Planning Transit Networks with Origin, Destination, and Interchange Inference

by

Catherine Vanderwaart

B.A., Swarthmore College (2003)

Submitted to the Department of Civil and Environmental Engineering
in partial fulfillment of the requirements for the degrees of
Master in City Planning
and
Master of Science in Transportation
at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
February 2016

Author . . . .
Department of Urban Studies and Planning
Department of Civil and Environmental Engineering
January 25, 2016

Certified by. . . . .
John P. Attanucci
Research Associate, Department of Civil and Environmental Engineering
Thesis Supervisor

Certified by. . . . .
Frederick P. Salvucci
Senior Lecturer, Department of Civil and Environmental Engineering
Thesis Supervisor

Accepted by . . . .
P. Christopher Zegras
Associate Professor
Chair, MCP Committee, Department of Urban Studies and Planning

Accepted by . . . .
Heidi M. Nepf
Donald and Martha Harleman Professor of Civil and Environmental Engineering
Chair, Departmental Committee for Graduate Students

Planning Transit Networks with Origin, Destination, and Interchange Inference

by

Catherine Vanderwaart

Submitted to the Department of Civil and Environmental Engineering
on January 25, 2016, in partial fulfillment of the
requirements for the degrees of
Master in City Planning
and
Master of Science in Transportation

Abstract

The institutional and financial circumstances at many transit agencies significantly constrain the bus planning process. Long-term planning focuses on major infrastructure projects, while short-term planning focuses on scheduling and minor service adjustments. Medium-range bus planning is given limited attention in many agencies, especially those with significant capacity constraints.

Recent research has developed a new method of assembling data that has the potential to be very useful to service planners: origin, destination, and interchange inference (ODX), which uses farecard and vehicle location data to provide a previously unavailable level of geographically precise disaggregate data on passengers' linked trips.

This research develops a framework for using ODX for medium- to long-range bus planning. It proposes a service planning process that targets limited resources at the areas that need them most. It develops tools and methods for using ODX data to design and evaluate realistic, practical, and incremental service changes to improve accessibility to key parts of the agency's service area. The process has five phases: identification of target locations, analysis of those locations, development of proposed service changes, evaluation of those proposals, and post-implementation review.

Several case studies are presented using data from the Massachusetts Bay Transportation Authority (MBTA), the transit agency for the Boston region. First, three target locations in the MBTA service area are analyzed. Service changes that would improve access to each of these locations are proposed and evaluated, including additional frequency on an existing route, the creation of a new route, and extensions of two existing routes. ODX and related data are used to analyze each proposal in detail in a process that can be replicated by other agencies with similar data.

Thesis Supervisor: John P. Attanucci
Title: Research Associate, Department of Civil and Environmental Engineering

Thesis Supervisor: Frederick P. Salvucci
Title: Senior Lecturer, Department of Civil and Environmental Engineering

Acknowledgments

To my advisors John Attanucci and Fred Salvucci, thank you for your wisdom, guidance, and support. Our weekly research meetings were some of the most educational moments in my time at MIT.

To the many people at the MBTA who supported this work, especially Laurel Paget-Seekins, Dominick Tribone, Brian Kane, Melissa Dullea, Greg Strangeways, and Brian Francis, thank you for answering my questions and offering suggestions for the project.

To Jay Gordon, who created ODX, Raphael Dumas, who brought it to the MBTA, and Gabriel Sánchez-Martínez, who manages the data warehouse where it lives, thank you for laying the technical foundations that made this thesis possible, and for sharing your technical expertise and SQL code.

To my fellow Transit Lab students, thank you for the support and camaraderie, and for making coming to work every day so enjoyable. Thanks especially to Raphael Dumas, David Maltzan, and Chris Southwick for the shared summers at the MBTA.

To Sandy Wellford, Kirsten Greco, Ginny Siggia, Shannon McCord, Ruth Yiu, Kiley Clapper, Kris Kipp and the rest of the DUSP and CEE administrative staff, thank you for making everything run so smoothly during my rather complicated time at MIT.

To my children Anna and Nathan, thank you for adding such joy to a time of hard work, and for pointing out every bus that passes by.

And finally to my wife Elisabeth, without whom this thesis would not have been possible, thank you for supporting me when I decided to go back to grad school, for doing so much for our family at work and at home, and for your love and encouragement all these years. We can do hard things, but maybe we won't have to for a little while.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

The bus is the most flexible and adaptable mode available to transit planners. Compared to subway tunnels, light rail tracks, or even Bus Rapid Transit ("BRT") busways and stations, the infrastructure associated with an ordinary bus route is minimal. Adding a new route can be as simple as putting up signs, installing benches, and publishing a schedule. This adaptability means that as a city grows and changes, the best response from a transit agency begins with modifying its bus network.

For transit agencies in large cities, this is easier said than done. Despite the rapid growth of both population and employment in the Boston area over recent years, the Massachusetts Bay Transportation Authority ("MBTA") last added a new bus route in 1994 (Belcher, 2015). Constrained by limited financial resources, the agency runs about the same number of revenue hours of bus service in 2015 as it did 20 years ago (See Section 1.2.5 below). Not only is much of this service on the same bus routes as 20 years ago, but many of these bus routes were operated as streetcar routes a century ago.

A series of winter storms in February 2015 crippled transit service, focusing public and political attention on the MBTA. As the system recovered and the governor appointed a panel to examine the agency, an editorial in *The Boston Globe* called on the agency to re-think its bus map (Editorial Board, 2015). At the same time, a wave of start-up companies has introduced bus services in several cities that adapt their routes and schedules weekly, or even every day (Jaffe, 2015). The heightened attention focused on the MBTA, along with growing public awareness of the benefits that new approaches can bring to bus service, has created an opportunity for the agency to examine its bus network and route planning methods.

While the MBTA has not added new bus routes in decades, it has added new technology. An automated vehicle location system ("AVL") records the position of each bus along every route in the system over the course of the day. Plastic, contactless CharlieCards and magnetic-stripe paper CharlieTickets replaced the old subway tokens in 2006. The new system, often referred to as an automated fare collection ("AFC") system, records which farebox or subway faregate a passenger uses to pay for a ride, and at what time. Automated passenger counters ("APCs") on a portion of the bus fleet record how many people board or alight at each stop, and therefore how many people are on a bus at any given time. Taken together, these new data sources (collectively referred to as "automated data collection systems" or "ADCS") provide a wealth of information about how riders use the transit system and how well it functions.

This thesis explores the ways in which automatically collected data can inform bus network planning. In particular, it builds on past work that uses AVL and AFC data to infer passengers' origin and destination locations ("OD") and to link trip stages into full journeys by identifying transfers. This algorithm, called origin, destination, and interchange inference ("ODX") produces a richly detailed data set of passengers' journeys through the system. The ODX data set is the basis for the analysis in this thesis, including an evaluation of how riders currently use Boston's transit system and how they might be affected by changes to the bus network.

1.1 The Growth of Boston

The Boston metropolitan area is home to nearly 4.5 million people. The Metropolitan Area Planning Council ("MAPC") projects that the population will grow by 6.6 - 12.6% by 2040, representing an increase of up to half a million people (Metropolitan Area Planning Council, 2014). The lower growth estimate is the "status quo" scenario, while the higher estimate is MAPC's "stronger region" scenario. The latter scenario assumes, among other things, that the population will prefer urban living and living in apartments or condominiums instead of single-family homes.

MAPC presents the "stronger region" scenario as the best path forward for Boston, but achieving these goals will require economic development, housing, and other policies that encourage this sort of growth. Given the already capacity-constrained automobile system, it will also require a transit system that is able to meet the needs of the growing urban population and enable residents to own fewer cars and drive fewer miles.

In a separate report on transit-oriented development, MAPC projects that there could be 130,000 new jobs near rapid and commuter rail stations by 2035 (Metropolitan Area Planning Council, 2012). This job growth is likely to be concentrated in several rapidly growing areas of the city, such as Kendall Square and the Seaport District. The transit needs of growing job centers will be explored further in Chapter 5.

1.2 The MBTA System

This section first provides a short history of public transit in the Boston region, followed by a more detailed look at contemporary developments and an overview of the MBTA system as it exists today. The section then offers context for the research presented here, including identification of other transit service in the region, the need for changes to the transit system, and an overview of the current long- and short-term planning processes.

1.2.1 A Brief History of the MBTA

Public (i.e. collective) transportation has a long history in Boston. Stagecoaches began operating in 1793, followed by omnibuses in 1826. The first streetcar line, powered by horses, opened in 1856. Private companies opened new lines over the following decades. These companies were eventually consolidated in the late 1800's as the system was electrified, and key routes began to be grade-separated as subways and elevated lines. The streetcar system continued to be an important part of the city's transit network through the 1940's (Sanborn, 1993).

The first segment of the subway, from Park Street to Boylston Street on what is now the Green Line, opened in 1897. The subway continued to grow in segments for many decades: the Red Line from Park Street to Harvard opened in 1912, and was extended south to Ashmont in the late 1920's. The Quincy branch opened in 1971 and was extended to Braintree in 1980, while the northern end of the line was extended to Alewife in 1985. The elevated line (now the Orange Line) began service from Sullivan Square to Dudley Square in 1901 and was extended south to Forest Hills in 1909. The line was extended north to Oak Grove in the 1970's, and the southern portion of the line was relocated as part of the southwest corridor project in the 1980's (Sanborn, 1993).

As the subway expanded, bus and streetcar service changed and adapted. The first bus route began operations in 1922 (Sanborn, 1993), and over the next few decades the bus took over more and more streetcar routes, often retaining the route numbers. Today most of the streetcar routes operating in 1940 continue to be served by buses, as seen in Figure 1-1 (Clarke, 2003). Other bus routes were added and discontinued regularly through the 1970's and 1980's as new rail stations opened and the city grew (Belcher, 2015).

1.2.2 Recent Changes to the MBTA Network

Since the extension of the Red Line to Alewife, the relocation of the Orange Line, and the associated changes to the bus network in the late 1980's, the pace of change for all modes has slowed significantly (Sanborn, 1993; Belcher, 2015). While relatively minor bus route changes have been common, only two new services have been added since 1990: the crosstown bus routes and the Silver Line.

A new crosstown route from Central Square to Boston City Hospital, the 47, was instituted in 1975. It now continues past Boston Medical Center to the Broadway Red Line Station (Belcher, 2015). Though the 47 was very successful, there were very few crosstown routes for many years. In the fall of 1994, three new crosstown routes, named CT1, CT2, and CT3, were instituted (Belcher, 2015). These routes overlap substantially with existing bus routes but provide limited-stop service along more circumferential paths than were available before. The CT1 runs from Central Square to Boston Medical Center, sharing much of its length with route 1. The CT2 offers a much longer circumferential route than other service that existed at the time, running from Ruggles through the Longwood Medical Area across the Charles River to Cambridge and north to Kendall Square and Sullivan Square. The CT3 runs from

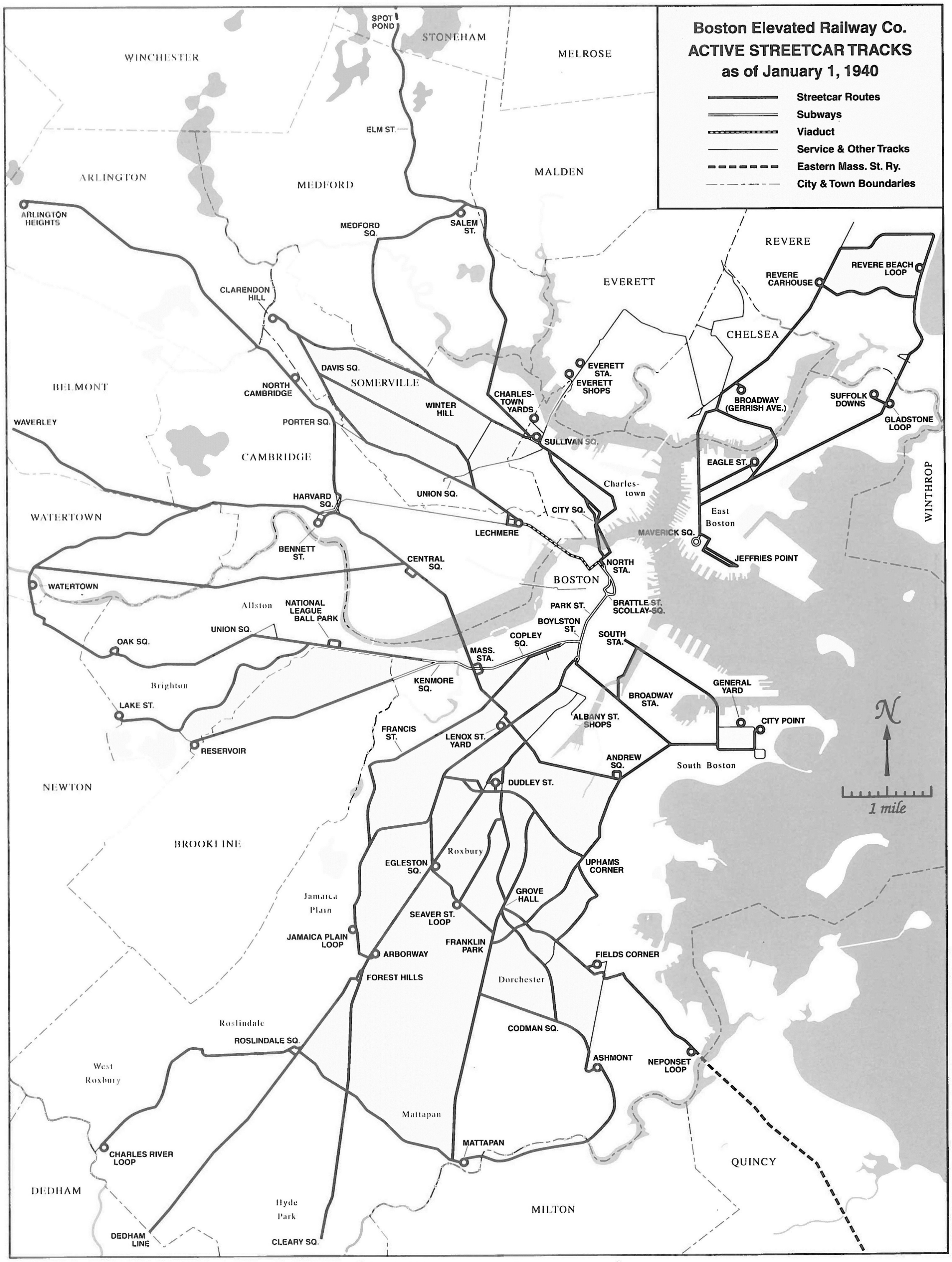


Figure 1-1: Active streetcar tracks, January 1, 1940 (Clarke, 2003)

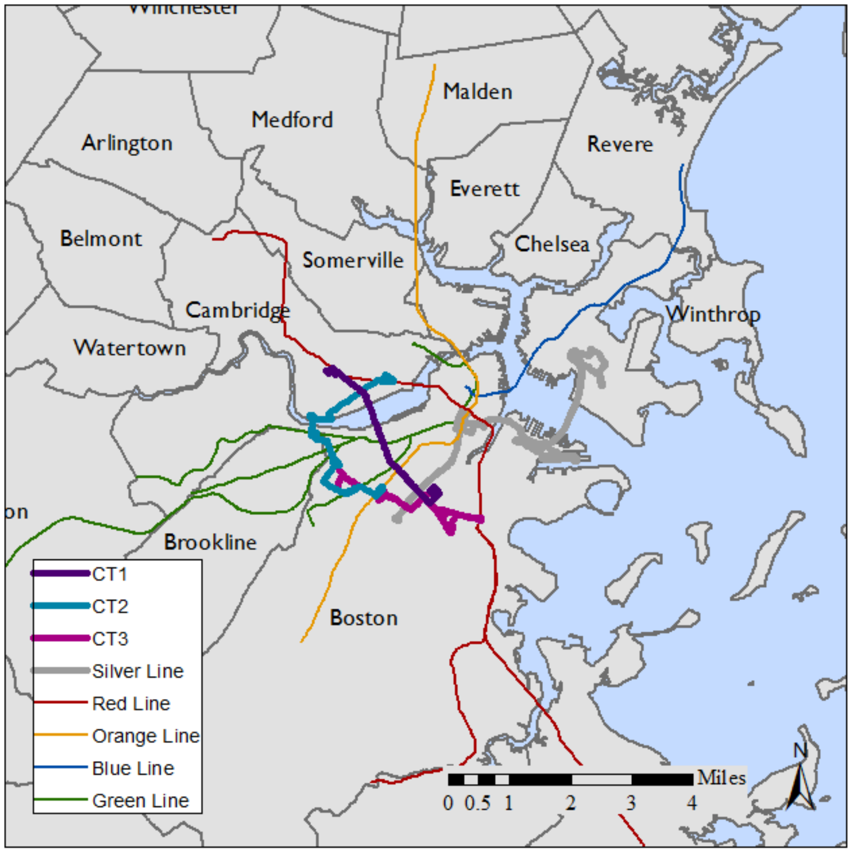


Figure 1-2: Silver Line and crosstown MBTA routes

the Longwood Medical Area to the Andrew Red Line station.

The other major expansion in recent years is the Silver Line. In 2002 the SL5 began operating BRT service along Washington Street from Dudley Square to downtown, and in 2009 the SL4 variant was added with service to South Station. The Silver Line Waterfront lines SL1, SL2, and SL3 opened in 2004, with a transitway tunnel from South Station to the Seaport District and service to Logan airport using dual-mode (electric and diesel) buses. The SL3 was later discontinued. These enhanced bus services are clearly branded and marked on the rail map in ways that distinguish them from the rest of the bus network, as seen in Figure 1-3 (Belcher, 2015).

1.2.3 The Current MBTA System

Today, the MBTA operates three heavy rail lines (the Red, Orange, and Blue lines), four Green Line light rail lines, the Mattapan high-speed trolley, four Silver Line BRT routes, and an extensive network of bus routes. All of these services accept CharlieCards and CharlieTickets. The system also includes commuter rail and ferry service, which are contracted out and operate on different fare systems. Figure 1-3 shows the rail, BRT, and Key Bus Routes for the system.

The system has nearly 1.3 million unlinked trips on a typical weekday, including

Figure 1-3: MBTA system map

approximately 540,000 trips on heavy rail, nearly 230,000 trips on the Green Line light rail, and almost 390,000 trips on bus (including the Silver Line). About 130,000 trips per day are on commuter rail, with the remaining few thousand trips on ferry and paratransit service (Massachusetts Bay Transportation Authority, 2014b). This ridership makes the MBTA the fifth-largest transit system in the United States.

The bus network includes 169 bus routes serving 8,100 stops over 745 route-miles via 13,000 bus trips daily. The routes include local, express, commuter, limited service, and crosstown routes. 15 of the routes with the heaviest ridership are designated as "Key Routes," with frequent service and upgraded amenities at stops.

The MBTA's service area includes 175 cities and towns with a combined population of 4.8 million people (Massachusetts Bay Transportation Authority, 2014b). Of these, 11 have service by all modes (heavy or light rail, bus, and commuter rail), 41 are served by bus and commuter rail, and the remainder are served only by commuter rail.

1.2.4 Other Transit Service in Boston

The MBTA is the region's public transit provider, but there are a number of other services operating in the MBTA's service area. Any analysis of MBTA service should be undertaken with an awareness of the role that these services currently play, particularly for mobility in certain parts of the city.

- The Charles River Transportation Management Association ("TMA") operates the EZRide Shuttle, offering weekday bus service between North Station and Cambridge serving Lechmere, Kendall Square, and Cambridgeport with peak hour headways of 8 to 10 minutes. The TMA is funded by employers and institutions in the EZRide service area in return for free rides for their employees and students. Members of the general public can pay a cash fare of $2.00 (Charles River Transit Management Association, 2015).

- The Medical Academic and Scientific Community Organization ("MASCO"), the TMA of the Longwood Medical Area, runs a number of shuttle services, mainly for employees of member institutions. Its M2 shuttle from the Longwood Area to Harvard via Massachusetts Avenue, which runs every 10 minutes during peak hours, overlaps significantly with the MBTA's route 1 bus (Medical Academic Scientific and Community Organization, 2015).

- A number of employers in the South Boston Seaport District run shuttles for employees. At up to 43 shuttles per hour in the peak, these services are a significant consideration when examining transit service to the Seaport District (Gordon, 2015).

- In 2014 a startup called Bridj launched as a "pop-up mass transit service" in Boston. The app-based service runs 14-passenger buses and changes routes based on demand. As of summer 2015, the service primarily runs from the Allston/Coolidge Corner area to employment centers like Kendall Square, Back Bay, downtown Boston and the Seaport District (Bridj, 2015).

- Several smaller and more specialized bus services operate around the region. Massport runs express buses to Logan airport from the Back Bay, Braintree, Framingham, Woburn, and Peabody. The Mission Hill LINK bus is operated by New England Baptist Hospital and connects the hospital to the nearby Roxbury Crossing Orange Line station. The Cambridgeside Galleria mall runs a shuttle to the Kendall Square Red Line station. A number of the colleges and universities in the area run their own shuttle services for students and employees. Other shuttles and local buses operate in suburban communities such as Alewife, Lexington, Waltham, Framingham, Needham, and Dedham (Massachusetts Bay Transportation Authority, 2014a).

1.2.5 The Need for Change

A 2012 report on crowding in the MBTA system found that ridership has grown by an average of 1.2% annually over the last twenty years, and that growth has accelerated in the last 5 years (Pollack, 2012). The report projects that continued growth will result in an additional 100,000 to 367,000 daily riders on the MBTA network within 10 years.

In particular, the report identifies five "hot spots," areas where transit demand is expected to increase significantly as projected residential and commercial development materializes. These hot spots are downtown Boston, Back Bay, Longwood Medical Area, the Seaport District, and Kendall Square. Chapter 5 will further explore the region's growth centers and the implications for transit.

Transit demand has been rising on its own, but in 2012 MassDOT announced a goal of tripling the mode share for transit, walking, and biking in Massachusetts between 2010 and 2030 as part of its GreenDOT environmental initiative (Massachusetts Department of Transportation, 2014). Realizing this goal will require policy changes that encourage more people to take transit, increasing demand on the MBTA network even further.

During this time of increasing population and ridership, the MBTA has been unable to expand service to meet rising demand. The number of vehicles operating in maximum service (i.e. fleet size) and the number of vehicle revenue miles for bus, heavy rail, and light rail were nearly constant over the period of 1992 - 2002 (Gordon, 2015), as seen in Figures 1-4 and 1-5. During this time bus, heavy rail, and light rail ridership grew by 20% and passenger miles traveled increased by 30% (Federal Transit Administration National Transit Database, 2013). The region's population increased by over 6% from 1990 to 2000 and grew another 3.5% by 2010 (Metropolitan Area Planning Council, 2014). Increasing ridership on the same service means that crowding levels have increased, and are likely to increase further.

Recent political and institutional changes have also created opportunities to re-examine bus service. After the MBTA struggled with the record snowfall in the winter of 2015, a special panel convened by recently elected Governor Baker led to the creation of a new fiscal and management control board (Scharfenberg, 2015a). This board began meeting in July 2015 to address the financial and management challenges the organization has faced in recent years. Also in response to the panel's recommendations, the Massachusetts legislature suspended the Pacheco law, which limits the ability of the MBTA to contract services to the private sector, for three years (Scharfenberg, 2015b). The temporary suspension of this law opens the door to contracting out some bus service, either to reduce costs or to expand service. The MBTA began exploring contracting options in August 2015 (Dunga, 2015).

1.2.6 Long-Term Planning

The MBTA's planning process has a number of layers. The highest level is the Program for Mass Transportation ("PMT"). The PMT, which is required by law, is a 25-year, fiscally unconstrained master plan that is updated every 5 years. Due

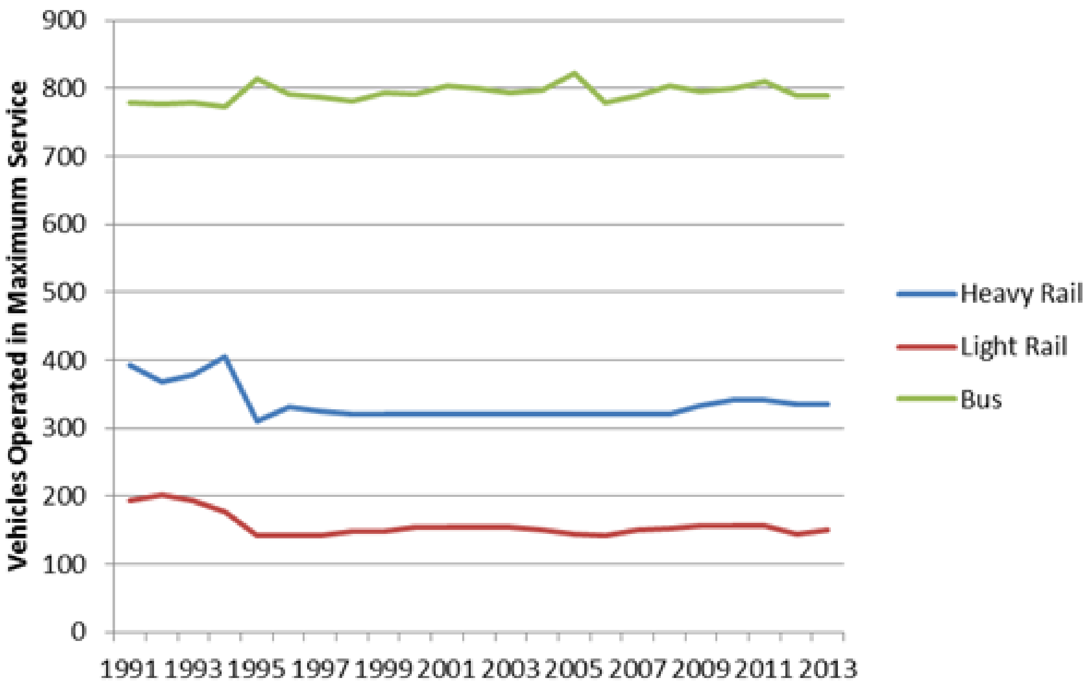


Figure 1-4: Change in MBTA fleet size, 1991 - 2013 (Federal Transit Administration National Transit Database, 2013)

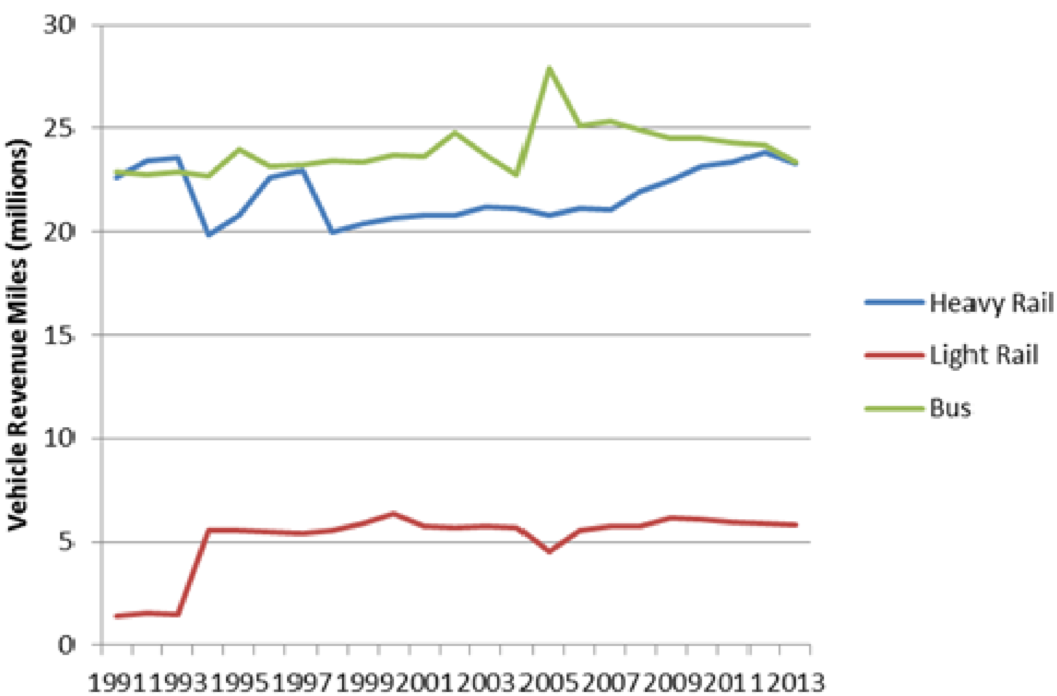


Figure 1-5: Change in MBTA service provided, 1991 - 2013 (Federal Transit Administration National Transit Database, 2013)

to its lack of fiscal constraints, it contains a wide range of large projects that would improve and expand service to the region but that may never receive funding for implementation (Massachusetts Bay Transporation Authority, 2009).

The most recent PMT, which is from 2009, divided the MBTA service area into seven regions. Each region was analyzed with respect to population and employment trends, traffic congestion, travel projections, and environmental justice. A number of "mobility problems" were outlined for each region, along with proposed solutions. These solutions ranged from increasing capacity on bus routes to major infrastructure projects.

The long-term vision developed in the PMT is implemented through the Capital Investment Program ("CIP"). This 5-year plan is fiscally constrained and updated annually, outlining which projects are going to be implemented and what sources will fund each. The PMT, therefore, contains many projects that would improve the transit system but that will not be implemented since funds are not available to include them in the CIP.

Changes to the network of ordinary bus routes require relatively little in the way of capital expenditures, so bus planning receives less attention than other modes in the PMT and CIP. The PMT calls for expansion of the bus fleet, but calls for these buses to be used mainly to increase capacity on existing routes (Massachusetts Bay Transporation Authority, 2009).

Most of the bus projects in the 2009 PMT are BRT projects. Two expansions of the Silver Line are proposed: The "Silver Line Phase III", a transitway tunnel to connect the Silver Line Washington Street to the Silver Line Waterfront via South Station; and the Silver Line Gateway, which would extend the Silver Line Waterfront from the airport into Chelsea. A transit tunnel under D Street to improve service on the Silver Line Waterfront is included as well.

The other major BRT project in the PMT is the Urban Ring, which has been discussed in various forms for decades. In the current proposal, it is a circumferential BRT route connecting the current Silver Line Waterfront route from the airport through Chelsea to Wellington, south through Somerville and Cambridge, across the Charles River through the Longwood Medical Area to Ruggles and north to the Seaport District. The locally preferred alternative from the most recent project study includes a transit tunnel under the Longwood Medical Area, which makes the project very expensive (A Better City, 2009).

The PMT also proposed adding "BRT features and technologies" to a number of existing routes, including many of the current Key Routes. The precise nature of these improvements is not specified.

The PMT also indicates some potential areas of improvement for the bus network. The possibility of additional circumferential service beyond the Urban Ring is raised. Improvements in a few suburban areas are suggested to make MBTA service useful locally rather than mainly providing access to Boston. These suburban areas include Lynn, Peabody, Salem, Beverly, Malden, Waltham, and Weymouth. Additional fixed or demand-responsive service is suggested for outlying areas in the west and southwest corridors, either directly provided by the MBTA or coordinated through partnerships.

Few of the bus projects proposed in the PMT are funded in recent CIPs. Funds are allocated in the most recent CIP for the purchase of new buses to replace the oldest portion of the fleet, as well as mid-life overhauls for the existing fleet, but these expenditures are not tied to any particular route. A small amount of funding is designated for bus stop amenities such as shelters and benches, but this is a minor piece of the overall plan (Massachusetts Bay Transporation Authority, 2015).

1.2.7 Short-Term Planning

While long-range planning happens through the PMT and CIP process, short term planning for MBTA bus service is led by the Service Planning Department. The Department drafts a service plan listing proposed modifications to each route. The plan is then reviewed for compliance with Title VI regulations on environmental justice and impacts to low income and minority populations. There is also an opportunity for public comment on the draft plan. The service plan is intended to be updated every two years; however, the most recent service plan is from 2008 (Massachusetts Bay Transporation Authority, 2008). A round of service cuts was implemented alongside a fare increase in 2012, but was not accompanied by a full service plan (Central Transportation Planning Staff, 2012).

The biennial service planning process is grounded on an assessment of how well each route complies with the service standards set forth in the Service Delivery Policy (Massachusetts Bay Transporation Authority, 2008). Each bus route receives either a "Pass" or "Fail" for weekdays, Saturdays, and Sundays for each of the standards for span and frequency of service, load, and net cost per passenger. A percentage value is assigned for on-time performance.

Staff in the service planning department propose changes to address specific problems on a route, typically those related to on-time performance and load. Typical recommendations include relatively minor alterations to routing or additional trips during peak periods. APC data is used to assess how many existing passengers would be impacted by a change. Ridership changes are predicted using simple elasticity models (Dullea, 2015).

Public workshops are also held to solicit suggestions for changes. Public complaints and comments are tracked on a ongoing basis and the suggestions incorporated into the process. The public comment phase may be contentious; the general view among staff is that the public dislikes any change that could be perceived as reducing service to anyone (Francis, 2015). Resources have been limited in recent years, and because the new service plan must operate within the allocated budget, major service increases such as new routes require service reductions elsewhere (Francis, 2015). Moreover, if any capacity is available, planners try to spread capacity among services around the network for reasons of equity and to make implementing changes more politically feasible, which limits the scope of the change that can be proposed for any single area. This makes it very difficult to generate support for change, either within the agency or among the public. As a result, strategic interventions in particular areas and experiments with new or extended routes are rare.

Smaller scheduling changes do not need to wait for the service plan process. Minor adjustments to routes and schedules are generally made on a quarterly basis.

1.3 Motivation for this Research

The transportation needs of the Boston region are increasing and evolving rapidly as the population and economy grow, but there is limited capacity for the MBTA to expand to meet those needs. Planned changes to the rail system in the near future are limited to the Green Line extension to Somerville and Medford, the long-delayed Blue-Red Connector, and power and signal improvements on the Orange, Red, and Green Lines. To serve rapidly growing areas such as Kendall Square, Longwood Medical Area, and the Seaport District, a well-planned and more effective bus network will become an increasingly critical component of the transit network. However, the current institutional structure does not provide good opportunities for medium- to long-term, comprehensive bus planning. Since the capital expenditures associated with improving bus routes are quite limited, bus planning receives little attention in the long-range and capital planning process. The service planning department must spend most of its capacity on short-term scheduling concerns and minor modifications to existing routes.

The size of the bus fleet and maintenance facilities can also limit the ability to expand service directly operated by the MBTA. However, the suspension of the Pacheco law provides a unique opportunity to add new contracted bus service in under-served, high-growth areas, or to provide more appropriately sized minibus service on lightly used routes or at times of day with low ridership. Contracted minibuses could free MBTA buses to be redeployed to growth areas and help break free of the zero-sum approach that currently stifles changes.

The relatively new availability of automatically collected data offers new tools and opportunities for more proactive, longer-range bus service and network planning to support such potential service improvement opportunities. In particular, ODX provides a new level of detail about how passengers use the system and enables detailed analysis of how potential changes would affect current riders. This research aims to fill the gap between the current short- and long-range planning process by exploring applications ODX for bus network planning.

1.4 Approach and Methodology

This thesis develops a framework for using ODX and other data to improve service planning. In recognition of the fact that the MBTA's service planning department has very limited resources, like many agencies around the country, the framework aims to develop simple, practical approaches and tools for service planners. Rather than attempting to be truly comprehensive, it targets analysis where it is likely to have the most impact, which makes the approach more useful within limited capacity of many agencies.

A five-phase proactive service planning process is proposed to enhance and complement the MBTA's existing biennial process. The phases are as follows: first, identification of locations within the service area that are likely to require additional bus service or changes to existing service; second, analysis of each of the locations selected; third, development of proposals for service additions and changes; fourth, evaluation of those proposals; and finally, implementation and post hoc evaluation. ODX is used in each phase of this process.

The framework presented in this thesis has been developed within the context of the MBTA's existing practices and available data, but it is designed to be generally applicable to other transit agencies that have ODX available. The theoretical framework and proposed process are presented first. Examples from the MBTA are then explored to illustrate the how the framework can be applied in practice and to develop the methods in more detail.

The methods developed in this research are a toolkit, designed to provide service planners with new analytical approaches to support decision-making and complement existing practice. The application of the methods must be customized based on the circumstances, requiring local knowledge of the areas being studied and a detailed understanding of current transit operations. However, the methods have been developed so that they can be used without extensive training in programming or new software packages. They rely mainly on analysis performed using a SQL database and a spreadsheet program such as Microsoft Excel, alongside a geographic information systems ("GIS") package such as ArcMap for geographic analysis. Most transit agencies have ready access to all of these components; open source alternatives to the standard commercial packages are available for smaller agencies or for stakeholders outside of agencies who wish to perform their own analyses when data sets are made public.

1.5 Thesis Structure

Chapter 2 describes the available data sources and the ODX algorithm and reviews the literature on the uses of automatically collected data for bus planning. Chapter 3 applies ODX to evaluate the MBTA network as a whole and to draw conclusions about how passengers typically use the system. Chapter 4 presents a framework for using ODX in bus planning and develops a five-phase, proactive, medium- to long-term service planning process. Chapter 5 develops examples of the first two phases of the process, identifying and evaluating several locations around the region where changes and additions to bus service are likely to be necessary, particularly in economic growth centers. Chapter 6 presents examples of the third and fourth phases of the process, proposing and evaluating improvements to the bus network to better serve these key locations. Chapter 7 offers conclusions and suggestions for further research.

Chapter 2

Origin, Destination, and Interchange Inference

Applications of ODX for network planning build on existing network planning methods using a variety of data sources and on the few existing applications of ODX that have been developed in the short time it has been available. Developing these new applications also requires a thorough understanding of the data sources and processing algorithms used to create the data set. This chapter provides that necessary background. First it reviews automatically collected data sources, their use at the MBTA, and their application to bus network planning. It also discusses existing bus network planning methods. It goes on to describe ODX in detail and review prior applications. The chapter concludes with an examination of some of the benefits and limitations of the data set for bus network planning.

2.1 Automatically Collected Data Sources

As explained in Chapter 1, there are usually three sources of automatically collected data available to transit agencies. Automated vehicle location data ("AVL") records the location of buses and trains over time. Bus AVL typically uses GPS technology, sometimes supplemented by odometer readings, while trains and light rail vehicles may use GPS or data from track signals, circuits, or sensors. For buses in Boston, there are three types of AVL data: "timepoint" data, which records the time at which each vehicle passes a handful of set timepoints on a route; "heartbeat" data, which records GPS coordinates for each vehicle every 60 seconds; and what is generally referred to as "announcements" data. Each bus is equipped with a system that provides audio announcements for the visually impaired. The bus's route, direction, and destination are announced each time the doors are opened ("external announcements") and the name of the next stop is announced to passengers upon leaving the prior stop and when approaching the next stop ("internal announcements"). Both time and GPS coordinates are recorded for every announcement. Since buses often do not stop at every stop, the announcements typically provide more data points per trip than the timepoint data, but are less consistent.

The second major source of automatically collected data is the automated fare collection system ("AFC"). In Boston this is often referred to as the CharlieCard system, though it also handles paper CharlieTickets. All transactions at ticket vending machines, station faregates, and bus and light rail fareboxes are recorded, with the most common being paying for a trip and adding value to a card or ticket. Cash transactions at bus fareboxes are also recorded. The most relevant parts of an AFC record are typically the time of the transaction, the ticket or card number, the farebox or faregate number, and the fare type. Fare types include both stored value transactions, where the cost of a single ride is deducted from the available balance on the card, and passes. The fare information also includes a variety of reduced fare categories such as students, seniors, and those using the Transit Access Program ("T.A.P.") for passengers with disabilities.

Automated passenger counters ("APCs") provide a third source of automatically collected data. Sensors on both front and rear doors detect passengers entering and exiting at each stop, resulting in a record of the number of boardings, the number of alightings, and the total number of passengers on the bus (load) after each stop. These counters are installed on approximately 12% of the MBTA bus fleet. These APC-equipped buses are rotated among the routes of the system so that counts are obtained for all routes for a variety of times of day and days of the week over several months. The distribution of APC data is uneven, however, since some vehicles are linked to specific routes. All of the fleet's 60' articulated buses have APCs, for example, resulting in nearly complete APC coverage for a few high-demand routes. All of the Silver Line diesel-electric buses have APCs as well.

2.2 Existing Bus Network Planning Methods

Traditional bus network planning methods have not relied on automatically collected data, which has only become available in recent years. There have generally been two approaches to the network planning problem. The first, commonly used within transit agencies but mostly absent from the research literature, is to treat network design as an art rather than a science. Public transportation textbooks often provide general information, such as the classification of network forms like grid, radial, and trunk-and-feeder networks or suggestions as to the distance between parallel bus routes (Bruun, 2007; Gray and Hoel, 1992). Concrete guidance as to how to apply these heuristics in a large, complicated city is lacking, so network design has become a matter of professional judgment and experience. Most bus networks in major U.S. cities have evolved incrementally over time rather than being designed from scratch, meaning that only a small number of route additions and changes are suggested at any one time. In older cities such as Boston, transit networks were initially developed by the private sector and routes were introduced or frequency was increased when revenue exceeded operating costs. Transit agencies now rely on subsidies and provide lifeline service as well as service on high-ridership corridors. The profit motive that once drove network change and expansion has lost its force, and service changes in many networks have become much less frequent. Once proposed, a new route may be evaluated using available data, including automatically collected data and complex models, but these data sources are not typically used in the route design process.

The other network planning method, common in the research literature but rarely implemented in practice, is to apply operations research methods. Generally the network design problem is formulated as a non-linear optimization problem, with objectives such as minimizing cost and travel time. Farahani, Miandoabchi, Szeto, and Rashidi provide a review of the various formulations and solution methods that have been developed using this approach (Farahani et al., 2013). All of these methods require a detailed origin-destination matrix, which can come from automatically collected sources or from other sources such as surveys, as an indication of demand. Some methods use suggested or existing routes as inputs, which are then modified, while others generate possible routes based on demand and a detailed mapping of the street network. Most methods plan for buses only and do not appropriately account for the existing rail network; Cipriani, Gori, and Petrelli's work in Rome is one exception (Cipriani et al., 2012).

While there might well be value in this sort of optimization of the MBTA network, the approach would be a difficult one. The Boston region's street network is complex, with many very narrow streets, one-way streets, and complicated intersections. Formulating an appropriate optimization problem would require a detailed representation not only of the general street network, but of the subset of specific streets that can accommodate buses and the turns buses can navigate. Current optimization methods assume a fixed level of demand; given the rapid growth in some areas of Boston outlined in Section 1.1, changes to the network must take trends in demand growth into account. Even if an optimization problem could be formulated and solved, the current political situation of the MBTA makes it highly unlikely that a complete redesign of the bus network could be implemented in the foreseeable future. Identifying significant but incremental improvements is much more likely to lead to positive changes in practice.

2.3 Prior Uses of Automatically Collected Data in Bus Network Planning

Furth, Hemily, Muller, and Strathman provide a thorough outline of potential uses for AVL and APC data (Furth et al., 2006), while Pelletier, Trépanier, and Morency review the literature on existing uses of AFC data (Pelletier et al., 2011). In both cases, few of the applications relate to long-term or network-level planning. Instead, a major focus is relatively short-term operations and planning issues. For example, Chapleau, Chu, and Allard develop and compare load profiles using AFC and APC data in the Montreal transit system (Chapleau et al., 2011).

Shireman uses automatically collected data to evaluate several MBTA routes (Shireman, 2011). Using automated sketch planning tools, he develops proposals for timetable adjustment, interlining, and route modifications to improve service in the selected area. His proposals demonstrate that such use of automated data can uncover efficiencies that result in improved service without additional cost.

Gutiérrez uses automatically collected data to propose changes to the bus network in Gipuzkoa, Spain (Gutiérrez de Quevedo Aguerrebere, 2012). The network he analyzes consists of 16 routes, several of which overlap for long stretches, that are largely divided into two separate subnetworks. Working with AFC and AVL data, Gutiérrez is able to create an origin-destination matrix for the network and propose route reconfigurations to substantially improve service.

Rosen uses automatically collected data to estimate the change in ridership from proposed changes in service at the MBTA (Rosen, 2013). Using inferred origins for bus trips, along with census and other data, she develops a stop-level demand model. She then applies that model to estimate the effect of changes to several routes, and to estimate the demand for a proposed new crosstown route in the urban core.

2.4 Current Uses of Automatically Collected Data at the MBTA

Tribone outlines the ways that the MBTA uses automatically collected data, both real-time and historical, for internal and external applications (Tribone, 2013; Tribone et al., 2014). Real-time data is used for operations and customer information, while historical data is mainly used for routine performance reporting. Archived AVL data is used as an input for Hastus, the MBTA's scheduling software, to make schedule adjustments based on actual running times. However, there is little use of archived data for longer-term network planning. The service planning department currently receives AVL, AFC, and APC information separately and has little capacity for complex analysis combining multiple data sources.

In addition to the bus planning work mentioned in Section 2.3, a number of other uses for the MBTA's automatically collected data have recently been developed through research partnerships. Several projects have relied on AFC data. Kamfonik used AFC data to evaluate the MBTA's Corporate Pass program (Kamfonik, 2013; Kamfonik and Block-Schachter, 2014). Similarly, Pincus used AFC data to evaluate the effects of a change in fares (Pincus, 2014). Chow used AFC records to prompt survey-takers to respond to questions about recent trips (Chow, 2014), enhancing the quality of survey responses.

Other research has used AVL data, such as Maltzan's work examining how real-time AVL data can be used to improve operations on high-frequency bus service (Maltzan, 2015). Tribone used multiple data sources to design improved daily performance reports for the rail system (Tribone, 2013).

2.5 Origin, Destination, and Interchange Inference

2.5.1 Development

Inference of origins and destinations using ADCS has been a subject of research since AVL and AFC systems became widespread. Early inference methods often had limitations such as only covering a single mode, inferring destination locations but not times (Zhao, 2004; Zhao et al., 2006), relying on schedules or fare transaction times rather than on AVL data (Barry et al., 2009; Chu and Chapleau, 2008), or assigning boardings to zones rather than individual stops (Farzin, 2008). Methods have varied across cities depending on data availability; the AFC system in the Minneapolis-St. Paul region records latitude and longitude for transactions at fareboxes on vehicles (Nassir et al., 2011), while the circuity of the transit network in Santiago led Munizaga and Palma to develop a generalized cost minimization method for inferring destinations rather than using the nearest stop to the next origin (Munizaga and Palma, 2012).

