in all cases, as demonstrated by the final column showing the ratio of transit accessibility to congested auto accessibility, which is always less than 1. This ratio is highest, at 0.696, for Downtown Boston, which is the hub of the rapid transit system. It is lowest, at 0.014, for Waltham, which is served by commuter rail and buses but does not have any rapid transit service. Quincy Adams and Boston Logan International Airport both have relatively low ratios as well, despite being served by rapid transit. According to Open Trip Planner, for the airport, the 30-minute travel time to reach downtown is beyond the flat portion of the decaying function, and the 10-15-minute travel time by auto is not. Other high density areas such as Cambridge have an even more dramatic travel time difference between transit and auto to Logan Airport, particularly due to the missing link between the Blue and Red Lines. Allston currently has the highest accessibility to workers by auto, because it is right off the exit to the turnpike rather than through slow city streets. At the same time, it has one of the lowest accessibilities by transit because it is essentially served only by buses.

Under free-flow conditions, locations with very high transit access, such as Kendall and Longwood, also have much higher auto access than the more “auto-oriented” suburban locations. This is likely due to the greater centrality of these areas, both in terms of jobs and of residents. This effect is diminished when congested travel times are used due to higher congestion in the center of the network. Congested travel times are calculated post-assignment, so the results reflect to a certain extent other constraints in the network such as high parking costs in some employment areas and low auto ownership rates in some residential areas. Calibration of the 4-step model incorporates the availability and cost of parking separately for workers and for visitors, given the differences in average parking duration. In fact, this is a critical and necessary aspect of the model calibration, in order to replicate the actual mode share, especially in the downtown area (Murga, 2015). Because this causes some modeled and actual commuters to switch mode to transit, it can lessen the decrease in accessibility by auto to areas with high transit usage, such as

Longwood. However, because auto mode share to these areas is still higher than 50%, demand during the peak still causes significant congestion and substantial decreases in travel times and accessibility.

Longwood shows slightly less of a reduction in accessibility after the impact of congestion, and ends up with higher auto accessibility than Kendall and Downtown under congested conditions, despite being further from the major highways. Longwood is closer to dense residential neighborhoods like Back Bay and Brookline and congestion has less of an absolute impact on both short trips and non-highway trips. This is supported by Figure 4.4, which shows residential densities within Route 128. Residential densities for zones outside of Route 128 are much lower, appearing predominately red in this scale, but there is large variation within the urban core as well. One notable low residential density zone is Logan Airport, which covers a large amount of space relatively close to Downtown Boston and the Innovation District. Because Longwood and Kendall are further from the airport, they retain a higher accessibility to workers due to higher radial access to a larger number of residential communities. This is especially true since the decay function used to calculate accessibility plateaus until 23 minutes, so residents beyond Logan Airport are less significant to all areas. This is a reminder that accessibility is highly dependent on land use, particularly local land use, and that street-level congestion is not the only factor with a significant impact on the relative accessibilities between areas within a region.

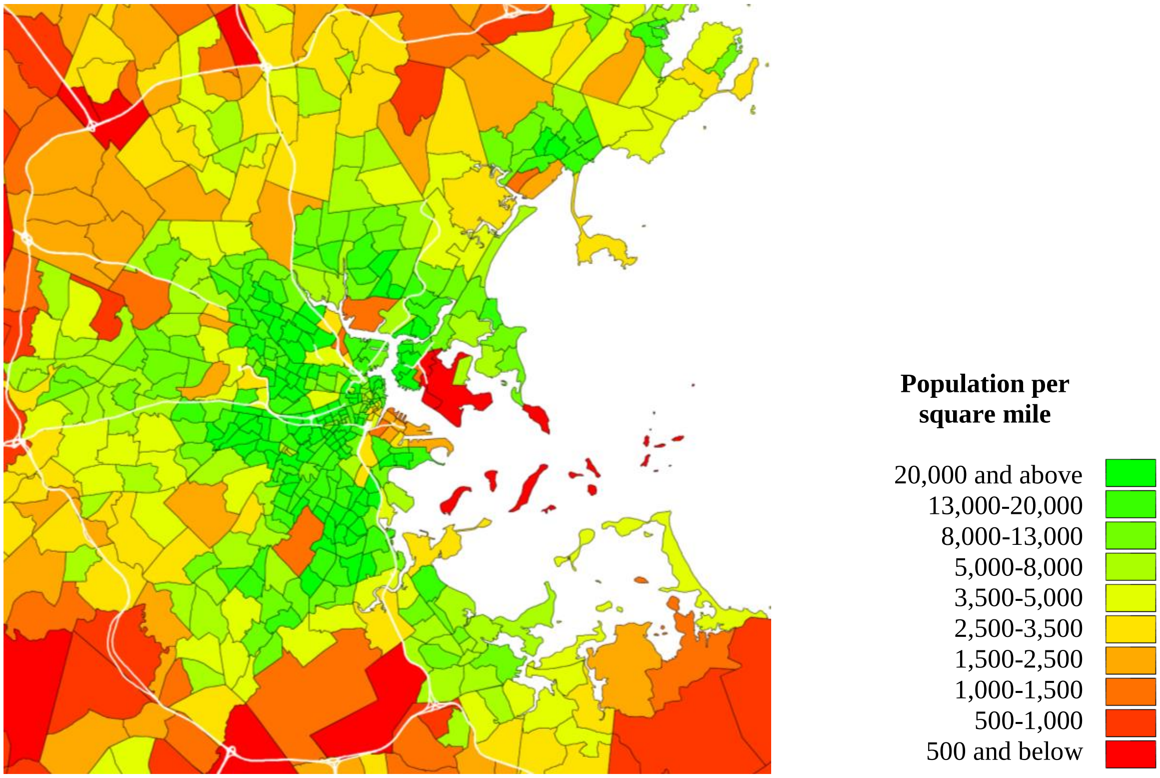


Figure 4.4: Residential density in the Boston area

High auto accessibility at transit-accessible locations could pose an issue as relative accessibility between modes has a large impact on mode choice, as will be discussed in the next section. This could mean that high accessibility by transit is not as effective when competing with much higher accessibility by auto. For example, approximately 43% of commuters to the South Boston Innovation District drive alone to work, because despite transit access being available, access by auto is much better (VHB, 2015). One way to encourage transit use is by restricting the availability or raising the cost of parking (to reflect the true cost, which is currently heavily subsidized by the employer) at the destination in cases where auto accessibility is relatively high but would have very high negative externalities on the transportation network, both locally and regionally. This phenomenon may also provide insights into the pressure by developers to add parking, until the cost of providing parking exceeds the perceived marginal increase in attractiveness to customers and tenants.

Additionally, this auto accessibility may be very vulnerable to congestion if unstable flows continue to occur. For example, while Newton is around 8 miles and 20 minutes from Kendall under free-flow conditions, according to Google Maps this can vary from 22 to 45 minutes during the AM Peak (Google Maps, 2016). The accessibility function used decays steeply during this range of travel times, and especially if commuters tend to add in a reliability buffer time and may therefore perceive their commute as the maximum travel time, it may not be valid to use the average congested travel time to calculate accessibility. Accessibility by auto may be lower than perceived and is likely to continue to decrease despite job and population growth in the area, due to the strong impact of congestion in the auto network.

4.4 Relative Accessibility and Mode Choice

Commute mode choice decisions can be influenced by a wide range of factors, some inherent to each type of mode and others as a result of local conditions. A study at the University of Minnesota looked not just at the differences between transit and auto as types of modes, but rather at their similarities – both are systems through which customers exchange time for access to destinations (Owen, Anderson, & Levinson, 2012). Choices are then assumed to be based on the relative accessibility of each mode, while other costs such as parking, fares, and gasoline are ignored by the authors in order to measure just the impact of travel time distance of attractions. The model was able to predict 41% of the variation in commute mode share in the Minneapolis-St. Paul metro area, when using just the relative accessibility of the origin block group.

In this thesis, accessibility of the destination is also tested to see if it could be as predictive of commute mode choice as accessibility of the origin. This analysis is applied to the greater Boston area, the local Boston area within Route 128, and the Western Corridor.

First, travel times by auto and by transit were generated for a network, which were then used to calculate accessibility for each origin (or destination) zone. Accessibility is defined as the number of jobs or workers with a certain travel time threshold and can be calculated in a few different ways. The Minnesota study used a binary weighing function that represents a cumulative opportunities measure of accessibility. In this method, accessibility is calculated for specific time thresholds and represents the number of origins or destinations that are reachable within that threshold. Different thresholds are considered separately and the 30-minute time threshold (close to the average commute time in the Twin Cities metropolitan area of 24.3 minutes) was considered the most predictive of mode choice. Thresholds above the average commute time (to accommodate the majority of commute trips) tend to work best. A weighted method can also be used, which is similar to the gravity model in that closer jobs or workers are weighted more heavily than those further away. It is less intuitive in everyday life but is in many ways a better indicator of accessibility.

This analysis uses a 60-minute travel time threshold with a time-decay for both auto and transit, calibrated to actual home-based work trips. While this is a different function than in the Minneapolis study, commute times in Boston tend to be higher than those in Minneapolis so a higher threshold makes sense (U.S. Census Bureau, 2010). The decay lowers the importance of the exact threshold value.

Commute mode shares were obtained for each origin (or destination) transportation analysis zone. These were obtained from CTPP mode share data. Values had to be projected to the same zones as the Cube Voyager output using a spatial join in GIS.

Finally, a regression model was applied to these data to measure predictability of mode choice by relative accessibility:

$$\left(\frac{N_{non-auto}}{N_{auto}}\right) = \beta_0 e^{\beta_1\left(\frac{A_{transit}}{A_{auto}}\right)} \tag{4.1}$$

N = number of commuters

A = accessibility

The first iteration was done for the Boston metropolitan area in Eastern Massachusetts, including parts of Essex, Middlesex, Suffolk, Norfolk, Plymouth, and Bristol counties. On the residential end, 74% of the variation in commute mode share could be explained by the relative accessibility of the origin zone, which is higher than what was found in the Minnesota study. On the work end, 49% of the variation in commute mode share could be explained by the relative accessibility of the destination zone. This may be lower than on the origin end because all zones are included, and those commuting to jobs outside of downtown areas are likely to consider factors other than time differently when making their commute decisions. Reverse commutes are generally served more comfortably by auto than regular commutes in the same amount of time because roadways in the reverse direction tend to be less congested and parking tends to be cheaper at the destination. However, at the same time, reverse commutes are generally served less comfortably by transit, as schedules are based on demand and would therefore be less convenient on lower demand routes or in lower demand directions. So while congestion and crowding are lower, this is outweighed by the decrease in service. Grouping these two types of commutes together could add variability to the results.

A second iteration was done to measure this impact, and it includes just zones within the Route 128 corridor. Zones in this area are assumed to have better access to transit as they are closer to Downtown Boston and within the core MBTA service area. Under 1% of zones have access to zero jobs by transit in 60 minutes, unlike 11% in the larger area considered previously. In both areas under 1% of zones have access to zero workers by transit on the destination end. Explanation of the variability increases slightly to 76% on the residential end and to 54% on the work end. This corresponds with the idea that zones outside of downtown are increasing the variability because they tend to encourage commuters to behave differently, though accessibility by origin is still more predictive than accessibility by destination on both ends.

Since this research focuses on the Western Corridor, the final iteration includes just zones along this corridor. This includes all zones within half a mile of either the I-90 Turnpike or the Worcester/Framingham commuter rail line. With 84% of the variability accounted for on the residential end and 61% on the work end, this area shows similar results to the area within Route 128 as similarly only 2% of zones have access to zero jobs by transit. It is probably more predictive because the turnpike and the commuter rail are not directly parallel, as demonstrated in Figure 4.5. There are some areas that have much higher transit accessibility and others that have much higher auto accessibility, even though they are less than a mile apart.

Figure 4.5: Western Corridor zones and major transportation options (turnpike in purple, commuter rail in orange)

It makes intuitive sense that relative accessibility has a strong impact on mode share, if commuters are viewed as rational decision makers adjusting their behavior to the best choice available to them. This is especially true since transit networks tend to be patchy as a function of station location, so accessibility by transit can vary greatly simply due to variations in access to the network itself.

4.5 Conclusions

An American Economic Review study observed that during the 2003 Los Angeles subway strike, average highway delay increased 47 percent, more than proportional to the amount of commuters who had to shift their mode from rail to auto (Anderson, 2014). This is because transit riders are more likely to travel along dense and already-congested corridors, so their marginal impact on the conditions of the roadway network is therefore disproportionally high. This implies that multi-modality is particularly important, and even critical, along dense transportation corridors, such as the Western Corridor in the Boston area. These corridors face strong congestion in the auto network, and due to the density of similar trips, there is great potential for people to be moved through the area more efficiently and comfortably by transit if the right investments are made.

Chapter 5 – Past, Current, and Future Demographic Trends

Transportation demand does not grow in isolation, but as a result of demographic and economic cycles in society. This chapter will analyze the extent of these socioeconomic and population trends in the Boston area, as they have generated increasing transportation demand over the past few decades and are expected to continue doing so in the next. Growth in transportation demand will then be projected into the future using results generated from a model in Cube Voyager with inputs reflecting expected changes in socioeconomic conditions (Murga, 2015).

Because the Boston area transportation network is already quite congested and demand is only expected to increase, improvements will need to be made to the system in order to fully satisfy area growth. This chapter will end with an introduction to the proposed changes to Western Corridor transit facilities that will be necessary to maintain an efficient level of throughput through the area into the future. This section will also illustrate the development potential generated by these changes to the network in order to justify the improvements. These investments will be further examined by the accessibility-based analysis in Chapter 6, which incorporates these levels of throughputs as well as the opportunities they allow access to.

Chapter 2 introduced the general theme of growth in the Western Corridor but this chapter will go further and look at more specific trends in demographics, demonstrated using graphics generated in TransCAD. This chapter will also use lessons learned from past trends to project future developments.

5.1 Changes in Population

Since the 1850 census, the Boston metropolitan statistical area has consistently grown in total population across all 10 year periods the census is recorded, as exhibited in Table 5.1. Since this table includes the entire metropolitan statistical area, it is shielded from trends such as suburbanization and instead is able to capture growth in the region as a whole. There have been periods of slow growth, such as the 1940s and 1980s, but there has not be a decade with a net loss in population in the metropolitan area since at least 1850.

Table 5.1: Boston Metro Area Population (U.S. Census Bureau, 1850-2010)

Year	**Metro Area Population**	**Percentage Growth**
1850	650,357	—
1860	830,998	27.8%
1870	978,346	17.7%
1880	1,205,439	23.2%
1890	1,515,684	25.7%
1900	1,890,122	24.7%
1910	2,260,762	19.6%
1920	2,563,123	13.4%
1930	2,866,567	11.8%
1940	2,926,650	2.1%
1950	3,186,970	8.9%
1960	3,516,435	10.3%
1970	3,918,092	11.4%
1980	3,938,585	0.5%
1990	4,133,895	5.0%
2000	4,391,344	6.2%
2010	4,552,402	3.7%

Growth in population is expected to remain steady, at a reasonable but non-exponential rate. According to the CTPS Long-Range Transportation Plan, the region’s population is expected to grow an average of 2.1 percent per decade for the next three decades (CTPS, 2015). This is more slowly than the last few decades, predominately due to emigration out of the region to other states or other parts of Massachusetts. International immigration and births are expected to make up the difference and be sufficient to keep the region at net-positive growth into the future.

5.1.1 Changes in Population Characteristics

Figure 5.1 shows changes in population across zones near Downtown Boston (U.S. Census Bureau, 1990; U.S. Census Bureau, 2000; U.S. Census Bureau, 2010). Large populations live in Boston’s South End, Cambridge, Somerville, and other both urban and suburban locations. Growth in population shows a relatively consistent slow upward trend across the area. In Figure 5.2, this same change is shown for Western Corridor communities. Communities further from downtown tend to show higher population growth for the two decades under analysis, likely in response to affordable housing shortages in the urban core and close suburbs.

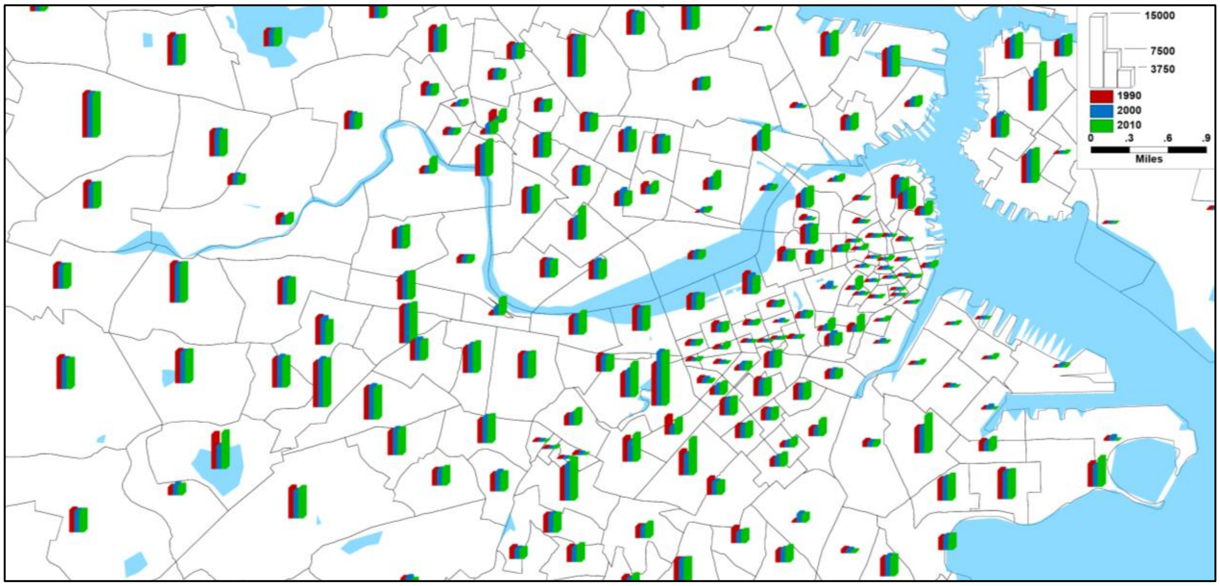


Figure 5.1: Population by TAZ for 1990, 2000, and 2010 in the urban Boston core

Figure 5.2: Population by TAZ for 1990, 2000, and 2010 for Western Corridor communities

5.2 Changes in Jobs

Many of these people moving into the Boston area have done so in order to follow job opportunities in the area. The number of jobs in the area has been growing in conjunction with population, though it is difficult to determine when one is the cause and the other is the effect, and vice versa. Over the past few decades, growth in jobs has been slightly higher than growth in population. Jobs grew 11.0% from 1980 to 1990 and 7.8% from 1990 to 2000 compared to 5.0% and 6.2% growth in population, respectively (Executive Office of Labor and Workforce Development, 2016). This could be partially due to yearly fluctuations as the unemployment rate is susceptible to a variety of different factors and changes often. For example, the change in the total labor force (including both employed people and unemployed job seekers) was 11.8% from 1980 to 1990 and 3.9% from 1990 to 2000, so about the same in the first decade as the change in jobs but much lower in the second. From 2000 to 2010, the labor force size increased by 4.5%, similar to population growth of 3.7%, but the number of employed people decreased by 1.5%. This is likely due to the 2009 recession as the number of employed people has increased every year since then. The following figure visualizes the change in number of people employed and size of the labor force over the past 40 years.

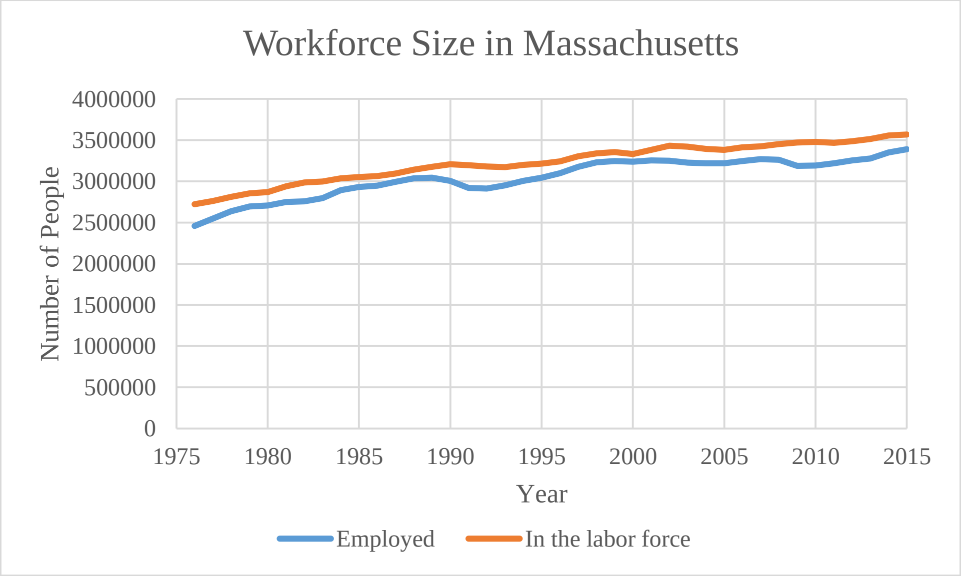


Figure 5.3: Employment and labor force sizes from 1976 to 2015 (Executive Office of Labor and Workforce Development, 2016)

In the future, job growth is also expected to remain steadily positive, with some higher growth expected in certain areas. These high growth areas tend to be close to Downtown Boston. This contrasts with trends seen in the 1960s to 1980s, when suburbanization brought both housing and jobs into the sprawling suburbs. Most notably, growth in high technology industries tended to occur around the Route

128 corridor, which led to the nickname "America's Technology Highway". Now, in part due to changing demographics and employee preferences, jobs are instead growing in areas like the South Boston Innovation District, Kendall Square, Longwood Medical Center, Back Bay, and the Financial District.