More recent research has overcome some of these earlier limitations. Wang developed methods to infer origins and destinations for London's bus network (Wang, 2010). Gordon expanded these methods to include the rail system, which includes both entry and exit transactions, and inter-modal transfers (Gordon, 2012; Gordon et al., 2013). The MBTA's inference system is based on the software that Gordon developed. Dumas adapted Gordon's software to accept inputs from the MBTA's data systems and to infer destinations for the MBTA's open rail network, which does not require passengers to tap or swipe a card to exit the faregates (Dumas, 2015). Several months of processed data became available to researchers in 2014. While the system continues to be refined and more recent data will made available shortly, this thesis relies on the data set from 2014.

2.5.2 Algorithm

Using ODX requires a conceptual understanding of the inference process; refer to Gordon and Dumas for the technical details. Exceptions and caveats specific to the MBTA implementation are described in Section 2.8 on ODX limitations.

For a trip that begins at a faregate, the origin of the trip is known definitively. For those beginning at fareboxes on-board vehicles, the timestamp of the farebox transaction is matched to the vehicle's location, as recorded by the AVL system. Inference rates for origins are quite high; the main barrier to inference is occasional failures of the AVL system.

Destination inference is based on other activity on the same card that day. (Destinations cannot be inferred for cash transactions.) The destination for a trip is assumed to be the stop on the current route that is closest to the origin of the next trip taken with the same card. For the last trip of the day, the destination is assumed to be the origin of the first trip of the day since most people return to their home location each day. Destination inference fails when there is only one transaction on the card that day, when a passenger is traveling in the opposite direction from the origin of the next trip, or when the current route does not pass within a reasonable distance of the next origin point, among other reasons. Destination inference rates, therefore, are much lower than origin inference rates.

When the destination of one trip is close in both space and time to the origin of the next, the two trips may be part of one longer journey that includes a transfer between vehicles. ODX applies a few other tests, including verifying that the trips are on different routes and are not in opposite directions, before identifying two trips as linked. Distinguishing a transfer trip from a brief activity, such as running an errand, is difficult, and such differentiation has been the subject of recent research (Nassir et al., 2015). The parameters of transfer inference for the MBTA are conservative; there may be transfers that are not identified by the algorithm, but there should be a low error rate for those trips that are identified as linked.

2.5.3 ODX Data Set

This thesis analyzes ODX output from October 2014. October 31st is excluded from the analysis; due to how the raw data is processed, bus origin inference was not available on this day. This data set includes 21,358,575 unlinked trips which represent 19,008,475 journeys. Of these, 31.4% are bus journeys, 60.5% are rail journeys, and 8.1% use a combination of bus and rail.

Rail trips begin with a fare transaction at a rail station faregate, so all rail trips have an origin location. A destination is inferred for 61.7% of unlinked rail trips, while 11.8% of rail trips are inferred to be part of longer journeys. This does not include transfers that take place behind the faregates; see Section 2.8 for more detail on rail transfers in the MBTA system.

For bus trips, 99.7% have inferred origin locations and 57.3% have inferred destination locations. 35.8% are inferred to be part of longer journeys.

Chapter 3 will examine this ODX data set in more detail and use it to evaluate the network as a whole.

2.6 Previous Applications of ODX

It is only recently that ODX data sets have become available to a few transit systems. Some of the recent research has focused on improvements to the algorithm rather than on applications, such as new methods to infer destinations for unlinked trips (He and Trépanier, 2015) and distinguish transfers from short activities (Nassir et al., 2015).

Pelletier, Trépanier, and Morency, in addition to the broad look at AFC data mentioned in Section 2.3, also discuss the use of inferred origins and destinations (Pelletier et al., 2011). Many of the applications they cite are related to classifying and characterizing users, while others focus on route-level analysis or the development of performance indicators. More recent applications are reviewed here.

Most of the existing applications of ODX data focus on understanding the travel patterns of individual riders. Viggiano examines the behavior of riders on a corridor served by multiple routes in London (Viggiano, 2013). By using inferred origins and destinations, she is able to identify riders whose trips are served by multiple routes on the corridor. This forms the basis of an in-depth examination of how riders choose between local and express routes, among other choices.

Devillaine, Munizaga, and Trépanier use inferred origins and destinations to identify passengers' activities in Santiago, Chile and Gatineau, Quebec, Canada (Devillaine et al., 2012). Similarly, Lee and Hickman combine inferred origins and destinations with land use data to identify trip purposes for passengers in the Minneapolis/St. Paul metropolitan area (Lee and Hickman, 2014).

Goulet-Langlois uses data from ODX in London to examine the travel behavior of a large group of riders over time. He uses clustering methods to group riders by their travel patterns, then connects those rider groups to demographics through survey data (Goulet-Langlois, 2015). He is able to identify the typical age or income level of regular commuters, for example, compared to the characteristics of those with less regular travel patterns. This can be used to segment the market into user groups so that messaging can be targeted to each group.

Other research has looks broader travel patterns. After developing inference methods for bus origins and destinations in London, Wang, Attanucci, and Wilson examine the variation in passenger flow and load profiles across several days and compare weekday to weekend activity on some sample bus lines (Wang et al., 2011). They also analyze the amount of time spent waiting at a transfer point between two bus routes.

Gordon and van der Hurk use inferred destinations for passengers on the MBTA's Red Line to evaluate the efficiency of the bus shuttle system that replaces trains during weekend construction work (Gordon and van der Hurk, 2014). Transport for London similarly use ODX to evaluate the customer impact of a closure to Putney Bridge (Marr, 2015). More broadly, Munizaga and Palma calculate an aggregated zonal origin-destination matrix for the Santiago system before and after some significant changes to the bus system (Munizaga and Palma, 2012).

In addition to developing ODX in Boston, Dumas uses it to analyze environmental justice and transit equity (Dumas, 2015). By looking at the locations where passengers first use their cards or tickets over the course of multiple days he infers where riders live. He then compares the travel of riders inferred to live in census tracts with mostly black populations to the travel of those in census tracts with mostly white populations. Prior research found that black commuters have longer commute times; the level of detail of the ODX data set means that Dumas is able to identify some of the sources of that discrepancy, including that commuters from census tracts with mostly black populations transfer more often for medium-length trips than those from mostly white census tracts. Dumas suggests a few network improvements that would reduce these transfers and lessen the racial differences in travel times.

The literature on origin-destination inference methods contains a number of suggestions for potential applications. These range from intermediate-level analysis steps, such as the development of load profiles for bus routes and calibration of demand models, to more direct applications such as longitudinal studies of how users respond to changes in service (Gordon, 2012; Gordon et al., 2013).

Barry, Freimer, and Slavin present a number of applications for the software they developed to query inferred origins and destinations for New York City Transit; it is unknown how many of these applications have been implemented (Barry et al., 2009). The applications include demand forecasting and regional model calibration, planning for service interruptions, evaluation of long bus routes for possible reconfiguration into two shorter routes, and travel survey validation.

2.7 Benefits of ODX

ODX provides a extremely rich new data source for analyzing a bus network, offering a more complete and reliable picture of riders' activity than previously available data sources. This section briefly describes previously existing data sources in Boston and examines the ways that ODX differs, with a focus on the new information ODX provides.

The most detailed source of data on riders' journeys has generally been rider surveys. The Central Transportation Planning Staff ("CTPS") of the Boston Metropolitan Planning Organization performed a system-wide passenger survey in 2008-2009 (Central Transportation Planning Staff, 2010); CTPS and the MBTA have performed other surveys with more specific goals in more recent years. For the system-wide survey, forms were distributed on-board buses and at rail stations from 6:00 a.m. to 3:30 p.m. on "typical" weekdays. About 49,000 responses were collected, with a response rate of about 20%, representing 8.6% of daily system ridership. The survey form asked detailed questions about the respondent's current trip, alternative methods of travel, and demographic information.

The results of the survey provide a wealth of information about how passengers use the system, including information not available in ODX such as the factors that went into a rider's choice to take transit, how long it took the rider to access transit, and the rider's age and income level. However, ODX provides a much larger and richer data set than the sample of trips represented in the survey. There were about 12,000 survey responses for bus trips; with well over 100 routes in the system the sample size is too small to be useful for stop-level analysis on any but the most heavily-used routes. Similarly, though the survey can provide a good overview of the number of passengers who transfer during their journeys, the sample is too small to provide data on how frequently any but the most common transfers occur. ODX's much larger data set does not have these limitations. The survey data were also collected over many days, so day-to-day variation in travel patterns cannot be examined as they can with ODX. The survey provides an excellent indication of general trends, but often cannot reliably answer very specific questions. It also has limited applicability for planners examining evening and weekend travel, since no surveys were handed out during these periods.

Another existing method of understanding the system is travel models. CTPS maintains a regional travel model that it has used to evaluate proposed changes to the transit system, including predicting the ridership impacts of a fare increase and some route-level changes in 2012 (Central Transportation Planning Staff, 2012). The model covers multiple modes of travel and can therefore offer predictions of how mode choice will change under different scenarios. However, regional travel models are inherently limited by the assumptions used to construct them. ODX provides data on the choices that riders actually make among routes or modes, rather than reflecting assumptions about passengers' route choices. It also captures some of the variability that riders experience in their travel times, since it is based on AVL data rather than published schedules.

APCs provide stop-level boardings and alightings for each bus route, and the

MBTA service planning department uses these data extensively. From the boarding and alighting figures, iterative proportional fitting ("IPF") can be used to generate an origin-destination matrix showing the number of passengers traveling between each OD pair (McCord et al., 2010). However, with counts available for only a portion of trips, there can be a very limited sample of trips for a particular route, direction, and time period on which to base IPF. ODX's much larger data set is more reliable in this regard. ODX also goes beyond the route level to include data on transfers, and tracks individual passengers over multiple trips, which cannot be done with APCs.

While the existing data sources provide a wealth of useful information, including some that ODX does not provide, ODX's scale makes it more useful for many types of analysis. It is now possible to look at the same users over a period of time, as Viggiano, Goulet-Langlois, and Dumas have done. It is also possible to examine the variation in aggregate travel patterns over a period of time, either to better understand the day-to-day variation in normal system operations or to do a comparison of travel times, ridership, and route choice before and after a change to the system.

The level of detail in ODX also provides a basis for predicting the effects of these changes on existing riders in advance. Since ODX provides information on full journeys, the network effects of a particular route change can be evaluated. The number of passengers who have a viable alternative route, or who transfer to or from a given route, can be taken into account more easily when considering a potential route change.

2.8 Limitations of ODX

While ODX provides a valuable new resource for transit planning, some caution must be employed. The limitations discussed in this section must be kept in mind while developing applications to ensure that these new applications do not rest on faulty assumptions about the underlying data.

The broadest of these limitations is that much of the data set is inferred. This may seem obvious, but when working with the data it is natural to treat inferred trips as if they represent a rider's actual behavior. On an aggregate level the travel patterns inferred by ODX appear to match system statistics quite well. On the individual level, however, a particular trip may not have occurred exactly as inferred. A rider may have alighted early on a return trip to run an errand, transferred within the rail system for one additional stop on a rainy morning but walked that distance in the afternoon, or taken other modes of transportation in ways that result in incorrect inferences about his or her transit trips that day. On the data level, when AVL data points are sparse the bus location between points is less certain, so boardings may occasionally be assigned to nearby stops instead of the correct ones.

The inference algorithm also fails to infer destinations a significant proportion of the time. This is often because only one trip was made that day on that card, so there is not enough information on which to base an inference. Approximately 62% of rail trips and 57% of bus trips have an inferred destination. Inference rates for different situations vary considerably; when a passenger transfers, the destination for the first stage of the journey is much more likely to be inferred than that for single-stage journeys. Determining scaling factors for the number of journeys for a specific OD pair is therefore not a trivial exercise. The ability to use only those trips or journeys with inferred destinations as a representative sample depends on the specific application and set of trips under consideration.

Similarly, the transfer inference algorithm identifies most of the transfers within the system, but as discussed in Section 2.5.2 the parameters the algorithm uses to identify transfers are conservative. This limits the number of trips that are linked incorrectly, but also leaves some trips unlinked that the passenger would consider part of the same journey.

Another broad limitation is that ODX data measures only the trips that passengers actually take on the transit system. There is no information about travel by other modes, such as driving, walking, or biking. There is also no data on latent demand, that is, passengers who might switch from driving private cars to taking transit if the transit service were to change, or people who are not traveling but would make new trips if offered a convenient transit option. Information on such demand may sometimes be obtained from regional travel models, but is generally quite difficult to obtain at a fine-grained level when considering a particular transit project.

Some of the limitations of the ODX data set used in this thesis are particular to the MBTA system. The entire rail network is considered as one system, so that a trip between any two stations is considered to be one stage of a journey, even if the stations are on different lines. The topology of the rail network is simple enough that for most pairs of stations the path is clear, and for nearly all station pairs the number of transfers required is the same regardless of the exact route chosen. Some of these paths and transfers have been affected by the closure of Government Center station, a major downtown transfer station serving the Blue and Green lines, for two years beginning in March 2014, but since the station is not directly served by bus (except a temporary, little-used shuttle bus during the station closure) the effect on any analysis of the bus network should be minimal. Transfers within the rail system are not included in the ODX output, but some limited transfer information can be added to the basic output when necessary for analysis.

Since the rail system is accessed via faregates (aside from Green Line surface stops, which will be discussed in more detail below), the time that a passenger spends waiting on the platform is part of the time recorded for their trip. For bus trips, there is no record of the time the passenger arrived at the stop, only the time of boarding. The duration of bus trips cannot be directly compared to that of rail trips for this reason. The time spent accessing the stop or station and the time spent traveling from the alighting location to the final destination are also not included in the travel time. This is particularly relevant for those who drive to suburban rail stations and those transferring from commuter rail or ferry. These other modes are not yet part of the CharlieCard system and are therefore not included in the ODX data set.

The ODX data set is also limited by technology and topology for light rail and BRT trips. Vehicles on the Green Line did not have AVL technology until the middle of 2015. Some riders board at stations with faregates, and their boarding locations are identified in the same manner as those for other rail trips. Other riders board at surface stations and pay at the farebox on-board the vehicle; their boarding locations can only be identified by branch and direction, such as Green Line B branch inbound. Much of the service to Brookline and Newton are via the Green Line, so the quality of the data available for these areas is significantly affected. The Mattapan high-speed line is a surface trolley with similar limitations; trips on this line are identified by direction only, not stop.

The SL4 and SL5 Silver Line BRT lines operate as regular bus lines from the perspective of ODX. The SL1, SL2, and SLW lines, however, are more like the Green Line in that some boardings occur at gated stations while other passengers pay at the farebox on board. Since most outbound riders on these routes board at South Station, those Silver Line trips whose destinations are not inferred cannot be distinguished from trips on the Red Line. In addition, boarding the SL1 at the airport is free, with free transfers to the Red Line at South Station; as a result, these trips are not yet included in the ODX data set. Passenger counters on the Silver Line buses can provide load profiles and crowding estimates, but cannot identify how the passengers transfer and move through the rest of the system.

A small number of bus routes have unusual operating circumstances that limit the ability of the ODX algorithm to correctly infer boarding or alighting locations. An off-board fare validator at the Haymarket Station stop on the route 111 bus is not currently inferred as a boarding on the next available route 111 vehicle; crowded conditions, very frequent service during peaks, and the potential for denied boardings all make this inference difficult. The 71 and 73 bus routes also operate somewhat unusually; there are long dwell times due to the fact that many passengers board at the outbound origin terminal at Harvard Square, so passengers are asked to pay upon exiting the vehicle at their destination. This peculiarity has not yet been properly accounted for in the ODX algorithm.

There are other trips that are not included in the ODX data set. Since it is based on the AFC system, any passenger who does not pay a fare is not included. By comparing AFC, APC, and manually-collected data, the MBTA has determined that the fare evasion rate is about 5% (and, conversely, that the farebox interaction rate is about 95%). Fare evasion is not distributed evenly, however. Relatively few rail passengers jump over the faregates. On some crowded bus routes, however, operators have been known to encourage passengers, particularly those with monthly passes, to board through the rear door (without tapping at the farebox) in order to speed up the boarding process at busy stops. This variability must be kept in mind when comparing ODX data on the use of different routes and modes. APC data can be especially useful in these cases for assessing the impact of fare evasion.

The fact that ODX is based on AFC data also means that it tracks cards, not passengers. Most monthly pass holders use the same card all the time and don't lend their card to anyone else. However, a stored value card may be used to pay multiple fares for two or more passengers traveling together. Passengers using paper tickets are also likely to use multiple tickets over a short period of time. Therefore the unique identification numbers in ODX do not always represent unique users.

Chapter 3

Network Evaluation

This chapter examines the MBTA bus and subway network as a whole using the ODX data set. It first briefly reviews the new information ODX provides, followed by a description of the methods used in the chapter. It then uses ODX data to examine many aspects of transit use, including the geographic distribution of journeys, journey distance and duration, waiting time, service frequency, transfers, mode, and the productivity of the system. The chapter concludes with a discussion of what the results reveal about how the MBTA network is structured and how it is typically used.

3.1 The Role of ODX

Examining data on transit system performance is routine; the MBTA Blue Book has collected statistics such as ridership by station or route and scheduled vehicle miles for a number of years, and current monthly MBTA scorecards report vehicle on-time performance. These statistics are useful for both an overall assessment of the network and evaluation of each route, but ODX offers the opportunity for a much more comprehensive analysis.

As discussed in Section 2.7, ODX makes it possible to do large-scale geographic analysis of travel in the region, because trip origins are identified not just with a route but with a stop. The inference of destinations and end times makes it possible to calculate and examine the distance and duration of trips. Finally, the inference of transfers enables an analysis of transfer behavior and the role that multi-modal journeys play in the network.

3.2 Methodology

The ODX data set is a single table in a SQL database that contains a row for each unlinked trip. This data must be processed before it can be analyzed at the journey level. A summary table was created that contains one row for each journey, consolidating the data from multiple stages. The information in this summary table includes the starting time and location, the ending time and location (where inferred), the number of bus and rail stages, the distance traveled by bus and by rail, the duration of the journey (when end time is inferred), the time spent waiting between stages, and the routes used.

Not all journeys can be used to analyze every aspect of the network. Virtually all journeys are included in measures of journey origins, such as geographic distribution of boardings. For statistics that rely on both origin and destination locations, only the subset of journeys with inferred destinations can be used. Similarly, journey duration can only be calculated when an end time is inferred for the journey; some rail trips in the data set have an inferred destination but no end time due to missing train tracking data.

In general, the largest possible subset of journeys is used for each measure. When only a subset of journeys are included, the results are scaled up by the percentage of all journeys that they represent. The journeys with inferred destinations are therefore treated as a representative sample of all journeys.

There are over 8,000 bus stops and rail stations in the MBTA network, so analysis across the entire network at the stop level is generally too disaggregate to be meaningful. Therefore, the stops and stations have been aggregated into zones. U.S. Census tracts were chosen for this analysis for several reasons. Tracts are generally large enough to contain several stops and nearly all tracts in the region contain at least one stop. At the same time, tracts are small enough to reveal patterns across municipalities and other subsets of the region. There is also a great deal of other data available at the tract level that may be easily brought into the analysis, such as population.

Each bus stop and rail station was assigned to a census tract using ESRI's ArcMap GIS software. This assignment was then imported into the ODX SQL database and the starting and ending census tract for each journey was determined. Some analysis aggregates journeys to the starting or ending census tract. Other analysis looks at pairs of census tracts and considers all of the journeys that have those two tracts as an OD pair; examples are included in Section 3.7 below.

Some of the analysis in this chapter includes all journeys from all times of day and days of the week. This is appropriate when considering statistics that reveal the network structure, such as the number of trip stages that are generally used to travel from an origin to a destination, or what mode is typically used. Other parts of the analysis, particularly those focused on travel times, rely only on journeys during a specific time period. The weekday morning peak period is typically used, as this is a critical period for any transit network. Based on the MBTA's own definition of its peak periods in the Service Delivery Policy, journeys are considered part of the morning peak if they begin between 7 a.m. and 9 a.m. (Massachusetts Bay Transportation Authority, 2010). October 13th was excluded from these analysis due to the Columbus Day holiday. Given the exclusion of October 31 from the data set as mentioned in Section 2.5.3, the data set includes 21 weekdays.

3.3 Geographic Distribution of Journeys

Where journeys begin is a fundamental aspect of travel within a transit system. The map in Figure 3-1 shows the average number of journeys originating in each census tract within the system during the weekday morning peak. Not surprisingly, many journeys begin in the dense areas of downtown Boston that contain a great deal of both residential and commercial activity. A substantial number of journeys also begin along the rail lines, particularly the Red and Orange Lines. In some cases, such as Kendall, Harvard, and Central Squares, these journeys likely begin as walking trips; in other cases, journeys began as automobile trips. This is particularly true at stations that have large commuter parking lots, such as Alewife on the Red Line and Oak Grove and Wellington on the Orange Line. In this figure and the others that follow, large numbers of journeys are inaccurately shown originating at the ends of the Green Line branches. This is due to the fact that Green Line origins stations were not inferred for the surface portion of the route. As a result, all surface Green Line journeys are mapped to the ends of the branches for this analysis.

Aside from the rail stations, close-in residential areas also have many journey origins. These include neighborhoods in the southern parts of Boston, communities to the west such as Watertown and Belmont, and northern cities such as Chelsea, Everett, and Medford. These areas lack rail service, so these journeys either use bus only or begin on bus and transfer to rail. Communities beyond the ends of the rail lines outside the inner core produce some journeys, but at a much lower rate than the inner suburbs and downtown areas.

Similar patterns are visible in Figure 3-2, which shows the average number of weekday morning peak journeys per capita originating at each census tract. Population figures for each census tract are from the 2010 U.S. Census. Here the rail stations with commuter parking are even more visible, supporting the conclusion that these stations attract automobile journeys from surrounding census tracts. Logan Airport also appears to generate a large number of journeys per capita; there are few residents in this tract, but many journeys by travelers landing at the airport. Downtown Boston generates only moderate numbers of journeys per capita during the morning peak, though as shown above the absolute number of journeys is quite large. This is likely due at least in part to the density of both population and of commercial space in the area.

The geographic distribution of journey destinations can also be considered using ODX data. Figure 3-3 shows the ending locations of journeys that begin during the weekday morning peak. The destinations are much more concentrated than the journey origins, with large numbers of journeys ending in downtown Boston, near Cambridge rail stations, in the Seaport District, and in other areas of Boston with many jobs such as Back Bay and the Longwood Medical Area. Most suburban communities attract very few journeys during the weekday morning peak.

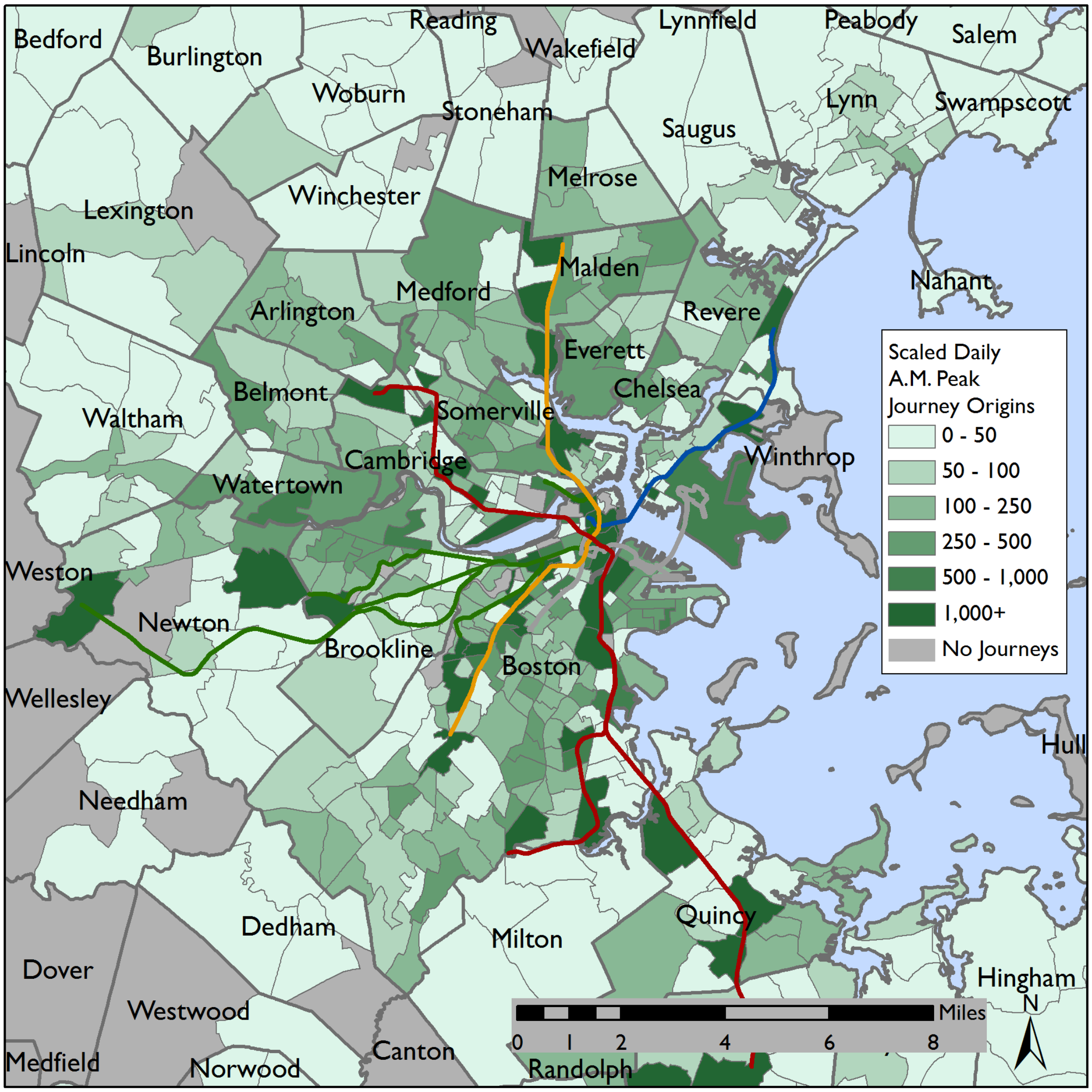


Figure 3-1: Scaled average weekday morning peak journey origins, October 2014

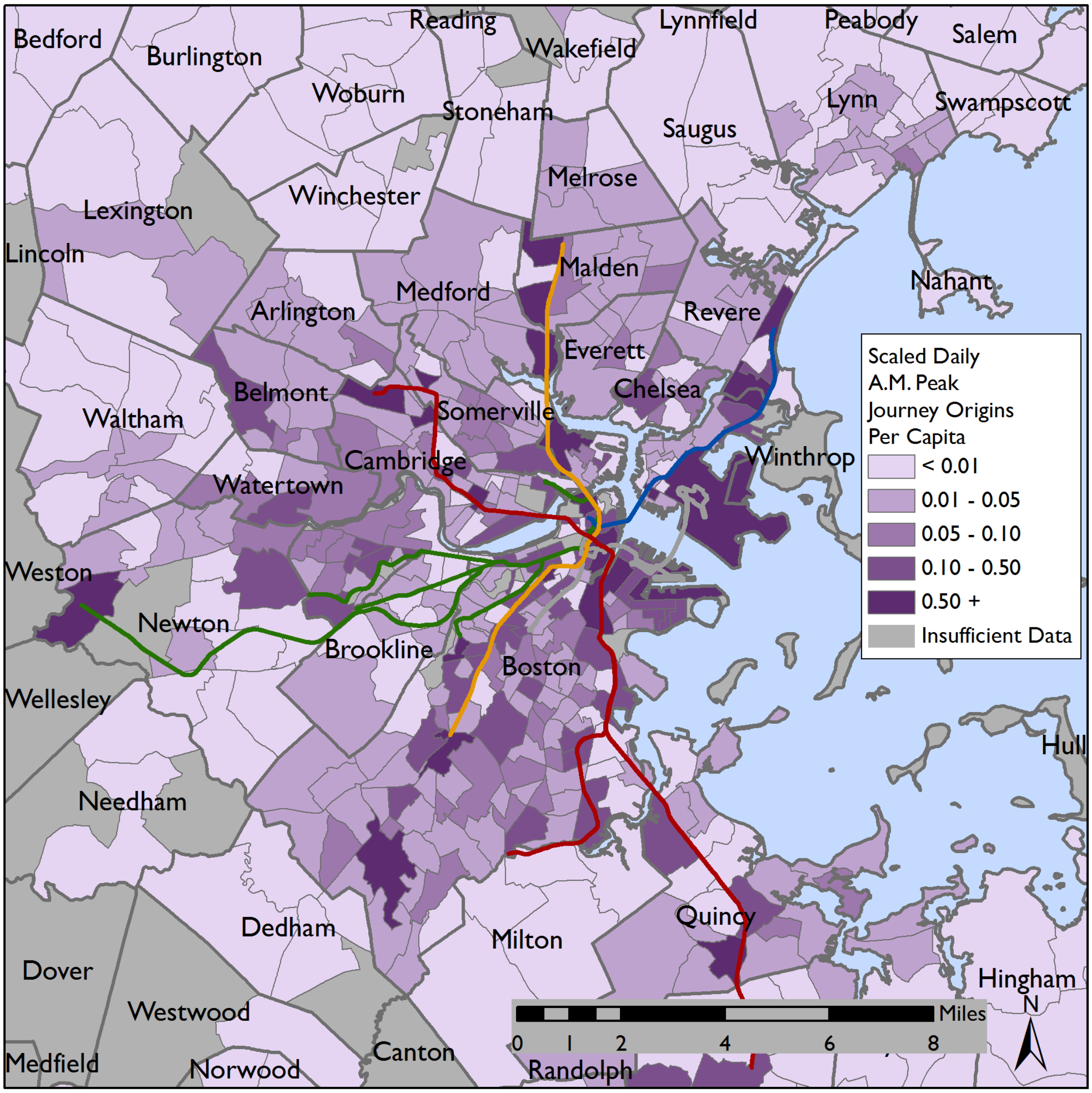


Figure 3-2: Scaled average weekday morning peak journeys per capita, October 2014

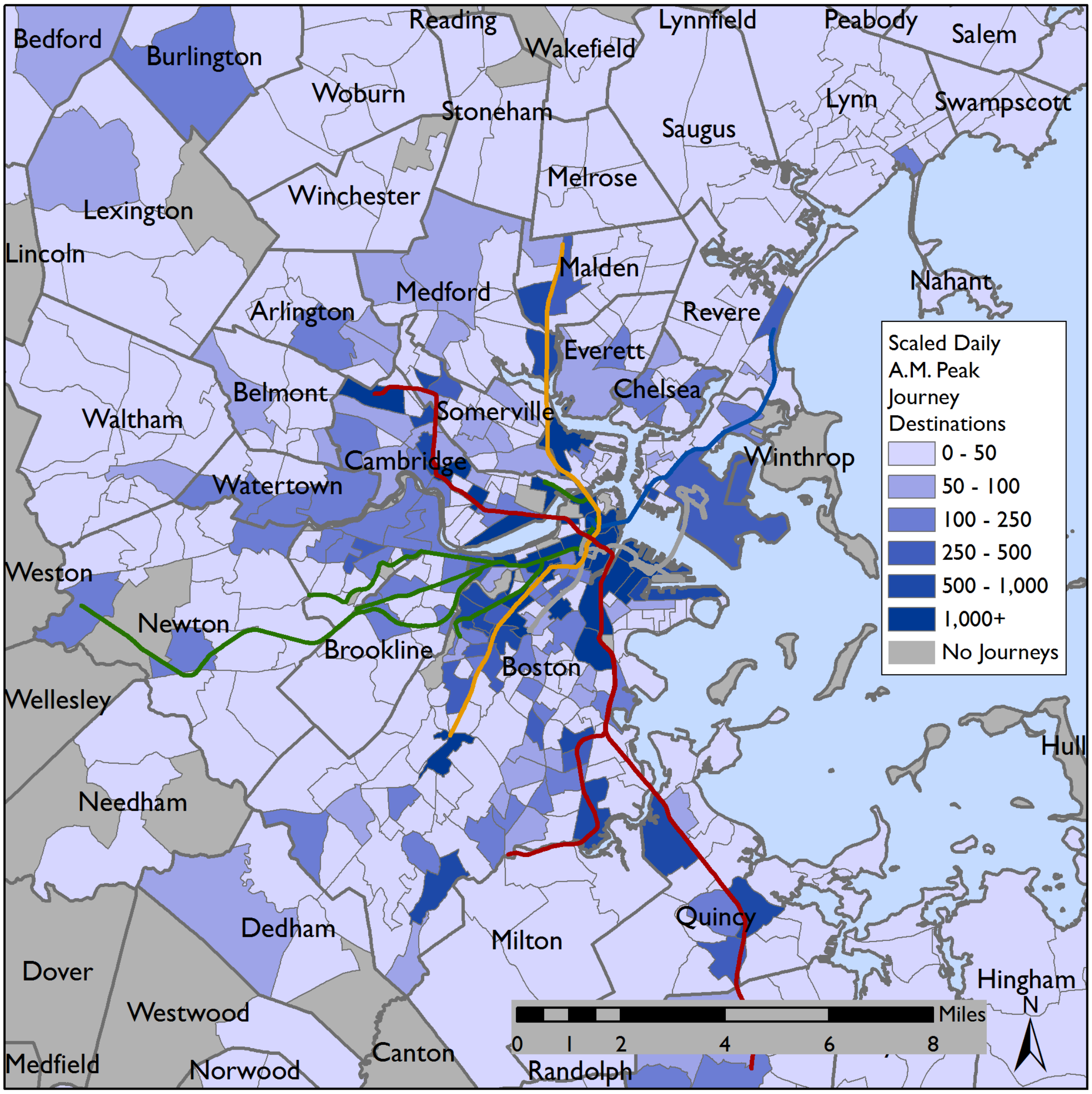


Figure 3-3: Scaled average weekday morning peak journey destinations, October 2014

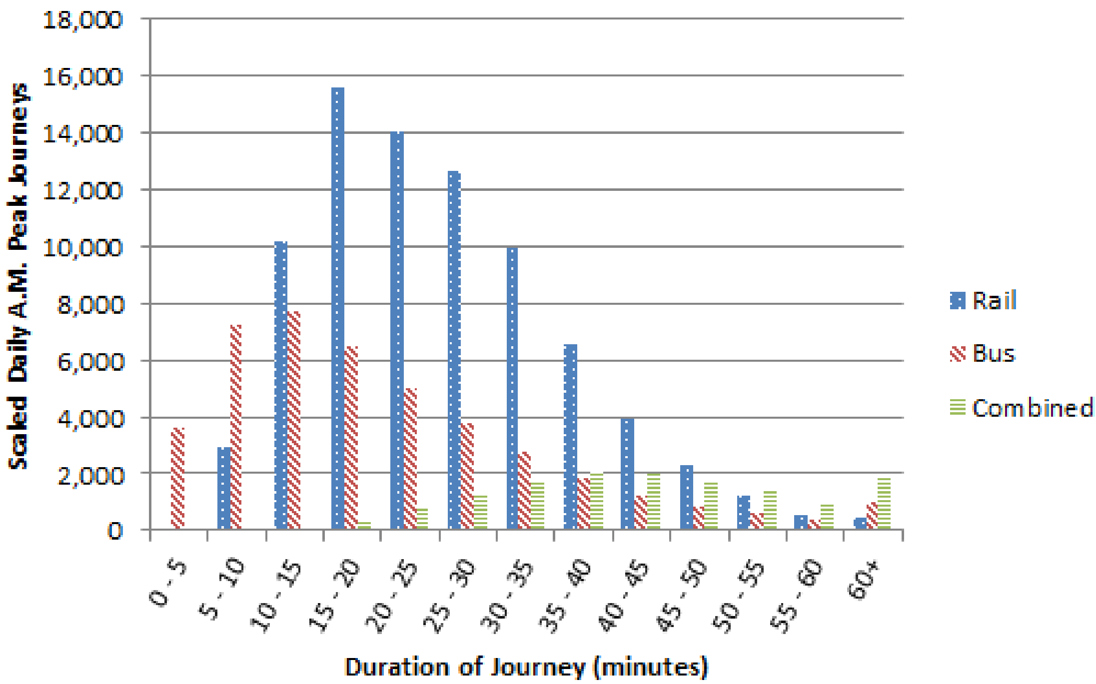


Figure 3-4: Distribution of duration of weekday morning peak journeys, October 2014

3.4 Journey Distance and Duration

Travel time and distance traveled are two other key aspects of a passenger's journey that can be examined with ODX. The overall distribution of weekday morning peak journey duration is shown in Figure 3-4. The most common duration for journeys is 15 to 20 minutes, with the majority of journeys taking between 10 and 30 minutes. About 2.7% of journeys are more than an hour; this is a combination of a some very long journeys and a few journeys whose end times are inferred incorrectly in the current iteration of ODX. Bus journeys are generally shorter than rail journeys, while journeys combining bus and rail are typically the longest. This has the potential to be misleading, however, because the waiting time between tapping in at a rail station and boarding the train is included in the duration of rail journeys, as is the time between journey stages, while the initial time spent waiting at a bus stop is not. A detailed examination of this issue is presented in Section 3.5. It is also important to note that as discussed in Section 2.8, these times do not include time spent accessing transit or walking from transit to the final destination, so a passenger's experience of their journey is generally longer than what is included here.

Typical journey duration also varies by location. Figure 3-5 shows the average duration of weekday morning peak journeys for census tracts that have at least 10 journeys during the sample period. This provides an estimate of how long residents from a particular location spend on their morning commutes. Not surprisingly, those living closer to downtown Boston typically have shorter journeys, regardless of destination, than those in outlying suburbs. The fact that journeys beginning in towns such as Waltham, Bedford, and Stoneham typically take close to or even more than an hour is probably closely tied to the observation above that these communities generate relatively few trips, either local trips or longer commute trips to downtown. It is not clear from this data whether these communities have long travel times because there is little demand to justify faster service, or whether there is little demand because the service is slow; it is quite possible that both are true.

The distance of journeys follows somewhat similar patterns. Figure 3-6 shows the average distance traveled for journeys from each census tract that has at least 10 journeys during the month. Not surprisingly, journeys originating closer to the center of the city tend to be shorter than those originating in outlying suburbs. Passengers traveling from the northwestern suburbs tend to have particularly long journeys, which goes along with the longer duration of these trips.

Typical journey distances vary by mode. As shown in Figure 3-7, the majority of bus journeys are under 3 miles, and many are even shorter. There are many similarly short rail journeys, but a larger proportion of rail journeys are 3 to 5 miles, with a nontrivial number longer than 10 miles. Journeys that use both bus and rail tend to be longer still; relatively few of these journeys are less than 3 miles. It seems that most people use rail for longer journeys, or use bus to access rail. Journeys of more than a few miles by bus are rare, perhaps as a result of the feeder or hub and spoke design of the network that encourages passengers to transfer to rail for longer trips. The diameter of the rail system is only about 20 miles and most trips on the transit system traverse only a portion of the city, so these relatively short average distances are about what would be expected; transit systems in other cities likely have very different patterns.

With distance and duration statistics available, the next step is to consider the speed of journeys. Figure 3-8 shows the average weekday morning speed of journeys from each census tract that has at least 10 journeys during the sample period. In general, speeds are higher in the suburbs and lower in the denser urban areas, though there is more variation within neighborhoods than with some of the other metrics. Newton and Watertown have speeds higher than other neighborhoods at similar distance from the city center, while Somerville, Brookline, and Boston's southern neighborhoods experience slower travel.

Figure 3-9 shows the distribution of speeds by mode. Bus is generally slower than rail, which is what would be expected when comparing a mode that travels in mixed traffic with one that has a dedicated right of way. Journeys that use both bus and rail are more similar to the distribution for rail than for bus. Since the rail portion of the journey is often longer, the rail speed may dominate. Also, since the bus portion of dual-mode journeys is often in the higher-speed suburbs, the average speed for the entire journey is comparable to rail much of the time.

Few journeys have average speeds approaching common posted speed limits in the area of travel. This may be due to the slow pace of travel in urban areas for all modes, with congestion, frequent traffic lights, and the region's labyrinth of twisty and one-way streets. Transit-specific factors such as dwell times at stops, time spent transferring, and the waiting time between tapping at a faregate and boarding a train likely also play a role, leading to speeds that are lower for transit than for driving.

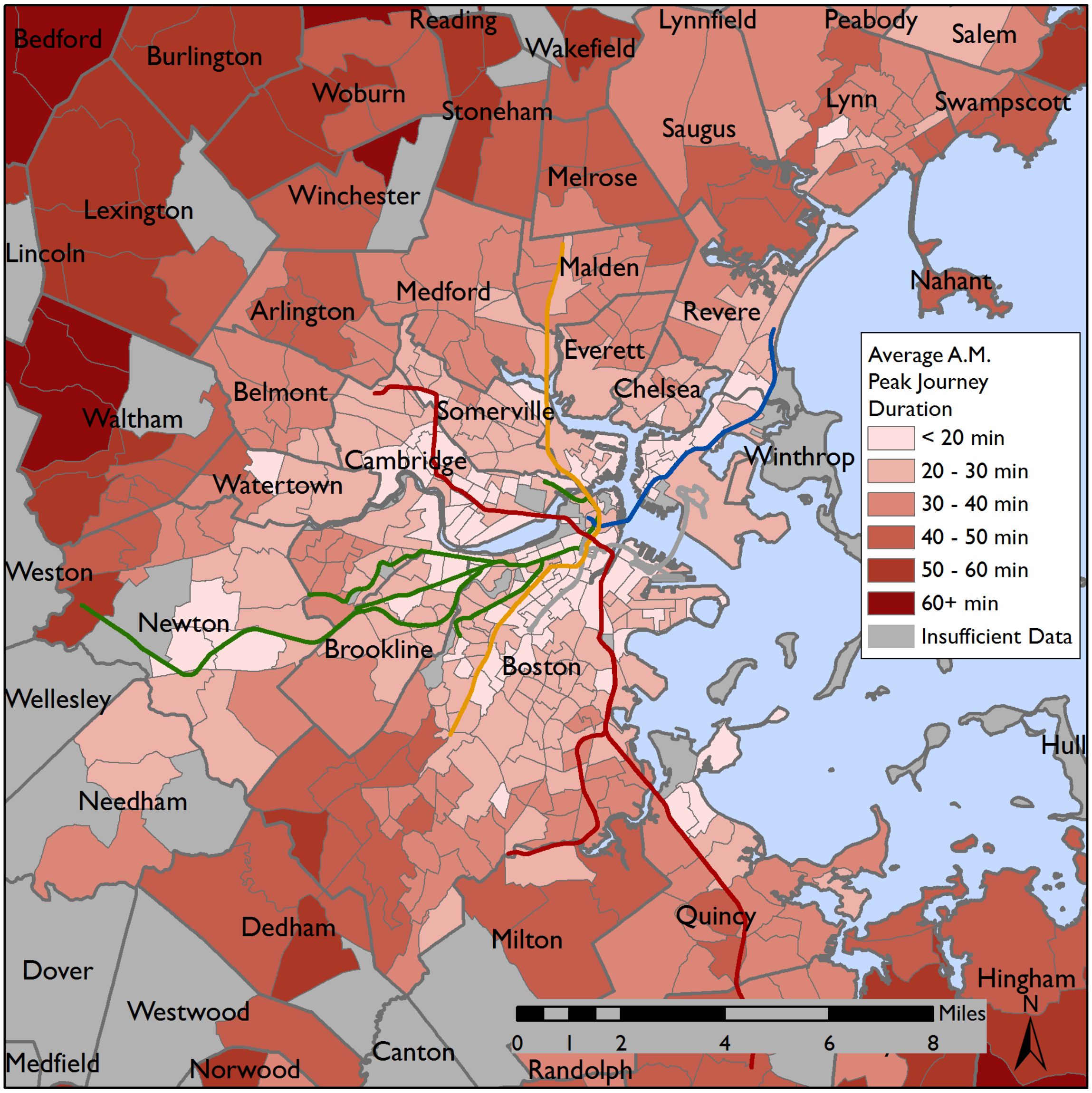


Figure 3-5: Average weekday morning peak journey duration, October 2014

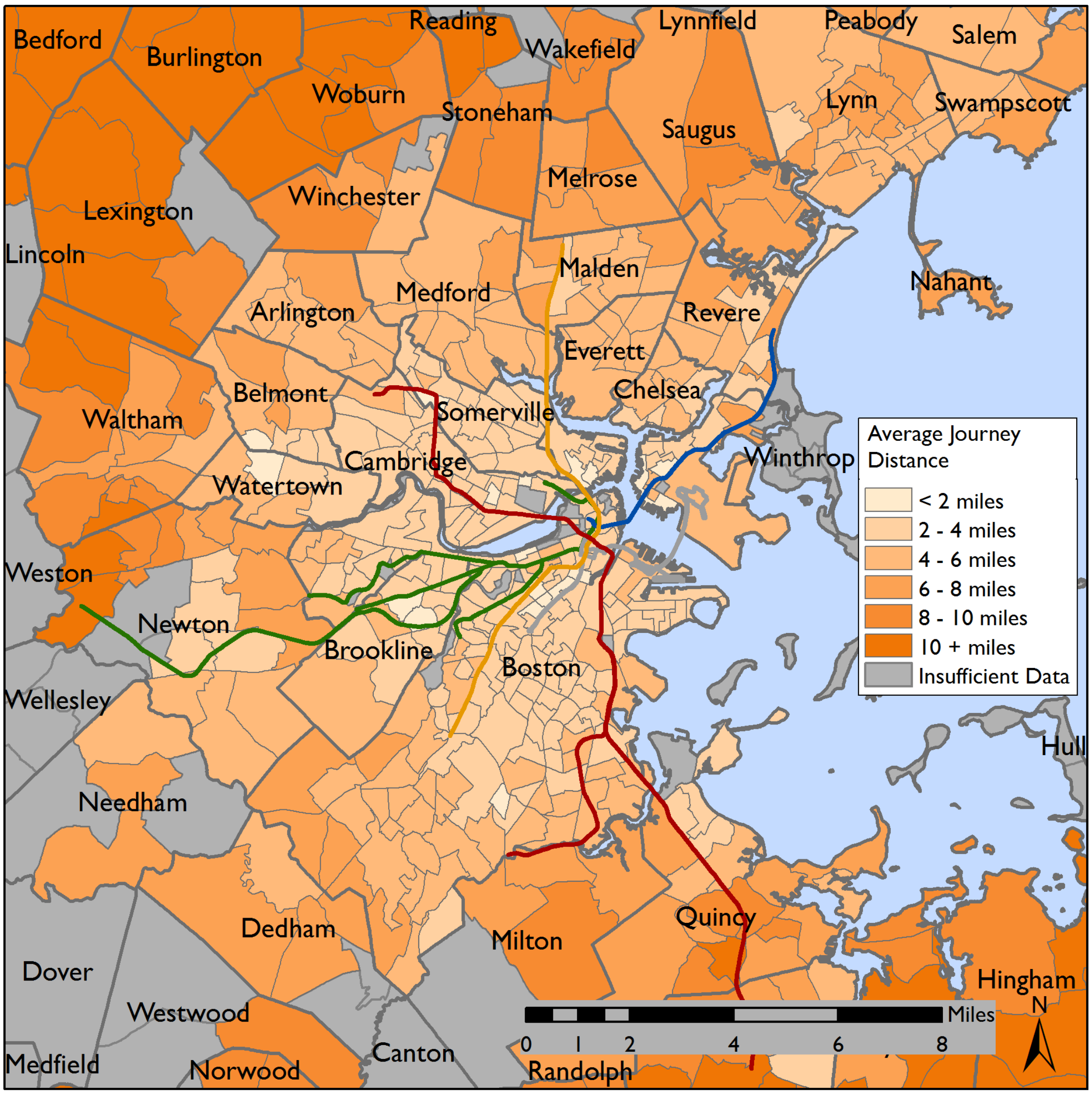


Figure 3-6: Average journey distance, October 2014

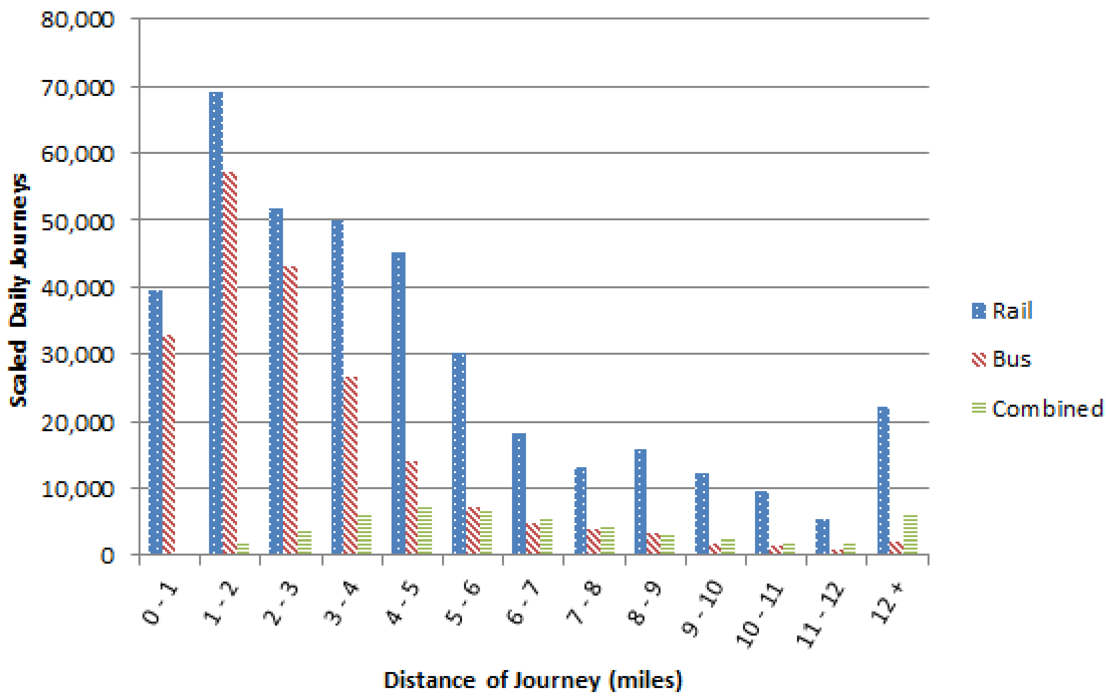


Figure 3-7: Distribution of distance of journeys, October 2014

3.5 Estimated Waiting Time for Bus Trips

As mentioned in Section 3.4, the calculation of the duration of journeys using ODX does not include the initial waiting time for bus journeys. In order to better compare bus and rail travel times, these initial waiting times can be estimated. An appropriate estimate depends on the frequency of the service for that trip. For this analysis, frequent service is defined as headways of 10 minutes or less, in accordance with the definition of "walk-up" service in the MBTA's Service Delivery Policy (Massachusetts Bay Transportation Authority, 2010). For infrequent service, passengers are likely to rely on the schedule and arrive at the stop shortly before the bus is scheduled to depart. For this analysis, the average waiting time for a bus boarding on an infrequent service is assumed to be three minutes before the scheduled departure time, plus the delay past schedule if the bus is late. So for a bus scheduled to depart at 8:34 a.m. that actually departed at 8:38 a.m., the waiting time is estimated at 7 minutes (3 minutes before the schedule plus 4 minutes of delay).