The South Boston Innovation District is a prime example of a high job growth area in Boston, and plans include high residential growth as well. A report released in January 2015 analyzed the potential transportation issues these changes could bring to the area (VHB, 2015). The following figure, taken from the report, shows recent trends in population and employment and projected future changes based off currently planned development and re-development projects. Both population and employment are expected to more than double by full build-out of the area. However, because of the small base population in 2000, population will continue to lag far behind employment growth. The difference between the number of jobs and population that can be housed was 22,000 in 2000, but it will grow to 39,000 by 2035 and 45,000 by full build-out. This will put significant pressure on available housing, and generate increased commute trip demand as employees will need to travel further to find affordable housing.

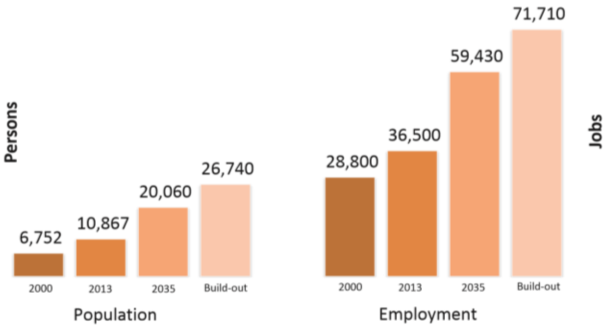


Figure 5.4: Population and employment growth in the South Boston Waterfront (VHB, 2015)

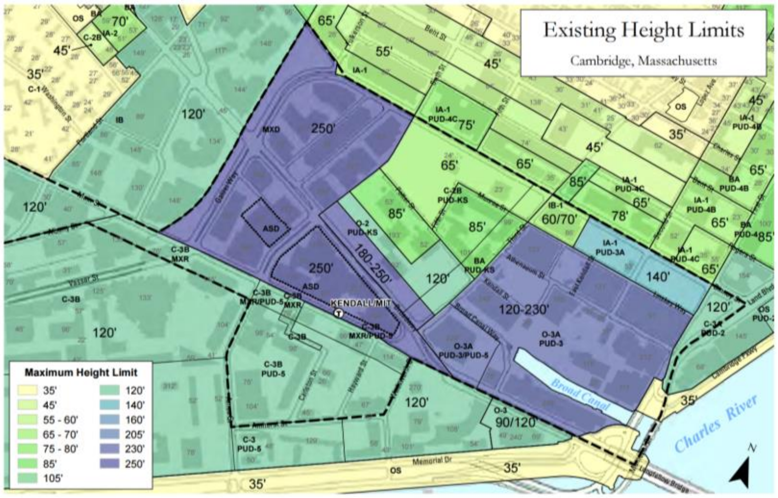
Since these projections are based on actual plans and zoning changes, they are likely to be relatively accurate. However, as this report shows, the transportation network is not currently sufficient to fully accommodate these developments and may be the most likely reason for actual growth to not be as high as projected. Another interesting element of the Innovation District is that while both commercial and residential properties are planned, they are not necessarily being used by the same people. In fact, only 17 percent of people currently living in the Innovation District work there, and similarly only 5 percent of people currently working in the Innovation District live there. This could change as the area develops into more of a "24-hour city" with amenities for greater livability, but since people chose where to live based on more than just their job location, employment growth in the area will still continue to have a significant impact on residential demand in other areas and on transportation network performance.

Kendall Square is another high growth area, in Cambridge right across the river from Boston. While previously an industrial center, due to its proximity to MIT, good transit access on the Red Line (particularly due to the Alewife extension in 1983, which allowed for an easy transfer to commuter rail at Porter Square), and investments by the federal government, it has grown into a high-technology center, with many biotech and technology firms and start-ups, as well as the Volpe Transportation Center. While some residential properties exist, and zoning laws may be altered in order to encourage more residential growth in the future, currently the area has very few residential properties. Kendall Square is near relatively expensive residential neighborhoods in Cambridge, Back Bay, and Somerville, but many commuters travel from locations further away, and often by car. The following table introduces future employment projections for Kendall Square, made by the Metropolitan Area Planning Council (MAPC) and by the City of Cambridge (Metropolitan Area Planning Council, 2011). Percentage growth in both is around 12-14 percent from 2011 to 2020 and 5 percent from 2020 to 2035, and variation between the two is due primarily to where current borders for Kendall Square are defined. Using the MAPC defined Kendall Square area, there were about 27,700 jobs in Kendall in 1990 and 30,100 jobs in 2000. This corresponds to 9% job growth from 1990 to 2000 and 38% job growth from 2000 to 2010.

Table 5.2: Future Employment for Kendall Square (Metropolitan Area Planning Council, 2011)

	2011	2020	2035
MAPC (TAZ)	41,498	46,487	48,877
City of Cambridge	66,000	74,935	78,787

Height limits for Cambridge, presented in Figure 5.5, currently restrict the amount of development that can occur in Kendall Square. However, these restrictions and zoning requirements are likely to change in the coming years as part of the development of the area. One notable point of uncertain development is the city of the Volpe National Transportation Systems Center. Currently a 13 story building built on just a fraction of the 14 acres of property available, it is now out for bids for redevelopment. The winning bids could potentially include much taller structures or at the very least, additional structures on the property, further increasing the density of the area. Residential development will likely be required as part of the project, which could lessen the transportation demand to a certain extent. However, as in the Innovation District, it is likely that this housing in Kendall will not be occupied entirely by Kendall employees. This is supported by the Nexus study discussed in Section 2.2, which noted that only 13% of new employees in Cambridge also seek housing in Cambridge (Murphy, 2015). Given the high level of job growth relative to residential growth projected in the absence of stricter zoning requirements, even this small proportion of new Cambridge employees seeking housing in Cambridge may be larger than the number of units that will become available.

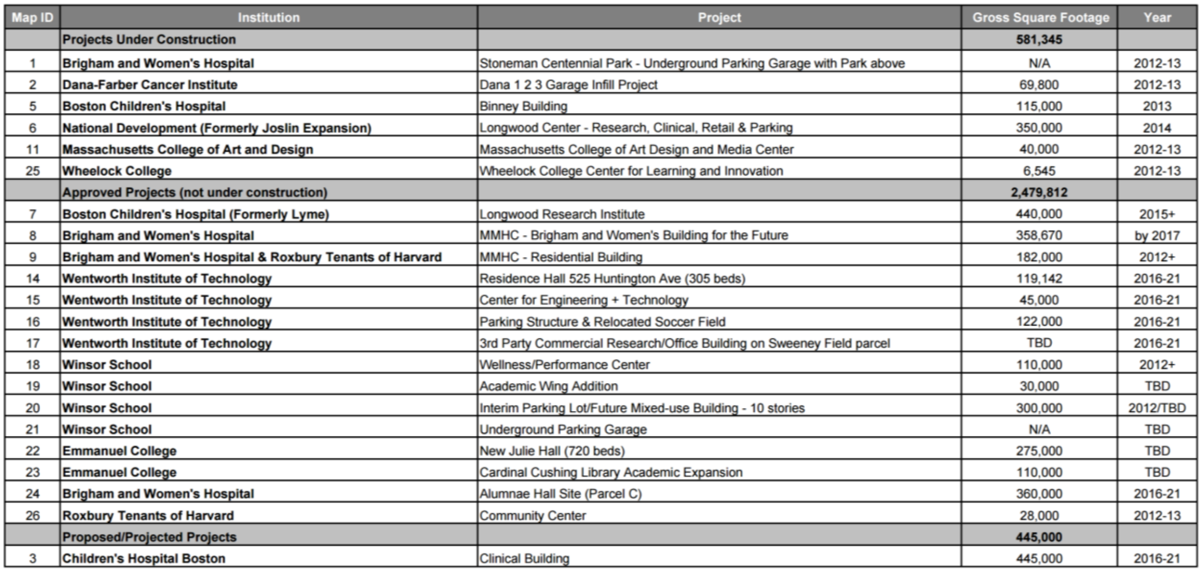


This map of the existing pattern of height limits indicates the highest area in the darkest color (up to 250 feet near the MBTA station), with the intermediate heights in the middle tone (up to 120 feet near the river, lower heights near neighborhoods—45 feet to 80 feet in some locations), and the lowest heights in the lightest tones (mostly 35 feet in the residential areas).

Figure 5.5: Existing height limits in Cambridge near Kendall Square (Cambridge Community Development Department, 2013)

Another high growth area in Boston in Longwood Medical Center. A cluster of hospitals and research institutions served by many transit lines, Longwood must face how to be easily accessible to both regular employees and patients, many of whom may have limited mobility. The Medical Academic and Scientific Community Organization (MASCO) believes the area, which already employs more than 45,000 people, generates an average of 1,100 new jobs and 7,500 job openings every year (MASCO Area Planning, 2012). The following table provides examples of projects planned and under construction as of 2012, to provide an idea of the level of growth currently occurring and soon to occur in the area.

Table 5.3: Current Development Projects in the Longwood Medical Area (MASCO Area Planning, 2012)



Map ID	Institution	Project	Gross Square Footage	Year
	Projects Under Construction		**581,345**	
1	**Brigham and Women's Hospital**	Stoneman Centennial Park - Underground Parking Garage with Park above	N/A	2012-13
2	**Dana-Farber Cancer Institute**	Dana 1 2 3 Garage Infill Project	69,800	2012-13
5	**Boston Children's Hospital**	Binney Building	115,000	2013
6	**National Development (Formerly Joslin Expansion)**	Longwood Center - Research, Clinical, Retail & Parking	350,000	2014
11	**Massachusetts College of Art and Design**	Massachusetts College of Art Design and Media Center	40,000	2012-13
25	**Wheelock College**	Wheelock College Center for Learning and Innovation	6,545	2012-13
	Approved Projects (not under construction)		**2,479,812**	
7	**Boston Children's Hospital (Formerly Lyme)**	Longwood Research Institute	440,000	2015+
8	**Brigham and Women's Hospital**	MMHC - Brigham and Women's Building for the Future	358,670	by 2017
9	**Brigham and Women's Hospital & Roxbury Tenants of Harvard**	MMHC - Residential Building	182,000	2012+
14	**Wentworth Institute of Technology**	Residence Hall 525 Huntington Ave (305 beds)	119,142	2016-21
15	**Wentworth Institute of Technology**	Center for Engineering + Technology	45,000	2016-21
16	**Wentworth Institute of Technology**	Parking Structure & Relocated Soccer Field	122,000	2016-21
17	**Wentworth Institute of Technology**	3rd Party Commercial Research/Office Building on Sweeney Field parcel	TBD	2016-21
18	**Winsor School**	Wellness/Performance Center	110,000	2012+
19	**Winsor School**	Academic Wing Addition	30,000	TBD
20	**Winsor School**	Interim Parking Lot/Future Mixed-use Building - 10 stories	300,000	2012/TBD
21	**Winsor School**	Underground Parking Garage	N/A	TBD
22	**Emmanuel College**	New Julie Hall (720 beds)	275,000	TBD
23	**Emmanuel College**	Cardinal Cushing Library Academic Expansion	110,000	TBD
24	**Brigham and Women's Hospital**	Alumnae Hall Site (Parcel C)	360,000	2016-21
26	**Roxbury Tenants of Harvard**	Community Center	28,000	2012-13
	Proposed/Projected Projects		**445,000**	
3	**Children's Hospital Boston**	Clinical Building	445,000	2016-21

The Boston area economy stands to benefit greatly from the agglomeration effects of these strong clusters of employment (Peralta-Quirós, 2013). However, it is important that in order for these positive changes to occur, we create a transportation plan that will serve growth in a sustainable way. A reactive approach to simply accommodate issues after they arise may come too late. Based off the Zupan observations mentioned in Section 2.1, the density of jobs in these areas is already beyond the level of what could be accommodated by the auto network alone, so all additional growth must be absorbed by transit.

5.2.1 Job Characteristics

Figure 5.6 presents number of jobs (as defined by the size of each circle) with broad categories of job types for each zone in the urban Boston area (Census Transportation Planning Products, 2010). Downtown Boston has a high concentration of professional office jobs, with industrial jobs being seen predominately in the outskirts and at Logan Airport.

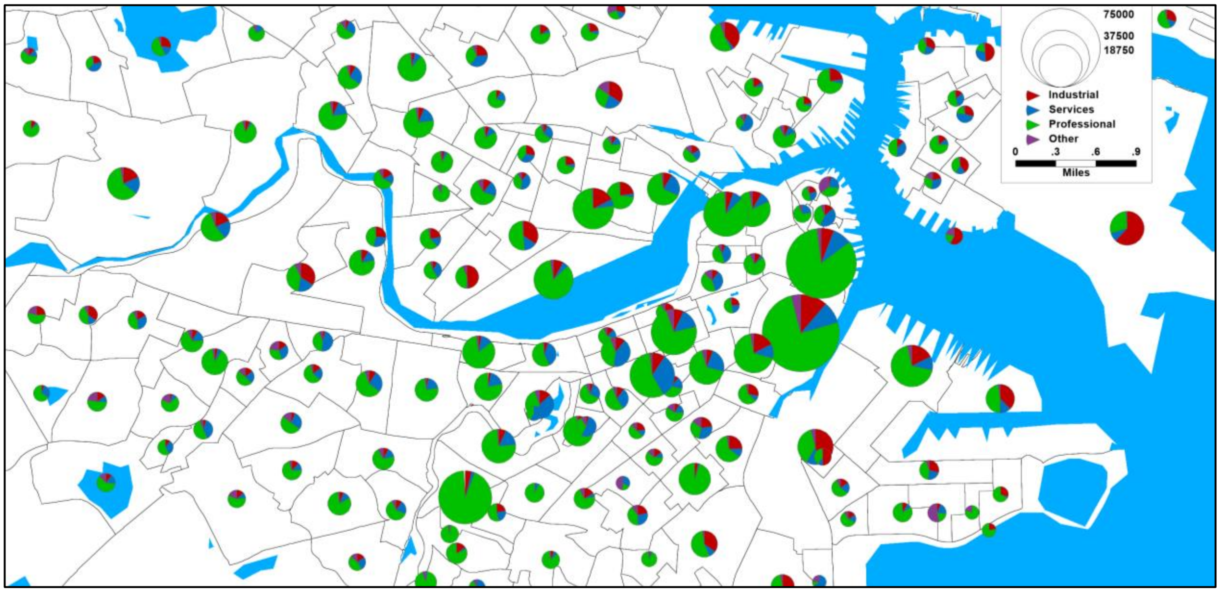


Figure 5.6: Area jobs by industry

While the Boston region has a diverse overall economy, jobs of the same type tend to cluster together. When “professional” jobs are separated into more specific sub-categories, these clusters begin to appear in Figure 5.7. Educational, health, and social science jobs have the highest concentration at known universities and health centers, but are also spread elsewhere due to primary schools and other local social services. A large share of employment in the Financial District is in finance, professional and scientific jobs are the largest category in Kendall Square, while public administration jobs are the highest near Beacon Hill. These trends are expected due to the characteristics of these areas, and are expected to continue. In fact, jobs of the same type tend to cluster together due to the agglomeration benefits to the economy, and this essentially lowers transportation costs for companies in the same industry. There are also agglomeration benefits to cities as a whole, which is part of why many new jobs are becoming available in dense urban areas rather than in suburban office parks, because of a larger accessibility to workers and other companies and services.

Figure 5.7: Area professional jobs by sub-industry

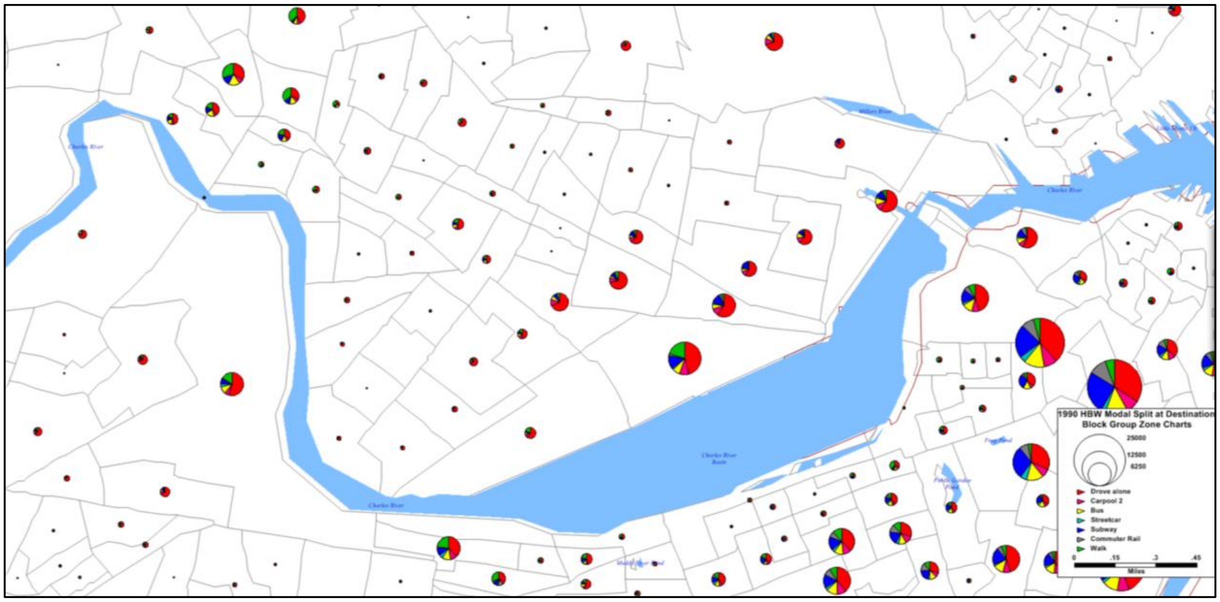
5.3 Current Transportation Demand

It makes sense that increases in population and jobs will lead to higher transportation demand, though this is highly dependent on where future residents will live relative to their work. Congestion exists in all directions in the Boston area, so new opportunities must be examined to make some corridors more appealing to commuters. One prime residential market for new residents corresponds to the Western Corridor suburbs, including urban neighborhoods such as Allston, and so this thesis will primarily focus on commuters in this area and their journey to work in and near downtown.

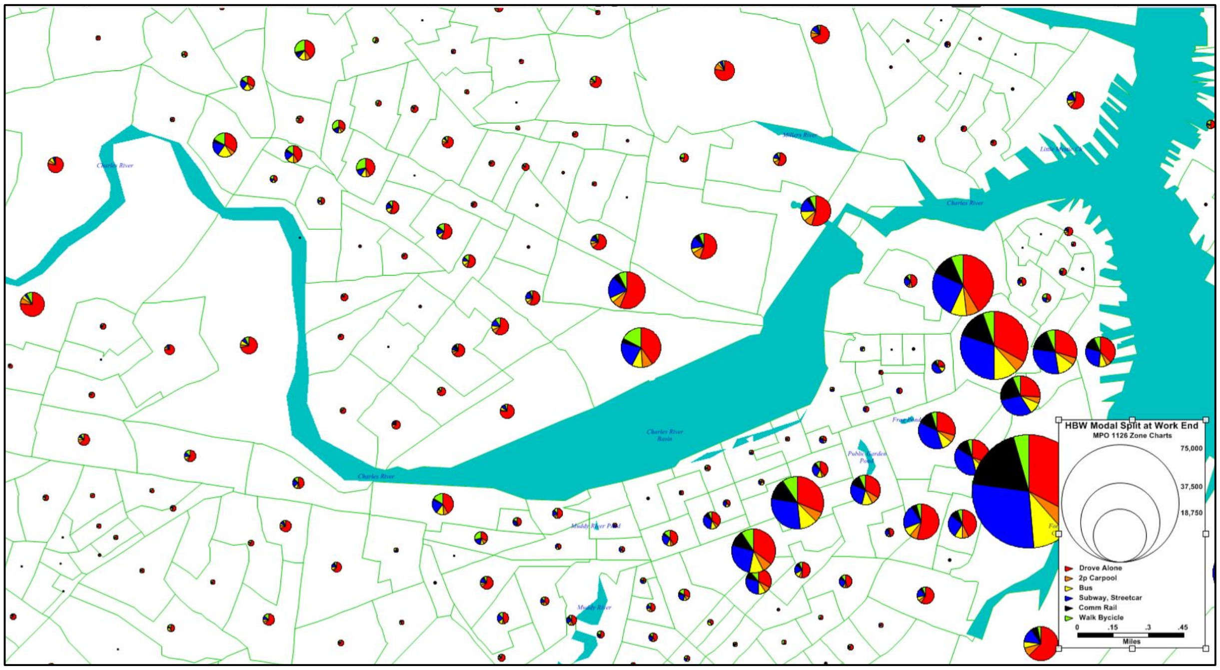
5.3.1 Current Demand Patterns

This journey is currently underserved by transit, particularly from the suburbs to any destination that is not Back Bay or the area around South Station. Transferring to the Silver Line at South Station to reach the Innovation District is possible, but capacity is constrained. Therefore, transit mode share to the

Innovation District is only 27% (VHB, 2015). Transferring to the Red Line at South Station to reach Kendall Square is possible, but is a circuitous and inconvenient route. Because of this, Kendall Square still has a 56% overall drive alone mode share for all employees, despite being considered a relatively transit-friendly area (U.S. DOT Federal Highway Administration, 2013). Mode shares for areas near Downtown Boston are visualized in the following figure, for CTPP estimates in 1990, 2000, and 2010.