For frequent service, passengers are unlikely to check the timetable but will instead arrive at the stop whenever they are ready to leave and assume that a bus will arrive shortly. For these passengers, the waiting time can be estimated as half of the time between the departure of the previous bus from the stop and the arrival of the bus used for the trip. When passenger arrivals at the stop are randomly distributed, this estimate will be equal to the average waiting time. While the estimate may significantly over- or underestimate the waiting time for a particular passenger journey, when many trips are aggregated these waiting time estimates should provide

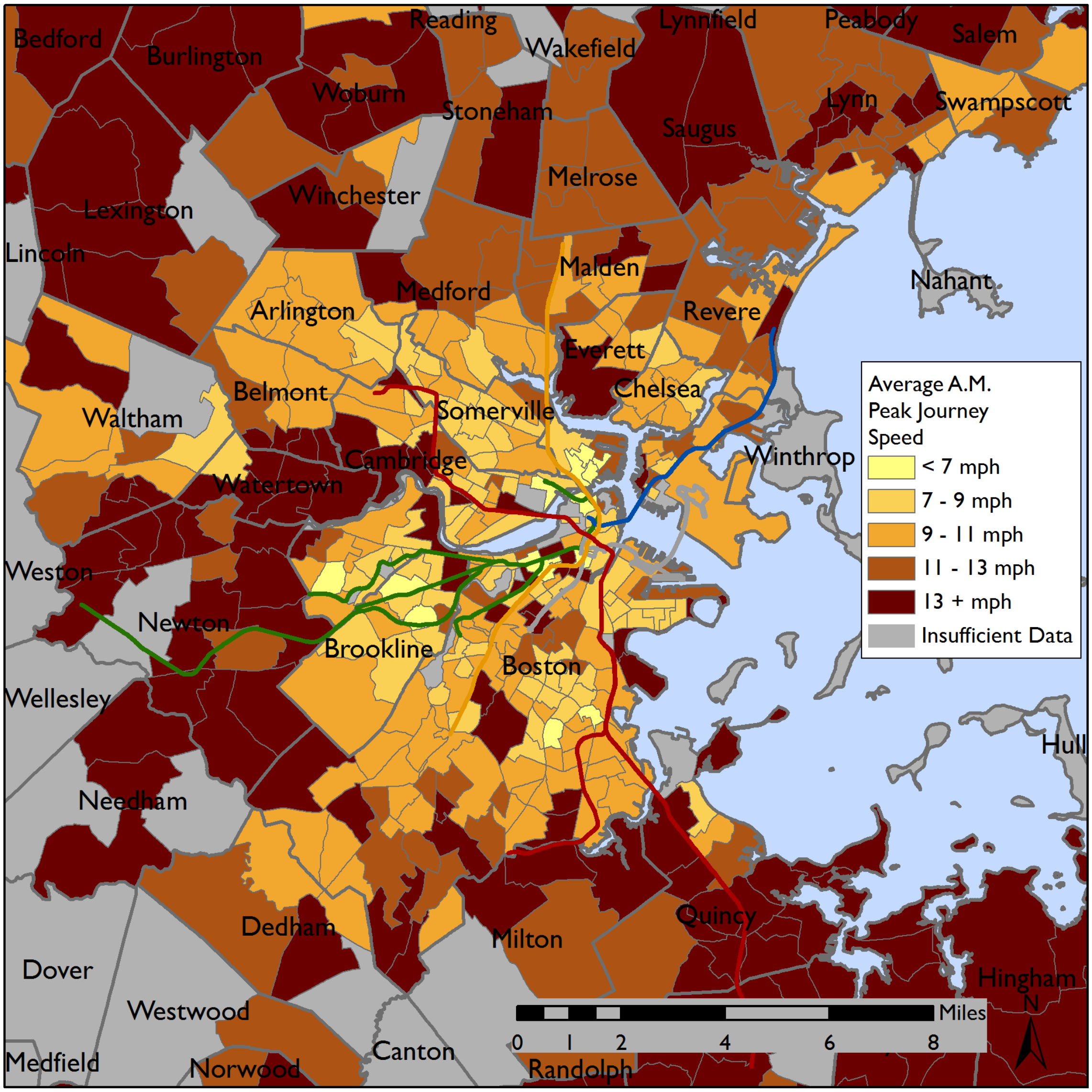


Figure 3-8: Average weekday morning peak journey speed, October 2014

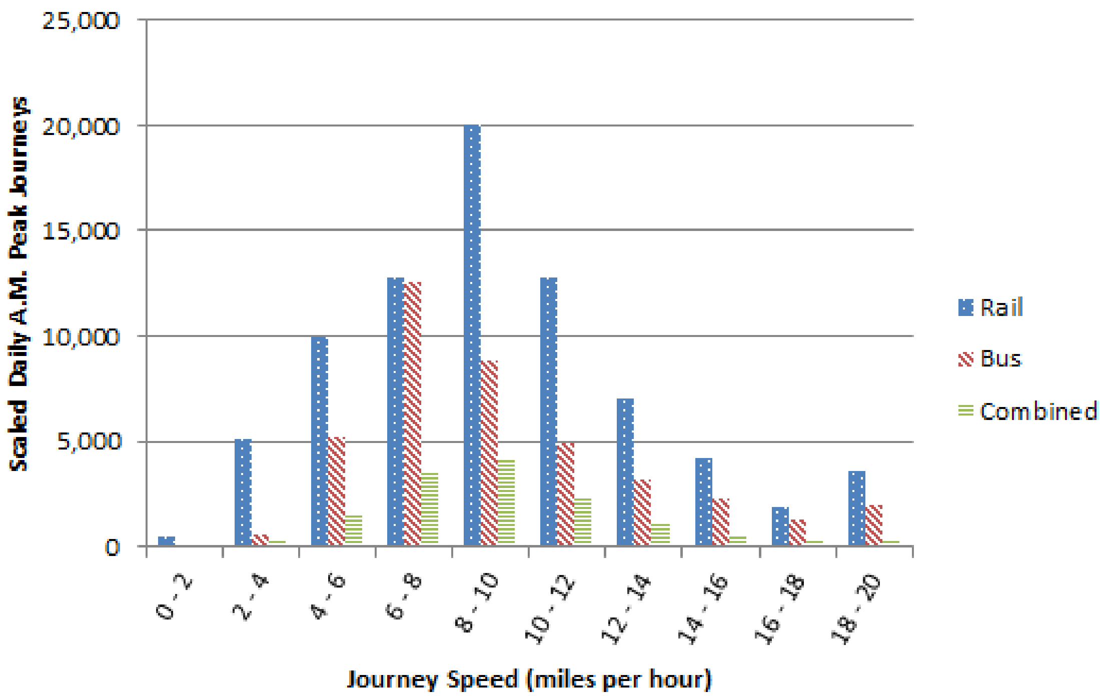


Figure 3-9: Distribution of speed of weekday morning peak journeys, October 2014

a sufficiently realistic approximation. The approximation does not take into account the effect of mobile apps and other real-time information that passengers may use to time their arrivals to the bus stop so that they wait only a brief time. These apps can reduce the amount of time that passengers spend waiting at the bus stop, though passengers still experience the reduced spontaneity of being required to time their departures and may simply be waiting elsewhere rather than using the time for other things. Therefore, the proposed estimates still capture the general impact on the passenger experience of irregular, infrequent, or delayed service.

For each bus boarding in ODX, several data points were collected. First, the bus of the same route and direction scheduled to serve the stop most recently was identified. For example, if buses are scheduled to arrive at 8:20, 8:30, and 8:40 a.m. and the boarding occurred when the bus arrived at 8:34 a.m., the most recent scheduled bus was at 8:30 a.m. The second-most recent bus was also identified, which is the 8:20 a.m. bus in this example, and the scheduled headway is calculated from these two times (in this case 10 minutes).

A table of "stop events," or times that a bus stopped at a bus stop, based on external announcements and timepoint data (described in Section 2.1) was available from the ODX preprocessing. The prior bus of the same route and direction to serve each stop was identified using this table, similar to the process described above for scheduled buses. The time between the prior bus and the bus used for the trip is the actual headway for the basis of the waiting time calculation described above.

This calculation is complicated by the fact that the "stop events" table is not comprehensive, in that it does not include the time at which a bus passes by but does

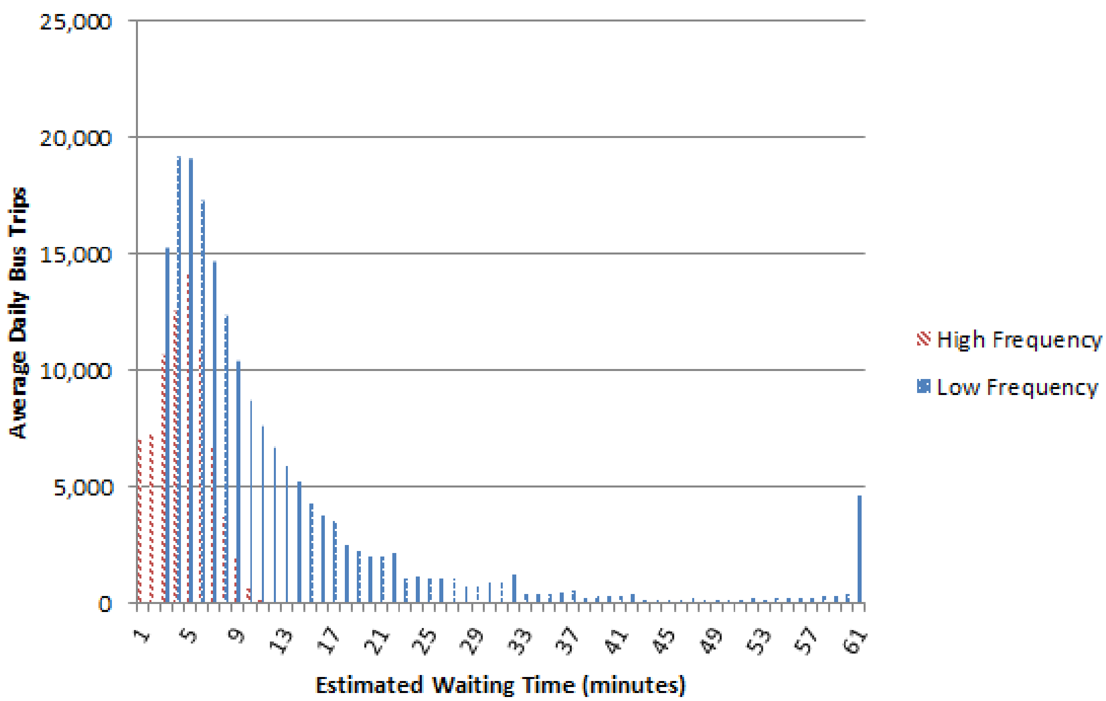


Figure 3-10: Estimated waiting time for bus journeys, October 2014

not stop. Therefore, the actual headway calculated in this manner is the headway since the prior bus stopped at the stop, while a bus that passed by in the interim is ignored. To account for this, the time since the second-previous scheduled bus (the 8:20 a.m. bus in the example above) is used as an upper limit for the value of the actual headway.

Figure 3-10 shows the distribution of waiting times for high and low frequency service. Most trips have only a few minutes of waiting time, but a significant number of passengers wait for more than 10 minutes, and many more than 20. Some passengers are estimated to wait for more than 60 minutes for low frequency service; this can be due to infrequent service that arrives before the scheduled time and leaves a passenger to wait for a long time, long gaps in service during the midday between the peaks that cause inflated estimates, and occasional very long delays. While very long waits are generally limited to low frequency service, the general pattern of waiting time is similar at all frequencies.

With the data gathered for this analysis, it is also simple to calculate delay, or the difference between the actual arrival of the bus and the previous scheduled arrival time. As Figure 3-11 shows, most boardings occur within only a few minutes of the scheduled time, though a small number of trips are delayed by up to an hour or more.

This estimate of wait time ignores some complexities of the network. A passengers is assumed to wait for a bus of the route that she used, regardless of whether buses of other routes that also serve her destination pass by while she is waiting. The degree to which this assumption holds varies depending on the circumstances of a shared-route corridor (Viggiano, 2013). In the MBTA there are a number of shared-route corridors

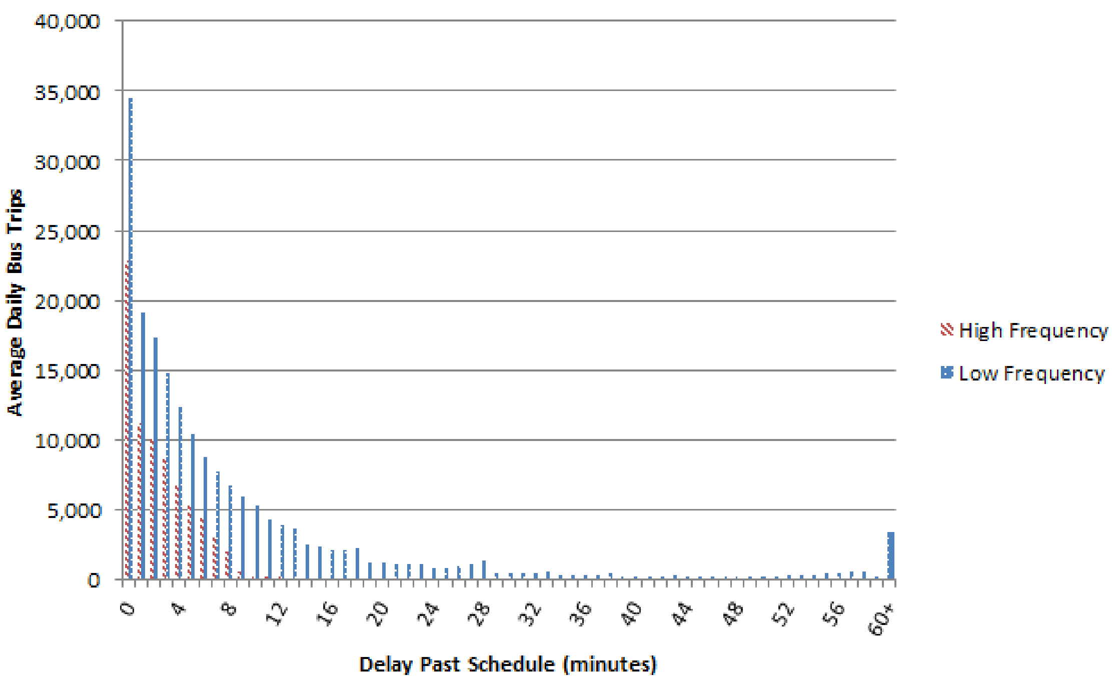


Figure 3-11: Delay past scheduled departure for bus journeys, October 2014

where passengers might take multiple routes depending on which arrives first, but the complexity of the computations to incorporate this into the estimates of waiting time are beyond the scope of this thesis. For these trips, therefore, the waiting times here may be modestly overestimated.

3.5.1 Effect of Waiting Time Estimates on Journey Duration Distribution

As noted in Section 3.4, the distribution of duration for bus and rail journeys cannot be directly compared using the times included in ODX due to the fact that bus trips do not include the initial waiting time. With the estimates generated above, it is possible to calculate a distribution that includes these estimates.

Figure 3-12 incorporates the waiting time estimates into the journey time and shows the distribution by mode. Compared to Figure 3-4, which does not include the bus waiting time estimates, bus journeys and rail journeys show much more similar distributions of travel time. The shorter duration of bus journeys compared to rail in Figure 3-4 is therefore mostly due to the differences in how travel time is measured, rather than to an actual significant difference in typical travel times.

3.6 Customer Experience of Service Frequency

One result of estimating waiting times using the methods described in Section 3.5 is that it is relatively simple to examine the frequency of service as experienced by

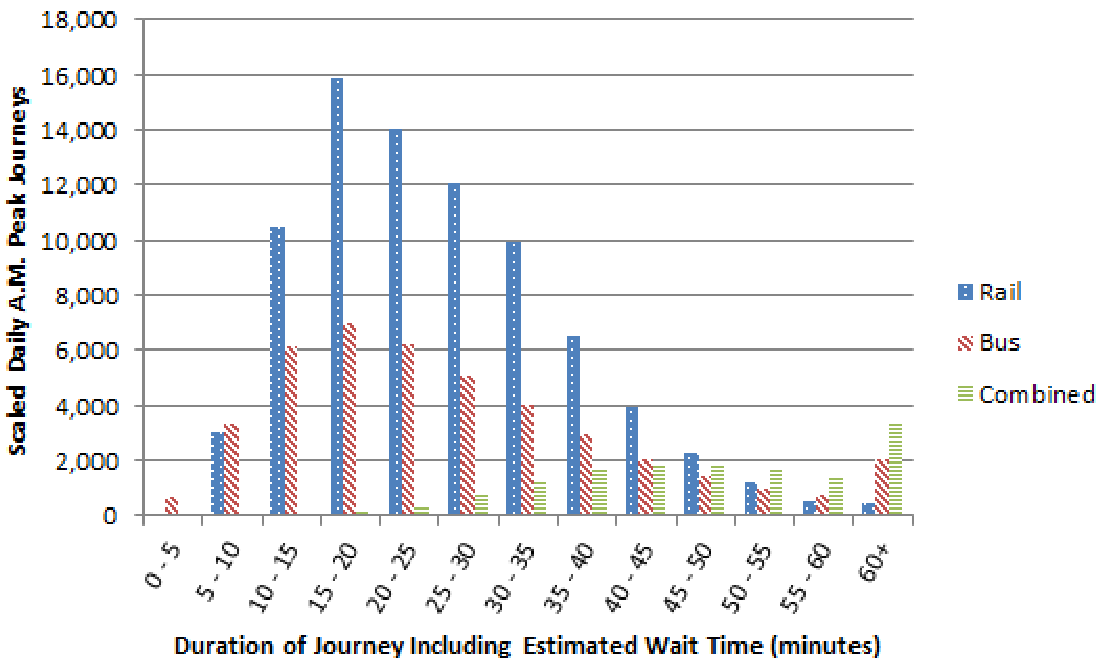


Figure 3-12: Average weekday morning peak journey duration with estimated bus waiting time, October 2014

the passenger. The time elapsed between the departure of the prior bus serving the passenger's destination and the arrival of the bus used for the trip has already been calculated.

Table 3.1 shows the number of bus boardings by frequency and time of day throughout the system. Despite the attention paid to peak service and the high volume of riders during this time, only 33% of boardings are during peak hours. The remaining 67% take place in the early morning, midday, evening, and weekend periods. Similarly, though the Key Bus Routes program described in Section 1.2.3 has increased the amount of high-frequency service, only 27% of boardings are on these trips. Overall, just over half the boardings in the system are on low-frequency, off-peak service, while just 13% are on high-frequency service during the peak period. This indicates that the off-peak and low-frequency services serve an important role in the region's travel patterns.

Table 3.1: Monthly bus boardings by time of day and frequency, October 2014

	Peak	Off Peak	Total
Low Frequency (> 10 minute headway)	1,733,915 20%	4,617,610 53%	6,351,525 73%
High Frequency (<= 10 minute headway)	1,164,910 13%	1,141,315 13%	2,306,225 27%
Total	2,898,825 33%	5,758,925 67%	8,657,750 100%

3.7 Transfers and Mode

One of the most significant improvements of ODX over existing data sources is the inclusion of information on transfers. However, the analysis is complicated by the fact that ODX only provides information on transfers outside of the rail faregates, and does not include any data on transfers among rail lines. Fortunately, the MBTA system is geometrically simple enough that there is an obvious path and number of stages for nearly all station pairs. Even in the cases where the exact path is not clear (e.g., transferring from the Red Line to the Blue Line when Government Center station is not closed for construction, or transferring between the Orange and Green Lines at North Station, Haymarket, or via the walking transfer between Downtown Crossing and Park Street), the minimum number of stages is always evident. Based on a data table provided by other MBTA researchers that shows the most likely path between each pair of stations, the number of stages for each rail trip was added to each journey in ODX. Based on this information, 79.5% of journeys in October 2014 were single-stage , 17.6% were two stages, and the remaining 2.9% were three or more stages.

Figure 3-13 shows the average number of stages for journeys originating in each census tract around the region. Not surprisingly, more transfers are generally required in outlying areas than in areas closer to downtown. Fewer journeys have transfers around the rail lines than in areas predominantly served by bus. Portions of Newton also have predominantly single-stage journeys, possibly due to the express bus service available in the area, as well as areas near Lynn that have a combination of express service to downtown and local trips.

In addition to averages for all journeys originating in a location, it is possible to consider the number of transfers between origin-destination pairs. Based on the nearly 500 census tracts in the service area, there were 19,692 pairs of census tracts that had at least 10 journeys between them during the month of October 2014. The minimum of 10 journeys is large enough to eliminate outliers and reduce the skewing effects of any unusual travel behavior without reducing the sample size of OD pairs more than necessary.

Figure 3-14 shows the distribution of the OD pairs based on the average number of stages for the journeys between each pair of census tracts. For most OD pairs, the average is very close to a whole number, that is, one, two, or three stages, which indicates that most of the journeys for that OD pair use that number of stages. Relatively few tracts appear to have a mix of single- and multi-stage journeys used to travel between them.

That impression is confirmed in Figure 3-15, which shows the distribution of OD pairs by the proportion of journeys between the census tracts that have each number of stages. Many OD pairs have 0% of the journeys between them take only one stage, indicating that a single-seat ride option is unavailable. Most tract pairs also have under 10% of their journeys use three or more stages, indicating that most places that people travel on the network can be reached with at most one transfer. As with other aspects of the network, it is impossible to tell the extent to which the lack of three-stage journeys is due to passengers opting not to use transit to travel to these

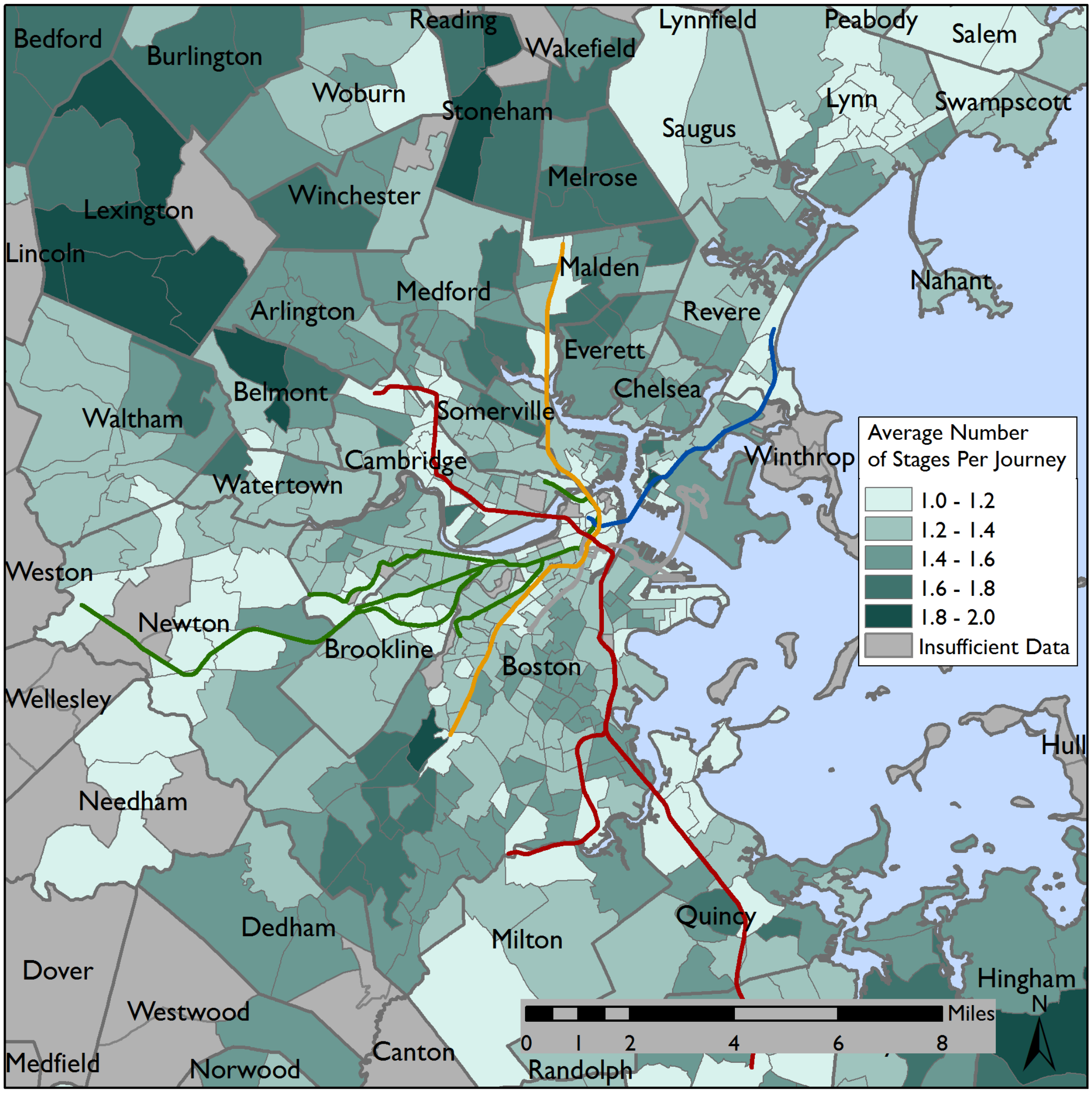


Figure 3-13: Average number of stages per journey, October 2014

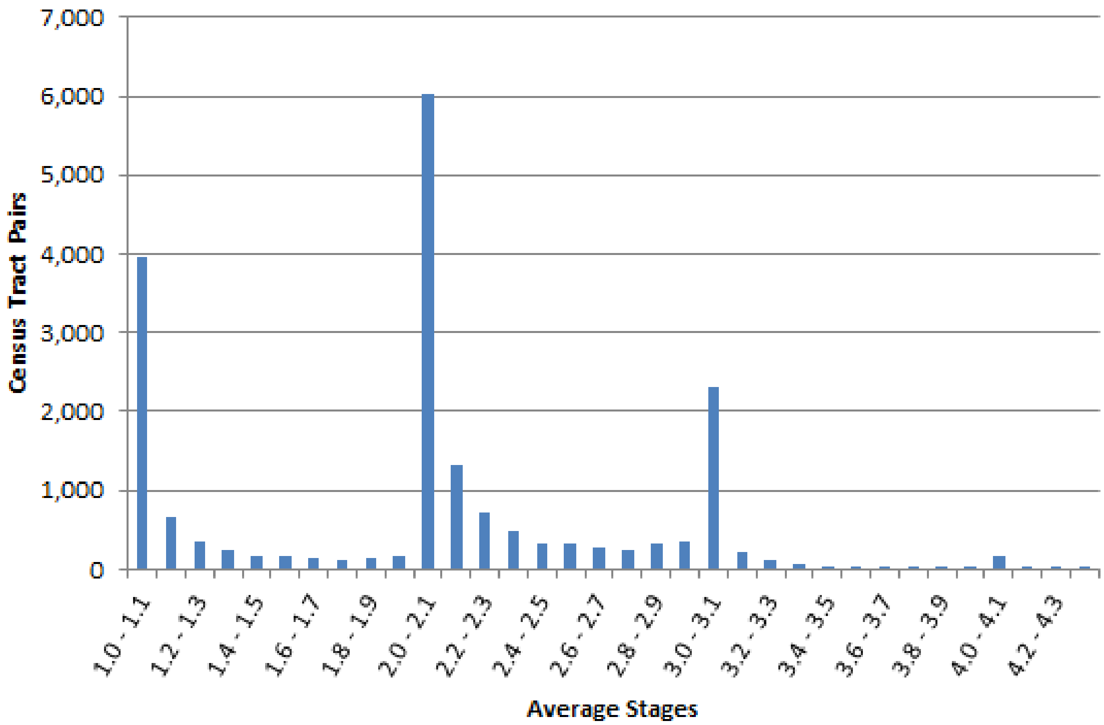


Figure 3-14: Average stages per journey for census tract pairs, October 2014

locations or whether more direct service has not been provided because there is little demand for travel between these OD pairs. The analysis in Chapter 6 will explore this question further when evaluating proposals that provide direct service between points where it is currently unavailable. Regardless of the cause, most OD pairs have over 90% of their journeys using the same number of stages.

The analysis methods for the mode of journeys are similar to those for the number of stages per journey. Each journey in ODX was assigned a mode, either bus, rail (including both light and heavy rail), or a combination. About 60.5% of journeys in October 2014 were by rail, about 31.7% by bus, and the remaining 7.8% used a combination of both bus and rail.

Figure 3-16 shows the distribution of census tract pairs by the proportion of journeys between the census tracts that use each mode. As with transfers, the journeys for each OD pair tend to be predominantly the same. For the vast majority of OD pairs, there are no journeys made by rail alone. This highlights the fact that relatively few census tracts have rail stations. For those OD pairs that do have journeys by rail alone, rail journeys typically represent over 90% of journeys. Similarly, most OD pairs have either a very small or a very large proportion of journeys made by bus or by a combination of bus and rail. For journeys to most destinations from most origins, there is a preferred mode, where there is a choice at all.

Considering mode and number of stages together, as in Figure 3-17, most bus and rail journeys are a single stage (journeys that use both bus and rail obviously cannot be a single stage). Among two-stage journeys, rail-to-rail transfers are most

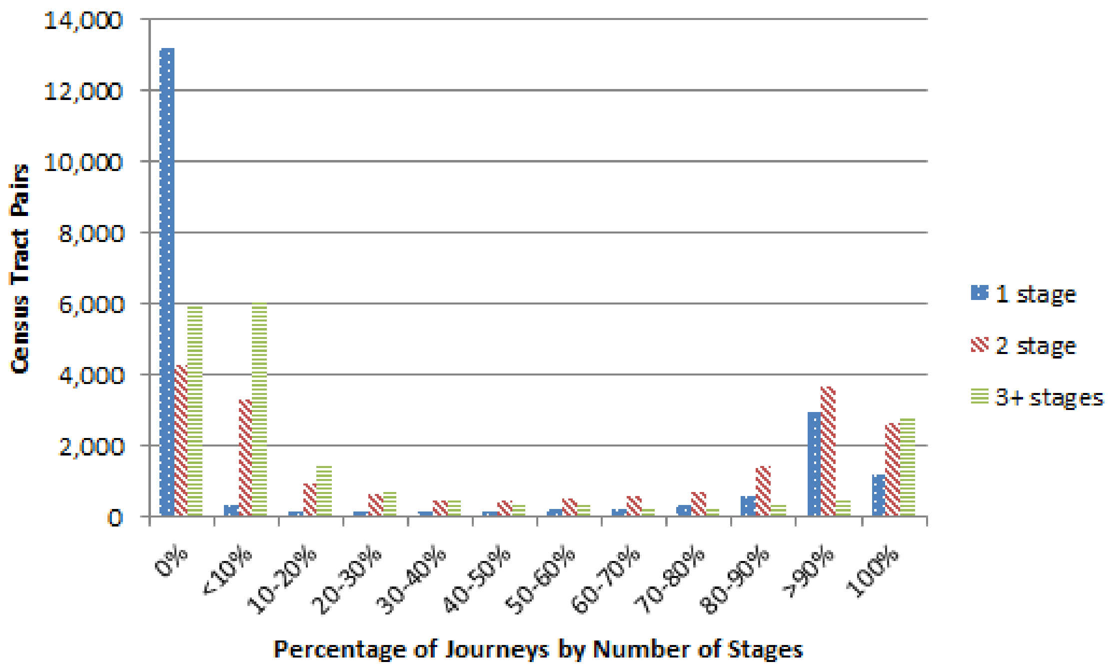


Figure 3-15: Distribution of stages per journey for census tract pairs, October 2014

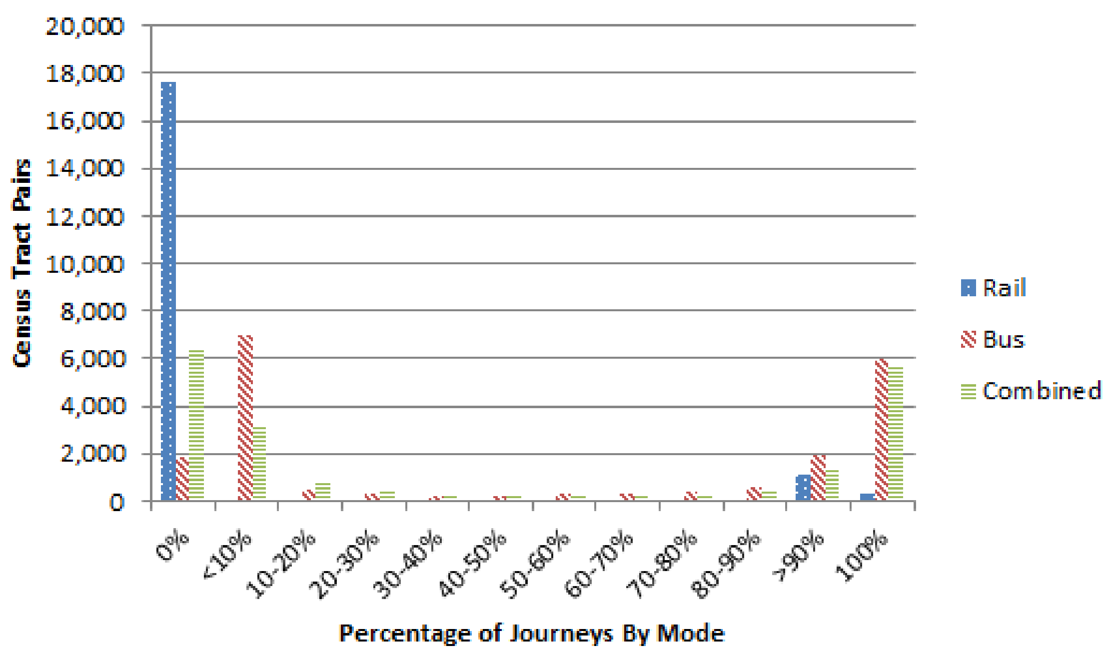


Figure 3-16: Mode of journeys for census tract pairs, October 2014

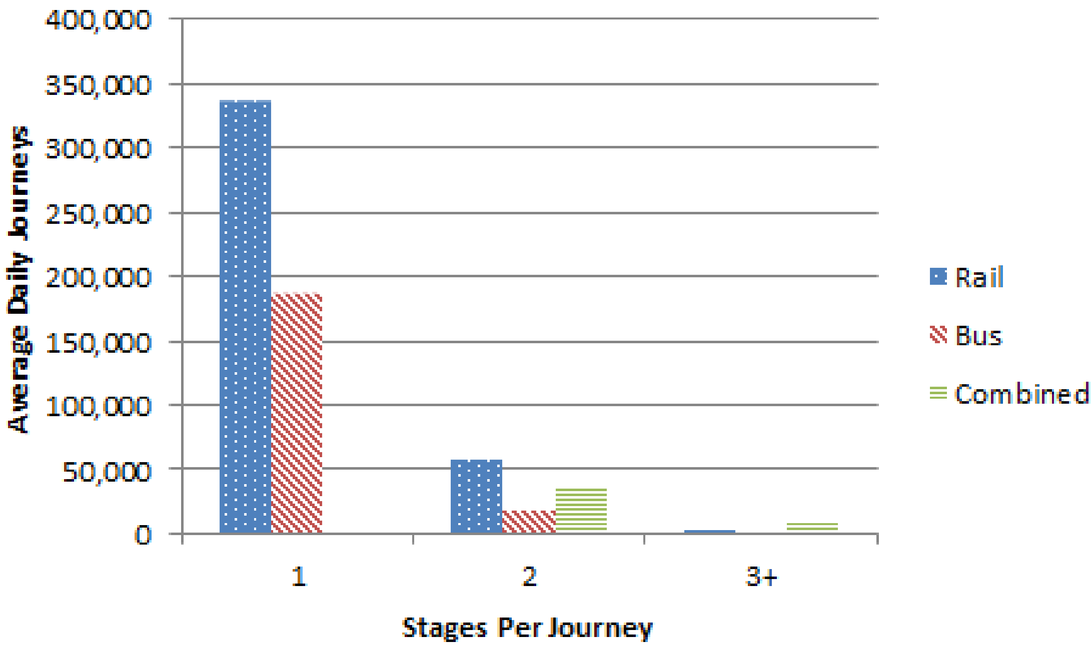


Figure 3-17: Average daily journeys by mode and number of stages, October 2014

common, followed by journeys that combine bus and rail. Bus-to-bus transfers are the least common way that multi-stage journeys are made. There are a small number of three-stage rail journeys, but most journeys of more than two stages are made by a combination of modes.

3.8 Productivity

A final useful statistic is the productivity of the service being provided. This is a common measure in the transit industry, and is typically calculated as passenger boardings per hour of service provided. Linking ODX data to the GTFS schedule data provides the passenger boardings for each scheduled bus trip, which can be aggregated in a variety of ways. It is important to note that the public schedule only includes hours of scheduled running time. Therefore, these productivity figures are not directly comparable to those used by other agencies or elsewhere in the MBTA. These other definitions are typically calculated using a definition of revenue hours that includes layover time at terminals, while others use non-revenue hours including layover time and pull-in and pull-out from the garage.

Figure 3-18 shows the overall productivity of the system on weekdays over the course of the day. It also separates inbound and outbound service; most routes are more crowded during the inbound morning peak and outbound afternoon peak given the region's overall commuting pattern, and some routes have higher frequency in the peak than in the off-peak direction. Productivity adheres to this pattern, with inbound productivity higher at the beginning of the day and outbound productivity

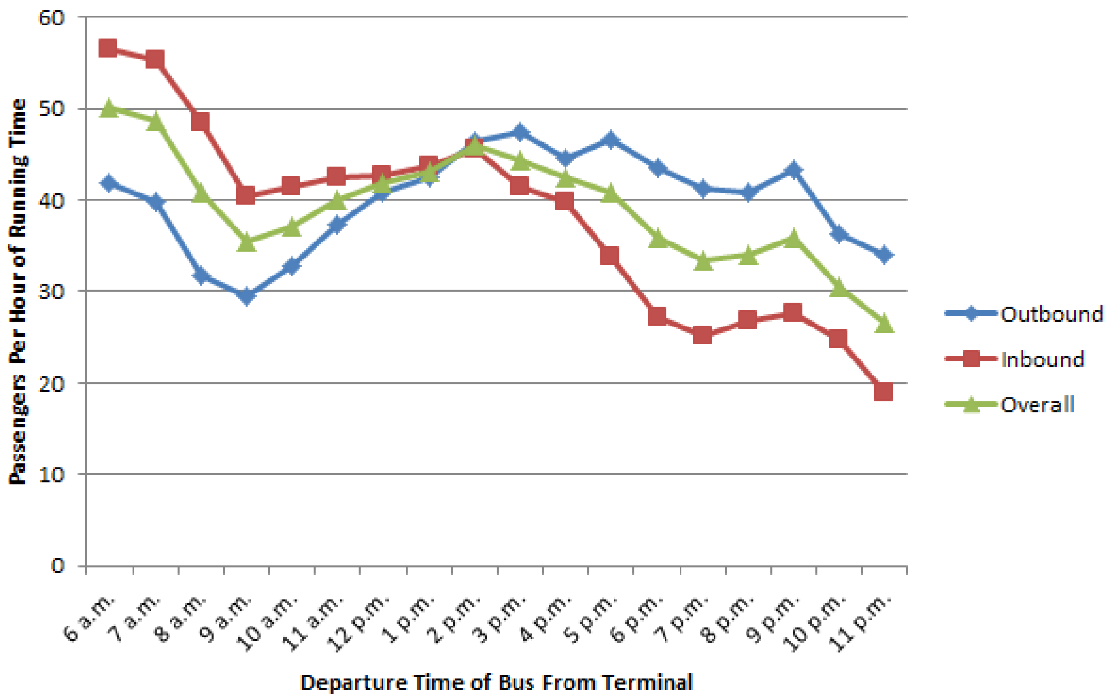


Figure 3-18: Average weekday passengers per hour of running time, October 2014

higher through the afternoon and evening. Somewhat surprisingly, overall productivity is not noticeably higher during the crowded peaks than the rest of the day. This may be due to several factors, including longer running times in the congested peak periods. Highly variable loads in the peaks may also contribute, with some buses operating with light loads due to bunching while others are full. Reductions in service levels in off peak periods, including shorter variations of long routes, also increase off peak productivity. The highest productivity occurs in the 2 to 3 p.m. hour. A number of MBTA routes run extra trips with route variants that serve local schools during this period; these trips are often quite crowded since they occur right as schools release students in the afternoon, increasing the productivity.

3.9 Interpreting the Results

Having looked at the data in a variety of ways, what conclusions can be drawn about how passengers use the MBTA system? First, despite the growth of economic centers outside of downtown Boston, a traditional commute pattern centered on the central business district is still dominant. A large proportion of the travel in the region is along radial lines, particularly the radial rail lines. Crosstown and circumferential travel is growing but still makes up a relatively small proportion of trips during peak hours. It is not clear whether this is due to lack of demand for these trips or due to the limited supply of circumferential routes that allow for direct journeys rather than a two-stage radial journey with a transfer in the central part of the network. Both factors likely play a role. The housing and employment patterns in the region still generate a radial commute for many, but the structure of the transit network and the fact that service patterns have not adapted to the growth outside of downtown undoubtedly strengthen and preserve these travel patterns.

Another aspect of the system that is clear from the data is that rail serves as the backbone of the system. Well over half of journeys use rail, and when rail is available passengers strongly prefer it to bus options. For most pairs of origins and destinations there is a strongly dominant mode. This indicates both that there is little competition between bus and rail, which can be seen as an efficient use of resources, and that there is relatively little redundancy in the network, which can lead to difficulty in handling disruptions and a general lack of resilience.

The vast majority of transfers are either within the rail system or between bus and rail. Many parts of the bus network function as feeders to the rail system, particularly those routes fanning out from outlying rail stations including Forest Hills, Alewife, Wonderland, Malden Center, Wellington, and Quincy Center. This is a clear result of the way in which the bus network has been designed, with virtually all bus routes having at least one terminal at a rail station. Bus-to-bus transfers, on the other hand, are relatively uncommon. This may be due to the way that the network is structured, or it may be due to the fact that with many routes operating at low frequencies bus-to-bus transfers are seen as inconvenient. The typically lower on-time performance of bus compared to rail may also play a role, as it can be easy to miss a connection and end up with a long wait. Similarly, all but a handful of journeys on the system are one or two stages, though a significant number of origin-destination pairs require three stages to travel between them. Again, this may be a function of demand for travel between those pairs of locations or it may be that travelers view transit as a poor choice for these trips.

Lastly, despite the attention paid to weekday peak service and the Key Bus Routes, most passengers' experiences of the MBTA network are of low-frequency service, and a significant portion of travel on the network is off-peak. These passengers likely value single-seat ride opportunities due to the significant time penalty often involved in transferring among low-frequency services.

Chapter 4

A Framework for Bus Service Planning

ODX provides a rich data set that has a wide variety of applications. System-wide analysis is one such application, as discussed in Chapter 3. Other applications are more ad hoc, such as managing the disruption around a bridge closure (Marr, 2015; Gordon et al., 2013). This chapter explores a third type of application: recurring, proactive bus service planning.

The ways that ODX can be used in bus service planning are quite diverse, ranging from identifying changes in travel patterns to uncovering reliability problems to determining the effect of service changes on existing riders. Latent demand, or demand by riders who are not currently using transit, can also be measured using ODX in the ex-post review process after changes have been implemented. The enhanced service planning process proposed in this chapter incorporates these and other ODX-based methods, along with a variety of other data sources and tools, to make the MBTA's existing biennial process more robust and proactive. The proposed process provides a framework for using ODX in bus service planning, demonstrating its usefulness and effectiveness at every point in the process. The five-stage process described here is designed to be performed in its entirety, but the framework is also intended to describe the types of situations in which ODX is useful and to demonstrate ODX-based tools and methods that may be applied in other contexts.

The chapter begins with an overview of the framework, including a discussion of how the proposed process fits within and improves upon the MBTA's existing service planning process. The subsequent sections present each of the five phases of the framework in more detail. The chapter concludes with a discussion of how some of the methods developed for each of the five phases might be applied outside of the context of this framework.

4.1 Framework Overview

As described in Chapter 1, the MBTA's current service planning process focuses on whether each route meets the service standards rather than on how well the system addresses the transportation needs of the region. While this assessment is an important one if the service standards are to have any weight, this reactive approach is insufficient on its own. The process proposed here serves as an enhancement to the existing methods, and includes five phases, as illustrated in Figure 4-1. Each of these phases will be described in detail later in this chapter:

1. Identifying where changes are most likely to be needed.
2. Analyzing existing travel patterns to and from these locations to determine the challenges at each.
3. Developing proposals for service changes to address these challenges.
4. Evaluating these proposals and determining which should be implemented.
5. Implementing the selected proposals and performing post-hoc evaluation of the service changes.

Chapter 1 described the MBTA's long-term planning process and the structure of the Program for Mass Transportation. The PMT also follows several steps: it analyzes each segment of the region, identifies "mobility problems" in each, and proposes solutions. Which solutions are implemented is determined by the Capital Plan. The process here for bus service planning mirrors this long-term process, but operates on a much shorter time scale and at a detailed level more appropriate for the time and financial resources needed to make changes to bus service. Despite these differences, the conceptual parallels will hopefully make the process more understandable to all stakeholders and increase its acceptance, both within the MBTA and in the community.

In focusing attention on areas where change is likely to be needed and by examining existing travel patterns, the changes developed through this approach are based on the mobility needs of the region, rather than on the more limited scope of individual route performance. This is a fundamental shift from thinking about service planning from the point of view of the transit provider, which is naturally concerned with how well it is providing the service it has promised, to the point of view of the passenger (or potential passenger), who cares more about whether he or she can get to a desired destination conveniently.

The approach also incorporates a wider range of data than the current process. Service planners currently use AVL data to analyze reliability and running times and APC data for load information. The proposed process used ODX in a variety of ways, which has the benefits described in Section 2.7. As Sections 4.2 and 4.3 will describe, the new process also offers opportunities to take advantage of a wide range of other data sources, including population and employment trends, demographic and socioeconomic data, economic development patterns, and traffic information, among others. This leads to proposals for service changes that better reflect the needs of a wide variety of constituencies. It also helps planners consider trends over time and what is likely to happen in an area in the future, rather than relying on a static snapshot of recent performance data.

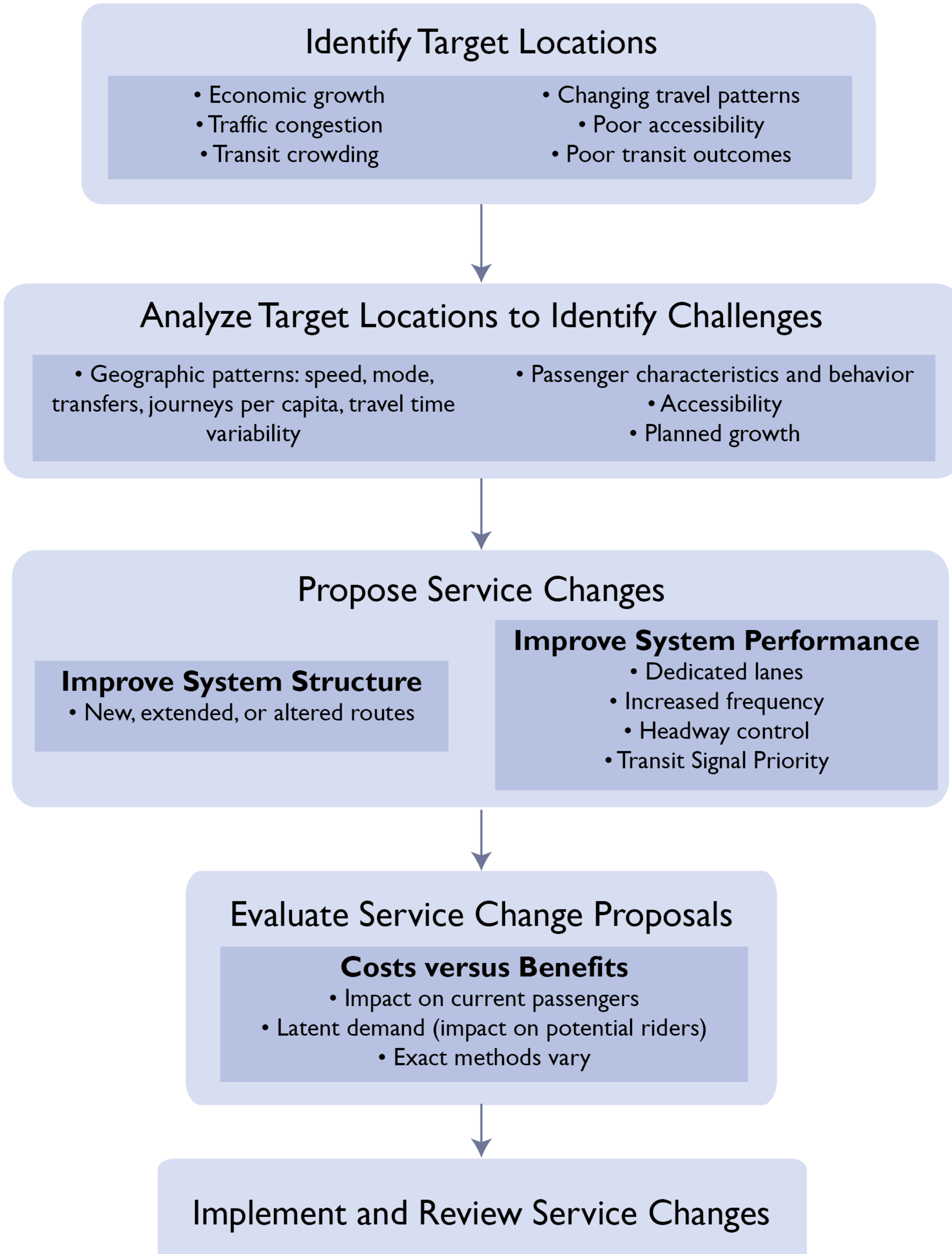


Figure 4-1: Framework for bus service planning with ODX

The process proposed in the framework is also flexible depending on the resources available. It can be used to identify how service should be expanded, or it can be used by a capacity-constrained agency to determine how best to reallocate resources to provide service that better matches the needs of the community.

4.2 Phase 1: Identifying Target Locations

The first phase of the process is identifying a set of target locations. Given the complexity of the MBTA network and the very limited planning resources the MBTA has available, a truly comprehensive analysis is not feasible, especially on a regular basis. Therefore, analysis should be focused on the areas where changes to the system are most likely to be needed and are likely to have the greatest benefit.

Over the many decades of bus service in Boston, and the decades of streetcar service before that, the city and the transit system have evolved together and adapted to each other. In many places, therefore, the basic structure of the network functions reasonably well. However, the MBTA system has been static in recent years, so locations that have experienced significant changes during that time are likely to be less well-served than those that have not changed much at all. These changing areas would therefore benefit from focused analysis. Areas with known congestion or accessibility problems are also likely to benefit.

The biennial service plan should choose a few of these areas to examine closely during each planning cycle. Over time, many different areas of the city will receive needed attention and service improvements. Some suggestions for types of locations to consider and how the locations should be identified are discussed in the sections below.

It is important to consider a variety of location types for several reasons. One is that the location choice has the potential to become politically contentious, and having multiple criteria and a variety of locations for each cycle is likely to reduce objections from the community. The locations chosen each cycle should be spread around the service area rather than concentrated in one place for similar reasons, and using multiple selection criteria makes this easier to achieve.

Choosing locations based on a variety of criteria is also more likely to lead to equitable outcomes and address more issues of concern. For example, examining only economic growth centers would naturally lead to a set of changes that would benefit these areas more than the rest of the city. If economic growth disproportionately benefits some subsets of the population compared to others, particularly if it benefits well-educated, high-income, and white individuals, focusing only on these growth areas raises serious concerns about equity. Whether current growth areas in Boston have disproportionate benefits is unclear, but the process proposed in this research should include a variety of location types in order to account for this possibility. This will reduce the likelihood of unintentionally benefiting some groups more than others. Such disproportionate outcomes are problems in their own right, as transit resources should generally be distributed equitably, but they may also present a legal problem. Title VI of the Civil Rights Act of 1964 prevents transit agencies that receive federal funding from enacting policies, programs, or activities that have the effect of discriminating on the basis of race, color, or national origin, even if those activities are neutral on their face. The Federal Transit Administration ("FTA") requires transit agencies to perform an equity analysis for any major service or fare change to determine whether the changes will have a disparate impact on minority populations or will impose a disproportionate burden on low-income populations (Federal Transit Administration, 2012). Choosing a variety of location types will make it more likely that the set of proposals developed will distribute benefits to people around the region in an equitable way.

4.2.1 Economic Growth Centers

One major type of location that should be analyzed is economic growth centers. Employment data from the U.S. Census, the Census Transportation Planning Products Program ("CTPP"), or state sources can show where the number of jobs has increased significantly over a recent 5- or 10-year period. These data can also indicate where the rate of employment growth is above average. In general, MBTA service will not have adapted to these changing needs, and transit services in these areas are likely to be at or near capacity.

Another source of data is municipal offices of planning and economic development, as well as local real estate and building permit records. These sources can help service planners anticipate where growth is likely to occur in the near future so that changes can be made to accommodate that growth.

4.2.2 Residential Areas with Below-Average Transit Outcomes

Though the Boston metropolitan area is diverse, its residential neighborhoods are mostly quite segregated. Following a report that African American commuters in the Boston area have longer commutes than white commuters (Williams et al., 2014), Dumas used ODX to compare the travel patterns of passengers from areas with mostly African American residents to those of passengers from mostly white areas (Dumas, 2015). To perform this comparison, he developed methods to infer the likely home locations of CharlieCard and CharlieTicket users from ODX data, then examined the travel of riders from different parts of the city. Dumas' work broadly confirmed the earlier study's finding that African American commuters have longer commutes, although he found the differences in commute times to be much smaller than suggested by the earlier studies. He determined that the disparity is due in significant part to a higher number of transfers for commuters from mostly African American communities than for journeys of commuters from mostly white areas.

While these studies focused on the travel differences of two racial groups, the methods can be used to examine transit equity more broadly among racial and ethnic groups as well as across income levels. Parts of the city with below-average transit outcomes may be good candidates for further study. In particular, low-income and minority communities should be examined when their transit outcomes are poor. Areas of high residential density or that are part of the urban core may also be good target locations. Outlying suburban areas may well have poor transit outcomes, but the extent to which studying these locations and implementing service improvements to low-density suburban communities is a high priority, or even feasible without a major increase in resources, will depend on the political climate and the judgment of service planners.

4.2.3 Areas with Changing Travel Patterns

While ODX data is currently only available for a few months, over time it will become available for longer periods. This will enable longitudinal analysis of travel patterns. Where travel patterns are changing, the transit network may need to change as well in order to appropriately serve the new demand.

For this analysis, as with some aspects of the network analysis in Chapter 3, aggregating stops and stations into some sort of zones is a necessary first step. This might be census tracts, traffic analysis zones ("TAZs"), or some other division based on the particular situation. Each trip and journey can then be assigned a starting and ending zone and the travel in each zone can be examined in the aggregate. Zones where the change in boardings, alightings, or transfers is out of sync with system-wide ridership patterns may indicate important target locations. Changes in the proportion of travel occurring at different times of day may also indicate a location with changing transit needs. These locations may fall under other categories, such as economic growth centers, but could also be areas where land use is changing, increasingly important transfer hubs, or newly developed residential areas.

In addition to considering total boardings, alightings, and transfers, ODX makes it possible to determine what role a particular location plays in individuals' travel and to identify some limited demographic information. The ODX output has a unique identifier for each CharlieCard or CharlieTicket, along with what type of fare was paid for each trip. Using the zone aggregation strategy described above, the number of journeys originating or ending in each zone, or the number of transfers being made in the zone, can be further broken down by fare category to determine the proportion of student, senior, and T.A.P. riders. The frequency with which passengers typically visit a location can also be calculated, as can the proportion of passengers' travel that involves the location. Looking at these statistics over time can reveal where the patterns of travel have changed, and therefore where the transit service may need to change as a result. Chapter 5 demonstrates this sort of analysis for a single time period.

A more visible indicator of changing travel patterns is the formation of Transportation Management Associations and the addition of private transit services to an area, such as shuttle buses. As described in Section 1.2.4, private buses serve Kendall Square, the Longwood Medical Area, the Seaport District, the airport, a number of university campuses, and the areas served by Bridj. These services tend to indicate that current MBTA routes are no longer adequate for the needs of an area.

4.2.4 Areas with Significant Transit Crowding

Parts of the transit network that are experiencing a high level of crowding may be good locations to study. There may be service improvements that can reduce the level of crowding, improving the speed and reliability of service. Reduced crowding also improves the experience of riders.

ODX provides the data needed to identify these areas of crowding (Southwick, 2016). With the boarding and alighting information from the ODX data set, load profiles can be developed showing the level of crowding at different points along a route. By looking at typical crowding levels at different times of day and days of the week across many routes, the most crowded points of the system can be identified. Anecdotal staff and customer reports of crowding at terminals, stations, or on particular corridors may also be useful.

4.2.5 Areas with Significant Traffic Congestion

Traffic congestion may indicate a good location to examine from a transit perspective for two reasons. First, congested areas are more likely to experience reliability problems due to transit vehicles that are stuck in traffic. Analyzing these areas more closely may reveal opportunities to improve the speed and reliability of transit service through measures such as transit signal priority, relocating a bus stop, or altering the route to avoid a particularly difficult intersection.

The other reason to examine areas of traffic congestion is that they may present an opportunity to encourage mode shift away from cars and towards transit by providing better transit service. This has the potential to reduce congestion, or to reduce the rate at which congestion is increasing. It can also offer passengers transit options that avoid the congestion that automobiles face through measures such as dedicated bus lanes and signal priority.

4.2.6 Areas with Poor Accessibility

One useful way of assessing the effectiveness of a transportation network is accessibility, or how well the network allows people to reach desired destinations. A common metric is the number of jobs that can be reached within a certain time, such as 30 minutes. The reverse metric of how many people or households (a proxy for potential employees) live within 30 minutes of a particular business location can also be quite useful. The processing required to calculate accessibility is significant, but tools such as OpenTripPlanner, which uses the schedules that transit agencies publish in General Transit Feed Specification ("GTFS") format, make the task significantly easier (Stewart, 2014).

Parts of the city with low accessibility are generally less attractive as places to live or to locate businesses. Improving service to these areas can assist economic development efforts, among other things.

4.3 Phase 2: Analyzing Target Locations

Once the target locations have been identified, the next step is to analyze the travel patterns for each one. ODX provides a rich source of information for this phase. Using the strategies described in Chapter 3 and Section 4.2.3, statistics on journeys to each destination from zones around the region can be calculated and displayed on a map. Some of the statistics that can be easily calculated in this manner include:

- The number of journeys from each zone to the location over a specific time period
- The median or average travel time to or from the location during a particular time period (such as the morning peak). A map showing the area that can be reached within 30, 45, or 60 minutes of a location would provide similar information.
- The average speed of journeys to the location, either the straight-line speed or the speed along the journey's path
- The average number of transfers for journeys to the location, or the average number of stages of those journeys
- The average time spent waiting during transfers on the way to the location
- The transit mode split among the journeys to the location (bus, rail, and light rail)
- The variability of travel time to the location
- The passenger characteristics and behavior described in Section 4.2.3, such as how often the typical passenger visits the location and what proportion of the journeys to a destination use discounted fares such as student and senior fares

Other statistics that might be of interest incorporate other data sources in addition to ODX, such as population figures, information about other modes, or additional information about the existing transit network:

- The number of trips per capita to the location
- The mode split among car, walk, bicycle, and transit for travel to the location
- The travel time by car or bicycle to the location, and how this compares to typical travel times by transit
- The area that can currently be reached from the location with no transfers (sometimes called single-seat rides), determined based on the map of the transit network

- The productivity (passengers per service hour) of the existing routes serving the destination

The particular set of statistics and maps generated for a location will depend on the type of location and its characteristics. A map showing the transit mode split for a location that is only served by bus would not be very informative, for example, while a map showing where students are beginning their journeys might be of particular interest if the location in question is a university.

Once the data has been collected, analyzed, and displayed clearly in maps and charts, the results must be interpreted. The goal is to identify problems and challenges for travel to and from a location, which will be addressed in later stages of the process. Examples of challenges that might emerge are that travel to a growing job center from a particular residential area is quite slow, that traveling a short distance to an important location in the city requires time-consuming and difficult transfers, or that transit is unusually slow compared to travel by private car when accessing a location from a particular direction.

No special tools or methods are required to draw conclusions from the assembled data. As the process was being developed and tested, the challenges for each location usually became readily apparent when the maps and charts were considered all together. Service planners with local knowledge of the location and the neighborhoods surrounding it will be well-positioned to identify the most important challenges for each location. Examples of this part of the process will be presented in Chapter 5.

4.4 Phase 3: Proposing Service Changes

The third phase of the process is developing possible solutions to the challenges identified in the second phase. This requires looking at each challenge in more detail and gathering additional data.

The solutions that are appropriate for a given problem will depend on what type of problem it is. Problems will generally fall into two categories: those of system structure, and those of system performance. The solutions for these two types of problems will often be quite different.

Problems of system structure are those that are due to the geometry of the transit network. There may simply be no reasonably direct path to get from an origin to a destination, or multiple transfers may be required. If this is the case, the solution will require changing the geometry of the network in some way: adding, altering, splitting, or extending a single route, or combining multiple routes. The exact proposals will have to be developed by service planners with knowledge of the area. The process can be supported by the information gathered in phase 2, and also by ODX data. The ratio of path distance to straight-line distance for a journey (called the "circuity ratio") is also available through ODX, which provides a quick way to identify situations in which the lack of a direct route is the cause of slow journeys. ODX data for a specific route, particularly the load profile, will also be useful. Understanding the load profile of a route may help determine whether it should be re-routed completely or whether a variant or branch should be added, for example.

Problems of system performance require different solutions. Even when there is a reasonably direct route from one place to another, the journey may still be slow or unreliable. Some of the statistics calculated from ODX in phase 2 may be useful here, such as the speed of journeys and variability of travel time. It is also relatively easy to join ODX data to schedule data in order to compare actual with scheduled travel times and to determine where delays affect the most people.

Possible solutions to problems of system performance include increased frequency on a route, operational strategies, bus priority measures, and other improvements along the route. For example, Maltzan demonstrated that better headway control at terminals can improve the reliability of service along a route (Maltzan, 2015). Bus priority measures include transit signal priority, queue jump lanes that allow buses to pass lines of cars waiting at signals, and bus-only or bus and high occupancy vehicle ("HOV") lanes. Other measures depend on the circumstances, bus stop relocation or consolidation, slight reroutings to avoid difficult left turns, timed transfers for key pairs of routes, and all-door boarding are among the possibilities to consider.

Another type of problem that cannot be solved by altering the network is that of journeys that are only efficient at certain hours due to a limited span of service or very infrequent service at some times of day. Changes to frequency and span of service are naturally the best ways to correct these problems, though when resources are limited it may be more feasible to improve service along a different path between the two locations.

Sometimes both structure and performance improvements will be reasonable ways to address a particular challenge, especially when there is an acceptable but not direct route between the origin or the destination. Improving an indirect route or adding a direct route, possibly eliminating a transfer, may both be good options.

The productivity measures (passengers per service hour) calculated in phase 2 may be helpful as a diagnostic tool that shows where the supply of service and the demand for travel are currently out of sync, or where there are features of the network or the underlying geometry of the city making it difficult to serve some trips. When an agency is considering a zero-cost reallocation of resources, productivity measures can also help identify where excess capacity exists so that it can be reallocated to some of the new or expanded services identified in this process.

It is important to note that changes to bus service will not be sufficient to address all of the problems that this process brings to light. Sometimes the underlying cause of the problem will be a different mode. If rail service is unreliable due to aging equipment, for example, it will likely be difficult and inefficient to address the issue solely by improving parallel bus service. Similarly, if problems on the rail system lead to the irregular arrival of large volumes of passengers seeking to transfer to bus, improvements to bus service alone cannot fix the problem completely. When this sort of issue is discovered during this process, operational measures on the rail system may generate some improvement. Serious problems should be referred to the long-range capital planning process.

Other problems may be difficult to fully address due to topological and geometric factors, such as a limited number of streets crossing a river or railroad, a convoluted street network, a large park located between the origin and destination, or streets that are too narrow to accommodate turning buses. All of these issues are present in the Boston area.

4.5 Phase 4: Evaluating Service Change Proposals

The fourth phase of the process is an evaluation of the proposals that were developed in phase 3, and a determination of which ones will be implemented. Decisions regarding implementation are based on an evaluation of the costs and benefits of each proposal.

Costs will generally be straightforward to determine. The main cost of most bus service proposals will be vehicle hours of service at each period of the day, which can be found using expected new running times and headways for any route that has changed or been added. Agencies are generally able to determine the monetary cost of these vehicle hours easily. Some proposals will have other costs as well, such as signs and benches at stops along a new route, moving a stop across an intersection, repainting a street to create a bus-only lane, or implementing signal priority or headway control measures. These costs should be fairly easy to estimate in most cases based on past experience with comparable projects.

Evaluating the benefits of each proposal is more complicated. Each proposal may have impacts on intial waiting time, in-vehicle time, waiting time at transfers, the number of transfers that riders make, crowding, reliability, accessibility, and ridership. The exact methods used to quantify these effects will depend on the proposal. There will generally be two components to the evaluation: the effects on current passengers, and the impact of the service change on demand for the service.

Existing methods can be applied to estimate the effect of service changes on demand. The sketch planning methods developed by Rosen are particularly relevant (Rosen, 2013), as they provide two ways of evaluating the demand impacts of a proposal. The first is a simple elasticity model. The second is a direct demand model, which she developed by performing a regression analysis on a number of variables affecting transit demand, such as population and distance from the central business district. These methods are simple to apply and can provide a useful estimate of how demand will be affected by service changes. The direct demand model is particularly useful when evaluating proposals for new services, either new routes or new variants or extensions of existing routes, as it does not rely on existing demand the way an elasticity calculation does.

The tools used to evaluate the effects on current passengers will be different for proposals that address problems of service provision or system performance than for proposals that address system structure. For system performance proposals, evaluation methods already exist in many cases. For example, Maltzan's work on headway control estimates the effects of various holding strategies at terminals (Maltzan, 2015). The formulas he uses to calculate the effective wait time based on a certain reliability level are standard in transit planning, and can be used to evaluate the impact of other measures aimed at improving reliability. The impact of efforts to increase the speed of buses along a corridor can be estimated based on AVL data and field observations.

For proposals that address system structure, ODX is the main source of data for determining the effects on current riders. Since ODX provides detailed data on where passengers started and ended their journeys and which route(s) they used, it is possible to identify those who would likely use a new service and calculate how much time they would save or lose, whether they would avoid any transfers, and other statistics about their travel. Examples of this sort of analysis are presented in Chapter 6. The prediction of which riders would likely switch to a new service can be thought of as the "day one" ridership, or the ridership that a new service would have in the short term. Increases in ridership due to latent demand tend to take longer to materialize, so significant day one ridership can be an important component in a decision to implement a new service. Sufficient early ridership is often necessary politically to keep a service running long enough for new riders to begin using the service.

Once the costs and benefits of each proposal have been determined, decisions can be made about which ones to implement. When multiple proposals provide different solutions for the same problem, it will typically make sense to implement only one. The final group of proposals selected for implementation should maximize benefits while minimizing costs, address the most significant of the challenges identified by this process, spread benefits to different areas and constituencies within the region, and be feasible with available resources. These decisions will ultimately be a matter of judgment, because the costs and benefits will not all be comparable. There is no single correct way to compare the value of a proposal that will eliminate transfers to one that will reduce crowding, for example, or to determine whether the benefits of a proposal to improve reliability are worth the cost. Experienced planners will need to balance all of these factors and decide on a set of improvements that best meet all of the goals.

The improvements will also generally need to be presented to the public for comment, and the proposals will likely need to be adapted based on that input. An advantage of the methods developed in this research is that they provide detailed information about who is likely to benefit from a proposal. The public process around transportation planning can be difficult because those who will be negatively affected by a proposal are often easy to identify and can be vocal in their opposition, while those who may benefit often do not realize the ways that a new piece of infrastructure or new bus route will improve their access, and thus remain uninvolved in the process. This research makes it clear who some of these beneficiaries are, which can aid in the public outreach process and help generate support for changes.

4.6 Phase 5: Implementing and Retrospectively Evaluating Service Changes

The final phase of the process is the implementation of the selected proposals, followed by a retrospective evaluation of their effects. The components of implementation will depend on the type and scale of the change, but may include funding, operations planning, issuing new timetables, and public information campaigns to announce the change. After a service change has been implemented, ODX data from before and after a change can be compared to identify the impact on passengers.

This post-hoc evaluation may include a variety of elements. At a basic level, the analysis should examine how travel times, speeds, and number of transfers have changed in geographic areas affected by the new or altered route. By comparing ridership on affected routes before and after the change, including ridership on the new route or altered portion of a route, it is possible to estimate the level of induced demand generated by the change. In many cases it will be possible to refine this analysis by considering a panel of card numbers that travel between relevant origins and destinations before and after the change to see whether they have changed their behavior in response to the service change or whether they are still using their old paths through the system.

The results of this analysis will shed light on several questions. The question that decision-makers will be most likely to ask is whether a service change was a positive one and whether it is having the intended effect on the network. Other questions are more process-based. Post-hoc evaluation can be used to examine the predictions made in earlier phases in a critical light in order to refine the methods for use in future analyses. This retrospective analysis should also provide the basis for the parameters selected for future analyses, such as the elasticities used in demand predictions and the strength of mode preferences and transfer penalties. It can also demonstrate how long it takes for passengers to adapt to a change in the network, by looking at time-series data from a few weeks to a year after a change is implemented.

4.7 Other Applications

While this framework is intended to be able to stand alone as a complete process, it also provides tools and methods that may be useful in other contexts. Analyzing the travel patterns around a specific location can be useful in a wide variety of circumstances outside the service planning process. Transport for London, for example, used ODX analysis of travel patterns over a bridge in planning for the bridge closure (Marr, 2015); researchers at MIT performed a similar analysis of how to optimize shuttle service during weekend closures of the Longfellow Bridge in Boston (Gordon and van der Hurk, 2014). Government Center station, a major downtown transfer hub in Boston, was closed for two years for renovations; location travel analysis could help with shuttle planning and customer communication strategies for future similar projects. Location analysis could also be performed at the request of a municipality due to a major planning effort or development project, such as the development of Assembly Square in Somerville, or to accompany a transit project on a different mode, such as the new Boston Landing commuter rail station currently under construction in the Brighton neighborhood of Boston.

The framework and proposed process can also be useful when political and financial changes occur. The recent suspension of the Pacheco Law in Massachusetts opens the door for contracting service (Scharfenberg, 2015b). This presents a significant opportunity for the MBTA to explore new methods of service delivery, including using minibuses on low-ridership routes, so that the existing MBTA fleet can be redeployed to routes and areas where service increases are badly needed. The framework and tools developed in this research can help the MBTA capitalize on this opportunity to make overdue changes to the bus network and to provide the analysis necessary to determine which changes are most important.

The approach outlined for Phase 4 in Section 4.5 need not be limited to evaluating proposals generated through this planning process. Proposals from other sources should also be evaluated in this manner before they are implemented. It may also be possible to adapt some of these methods to evaluating other types of proposals, such as implementing BRT or diesel multiple unit ("DMU") service. The retrospective evaluation methods described in Section 4.6 can also be used to evaluate the impact of changes implemented outside this service planning process, including temporary service disruptions due to construction or service altered for special events.

4.8 Conclusion

This chapter presented a proactive bus service planning process. By selecting a small number of locations in each planning cycle, in-depth, comprehensive analysis becomes feasible. Problems with the current network can then be identified, whether they are issues of system performance or issues of system structure, and solutions proposed and evaluated.

A variety of data sources are useful in this process, predominantly ODX. The end result is a planning process that is proactive and responsive to the city's changing transportation needs, rather than simply reacting to deficiencies in the performance of the current system. The process also provides tools that are useful in a variety of other situations.

The next two chapters offer examples of how the first four phases of this process can work in practice. (The final retrospective evaluation phased is not included because no significant network changes occurred during the period for which data is available.) As these examples demonstrate, the framework for the process is relatively simple, but the analysis involved in implementing it can become time-consuming. In order to make the process as practical as possible, these examples develop techniques that can easily be adapted to a variety of new locations and service changes. The tools are limited to those that transit agencies generally have available, including an SQL database, a spreadsheet program, and a geographic information systems package. While commercial software such as ESRI's ArcMap was used to develop the techniques in this thesis, they can generally be applied using open-source packages such as qGIS. This makes the tools accessible both by smaller transit agencies with limited software budgets and by community stakeholders conducting their own analyses.

Chapter 5

Identifying and Evaluating Target Locations

This chapter provides detailed examples of the first two phases of the enhanced service planning process described in Chapter 4. Section 5.1 briefly describes the selection of the example locations. Sections 5.2 through 5.4 analyze the three example locations in detail using ODX and other data, and identify the most significant challenges for the public transit system in each area. Section 5.5 offers a brief look at a fourth location.

5.1 Identifying Target Locations

As described in Section 4.2, the recommended process for identifying the target locations involves analysis of population, employment, and travel trends in order to select those parts of the city that are most likely to benefit from focused transit planning, particularly those parts of the city that have experienced rapid change but where the transit system has not yet adapted to the increase in demand. While ODX data is useful in this process, this first phase relies less heavily on ODX than the later phases do. Therefore, the full analysis recommended as part of the process is not included in this thesis. Rather, the locations have been selected based on prior knowledge of the Boston region in order to provide a variety of illustrative examples.

Three primary locations were selected: Kendall Square, Longwood Medical Area, and the neighborhoods of Mattapan, Dorchester, and Roxbury. Kendall Square and Longwood Medical Area are both rapidly growing job centers, and were both identified as congestion "hot spots" in a 2012 report on the future of the MBTA (Pollack, 2012). The choice of Mattapan, Dorchester, and Roxbury is based on Dumas' work on disparities in transit outcomes in minority neighborhoods (Dumas, 2015). The importance of each of these locations is explored in more detail in the sections below; all would likely be identified as important targets for analysis by a full study of the kind described in Section 4.2. In the case of Kendall Square and Longwood Medical Area, rapid growth of employment, high transit congestion, significant traffic congestion, and reliance on employer-sponsored shuttles would have pointed to these locations.

In the case of Mattapan, Dorchester, and Roxbury, high transit crowding levels and disparate transit outcomes in a minority residential area would have identified the area as an important target of study.

These three locations are all extremely important from a public transportation perspective and have heavy transit use. However, the existing transit network, patterns of travel, and geographic features of the three locations are quite different. The following three sections focus on each of these areas in turn, providing diverse examples of how the location analysis process described in Section 4.3 works in practice. The chapter concludes with a brief discussion of the Seaport District, a rapidly growing area with some difficult transit challenges.

5.2 Kendall Square

Kendall Square is a rapidly developing commercial office area of Cambridge, adjacent to the Massachusetts Institute of Technology campus and surrounding the Kendall Square subway station on the MBTA's Red Line. It has a high concentration of technology, biotechnology, and startup companies in both traditional office and research laboratory space, along with restaurants and a modest amount of housing. Three major developments are currently in the planning stages. The MIT Kendall Square Initiative will add six new buildings to the northeastern edge of campus, mostly on existing parkings lots (MIT News Office, 2015); the Cambridge Redevelopment Authority's Kendall Square Renewal Plan will add one million square feet of office and residential space; and the redevelopment of the 14-acre, federally-owned site of the John A. Volpe National Transportation Systems Center will relocate the federal building to make way for additional development (Feijo, 2015). These three projects will add millions of square feed of residential, commercial, and retail development to the area, which already experiences both transit and automobile traffic congestion. About 38% of employees in Kendall Square commuted by transit in 2010 (Cambridge Community Development Department, 2013), with that percentage expected to rise, so enhancing the transit network is a priority.

Existing regional transit access to Kendall Square is illustrated in Figure 5-1. Direct access is limited to the area around Red Line stations and to close-by areas served by bus routes. Kendall Square is served by four MBTA bus lines: the CT2, which runs from Sullivan Square to the north and through Longwood Medical Area to Ruggles to the south; the 64 from Allston and Brighton via Central Square (during peak periods only); the 68 from Harvard Square and the 85 from Union Square in Somerville (Massachusetts Bay Transportation Authority, 2014a). The EZRide shuttle, described in Section 1.2.4, connects Kendall Square to North Station and Cambridgeport, though as a non-MBTA service it is not included in Figure 5-1.

Areas to the northwest and southeast are generally accessible via a bus-to-rail connection to the Red Line, while parts of the region to the north, northeast, south, and southeast require a bus-to-bus transfer or multiple transfers to access Kendall Square. These areas include Chelsea, Everett, Malden, Melrose, portions of Medford, and the southern Boston neighborhoods of West Roxbury, Hyde Park, and Roslindale.

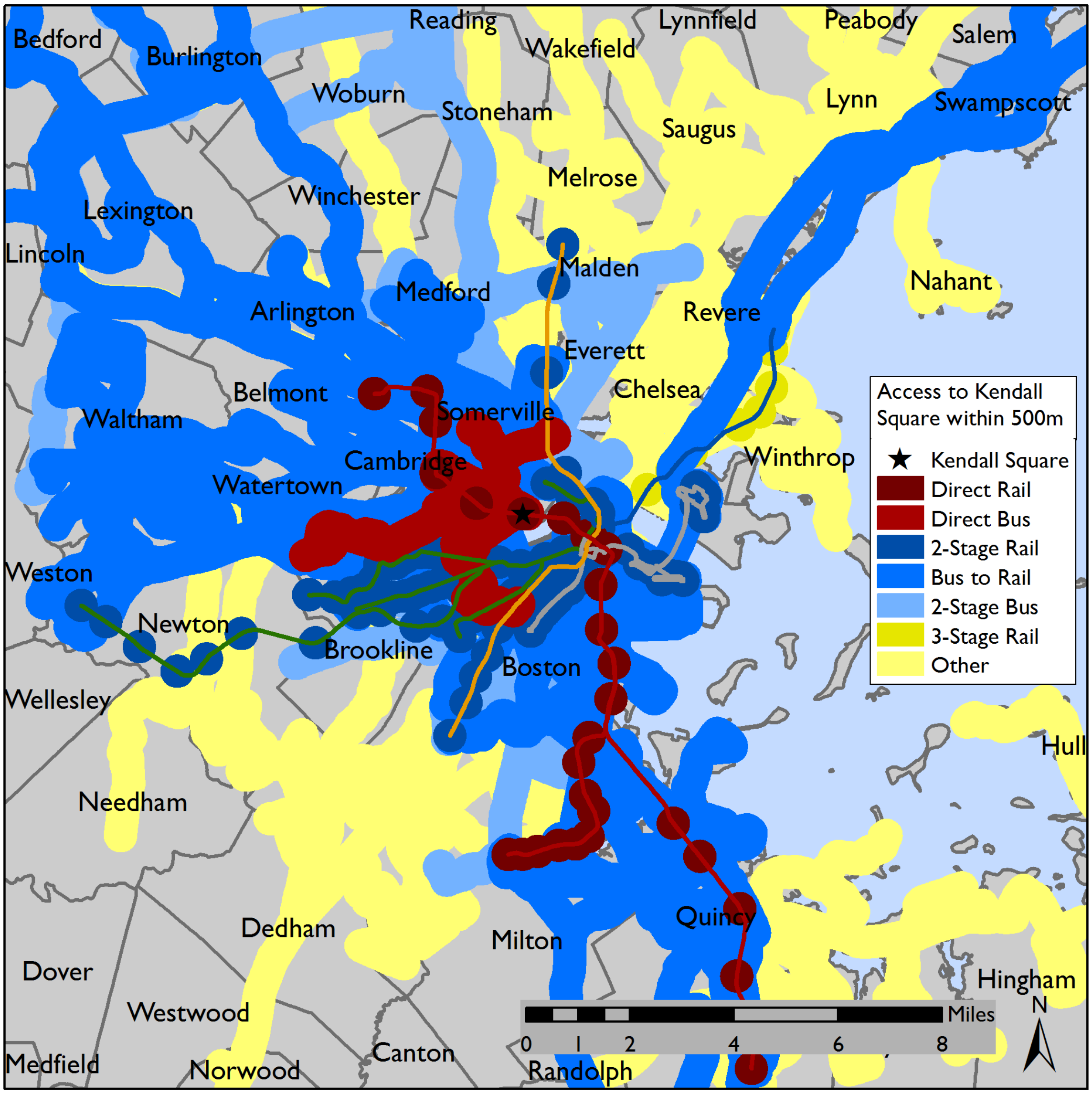


Figure 5-1: Access to Kendall Square on the existing MBTA network

For a growing employment center, poor access to so many relatively close residential communities is a cause for concern.

In addition to considering basic information about the area and the transit network, the proposed service planning process calls for analyzing ODX data to identify travel patterns in a target location. For this analysis the bus stops in Kendall Square were identified, and journeys beginning or ending at those stops or at the Kendall Square Red Line station were considered. Aggregate statistics were calculated for this set of journeys. The non-Kendall end of each journey was also associated to a census tract so that the statistics for each census tract could be calculated and displayed on maps. In some cases only weekday morning peak period journeys to Kendall Square were included in order to ensure appropriate averages and comparisons for speed of travel, duration of journeys, and other factors that vary throughout the day. A number of maps, graphs, and tables were generated through this process. The ones that most clearly reveal patterns or challenges for travel in Kendall Square are included in this section; the remainder are included in Appendix A for reference.

Table 5.1 shows the aggregate statistics for travel to and from Kendall Square in the ODX data set. Rail journeys make up a much higher proportion of journeys to or from Kendall Square than in the system as a whole, with only 3.4% of journeys made by bus alone. With transit demand poised to increase significantly in coming years, additional bus service is one way to accommodate new demand while also improving Kendall's accessibility to the region. The flexibility of bus service is also appealing because transit demand at Kendall is highly peaked, as shown in Figure 5-2, with a strong commute pattern of inbound morning journeys and outbound afternoon journeys. It is generally easier to run more service in one direction than the other with buses than with rail, and it is also more common to run peak-only bus services or route variations that could help accommodate increased demand during peak times.

Table 5.1: Statistics on travel to and from Kendall Square, October 2014

	Kendall Square	MBTA System
Total daily journeys	24,403	633,616
Distinct cards used (monthly)	122,378	1,842,250
Monthly journeys per card	6.0	10.3
Bus journeys	3.4%	31.4%
Rail journeys	89.5%	60.5%
Bus and rail journeys	7.1%	8.1%
1-Stage journeys	79.1%	79.5%
2-Stage journeys	18.0%	17.6%
3+-Stage journeys	2.9%	2.9%

The disaggregate data in ODX enables an analysis of how often individuals travel to Kendall Square. The total number of journeys originating in Kendall Square during the month of October 2014 on each farecard was calculated, along with the total number of journeys for that farecard. The number of journey origins in Kendall was doubled to approximate the total number of journeys either beginning or ending

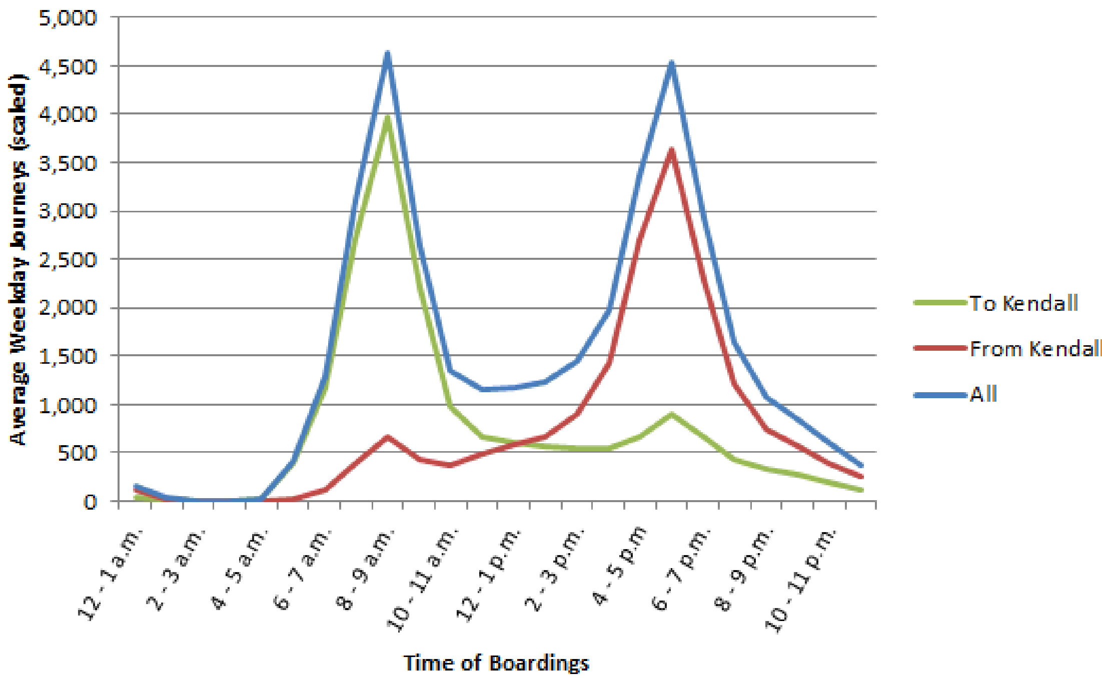


Figure 5-2: Journeys to and from Kendall Square by time of day

in Kendall (that is, to estimate the amount of travel that was connected to Kendall Square in some way). Destination inference was not used for this analysis because it is incomplete, and scaling destination inference is difficult on a disaggregate level. The results are presented in Figure 5-3. The bottom blue portion of the leftmost bar represents those journeys that are on cards where only one or two journeys begin or end at Kendall and these journeys are less than 20% of the travel on the card for the month; these are regular transit users who mostly travel elsewhere in the network and occasionally visit Kendall. The top, lighter blue, pattered portion of the rightmost bar represents those journeys made on cards where there were at least 30 journeys in the month, at least 80% of which were to or from Kendall; these are frequent transit users, likely commuters, who mostly use transit for travel to and from Kendall Square.

Much of the travel to and from Kendall Square is due to passengers who travel to Kendall frequently, often exclusively or nearly so. Infrequent visitors make up a relatively small proportion of travel to Kendall. This indicates that route variations, peak-only bus routes, and other services that tend to appeal to those who make a trip frequently and are able to maximize the efficiency of their route choices may be good options for Kendall Square. It may also indicate that passengers traveling to Kendall tend to be those who are employed or have regular business there, and who consequently may be able to choose to live somewhere with an easy commute. For a very different pattern of travel, see the discussion of Longwood Medical Area in Section 5.3 below.