(a) CTPP 1990 modal split on the work end (Murga, 2012)



(b) CTPP 2000 modal split on the work end (Murga, 2012)

(c) CTPP 2010 modal split on the work end (Census Transportation Planning Products, 2010)

Figure 5.8: Modal split in Boston and Cambridge over the past three decades

As demonstrated by the schematic in Figure 5.9, currently the only exit from the turnpike at the Allston Interchange is to the north toward Cambridge Street. This off-ramp is therefore heavily congested during peak hours with commuters traveling to all employment areas to the west of downtown, including Kendall Square and Longwood Medical Center. A southern exit, as is currently being studied by MassDOT, could more directly provide access to Commonwealth Ave. This would allow Longwood commuters to shift their path to the new ramp, reducing local congestion and allowing the auto network to better serve auto commuters to both areas.

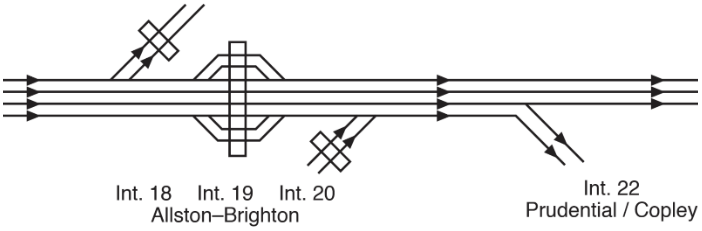


Figure 5.9: Current Allston Interchange ramp configuration (Boston Regional Metropolitan Planning Organization, 2012)

Transit paths for Western Corridor commuters vary depending on the destination of the trip, even within the dense urban area. Currently, commuter rail users traveling to Longwood can alight at Yawkey Station and complete the short remainder of their journey in a shuttle. Therefore, Longwood commuters are not expected to heavily utilize West Station unless better bus connections are available there, which is unlikely given street-level congestion. Kendall commuters currently do not have a convenient rail link from the Western Corridor, and those who do take the Framingham/Worcester commuter rail line must travel via South Station in downtown and transfer to the Red Line. These commuters are therefore expected to benefit greatly from West Station, but only if a link along the Grand Junction is added to Kendall. Commuter rail users traveling to the Innovation District also remain on the vehicle until South Station, where they transfer to a Silver Line bus. This will continue to be the most convenient transit path to the Innovation District, but the Silver Line is heavily overcrowded and there is not much room for expansion of service given infrastructure constraints. There is however potential for reorganizing the existing service. This is an example of a case in which an unrelated project, the Blue-Red connector, could have a significant impact on Western Corridor commuters. This link would allow those traveling from Cambridge to East Boston or Logan Airport to avoid the Silver Line and transfer from the Red Line to the Blue Line at Charles MGH Station instead, freeing up space on Silver Line buses for those traveling to the Innovation District, which the Silver Line serves most directly. Commuters to Back Bay and Downtown Boston are currently adequately served by the Framingham/Worcester commuter rail line, as it feeds these areas directly, but could benefit from lower headways and supplementary DMU service.

5.3.2 Commuting to MIT Survey

Using the methods outlined in an MIT Transit Lab Thesis “Understanding the Evolution of Transportation Pricing and Commuting at MIT: A Study of Historical Commuting Data”, commute mode choice characteristics can be analyzed for MIT employees segmented by home location (Hartnett, 2016). This thesis uses the results of an MIT commuting survey conducted in 2014, when almost 60% of students, faculty, and staff voluntarily provided information on their commuting habits. In this analysis, student and contractor responses are excluded, since MIT employees are considered to be the most similar to current and future Kendall Square employees. Mode choice is split into four categories – drive alone, transit, active (walking and biking), and other (including carpooling and telecommuting).

The results for commuter respondents to the 2014 survey in the Western Corridor are summarized in Table 5.4. This subset of commuters includes those residing in census block groups within 0.5 miles of the I-90 Turnpike or the Worcester/Framingham commuter rail, excluding those to the east of the Allston Interchange.

Table 5.4: Mode share for Western Corridor commuters to MIT

Drive Alone	Transit	Active	Other
38%	38%	14%	11%

Transit mode share in the entire Western Corridor is roughly equivalent to drive alone mode share. Block groups with the highest transit mode share tend to be those with a Framingham/Worcester commuter rail station or those closest to MIT, in Allston and Brighton. Alternatively, 53% of all block groups in the Western Corridor where at least one MIT employee resides have zero transit mode share and likely poor access to the transit system.

To analyze the potential modal shifts in the Western Corridor that could occur after improvements are made to the transit system, towns considered part of the Western Corridor, namely Allston, Newton, and Framingham, are compared to similarly distant areas or towns not considered to be part of the Western Corridor, Porter Square, Waltham, and Acton. These latter neighborhoods or towns have better access to transit and are more likely to have a one-seat ride to MIT. Results are summarized in Table 5.5.

Table 5.5: MIT employee commute mode share for selected towns and areas

	Approximate Distance to MIT (miles)	Drive Alone	Transit	Active	Other
Allston	2	7%	64%	23%	6%
Porter	2	6%	70%	20%	4%
Newton	8	64%	13%	9%	14%
Waltham	8	50%	32%	5%	12%
Framingham	20	61%	16%	0%	23%
Acton	20	31%	60%	0%	9%

Situated close to MIT in the urban Boston core, Allston and Porter have similarly low drive alone mode shares at 7% and 6%, respectively. However, Porter is accessible directly by the Red Line while Allston must be accessed by the slower bus network, leading to a higher transit mode share for Porter and a higher active mode share for Allston, as walking and biking become more competitive in travel time with transit.

As expected, active mode share tends to decrease as distance from MIT increases. Drive alone mode share generally increases as distance from MIT increases, but this varies depending on the level and convenience of transit access from that origin. Newton and Framingham lie along the Framingham/Worcester commuter rail line while Waltham and Acton lie along the Fitchburg commuter rail line. Waltham is also connected by a one-seat bus ride to MIT on the 70/70A. The Fitchburg line stops at Porter Square, a Red Line station, before reaching Downtown Boston. This allows Fitchburg commuters to transfer at Porter Square in order to reach MIT without detouring through Downtown. However, Framingham/Worcester commuters do not have a similarly convenient option to reach MIT and must either transfer to the Red Line at South Station or make multiple transfers from Yawkey. This results in a significantly lower transit mode share for these Western Corridor commuters.

The transfer at Porter Square is analogous to the potential link that could be provided at West Station, from the Framingham/Worcester commuter rail line to Grand Junction service into Kendall. Given the substantial difference between transit mode shares for current towns along the two commuter rail lines, this link at West Station has the potential to impact regional travel behavior, rather than just locally in Allston. This impact applies to Newton and Framingham, with the assumption that mode share could become more like Waltham and Acton, respectively.

5.3.3 Recent Changes in Traffic Conditions

In recent years, technological advances have allowed for new methods of collecting data on roadway conditions. One example is monitoring Bluetooth signals, by capturing the same signal from a car at multiple points along a roadway and using the time between observations to calculate the travel speed. In the Boston area, Bluetooth data began being collected on July 4, 2012 on I-93 and on May 24, 2013 on I-90. In this brief analysis, the first work-week in October is observed across the years in which data is available in order to gauge unreliability in travel times (KCUS, 2016). This week was chosen at random, at a point in the fall such that weather and school holidays would not have an effect.

On the I-90 Turnpike, travel speeds were collected westbound between the Allston Interchange and the Newton Corner exit in October 2013, 2014, and 2015. Across all 5-minute intervals during the weekday evening peak for the five weekdays between October 1 and October 7, the average, minimum, and maximum speeds and standard deviation are reported in Table 5.6.

Table 5.6: Travel speed distributions on I-90 westbound during the evening peak (4 pm – 6 pm) (miles per hour)

	2013	2014	2015
Average	23.4	22.0	22.1
Standard Deviation	*10.1*	*10.0*	*13.2*
Minimum	15.3	8.5	5.7
Maximum	68.3	55.7	62.4

Average, minimum, and maximum travel speeds all tended to decrease slightly over this three-year period, while the standard deviation tended to increase. This indicates that congestion is increasing on the roadway, and moving conditions into the unstable regime where speeds become more variable as small fluctuations in demand or minor incidences have a strong impact on travel conditions. In 2013, free-flow travel was possible at some point during the peak as demonstrated by the maximum speed exceeding the speed limit. However, this is not true for the same week in 2014 and 2015. If the peak is extended into the shoulders, from 3 pm to 7 pm, free-flow travel still seems possible at some point during the time interval, though average, minimum, and maximum speeds are all decreasing during the extended evening peak over this three-year period.

Table 5.7: Travel speed distributions on I-90 westbound during the extended evening peak (3 pm – 7 pm) (miles per hour)

	2013	2014	2015
Average	31.1	29.8	29.7
Standard Deviation	*18.0*	*17.3*	*20.2*
Minimum	14.9	8.5	5.7
Maximum	72.0	69.9	68.8

Changes in travel speeds on I-93 during peak hours are more variable, and for the week under analysis, average speed actually tended to increase slightly during the morning peak inbound from the north. However, standard deviation also increased, so this could be more indicative of higher variability in travel times than of an improvement in travel conditions, especially given the small sample size. The speeds in Table 5.8 are at locations roughly equally close to Downtown Boston as the location of I-90 travel speeds, between Medford and Somerville in the north and Milton and Dorchester to the south.

Table 5.8: Travel speed distributions on I-93 during the morning peak (7 am – 9 am) (miles per hour)

Direction	Southbound from the North				Northbound from the South			
Year	2012	2013	2014	2015	2012	2013	2014	2015
Average	18.9	19.3	20.4	25.2	20.6	19.9	15.1	19.6
Standard Deviation	*5.0*	*6.0*	*6.4*	*6.5*	*2.4*	*2.5*	*2.9*	*2.9*
Minimum	8.8	11.8	12.9	15.7	13.3	12.1	9.5	12.2
Maximum	33.9	49.0	39.0	42.4	29.1	28.0	22.9	29.2

Because of the small sample size, the results of this study cannot provide conclusions on overall trends in travel speeds on the turnpike during these times. However, this does provide some indication of the high level of variability in travel speeds during peak hours, even within just one week. This high level of variability could necessitate the addition of a reliability buffer time for trips when arrival time is critical for the user, thus increasing total travel time and decreasing effective accessibility.

5.4 Changes in Transportation Demand

5.4.1 Back of the Envelope Projections

Building off the analysis on current roadway and transit capacity and demand in Sections 2.3 and 2.4, future conditions can be estimated. Future traffic growth is projected in the Allston Interchange ENF as 0.25% per year, so for 20 years (2014-2035) not compounded, as is done in the ENF, this adds up to a 5% total (MassDOT, I-90 Allston Interchange Project Environmental Notification Form, 2014). If the turnpike is assumed to be at capacity and growth in traffic is considered equivalent to growth in trips (across all modes), all growth – 5,400 inbound trips and 5,400 outbound trips – could be accommodated by existing excess capacity on commuter rail, though this will likely require some commuters to stand for long trips, which is not considered within comfortable capacity and is likely not a sustainable long-term solution. However, not all users will be adequately served by commuter rail, but it is assumed that since the turnpike is at capacity a mixture of new and existing users for which the commuter rail trip is adequately convenient will shift mode to transit. A map of the Western Corridor is included below for clarity.

Figure 5.10: Boston high growth employment areas (yellow) and Western Corridor transportation

Table 5.9: Future travel demand under Allston Interchange ENF assumptions

	Weekday		Peak	
	Inbound	Outbound	Inbound AM	Outbound PM
Turnpike	73,500	73,500	22,100	22,100
Commuter Rail	11,900	11,700	7,100	6,500
Green Line	22,800	24,100	7,500	7,500
Turnpike Buses	4,500	4,100	2,200	1,800
Total	**112,700**	**113,400**	**38,900**	**37,900**

If future growth is higher than projected in the ENF, it becomes more difficult to accommodate all trips during peak travel times without allowing turnpike traffic to grow (which is not possible during peak hours) or further increasing transit service. The next scenario assumes growth of 1% per year compounded, leading to a total growth of 22% from 2015. This is a high growth scenario, but it is possible if high growth areas in Boston continue to grow and employees see the Western Corridor as a viable residential location to commute from. These assumptions lead to an additional 23,600 inbound trips and 23,800 outbound trips per average weekday.

Holding turnpike traffic constant, and assuming the Green Line D Branch is also at capacity during the peaks, this growth can be served by existing capacity on commuter rail and turnpike bus infrastructure including incremental improvements such as double-tracking and passenger rail prioritization, although with small margin for growth. Furthermore, given the level of crowding, it is likely that service will need to improve in order to retain users and encourage the required mode shift, especially since any additional congestion on the turnpike will decrease attractiveness of both auto and the Turnpike Express buses. This includes increasing the overall number of trips and introducing service to additional OD pairs by adding new bus and DMU services. The changes in transit supply that will be necessary to accommodate this growth are described in Section 6.6.

Table 5.10: Future travel demand under high growth assumptions

	Weekday		Peak	
	Inbound	Outbound	Inbound AM	Outbound PM
Turnpike	73,500	73,500	22,100	22,100
Commuter Rail	21,600	21,600	8,100	7,200
Green Line	25,100	26,500	7,500	7,500
Turnpike Buses	10,700	10,200	7,400	7,200
Total	**130,900**	**131,800**	**45,100**	**44,000**

5.4.2 Modeled Projections

In order to gain a more well-rounded perspective of transportation changes in the area, the Cube model was utilized. If growth as projected is allowed to occur in the absence of any changes to the transportation network, by 2030 much of the auto and transit networks will be capacity constrained during peak hours. This will lead to limits in accessibility growth as the number of jobs available within a desirable travel time during peak hours will grow more slowly than the number of jobs in the region. The following figure is colored based on this measure, that is, the number of jobs accessible to each zone within 60 minutes under the time-decay that will be introduced in Section 6.1.

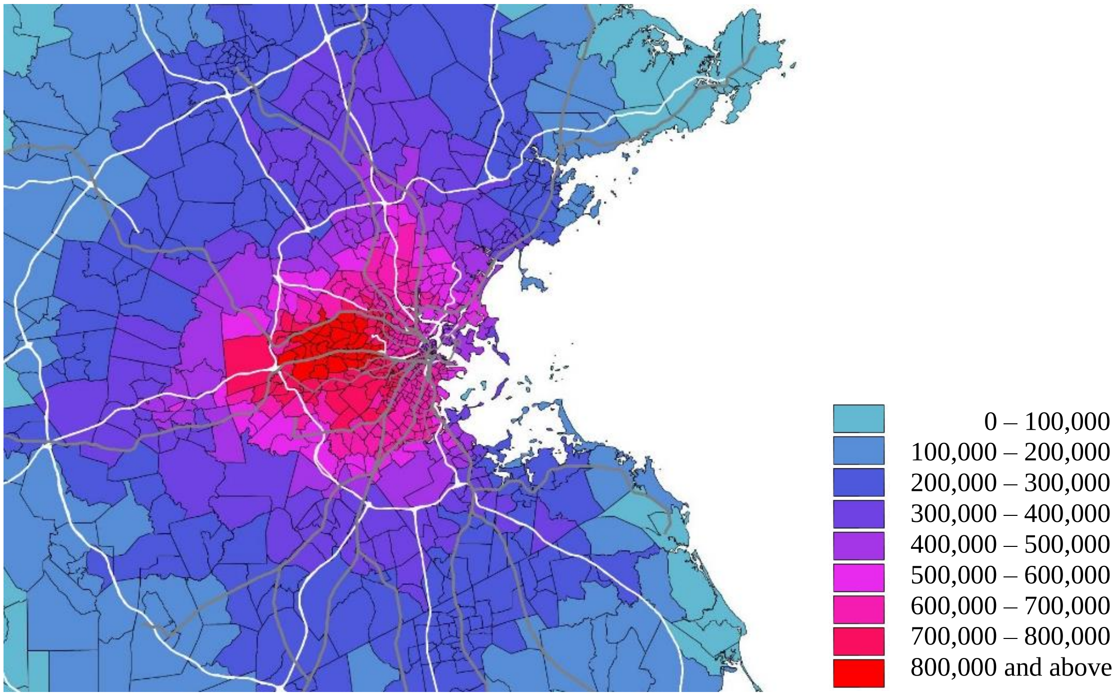


Figure 5.11: Projected 2030 accessibility to jobs by auto

This graphic is the baseline no build scenario that should be compared to figures that will be presented in Chapter 6, where results of the same socioeconomic changes under an improved transportation network will be presented, in an attempt to better accommodate growth in the area. These improvements have been introduced throughout this thesis and will be summarized in the next section.

5.5 Proposed Solutions to Satisfy Growth by Addressing Transit Capacity Constraints

In order to address capacity constraints facing increasing transportation demand in the Boston area, improvements must be made to the system. Some improvements have been proposed by MassDOT and other additional improvements are proposed in this thesis, as they appear to be necessary to accommodate growth. Many of the proposed improvements to the Western Corridor will occur locally in Allston. The following figure shows the importance of the Allston Interchange, where these improvements will take place, in the context of proximity and access to many high growth areas previously mentioned. This figure was taken from a presentation of the Allston Interchange Improvement Project, so it is clear MassDOT also realizes the importance of this interchange in the context of the larger region.

Figure 5.12: Importance of Allston Interchange as providing access to high growth areas (MassDOT, 2015)

However, simply local changes will not be sufficient to address capacity constraints. Regional changes proposed are exclusively on the transit side, and include double tracking and additional service on existing commuter rail lines as well as new high-frequency DMU service on existing tracks. These improvements are expected to encourage a modal shift to transit, thereby alleviating capacity constraints across the transit network and encouraging a sufficient modal shift to keep turnpike traffic below the volume that would lead to unstable flow and loss of capacity. Restricting parking supply and charging market price at the destination will be another effective strategy to encourage users to take transit instead of driving, since parking is expensive for the employer to provide and/or for the employee to pay for, provided the capacity of transit is expanded to accommodate the added ridership and more effective operations are achieved.

In summary, the proposed changes include:

Roadway:

- All-electronic tolling on the turnpike, which could include some trials with time or demand based tolling
- Reconstruction of the Allston Interchange, either as a new viaduct or on the ground level

- Direct or better access to Commonwealth Avenue from the Allston Interchange turnpike exit, to improve local flow and reduce congestion on Cambridge Street. This will provide better connectivity to destinations in the south on Figure 5.12, such as Longwood Medical Center

Transit:

- Dispatching priority shifted to passenger rail
- Removal of the single-track constraint through Beacon Park Yard
- Construction of West Station as a two-platform, four-track station with multimodal connections
- Added stops to Framingham/Worcester commuter rail line at Boston Landing and West Station
- Introduction of improved high frequency signal capacity
- Increased frequency on commuter rail, as well as changes to patterns that serve just some stops (particularly if new services can better serve these patterns), such as running express service
- Increased frequency of Turnpike Express buses, and new express bus service to the Seaport/Innovation District
- Better signaling on the Red Line and Green Line to allow for shorter headways
- Shuttle DMU service
  - On the Grand Junction from West Station through Kendall to North Station
  - On existing commuter rail tracks from West Station through Back Bay to South Station
  - Extended up commuter rail tracks through Newton to Route 128
- Blue to Red connector
- Three-car trains on the Green Line Riverside branch, effectively increasing capacity by 50%
- Logan to South Station direct bus, which would allow the Silver Line tunnels to serve the Innovation District at higher capacity

5.5.1 Planning Horizons

Large infrastructure improvement projects involve many years of planning and compromising before they can be constructed and eventually opened to the public. Because of this lengthy time scale, societal changes often happen between project proposal and completion, both in anticipation of the improvements as well as independently of the project. This creates a situation in which incremental changes in infrastructure, as they are completed, are often already utilized before the full project is completed. This was the case in the Central Artery & Tunnel Project when the Ted Williams Tunnel was opened long before the completion of the Central Artery Tunnel, though it was only open to commercial and off-peak traffic for much of that time. This will likely be the case again with the Allston Interchange Improvement Project and it is therefore useful to look at each piece of the project individually in the context of when it will be available in the timescale of the overall proposed changes to the Western Corridor.

Figure 5.13: Projected Timeline for Allston Interchange Improvement Project (MassDOT, I-90 Allston Interchange: A Multimodal Transportation Project Task Force Meeting #11, 2015)

The overall timeline for the project is included in the figure above. Ownership of the Framingham/Worcester line tracks has already been transferred to the MBTA, so dispatching priority to passenger rail is already assumed to be in place. Because of this and because Beacon Park Yard is no longer used as a maintenance yard, the single-track constraint through Beacon Park Yard could be resolved in the near future, that is, in the 2020 planning horizon. However, there may be some staging involved during construction of the Allston Interchange Improvement Project, so both tracks may not be operational in the short term. However, by the 2030 completion of the full Allston Interchange Improvement Project, the single-track constraint will definitely be rectified.

West Station is proposed as a two-platform, four-track station. However, as part of the environmental permitting application process, MassDOT has not proposed analysis of the use of the second platform and pair of tracks. Because of the length permitting process required to add new transit service though an urban area, this additional element was excluded from the original plans so that the structural integrity of the highway viaduct could be addressed without additional delay. However, this development is vital to the continued growth of the Boston area and particularly Kendall Square. Therefore, in this thesis the DMU shuttle improvements are assumed to also be added by the 2030 planning horizon, which is a feasible scenario, if planned strategically.

Over time, both demographics of an area and the transportation network serving it will change in various ways. This is particularly true in Allston, where a large space will be freed up for development after these changes are made, a space that will be highly accessible to the transportation network. Because accessibility measures capture the impact of both number of opportunities and travel time, it is important to introduce this concept of varying planning horizons before leading into the next chapter. There, the accessibility-based analysis over time of changes to the Western Corridor to existing growth nodes will be performed. A further accessibility-based analysis of Allston as an employment center, available after the initial 2035 planning horizon, can then be implemented.