Looking at the geographic patterns in the ODX data for Kendall Square, the general patterns broadly reflect the available access described above. Figure 5-4 shows

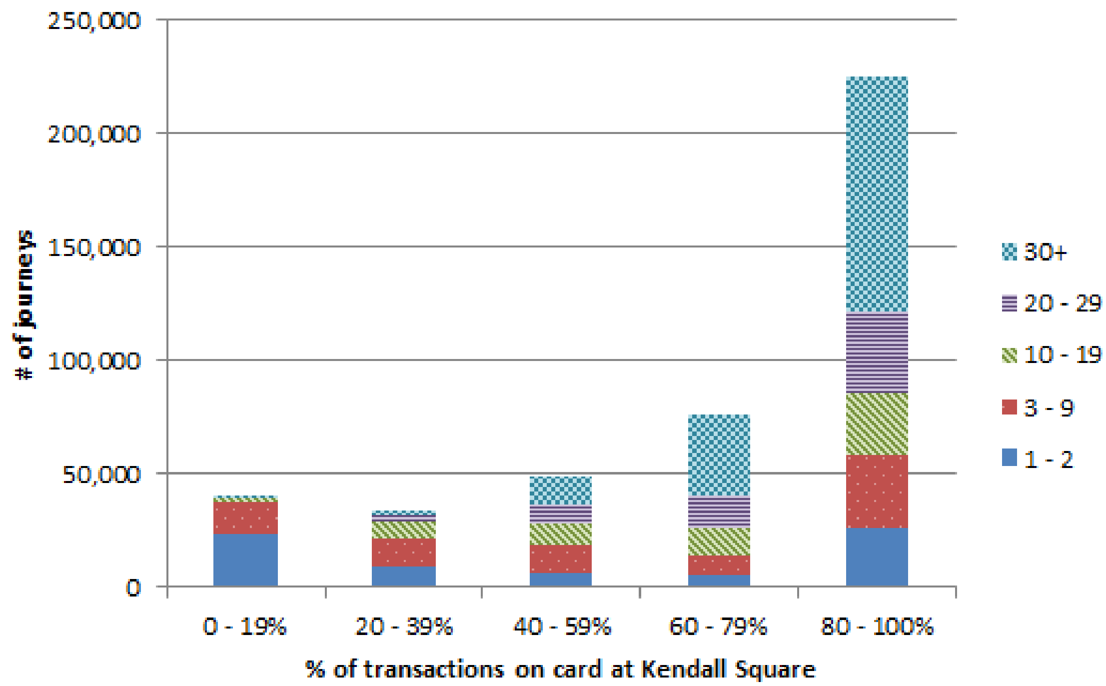


Figure 5-3: Number of journeys per farecard at Kendall Square, as a % of all journeys

the journeys per capita to Kendall Square from around the region for the weekday morning inbound commute. The areas with better access, particularly along rail lines and in the the western inner core cities and towns such as Arlington, Belmont, and Watertown, generate significantly more trips than the areas with poorer access. Rail stations along the outlying branches of the Red and Orange Lines generate high numbers of trips per capita; in some cases this is likely an indication that some passengers are driving from nearby census tracts and parking in the stations' parking lots to access rail. Since there is not a good source of data on automobile access to rail, it is not included in the travel time, number of transfers, or other statistics about these journeys. In the case of other stations, particularly those without significant parking supply, employees who work in Kendall Square who are within walking distance to rail may be more likely to choose transit, and employees with jobs in Kendall Square may be more likely to choose to live near rail stations.

The high levels of journeys per capita in Belmont, Arlington, and Watertown indicate that a bus-to-rail transfer is not necessarily a barrier to high rates of transit use. This offers some useful context for how additional bus services might be designed to increase access to Kendall. The areas near the Orange and Red Lines seem to generate most of the trips; very few commuters begin their journeys at Blue Line stations, and the number of journeys from the areas served by the Green Line is significantly lower than other similarly dense residential areas on the northern Orange Line. The data limitations on the Green Line described in Section 2.8 make it difficult to determine the journeys generated per capita at each location along the line. With these journeys mapped to the ends of the branches, a very high number of trips

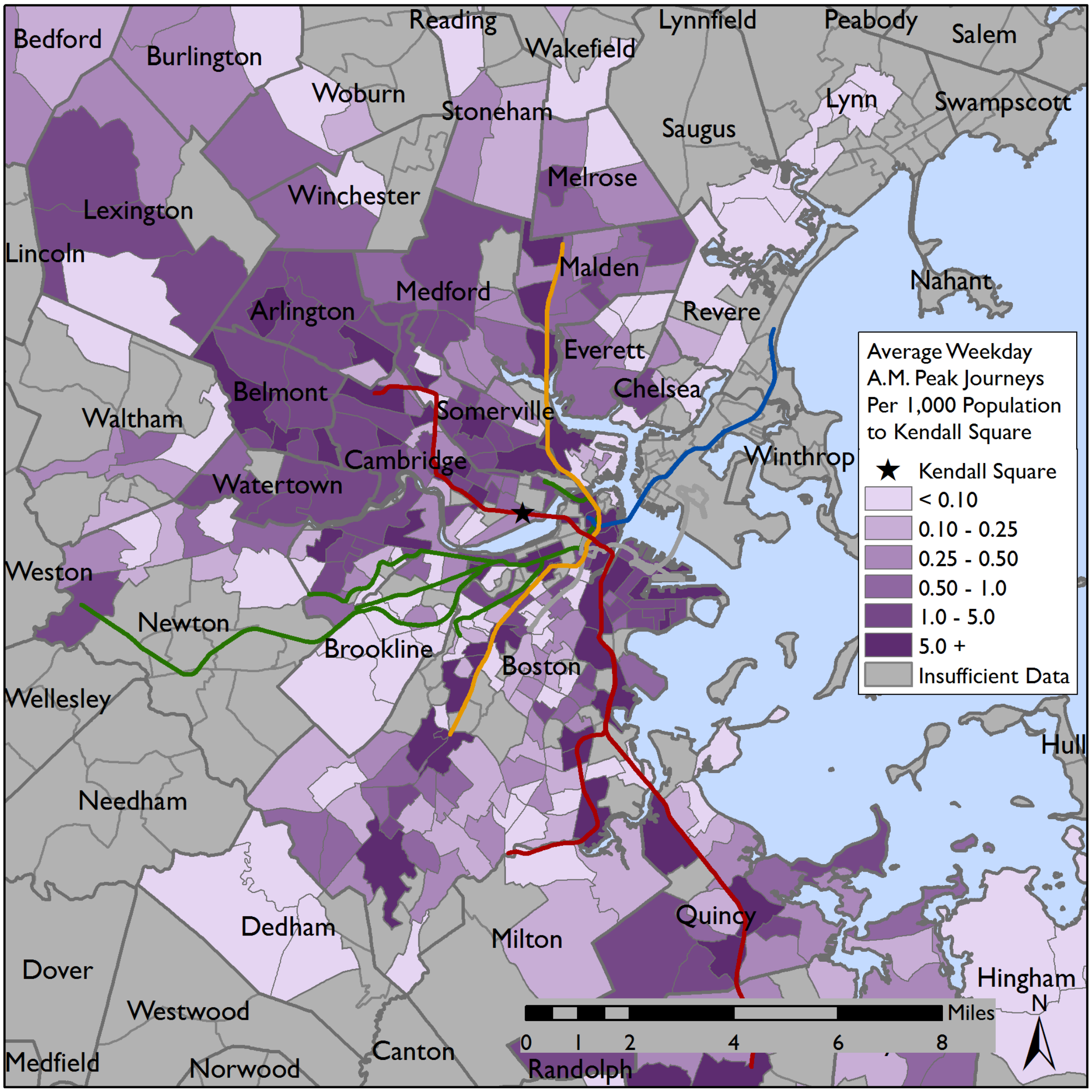


Figure 5-4: Average weekday morning peak journeys to Kendall Square per 1,000 residents

per capita in these tracts would be expected if many passengers are beginning their journeys along the Green Line; this pattern is not observed.

The overall geographic travel pattern is also apparent in how long passengers spend on their commutes. Figure 5-5 shows the average travel time for journeys with an inferred destination of Kendall Square in the ODX data set. The shortest travel times are, naturally, from the immediately surrounding areas. Outside the immediate area, however, areas that are similar distances from Kendall may have quite different travel times. The northern portions of Somerville, Chelsea, Everett, and Charlestown all have longer travel times than areas to the west of Kendall in Cambridge, Belmont, and Arlington. Access from Brookline also takes longer than from other areas of similar distance.

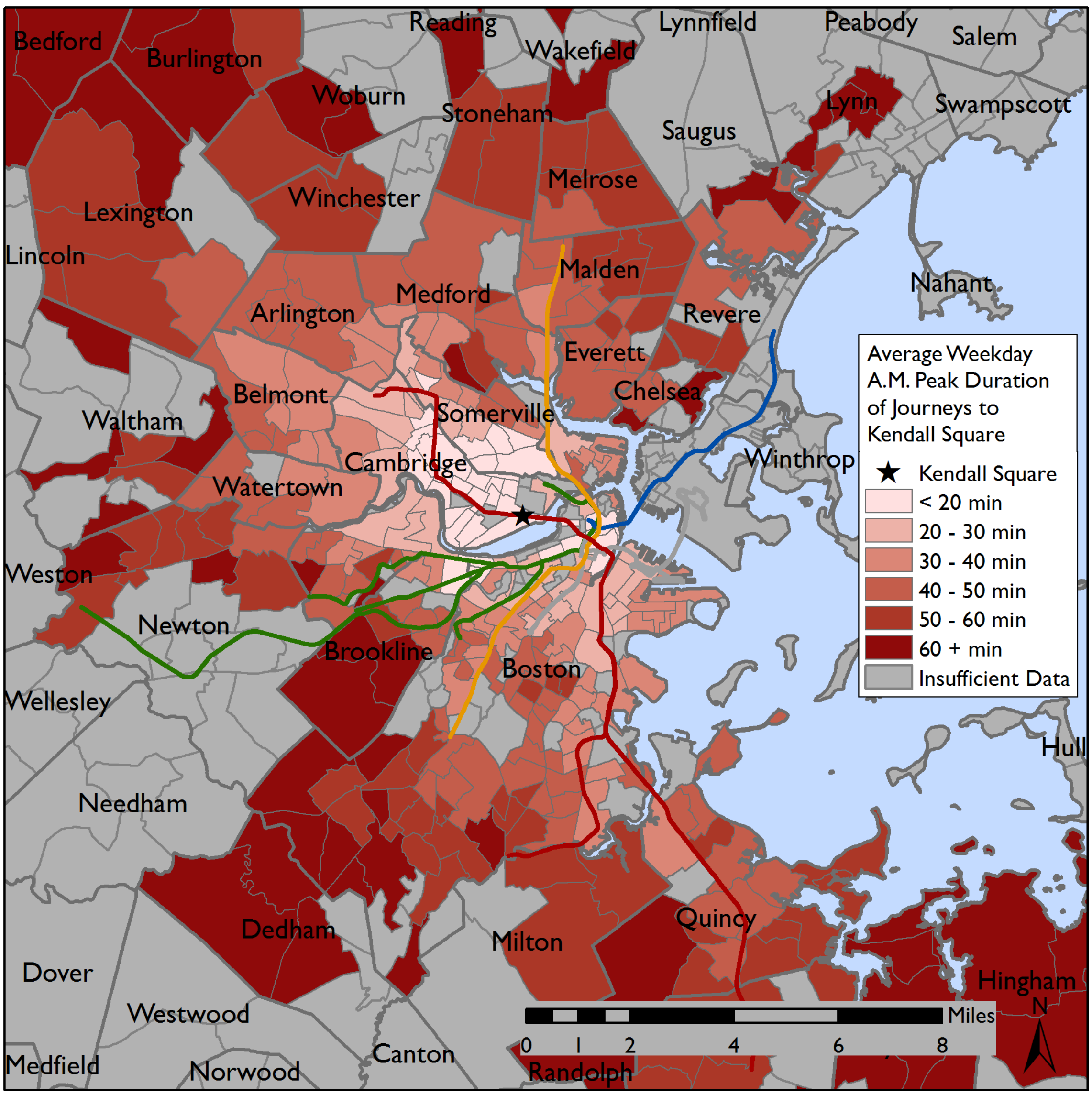


Figure 5-5: Average weekday morning peak travel time for journeys to Kendall Square

While the proposed planning process calls for examining as much data as possible for each target location, only a sample of the analysis could be included in this chapter. The overall patterns of travel observed in the data presented in this section can also be seen when looking at ODX data for the number of stages per journey, the speed of journeys, and the total number of journeys from census tracts around the region. These maps are included in Appendix A.1 for reference.

5.2.1 Kendall Square Challenges

Based on the data presented above, there are a number of observations and conclusions that should inform proposals to improve service to Kendall Square. First, Kendall relies heavily on the Red Line. While this is expected given the relative capacity and frequency of the Red Line compared to bus, it limits the accessibility to Kendall from areas that are not easily accessible to the Red Line. Even passengers transferring from the Orange Line face slower journeys, and passengers do not appear to take the Green Line to the Red Line in large numbers. Better connections to these rail lines that do not require transfers at the crowded downtown rail transfer stations could improve access. Passengers appear to use bus-to-rail connections in relatively high numbers when they are convenient, as they are from Arlington and Belmont to the Red Line to Kendall, so good bus connections to rail lines should be a priority. The frequency of bus routes serving Kendall is also important to consider; the Red Line generally operates at headways of around 5 minutes during the peak hour, while some of the important bus routes in the area only run every 20 to 30 minutes.

Few passengers travel to Kendall from areas along the Blue Line, which is not surprising since multiple transfers are required. Relatively few passengers travel from Brookline and southern neighborhoods of Boston such as Roslindale and Roxbury, despite the fact that these residential neighborhoods are only a few miles from the jobs in Kendall Square. Access from the north and northeast, including Chelsea, Everett, Malden, Melrose, and parts of Medford, is slow and indirect. All of these areas would benefit from better access from the Orange, Green, and Blue Lines and better direct bus or bus-to-bus access.

The overall travel patterns in Kendall Square are highly commuter-oriented, as seen in the volume and direction of demand in the morning and afternoon peaks. Many of the passengers traveling to Kendall do so frequently, with relatively few occasional visitors. This highly commuter-oriented pattern has implications for planning, policy, and development in Kendall Square. In particular, transportation demand management programs at existing employers and the mix of housing and office space in future development are critical issues, though they are beyond the scope of this thesis. The most significant implications of the commuter-oriented pattern for the MBTA relate to the span and frequency of service: bus service in particular should be much more frequent in the peaks, and the option of running additional peak-only services or route variants should be explored.

Some of the existing MBTA capital planning proposals would address some of the issues identified in this section. The Blue-Red Connector, connecting the Blue Line to the Red Line at the Charles/MGH station, would greatly improve access to Kendall from East Boston, Chelsea, Revere, and the north shore. The Urban Ring

BRT, described in Section 1.2.6, would also greatly improve access from the northeast, including Everett and Malden, and from the southern neighborhoods of Boston such as Roxbury. Both of these projects were proposed in the most recent Program for Mass Transportation (Massachusetts Bay Transporation Authority, 2009), though no funding has been designated for either project in recent capital plans. Without these projects, additional bus service is the best available way to improve access to the area.

The Green Line Extension project will also affect Kendall Square, improving access from Somerville and Medford. However, this access requires either a transfer downtown at Park Street or a bus connection from Lechmere Station. Lechmere and Kendall are currently connected by the EZRide shuttle, but not by any MBTA service.

5.3 Longwood Medical Area

The second area of study selected for this thesis is Longwood Medical Area ("Longwood" or "LMA"). As the name implies, it contains a number of hospitals and clinics, including Beth Israel Deaconess Medical Center, Brigham and Women's Hospital, Children's Hospital, and Harvard Medical School. Several colleges and universities also have campuses in the area, including Emmanuel College, Simmons College, the Massachusetts College of Art and Design, the Massachusetts College of Pharmacy, Wheelock College, and Wentworth Institute of Technology. The northeastern edge of the area is home to the Isabella Stewart Gardner Museum and the Museum of Fine Arts, with Northeastern University beyond.

Longwood, therefore, is a major destination for hospital and university employees, patients and families of patients, students, and even tourists. Not surprisingly, the area experiences heavy traffic congestion. It is bounded to the northeast and northwest by parks, which limit the number of roads that enter the Longwood area. This increases congestion on the few available routes. Some of the roads running along the edges of these parks are currently closed to bus traffic, Riverway being the most important.

Longwood is located between the D and E branches of the Green Line, with the Longwood stop on the D Line and the Museum of Fine Arts, Longwood Medical Area, and Brigham Circle stops on the E Line serving the area. The area is served by quite a few bus routes, particularly those coming through the Ruggles Orange Line stop to the east, including the 8, 19, 47, CT2, and CT3. The 66 also serves Longwood from the east, originating at Dudley Square. The 60 and 65 run along Brookline Avenue on the northwest edge of the area, and the 39 runs along Huntington Avenue on the southeast edge. A map of the access that these routes provide to the region is shown in Figure 5-6. The area is also served by a number of shuttles run by MASCO, as described in Section 1.2.4.

Access to Longwood relies heavily on direct bus, bus-to-rail, and bus-to-bus connections, and correspondingly little on rail, particularly when compared to access to Kendall (Figure 5-1). Access from the areas around the Quincy branch of the Red

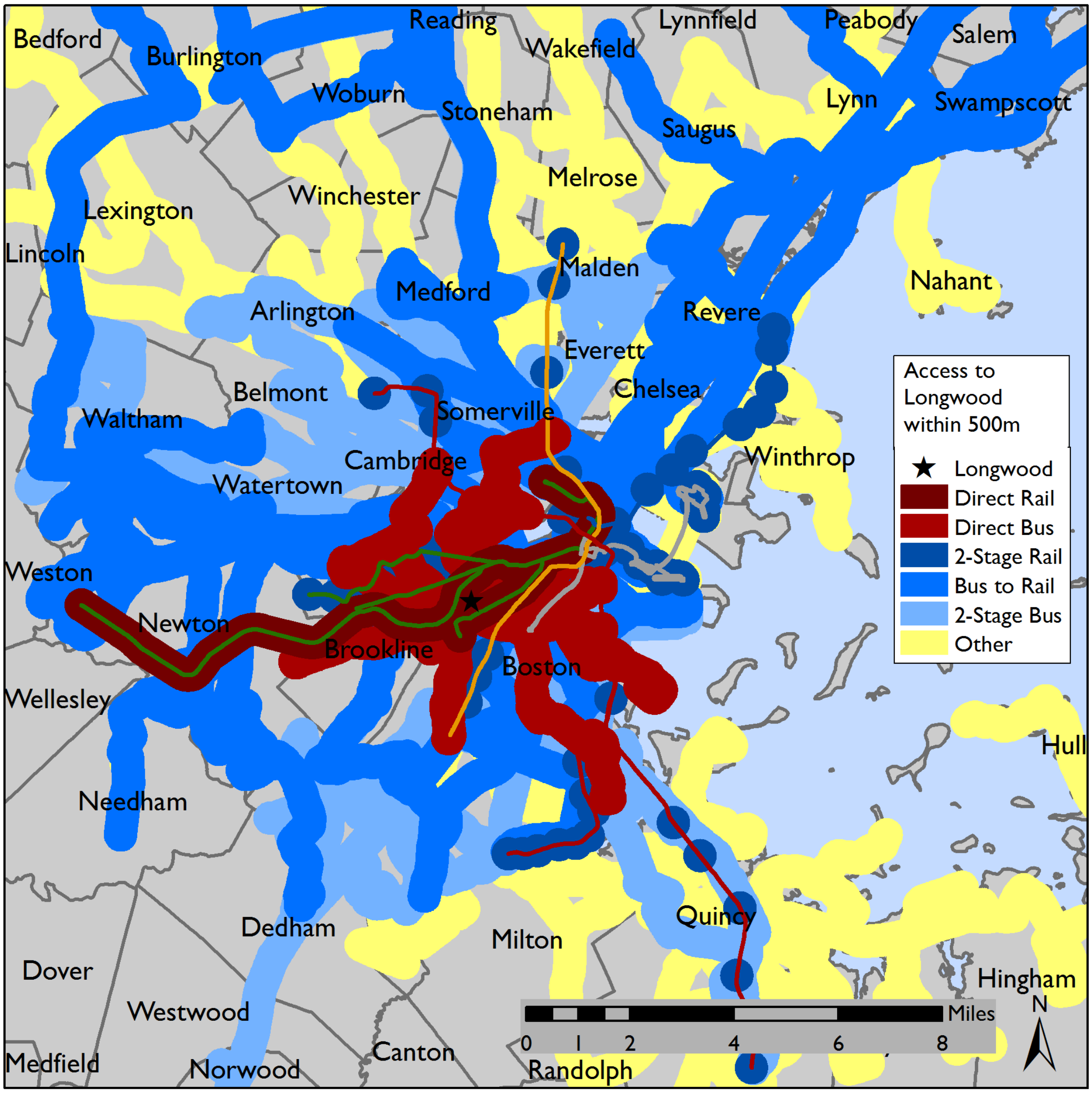


Figure 5-6: Access to Longwood Medical Area on the existing MBTA network

Line is spotty, as is access from northern cities and towns such as Melrose, Malden, and Everett and northwestern areas such as Winchester and Lexington. The eastern parts of Cambridge have fairly good access, but western Cambridge, Watertown, Belmont, and Waltham rely on bus-to-bus connections or bus connections to the Green Line branches to reach Longwood. Access from Roslindale and Hyde Park in southern Boston similarly relies on bus-to-bus connections.

Table 5.2 shows some basic statistics about journeys to and from Longwood on the MBTA system. A much larger proportion of these journeys are by bus than in the system as a whole, 78.4% compared to 31.4% for the entire network. A somewhat higher proportion require a single transfer, and more than 4% of journeys are three or more stages, compared to just under 3% for the whole network. Ensuring that these bus connections are working well is a key piece of access to Longwood.

It is important to note that in most cases passenger boardings on the Green Line branches at surface stations are not geographically located, as described in Section 2.8, which has an effect on the statistics in Table 5.2 and in the remainder of this section. The 12.5% of journeys in the Longwood area that are by rail are those where the origin or destination at Longwood was able to be inferred based on the other use of the card that day; the actual percentage is likely somewhat higher.

Table 5.2: Statistics on travel to and from Longwood Medical Area, October 2014

	Longwood	MBTA System
Total daily journeys	8,227	633,616
Distinct cards (monthly)	48,362	1,842,250
Monthly journeys per card	5.1	10.3
Bus journeys	78.4%	31.4%
Rail journeys	12.5%	60.5%
Bus and rail journeys	9.1%	8.1%
1-Stage journeys	71.3%	79.5%
2-Stage journeys	24.5%	17.6%
3+-Stage journeys	4.2%	2.9%

Compared to the distribution for Kendall Square shown in Figure 5-2, travel to Longwood has longer peak periods and more midday travel, as seen in Figure 5-7. The strong demand in the early afternoon around 2 or 3 p.m. may be in part due to students traveling home from the Boston Latin School, a large public high school that is located within the study area. Figure 5-8 confirms that student trips represent about 10% of travel to and from Longwood Medical Area, moderately higher than the proportion in the system as a whole; Kendall Square and the Mattapan study area are included for additional context. Travel is very strongly inbound in the morning and outbound in the afternoon, which is not surprising for an area with many large employers and little housing.

Figure 5-9 shows the number of journeys to and from Longwood Medical Area by how many of these journeys there are on each farecard; an explanation of how this graph was developed can be found in Section 5.2 and Figure 5-3. In contrast

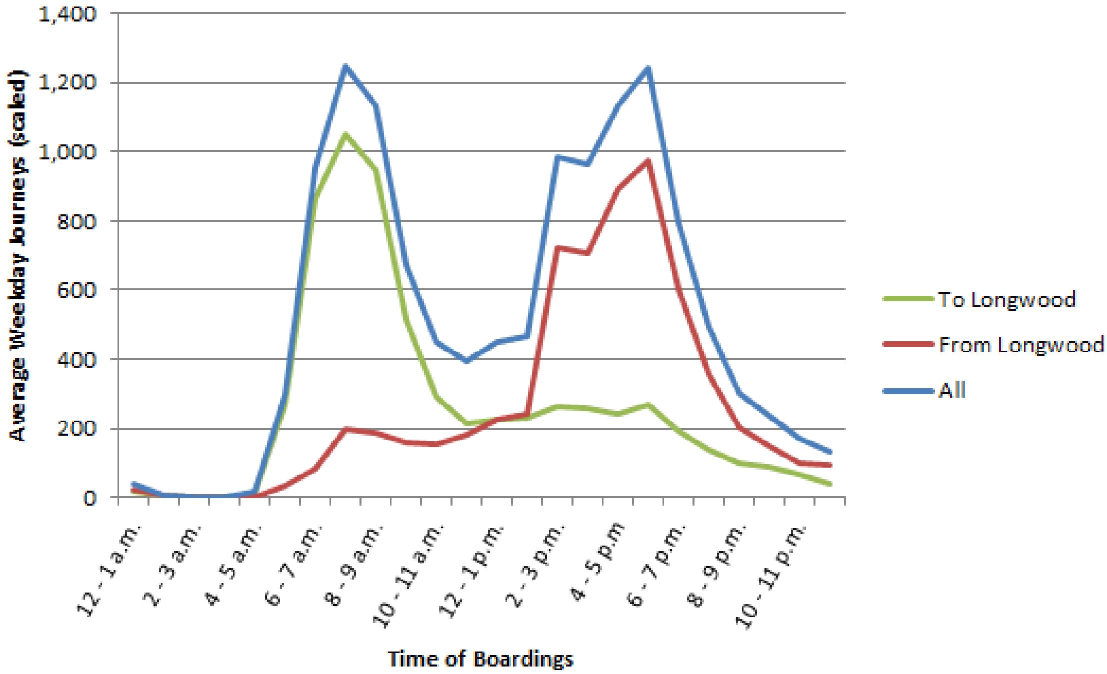


Figure 5-7: Journeys to and from Longwood Medical Area by time of day

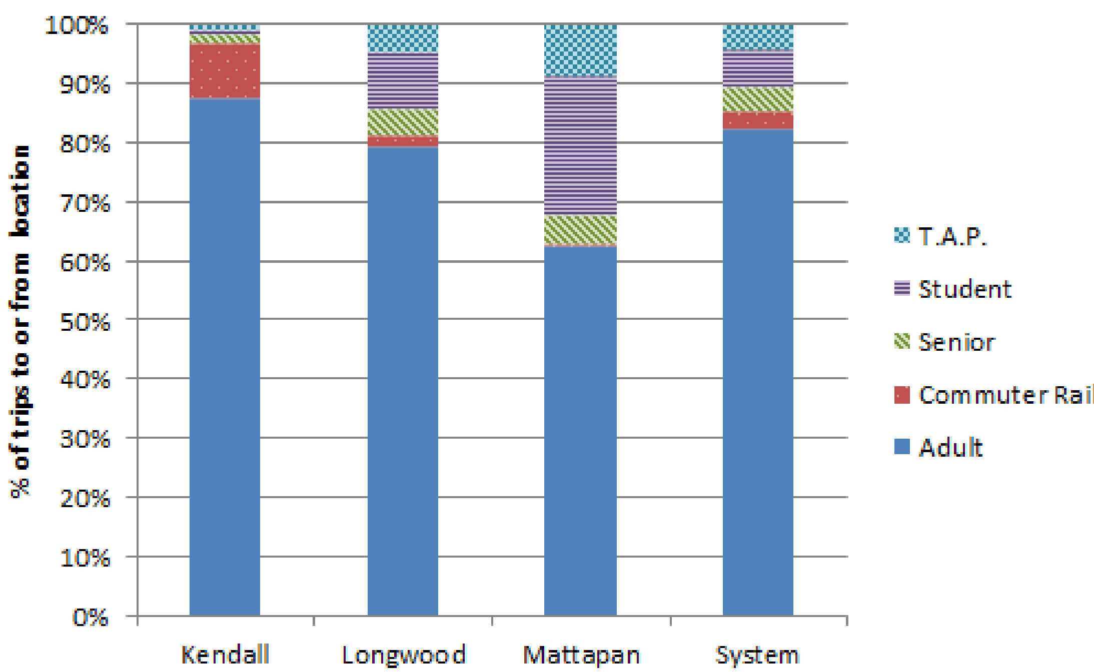


Figure 5-8: Proportion of trips by fare category for each study area

to Kendall Square, where most travel is by those who travel to the area frequently, Longwood has a large number of very infrequent visitors and also a large number of occasional visitors who travel to Longwood several times during the month but also use transit regularly elsewhere in the system. This means that legibility of the network and consistency of service is likely to be more important in Longwood than at a destination like Kendall, since occasional travelers tend to be navigating an unfamiliar route or traveling at different times of day or days of the week. It may also indicate that passengers are traveling to Longwood from less convenient locations around the region; patients do not generally choose where to live by how easy it is to access a clinic or doctor, and employees of the large health systems may work at multiple locations during the month. This makes gaps in accessibility at Longwood a more significant problem than they are in a destination like Kendall Square.

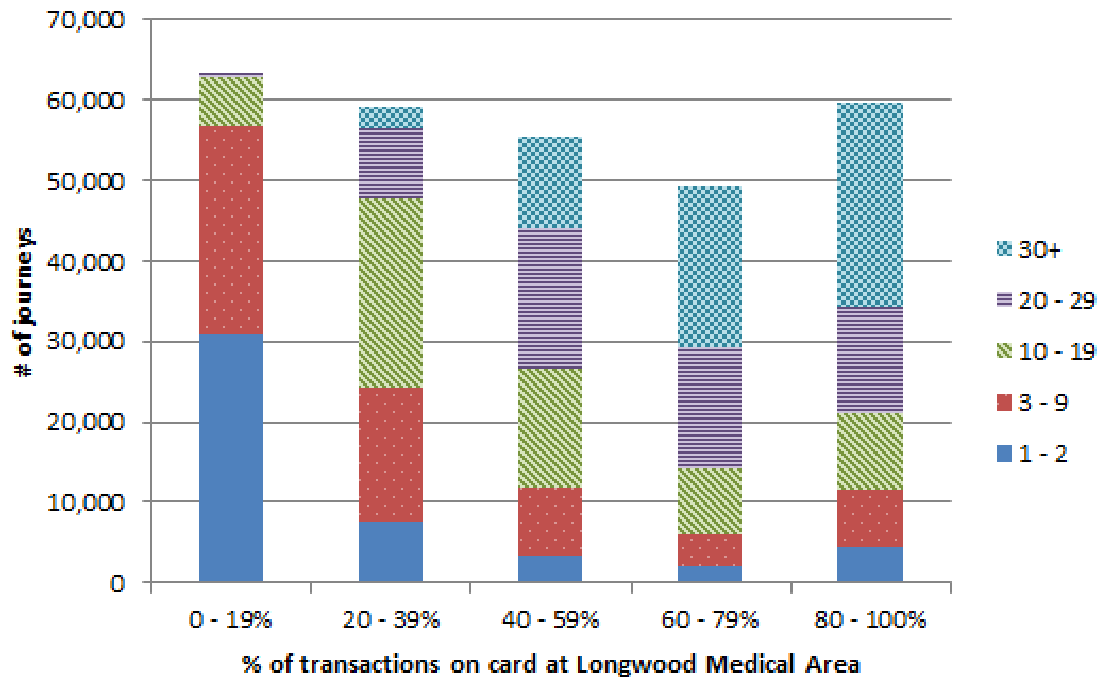


Figure 5-9: Number of journeys per farecard at Longwood Medical Area, as a % of all journeys

Taken together, Figures 5-10 and 5-11 reveal interesting patterns about travel to Longwood. Figure 5-10 shows the number of journeys per 1,000 residents from census tracts around the region. Journeys to Longwood are spread over a fairly large portion of the region, including most of the residential areas to the west and south such as Watertown, Brookline, and the southern portion of Boston. The northern Orange Line stations have high rates of journeys, possibly due to the relatively easy bus transfers at Ruggles.

Figure 5-11 shows the duration of journeys to Longwood during the weekday morning peak. Journeys from much of the Boston region take close to or over an hour, including from some areas that have moderate levels of trip generation. Watertown, Belmont, and parts of Cambridge are perhaps 5 miles away, yet the journey can

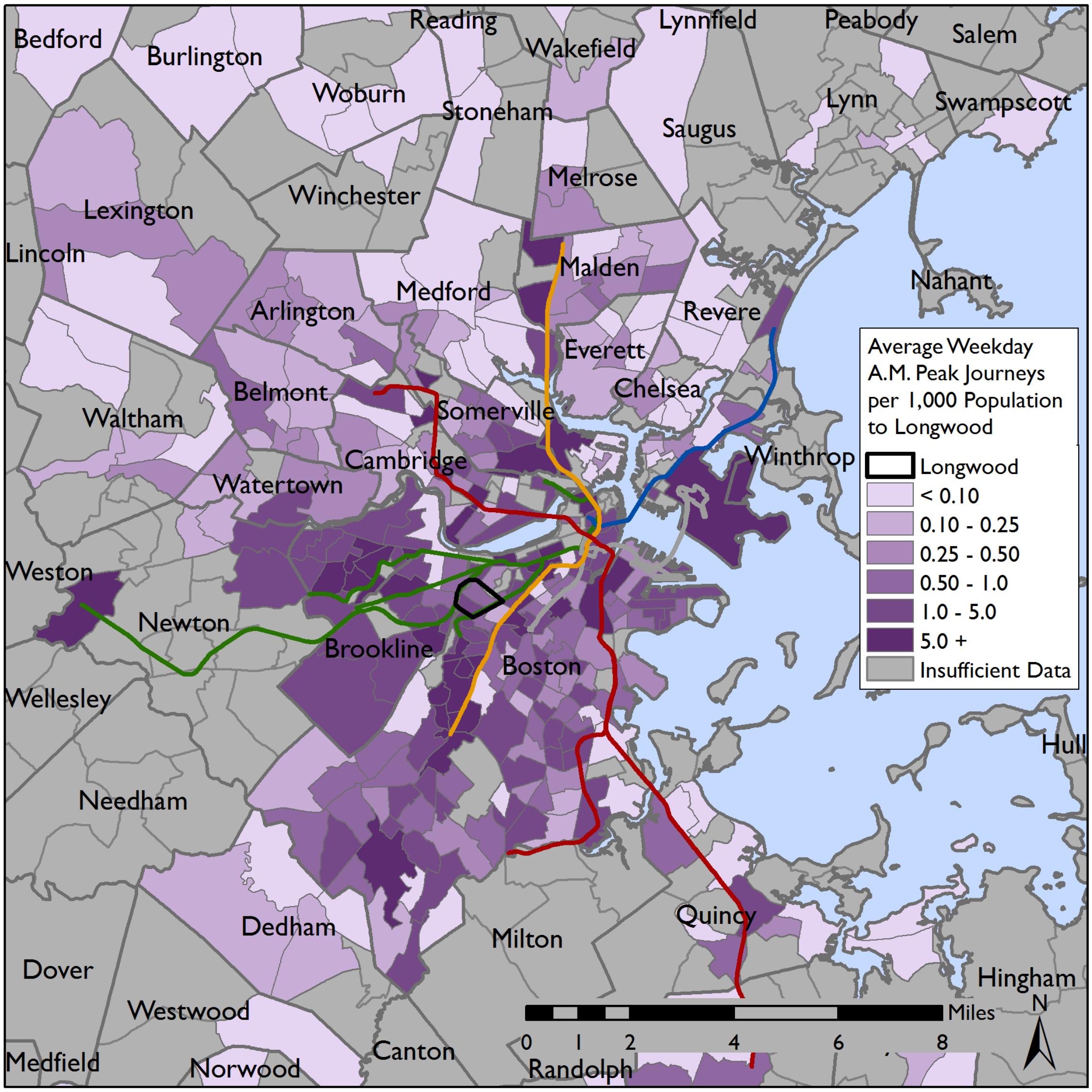


Figure 5-10: Average weekday morning peak journeys to Longwood Medical Area per 1,000 residents

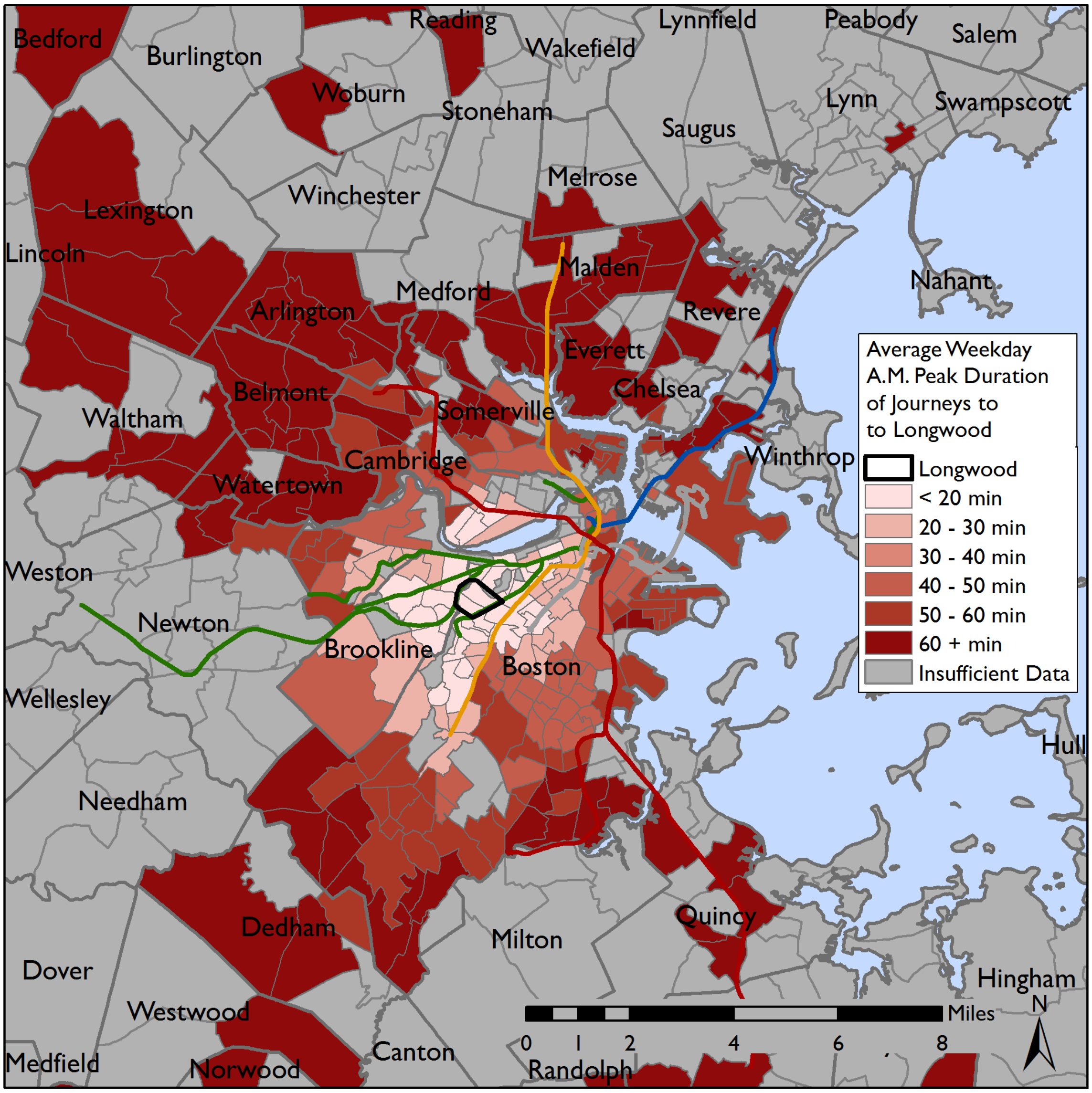


Figure 5-11: Average weekday morning peak travel time for journeys to Longwood Medical Area

take upwards of an hour. The same is true for those coming from the areas near the Ashmont Red Line station. Journeys from cities and towns to the north of Boston also take over an hour, even when starting from a rail station. Providing transit options that shorten these journeys would save time for existing passengers and would likely encourage some people who currently use a different mode to switch to transit.

As with the analysis of Kendall Square in the previous section, all of the data collected on Longwood could not be included here. Additional analysis can be found in Appendix A.2.

5.3.1 Longwood Medical Area Challenges

The most significant challenge for the Longwood Medical Area is simply increasing the speed of journeys. Since the area relies so heavily on buses and already faces significant traffic congestion, this is no easy task. One option to improve speed from some locations is additional direct bus service. This could improve travel for some of the passengers from relatively close-by areas that have very long journey times, such as the Watertown and Belmont area and the southern portions of Boston near Ashmont and Mattpan.

In addition to introducing more direct routes, measures that focus on increasing the speed of existing routes will need to be considered. Analysis of AVL data for each route to identify the slowest segments would be the first step in identifying the most useful changes. Signal priority and queue bypass lanes are likely to be important options within the Longwood area, as the route most buses take through the area passes through a number of lights and involves several turns, including left turns.

Since Longwood is served by the Green Line, the Green Line Extension will improve access from the areas that it serves, particularly Somerville and Medford. Improvements to speed, frequency, and reliability on the Green Line should also be a high priority for improving transit service to Longwood, as it is the only rail service available in the area.

The proposed Urban Ring BRT line, described in Section 5.2.1, would pass through Longwood and would greatly improve access from around the region. Access would be particularly improved to Cambridge and northern locations such as Sullivan Station, Wellington Station and Everett, and to the east through Ruggles and Dudley Stations. The project as proposed includes a very expensive tunnel underneath the Longwood area, which is one indication how difficult planners have found it to address congestion on surface streets. Unfortunately, the expense also limits the likelihood that the project will be built in the near future. In the meantime, bus planners will have to work with city transportation officials and MASCO and do the best they can to improve service for the many employees, patients, students, and visitors traveling to Longwood.

5.4 Roxbury, Dorchester, and Mattapan

As described in Section 2.6, Dumas used ODX to analyze the disparity in transit travel times for commuters from mostly black and mostly white census tracts (Dumas, 2015). He concluded that the transit outcomes in mostly black census tracts were moderately worse than those in mostly white census tracts, in large part due to greater reliance on bus, and longer bus journeys with more transfers.

Figure 5-12 shows the dispersion of public transit users by race in the Boston area, with the region of concentrated black transit commuters outlined. The area selected for study in this thesis is a subset of this outlined area. Regions with relatively few transit commuters have been omitted, as has the northern portion of the area. This is due to the fact that the northern portion is close to Dudley Square, a major bus transfer hub, and has somewhat different travel patterns than the southern part of the region. These two areas should therefore be considered as separate target locations. The final study area can be seen in Figure 5-13 and in many of the other maps in this section. It consists of 21 census tracts covering 4.46 square miles. The 2010 population of these census tracts was 83,724 people, or about 13.6% of the population of the city of Boston. The area will be referred to as the Roxbury, Dorchester, and Mattapan study area, the RDM study area, or RDM.

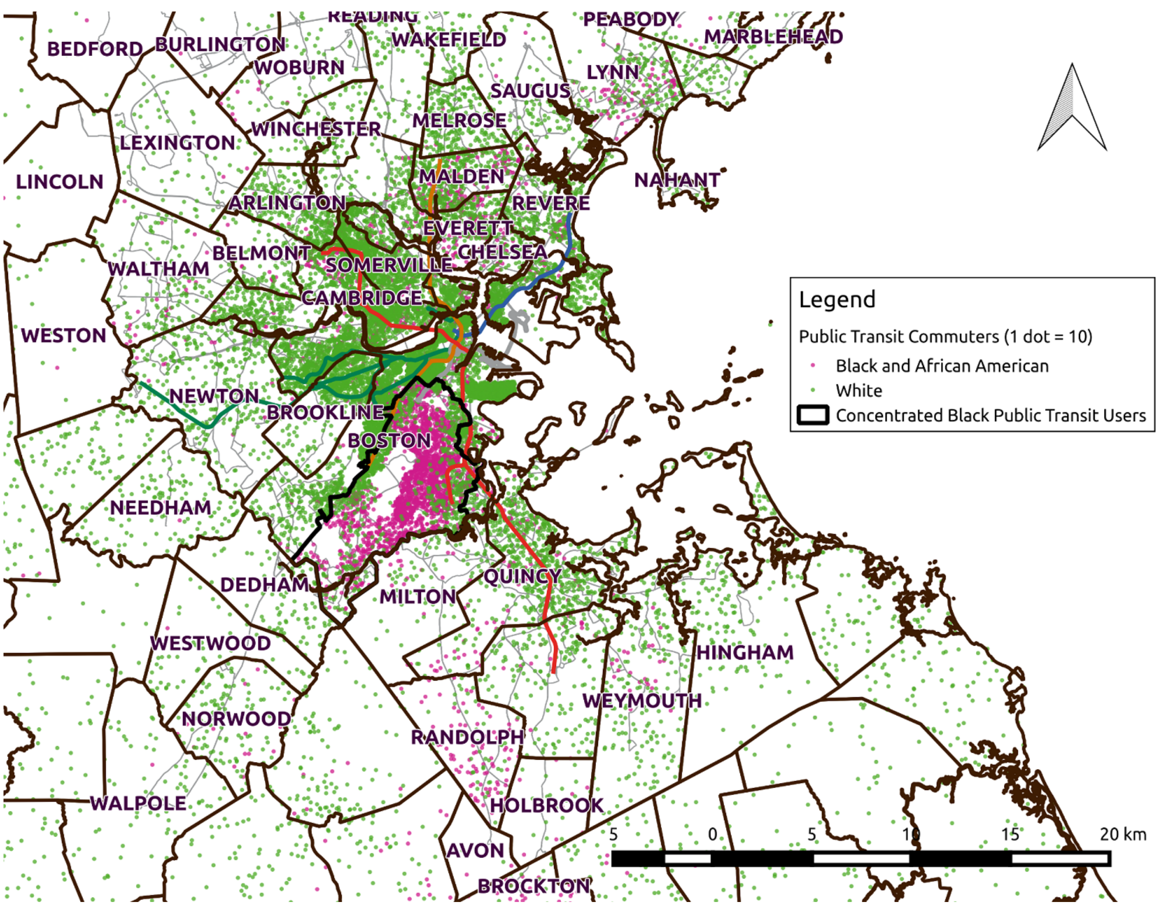


Figure 5-12: Density of public transit commuters in Boston by race (Dumas, 2015)

The study area overlaps significantly with the area examined in the MBTA's 2012 Roxbury-Dorchester-Mattapan Transit Needs Study (Massachusetts Department of Transportation, 2012). The study, which included extensive community involvement, developed a number of short-, medium-, and long-term recommendations for improving transit service in these communities. Many recommendations were operational, such as better snow removal at bus stops, a new policy for strollers on buses, and improvements to on-time performance. Changes to the frequency of service and stop spacing were also recommended. Long-term recommendations included improvements to the Fairmount commuter rail line and building a new light rail line through the area. The study provides a useful complement for the work contained in this thesis; both the data-driven methods demonstrated here and community-based outreach of the Transit Needs Study are important planning tools. Each can provide support for and help evaluate the ideas and proposals generated by the other; good service planning must incorporate both.

The need for community-based planning is especially strong in the RDM study area since the Transit Needs Study followed a difficult period for transit planning in the area. In 2009 MassDOT planned to add dedicated bus lanes and other BRT features to route 28, calling the project the 28X. The community engagement process was rushed, however, due to deadlines for federal stimulus funding. The community ultimately rejected the plan and the proposal was withdrawn. The community's concerns included the rushed process, the proposed increase in stop spacing, and the removal of recent streetscape improvements in the median on Blue Hill Avenue (Poftak, 2015). Any future proposals will need to have a thorough community engagement process to win the support of those who remain skeptical of MBTA proposals in the wake of the 28X failure.

Since the RDM study area is larger than Kendall Square or the Longwood Medical Area, there is more existing transit service. Regional access is shown in Figure 5-13. The Fields Corner and Shawmut Red Line stations are within the study area, as is the Mattapan station of the Mattapan high speed line that continues the Red Line past Ashmont. Many bus routes serve the area, including the following:

- 9 routes providing service to the Orange Line to the northwest at Jackson Square, Roxbury Crossing, or Ruggles (the 14, 15, 19, 22, 23, 28, 29, 44, and 45),
- 3 routes that serve the Forest Hills Orange Line station to the east (the 16, 21, and 31),
- 3 routes that serve the Andrew Red Line station the northeast (the 16, 17, and 18)
- 9 routes providing service mainly to the south (the 24, 33, 201, 202, 210, 215, 217, 240, and 245),
- 2 routes that operate entirely within the study area (the 26 and 27)

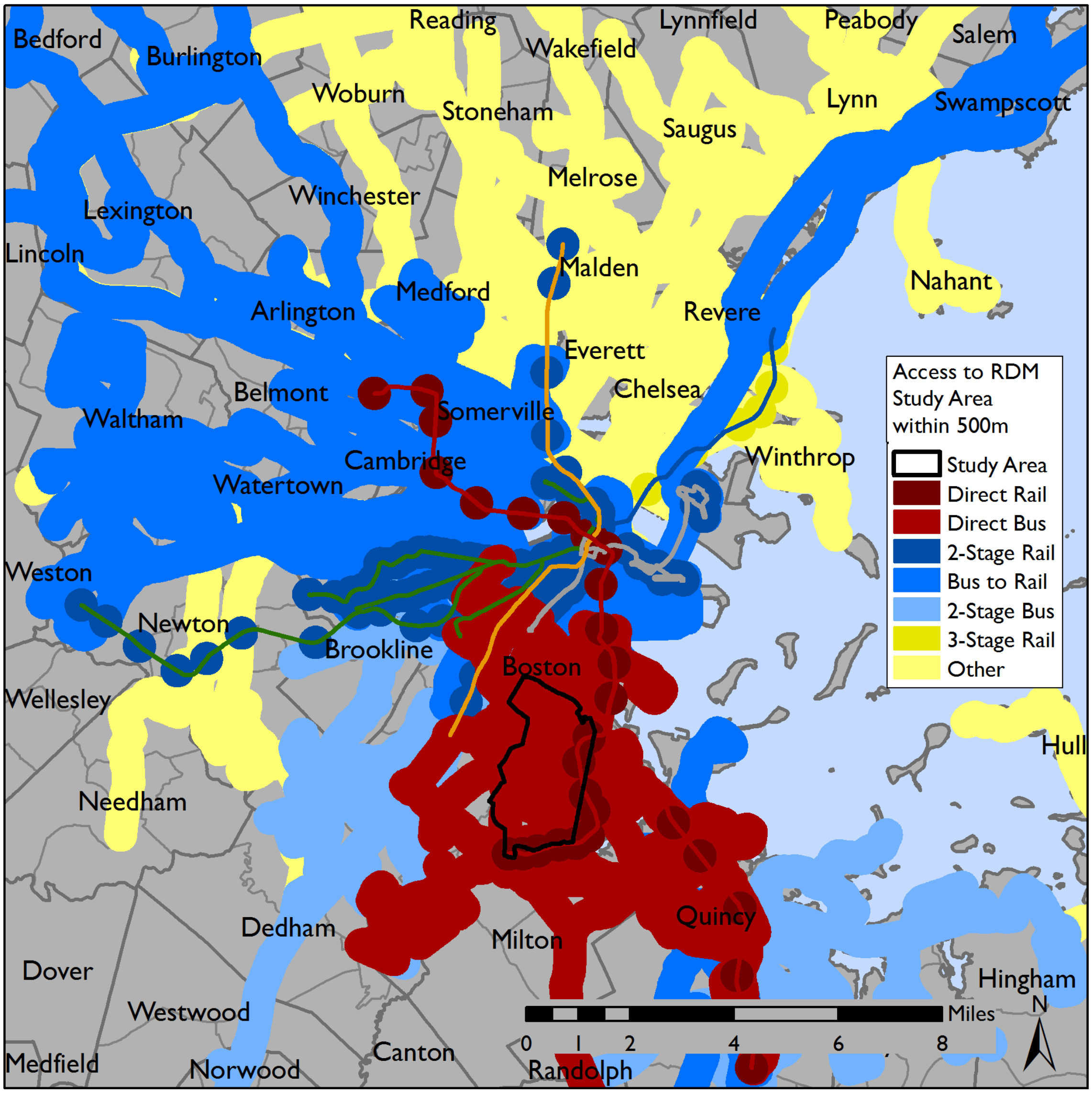


Figure 5-13: Access to the RDM study area on the existing MBTA network

With so many bus routes, the study area and its immediate surroundings are generally well-served by direct bus routes. Since the Red Line is part of the study area, Cambridge and the northern inner core cities and towns are generally reachable via a rail-to-bus transfer. However, this reveals an important difference between the analysis for a job center such as Kendall Square or Longwood and that for a residential area: the job centers considered in this thesis have small footprints, so a route serving the center is useful to most people going to that center, while a residential area such as the RDM study area is large enough that a route serving part of it may not be easily reachable by all residents. This is the case with the Red Line, on the edge of the study area. Residents near the Red Line have reasonably good access to the northwest via a 2-stage journey, while those at some distance from the Red Line have poor access to those areas because the journey requires multiple transfers.

The northern inner core cities and towns such as Everett, Chelsea, and Malden, are very difficult to reach from any part of the study area, as are parts of Newton to the west. This poor connectivity among inner core areas of the region is likely an inconvenience for some people, but is not necessarily a critical deficiency. Perhaps a more important issue for RDM as a residential area is access to jobs and other common destinations. The only direct access to downtown Boston is via the Red Line; for residents or jobs more than a reasonable walk from the Red Line all journeys require either a bus-to-bus or bus-to-rail transfer.

Similarly, for those living near the route of the 19 bus from Fields Corner to Kenmore via Dudley Square and Ruggles, access to Longwood Medical Area is good during the peak hours that the 19 continues from Ruggles through Longwood to Kenmore. For all other residents of the study area, access to Longwood requires a bus-to-bus transfer. Getting to the Seaport District always requires a transfer; for those not living close to the Red Line, it generally requires two.

Table 5.3 shows some statistics on travel in the study area. About two-thirds of journeys are by bus, with about a fifth by rail and the remainder a combination. Larger percentages of the journeys from the RDM study area are multi-stage or use both bus and rail than for the system as a whole, including nearly twice as many journeys of three or more stages. This aligns with Dumas' findings that longer travel times for RDM commuters are due to needing to transfer more often.

Figure 5-14 shows the travel to and from RDM over the course of the day. While there is higher demand in peak periods, the overall pattern is much less strongly peaked than that for Kendall Square or Longwood; midday travel is more significant, the afternoon peak in particular is quite long, and the direction of travel is less uniform than at the job centers. Frequencies that provide high-quality all-day service are important on the routes serving this area.

When considering weekday morning peak travel for Kendall Square and Longwood Medical Area, the most important journeys to consider are those with a destination at the location in question, since that is the direction of peak travel. For the RDM study area, which is largely residential, the peak direction of travel in the morning is away from the study area, as seen in Figure 5-14.

Figures 5-15 and 5-16 show statistics for journeys originating in the RDM study area during the weekday morning peak period. Figure 5-15 shows the number of

Table 5.3: Statistics on travel to and from RDM study area, October 2014

	RDM Study Area	MBTA System
Total daily journeys	31,631	633,616
Distinct cards (monthly)	144,644	1,842,250
Monthly journeys per card	6.56	10.3
Bus journeys	67.1%	31.4%
Rail journeys	21.5%	60.5%
Bus and rail journeys	11.4%	8.1%
1-Stage journeys	69.4%	79.5%
2-Stage journeys	25.4%	17.6%
3+-Stage journeys	5.2%	2.9%

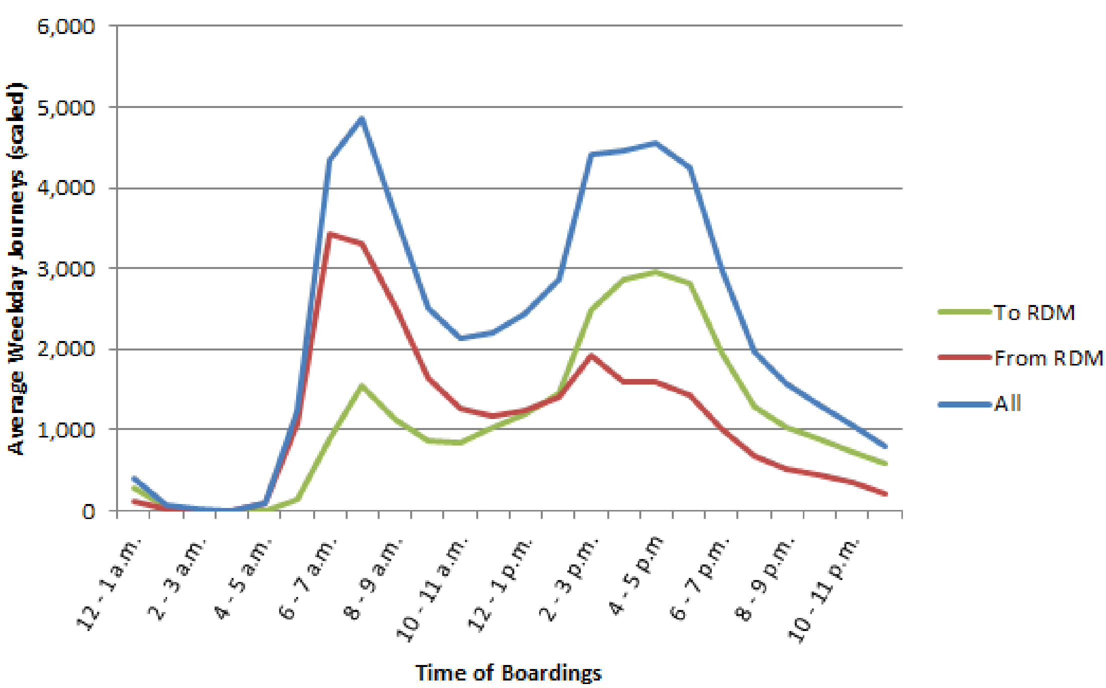


Figure 5-14: Journeys to and from the RDM study area by time of day

journeys from RDM to each census tract around the region. Destinations are concentrated near downtown and along rail lines, particularly the Red and Orange Lines. A significant number of journeys remain within the study area; though it is largely residential, there are enough jobs, stores, and schools in the area that these trips are not surprising. A more general view of inbound journeys to the RDM study area is included in Figure A-8.

Aside from census tracts along the Red and Orange Lines, there are relatively few journeys to the northern and western parts of the region. In some cases there may simply not be very much desire to travel from one residential area of the region to another; in other cases the difficulty of the transit trip may be discouraging passengers from using transit or from making the trip at all.

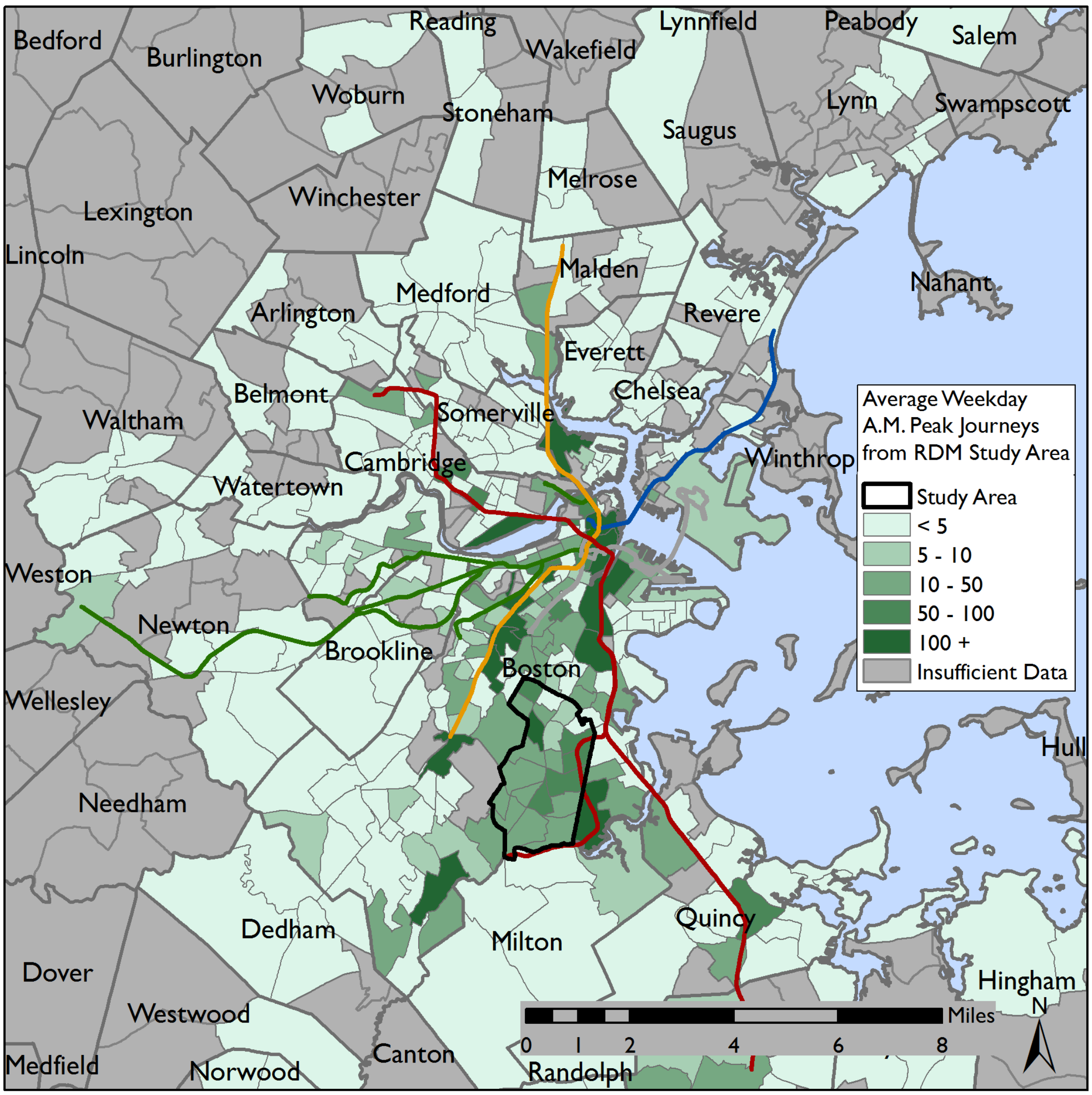


Figure 5-15: Average weekday morning peak journeys from the RDM study area

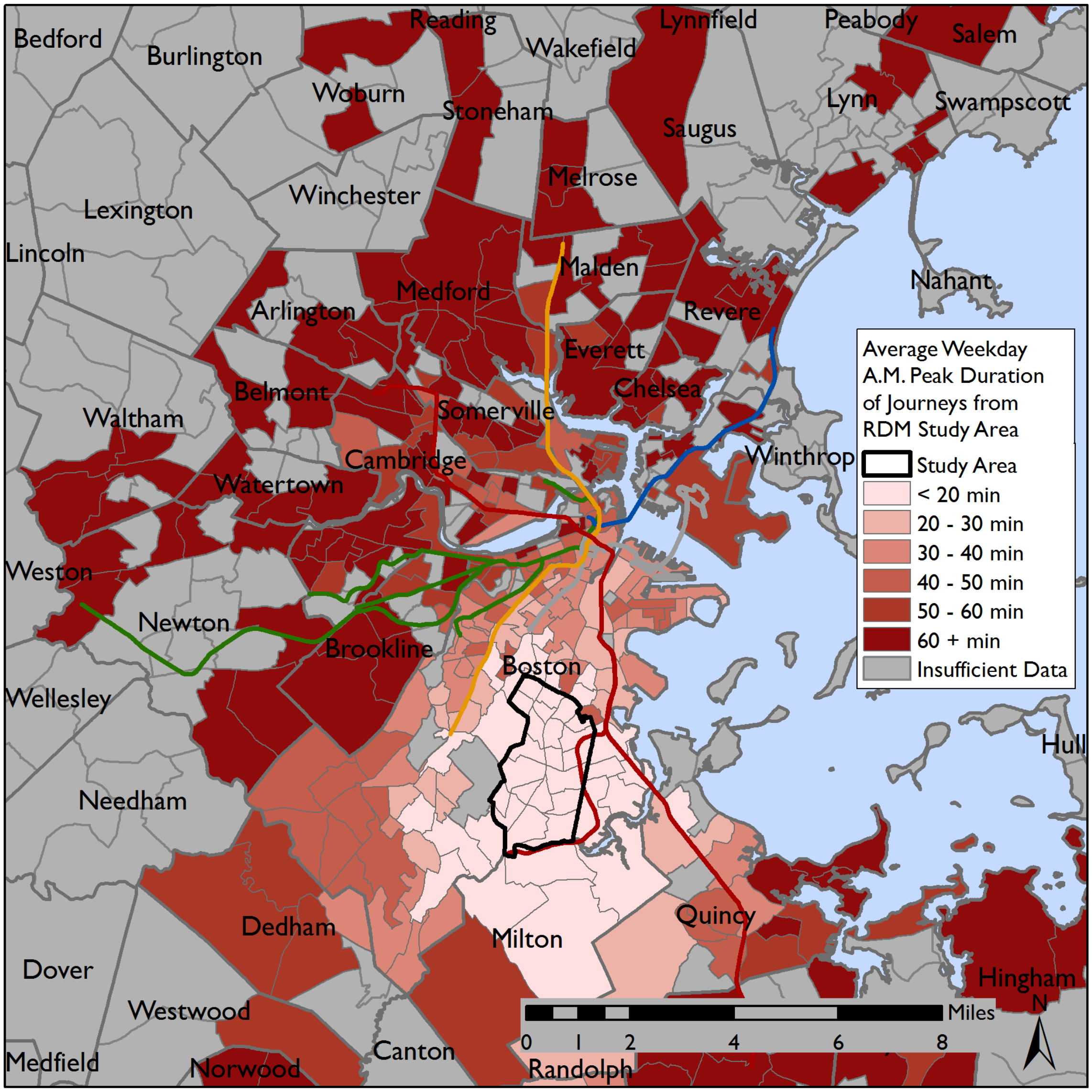


Figure 5-16: Average weekday morning peak travel time for journeys from the RDM study area

Figure 5-16 shows the average duration of journeys originating in the RDM study area and traveling to each census tract in the region. While journeys to census tracts close to the study area are short, there is a significant increase in travel time for journeys north of Dudley Square (the southern end of the Silver Line). Parts of downtown, Back Bay, and the Longwood Medical Area all take longer to reach than areas a similar distance away to the south and west, and take as long to reach as some parts of Cambridge significantly further away. Getting to the northern and western inner core cities and towns, including parts of Somerville, Cambridge, and Brookline, generally requires at least an hour. Residents of RDM therefore have long travel times to many of the job clusters in the region.

Additional analysis is included in Appendix A.3.

5.4.1 Roxbury, Dorchester, and Mattapan Challenges

The most significant issue for the RDM study area is good access to job centers, including downtown, Longwood Medical Area, the Seaport District, and Back Bay. Those who live within walking distance of the Red Line have significantly more access than those who must start their journeys by bus. Getting downtown from RDM on the bus always requires a transfer, usually at Dudley Square to the Silver Line or at Ruggles to the Orange Line. Getting to Longwood Medical Area is also more difficult than the distance would suggest, especially for those who do not live on the route of the 19 bus. The Seaport District, a rapidly growing economic center, is quite difficult to reach from RDM and requires multiple transfers to travel only five or six miles.

The geographic distance of the RDM study area from other inner core communities at a similar distance from downtown makes it understandable that these trips are slow, but improvement is possible. Improving the connection to downtown would improve the connection to cities and towns to the north as well, since most journeys to these northern communities must pass through downtown.

Some proposed long-range projects could improve access from the area. The Urban Ring, described in Chapter 1 and in Section 5.2, would improve access to Longwood and Kendall Square to the northwest, and the Seaport District, Chelsea, and Revere to the northeast. The 2009 Program for Mass Transportation called for extending BRT (Silver Line) service from Dudley south to Ashmont and Mattapan stations along the routes of the 23 and 28 buses, which would improve access to downtown and could be configured to provide a one-seat ride to downtown (Massachusetts Bay Transporation Authority, 2009). More recently, the MBTA has been considering diesel multiple unit ("DMU") service along the Fairmount commuter rail line (Dungca, 2015), as recommended in the Roxbury-Dorchester-Mattapan Transit Needs Study (Massachusetts Department of Transportation, 2012). This "Indigo Line" would provide much more frequent service along the commuter rail corridor through the RDM study area, improving access to downtown for many residents who do not live within walking distance of the Red Line. Dumas found that this service would significantly reduce the difference in travel times between white and black commuters in Boston (Dumas, 2015).

While all of these projects would greatly improve transit service in the RDM study area, none of them are likely to be implemented quickly. In the meantime, bus service changes can provide some short-term improvements. As with Longwood Medical Area in Section 5.3.1, analysis of AVL data to improve service on existing routes will be an important component of any service planning effort in RDM, since there are already so many routes serving the area. However, changes to the bus network itself may also provide some benefit. Some potential improvements will be discussed in the next chapter.

5.5 Seaport District

Any transportation analysis of the greater Boston region will inevitably identify the Seaport District as an area with significant transportation challenges and need for transportation investment (Pollack, 2012), so it will be discussed briefly here. The area, also known as the Innovation District or the South Boston Waterfront, is a former industrial area just east of downtown Boston that is rapidly adding housing and commercial office space to complement the remaining maritime uses. From 2000 to 2013, the area added 10 million square feet of development, 4,100 residents, and 7,700 new jobs, and the growth is expected to continue in the coming years (VHB, 2015). The main transit service is the Silver Line 1 and Silver Line 2 bus rapid transit routes, with the SL1 passing through the District and continuing on to serve the airport while the SL2 continues further east within the District. A small number of regular bus routes also serve the area, along with a number of private shuttles transporting employees in the District to rail stations, particularly North and South stations (Gordon, 2015). The Silver Line and the roads serving the area are nearing capacity and congestion is becoming a significant problem (Gu et al., 2014), so the area is a prime candidate for the sort of analysis recommended by this thesis.

The data limitations described in Section 2.8, however, prevent this analysis from being conducted using the version of ODX on which this thesis is based. The Silver Line is a mix of surface bus stops, where passengers tap on at the farebox, and stations with off-board fare collection, including a behind-the-faregates transfer to the Red Line at South Station. The version of ODX used in this research does not properly account for this unusual mix of data inputs on the same route; passengers who board on the surface and tap at a farebox are unable to be inferred as transferring into the rail system. A new version of the ODX algorithm that addresses this issue for the Silver Line and the Green Line, which has similar data complexity, is in the beta testing phase (Sánchez-Martínez, 2015). Given the proportion of transit ridership in the district that uses the Silver Line and the forthcoming improvements to the data set, a full analysis of the Seaport District is not included in this thesis. However, some brief ideas on proposals and analysis for the area will be included in Chapter 6.

5.6 Conclusion

This chapter has presented examples of the use of ODX data for analyzing specific locations, as recommended in the second phase of the framework described in Section 4.3. By assembling and examining a wealth of data about travel to each location, it is possible to draw conclusions about the ways in which access to these locations could be improved. While the examples presented here are in the context of the proposed enhanced service planning process and focus on locations with particularly critical challenges, the approach is transferable to other locations and uses. For example, a location analysis could be performed for Assembly Square now that the new Orange Line station has opened; for the area around the new West Station on the Worchester commuter rail line; for the areas around the planned stations of the Green Line Extension to Somerville and Medford; or to better understand the significant transportation impacts of the proposed Wynn casino, which is in the environmental review process in Everett (Woodward, 2015). These locations may have fewer journeys, but the analysis process using ODX will still be able to reveal useful patterns in how passengers travel to and from the locations by transit.

Chapter 6

Proposing and Evaluating Service Changes and Additions

Chapter 5 identified the major challenges facing the transit network in the study locations on Kendall Square, Longwood Medical Area, and Roxbury, Dorchester, and Mattapan. This chapter builds on that work by proposing changes and additions to the bus network to address some of those challenges. It goes on to perform a detailed analysis of each proposal using ODX data, demonstrating some of the new methods and techniques that this data has made feasible. These examples serve as case studies to illustrate the third and fourth phases of the enhanced service planning process proposed in Chapter 4.

The examples here are grounded in the analysis of travel behavior across the network presented in Chapter 3. That analysis showed a strong preference for direct routes over ones that require transfers, and a preference for bus-to-rail transfers over journeys that use multiple bus routes. Given that many bus boardings are on low frequency and off peak service (see Section 3.6), creating new direct routes or extending or modifying existing routes to provide direct journeys at all times of day has the potential to greatly improve passengers' experiences. The benefits of increasing the frequency of important routes will also be considered.

6.1 Crosstown Service Through Kendall Square

Section 5.2.1 identified a number of challenges for the bus system in Kendall Square. One need was an improved connection to the Orange Line, particularly the northern branch, which could be achieved by improving the bus connection between Kendall Square and Sullivan Square stations. Passengers could replace the downtown transfer from the Orange Line to the Red Line at Downtown Crossing with a short bus trip. Another challenge identified was better access to the northern inner core communities such as Chelsea, Everett, and Malden. Since many of the bus routes serving these areas terminate at Sullivan Square, a better connection addresses that problem. The two stations are currently connected by the CT2, which has 20 to 25-minute headways during peak periods and 30-minute headways in the midday, and does not run in the evenings or on weekends. These frequencies lead to long waits, making it a less attractive option compared to the downtown rail transfer.

Access from the south is also a challenge. Passengers seem to avoid taking the Green Line to the Red Line, and travel times from the Brookline area in general are long. Improved bus access between the Green Line branches and Kendall Square might attract new passengers and reduce travel times for current riders. The connection between the Lechmere Green Line station and Kendall was also noted as one that will be of growing importance as the Green Line Extension is built.

As described in Section 4.4, there are two general approaches to addressing challenges like these: improve system performance, or improve the system structure. Each of these approaches suggests a proposal that will be evaluated here.

Rosen proposes a new route that would address many of the challenges at Kendall by improving system structure. The proposed route, seen in Figure 6-1, connects the Sullivan Square, Lechmere, Kendall Square, and Kenmore rail stations (Rosen, 2013). As a new circumferential or crosstown route, Rosen refers to this route as the CT4, and this thesis will adopt that terminology.

Rosen's proposal is part of a package of improvements developed with the aim of increasing MBTA ridership to improve the region's air quality. When the Central Artery Tunnel, also known as the Big Dig, was constructed, part of the project was to extend the Green Line to Somerville and Medford as an air quality mitigation measure. The Green Line Extension is years behind schedule, so the MBTA must find other ways to produce the same air quality improvements that the delayed Green Line project would have produced. By connecting major rail stations that are currently poorly connected, the CT4 is designed to attract new riders to the MBTA system and away from private automobiles. Rosen notes that the route could either be operated by the MBTA directly or contracted out to a private operator.

Rosen proposes a long-term variation of the route in Figure 6-1 that would require a new bridge over train tracks to connect to Inner Belt Road, shortening the distance from Sullivan to Lechmere; this variation is not considered here due to the infrastructure costs involved. The earlier proposal also relies on a new connection from Third Street to Main Street at Kendall Square, which has since been constructed.

Gordon revisits the CT4 in his work (Gordon, 2015). He updates Rosen's cycle time analysis to account for congestion increases since the original proposal. He also considers some legal changes since the original proposal that make it easier for the MBTA to contract out bus operations to private operators, and develops a more detailed proposal for how that might work in practice. For the purposes of the analysis in this thesis, it does not make a difference who operates the route, but the feasibility of contracting it to a private operator makes the proposal more realistic and achievable given current constraints on MBTA resources, including storage and maintenance capacity constraints that limit the size of the bus fleet.

Alongside the proposal for improving system structure by adding the CT4, this chapter will consider a separate proposal to improve system performance. Improving system performance can only address some of the challenges identified above; no incremental improvement on an existing route will connect Kendall to Lechmere. However, improving service on the CT2, which runs from Sullivan to Ruggles, would

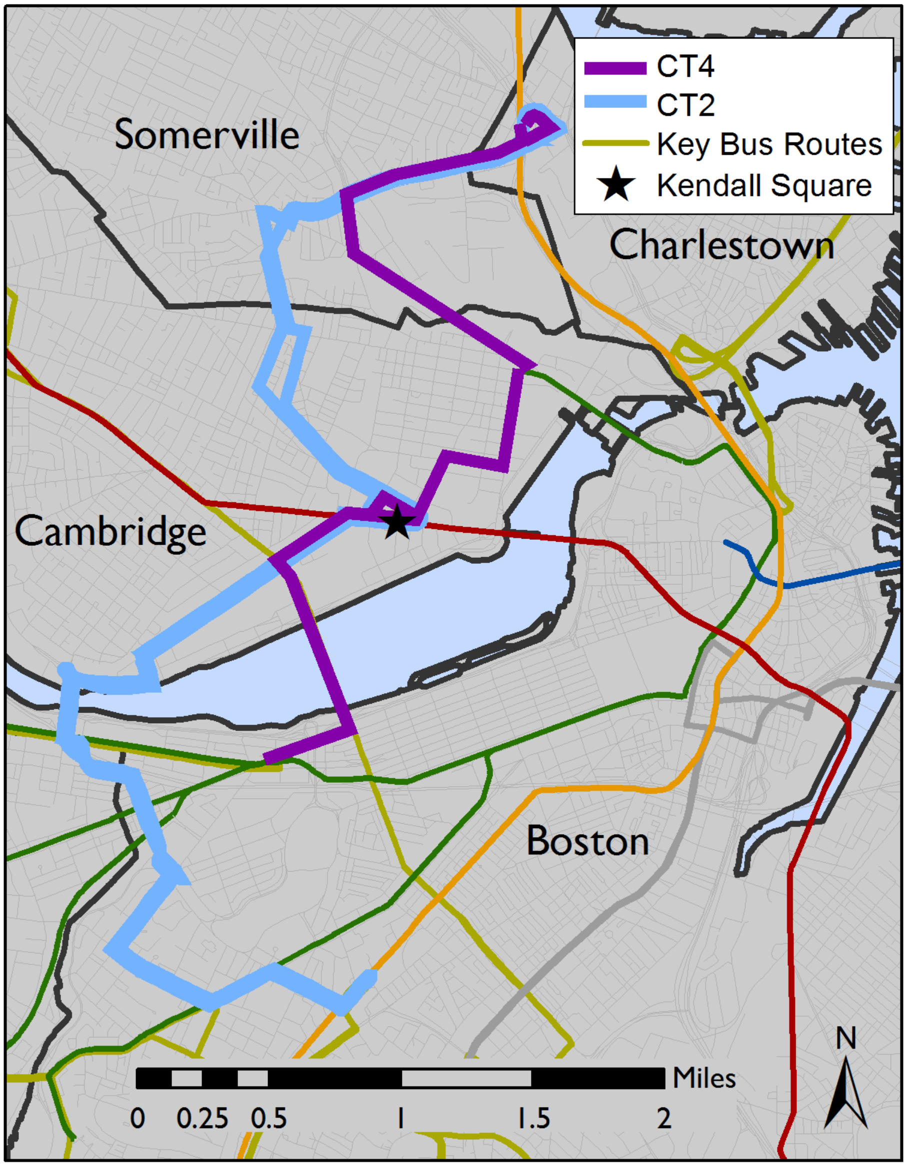


Figure 6-1: Existing CT2 route and proposed CT4 route

improve connections to Sullivan Square and the Orange Line and bus routes serving that station. It would also improve access from Brookline and the branches of the Green Line.

Evaluating the impacts of each of these proposals requires several different techniques. There are two main components to the total impact, as described in Section 4.5: the effect on current riders, and ridership growth from new passengers who were not previously using the transit system. The effect on current riders will be the focus in this chapter. The increase in ridership due to new proposals can be estimated using the methods developed by Rosen, and will be discussed in Section 6.1.4. Since ridership increases often take some time to develop after a new service is introduced, the effect on current riders offers a useful estimate of the short-term ridership potential for a new service.

The evaluation of the impact on existing riders has three parts. The first is examining the impact on those riders who made journeys that both started and ended on the route of the CT4 and would be able to use the route for their entire journey. Some of these riders made single-stage journeys using routes that share part of the path of the CT4, while others had to transfer but would have been able to use the CT4 to make a single-stage trip. This type of journey is explored in Section 6.1.1, along with a similar exploration of journeys that already use the CT2 or that might benefit from doing so.

A more complicated component of the analysis is identifying those passengers who made a multi-stage journey but who could have saved time by making a different multi-stage journey, taking the CT2 or CT4 for one of the stages. These journeys are analyzed in Section 6.1.2.

A third component of the analysis is determining the ridership that might have been able to use the CT4 instead of the EZRide shuttle along the part of the CT4 route that is served by both. This is discussed in Section 6.1.3.

There are some factors that complicate this analysis. Much of the CT4 route runs alongside existing MBTA services, often for only short stretches. Passengers taking these other routes along these short stretches would have a new route option if the CT4 were introduced, increasing the frequency of service available to them. Their waiting time would be decreased, though their in-vehicle travel time would be the same. These trips must be identified separately from those that would take a geometrically different path and save in-vehicle travel time in order correctly state the potential benefits of the new route.

A complication that cannot be addressed simply through careful analysis is that some passengers currently take paths through the system that are sub-optimal. Sometimes it is a matter of mode preference; sometimes a path is suboptimal geometrically but the better path is not available at the time of the trip due to a limited span of service or very infrequent service on one of the routes involved. Passengers may also run brief errands that ODX infers as transfers rather than separate trips, and sometimes passengers simply don't take the fastest path to their destination. Accounting for this variation when determining how many passengers are likely to use a new or modified route is important, but not straightforward.

Partly for this reason, the analysis below applies the same analytical techniques to both the proposed CT4 route and to the existing CT2. This allows for a more nuanced examination of how these complicating factors might affect demand. It also provides useful data on which to base a decision about what service change should be implemented given the resources available.

Another consequence of these complications is the importance of the final phase of the proposed enhanced service planning process where proposals are evaluated after they have been implemented, as described in Section 4.6. Retrospective analysis will provide critical feedback, allowing planners to assess how well they accounted for factors such as passenger mode preference, so that future analyses may account for these factors more accurately.

6.1.1 Passengers Traveling Within the Routes

The first step of the analysis is examining journeys that both start and end on the route of the CT2 or CT4. There are three types of these journeys: journeys that use only bus, journeys that use only rail, and journeys that use a combination of bus and rail. To identify these journeys, buffers were calculated around the routes of the CT2 and CT4 using GIS, and the specific bus stops and rail stations within each buffer were identified. This list of stops and stations was imported into the same database as the ODX data so that those journeys that both begin and end within a short distance of the route could be identified. Mode, number of stages, and other characteristics of each journey were identified using the same methods described in Chapter 3. Results have been scaled to account for the fact that only journeys with inferred destinations can be identified using these methods.

In order to develop a nuanced picture of how the CT2 currently functions within the network and how the CT4 might function, two buffers were drawn. The first used a distance of 100 meters, which is large enough to contain stops that might be located across an intersection or around a corner, but is small enough that only journeys whose origins and destinations truly lie on the route in question are included. The second buffer aims to capture those journeys whose origins and destinations are within a short walk, typical of a bus catchment area. A buffer distance of 500 meters was chosen for this purpose.

The category of journeys that use both bus and rail is actually the simplest to analyze. There are relatively few of these journeys, as seen in Table 6.1. Since the numbers are small, it is reasonable to make the simplifying assumption that all of these journeys would be more efficient using the CT2 or CT4, since no transfer would be required.

Bus journeys that both start and end on the route are more numerous. Bus journeys may fall into one of three categories: journeys on the existing route (in the case of the CT2), single-stage journeys that use an existing route operating on the same path as the route in question, and multi-stage journeys. Journeys on the existing route and journeys operating on an equivalent service would not see any savings of in-vehicle travel time with improved frequency on the CT2 or the introduction of the CT4, but waiting times would decrease due to the increased frequency, at least for passengers aware of all of their route options. Multi-stage journeys would have

Table 6.1: Average daily scaled ODX journeys within the CT2 and proposed CT4, October 2014

		CT2		CT4	
Buffer Distance		100m	500m	100m	500m
Bus	On Route	951	951	0	0
	Other 1 Stage	429	1,216	372	1,216
	Multi-Stage	18	59	5	18
Rail	Faster on Rail	439	449	0	0
	Slower on Rail	150	226	438	702
	Uncertain	15	40	240	1,026
Bus and Rail		37	84	7	24
Total		2,039	3,024	1,063	2,986

shorter in-vehicle time and no between-stage waiting time. There are very few of these journeys.

These categories are summarized in Table 6.1. There are nearly 1,000 single-stage bus journeys on the CT2 per day; of course, there are no existing journeys on the CT4. The CT2 appears to carry about two-thirds of the single-stage journeys that start and end very close to the route, and about 44% of those within a reasonable walking distance of the route. Increased frequency on the CT2 would presumably increase these shares, while introducing the CT4 at frequencies similar to the CT2 might be expected to attract a similar share of the existing single-stage journeys along the path of the route.

Rail journeys were considered separately from bus journeys. In some cases, such as travel from Lechmere to Kendall, travel time is clearly lower on the bus than by rail. In other cases, such as from Sullivan to Ruggles, the CT2 is slower than the single-stage trip on the Orange Line. To analyze rail journeys, GTFS rail and bus schedules along with Google Maps trip planning and traffic information were used to estimate travel times by each mode. In most cases one mode is clearly preferable. In a few cases, however, the travel times are comparable and which mode was faster depends on time of day, traffic congestion, wait time for rail transfers, and other such factors. Sullivan Square to Kenmore falls into this category, as does Lechmere to Kenmore. Despite both being on the Green Line, the Lechmere to Kenmore trip can be quite slow; Lechmere is only served by the relatively infrequent E branch, which does not serve Kenmore. These trips therefore require a transfer, usually at Park Street.

Table 6.1 shows the results of this rail analysis. There are significantly more journeys on rail that would be slower using the CT4 than there are for the CT2, which is an indication that a large proportion of passengers are already choosing the most efficient route available. If the CT4 were introduced, the proportion of rail passengers who would switch to the new service could be expected to be similar to the proportion of passengers who currently use the CT2 compared to those who remain on rail. The frequency of service chosen for the CT4 would affect the rate at which passengers switch from rail; the proposed headways of 10 minutes during peak periods are likely to attract more passengers than the CT2 currently does. When the results are expanded to include journeys using stops and stations within 500 meters, a larger proportion of passengers are currently using rail even though the CT2 would be faster. This indicates that some passengers are likely choosing to experience longer in-vehicle time in order to reduce time spent walking and waiting.

There are significantly more journeys on the CT4 route where the time savings are uncertain than on the CT2 due to the fact that the Lechmere to Kenmore journeys are in this uncertain category. There may be more of these journeys with uncertain time savings for the CT2 than are shown in Table 6.1, but the Green Line data limitations described in Section 2.8 mean that many of the journeys beginning or ending at one of the surface stations served by the CT2 are not able to be included here.

Average daily results are useful, but there can be distortions due to the fact that some services, such as rail, have much longer spans of service than bus routes such as the CT2, which does not run after about 7 p.m. or on weekends. Therefore, the analysis was repeated for the weekday morning peak, on an hourly basis, when all services are running at their shortest headways. These figures are presented in Table 6.2. The overall pattern of journeys is similar to the daily figures, though a larger proportion of the journeys within a short distance of the CT2 route are using the route rather than one of the parallel route options. These hourly figures are also useful for understanding the potential effects of these service changes on a per-trip basis. For example, 20-minute headways would be three trips per direction per hour. If travel on the CT2 is relatively even in the two directions during the peak hour since it is circumferential service serving a number of key locations, dividing the figures in Table 6.2 by six provides an estimate of the trip-level impact; the passengers taking rail despite the fact that the CT2 would be faster reduce the CT2 ridership by two or three passengers per trip. The volume of within-route journeys today, therefore, is likely to be considered insufficient on its own to justify instituting the CT4 or adding substantial amounts of additional service on the CT2.

Table 6.2: Average scaled ODX journeys per hour during the weekday morning peak within the CT2 and proposed CT4, October 2014

		CT2		CT4	
Buffer Distance		100m	500m	100m	500m
Bus	On Route	190	190	0	0
	Other 1 Stage	44	133	38	129
	Multi-Stage	2	6	1	2
Rail	Faster on Rail	48	50	0	0
	Slower on Rail	12	14	33	49
	Uncertain	1	3	15	47
Bus and Rail		41	10	0	2
Total		338	406	87	229

The contribution of these within-route journeys to the overall impact of the proposals is discussed in Section 6.1.4.

6.1.2 Other Passengers Benefiting From CT2 and CT4 Proposals

In addition to considering the journeys that would have a one-seat ride on the CT2 or CT4, it is important to consider the network effects: those journeys that could use the CT2 or CT4 as part of a two-stage journey. The journeys to be considered for this analysis are those with only the origin or the destination, but not both, along the route. The methods used here are designed to be relatively simple to apply and produce estimates for the number of passengers affected by a change, not a precise count. Therefore, simplifying assumptions are made in several places.

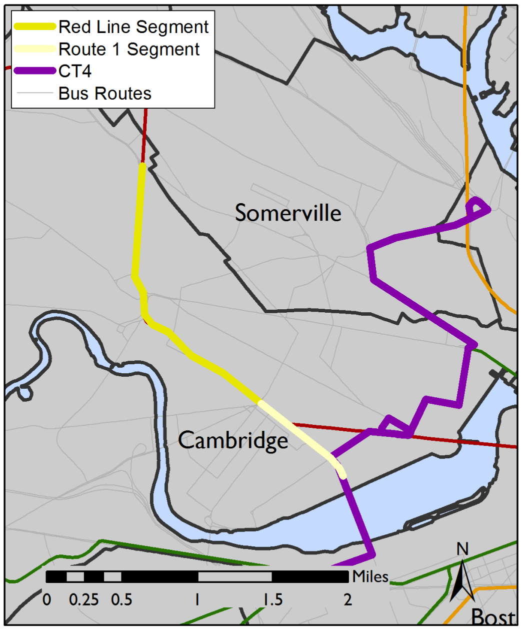
There are reasons to prefer these simpler methods to other existing analytical tools. More complex methods tend to rely on shortest-path calculations and other model outputs, but these do not typically account for the mode preferences and other seemingly irrational behavior described in Section 6.1.1. Since some passengers do not take the most efficient path, models are likely to produce results with a significant margin of uncertainty. Accounting for these passenger preferences is possible in some models, but adds to the complexity of the modeling process. The tools presented here are significantly simpler to apply and produce results that are sufficiently accurate to be useful for decision-makers.

Journeys that have only one stage and either start or end on the route in question are very unlikely to be able to benefit from changing their behavior to use the CT2 or CT4; these passengers already have a one-seat ride and introducing a transfer would likely slow their journey. There are relatively few journeys of three or more stages in the network as a whole, and the complexity of the analysis increases as the number of stages increases. Therefore, only two-stage journeys are considered here.

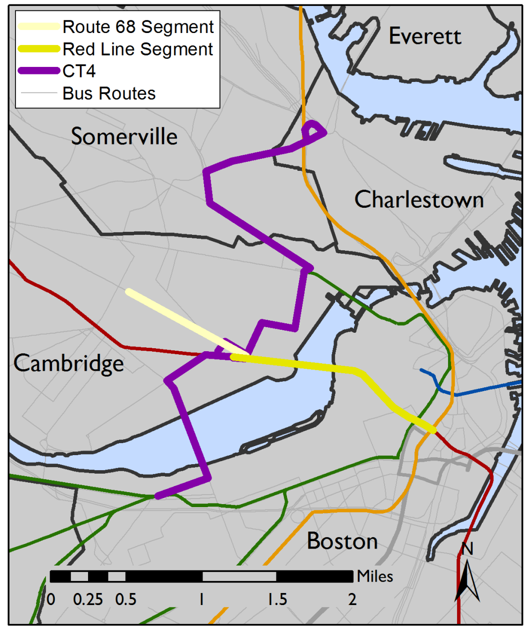
There are several ways that a two-stage journey that either starts or ends on the route can interact with the route. Example journeys interacting with the proposed CT4 route are shown in Figure 6-2. The primary considerations are how many of the starting and ending locations of the journey's two stages are on the route, and whether one or both of the stages intersect the path of the route in question. The simplest case, which will be referred to as Type A, is where only one stage intersects the route and only one stop is on the route. An example of this case is shown in Figure 6-2a, where a passenger travels from Porter Square to Central Square on the Red Line, then transfers to the route 1 bus to MIT. In this case, the passenger would be unable to use the CT4 on this journey.