Chapter 6 – Accessibility-Based Analysis of Infrastructure Improvements

Accessibility measures incorporate the impact of both network conditions and the opportunities this network provides access to. In this thesis, accessibility measures are calculated separately for each mode and are used for two main purposes. The first is to compare areas within the region, while the second is to measure changes in accessibility over time due to, among several factors, growing road congestion, potential improvements to the transit system, and new land use development. Since accessibility measures both travel times and job or residential opportunities, it should capture as well the impact of economic changes, network infrastructure changes, and changes in congestion levels.

This thesis will explore a new framework of evaluating investment opportunities in Massachusetts based on the changes in accessibility these investments can provide. This framework is partially motivated by Massachusetts Secretary of Transportation Stephanie Pollack's interest in joining the National Accessibility Evaluation Pooled-Fund Study. This project, led by the Minnesota Department of Transportation, will provide detailed measures of accessibility over time to member states, as well as annual reports to summarize results for all states. Once this detailed data becomes available in late 2016, there will be much potential for additional accessibility-based analysis for future transportation investment and land use proposals. It will be important to consider throughput alongside these accessibility measures in order to monitor changing levels of congestion and their impact on travel times.

Past trends can help inform future projections. For example, a study introduced in Section 4.4 demonstrated the strong relationship between relative modal accessibility and mode choice. This relationship will continue as changes occur across all modes in the future, so changes in mode choice are expected to occur in conjunction with changes in relative accessibility. With large enough improvements to the transit network, the induced modal shift should be sufficient to address the capacity constraints of the highway network in the Western Corridor sufficiently to avoid degradation into unstable flow.

This chapter will demonstrate the process of modeling future changes to the transit system and consider how these changes (as well as an increase in the number of jobs) will change accessibility in the area across all modes. Throughout this process, it will also be important to integrate travel speed and throughput measures as estimated by the Cube Voyager model, rather than just the accessibility result, in order to disentangle changes in traffic conditions from changes in jobs and demographics (Murga, 2015).

6.1 Measures of Accessibility

6.1.1 Literature Review

Accessibility is a topic that has been explored in the transportation field for decades, leading to a variety of proposed metrics based on slightly different assumptions. In 1959, Hansen observed that the concept of accessibility had already been accepted as a strong factor for the growth potential of an area, and this was one of the first attempts to actually quantify that impact (Hansen, 1959). In 1977, it was observed that in the midst of suburbanization, there were interesting trends occurring as the prevalence of the automobile was shifting commuter preferences and habits, motivating research to attempt an accessibility-based analysis to uncover the possible causes and effects of these trends (Black & Conroy, 1977). More recently, as suburbanization has been decreasing in many cases, it has become even clearer that the initial assumptions about accessibility as a significant driver of development were correct.

There are a variety of different ways to measure accessibility. Many have been explored over time, as no single measure has been found to truly capture the contribution of every potential scenario that could occur regionally. Most measures have a final cut-off time beyond which jobs or residents are considered inaccessible, as the economic interdependency within a region is much stronger than that between regions. However, where this cutoff should occur is highly debatable and often has a large impact on the results of a study.

Up to that cutoff time, most measures define an impedance function. These functions draw from the assumption that an opportunity right next door is more valuable than one further away. Therefore, equations are developed in which additional travel time cost diminishes the value of an opportunity at that destination, following a specific curve or function. How strictly it is diminished, however, is up for debate. Examples of some functions are provided in Figure 6.1. Some measures, such as (a) and (b), consider all opportunities up to the final threshold equally, while functions such as (d) strictly punish opportunities that are even just 10 minutes away from the origin. Because the resulting accessibility measure is more a comparison measure rather than a raw value with inherent meaning, it is not the resulting value of these measures that matters, but instead how they capture the impact of regional characteristics, such as employment clusters and residential sprawl, in order to better determine the actual level of opportunity perceived at an origin relative to another.

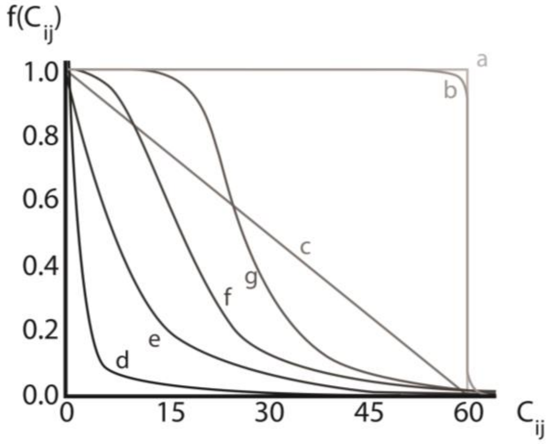


Figure 6.1: Example impedance functions (based on (Kwan, 1998))

One study explored the correlation between measures in Cleveland, Ohio, and found just a 0.549 correlation between identical decay functions, one with a cutoff of 30 minutes and the other with a cutoff of 40 minutes (Kwan, 1998). This is likely regionally specific to the Cleveland area, but it is interesting that such a relatively small difference in cutoff times, a decision that could have been taken lightly, could have a surprisingly large impact on the results of a study.

However, in most cases, there are high correlations between these different measures. For example, calculations across all measures will consistently show that a point in the Financial District of Downtown Boston is more accessible than a point in the much less urban town of Haverhill, Massachusetts. However, issues can arise when comparing two more similar areas, such as the Financial District and the Innovation District. This scenario can also lead to many other complexities and questions to be raised such as: should 30 minutes by auto be considered the same as 30 minutes by transit? Should those 30 minutes by auto be considered equally, whether the driver travels 30 miles at 60 miles per hour in free flow conditions, or 10 miles at 20 miles per hour in extremely congested conditions? What is the impact of a reliability buffer time, if the driver knows that travel times can vary due to unstable traffic conditions and may therefore leave earlier than he or she would prefer?

6.1.2 Accessibility Measure Used in this Thesis

The MIT Thesis "Exploring The Relationship Between Destination Accessibility, Cluster Formation and Employment Growth in Kendall Square" examined the gravity model, calibrated to real-world trips (Peralta-Quirós, 2013). This is based on literature that shows that the optimal commute time is not necessarily zero. In fact, many workers seem to prefer to have some separation between home and work, or at the very least, they are indifferent to short trips. This model is also regionally dependent, as it is influenced by the distribution of home and work clusters, as well as by the transportation network level of service between them. It can also depend on living preferences (including affordability) between urban, rural, and suburban areas. Calibrating the model to real world trips assumes that this will reveal the preferences of travelers, however it may instead simply be demonstrating how they react in a constrained world, where they may not be able to satisfy all their preferences. It does however reveal information on tolerance thresholds for commuting, as it is based on behavior that actually occurred.

Because this thesis is mainly concerned with peak-hour commute trips, the calibration developed for home-based work trips is used (Peralta-Quirós, 2013). This function was calibrated for trips across all modes. Using this function, all opportunities within the first 23 minutes of travel time are assumed to be equally valuable, and beyond that, the decay function in equation (6.1) is used to calculate the relative value of an opportunity at that distance compared to an opportunity at zero distance. In addition, analysis of accessibility of potential employees to employers is modeled in a similar manner.

$$f(C_{ij}) = \begin{cases} 1, \; C_{ij} < 23 \\ 12.5 * C_{ij}^{-0.35} * e^{-0.062*C_{ij}}, \; C_{ij} \geq 23 \end{cases} \tag{6.1}$$

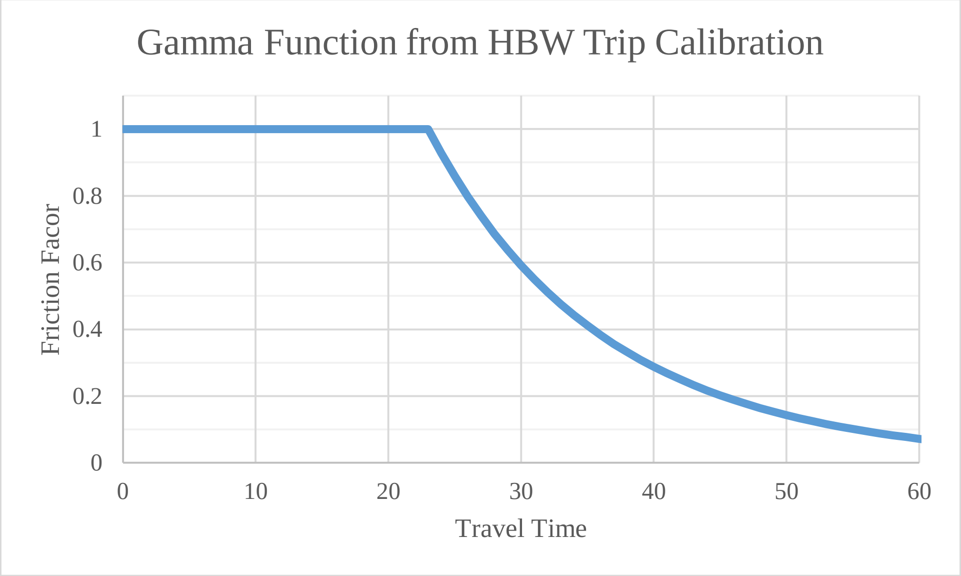


Figure 6.2: Travel time decay function for commute trips in the Greater Boston Area (Peralta-Quirós, 2013)

Throughout this analysis, accessibility measures are calculated for each mode individually rather than across all modes. This is done in order to better compare the differences in accessibility provided by each mode, because future changes to the network are expected to have different impacts on their accessibilities relative to each other. Furthermore, it is necessary to weigh the relative flows served by each mode rather than simply what could be served by the network.

6.1.3 Gamma Function Sensitivity Analysis

In order to ensure that the accessibility measure used is adequately revealing the differences in attractiveness of job areas, a sensitivity analysis is performed on the rankings performed in Section 4.3 to determine whether different measures would have resulted in different rankings. For example, two gamma functions, described by equations 6.2 and 6.3, are compared to the one chosen in equation 6.1. These three gamma functions have similar steepness of decay and vary primarily in where the cutoff, between the plateau of indifference and the decay regime, is. In equation 6.2 the cutoff is at 15 minutes and in equation 6.3 it is at 30 minutes, on either side of the chosen, calibrated cutoff of 23 minutes in equation 6.1. All three functions have a final cutoff at 60 minutes.

$$f(C_{ij}) = \begin{cases} 1, \ C_{ij} < 15 \\ 2.9 * C_{ij}^{-0.50} * e^{-0.059 * C_{ij}}, \ C_{ij} \geq 15 \end{cases} \tag{6.2}$$

$$f(C_{ij}) = \begin{cases} 1, \ C_{ij} < 30 \\ 27.0 * C_{ij}^{-0.42} * e^{-0.065 * C_{ij}}, \ C_{ij} \geq 30 \end{cases} \tag{6.3}$$

The resulting rankings in accessibility to workers by auto on the congested network are listed in Table 6.1, and by transit are listed in Table 6.2.

Table 6.1: Accessibility rankings to workers by auto on the congested network

Ranking	Equation 6.2 (15 minute)	Equation 6.1 (23 minute)	Equation 6.3 (30 minute)
1	Allston	Allston	Allston
2	Waltham	Waltham	Waltham
3	Longwood	Alewife	Alewife
4	Alewife	Longwood	Longwood
5	Kendall	Kendall	Kendall
6	Downtown	Downtown	Downtown
7	Innovation	Innovation	Innovation
8	Logan	Logan	Logan
9	Quincy Adams	Quincy Adams	Quincy Adams

Rankings of areas by accessibility by congested auto stay roughly the same regardless of the plateau cutoff value used. One notable exception is that Longwood drops in the rankings when the cutoff is extended from 15 to 23 minutes (and remains there at 30 minutes). This corresponds with the idea that the high auto accessibility at Longwood is primarily due to the high density in the immediately surrounding area, on surface roads which are less vulnerable to congestion. Accessibility to suburban workers is therefore considered roughly equivalent at Longwood than at other similar areas such as Kendall and Downtown Boston.

Table 6.2: Accessibility rankings to workers by transit

Ranking	Equation 6.2 (15 minute)	Equation 6.1 (23 minute)	Equation 6.3 (30 minute)
1	Downtown	Downtown	Downtown
2	Longwood	Kendall	Kendall
3	Kendall	Longwood	Innovation
4	Innovation	Innovation	Longwood
5	Alewife	Alewife	Alewife
6	Allston	Logan	Logan
7	Logan	Allston	Allston
8	Quincy Adams	Waltham	Waltham
9	Waltham	Quincy Adams	Quincy Adams

There is slightly higher variation in rankings when using travel times by transit, showing a higher sensitivity to the plateau cutoff in this case. This is likely due to the lower initial variation between similar areas and the higher "lumpiness" of the transit network. No area changes by more than two positions, and most change by zero or one, so the general trends are consistent and the rankings are still not particularly sensitive to the cutoff value used.

6.2 Methods

In order to calculate and visualize accessibility measures, two software packages are used. The first is Conveyal Analyst, which will be introduced in Section 6.2.1, and the second is Cube Voyager, which will be introduced in Section 6.2.2.

6.2.1 Conveyal Analyst

Conveyal Analyst evolved from Open Trip Planner and is an open-source package with an intuitive framework for visualizations (Conveyal, 2016). However, this software does not rely on the full four step model and rather infers land use and travel time information from static input files. This means that capacity constraints can only be addressed by adjusting network travel times directly, generally to currently congested conditions and not in a directly iterative manner for future conditions. However, this second step can be done manually after the initial results have been produced.

In order to model changes to the transit network, changes needed to be made to the input General Transit Feed Specification (GTSF) files. Using the GTFS Editor, these modifications can be made to the transit system, and can then be imported into Transport Analyst for visualization of the resulting changes in accessibility. First, West Station and Boston Landing Station were added to the Worcester/Framingham commuter rail line. Schedules on this route were modified from timetable based to frequency based in order to better enable a sensitivity analysis of trip frequency in Analyst. These simplified schedules, with the same total number of trips as currently scheduled by the MBTA, are outlined by time period in Table 6.3.

Table 6.3: Simplified current Worcester/Framingham commuter rail schedules

Inbound				
Period	Start	End	Headway	Number of Trips
AM	5:00 AM	10:00 AM	0:30	10
PM	10:00 AM	12:00 AM	1:00	14
Weekend	7:00 AM	11:30 PM	1:50	9

Outbound				
Period	Start	End	Headway	Number of Trips
AM	5:00 AM	3:00 PM	1:00	10
PM	3:00 PM	8:00 PM	0:30	10
Evening	8:00 PM	12:00 AM	1:00	4
Weekend	7:00 AM	11:30 PM	1:50	9

Secondly, a new route was examined from West Station to North Station along the Grand Junction in Cambridge, with multiple route patterns to enable testing of extensions of this service along the commuter rail right-of-way to Route 128. The stops served within Route 128 by the two proposed services are visualized in the following figure, which for this new service include North Station, Kendall Station (near the current Kendall/MIT Red Line Station), West Station, Boston Landing, Newtonville, West Newton, Auburndale, and an additional stop at Riverside, the terminal of the D branch of the Green Line. South Station and Back Bay also continue to be served and make up the remaining stations within Route 128.

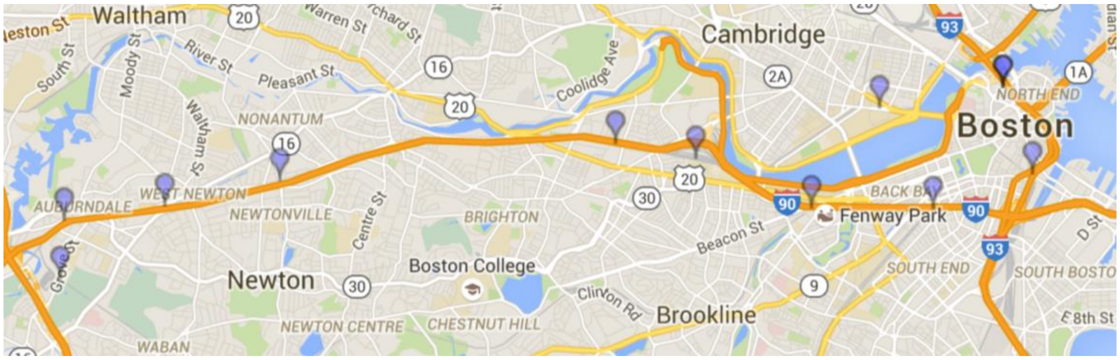


Figure 6.3: Stops served within Route 128 by proposed transit services

6.2.2 Cube Voyager Model

Using the Cube Voyager model, accessibility is calculated by generating travel time skims and combining those results with the input socioeconomic characteristics using the selected gamma function. The four-step model includes the assignment step, which more directly considers capacity constraints. Results were integrated for each of 986 TAZ's across all other TAZ's, though with the chosen function, only opportunities within a 60-minute travel time were included for each mode. The resulting accessibility incorporates changes in travel times and travel throughput in order to better capture the impacts of infrastructure changes along the travel corridor.

The procedure to add new or modify existing transit service is similar for all transit improvements under analysis, so just the Grand Junction rail link will be summarized as an example. First, rail tracks were added in the model through Cambridge along the Grand Junction corridor. The Grand Junction travels on a different bridge over the Charles River than autos, pedestrians, and bikes, and then continues along a gap within the street network that is visible in the existing Boston network in Cube. These new links needed to be created in both the Boston network file and the rail file to ensure travel along those nodes. The new service travels along links already existing in the network, whenever possible, based on an accurate representation of reality as DMU service runs on the existing commuter rail tracks. The tracks included in the new service currently serve the Framingham/Worcester commuter rail line to the west and the Fitchburg commuter rail line to the north. DMU service traveling on commuter rail is assumed to travel at the same speed as existing commuter rail service, 40 miles per hour. Travel through Cambridge on the Grand Junction tracks is expected to be much slower, 20 miles per hour, mainly for safety reasons due to the high number of at-grade crossings. Resulting travel characteristics are displayed in Table 6.4.

Table 6.4: Link travel characteristics for Grand Junction service (proposed stops in bold, where 893998 is West Station, 88444 is Kendal Station, and 894282 and 894290 are North Station)

Inbound Link Characteristics				
Origin	Destination	PT Speed	PT Time	Distance
893998	894024	40	0.5274	0.3516
894024	**88444**	20	4.0707	1.3569
88444	894121	20	2.4435	0.8145
894121	894131	40	0.1767	0.3021
894131	894145	40	0.2893	0.1691
894145	894201	40	0.4295	0.2351
894201	894211	40	0.1753	0.1168
894211	894226	40	0.0756	0.0504
894226	894232	40	0.0854	0.0569
894232	894276	40	0.7342	0.4895
894276	**894282**	40	0.0547	0.0365

Outbound Link Characteristics				
Origin	Destination	PT Speed	PT Time	Distance
894290	894280	40	0.0562	0.0365
894280	894232	40	0.7351	0.4895
894232	894226	40	0.0854	0.0569
894226	894211	40	0.0756	0.0504
894211	894201	40	0.1753	0.1168
894201	894145	40	0.4295	0.2351
894145	894131	40	0.2893	0.1691
894131	894121	40	0.1767	0.3021
894121	**88444**	20	2.4435	0.8145
88444	894024	20	4.0707	1.3569
894024	**893998**	40	0.5274	0.3516

Walk and auto times on the new rail tracks modeled are set to 99 minutes since they represent an exclusively rail right-of-way track, not shared with any other mode. At-grade crossings are considered full-speed for trains traveling through, but traffic signals need to be added in order to ensure that cars are prevented from traveling across the intersection at the same time as the train passes through.

After the transit service has been incorporated into the model, stops need to be connected to the walk network and to other transit lines in order for passengers to be able to access the new service. This was straightforward for North Station as it is an existing station, so the new nodes simply had to be connected to existing stop nodes, representing stations, for the Green Line, Orange Line, and commuter rail. As the new service will run on existing commuter rail tracks, it will be much quicker to transfer to commuter rail than to the MBTA subway lines via the walkway under Causeway Street. This was included in the model by using the stop node for the North Station Commuter Rail Station as the stop node for the new service, rather than using the stop node for the North Station MBTA Station where the Orange and Green lines stop. This may have a slight impact on transfers to the Orange Line, as it will increase the walk time during the transfer, but this is a reasonable depiction of reality. New development under construction at North Station includes a much more seamless, weather-protected transfer that should mitigate this impact, which was reflected when modeling future changes. Another potential stop that could be added is at or near the new Lechmere stop, after the Green Line extension is completed, at North Point.

Kendall Station and West Station are new stops, so additional walking links needed to be added. Walk times were calculated based on an average walk speed of 3 miles per hour. The transfer between the new service at Kendall Station and the Red Line at Kendall/MIT is currently assumed to occur as a 0.2 mile (4 minute) walk on Main Street, outside fare control but with a free transfer, when a CharlieCard is used. Future investment could provide an underground tunnel onto the Red Line platform with stairs down into the tunnel within fare control at Kendall Station for a more seamless transition. This will not decrease the distance but it will make the transfer less onerous, especially under unfavorable weather conditions. This change will be reflected with a lower penalty for transferring. West Station is not near any existing MBTA rail stop so instead it was connected with walking links to the street network in Allston. West Station was also added to the Framingham Inbound and Framingham Outbound commuter rail lines so that commuters from further west could have access to the new service with just one transfer, and can thereby access Kendall and North Station much more conveniently than under current conditions.

To modify the Worcester/Framingham commuter rail service, existing stop nodes and links were maintained and headways were modified for each period, depending on the scenario under analysis. Frequency improvements on this service are possible, with an improved signal system and added rolling stock. The MBTA Fiscal Control Board has authorized procurement of a new positive train control, so it is assumed that sufficient changes will be made at the Western Corridor through Back Bay to South Station that much higher train frequency will be feasible. Sufficient added rolling stock is assumed to be purchased to provide the needed capacity. This will increase throughput capacity and could also improve travel times for existing trips.