Type B interactions, illustrated in Figure 6-2b, have two stages intersecting the route. Two stops, one from each stage, are on the route. The example shown is a passenger boarding route 68 near Inman Square in Cambridge, traveling to Kendall Square, then alighting and transferring to the Red Line to Downtown Crossing. These passengers are also unable to use the route on their journeys.

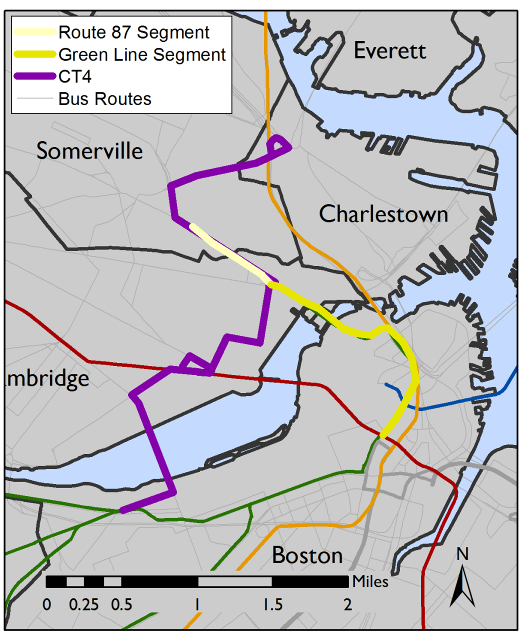
In type C interactions, passengers use one of the routes that serves a portion of the CT4 path. The example in Figure 6-2c shows a passenger boarding route 87 in



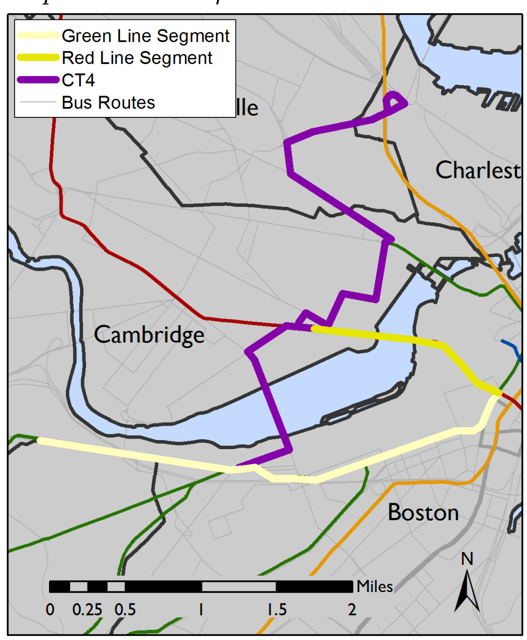
(a) Red Line from Porter Square to Central Square, transferring to route 1 to MIT: one journey segment intersects the CT4, with one stop on the CT4 route



(b) Route 68 from Inman Square to Kendall Square, transferring to the Red Line to Downtown Crossing: two journey segments intersect the CT4, with two stops on the CT4 route



(c) Route 87 from Somerville to Lechmere along the path of the CT4, transferring to the Green Line to Park Street: two journey segments intersect the CT4, with three stops on the CT4 route



(d) Green Line B branch from Babcock Street to Park Street, transferring to the Red Line to Kendall Square: two journey segments intersect the CT4, with one stop on the CT4 route

Figure 6-2: Examples of how a two-stage journey can interact with the proposed CT4 route

Somerville, along the route of the CT4, and traveling to Lechmere before transferring to the Green Line to Park Street. In these cases, both stages intersect the route, and three of the four stops are at locations along the route. If the CT4 were introduced, these passengers could use the new route and would experience reduced headways, and therefore lower waiting times. These passengers would not experience reduced in-vehicle time.

Finally, in type D interactions, both stages of the journey intersect the route, but with only one of the four stops on the route. For example, the passenger in Figure 6-2d boards the Green Line B branch at Packards Corner and travels downtown, crossing over the route of the CT4. The passenger then transfers to the Red Line at Park Street, and arrives at Kendall Square, which is on the CT4 route. Passengers making such journeys are likely to be able to save in-vehicle time by using the route in question, since on their current paths they cross the route, transfer, and then double back to a point on the route, taking two sides of a triangle instead of the direct path the route provides. The precise time savings will depend on the relative speeds and frequencies of each of the options. While in many cases the direct bus option will be faster than even a rail-to-rail transfer, is is possible that some rail-to-rail transfers will need to be excluded under some circumstances based on the particulars of the proposal being analyzed.

This analysis uses the same buffers and sets of stops and stations described in Section 6.1.1 above. The set of journeys with either an origin or a destination on the route was identified, excluding the journeys with no inferred destination, and the origins and destinations of the component journey stages were determined. The coordinates of these origins and destinations were found from the GTFS stop data, and the results imported into ArcMap. Using the "XY to Line" tool, straight lines were drawn between each pair of points, representing the straight-line path of each journey stage. Those journey stage paths intersecting each of the route buffers were identified, and the results exported from GIS and imported into the ODX database. For each two-stage journey with an origin or destination on the route it was then possible to calculate the number of journey stages intersecting the route and the number of stops on the route. Journeys that have interactions with the route of types C and D, as described above, will benefit from the service improvement.

This method gives a good approximation of the number of journeys interacting with the route in each of the ways described above. In a few cases, however, the straight-line approximation of the path of the journey stage caused an incorrect result. The most significant instances of this are on the Orange Line, where the straight-line path of a rail journey stage from Oak Grove or Malden to Downtown Crossing does not intersect the CT2 or CT4, but the actual path passes through Sullivan Square, where a transfer would be possible. A similar pattern occurs with some of the Orange Line stations to the south of Forest Hills. Since there are a significant number of Orange Line journey stages, the coding on these stages was altered manually to show that they intersect with the CT2 and CT4 paths.

The results of this analysis are presented in Table 6.3. As in Section 6.1.1, it is also important to consider only the weekday morning peak, as presented in Table 6.4. The rail-to-rail journeys crossing the CT2 or CT4 twice are the largest subset of journeys by a significant margin. Applying the travel time analysis described in Section 6.1.1 above, the in-vehicle time for all these journeys can be assumed to be shorter on the bus route than the rail-to-rail option. In a small number of cases, the current journey is already served by a one-seat bus ride, such as Lechmere to Porter, served by the 87, or Sullivan to Harvard, served by the 86. This provides some useful context for any prediction of how many of these rail-to-rail journeys are likely to use an improved CT2 or new CT4, as it indicates that some passengers have very strong mode preferences for rail.

Table 6.3: Average daily scaled ODX journeys starting or ending on the CT2 and proposed CT4, October 2014

Scenario	Mode	CT2		CT4	
Buffer Distance		100m	500m	100m	500m
Type C	Bus: Use route already	159	167	0	0
	Bus: Use other routes	272	473	66	164
	Bus and rail: Use route already	241	241	0	0
	Bus and rail: Use other routes	478	632	159	767
Type D	Bus	144	214	5	10
	Bus and rail	136	345	60	84
	Rail	2,715	3,059	2,917	4,310
Total Type C: Headway reduced		1,150	1,513	225	931
Total Type D: In-vehicle time savings		2,995	3,615	2,982	4,404

Table 6.4: Average scaled ODX journeys per hour during the weekday morning peak starting or ending on the CT2 and proposed CT4, October 2014

Scenario	Mode	CT2		CT4	
Buffer Distance		100m	500m	100m	500m
Type C	Bus: Use route already	25	26	0	0
	Bus: Use other routes	20	38	8	20
	Bus and rail: Use route already	44	4	0	0
	Bus and rail: Use other routes	59	86	26	104
Type D	Bus	22	32	0	1
	Bus and rail	24	55	13	16
	Rail	374	434	276	358
Total Type C: Headway reduced		148	154	34	124
Total Type D: In-vehicle time savings		420	521	289	375

Many more journeys use routes parallel to the CT2 than the CT4, which is not surprising since the CT2 runs parallel to more routes, particularly on its segment through Longwood. CT2 service increases would benefit many more passengers through reducing headways, while more of the beneficiaries of a new CT4 would save in-vehicle time.

The volume of weekday morning peak trips impacted by these network effects is larger than the volume of journeys within the route discussed in Section 6.1.1. The 420 journeys of type D for the smaller buffer for the CT2 would fill eight buses nearly to capacity during each peak hour, requiring significantly reduced headways during peak hours. While many of these rail journeys are unlikely to switch mode, there is a sufficient volume of beneficiaries due to network effects to justify service adjustments.

Further discussion of these network effects in the context of the overall impact of the proposals is included in Section 6.1.4.

6.1.3 EZRide

If the MBTA began running the CT4, some of the current riders on the EZRide shuttle would have an additional choice for their journeys among Lechmere, Kendall Square, and destinations on First Street. A recent EZRide passenger survey asked riders about their origins and destinations; 44 out of the 1,084 responses, or 4.06%, traveled among these stops (Gascoigne, 2015). EZRide's average daily (weekday) ridership is about 2,400 people, so about 100 daily passengers would have an additional route option if the CT4 were available. Those passengers who would be willing to take either route would experience reduced headways, though there might be fare impacts for some passengers.

EZRide ridership figures by time of day are not publicly available. For simplicity, this analysis estimates that about a third of the daily journeys occur during the two-hour duration of the morning peak, and therefore about 15 journeys per hour would be affected by the introduction of the CT4. This may not represent all of the demand for travel along this route, as members of the public who typically use MBTA services need to pay an additional fare to use the EZRide bus, and many MBTA riders may not be aware that the service is open to the public.

Other private transit would also be affected, though ridership figures are not publicly available and so they cannot be accounted for here. The Cambridgeside Galleria mall runs an employee shuttle to Kendall Square, a trip that would be directly served by the CT4. The CT4 would also serve portions of the MIT Shuttle route.

6.1.4 Overall Impact of CT2 and CT4 Proposals

In order to get a clearer sense of the overall impact of each service improvement option, the average daily results of the analysis from Sections 6.1.1 to 6.1.3 have been summarized in Table 6.5. Average hourly morning peak results are presented in Table 6.6.

There are broadly similar numbers of beneficiaries for the two proposals, though the nature of those benefits differs. More of the beneficiaries of the CT2 proposal would be existing riders who would experience reduced headways than with the CT4 proposal, which is not surprising given that the CT2 already exists and parallels more routes than the CT4. The range of the number of passengers who might experience reduced in-vehicle travel time varies more for the CT4, from about 3,700 per day who

Table 6.5: Average daily scaled ODX journeys with the potential to benefit from CT2 and CT4 proposals, October 2014

		CT2		CT4	
Buffer Distance		100m	500m	100m	500m
Within Route	Taking route	951	951	0	0
	Taking 1-Stage trip on parallel route	429	1,216	372	1,216
	Taking multi-stage bus trip	18	59	5	18
	Taking slower 2-stage rail	150	226	438	702
	Taking similar duration rail	15	40	240	1,026
	Taking bus and rail trip	37	84	7	24
Network	Taking multi-stage bus trip using route (Type C)	144	214	5	10
	Taking multi-stage bus trip (Type C)	165	167	0	0
	Taking multi-stage bus trip of Type D	285	514	71	169
	Taking bus and rail trip using route (Type C)	136	345	60	84
	Taking bus and rail trip using parallel route (Type C)	241	241	0	0
	Taking bus and rail trip of Type D	483	643	163	770
	Taking 2-Stage Rail	2,715	3,059	2,917	4,310
EZRide		0	0	100	100
Total		5,766	7,757	4,379	8,428
Headway Improvements		2,553	3,731	706	2,254
Travel Time Savings		3,214	4,026	3,672	6,174

Table 6.6: Average scaled ODX journeys per hour during the weekday morning peak with the potential to benefit from CT2 and CT4 proposals, October 2014

		CT2		CT4	
Buffer Distance		100m	500m	100m	500m
Within Route	Taking route	190	190	0	0
	Taking 1-Stage trip on parallel route	44	133	38	129
	Taking multi-stage bus trip	2	6	1	2
	Taking slower 2-stage rail	12	14	33	49
	Taking similar duration rail	1	3	15	47
	Taking bus and rail trip	41	10	0	2
Network	Taking multi-stage bus trip using route (Type C)	25	26	0	0
	Taking multi-stage bus trip using parallel route (Type C)	20	38	8	20
	Taking multi-stage bus trip of Type D	22	32	0	1
	Taking bus and rail trip using route (Type C)	24	55	13	16
	Taking bus and rail trip using parallel route (Type C)	44	44	0	0
	Taking bus and rail trip of Type D	59	86	26	104
	Taking 2-Stage Rail	374	434	276	358
EZRide		0	0	15	15
Total		822	1,072	425	741
Headway Improvements		383	517	87	268
Travel Time Savings		439	555	338	473

travel to and from destinations very close to the route to a little over 6,000 whose destinations are within a larger buffer distance from the path of the CT4.

In the weekday morning peak period, there are more passengers who would benefit from increased service on the CT2 than would benefit from taking the CT4, both in terms of reduced headways and in terms of in-vehicle travel time savings. This may be due to the existing passengers on the CT2 and parallel routes who would experience reduced headways, the large number of passengers who travel to Longwood on the CT2 route in the morning peak, and other factors. This does not include any sort of induced or latent demand, which is likely to be greater for the CT4 as a new route than for the CT2 as an existing route.

It may seem at first glance that many of the passengers taking the journeys listed in Tables 6.5 and 6.6 who would experience reduced in-vehicle time using the CT2 but are currently using another route are making a poor route choice. However, those who are currently traveling by rail in the peak periods are likely experiencing headways of five or six minutes on the Red and Orange Lines. The CT2, on the other hand, is scheduled to arrive every 20 minutes or so during the morning peak and approximately every 25 minutes during the evening peak, and delays resulting from traffic congestion increase the effective headway even further. Taking a longer two-stage rail journey instead of waiting for an infrequent bus may be a faster choice, and is almost certainly a less frustrating one.

There is plenty of latent demand within the pool of current riders for both improved service on the CT2 and the introduction of the CT4. In order for these passengers to experience benefits, however, the headways and reliability must be at a level to attract passengers from rail. Headways of 10 minutes, as originally proposed by Rosen for the CT4, would be appropriate on both routes. Rosen's elasticity model also provides a useful estimate of the latent demand from passengers switching from other modes or making new trips due to better frequency on the CT2; the model's elasticity of ridership with respect to service is -0.46, with a recommended sensitivity range of +/-0.1 (Rosen, 2013). A frequency increase that cuts headways in half, therefore, would be expected to increase ridership by 27 - 46%, or 768 - 1,292 passengers per day for the CT2. This is a general model for the increase in ridership that comes with increased service levels, so the estimated increase in ridership is due to new trips attracted to transit, not to trips switching from different routes. This level of latent demand is likely similar for the CT4, though there is no existing CT4 ridership on which to base such an analysis, and is in addition to the existing passenger benefits shown in Tables 6.5 and 6.6.

Rosen's direct demand model predicts ridership of 4,300 to 7,100 passengers per day on the new CT4 route. This range is similar to the number of passengers who would save time on the new route as calculated in this section, plus the latent demand estimated using Rosen's elasticity model for the CT2. The fact that the two different methods arrive at roughly comparable estimates for ridership on the new route strengthens the confidence in both methodologies.

Given the large number of passengers benefiting from improved service on the CT2 or CT4, measures to ensure reliability should be a high priority. Signal priority through Kendall Square, queue jump privileges for the CT2 over the Boston University Bridge, and a bus lane for the CT4, route 1, and CT1 across the Harvard (Massachusetts Avenue) Bridge should all be considered.

6.1.5 Implementation

The benefits of implementing the CT4 and increasing the level of service on the CT2 are generally similar. In order to determine which proposal to implement, consideration must be given to costs, logistics, and political considerations. The CT2 currently runs every 20 minutes or so during the morning peak using 6 buses, every 25 to 30 minutes during the midday using 3 to 4 buses, and every 25 minutes during the evening peak using 5 buses (Massachusetts Bay Transportation Authority, 2014b). Reducing headways to 10 minutes during peak periods and 15 minutes during the midday would require an additional 6 buses during the peak and 3 or 4 buses during the midday. As an existing MBTA route this additional service could not be contracted separately, so this additional frequency would likely require reallocating buses from elsewhere in the network during peak hours.

Gordon's analysis of the CT4 includes estimates of cycle times and the number of buses required to operate the route (Gordon, 2015). Since it is somewhat shorter than the route of the CT2, it requires fewer total buses to achieve the same frequency. That analysis shows that 10-minute headways during the peak and midday periods would require 8 buses during most of the day, with 10 required during the more congested evening peak. As a new route, the MBTA would have the option of contracting the route to a private operator rather than relying on its own fleet. Gordon outlines a proposal for contracting the route to the Charles River TMA, the provider of the EZRide shuttle. The proposal calls for phasing in the route, beginning with four buses that operate alongside the current EZRide service. This would provide desirable frequency on the parts of the route already served by EZRide and lower frequency elsewhere. The proposal then calls for gradually adding buses as ridership on the route builds and more buses can be procured or reassigned from the existing EZRide routes.

Fewer buses would be required to achieve the desired frequency on the CT2 than the CT4, but any service increase along the corridor would be beneficial. Given the current fiscal and fleet size constraints facing the MBTA, contracting out the CT4 route may be a more feasible option. Introducing the CT4 also targets the increased service along the part of the corridor where it has the most benefit for Kendall Square, since any new buses devoted to the CT2 will spend significant time on the portion of the route through Longwood.

6.2 Access to Longwood from the Northwest

The analysis of the Longwood Medical Area in Section 5.3 found that access to the area from the northwest is very slow, particularly areas such as western Cambridge, Belmont, Watertown, and Waltham. These largely residential areas are fairly close to Longwood as the crow flies, so it is likely that there are a good number of residents of these areas who work in Longwood. However, the lack of direct routes and a reliance on bus-to-bus transfers leads to long travel times, so many of these employees likely commute by private car. This section of the thesis will explore options for improving transit access to reduce travel times for existing passengers and shift mode share to transit.

A bus route connecting Longwood to the northwest would have to pass through Brookline and Brighton. The 66 already runs from Longwood through these areas to Harvard Square, so new service would be most beneficial elsewhere, to serve new riders. Options crossing the Charles River further west, to the Arsenal area of Watertown, are the most promising possibilities.

Considering the options for a route from Longwood through Brookline and Brighton to Arsenal, one sees that the existing route 65 already runs along one of the most likely paths from Longwood through Brookline, ending at Brighton Center. Extending route 65, therefore, may be the most logical and efficient way to provide new service connecting Longwood to the northwest. Options for this route extension will be explored in this section.

The current route begins at the Kenmore Green Line station, travels down Brookline Avenue through the Longwood Medical Area and turns up Washington Street near the Brookline Village station of the Green Line D branch. It follows Washington Street to Brighton Center and ends in a loop around Chestnut Hill Avenue. The schedule is somewhat irregular, with service every 10 to 15 minutes during the morning peak and every 20 to 35 minutes during the midday. The typical weekday ridership is about 2,500 passengers (Massachusetts Bay Transportation Authority, 2014b).

From its current terminal in Brighton Center, the route could easily continue north to the Arsenal and Watertown Malls, which are across the street from each other. This area has a lot of retail and is a growing commercial center, with a Target, a Home Depot, and the Arsenal on the Charles development which houses the headquarters of athenahealth. Several retail and commercial developments are in the planning stages, and athenahealth is adding employees (Breitrose, 2015; Reiss, 2015b; Wallack and Weisman, 2013). The Arsenal on the Charles runs shuttles to Harvard Square and Back Bay for tenants (The Arsenal on the Charles, 2015), and local leaders are considering the creation of a transportation management association with the goal of providing public shuttle service to supplement the existing MBTA bus routes, including shuttles to Longwood Medical Area (Reiss, 2015a). The planning process proposed in this thesis would likely identify Arsenal as a location in need of analysis within the next few years, so being able to improve access to Arsenal as part of the Longwood planning process is a worthwhile secondary goal. Serving Arsenal would connect the 65 with the heavily used 70 and 70A routes along Arsenal Street.

There are two ways that a bus could get from Brighton Center to Arsenal. The first is to turn right from Washington Street and take Market Street, which is already served by the 86, then turn left on Arsenal Street. The other is to turn right from Washington Street onto Parsons Street and follow it to the Charles River, then go around the traffic circle and over the river on North Beacon Street, and turn right on Greenough Boulevard behind the Arsenal Mall. The route could then turn left onto Arsenal Street. If the route were to end at this point, there are a variety of possible turnaround and layover points surrounding the two malls. In the future, development may alter the street configuration around the Arsenal Mall, potentially enabling a more direct path through the Arsenal Mall area. See Figure 6-3 for a map of these options.

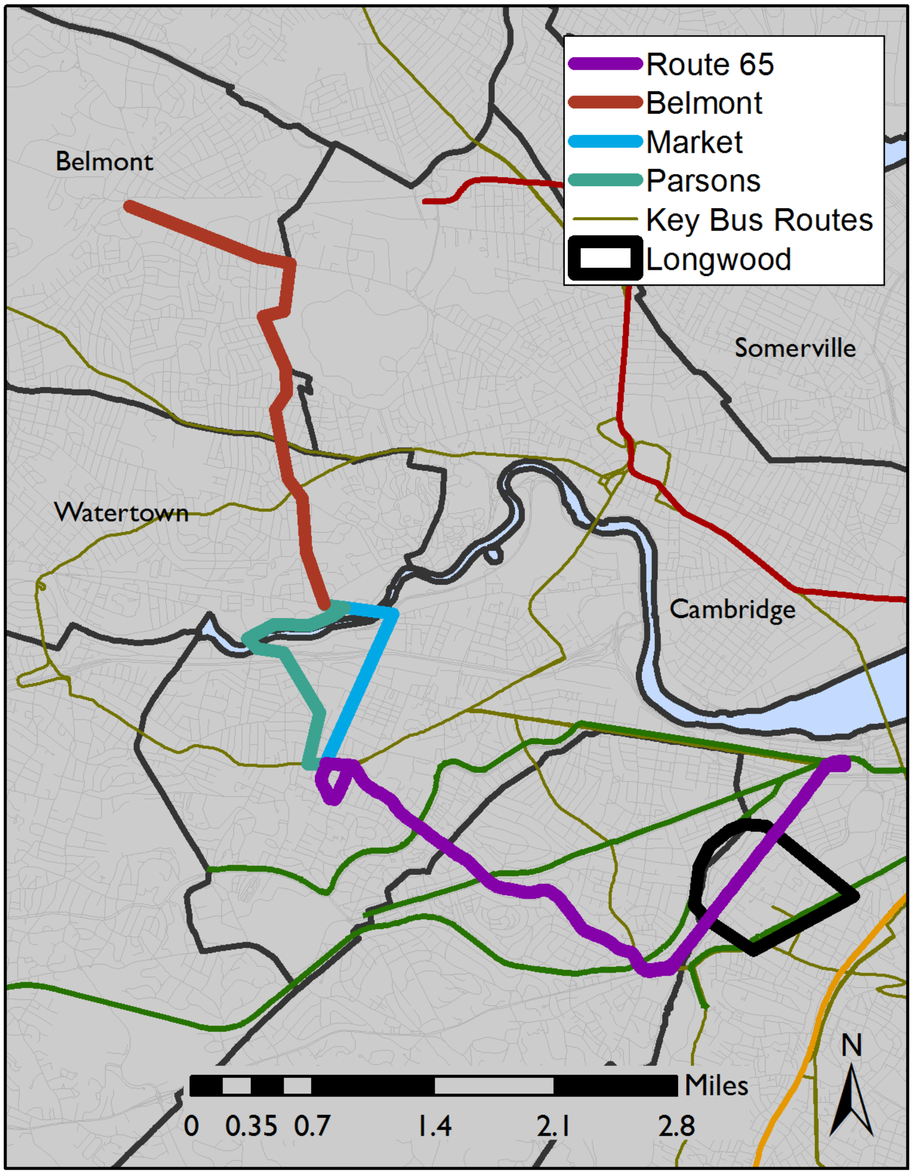


Figure 6-3: Possible alignments for an extension of route 65

While this route extension is a good option, it is quite short. To extend the route further to the northwest, a bus would have to take one of the main streets through Watertown, such as Arlington (either directly from Arsenal or via Elm Street alongside the mall), School, or Common. Of these, Arlington Street is the widest and least residential, making it the best option for introducing a new bus route. Arlington Street continues as Grove Street north, intersecting the 71 and 73, then intersects route 75 and turns into Blanchard Road. A logical end point for a route in this area is the Belmont commuter rail station, since it already serves as a terminal for the 74 and 75. To reach the station, the extended 65 would turn left from Blanchard Street onto Concord Avenue.

This extended route serves an area that is almost entirely unserved by north-south service; service in the area generally runs east-west and feeds the Harvard Square and Central Square Red Line stations in Cambridge. The extended route would serve as a circumferential connector of several bus routes, including the 71 and 73, which are Key Bus Routes. It also connects the important residential areas of Belmont and Watertown to Longwood, providing a one-seat ride instead of what is often a multi-transfer journey in the current network.

This section will examine both the Parsons and Market Street routing options, along with the further extension to Belmont. As with the analysis of the CT4 in Section 6.1, the effect on existing journeys that both start and end on the proposed route will be considered, followed by an examination of those journeys that could use the extended route as one stage in a longer journey. A brief exploration of a method for estimating latent demand is also included.

6.2.1 Passengers Traveling Within the Extended Route

As with the analysis of the CT4 in Section 6.1.1, the first step is to look at the journeys that both start and end on the proposed route. Since this is a route extension rather than an entirely new route, only journeys that would use the extended portion of the route are included here; if these journeys used the route, they would be an incremental addition to the existing route ridership.

These journeys fall into several categories, as summarized in Table 6.7. Some journeys are bus-only, either using a single stage or multiple stages. Others use a combination of bus and rail, for example taking route 70 to the Red Line, then transferring to the Green Line to one of the stops on the route. The route extension does not serve any light or heavy rail stations, so there are no journeys in the analysis that use only rail. As with the CT4 analysis, both 100 meter and 500 meter buffers were used around the route.

There are a few important observations about these results. There are more journeys right along the Market Street option, within 100 meters of the route extension, than along the Parsons route. Given that the 86 bus runs along the Market Street section and the Parsons Street section travels largely on streets not currently served by any route, this is not surprising. What is more surprising is how many more journeys there are within 500 meters of the Parsons route than within that distance of the Market Street route. Upon closer examination, the 500 meter buffer around the Parsons option includes some stops of route 57 that are not included in the other buffers, so these figures include some journeys on the 57. These journeys are not likely to use the less-frequent, less-direct 65 to travel to Kenmore instead of the 57, which is a Key Bus Route.

Another observation is that the Belmont addition, though longer, adds relatively few journeys in most categories. It does show a fair number of single-stage bus

Table 6.7: Average daily scaled ODX journeys starting and ending on the proposed extended route 65, October 2014

	100m Buffer			500m Buffer		
	1-Stage Bus	Multi-Stage Bus	Bus and Rail	1-Stage Bus	Multi-Stage Bus	Bus and Rail
Parsons Street	2	0	0	276	50	4
Market Street	28	10	1	52	37	4
Belmont via Parsons Street	2	4	2	747	57	17
Belmont via Market Street	30	12	4	523	44	18

journeys that would be able to use the extended route, which is unexpected given that no route currently travels the path of the proposed extension. Closer examination reveals that many of these journeys are very short trips, within the 500 meter buffer, on routes 71 and 73. As described in Section 2.8, these two routes are unique in the MBTA system because they typically require riders to tap as they alight on outbound trips, rather than when they board. This leads to incorrect origin and destination location inference on these trips, with the inferred origin typically very close to the actual destination where the tap occurred. These journeys are also unlikely to switch to the extended route. This limitation also means that transfers to the 71 and 73 from other routes may not be properly inferred, so any journeys from Longwood to Watertown, such as those via the 66 and 71, are likely to be undercounted.

The Green Line data limitations described in Section 2.8 also affect these results. Boardings at Kenmore are likely to be properly inferred, but those at other stations along the 65 are not. This means the bus-to-rail figures listed in Table 6.7 are likely to be underestimates.

The data in Table 6.7 also suggest that the 100 meter buffer is too small for this analysis. Unlike the CT4, where many passengers already had somewhat similar service available for at least part of their journey, most of the proposed route extension travels along streets with no current service. In this case, the larger buffer may give a more accurate sense of how many riders will be affected, since passengers are more likely to walk a short distance to access a service that is very different from what is currently available because it may be a significant improvement over the alternatives available for that trip. The 500 meter buffer will therefore be used in the remainder of this analysis.

Given all these factors, the estimate of how many passengers would benefit from the extension will be rough. Approximations based on the data in Table 6.7 and the factors discussed in the preceding paragraphs will be used for the remainder of this analysis for simplicity. The estimates chosen are 75 daily passengers benefiting from the Parsons extension, 100 benefiting from the Market extension, and 150 from the Belmont extension (taking either path to Arsenal).

Figures for the weekday morning peak only are presented in Table 6.8. For this period, the approximations are that about 15 passengers are estimated to benefit from the Parsons extension, 10 from the Market extension, and 25 from the extension to Belmont.

Table 6.8: Average scaled ODX journeys per hour during the weekday morning peak starting and ending on the proposed extended route 65, October 2014

	100m Buffer			500m Buffer		
	1-Stage Bus	Multi-Stage Bus	Bus and Rail	1-Stage Bus	Multi-Stage Bus	Bus and Rail
Parsons Street	0	0	0	38	9	1
Market Street	2	2	0	3	6	1
Belmont via Parsons Street	0	1	0	87	11	4
Belmont via Market Street	2	3	1	52	7	4

6.2.2 Other Passengers Benefiting from Proposed Extension

Journeys that both start and end on the route are not the only ones that have the potential to be affected by the proposed route extension. The methods used to calculate the network effects of the CT2 and CT4 proposals in Section 6.1.2 are applied here, though the circumstances of the route 65 extension require some modifications. Only those journeys that are affected by the extension itself are considered; journeys that could use the 65 without the extension are not included. There are no rail-to-rail journeys to consider, therefore, since the extension does not cross any rail lines. This also means that, unlike with the CT2, there is no need to consider which journeys are already using the route. Aside from a brief stretch of Market Street that is shared with the 86, the extension does not have any overlapping service, further simplifying the calculations.

The results are presented in Table 6.9. Here the additional journeys affected by continuing the extension to Belmont are much more significant, which makes sense given how many well-used bus routes the extension crosses.

Table 6.9: Average affected daily scaled two-stage ODX journeys starting or ending on the proposed extended route 65, October 2014

	Bus	Bus and Rail	Total
Parsons Street	75	70	144
Market Street	64	78	142
Belmont via Parsons Street	95	126	221
Belmont via Market Street	85	134	219

There are two other components to the network analysis that did not need to be addressed for the CT4. The first is journeys of more than two stages. There were relatively few of these journeys affected by the introduction of the CT4, and with so many overlapping routes it would be difficult to identify those that would benefit. With the route 65 extension, however, these journeys make up a larger portion of the total, and since the extension passes through an area that is more sparsely served, it is possible to identify the beneficiaries using the same intersection methods used above. Journeys that pass through the extended route multiple times but only have one stop on it are assumed to have the potential to save time using the newly extended route. The results of this analysis can be seen in Table 6.10.

Table 6.10: Average affected daily scaled ODX journeys of three or more stages starting or ending on the proposed extended route 65, October 2014

	Bus	Bus and Rail	Total
Parsons Street	20	54	73
Market Street	17	59	76
Belmont via Parsons Street	28	115	143
Belmont via Market Street	25	120	146

The other journeys that must be considered are those using two routes that cross over the extended route 65 but which are not identified as type C or D using the methods from Section 6.1.2. In contrast to the CT4, where most routes terminated at the point where they intersected the CT4, 20 different routes pass through the extended 65 and continue. A passenger who takes the 71 to Harvard Square from a point in between the extended route and Harvard and then takes the 86 back out to Brighton Center, therefore, might be able to save time by taking the 71 outbound instead, transferring to the extended route 65 to Brighton as shown in Figure 6-4. Whether a given journey would save time using the extended 65 depends on the distances traveled, but it is difficult to accurately calculate distances in this case because many of the relevant journeys use the 71 and 73 and therefore have poor location information for the reasons described in Section 6.2.1. The number of journeys that would save time is therefore approximated for the purposes of this analysis, and is estimated at a quarter of the total number of journeys of this type. These journeys are found using the intersection methods described above; the relevant trips are two-stage journeys that intersect the route once, with one stop on the route, and where both stages are on routes that intersect the extended 65. These journeys are presented in Table 6.11.

The results for the weekday morning peak hour are presented in Tables 6.12, 6.13, and 6.14. These figures are important both because the weekday morning peak hour is when the system is closest to capacity, and also because most routes run most frequently during the peaks. Therefore, the peak gives the best sense of the structural benefits of the proposed route extension, without complicating factors such as the different spans of service of different routes.

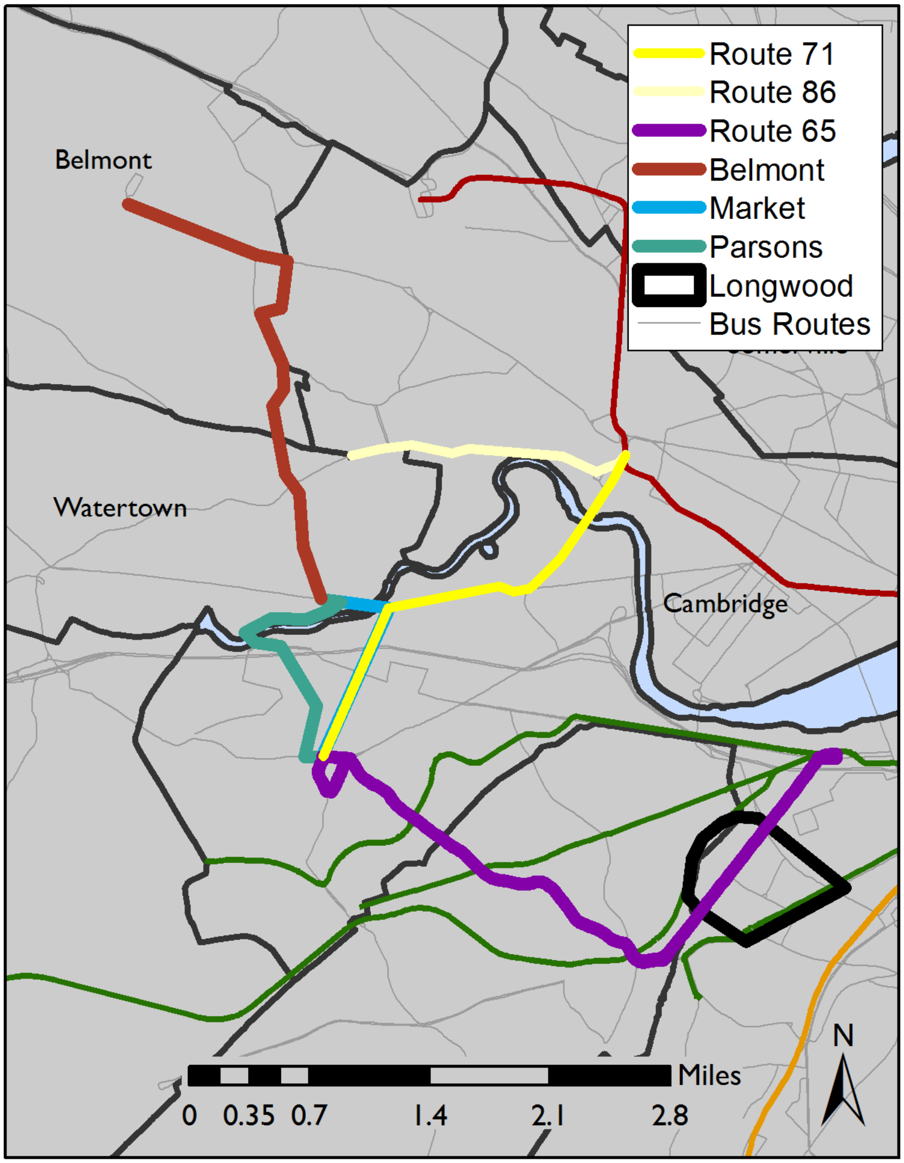


Figure 6-4: Example of journey using two routes intersecting the proposed extended route 65: route 71 to route 86, transferring at Harvard Square

Table 6.11: Average affected daily scaled ODX journeys using routes intersecting the proposed extended route 65, October 2014

	Total	Estimated Affected
Parsons Street	330	83
Market Street	273	68
Belmont via Parsons Street	344	86
Belmont via Market Street	286	72

Table 6.12: Average affected scaled two-stage ODX journeys per hour during the weekday morning peak starting or ending on the proposed extended route 65, October 2014

	Bus	Bus and Rail	Total
Parsons Street	7	8	15
Market Street	5	8	13
Belmont via Parsons Street	9	15	25
Belmont via Market Street	7	16	23

Table 6.13: Average affected scaled ODX journeys per hour of three or more stages during the weekday morning peak starting or ending on the proposed extended route 65, October 2014

	Bus	Bus and Rail	Total
Parsons Street	1	5	7
Market Street	1	6	6
Belmont via Parsons Street	2	14	16
Belmont via Market Street	2	14	16

Table 6.14: Average affected scaled ODX journeys per hour during the weekday morning peak using routes intersecting the proposed extended route 65, October 2014

	Total	Estimated Affected
Parsons Street	41	10
Market Street	31	8
Belmont via Parsons Street	40	10
Belmont via Market Street	30	7

6.2.3 Latent Demand

Since the proposed extension is quite different from other routes in the area and serves an area where transit service is relatively sparse, latent or induced demand from travelers switching modes or deciding to make new trips is an important factor. Rosen's direct demand model provides a means of estimating the number of new riders as a function of the increase in the number of bus trips to each stop (Rosen, 2013). The other variables in the model are households with vehicles, households without vehicles, workers, income per capita, distance from the central business district, and rail feeder trips. Rosen's model is at the stop level, with the household and other figures allocated to each stop. Recreating this stop-level model with current ODX ridership data is beyond the scope of this research, but it is fairly simple to replicate the model at the census tract level. Households with and without vehicles and median household income for each census tract in the region were obtained from the American Community Survey 2012 5-year estimates, scheduled weekday bus trips and rail trips were calculated from the published GTFS schedules, distance to the central business district was calculated from the centroid of each census tract, employment was obtained from the Census Transportation Planning Products Program, and average weekday bus boardings in October 2014 were used for bus ridership. As with Rosen's model, the best fit was a log-log regression model. The results of this regression are shown in Table 6.15. The model coefficients are broadly similar to Rosen's and all are significant at the 0.05 level or better, with a very high R-squared value. Reconfiguring the stop-level model at the tract level appears to produce a workable model.

Table 6.15: Census tract level direct demand model regression results (dependent variable is log of daily ridership)

	Coefficient	Std. Error	t-Statistic	Significance
Households with vehicles	0.642	0.118	5.430	***
Households without vehicles	0.134	0.048	2.793	**
Employment	-0.270	0.116	-2.330	*
Median Household Income	-0.251	0.055	-4.589	***
Distance to CBD (m)	-0.159	0.036	-4.491	***
Bus Trips	1.244	0.039	31.675	***
Rail Trips	0.054	0.025	2.186	*

Summary Statistics
Adjusted R-Squared = 0.975
N = 499
Significance codes: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

By considering the additional trips to the nine census tracts that the extension will serve, the model can be use to predict the additional ridership that will be generated by the extension. As in Rosen's work, an adjustment factor was applied to each census tract to account for the difference between the model output and the actual ridership. The model predicts that extending route 65 to Belmont at the current service frequency would lead to an increase of about 370 passengers per weekday. However, this estimate is likely to be too low. The model would predict the same results for increased frequency on an existing route as it does for the additional trips of implementing this newly extended route, while these two types of service changes may have quite different impacts. Currently, traveling to Longwood or Kenmore from Watertown requires at least one transfer and a circuitous path, so it is safe to assume that many people who have the option choose to drive instead of taking transit. Since the extended 65 is very different than the existing routes and would provide a particularly important new connection, the model's estimate is likely to be conservative.

6.2.4 Overall Impact of Route 65 Extension

The net impact of the route 65 extension is summarized in Tables 6.16 and 6.17. The total number of journeys affected is divided by the number of round trips the 65 currently makes during that period (36 trips per day, and 5 trips per hour in the morning peak) in order to approximate the number of passengers who might begin using the route in the peak direction. Depending on the time period and route alignment, somewhere between 7 and 27 additional passengers per trip would benefit from using the extended route 65 instead of their current path through the network. The greatest benefit is naturally generated by extending the route all the way to Belmont, though significant benefits are seen from the shorter extensions to the Arsenal area of Watertown. The difference between the Parsons Street and Market Street alignments is not significant.

Table 6.16: Average daily scaled ODX journeys affected by proposed route 65 extension, October 2014

	Within Route	Network: 2 Stage	Network: 3+ Stage	Network: Inter-secting Routes	Latent Demand	Total	Per Round Trip
Parsons Street	75	144	73	83	N/A	375	10
Market Street	100	142	76	68	N/A	386	11
Belmont via Parsons Street	150	221	143	86	370	970	27
Belmont via Market Street	150	219	146	72	370	957	27

Table 6.17: Average scaled ODX journeys per hour during the weekday morning peak affected by proposed route 65 extension, October 2014

	Within Route	Network: 2 Stage	Network: 3+ Stage	Network: Intersecting Routes	Latent Demand	Total	Per Round Trip
Parsons Street	15	15	7	10	N/A	47	9
Market Street	10	13	6	8	N/A	37	7
Belmont via Parsons Street	25	25	16	10	N/A	76	15
Belmont via Market Street	25	23	16	7	N/A	71	14

These figures are relatively rough estimates, given the data limitations described in the previous sections. However, they provide a sense of the order of magnitude of the benefits. The additional daily ridership could be a nearly 25% increase over present day from passengers who already use transit switching to the extended 65, and a nearly 40% total increase including a conservative estimate of latent demand. This demand would be sufficient to justify increased service levels on the route. Travelers take time to begin using a new service, so the figures presented in the first four columns of Tables 6.16 and 6.17 provide an estimate of the ridership that would be likely to use the service early on, since doing so would not require switching mode.

6.2.5 Implementation

In order to determine the best means of implementing the proposal, costs must be considered. Since no route currently runs along most of the proposed extension, cycle time must be estimated as shown in Table 6.18. The times in the table are taken from the free-flow driving times from Google Maps, multiplied by 1.5 for off peak and by two for peak to account for dwell time, traffic congestion, and the increase in required layover time. If current headways are maintained, the route extension to Arsenal requires three buses in the peak and only one additional bus in the off-peak period, while the full extension to Belmont requires six buses in the peak and two in the off peak.

There are a variety of possible alignments for the route. The Parsons and Market alternatives are the most obvious, but the route could also take Market Street from Brighton Center and then turn left on Faneuil Street to serve the Faneuil Gardens housing complex and the small commercial center near the Faneuil Street Market.

Table 6.18: Estimated cycle times and vehicle needs for proposed route 65 extension

	Extension to Arsenal		Extension to Belmont	
	Peak	Off Peak	Peak	Off Peak
Current headway	12	35	12	35
Current cycle time (min)	72	70	72	70
Current vehicles	6	2	6	2
Additional time for extension	30	23	64	48
New cycle time (min)	102	93	136	118
Vehicles required	9	3	12	4
Additional vehicles	3	1	6	2

The route would then turn right up Brooks Street to cross the Charles River. In the Arsenal area, the route could turn on Arlington Street directly, or could take Elm Street to provide service closer to Target and other retail establishments. The final routing depends on operational concerns such as street width and locations for bus stops as well as community preferences.

The full route extension could be implemented immediately, or the extension could be phased in by first running to Arsenal and then extending to Belmont at a later date, or by running to Belmont during the off peak and every other trip during the peak. The initial route extension could operate at the same frequencies as the current route, though additional service is likely to become necessary as ridership increases. The route from Brighton Center to Belmont could be contracted out to be run with minibuses for a period of time, in order to build ridership at lower cost. Planners could also consider options for entirely new routes that serve the demand that this analysis has shown in the extension area, perhaps running from Ruggles through Longwood to Brighton Center and on to Belmont. This would require more resources than simply extending the existing route, but as a new route it could potentially be contracted out rather than using any additional buses from the MBTA fleet. A variety of options for a contracted new route could be considered, including a path from Longwood to Arsenal that serves the planned Boston Landing commuter rail station in Allston and the nearby New Balance offices, rather than passing through Brighton Center. Such a route could also serve Coolidge Corner, rather than taking the current path of route 65 along Washington Street. Any of these options might be feasible for the initial implementation. Over time, the projected ridership growth on the route of nearly 40% will likely require increased frequency to accommodate the increased ridership.

Given the data limitations in this case study, the route 65 extension provides an excellent opportunity for an ex post facto analysis in the months after the service is introduced. ODX data will be collected on an ongoing basis in the future, so a detailed before and after comparison of travel patterns from Watertown and Belmont could be completed. In addition, the new version of ODX will soon provide more accurate and comprehensive Green Line data, which could enhance the current analysis and provide more detail for an ex post facto review.

6.3 Connecting Roxbury, Dorchester, and Mattapan to Longwood

The analysis in Section 5.4 identified access to the Longwood Medical Area and other parts of the city to the northwest as a significant challenge for the RDM study area. A new bus route in this area would probably not be necessary given the current density of existing routes that terminate at or near Ruggles Station on the Orange Line, which is 0.5 - 1.0 miles from many of the hospitals and clinics at Longwood. Therefore, this section will examine possibilities for extending one of these existing candidate routes to serve Longwood.