6.3 Current Accessibility

6.3.1 Accessibility to Jobs

Visualized using the Cube Voyager model, Figure 6.4 shows the current accessibility by auto to jobs in the Boston area. Each zone is colored according to the number of jobs available within 60 minutes across all other zones, calculated using the decay function in equation 6.1. The results follow a very distinct ring pattern, with accessibility highest closest to downtown and lower in the outlying areas. Major highways are included in white in the figure.

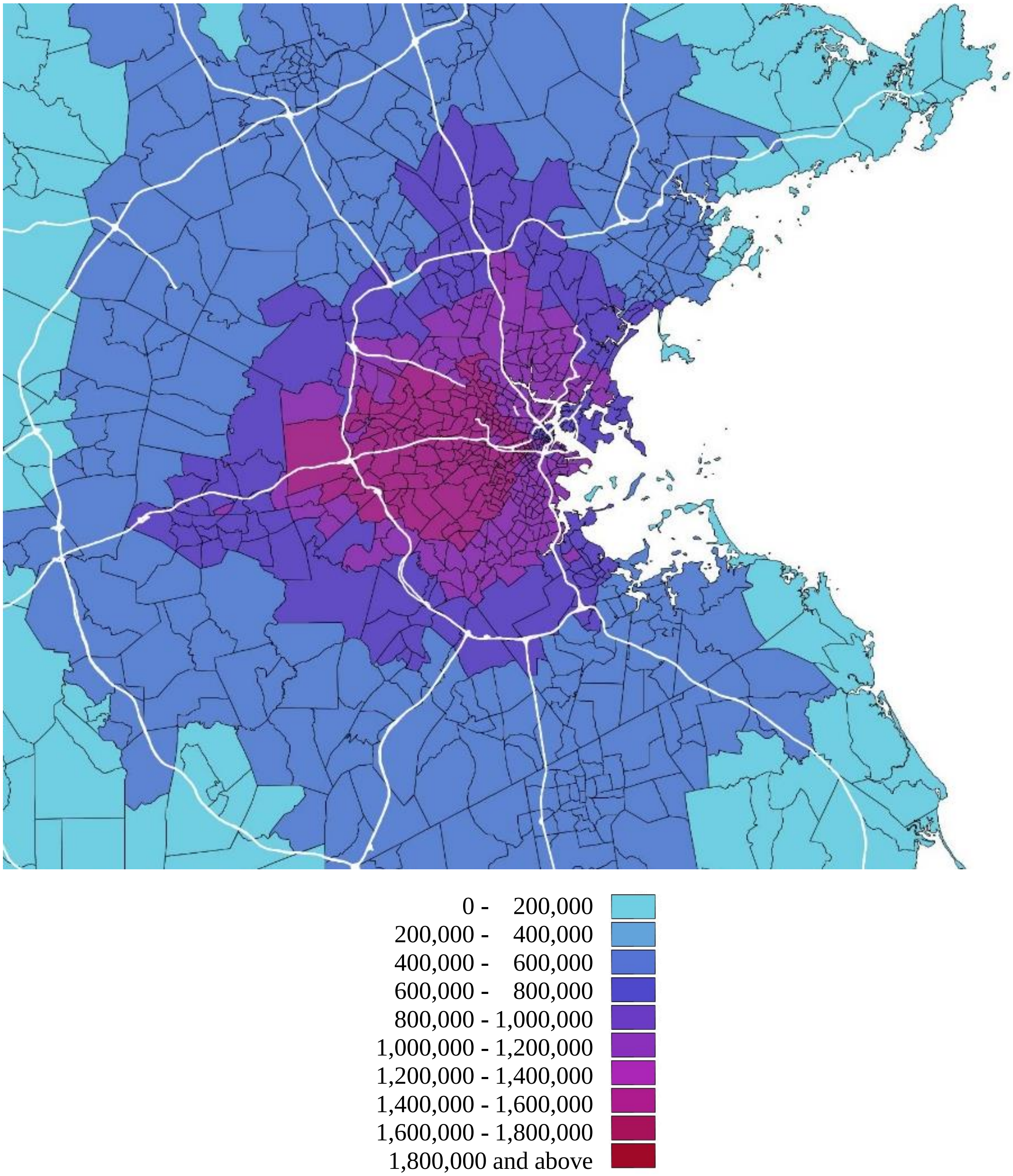


Figure 6.4: Current accessibility to jobs by auto in Boston, using congested travel times (Murga, 2015)

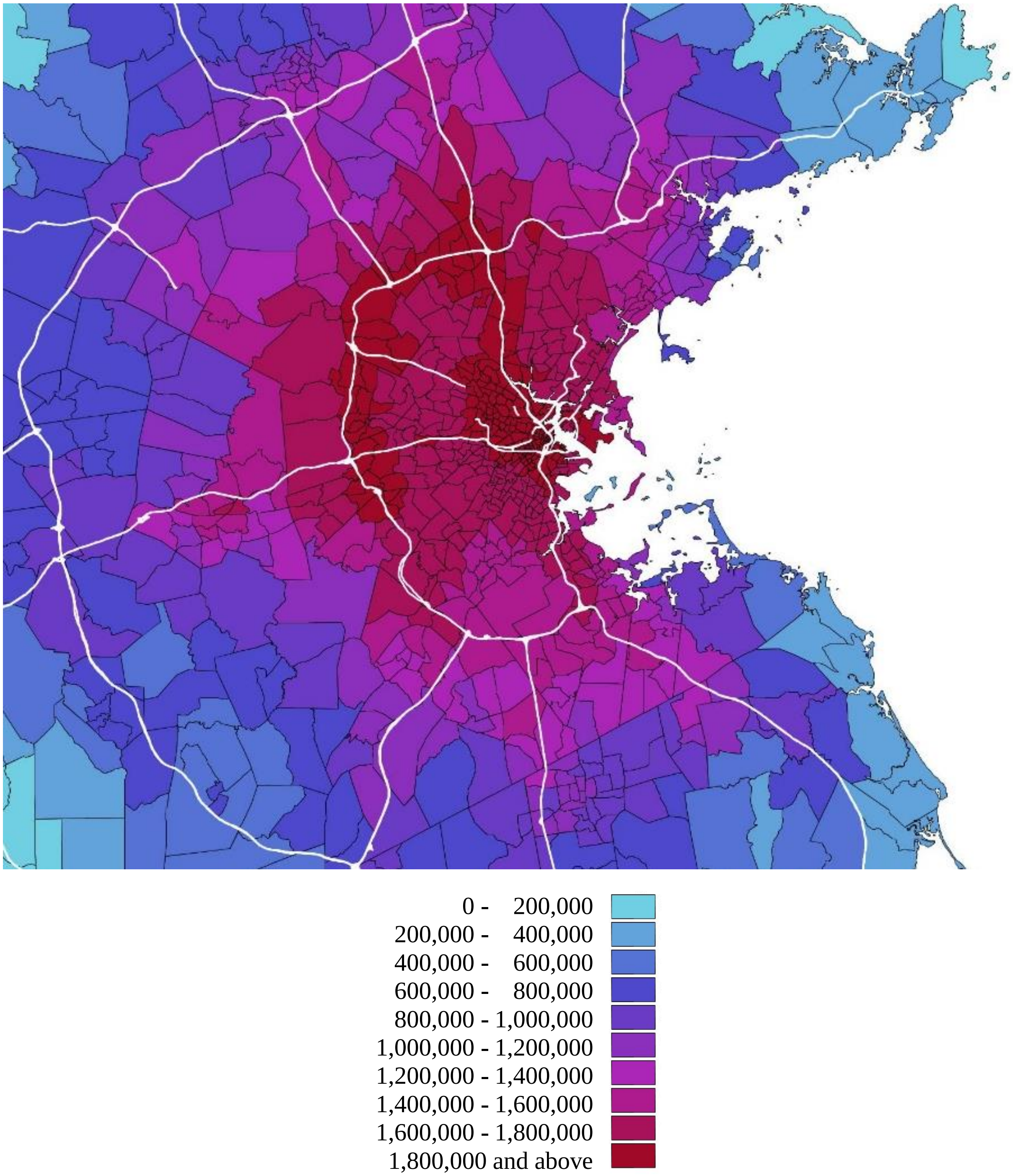
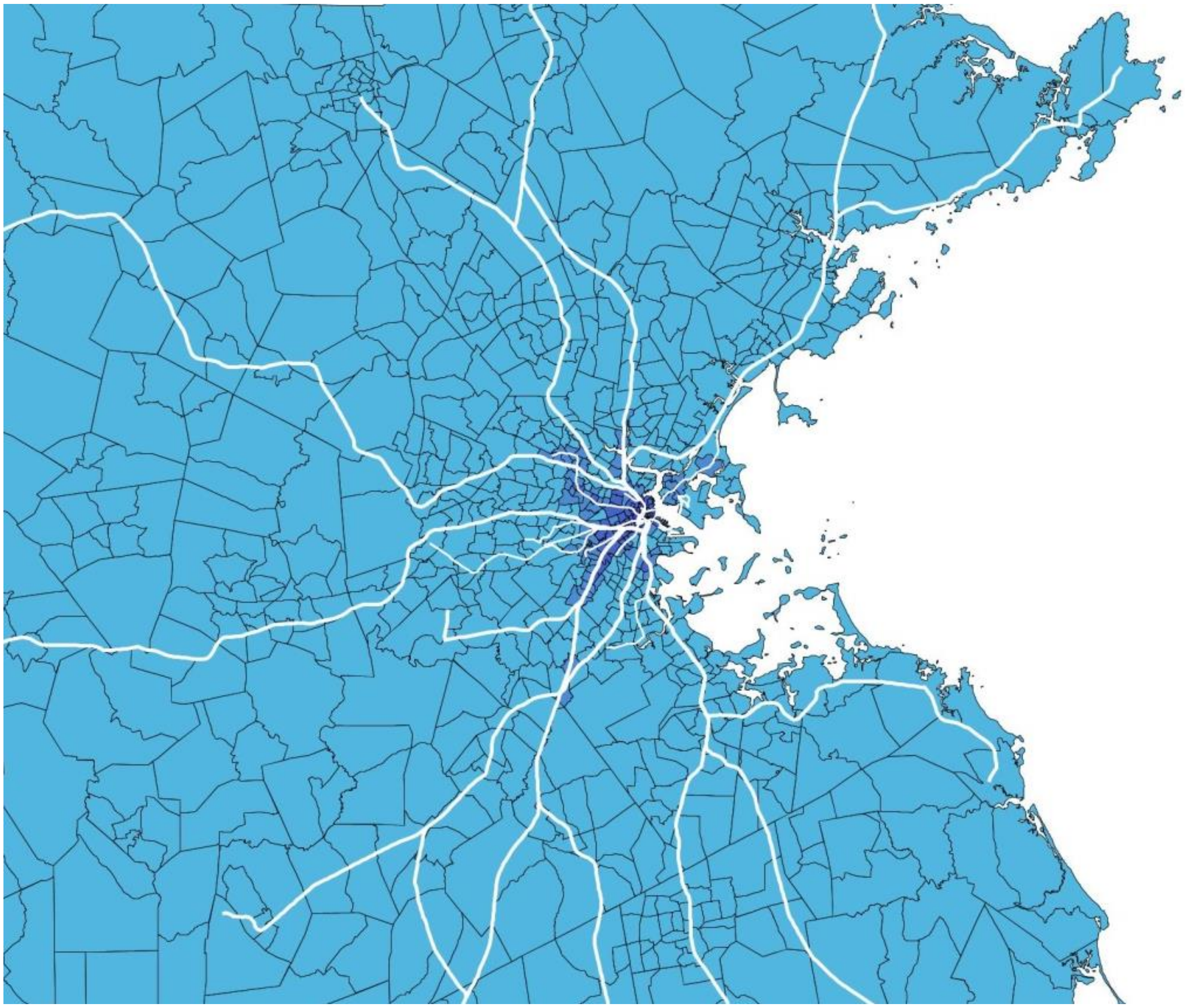


Figure 6.5: Current accessibility to jobs by auto in Boston, using free-flow travel times

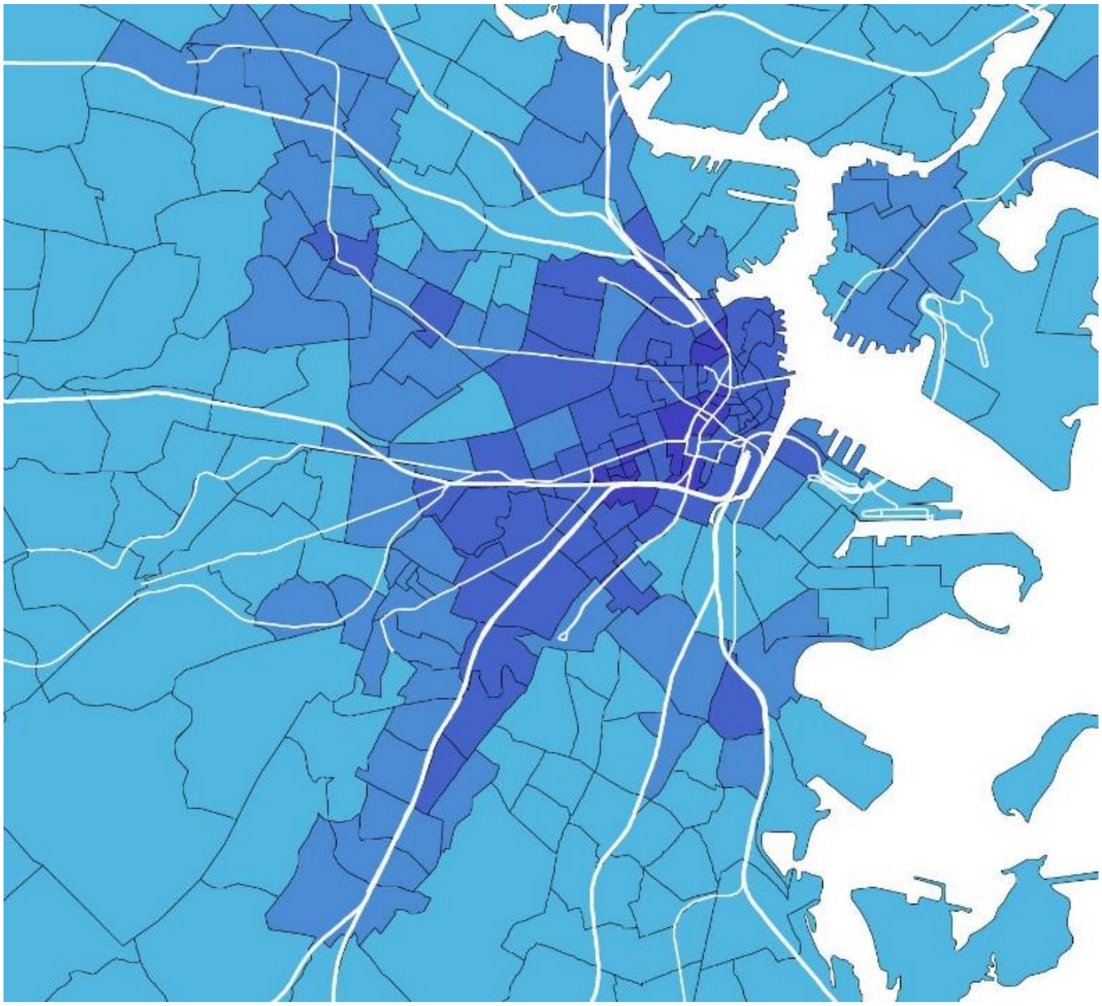
Figure 6.4 should be compared to Figure 6.5, in which free-flow travel times (representing time periods with very low traffic flows) were used to calculate accessibility. As expected, accessibility is much higher across the entire metropolitan area since travel times are lower, by a factor of roughly two. However, it is also interesting that the relative accessibility between areas has shifted as well. For example, in Figure

6.5 there is a cluster of higher accessibility around the Route 128 corridor, appearing a bit redder in the figure than areas both outside and inside Route 128. It should be noted that there is a relatively high concentration of jobs around this highway, so this makes sense, but it is all but erased when congested travel times are used instead. This is likely because it is a very auto-oriented area with limited transit options, so most trips to this area must be taken by auto, as opposed to the more multi-modal assignment that occurs when transit access is also available. This increases the impact of congestion during peak hours and diminishes the time proximity of these jobs to other residential areas.

Current accessibility by transit is much lower than that by auto. Figure 6.6, which uses the same scale as Figures 6.4 and 6.5, remained exclusively blue, meaning that all values are in the lowest four of the ten categories that auto accessibility fell within. This figure also includes, in white, the rapid transit and commuter rail lines currently serving the Boston area.



(a) Regional transit accessibility in the Boston area



(b) Local transit accessibility in the urban Boston core

0 - 200,000	🟦
200,000 - 400,000	🟦
400,000 - 600,000	🟦
600,000 - 800,000	🟦
800,000 - 1,000,000	🟪
1,000,000 - 1,200,000	🟪
1,200,000 - 1,400,000	🟪
1,400,000 - 1,600,000	🟪
1,600,000 - 1,800,000	🟥
1,800,000 and above	🟥

Figure 6.6: Current accessibility to jobs by transit in Boston

While transit accessibility is much lower than that of the road network, it is still a very critical element of the Boston transportation network. Referring back to the Zupan density observations discussed in Section 2.1, transit usage is critical to induce and sustain high density development. Therefore it is most important that there is at least some transit accessibility, especially in the most highly job-dense areas, in order to supplement the accessibility provided by the auto network, which is easily congested and cannot provide sufficient throughput on its own.

6.3.2 Accessibility to Workers

Accessibility to workers shows a similar trend across the area as accessibility to jobs, both for the roadway network (Figure 6.7) and the transit network (Figure 6.8). The number of working-age residents within a 60-minute travel time on the specified mode, after the decay in equation 6.1, determines the coloring of each zone. There are some corridors along which higher levels of accessibility extend further into the suburbs, such as along the I-90 and I-93 for auto and along the Orange Line for transit.

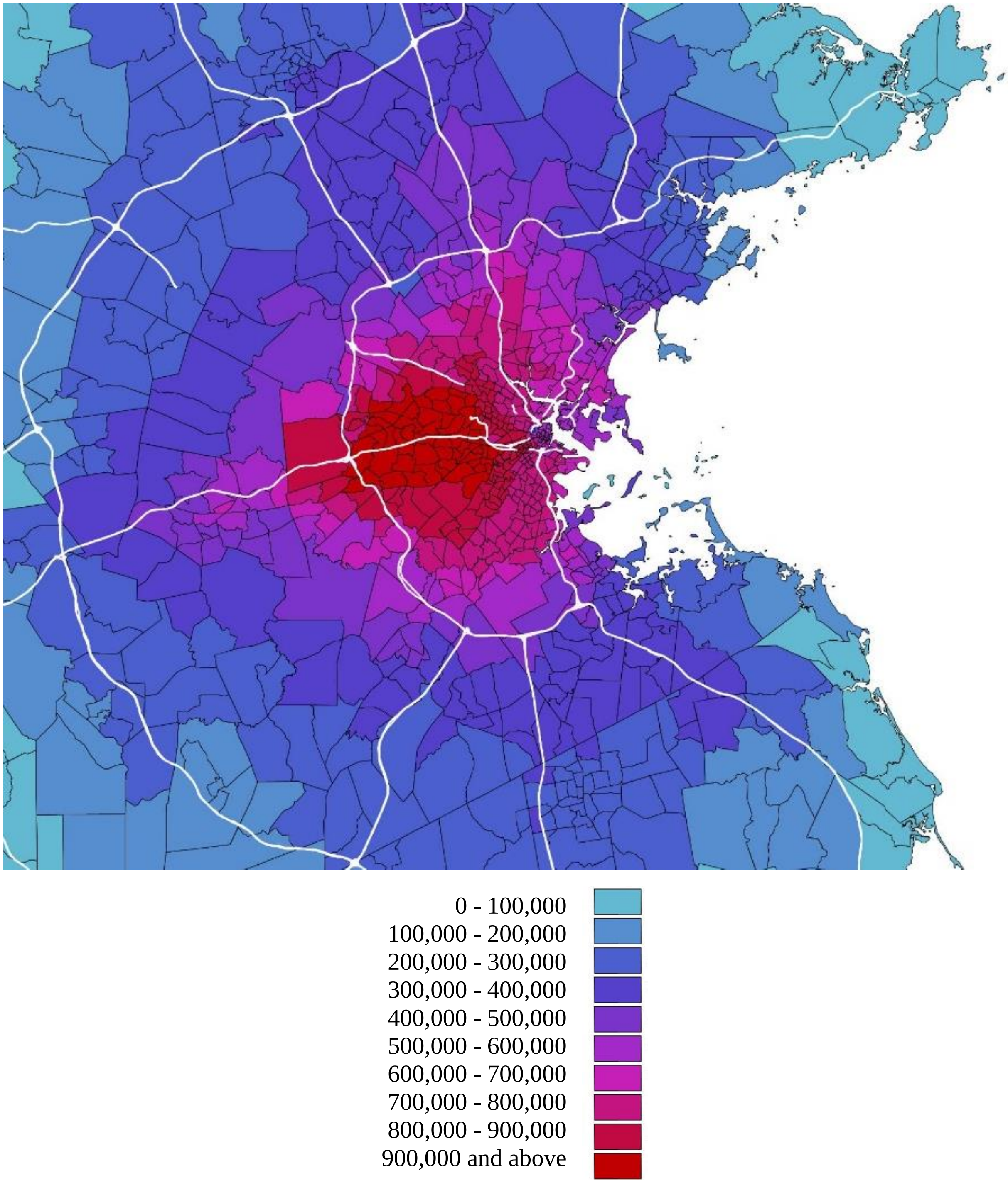


Figure 6.7: Current accessibility to workers by auto in Boston

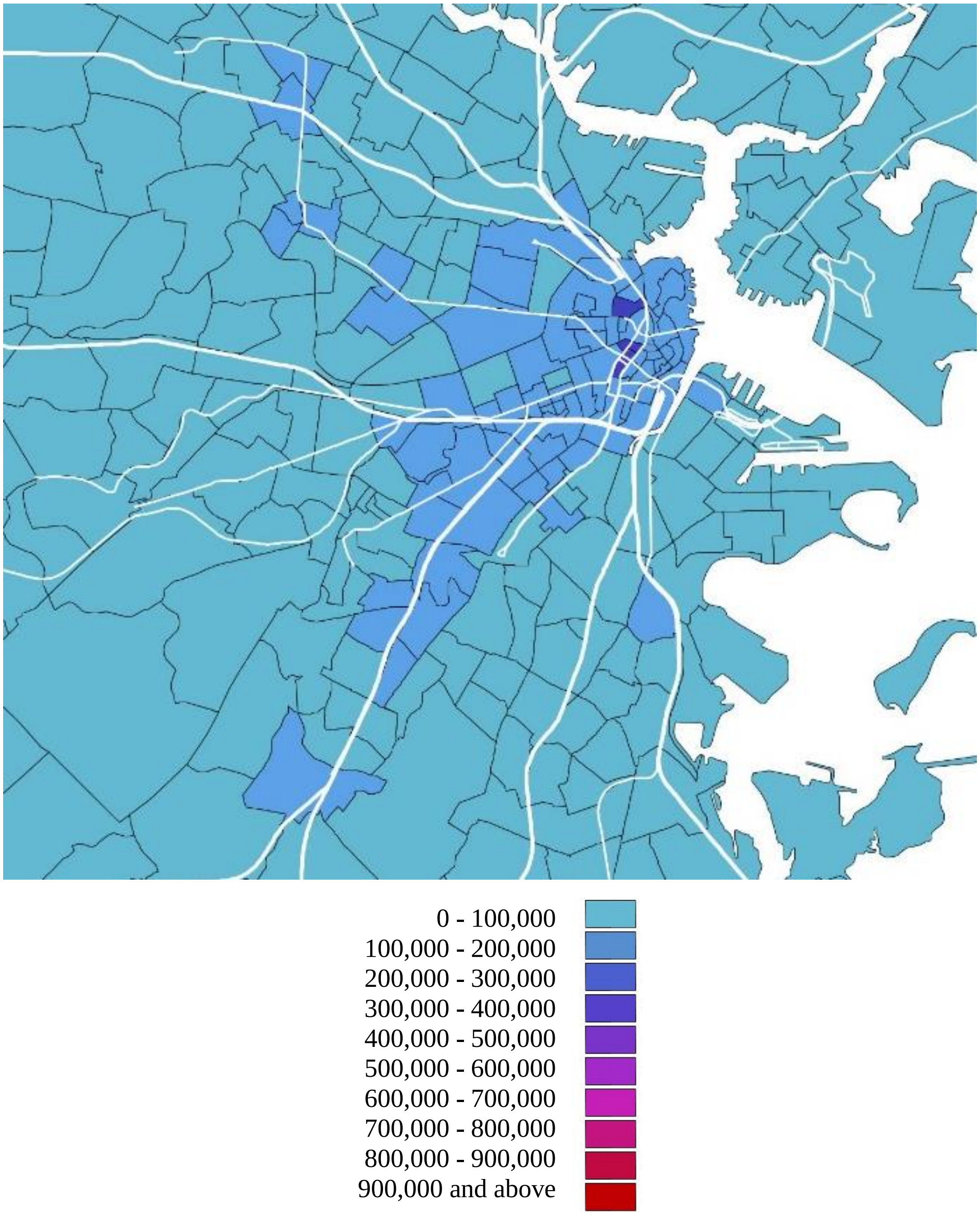


Figure 6.8: Current accessibility to workers by transit in Boston

When comparing high-growth employment areas and the accessibility changes infrastructure improvements could generate, it will be most useful to look at accessibility to workers as it is assumed that this is what these areas are competing for. However, accessibility to jobs is also very important due to the agglomeration impacts companies benefit from when strong links to other employment areas are maintained.

6.4 Impact of Infrastructure Improvements on Accessibility

Incremental improvements to the transit network could have small negative impacts on accessibility for some neighborhoods, if new stops are added along a corridor through which there was previously no dwell time. However, the changes are expected to increase overall accessibility in the Boston area in a much more significant and structured way. Each proposed change to the network will be analyzed individually to measure these impacts in terms of travel times and accessibility by transit, before network-level changes (including on the auto network) will be re-evaluated in Section 6.7. The incremental changes include:

- Addition of West Station and Boston Landing to the existing commuter rail line
- Introduction of a new service, using DMU vehicles on existing freight rail tracks through Cambridge
- Extension of this DMU service along the commuter rail tracks to better serve additional origin-destination pairs
- Experimentation with different patterns of service, such as forcing transfers to Back Bay and South Station at West Station and improving bus transfer potential
- Completion of the Green Line extension, Blue Line to Red Line connector, and other changes not specifically in the Western Corridor that will be considered jointly to help meet regional transportation demand in the planning horizon

6.4.1 Addition of West Station and Boston Landing to the Framingham/Worcester Commuter Rail Line

The first transit improvement is to add Boston Landing and West Station to the Framingham/Worcester Line. Both are assumed to be in place by 2025. The addition of these new stations may slightly increase travel times by transit to Downtown Boston for Western Corridor commuters of the outer suburbs, because of the added dwell time and time spent decelerating and accelerating into and out of the two stations, which are both particularly onerous for commuter rail vehicles. However, because the single-track constraint through Beacon Park Yard will simultaneously be relieved, there will be some increase in travel speeds and in reliability that could counteract this increase in dwell time. For the models used in this thesis, this is assumed to result in a net increase in travel time between Newtonville and Yawkey stations from 10 minutes to 12 minutes. While this does not seem like a very dramatic change, it is important to ensure that it will not have too negative an impact on some, particularly existing, users before introducing the benefits it could provide.

To measure this impact, changes in travel time isochrones are visualized for the transit network. Figure 6.9 shows how far into the Western Corridor can be accessed from South Station within 60 minutes, on average, before and after the introduction of West Station and Boston Landing. In plots like this one, areas in yellow are accessible within 60 minutes before the change is made and areas in blue are accessible within 60 minutes after the change is made. In this case, the area in yellow is slightly larger than the area in blue, meaning that adding West Station and Boston Landing to the existing commuter rail results in a marginal decrease in area accessible to the west within 60 minutes from South Station. This is assuming average accessibility within the AM peak, which means a random arrival at the chosen location between 7 am and 9 am, and being able to board the next vehicle on the shortest path once it arrives.

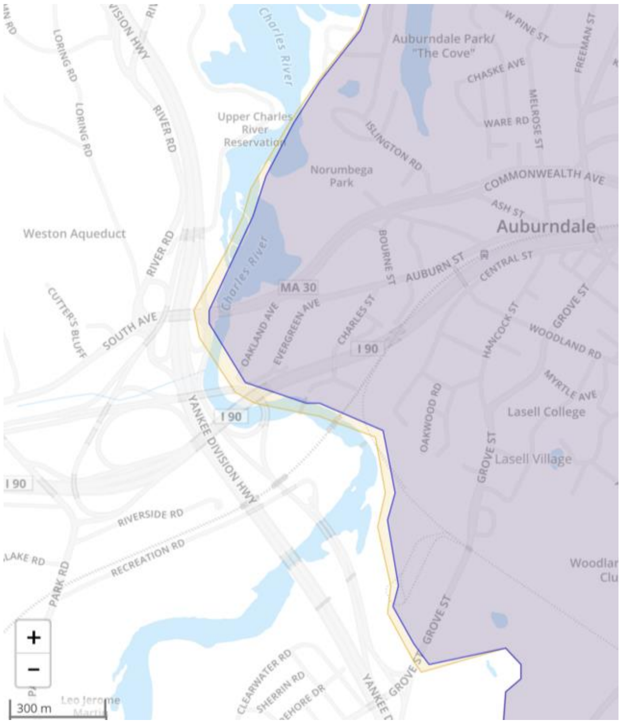


Figure 6.9: Change in 60-minute travel time isochrone from South Station (Conveyal, 2016)

Much more significant changes are visible when looking at transit accessibility to Allston at the location of the new West Station in Figure 6.10. The addition of West Station improves accessibility not only through the Western Corridor, but throughout the network because of the potential transfers made available by the introduction of rail service to this area, which was previously served only by buses without a significant amount of walking. This is reflected in the following figure, where the area in blue is larger than the area in yellow, meaning that more area is accessible within 60-minutes after this change is made.

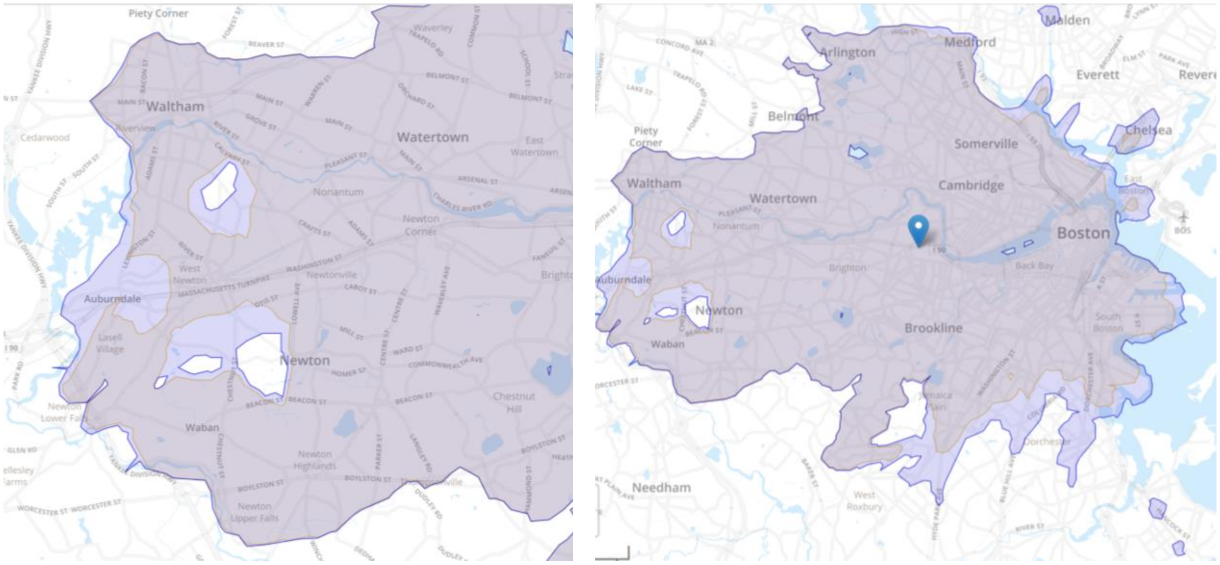


Figure 6.10: Change in 60-minute travel time isochrone from West Station, regionally and in the Western Corridor, respectively

Another way to look at changes in travel time due to changes in infrastructure is to assess the change in travel time to areas that were already accessible by transit within the time threshold, in this case 60-minutes, but have become even more accessible due to improvements that have been made to the network.

Figure 6.11 presents the areas that become more accessible to Allston at West Station simply because the Worcester/Framingham commuter rail line will add a stop at this location that it already passes through. This includes bringing areas already accessible within 60 minutes, such as Downtown Boston, closer and thereby making opportunities there more accessible when a travel time decay function is used. At the same time, the area that can be reached within 60-minutes increases, as was visualized by the isochrones in Figure 6.10, and additional jobs and residents become available within that time.

In Figure 6.11, areas in yellow show no change in travel time by transit from West Station due to the addition of stops at West Station and Boston Landing. These areas are mostly to the north and south of West Station, which is not conveniently served by the Framingham/Worcester commuter rail line, or areas close by to the west that are served better by existing bus options than the low frequency commuter rail, so the shortest path does not change and neither does the average accessibility. Areas in purple or pink become closer in travel time and, as expected, these are areas to the west and to the east on commuter rail, notably Newton, Downtown Boston, and the Innovation District. Areas in grey are not accessible within 60-minutes before or after the change.

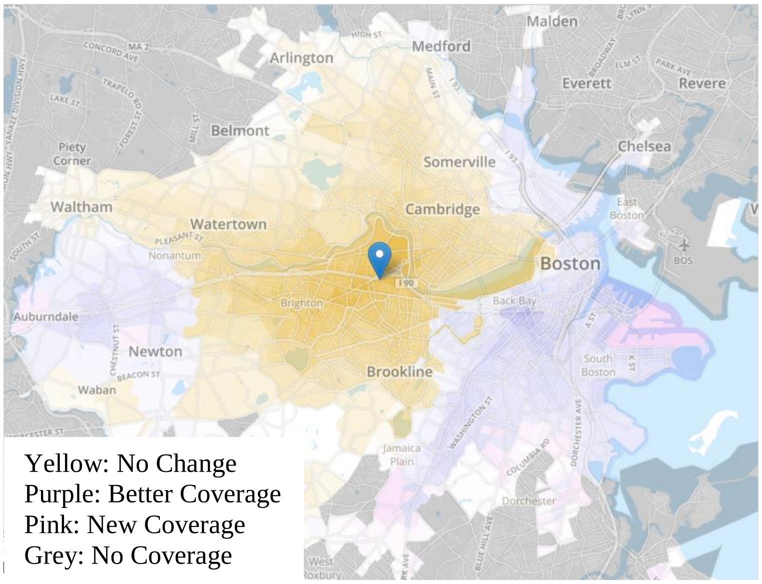


Figure 6.11: Changes in areas accessible to West Station

While changes in travel time isochrones are important, it is more interesting to assess what changes in opportunities these changes in travel time will provide, as presented in Figure 6.12. In this plot, the blue line represents incremental accessibility before the change and the green line represents incremental accessibility after the change. Grey zones are confidence intervals, from worst-case (just missing a transit vehicle) to best-case (immediately boarding a transit vehicle) accessibility. Incremental accessibility is the additional number of residents or jobs for each additional minute of travel time.

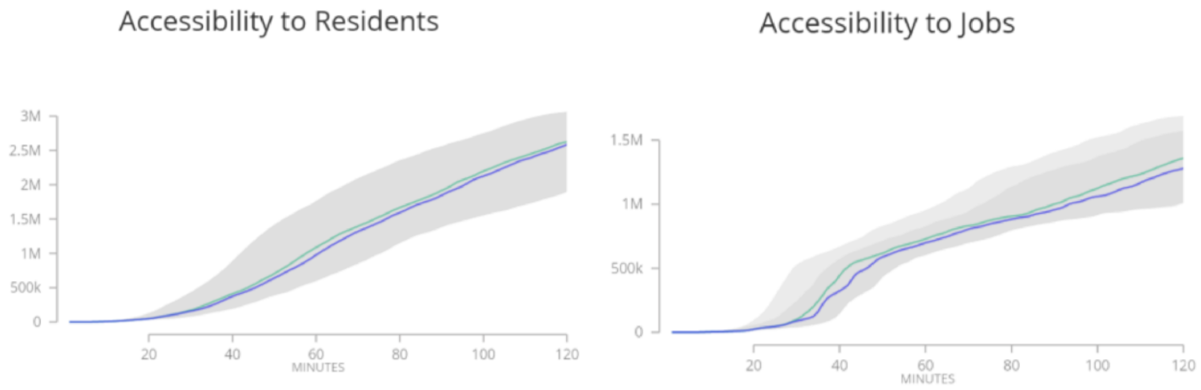


Figure 6.12: Changes in accessibility of residents and jobs to West Station (blue is before, green is after)

The change in number of residents accessible at each additional minute of travel time is consistently positive across a 120-minute travel-time interval from Allston at the location of West Station. The change in jobs is more unsteady due to a less even distribution of jobs across the area, which tend to be concentrated in certain dense areas. Notably, Downtown Boston, which used to be around 35 to 50 minutes away by transit, is now around 25 to 40 minutes away. This is particularly significant given the decay function used to calculate numerical accessibility measures begins to decay at 23 minutes, based on calibration to real home-based work trips. Therefore, the commute time from Allston by transit to the job-dense downtown becomes not just shorter but also reaches close to this threshold of indifference, which could transform Allston into a significantly more attractive residential neighborhood in terms of transit-accessibility. This is likely understood by current residents of the area, and could contribute to the high degree of public participation in the planning process of the Allston Interchange Improvement Project and its many multi-modal components.

6.4.2 Transfers at West Station to the Grand Junction

Once West Station has been added, it can be used as a transfer point to the new service along the Grand Junction. This service will first be introduced as a three-stop route from West Station through Cambridge to North Station, as shown in Figure 6.13. Additional stations could be added later, such as near the new Lechmere Green Line station and North Point development once the Green Line Extension has been completed.

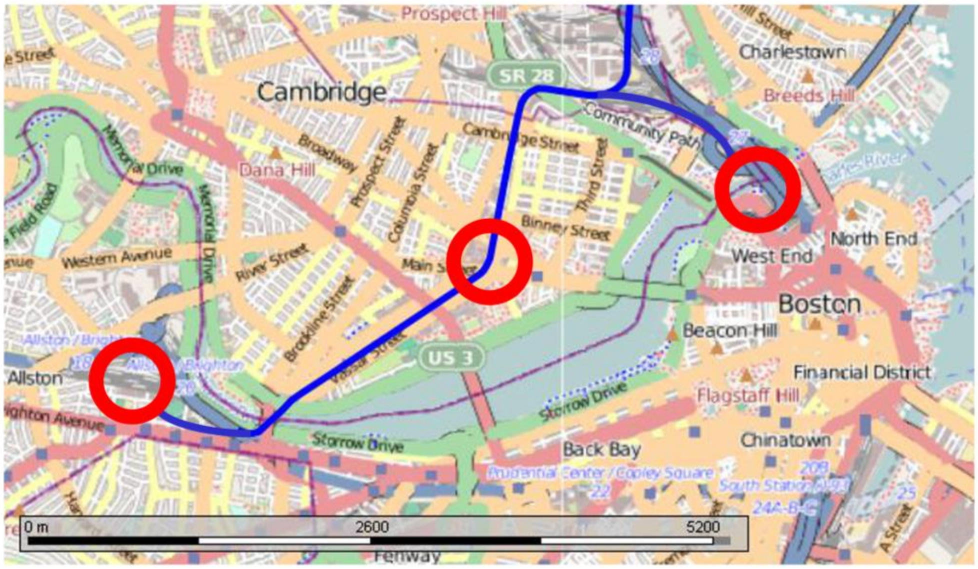


Figure 6.13: Grand Junction service and proposed stops

With this new service added, larger network-level changes are expected to occur than in the previous section. This is true not just for West Station, but also for Kendall Station as it will receive service by this new route. North Station is also expected to see major increases in accessibility because, while it is already served by two rapid transit lines and four commuter rail lines, it currently has limited access to the west and south, other than via the Riverside branch of the Green Line or for a certain distance by the Orange Line, though they both have many stops through downtown before providing access to these areas.

At West Station, this new link appears to have a significant impact on travel times and accessibility to areas not just in the west. In Figure 6.14, colors indicate the change in travel time generated by this new service. While there is little change to areas close by (yellow), this visualization shows significant travel time changes to many areas in the region, where the purple-blue color indicates faster access and the pink indicates new coverage within the 60-minute travel time threshold. For example, travel time to the airport is now possible within 60-minutes and travel time to the Financial District is significantly decreased despite the Grand Junction not directly providing service to this destination.

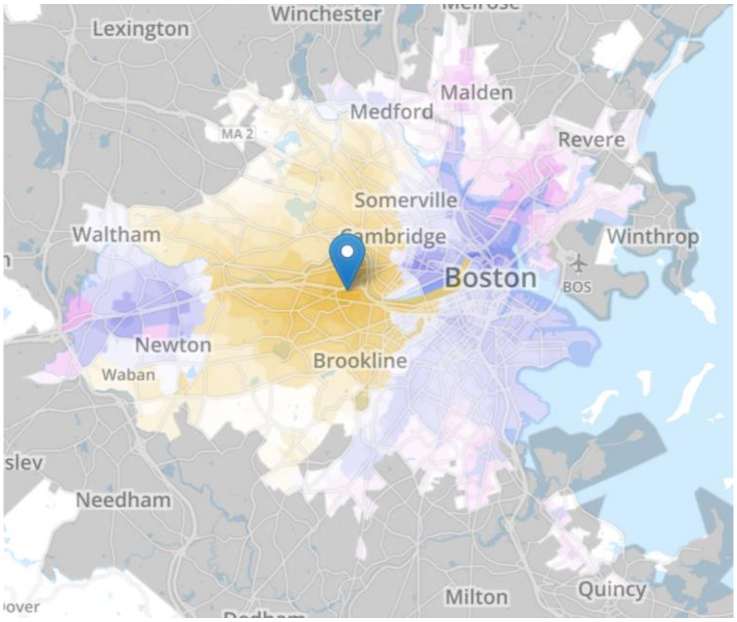


Figure 6.14: Changes in areas accessible to West Station with Grand Junction service

The change in jobs and residents in Figure 6.15 is significantly greater than in Figure 6.12, which only included the addition of West Station and Boston Landing. Opportunities available before the change are in blue, with a dark grey confidence interval, while opportunities available after the change are in green, with a light grey confidence interval. The large jump in number of jobs now begins at around 20 minutes of travel time from Allston, further into the plateau of indifference for home-based work trips. The first area to become accessible is Kendall Square, and then the jobs in Downtown Boston begin to appear at around 25 minutes.

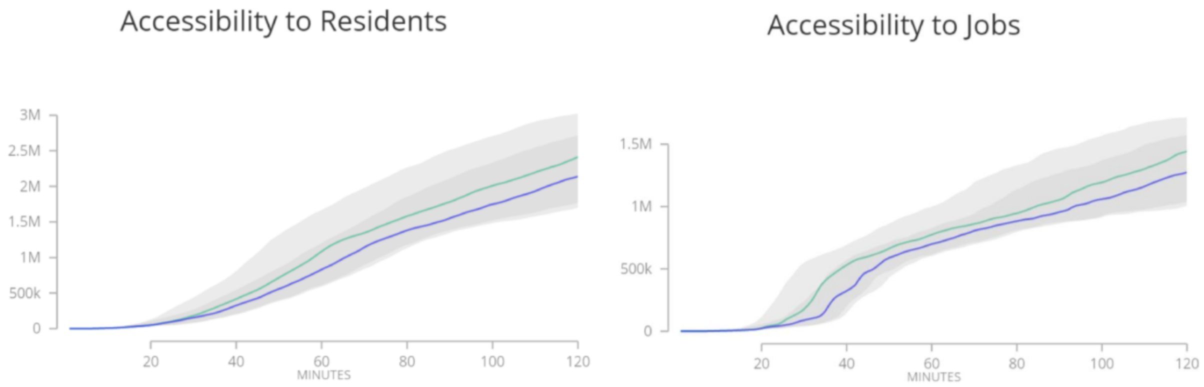


Figure 6.15: Changes in accessibility of residents and jobs to West Station with Grand Junction service (blue is before, green is after)

Changes in accessibility by transit at Kendall Square are less significant, likely because strong transit service already exists to this destination unlike at West Station. Interestingly, accessibility to residents in Figure 6.17 increases by a greater amount than accessibility to jobs. This makes sense because the areas that are becoming more accessible are in the Western Corridor and in East Boston or Revere, which tend to be more residential areas. Alternatively, these same areas would also become more accessible to Kendall with the Blue-Red Connector. Transit services to job-dense areas such as Back Bay and South Boston were already strong and so accessibility by transit to these areas does not change much due to Grand Junction service. Since Kendall is a job destination and is expected to continue being so, it benefits most from changes in residential and worker accessibility. As was discussed in the Nexus study in Section 2.2, many new employees to Kendall are seeking housing outside of Cambridge, so making these areas more transit-accessible will hopefully allow these preferences for living location to be better served by the transit network, increasing transit commute mode share to Kendall. Job areas also benefit from increased access to other jobs for a variety of reasons, but with the more pressing concern being accessibility to home locations for Kendall workers, this trend in accessibility changes seems promising.

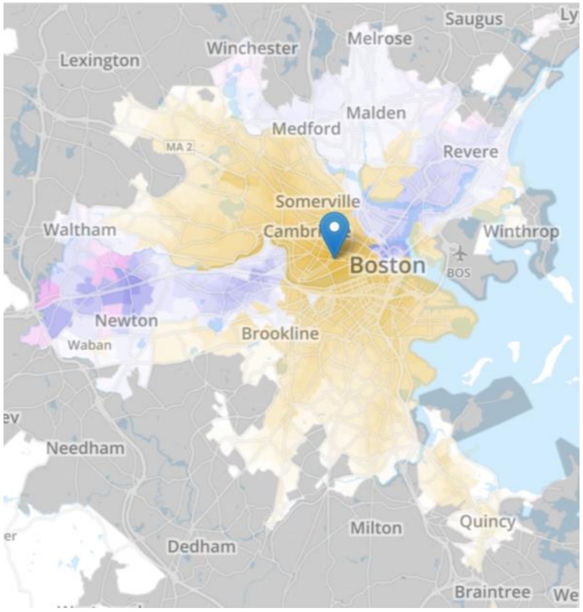


Figure 6.16: Changes in areas accessible to Kendall Station with Grand Junction service

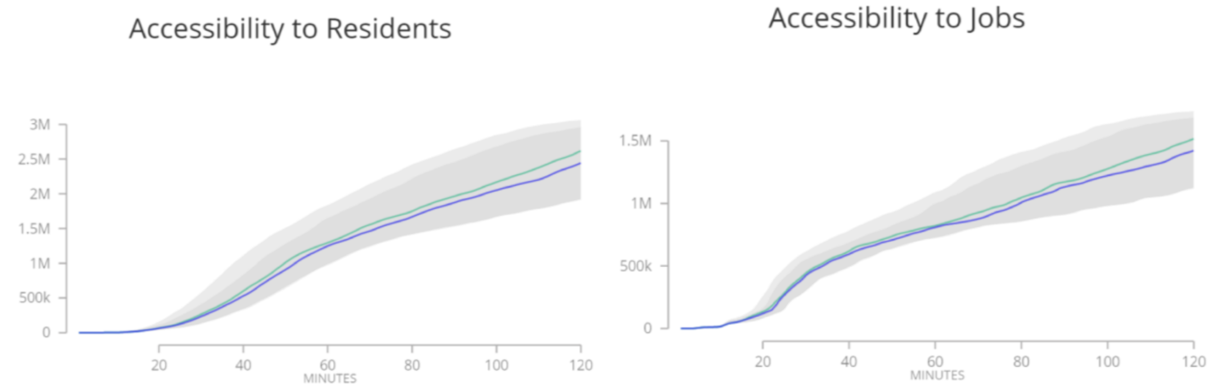


Figure 6.17: Changes in accessibility of residents and jobs to Kendall Station with Grand Junction service (blue is before, green is after)

Travel times to North Station stay roughly the same for most of the region, with the notable exception being the Western Corridor. Access to the Boston area suburbs is currently segmented by the commuter rail system, as all trains terminate at either South or North Station. While other solutions such as the North-South Rail Connector are currently being proposed, it is interesting that a seemingly unrelated improvement to train service on freight tracks through Cambridge could end up having a significant impact on this same gap in the transit network. This is the exact trend that could help lower the difference in transit usage for MIT commuters to the west along the Fitchburg and Framingham commuter rail lines, as was discussed in Section 5.3.2.

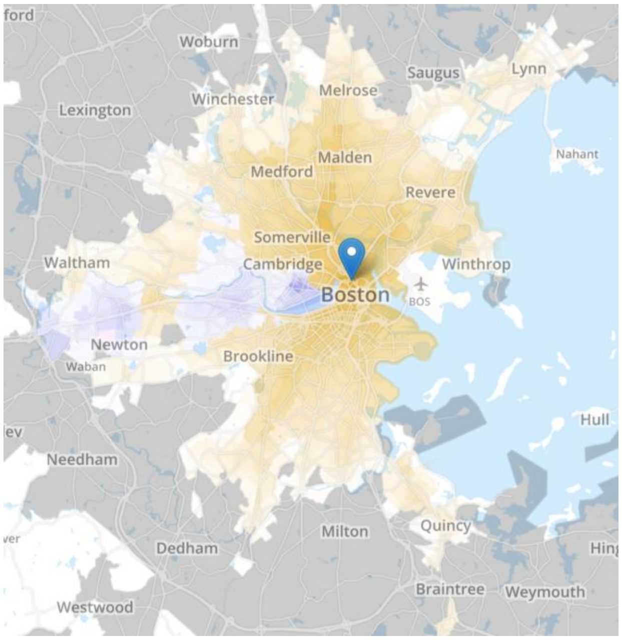


Figure 6.18: Changes in areas accessible to North Station

However, because the change in travel times to the Western Corridor from North Station is on the order of 5 minutes or less, and because of the low density of jobs and housing in the Western Corridor, the difference between incremental accessibility to North Station before (green) and after (blue) making these transit improvements is not significant, and the green and blue lines are barely distinguishable in Figure 6.19, creating a less transformative change at North Station than at West Station or Kendall.

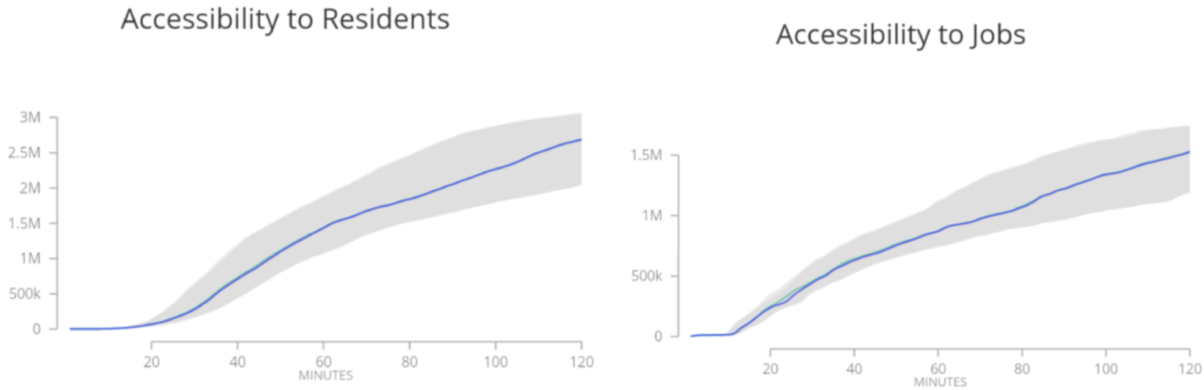


Figure 6.19: Changes in accessibility of residents and jobs to North Station with Grand Junction service (blue is before, green is after)

6.4.3 Extension of Grand Junction Service to the West, Along Existing Western Corridor Commuter Rail Lines

Another proposed service addition is to extend this service along the Framingham/Worcester tracks to the Riverside terminal of the Green Line. While no additional stops are served by this pattern that were not already served by some sort of rail service, the direct links that this new service will provide as well as the improved frequency of transit service could be sufficient to attract additional users out of their private vehicles and onto transit. This is particularly true because transfers are considered to be onerous to transit passengers, equivalent to 5 to 10 minutes of additional travel time beyond the time spent waiting for an additional vehicle to arrive. Changes in travel times by transit are shown in Figure 6.20 from the Western Corridor to Kendall, between providing Grand Junction service with a transfer at West Station and providing a direct DMU service along the Grand Junction through West Station out to Auburndale. The result is better coverage throughout the entire corridor served by the extended service, but not beyond the terminal at Route 128.

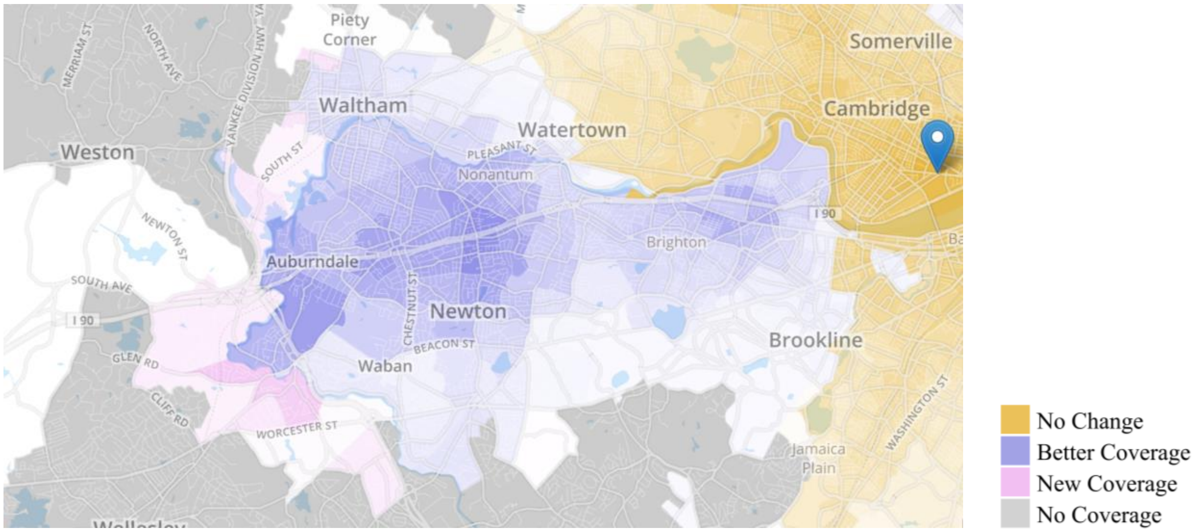


Figure 6.20: Changes in areas accessible to Kendall

Because in the short-term commuter rail frequency is, and will continue to remain, relatively low, with a maximum of two trips per hour, transfer potential from a 10-minute headway Grand Junction service is limited, which is what causes the difference in travel times. If transfers were timed, there would be no difference in travel time at the same frequency, as long as the platforms are assumed to be close together. Cross-platform timed transfers are currently used in other heavy rail systems, such as BART in the San Francisco Bay Area. In the short term, when West Station is not a high traffic origin or destination and rather predominately a transfer point, it would make sense to schedule the DMU service based on the commuter rail schedule, in order to increase the convenience of these transfers. This would be possible with headways as low as those described in Table 6.3, at a minimum of 30 minutes during some peak hours. This would likely have minimal infrastructure impacts in Cambridge, for example the single track portions of the Grand Junction would be sufficient to carry this low level of service. Vehicle procurement and better signaling at intersections would still be necessary. This low headway service along the Grand Junction would be a good short-term solution, especially since improvements in headway without extension of the service would not provide significant increases in accessibility over timed transfers from the short shuttle in the short-term. However, increasing commuter rail frequency also needs to happen in order to enable sufficient throughput capacity.

However, these low headways would not have sufficient capacity to carry growth in the area. Therefore, the proposed service should have headways of 10 minutes during peak hours and 15 minutes during the off-peak, with each third vehicle extending service out to Auburndale. The short pattern shuttles will time their arrival at West Station with a commuter rail vehicle, whenever possible. This proposed service matches well with the existing commuter rail schedule, the short-term uses of the transit corridor, and would provide sufficient capacity to serve growing travel demand in the longer-term.

6.4.4 Other Service Patterns

Once DMU vehicles have been procured, there are a variety of different patterns of operation. For example, all or most Framingham/Worcester commuter rail vehicles could terminate at West Station, forcing transfers to two separate DMU shuttles, one through Kendall to North Station and the other through Back Bay to South Station. If these transfers are timed, this could better utilize existing vehicle and infrastructure constraints and more efficiently serve a larger number of origin-destination pairs, though technically not with direct service. If transfers are not timed, this change would not be welcomed by many users, unless the service operates with high frequency.

Given track constraints through Back Bay and platform constraints at South Station, increasing frequency on the West Station to South Station shuttle service may not be possible. This shuttle is also semi-redundant with the Green Line B branch, and so it does not increase local accessibility beyond extending capacity. If the North-South Rail Link project is pursued, this link could be part of a larger network to complete some segments of the urban ring. However, under the current 2030 planning horizon, switching from commuter rail vehicles to DMU vehicles from West Station through Back Bay to South Station does not provide many additional benefits in accessibility, and it may worsen the trip for existing commuter rail users by forcing a transfer.

6.5 Projected Changes in Relative Accessibility and Mode Choice

Under this optimistic view of future conditions in the Western Corridor, it is expected that accessibility by transit will improve to a greater degree than accessibility by auto. Potential transit improvements are plenty and in this scenario, all potential improvements will be considered to have been completed. While the auto network will benefit slightly from all-electronic tolling and the straightening of the turnpike through Allston, this impact is not expected to be significant for capacity or travel time. One proposed change to the highway network that is worth noting is the reconfiguration of the Allston off-ramps, as is currently being tested by MassDOT. If better connections are provided toward the Longwood Medical area by connecting the turnpike not just to Cambridge Street but also to Commonwealth Avenue, there could be a significant benefit in reducing local street congestion.

A larger benefit to the auto network will occur if enough drivers are diverted to other modes (including carpools) and demand returns to levels within practical road capacity. If a network is operating just below capacity, travel speeds could be close to free flow travel. However, if network demand is just slightly higher and exceeds capacity, or if a random traffic variations occur, conditions become much more unstable and travel speeds diminish drastically. While the drop in throughput is concerning, the quick transition between stable and unstable traffic conditions has negative impacts as well, as it may require the addition of reliability buffer time to ensure on-time arrival at a destination.

By modifying the two main factors of accessibility for auto and transit, network travel times and number of jobs, in the mode share by accessibility equation used in Section 4.4, the potential future of mode share in the Western Corridor can be estimated. This is achieved by using the same regression model as in Section 4.4 with $N_{nonauto}/N_{auto}$ as the output, where for each mode N is the number of commuters and A is the accessibility, defined as the number of jobs within a 60-minute commute with a distance-decay so that closer jobs are weighted more highly. The number of jobs in the area is independent of mode choice, and under a high-growth scenario the number of jobs within a 60-minute commute is expected to increase for both transit and auto. However, given the infrastructure changes proposed, accessibility to jobs is expected to increase more for transit than it is for auto, and thus the ratio of transit accessibility to auto accessibility is expected to increase. The β_0 and β_1 parameters in this equation will remain the same as under present conditions, assuming commuter preferences and behavior stay about the same. Under these assumptions, the following equation that was previously used for regression in Chapter 4 can now be used to predict the ratio of non-auto mode share to that of auto mode share.

$$\left(\frac{N_{non-auto}}{N_{auto}}\right) = \beta_0 e^{\beta_1\left(\frac{A_{transit}}{A_{auto}}\right)} \qquad \text{(4.1 revisited)}$$

N = number of commuters
A = accessibility

Modeled results for present day conditions produce a $N_{nonauto}/N_{auto}$ ratio of 0.362, which corresponds to a 73.4% auto mode share and a 26.6% non-auto mode share. For future predictions, under the assumption that accessibility by transit will increase to a larger degree than accessibility by auto given highway constraints, auto mode share is expected to decrease and non-auto mode share is expected to increase.

By increasing transit accessibility in the Western Corridor based on the future scenario proposed, auto mode share decreases to 71.8% in the entire Boston area, a 2% overall decrease. Isolating zones just in the Western Corridor, auto mode share decreases from 65.5% to 59.0%, meaning almost 10% fewer commute trips are being made by auto (these values are lower than those for the greater Boston area in both cases due to the exclusion of many more suburban zones than urban ones).

This model equation simplifies the cyclic effect between mode share and accessibility – so that, as demand for a mode increases, in the absence of changes to capacity, it becomes a less desirable and slower choice, due to crowding causing discomfort and congestion, and leading to slower travel times. The Cube model outputs, that these results are calculated from, takes this into account as congested travel times reflect assignment changes in the new transportation network. It also integrates changes in customer preferences and comfort over time to a certain extent, as some attributes such as value of time are segmented by income level and other socioeconomic characteristics.

The results of this exploration into changes in mode choice due to changes in relative accessibility provide justification for investment in transit infrastructure improvements in the Western Corridor, as a 20% increase in relative accessibility of transit is predicted to increase non-auto mode share by 10%. This demonstrates the perceived direct link between changes in relative accessibility and mode choice and how a modal shift can be accomplished by strategic infrastructure improvements.

6.6 Capacity Modifications to Accessibility

While it is clear that these infrastructure improvements will increase transit accessibility, both between already linked locations and more directly for new origin-destination pairs, this will only be useful to growth in the Boston area if supply is sufficient to meet demand. Current transit service and supply was introduced in Section 2.4, and is summarized below.

Table 6.5: Current Western Corridor transit service (number of trips per period)

	Weekday		Peak	
	Inbound	Outbound	Inbound AM	Outbound PM
Commuter Rail	24	24	9	8
Green Line D	138	138	30	30
Turnpike Buses	223	214	111	94
Grand Junction	0	0	0	0

In order to meet growing demand in transportation, additional capacity will need to be added to each of these services. Because there is additional space on the commuter rail tracks, more service can be added if more vehicles can be procured. Therefore, it is assumed that frequency on the Framingham/Worcester commuter rail line could be increased by 50% to 36 trips in each direction per weekday relatively easily. Service on the Green Line can be expanded by purchasing additional vehicles to convert some D-line two-car trains into three-cars, particularly during peak hours, since the tracks are capacity constrained, particularly through downtown where they are shared with the other Green Line branches. Turnpike buses, running on existing roads, are also only constrained by vehicle procurement, so it will only be effective to increase frequency on these services if it is possible to maintain stable conditions on the turnpike. Grand Junction service, when first introduced, is assumed to run at 10 minute headways through Cambridge during the peak and 15 minute headways through Cambridge during the off-peak, with each third trip completing the extension to Auburndale on the commuter rail tracks.

Based on these assumptions, in order to meet projected demand, calculated in Section 5.3, the following frequencies are proposed using back-of-the-envelope calculations from projected demand:

Table 6.6: Proposed Western Corridor transit service (number of trips per period)

	Weekday		Peak	
	Inbound	Outbound	Inbound AM	Outbound PM
Commuter Rail	36	36	12	12
Green Line D	138	138	30	30
Turnpike Buses	223	214	111	94
Grand Junction	92	92	18	18

It is assumed that each additional commuter rail vehicle can carry 600 to 900 passengers, but that optimally it will only carry 600 passengers due to comfort restrictions for the relatively long travel time (MBTA Service Planning Unit, 2010). Switching to three-car trains during peak hours on the Green Line will add additional capacity of 100 to 125 passengers per train, leading to a capacity of 300 to 375 passengers per existing or new trip. It is assumed that vehicles can be filled to the upper end of capacity, and that three-car trains will be used during the peak and two-car trains during the off-peak. Turnpike buses can carry 40 to 70 passengers, though since this service travels on congested roadways, it should not be expanded unless turnpike flow can be maintained at a reasonable quality, and unstable flows are avoided. Comfortable capacity is defined at 50 passengers so that most can get a seat while traveling on the turnpike.

Finally, DMU vehicles tend to hold around 120-170 passengers per car, and two-car trains seem feasible for initial service due to the quick travel time through the many at-grade crossings in Cambridge. It is expected that DMU passengers will be willing to stand for the short duration of this trip, so capacity is calculated at the upper end of the range for this mode. Therefore, these improved frequencies will lead to the following overall transit capacity through West Station, or a point parallel to it, in terms of number of comfortable passengers:

Table 6.7: Proposed Western Corridor transit capacity (number of passengers)

	Weekday		Peak	
	Inbound	Outbound	Inbound AM	Outbound PM
Commuter Rail	21,600	21,600	7,200	7,200
Green Line D	38,300	38,300	11,300	11,300
Turnpike Buses	11,200	10,700	5,600	4,700
Grand Junction	31,300	31,300	6,100	6,100
Total	**102,400**	**101,900**	**30,200**	**29,300**

This supplemented service, theoretically sufficient to carry growing demand in the Western Corridor alongside the turnpike, is used as an input to the Cube model in order to measure the impact of these transit improvements on the auto network using the four-step model, described in the following section. The current model in Cube considers transit capacity as a static, maximum level of throughput rather than as a function of volume as is done on the roadway, but since these levels of service should allow demand to remain below capacity this should not impact the results.

6.7 Changes to Auto Accessibility due to Induced Mode Shift

In order to generate the projected changes in auto accessibility that these transit improvements will allow for, the four-step model needs to be re-run using the new network. This is necessary in order to measure the impact of congestion after re-assigning trips to the new paths available, so a simple shortest-path routing would not be sufficient. The model was run using the projected 2030 socioeconomic characteristics described in Chapter 5. This step is necessarily to ensure that transit service is not only available at the sufficient capacity, but that its level of service is high enough to induce the appropriate modal shift. Improvements in the Western Corridor and in the region as a whole, as described in Section 5.5, are all included in this final run of the four-step model, and results are projected in Figure 6.21. Each zone is colored by the number of workers accessible within 60-minutes under the calibrated travel time decay function. With these improvements, accessibility to workers is projected to stay roughly equivalent to current values, which is a more promising future than the degradation of accessibility when no changes are made, as was shown in Figure 5.11.

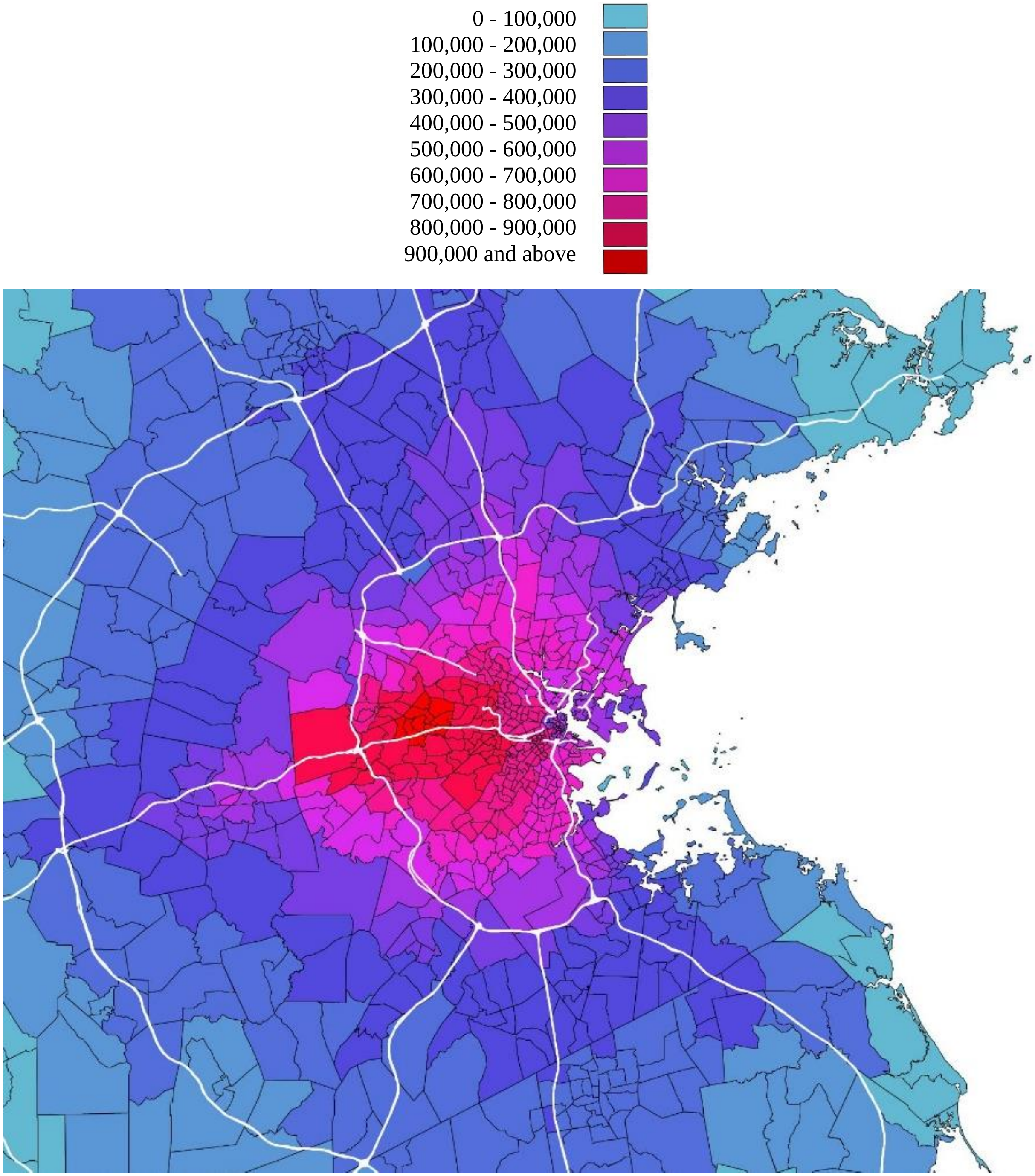


Figure 6.21: Projected 2030 accessibility to workers by auto

In the absence of improvements to the transit system, the impact of growth in transportation in this planning horizon would have a strong negative impact leading to the degradation of conditions in the network. Demand on the turnpike was modeled at 82,000 vehicles per day, beyond effective capacity and in the unstable range described in the highway capacity manual during peak hours. However, due to the added capacity provided by the new transit services, this additional demand in transportation can be met in the Western Corridor. The following table provides approximate values for projected volumes on all transportation options in the Western Corridor if the improvements described in this thesis are implemented in full.

Table 6.8: Projected 2030 travel demand through Allston Interchange / West Station

	Weekday		Peak	
	Inbound	Outbound	Inbound AM	Outbound PM
Turnpike	74,000	74,000	23,000	23,000
Commuter Rail	11,400	11,100	7,200	7,200
Green Line	27,200	28,800	9,000	9,000
Turnpike Buses	5,300	4,900	2,600	2,200
Grand Junction	8,800	7,400	4,400	3,700
Total	**126,700**	**126,200**	**46,200**	**45,100**

Maintaining turnpike volumes by accommodating travel growth on transit, by encouraging existing and new users to shift modes, will be the only way projected economic and transportation growth can be accommodated in the Western Corridor in the 2030 planning horizon. In fact, some of the transit services, such as the Grand Junction shuttle, will still retain excess capacity by this time. This will allow for growth beyond the 2030 planning horizon as well.

6.8 Allston as a Growth Node

Growth by 2030 can be inferred from construction records and existing zoning regulations, and is relatively predictable. Growth beyond that planning horizon is less certain. Dense employment areas like Kendall Square and Longwood Medical Center will eventually run out of space, or at least space on which continued affordable development could occur. If growth is to continue, it will probably need to occur in a new area. Much of the Boston urban core already has high job density, and Beacon Park Yard is one of the few locations with empty space still available, as depicted in Figure 6.22.

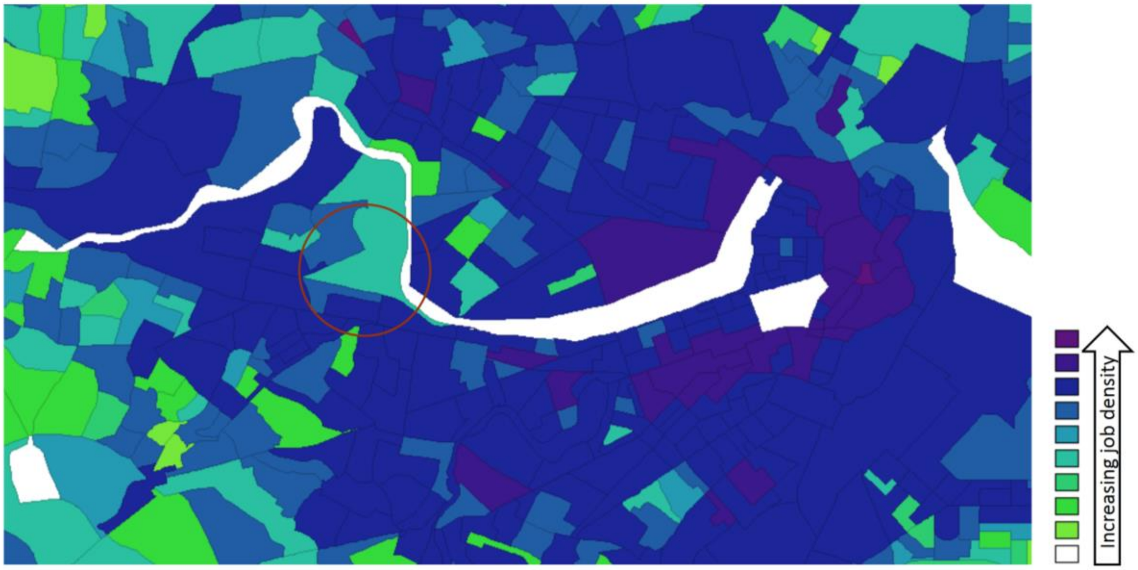


Figure 6.22: Job density in the Boston urban core

Once the construction of the reconfigured Allston Interchange is completed, there will be a large amount of developable land opened up with high accessibility, and thus capable of becoming a new growth node. The square footage available could rival that of the Prudential Center, a similar development built on land previously occupied by transportation infrastructure. Beacon Park Yard, or the location of the new West Station in Allston, already has high accessibility by auto, but that is not sustainable for high density growth, as explored in the Zupan density observations in Section 2.1. West Station will help provide the necessary transit accessibility. It is clear from the results of the accessibility-based analysis that the addition of West Station, increased commuter rail frequency, and new DMU shuttle service will greatly improve transit accessibility to this area, and will likely be able to sustain any development that should occur. Another way to improve accessibility would be to add an additional station on the Grand Junction service at the new Lechmere Green Line station near the North Point development. This would improve accessibility to residents at West Station as well as to Kendall Station. Kendall Station and Lechmere are already linked by the EZ Ride, but DMU service should be faster and more reliable and will introduce a new transit link to West Station, allow future residents to reach future employment in Allston. The corresponding changes in travel time isochrones and accessibility to workers due to the transit improvements proposed in this chapter are visualized in Figures 6.23 and 6.24.

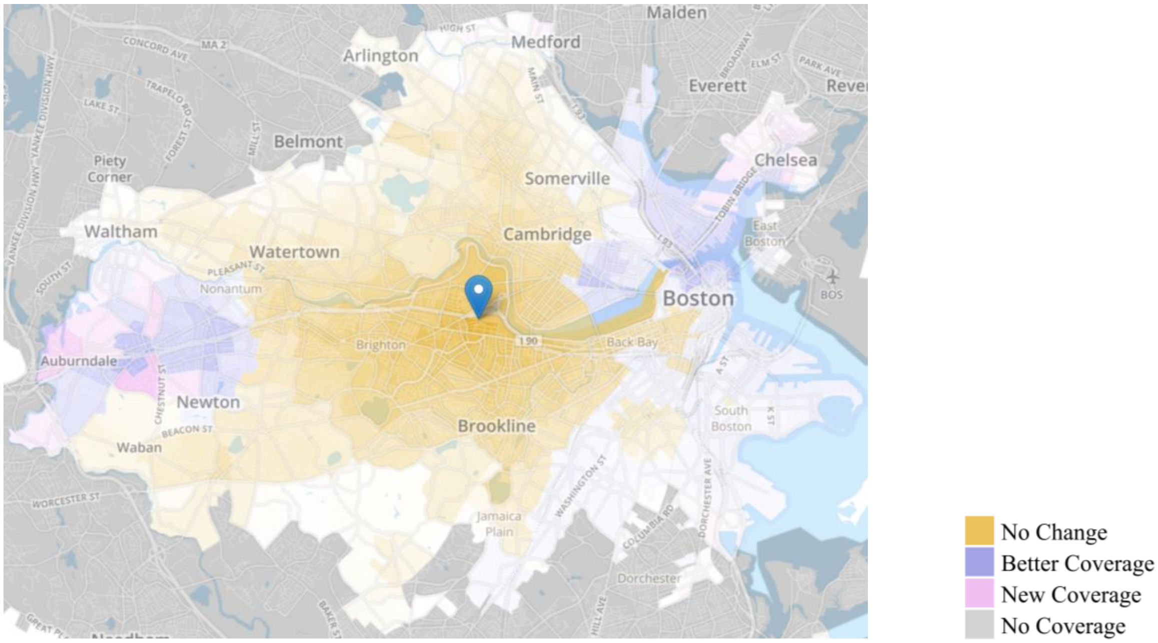


Figure 6.23: Projected changes in travel time isochrones from West Station

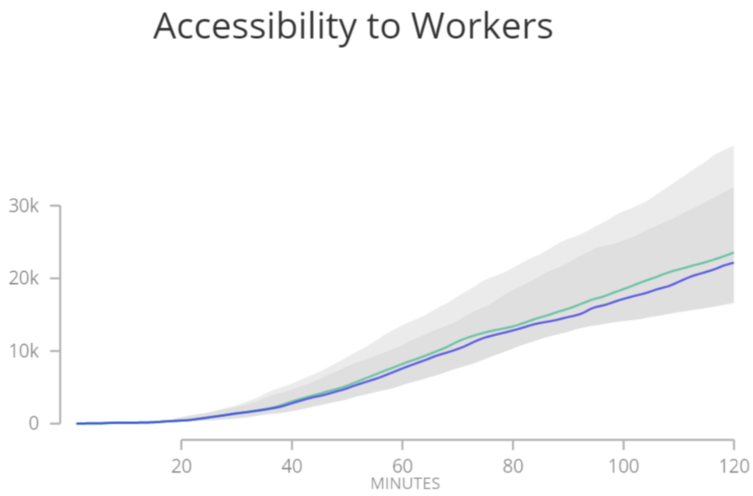


Figure 6.24: Projected changes to accessibility to workers at West Station (blue is before, green is after)

Chapter 7 – Conclusions

In the context of economic growth in the Boston area, strategic investments in transportation infrastructure need to occur in order to avoid stifling growth and discouraging employers and residents from investing in the region. In this thesis, a high capacity transit system was added to the current network in order to help accommodate growth that could not be served by the auto network alone. Using projected economic trends and corresponding transportation network demand, including modal preferences, a system was designed that could adequately serve the travel demand projected for the 2030 planning horizon.

7.1 Findings and Recommendations

In order to accommodate an increase in Western Corridor transportation demand, making improvements to the transit network will be much more effective than making improvements to the auto network, though both will be necessary and possible to a certain extent. Therefore, a multi-modal transportation system was designed to serve future demand by 2030, and to induce a modal shift from auto to transit.

The DMU shuttle along the Grand Junction from North Station through Kendall to West Station and the longer shuttle out to Newton and Route 128 both serve new transit origin-destination pairs directly. Providing additional DMU shuttles, such as one from South Station through Back Bay to West Station, and varying levels of commuter rail service, could also help meet this demand in the longer term once other transit network constraints are resolved. Interestingly, these improvements to the Western Corridor can also have positive impacts on accessibility for other areas, such as providing a one-seat ride from North Station to Kendall rather than forcing a transfer between the Green and Red Lines for this trip, or onto congested roads on the EZ Ride.

In this analysis, comfort was considered as part of transit capacity constraints. In past research, it has been shown that capacity constraints on transit can have a significant impact on operations, including unreliability as demand approaches capacity. Capacity can be loosely defined as percent of seats occupied, people per square foot, or number of passengers standing. In this thesis, for longer-distance services, such as commuter rail, comfortable capacity is defined as 100% of seats occupied. For shorter-distance services, such as rapid transit, it is defined as full standing capacity. Comfortable capacity is not necessarily a binding constraint, as a passenger who will need to stand on a long distance trip will still be able to board the vehicle and arrive at the correct time. However, it may have an impact on future travel, especially for choice users.

This is particularly relevant for routine commute trips, where a mode shift to transit will be necessary but will only be sustainable if comfortable capacity is maintained.

While buses must run on congested roads and are less reliable than rail, they are an important piece of the transit network, especially for the last few miles of long commute trips. If turnpike congestion can be mitigated to avoid unstable flow, express bus service expansion to the Innovation District and increased frequency on existing services are both recommended. Strong bus connections at West Station are therefore necessary, especially in the time before local development occurs, in order to allow for effective use of this new station. Some simple adjustments, such as extending routes 64, 66, and 70 to stop at this station, were considered in this analysis, but additional new routes could be introduced in the future in order to serve even more demand.

Not all users will be able to use the transit system, even after these improvements, for a variety of reasons. These include proximity to a station and complicated multi-trip commute paths, such as daycare drop-off or shopping within a home-based work trip. To help serve these passengers by auto, a possible traffic decrease on the turnpike due to the induced mode shift will be necessary. This will bring conditions into a more stable range, though not necessarily to one that is uncongested during peak hours, which is expected as any excess roadway capacity will likely be refilled by induced demand.

As West Station is being planned, many of these ideas are being integrated into the process. For example, full bus and pedestrian connections are being planned at the station, but no park-and-ride is included despite it being a commuter rail station. This indicates that MassDOT sees this as a more urban location, that rapid transit will serve more effectively in the future than commuter rail. However, this could have some impacts on travel behavior for people with limited mobility, as the area around Allston is not currently very dense and most residents will have to walk at least half a mile, which is not feasible for everyone. Still, there will be a drop-off facility, which may be useful for some.

This thesis worked backwards from what is possible given the constraints of the transportation network, by designing a transit system capable of serving growth in the Western Corridor. While this high capacity design is favorable, it is possible to push back onto a slightly lower capacity system that can still help the area, as a short-term, cost-effective solution, and of course, leaving the potential for expansion of this service in the future. For this research, the DMU service proposed is a North Station to West Station shuttle, which can eventually be expanded to Route 128. The framework of this thesis is to start modeling transit capacity as high as possible, and then work backwards to capacity that is actually required to alleviate all constraints to growth. This is an effective strategy in the context of capacity constraints that could restrict economic development.

7.2 Future Research

There are a variety of applications of using an accessibility-based analysis to investigate other infrastructure projects in the Boston area, as well as in other parts of the world. The impact of congestion on travel times and of economic growth on transportation network demand are both very important, and when considered together can provide valuable information on the attractiveness of different areas to employers, residents, and employees.

In this thesis, parking constraints were included in the model in Cube Voyager, and had an impact on modal split, trip assignment, and thereby network congestion. However, these constraints, and particularly changes in parking price or availability were not explicitly subjected to sensitivity analysis. Parking limitations are expected to play a large role in mode choice decisions, especially as employers are moving more toward market-based pricing and non-auto commute incentives, and this topic is ripe for additional exploration in the context of accessibility and mode choice.

Throughout this research, accessibility was calculated using average travel time, usually during peak hours. However, the variability in travel times during the peak could have a large impact on observed travel times, if users are inclined toward planning using a reliability buffer time. Further research could explore this impact, to understand how it affects perceived accessibility and mode choice. It is expected that individuals and developers use their current perception of travel time to make investment decisions, such as where to locate, but will eventually change their behavior, such as how and when to commute, in real time as they better understand the situation from actual experience. This would be especially interesting when projecting changes in travel times into the future, as this disconnect between current perception and eventual reality continues to evolve. Therefore, adding future reliability buffer time to calculate actual future accessibility could be a very interactive planning tool. Availability of Bluetooth data makes it clear that reliability is already low, and appears to be getting worse just over the past few years.

Once DMU vehicles have been procured by the MBTA, there are many other service patterns for which they could be utilized on other existing railway tracks in order to provide more rapid transit on existing commuter rail routes with relatively low infrastructure costs. Accessibility-based analysis of other patterns of service could be useful to determine where these new vehicles would be best placed, which will be possible given the data on accessibility that will become available to MassDOT this summer. DMU vehicles could also be replaced by EMU vehicles, providing higher capacity but at a higher cost.

It was determined that in the Western Corridor, improvements to the transit network could be sufficient to stabilize traffic volumes on the auto network at current levels. These sorts of changes will be necessary in order to help meet MassDOT’s goal to triple non-auto mode share in Massachusetts from 2010 levels by 2030. However, in order to determine whether and how this goal can be met, this same analysis needs to be done for the entire state of Massachusetts. It seems promising that with appropriate and strategic infrastructure investment, this goal can be met, but further analysis is required to determine the level of investment necessary and the corresponding modal split.

7.3 Closing Remarks

In the absence of improvements to the transit system, the impact of growth in transportation demand in this planning horizon would have a strong impact on the degradation of conditions in the network. It is prudent that for future projects capacity constraints be anticipated before they lead to unfavorable consequences and while they can still be easily resolved. This approach would be more cost-effective in the long run than the current reactionary approach to transportation planning utilized by most governments and planning departments.

Throughout history, it has been shown that investments in infrastructure pay off much more than is initially invested. However, this investment cycle needs to be continuous, as the state is faced with aging infrastructure and degrading conditions, both structurally and operationally, and elements reach the end of their effective life cycle. This transition point also provides a unique opportunity for better design of new construction now that lessons have been learned from past successes and failures. This includes designing a more effective network structure that can serve demand in a more sustainable way, not just what we have come to expect given current and past experience.

Of course, developing the political will to finance additional transit investments is required to achieve the expanded multimodal capacity and improved quality of flow to support continued economic growth, as is proposed in this thesis. But the first step toward building necessary infrastructure is to identify the investment required, and the benefits that can be produced, in order to inform the political process and shape appropriate policy.

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