Several routes pass through the study area and terminate not far from Longwood, as shown in Figure 6-5. The first is route 22, which begins at the Ashmont Red Line Station, crosses the study area, then intersects the Orange Line at Jackson Square and continues north through Roxbury Crossing to Ruggles Station. The second route is the 23, which also begins at Ashmont but turns north along Warren Street to pass through Dudley Square before continuing to Roxbury Crossing and Ruggles. The 28 begins at the Mattapan Red Line station and heads north on Blue Hill Avenue, then joins the 23 on Blue Hill Avenue to serve Dudley, Roxbury Crossing, and Ruggles Stations. Finally, the 29 starts at Mattapan Station and follows the path of the 28 before turning left on Seaver Street to Jackson Square Station. During most times of the day, the route terminates at Jackson Square; after 8 p.m. it continues north through Roxbury Crossing to Ruggles.

The 23 and 28 are Key Bus Routes, and have some of the heaviest ridership in the system. As mentioned in Section 5.4, a 2009 proposal to upgrade the routes to BRT was withdrawn after being met with opposition from the local community, so altering these routes would require an especially careful and inclusive community planning process. The type of analysis shown here would provide useful information for planners to use in such community engagement efforts.

The Roxbury-Dorchester-Mattapan Transit Needs Study highlights the need for better connections for RDM passengers to Longwood (Massachusetts Department of Transportation, 2012). The Study proposes rerouting route 28 so that it would pass through Roxbury Crossing and continue on to the Brigham Circle Green Line station, at the southern corner of the Longwood Medical Area. The Study notes that passengers currently transferring to the Orange Line at Ruggles would be able to make the same transfer at Roxbury Crossing, but does not address the bus-to-bus transfers made at Ruggles or consider other options for a connection to Longwood. It concludes that detailed study of the proposal would be required.

This analysis will consider all four of the routes listed above to see whether extending route 28 is, in fact, the best option. However, it will consider a different extension than that suggested by the Transit Needs Study. The Study's choice of Brigham Circle as a final destination was due to congestion closer to the heart of Longwood, but major destinations such as Beth Israel Deaconess Medical Center are over half a mile from Brigham Circle. The limited length of the extension also misses the opportunity to increase currently limited circumferential connections in the area. By extending

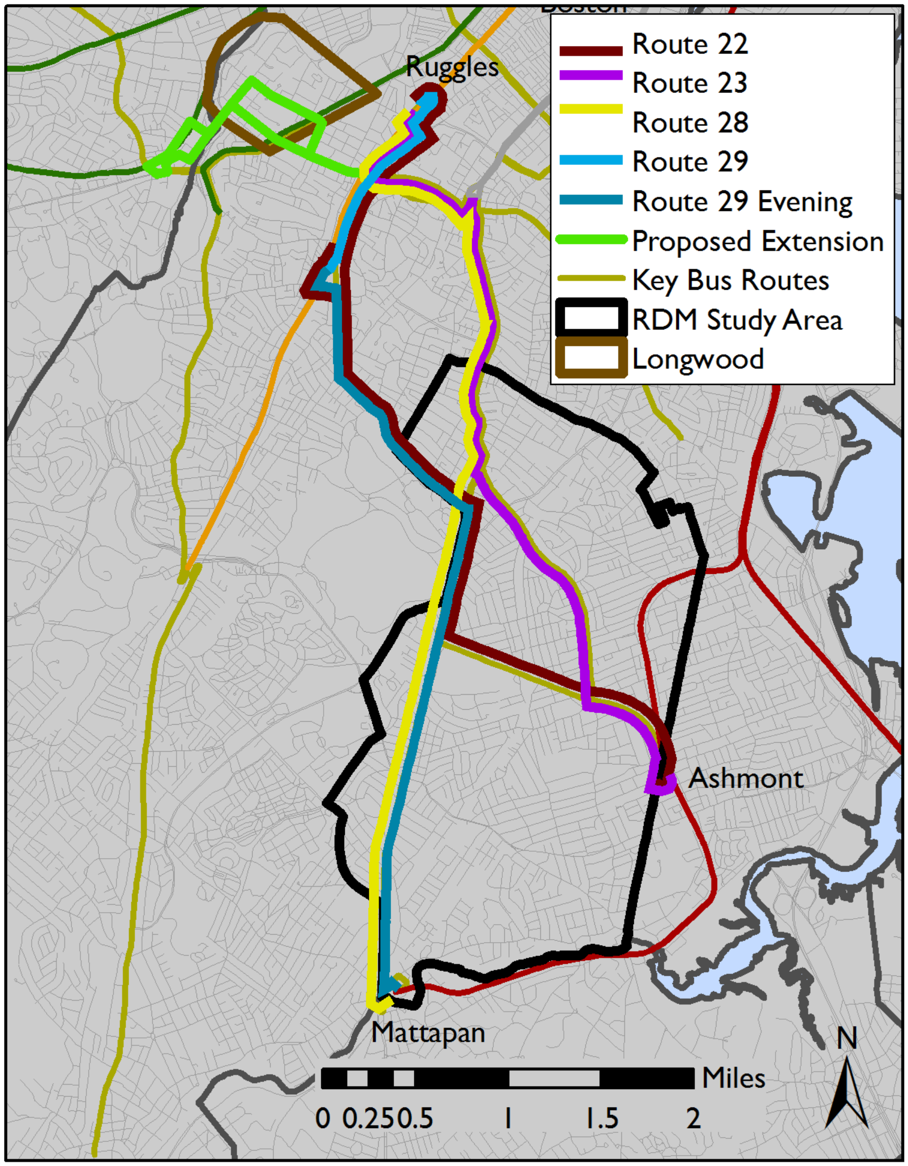


Figure 6-5: Routes serving the RDM study area with a proposed extension to Longwood

a route through Longwood a short distance to intersect the D branch of the Green Line, the extension can not only improve access for those from the RDM study area but can also improve access to Longwood and the Orange Line from Brookline and Newton.

This analysis, therefore, will consider a route extension that follows the path shown in Figure 6-5. The proposed extension passes through Roxbury Crossing, continues along Tremont Street and turns right on St. Alphonsus Street, then left on Longwood Avenue through the heart of Longwood. The route then turns left onto Brookline Avenue and continues for about 7/10ths of a mile to the Brookline Village station on the D branch of the Green Line. The route can either serve the station at Pearl Street and return back up Brookline Avenue, or it can cross over the Green Line at Washington Street, turn right on Station Street (which turns into Kent Street) and then turn right onto Aspinwall Avenue to return to Brookline Avenue. The preferred option depends on operational considerations such as layover space and signal timing, but the difference is negligible from the point of view of this ridership analysis. The route could return to Roxbury Crossing via Francis Street and Tremont Street to reduce the time lost to traffic congestion on Longwood Avenue.

As with the previous proposals presented in this chapter, there are several components to the analysis. Unlike the previous proposals, in this case there are some existing riders of the candidate routes who may be negatively affected by the route change; an examination of the effects on these riders will be presented first. Then, existing passengers who would be able to convert to a single-seat ride under the proposal will be considered, followed by a look at those riders who would be likely to use the newly extended route as part of a faster two-stage journey. Due to the density of transit service in the area, latent demand is less likely to be a significant factor than in the prior case studies and will not be included here.

6.3.1 Effect on Existing Passengers

Passengers who currently board or alight north of Roxbury Crossing on any of the four candidate routes must be considered to properly assess the impact of the proposal. There can be several different types of passenger responses to a change in the existing routing:

- Some passengers may be able to switch to a different route that serves the same stops. These passengers may experience increased waiting time due to no longer being able to take their current route. Some might also experience increased travel times, depending on the particular paths of the routes being considered. Some of these passengers may also have the option of continuing to use the same (extended) route but might change transfer locations or walk farther to access the route.

- Passengers whose initial origin or ultimate destination is at Ruggles, or between Ruggles and Roxbury Crossing, will have to either add a transfer or walk further to access transit. These passengers will be negatively affected by the proposal to varying degrees.

- As the Transit Needs Study points out, some passengers who are transferring to the Orange Line or to other bus routes may be able to make the same transfer in a different location, typically either Roxbury Crossing or Dudley Square, that would still be served by the extended route. These passengers will experience little to no increase in travel time. They have chosen to transfer at Ruggles rather than Roxbury Crossing or Dudley Square, however, so they may consider Ruggles to be preferable to the other options in some way, perhaps related to station layout or amenities. These passengers may experience a small negative effect from being forced to transfer at a less preferable location, particularly since there are only a few curbside shelters at Roxbury Crossing as compared to the large bus station at Ruggles.

- Passengers who currently transfer to routes CT2, CT3, or 43, which all originate at Ruggles, will no longer have this transfer available and will be significantly inconvenienced. The handful of passengers who walk from Ruggles to route 39 will also have a poorer connection. Similarly, passengers who use route 22 or evening service on route 29 to transfer at Ruggles to the 8, 19, or 47 would no longer have this transfer option (passengers on the 23 or 28 could still transfer to these routes at Dudley Square). However, since all of these routes serve Longwood, some of these passengers would benefit from being able to take the proposed extended route directly to their destinations and not be forced to transfer at all. Those whose destination is not served by the extended route may require an extra transfer and would likely experience a significant negative impact from the proposal.

The number of passengers whose boarding is affected in the first three ways is shown in Tables 6.19 through 6.22, for each candidate route in turn. The number of passengers affected by the final item on the list, that of the transfer no longer being served, is minimal: the average daily number of passengers affected by these bus-to-bus transfers is 64 for route 22, 24 for each of routes 23 and 28, and only 5 for route 29. In all cases at least two-thirds of this small number of affected trips have a different route available that serves the origin and destination. These journeys will therefore not be presented in the tables below in order to simplify the analysis.

Only boarding locations are considered here due to the difficulties of working with inferred destinations. If a similar analysis were performed for destinations, appropriate scaling would be difficult since inference rates vary across these types of trips. A destination is more likely to be inferred when the trip is followed by a transfer to another route, and less likely to be inferred when the trip concludes with a walk to the passenger's destination. In order to account for these scaling difficulties, only boardings will be analyzed here, and the number of affected destinations in each category will be assumed to be the same since travel behavior over the course of the day is generally fairly symmetrical. For the weekday morning peak hour, the number of affected destinations will likely be higher than the affected origins since so many trips in the morning peak are northbound. Figure 5-14, part of the initial analysis of the RDM study area, shows that the number of trips leaving the study area is roughly

Table 6.19: Route 22 scaled passenger boardings affected by proposed rerouting to Longwood, October 2014

	Average Daily		A.M. Peak Hourly	
	No other route available	Other route available	No other route available	Other route available
Average daily trips on route	5,576		N/A	
MBTA reported typical weekday trips	8,656		N/A	
Change transfer location	39	136	0	3
Origin no longer served	91	388	3	12
Not affected	4,843		394	

Table 6.20: Route 23 scaled passenger boardings affected by proposed rerouting to Longwood, October 2014

	Average Daily		A.M. Peak Hourly	
	No other route available	Other route available	No other route available	Other route available
Average daily trips on route	8,266		N/A	
MBTA reported typical weekday trips	12,527		N/A	
Change transfer location	90	314	5	16
Origin no longer served	169	590	6	40
Not affected	7,071		636	

Table 6.21: Route 28 scaled passenger boardings affected by proposed rerouting to Longwood, October 2014

	Average Daily		A.M. Peak Hourly	
	No other route available	Other route available	No other route available	Other route available
Average daily trips on route	8,584		N/A	
MBTA reported typical weekday trips	14,057		N/A	
Change transfer location	111	275	3	13
Origin no longer served	311	674	7	34
Not affected	7,127		530	

Table 6.22: Route 29 scaled passenger boardings affected by proposed rerouting to Longwood, October 2014

	Average Daily		A.M. Peak Hourly	
	No other route available	Other route available	No other route available	Other route available
Average daily trips on route	1,342		N/A	
MBTA reported typical weekday trips	2,178		N/A	
Change transfer location	0	18	0	0
Origin no longer served	0	47	0	0
Not affected	1,269		153	

twice the number entering during the weekday morning peak period. Therefore, the number of affected destinations will be assumed to be double the number of affected origins for this time period.

The first thing to notice is that the number of daily trips on each route in ODX is significantly lower than reported by the MBTA (Massachusetts Bay Transportation Authority, 2014b). This is likely due to two factors. One is that the MBTA reports a "typical" weekday, likely based on APC data and infrequent manual counts, while the ODX average is more comprehensive and includes weekends and holidays. Given the findings of Section 3.6 that a large proportion of trips occur on weekends and during other off-peak periods, these more comprehensive averages are appropriate for this analysis. The other factor is that relatively low farebox interaction rates have been reported on at least some of these candidate routes (Massachusetts Executive Office of Transportation, 2009). Some of this may be outright fare evasion, although on these routes passengers with passes are sometimes allowed or even encouraged to board crowded buses through the rear doors without tapping at the farebox in order to expedite boarding and even out passenger loads in the vehicle.

About 13% of the boardings on route 22, 14% of the boardings on route 23, 16% of the boardings on route 28, and 5% of the daily boardings on route 29 are affected in some way. Route 29 has the fewest total passengers and lowest percentage of passengers affected, both because it is generally a lower-frequency and lower-ridership service than the other routes and because it only serves the stops from Roxbury Crossing to Ruggles during the evening period.

Assuming that the percentage of trips with affected destinations over the course of the day is similar, the total proportion of affected trips is about double these percentages. The largest group of affected passengers is not those transferring to another route or to the Orange Line, but those whose initial origin or final destination is at Ruggles, north of Roxbury Crossing. In all cases, however, at least two-thirds of these passengers have another route option available. The second-largest group is those who would have to change transfer location. As mentioned above, only small numbers of passengers would no longer be able to make their transfer, have no alternative route available serving their trip, and not be able to use the proposed extended route (the actual numbers are 10 passengers per day or fewer, depending on the route). The small group of riders who would be unable to make their current transfer but would be able to use the extended route to Longwood would benefit from the proposal; these journeys will be captured by the analysis in Section 6.3.3.

The number of passengers who would experience significant negative effects is small, so it is unlikely that choosing any of these routes to serve Longwood would cause more than a negligible number of passengers to stop using transit. However, some passengers would be predicted to shift to a different route for their journey. There is no simple way to know exactly how many passengers would use a different route, so this analysis will use a range of estimates. The low end of the range will be 50% of those affected boardings and estimated alightings that have an alternative route available and who cannot simply transfer in a different location or take the new route to Longwood. The high end will be 75% of those boardings and alightings that have an alternative route available but cannot take the new route to Longwood or would have to change their transfer location. Not all passengers can be expected to make the change given the differing frequencies and schedules among the routes, and the estimate levels are selected to reflect that. See Tables 6.23 and 6.24 for these ranges.

Table 6.23: Estimated daily passengers switching routes due to each candidate route extension to Longwood, October 2014

	Low estimate	High estimate
Route 22	423	838
Route 23	606	1,380
Route 28	689	1,446
Route 29	51	103

Table 6.24: Estimated passengers per hour switching routes during the weekday morning peak due to each candidate route extension to Longwood, October 2014

	Low estimate	High estimate
Route 22	20	38
Route 23	63	130
Route 28	53	108
Route 29	0	0

6.3.2 Passengers Traveling Within the Extended Routes

The second component of the analysis is the journeys that may be able to use an extended route for a faster and better single-stage journey instead of the current multi-stage journey that may or may not include the current route. The results, calculated using the same methods described in Sections 6.1.1 and 6.2.1 above, are presented in Table 6.25.

Table 6.25: Average daily scaled ODX journeys starting and ending on the candidate routes extended to Longwood, October 2014

		Route 22	Route 23	Route 28	Route 29
100m buffer	1-stage bus	100	379	378	100
	Multi-stage bus	126	192	232	164
	Multi-stage rail	49	32	27	44
	Multi-stage bus and rail	24	6	7	25
500m buffer	1-stage bus	232	648	633	230
	Multi-stage bus	240	378	464	329
	Multi-stage rail	104	58	47	93
	Multi-stage bus and rail	53	16	18	54

The existing single-stage bus journeys that would be able to use the newly extended route mostly begin or end at Roxbury Crossing or Dudley Square on routes 8, 19, 47, or 66. Since routes 23 and 28 serve Dudley Square but routes 22 and 29 do not, more of these journeys would be able to use an extended route 23 or 28. These passengers would benefit from the reduced waiting time that would result from having another route serve the same stops. The multi-stage journeys would have a larger benefit, since a single-stage option would now be available, eliminating a transfer and reducing travel time. The effects for multi-stage journeys are more similar across routes, with route 28 having the largest number of potential beneficiaries at both buffer distances.

The results for the weekday morning peak only are shown in Table 6.26. The pattern at the peak hour is similar to the all-day results.

Table 6.26: Average scaled ODX journeys per hour during the weekday morning peak starting and ending on the candidate routes extended to Longwood, October 2014

		Route 22	Route 23	Route 28	Route 29
100m buffer	1-stage bus	10	49	49	10
	Multi-stage bus	9	17	18	12
	Multi-stage rail	6	3	2	5
	Multi-stage bus and rail	2	0	1	3
500m buffer	1-stage bus	24	77	73	24
	Multi-stage bus	17	33	37	25
	Multi-stage rail	16	7	5	14
	Multi-stage bus and rail	6	1	3	7

6.3.3 Other Passengers Benefiting from Proposed Extension

The final component of the analysis is identifying those journeys that could use the extended candidate route as part of a longer journey and do not currently use the candidate route. This analysis was done using the method described in Sections 6.1.2 and 6.2.2 above on the CT4 and route 65 extension. Multi-stage journeys that start or end on the larger bus and rail network were identified, then the number of journey stages intersecting the extended route was calculated. The journeys that are of type D as defined in Section 6.1.2 are assumed to be able to save time by using the proposed route extension. As with the extension for route 65, this analysis was done using a 500 meter buffer around the routes. All journeys of more than one stage were considered, not just two-stage journeys. Only those journeys that could use the extension portion of the extended route were included in the results, which are presented in Table 6.27. The journeys on rail or using both bus and rail may be undercounted, as both the surface Green Line and the Mattapan trolley data in ODX is imperfect. The analysis of journeys using intersecting routes that was necessary for the route 65 extension analysis (see Figure 6-4) was not performed here, as the current route structure indicates that very few journeys would be affected in this way.

Table 6.27: Average daily scaled ODX journeys able to use candidate routes extended to Longwood as part of a longer network journey, October 2014

	Route 22	Route 23	Route 28	Route 29
Multi-stage bus	3	2	33	169
Multi-stage rail	112	155	153	110
Multi-stage bus and rail	17	27	102	117
Total	131	183	287	396

Extending route 29 provides the largest benefit for this component of the analysis, followed by route 28. Routes 22 and 23, which start at Ashmont rather than Mattapan, have somewhat lower benefits.

Results for the weekday morning peak are presented in Table 6.28. Again, extending the routes that begin at Mattapan provides greater benefits for this component of the analysis than extending those that begin in Ashmont.

Table 6.28: Average ODX journeys per hour during the weekday morning peak able to use candidate routes extended to Longwood as part of a longer network journey, October 2014

	Route 22	Route 23	Route 28	Route 29
Multi-stage bus	0.3	0.1	3.0	12.2
Multi-stage rail	25.3	34.5	35.3	25.0
Multi-stage bus and rail	0.2	3.4	13.5	12.7
Total	25.7	38.1	51.8	49.9

6.3.4 Overall Impact of Extending Candidate Routes to Longwood

To determine the overall impact of the proposal for each route, the different components of the analysis from the sections above were combined. The average of the low and high estimates for riders switching away from each route was used. The passengers who would benefit from a new single-stage journey were divided into those already using the route and those who would now switch to using the route. The net impact for each proposal is shown in Table 6.29. Extending service on route 29 clearly has the largest benefit with the least disruption to existing riders.

Table 6.29: Average daily scaled effect of candidate route extensions to Longwood, October 2014

	Route 22	Route 23	Route 28	Route 29
Passengers switching away from route	631	993	1,068	77
Existing route passengers benefiting from new 1-stage journey	103	158	119	10
New route passengers with 1-stage journey	294	294	410	466
New route passengers with multi-stage journey	131	183	287	396
Net effect on route ridership	-206	-516	-370	785

Extending either of the routes beginning at Mattapan would provide more benefit than extending one of those beginning at Ashmont. Routes 28 and 29 provide similar levels of benefit to riders who would have an improved option for getting to Longwood. However, only on route 29 does the benefit outweigh the level of disruption to existing passengers. This is due to the fact that there are many fewer passengers disrupted on route 29 than on any other option, since it would only be rerouted away from existing stops in the late evening. Extending route 29 is also a good option since as one of the less frequent routes under consideration, extending the route at current frequencies initially would cost the least and add the least bus traffic to the Longwood area. Extending a less-frequent route could help gauge the demand and the operational effects without adding unnecessary initial costs.

Extending the 29, however, will shift riders to the route and require a corresponding increase in service. Current ridership is about 1,300 passengers per day as seen in Table 6.22, so the extension to Longwood has the potential to increase ridership on the route by about 60% before accounting for any new riders who might be attracted to transit by the direct route option. This would require a significant increase in frequency, from the current irregular headways of 15 to 70 minutes to every 10 to 30 minutes depending on time of day.

Considering only the peak period, Table 6.30 shows the increase in passengers per hour during the weekday morning peak. While the net effect of extending route 22 or 28 is positive in the weekday morning peak hour, the results for route 29 are still significantly better. Buses on route 29 have a crowding standard of 55 passengers during the peak hour, so these figures support adding at least two trips per hour to bring headways down to every 10 to 12 minutes during the peak.

Table 6.30: Average effect per hour during the weekday morning peak of candidate route extensions to Longwood, October 2014

	Route 22	Route 23	Route 28	Route 29
Passengers switching away from route	29	97	81	0
Existing route passengers benefiting from new 1-stage journey	7	13	8	1
New route passengers with 1-stage journey	32	28	37	45
Passengers saving time on multi-stage journey	26	38	52	50
Net effect on route ridership	29	-31	9	95

Most of the increase in ridership on route 29 would come from riders switching from other routes, particularly route 22 and 28. Making route 29 a more attractive service by increasing the frequency and extending it to Longwood therefore provides an opportunity to reduce crowding on route 28, improving comfort and reliability on that route. Until significant improvements can be made to the route 28 corridor, such as dedicated bus lanes, finding ways to better balance the passenger loads among routes serving the same corridors is a good option for improving service for everyone in the area.

6.3.5 Implementation

As with the other proposals, it is important to consider the costs of extending route 29. Running times have been estimated based on the scheduled round-trip running time for the CT2 from Ruggles to Longwood, which should be similar to the time for the 29 to travel from Roxbury Crossing to Longwood, and for route 65 from Longwood to the Brookline Village Green Line station. A few minutes of extra layover time have been added due to the congestion the route is likely to experience in the Longwood area. The final off-peak estimate is about 1.5 times the uncongested driving time as estimated by Google Maps, which indicates that the estimate is reasonable. The estimates in Table 6.31 show that the extension would require an additional three vehicles in the peak periods, and an additional two vehicles off peak. The estimates for the off peak period are approximate, as the headways vary from 15 to 70 minutes depending on the time of day. The variants that serve Franklin Field Housing and that continue to Ruggles in the evening further complicate the calculations of current and projected vehicle requirement. These details of scheduling and vehicle requirements are beyond the scope of this thesis.

Table 6.31: Estimated cycle times and vehicle needs for proposed route 29 extension

	Peak	Off Peak
Current headway	16	20
Current cycle time (min)	64	60
Current vehicles	4	3
Additional time for extension	36	30
New cycle time (min)	100	90
Vehicles required	7	5
Additional vehicles	3	2

As discussed in the previous section, extending route 29 to Longwood would be expected to increase ridership on the route by 60%, enough to justify substantial increases in service. These increases in service would require additional resources beyond those shown in Table 6.31. Since most of this increase in ridership would be passengers switching from other routes, it may be possible to reallocate a small number of vehicles from one or more of these other routes. However, widespread crowding on buses throughout the RDM study area means that it would be preferable to use the route extension to increase the total amount of service to the area.

As described in Section 5.4, any proposal affecting the RDM study area requires a thoughtful community engagement process. Given the context of community opposition to the route 28X project, ensuring opportunities for input and modifying the proposal to address community concerns will be a key step of the implementation process.

6.4 Improving Access to the Seaport District

As mentioned in Section 5.5, the Seaport District is another important focus area for transportation analysis. Since the ODX data set is not currently sufficient for a true analysis due to the Silver Line data issues described in Section 2.8, proposals for improving service cannot be based on the kind of analysis described in this chapter. However, there are still possibilities for new routes to serve the area. These new routes would make excellent case studies for an ex-post review process, the fifth phase of the recommended service planning process, since the new iteration of ODX will become available to evaluate the effects of the new services.

With so many private shuttle routes, one significant improvement would be a consolidated service connecting major employers to key rail stations, particularly during peak hours. Such a consolidated service has already been proposed (A Better City, 2015); making the shuttle open to the public and including MBTA fareboxes would be required for the data to be included in ODX.

Another promising new route would begin at the Andrew Red Line station and serve the Seaport District via D Street, then continue into downtown Boston, likely to North Station. This would relieve some of the crowding on the Silver Line by adding another connection from the Red Line to the Seaport that might be more appealing to those traveling from the south. The route would also eliminate a transfer for those coming from the Roxbury, Dorchester, and Mattapan study area via the 16, 17, and 18 bus routes, providing much better access from a densely populated area to a key job center in the city.

6.5 Conclusion

The examples and case studies in this chapter demonstrate the methods for using ODX to evaluate service changes. The details of each application vary, sometimes significantly, but the general approach is similar. The effects of a proposal are broken down into several parts: the impact on existing riders, the identification of those who could use the route for a single-stage journey, the evaluation of the network effects, and consideration of latent demand. The network effects are the most complicated to calculate, but the impact of a proposal can be estimated by considering the ways that the paths of current passengers intersect the route.

The approach is not a precise formula, but rather a toolkit that service planners can apply when evaluating a service change. Detailed knowledge of the existing network and the surrounding areas are necessary to ensure that the methods are applied in the most appropriate way for the particular circumstances of a given proposal.

The examples in this chapter offer insight into how the network is being used and how service planners might consider enhancing it. While each proposal arose from examining a single location, several of the case studies address multiple needs, such as the proposal based on analysis of Roxbury, Dorchester, and Mattapan also improving access at the Longwood Medical Area, or the new CT4 route aimed at improving the network around Kendall Square also enhancing service around Lechmere and Kenmore. These synergies will occur with many new proposals, so service planners who know the region well may be able to use the analytical methods developed in this research to achieve benefits for a wider area than the initial target location.

Another insight, particularly from the analysis of the CT2 and CT4 routes in Section 6.1, is that there are parts of the current network that have a structure that could serve passengers well, but where the actual service falls short. Many passengers stand to benefit from using the CT2, but service is too infrequent and unreliable, and the span of service is too limited, for these passengers to use the service as it operates today. Some passengers may also simply prefer to use rail rather than bus, despite bus service sometimes offering a shorter trip. Focused attention on improving bus service and on marketing and customer information might encourage some passengers to switch modes. An exploration of these mode preferences and other ideas for future work will be discussed in the next and final chapter.

Chapter 7

Conclusion

This research develops a framework for using automated individual passenger origin, destination, and interchange inferences in bus service planning[1]. Case studies and examples are used to demonstrate the framework's methods and identify several additions and alterations to current MBTA bus service that would improve accessibility to key locations. This final chapter summarizes the framework and case studies and offers recommendations and suggestions for further research.

7.1 Summary and Findings

7.1.1 Research Approach

Though many components of this research could be easily adapted for use by other transit agencies, the framework and methods are firmly grounded in the MBTA context. The basis of the research is a bus network that has changed very little in recent decades despite rapid growth in the region. Institutional constraints make significant change difficult. Bus service planning receives little attention in the long-range planning process since it is not capital-intensive, while the short-term service planning process is focused on changes to address problems with current service, such as increasing the frequency on a route at a particular time of day to address crowding. The agency's service planning department does not have the staff time available for extensive longer-term analysis, so such longer-term analysis is often contracted to the regional MPO staff planners at CTPS. While both MBTA service planners and CTPS rely on AFC, AVL, and APC data in their analyses, the relatively new ODX data set has not yet been adopted as a tool in service planning.

The framework developed in this research therefore focuses on the ways that ODX data can improve the service planning process, focusing attention where it is most needed using practical tools and methods. The methods are pragmatic, intended to provide good estimates that can support decision-making. The tools used are a SQL

[1] Origin, destination, and interchange inference ("ODX") combines farecard and vehicle location data to infer boarding and alighting locations and to link trip stages into full journeys. A complete description of the process and the resulting data set are presented in Section 2.5.

database, GIS software, and a spreadsheet program, all of which are likely already in use in most transit agencies. This is a very different approach from that taken in the academic literature on using data in service planning described in Section 2.2, which tends to formulate the transit network as a complex optimization problem. While the results of such an approach are more comprehensive than those of the methods developed here, the approach requires an knowledge of operations research, specialized programming skills, and is difficult to implement in practice.

While this research's pragmatic approach arose from the limited resources that the MBTA has available, it is appropriate in a wide variety of agencies. Service planning can never be completely automated, and will always rely on detailed local knowledge, the judgment to balance competing goals, and an understanding of the political aspects of planning transit service. This process reflects that reality by providing tools and data to support service planners rather than using data to develop an "optimized" service plan that can never be implemented. While a few cities, such as Houston, have implemented radical reconfigurations of their bus networks, most agencies are able to make only incremental changes most of the time. This research provides tools that support this incremental approach.

The pragmatic methods are widely useful for another reason. The findings in some of the case studies in this research also point to a nontrivial number of passenger journeys that do not follow the quickest route or shortest path. While this research did not explore the effects of mode preference, the disutility of transfers and waiting time, perceptions of service reliability, and other factors influencing travel behavior through a transit network, the influence of these factors was visible in the results. This points to the use of estimates and approximations as the most suitable way to analyze transit data, since more complex methods are unlikely to accurately reflect the complex reality of passenger behavior. The optimization methods will therefore generally add complexity to the analysis without significant improvement to the accuracy of the results.

7.1.2 Current MBTA Network Evaluation

As a foundation for using ODX for specific applications and service planning methods, this research uses ODX to examine the MBTA network as a whole. By grouping bus stops and rail stations by census tract, it is possible to see geographic patterns in travel throughout the system. There is a strong commute pattern over the course of the day, with morning peak trips originating in the residential and suburban areas and ending in downtown Boston, and the reverse in the afternoon. More central areas have higher trips per capita, as do rail stations with parking that attract passengers from a wider geographic area. Journeys beginning in central areas are typically shorter in both length and duration than journeys from more suburban parts of the region. Central areas also typically have lower travel speeds and fewer transfers.

Examining the journeys that travel between pairs of census tracts also reveals aspects of the network structure. Most census tract pairs have a dominant number of stages for journeys between them; that is, most journeys between two points have the same number of transfers regardless of the mode or route used. When rail is available, it is nearly always the dominant mode, but many origin-destination pairs in the system are only served by bus or by taking a bus to access rail.

In order to compare travel times by mode, waiting times for bus journeys can be estimated using AVL data to calculate the headway and the delay the passenger experienced for a particular trip. When waiting time is included for both bus and rail, the distribution of the duration of journeys is similar for each mode. The calculation of the headway that each passenger experiences also reveals that just over a quarter are on high-frequency service, and about a third of all bus boardings are during peak periods. Despite the attention that planners pay to high-frequency peak-period service, most bus trips are not on these services.

Overall, the network analysis shows that the rail system is the backbone of the network. Bus is mainly used when rail is not available or as a feeder to the rail system. Relatively few journey involve bus-to-bus transfers, due to the geometry of the network and the long wait times that frequently accompany these transfers.

7.1.3 The Proposed Framework for Service Planning

The framework developed in this research has five components, each of which uses ODX at a different phase of the service planning process, as seen in Figure 7-1. Taken together, the phases form a new service planning process that complements the existing biennial service plan with a proactive look at parts of the network that need additional attention. Separately, the components of the process can be used in other situations to enhance planners' understanding of how the network is being used and how changes are likely to affect existing passengers. In general, the process represents a shift from the current service planning process, which assesses the service that has been provided against the service that has been promised, to a more passenger-centric approach that assesses how easily passengers and potential passengers are able to reach their destinations.

The first phase of the framework is identifying target locations around the region that require further study. Since a truly comprehensive analysis is likely too complex and time-consuming to be feasible, and since many parts of the network function fairly well, the goal is to target locations that have changed recently or that have particular transportation challenges. Many different types of areas may be included, such as residential areas with poor transit outcomes, growing job centers that have not yet had appropriate service increases, congestion hot spots, and locations where significant new development is planned. ODX data can be used in this phase to identify areas with changing travel patterns or poor transit outcomes.

The second phase is examining the selected locations in detail. This includes basic data such as population, employment, and the structure of the existing transit network. It also includes extensive analysis using the stop-level information gained from ODX, including the number of trips to and from a location by mode and time of day, typical travel times and travel speeds, where trips originate, and whether most trips are from infrequent visitors or regular commuters. From this analysis, the challenges for access to each area by transit are identified.

The third phase is proposing changes to service to address the challenges at each

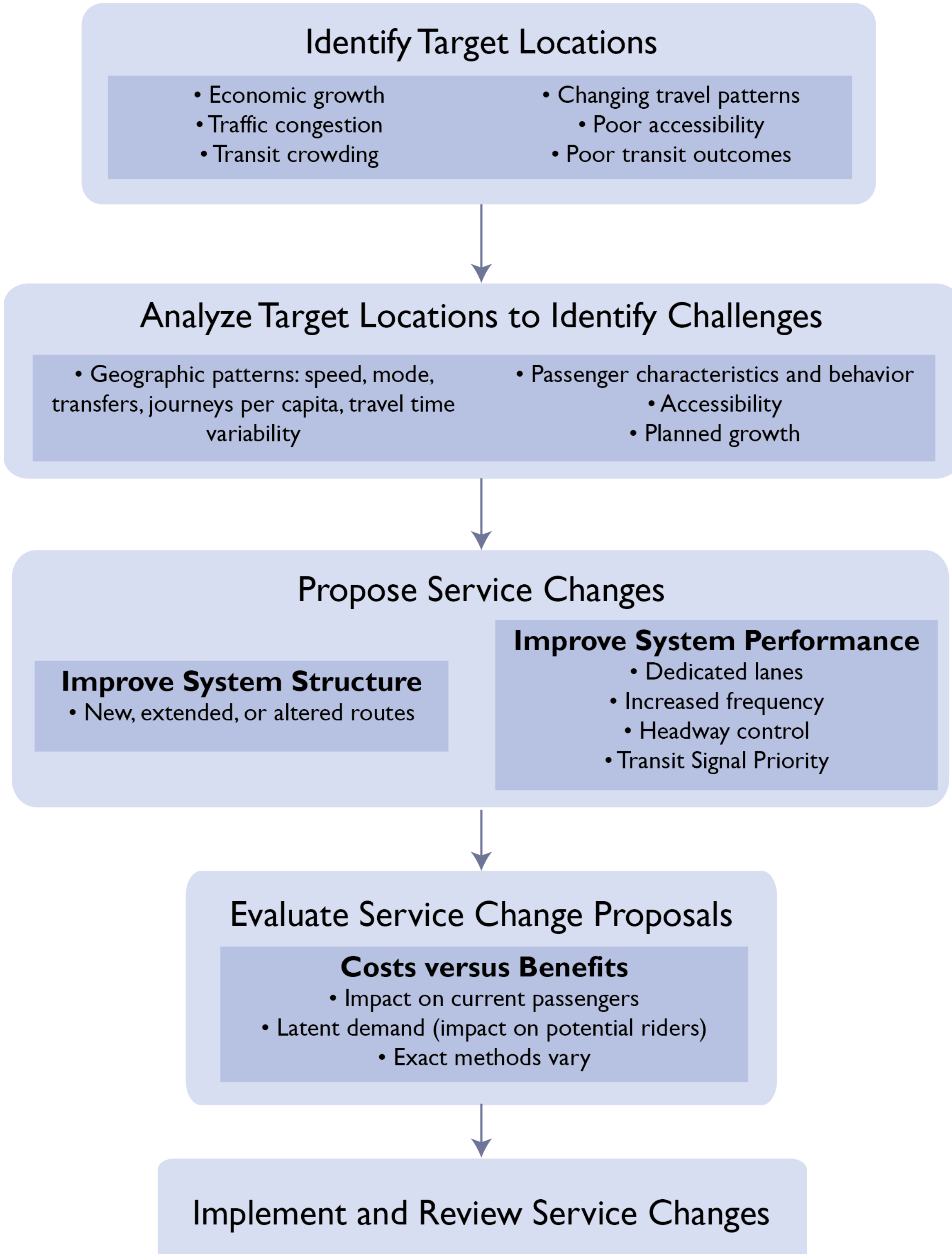


Figure 7-1: Framework for bus service planning with ODX

location that were identified in the second phase. For problems of system structure, where the geometry of the transit network is the cause of long journeys and poor access, the proposed solutions will be changes to the underlying structure of the network. These changes may be new routes, route extensions, or other changes to existing routes. For problems of system performance, where travel is reasonably direct but speeds are slow, measures to improve the performance of the system should be proposed. These might include increased frequency to reduce waiting times, dedicated bus lanes, transit signal priority, additional focus on headway control, and other such measures.

The fourth phase is evaluating the proposed service changes and determining which changes to implement. The appropriate methods vary depending on the type of proposal and the analysis should be tailored to the specific situation, as shown in the case studies in Chapter 6. For proposals that aim to improve existing service, prior research has in many cases developed appropriate analytical tools, such as Maltzan's work on headway control (Maltzan, 2015). For proposals that alter the network by adding new routes or extending existing routes, this thesis presents new methods. This new analysis approach involves several components, including identifying the effects of a proposal on existing passengers of an altered route, identifying those passengers who could use the proposed new or altered route for a single-stage journey, and finally identifying those passengers who could use the new or altered route as one stage in a longer journey. This last component, the "network analysis," examines how journeys cross over the route in question, identifying those passengers who could take a shorter trip on the new route rather than crossing over it and then backtracking to intersect it. Latent demand for the service by potential passengers currently using other modes is also considered.

The fifth and final phase is a post-hoc evaluation of service changes after they have been implemented. While examples of this phase were not included in this research due to data limitations, retrospective evaluation of service changes is vital for further refinement of the methods developed here and a better understanding of how passengers adapt their travel behavior to changes in the network. Developing methods for retrospective analysis is an important area for future research.

For all phases, the proposed framework provides useful tools and data applications that can assist service planners in their work, but still requires local knowledge and professional judgment in order to develop useful, realistic proposals. The results from the analysis in this framework can indicate that a proposal is likely to succeed and can help planners communicate why a proposal should be implemented. Actually implementing changes, however, including generating community support, is still the same technical, political, and financial challenge that it has always been.

7.1.4 Case Studies

Three case study locations were presented and examined in detail: Kendall Square, Longwood Medical Area, and Roxbury/Dorchester/Mattapan. A service change was proposed and evaluated for each location.

Kendall Square is a rapidly growing employment center on the Red Line in Cambridge. While the Red Line is approaching capacity and may present access challenges in the future, current access to Kendall is generally good from areas served by the Red Line. There are few bus routes to Kendall, however, leading to much poorer access from the north and northeast in particular, such as the inner core communities of Everett and Revere. A new route previously proposed by prior researchers from Sullivan Square through Lechmere and Kendall to Kenmore would address many of the access challenges that Kendall Square faces, as would increasing the current infrequent service on the CT2. This research showed significant demand for either option. Many current passengers who would have a shorter trip using the CT2 are not currently using the route due to reliability concerns, poor frequency, and a limited span of service. The new CT4 has even greater potential since it serves origin-destination pairs that do not currently have a direct connection. The logistics of implementation may determine which option is better; since the CT4 would be an entirely new route it would be more expensive and require more buses, but as a new route it would also be possible to contract it out to a private operator in a way that is impossible with the CT2.

The second area examined is Longwood Medical Area, where many hospitals and clinics are located. The area, which is a short distance from downtown Boston, is served by many bus routes, mostly those coming from the east and northeast, and the Green Line D and E branches that provide east-west connections. Transit access to the northwest is poor, and the neighborhoods to the southeast are mostly inaccessible by a direct route despite being fairly close to Longwood. This research proposes and analyzes an extension to route 65, continuing north through the existing terminal at Brighton Center to serve the Arsenal area of Watertown and on to the Belmont Center commuter rail station. This route extension would serve areas that have bus routes running east to west but have few options north to south. The methods developed in this research show that a significant number of existing riders could save time using the route extension. Since the extension is unlike any of the other transit service available in Watertown and Belmont, the latent demand is also likely to be significant once the route becomes established. Combined, the demand from existing transit riders and new passengers is predicted to increase ridership on route 65 by about 40%. The route 65 extension would be the most straightforward way to serve this demand, though the research also explores other implementation options. These options include contracting a new route or using minibuses for the extension portion of the route.

A study area comprising parts of the Roxbury, Dorchester, and Mattapan areas was also examined, based on Dumas' findings that residents of this largely minority community have moderately longer transit commutes than similarly situated white areas (Dumas, 2015). The area is served by the Ashmont branch of the Red Line and the Mattapan high-speed trolley. It is also criss-crossed by a complex network of bus routes, most of which originate at Red or Orange Line rail stations and terminate at Ruggles station to the north. No bus route extends further north than Ruggles, and only the 19 peak-hour service continues past the Orange Line to the west. This means that these densely populated communities have very limited direct access to Longwood Medical Center, which is both an employment center and a frequent destination for people with medical needs. This research examines rerouting or extending four different routes (the 22, 23, 28, and 29) from the Ruggles area to serve Longwood and continue on to connect the Green Line D branch at Brookline Village, adding an important circumferential connection. The research explores in detail the effect of the proposed extension on existing passengers and also the potential benefits to passengers who could save time or make fewer transfers for their existing journeys. Of the four routes studied, route 29 has the best estimated results with the least disruption to existing passengers. The number of riders who would likely benefit from the route 29 extension is expected to increase route ridership by about 60%, sufficient to justify significant service increases on the route.

As the case studies demonstrate, the methods developed in this research are a toolkit for service planners, not a precise formula to follow. The analysis necessary in each case varies slightly. The proposed CT4 intersects several rail lines, including two intersections with the Green Line, which has implications for relative travel times. The geometry of the route 65 extension requires special consideration of journeys on routes that cross over the proposed extension. Reroutings, such as those considered near Ruggles, require considering existing passengers in ways that do not affect the other proposals. The approach developed in this thesis, therefore, must be applied with careful consideration of the particular circumstances of the proposal in question.

The case studies also demonstrate that the needs of different areas of the city are closely intertwined, and one proposal can serve multiple goals. The proposal to extend a route from the RDM study area is designed to better serve the residents of that area, but also addresses a challenge identified in the Longwood analysis. The CT4 is centered around Kendall Square, but serves a much more general deficit in circumferential service connecting the rail lines outside of downtown. It also addresses the needs of passengers who have good access to Sullivan Square from the north, to the Green Line branches via Kenmore to the west, and to a key commuter rail branch at the Yawkey station near Kenmore. Therefore, these tools will be especially useful in the hands of planners with detailed knowledge of the region and the existing transit system, who may be able to more easily identify solutions that address multiple challenges.

7.2 Next Steps and Recommendations

The ongoing development and refinement of the ODX tool will address some of the limitations of the data set used in this thesis. In particular, the poor data from the Green Line surface sections and from the SL1 and SL2 Silver Line branches through the Seaport District will be replaced by more accurate and comprehensive data that is in line with that from the rest of the system. Since all of the case studies presented here are affected by the Green Line data in particular, the new data set should be used to refine the analysis performed in this research.

The improved data on the Silver Line also provides an opportunity to do a location analysis of the Seaport District as one of the region's fastest-growing job centers. The proposal for a new route from Andrew Station through the Seaport District should be analyzed using the methods developed here, and other proposals should be developed and analyzed for the Seaport.

The methods in this thesis can also be used to look at a number of other key locations around the region and at changes to the transit system beyond regular bus service. The Silver Line Gateway expansion through Chelsea and the Green Line extension through Somerville and Medford could also be considered using the methods presented in the case studies in this research. Dumas' analysis of the effects of DMU service on the Fairmount Line is another candidate for examination using these methods; Dumas' analysis did not consider the full range of benefits to those who could use the service as part of a multi-stage journey. The methods developed in this research can also be expanded and adapted to help service planners identify how regular bus service in these areas might need to change in order to adapt to these high-capacity rail and bus projects.

The current political circumstances of the MBTA offer another opportunity to use the methods developed here. The three-year suspension of Massachusetts' Pacheco law allows the MBTA to contract with private operators to provide service, which provides a unique chance to experiment with new services without having to reallocate buses from existing service elsewhere. The process proposed by this research is an excellent starting point for identifying potential new services to be run by private contractors.

While this research has focused on the benefits of ODX for proactive service planning, researchers and MBTA staff should not lose sight of the many benefits that ODX offers for one-time project and ad hoc analysis. During the course of this research, a number of potential uses were considered in conversations with MBTA staff, including using the boarding location data in ODX to identify where to locate off-board fare machines or where to experiment with off-board fare collection, identifying the stops and stations used most frequently by passengers with disabilities, examining the transfers among bus routes in detail when redesigning an intersection, determining how many passengers are responding to the Green Line's crowding and reliability issues by using the bus for journeys that could be made using the Green Line, and identifying the locations with heaviest use of the late-night service pilot program.

This research has proposed a new route and two extensions to existing routes, but the details of implementation are outside the scope of the project. Careful consideration will need to be given to exact route alignment, scheduling, and other operational details. Given the current political climate surrounding the MBTA, there may also be opportunities to experiment with new methods of service delivery. As Gordon found, the proposed CT4 could easily be contracted out to enable new service without increasing the size of the MBTA's operating fleet (Gordon, 2015). The recent relaxation of the Pacheco law makes contracting the route an even more feasible option. This may make the CT4 preferable to the option of adding more peak-hour service on the CT2, which would require additional MBTA buses.

The proposed extension to route 65 is fairly long, at about 4.5 miles. The extension portion of the route, therefore, is long enough to run as a separate contracted minibus route with a timed transfer to the 65 at Brighton Center. This would allow ridership to build at fairly low cost before the extension is folded into the regular route. The extension could also be phased in, running first only to the Arsenal area in Watertown and then later adding the full extension to Belmont Center. An alternative implementation plan would be to design a different route serving the path of the extension and continuing on through Brighton and Longwood to a different terminal station, perhaps at Ruggles. As a brand-new route, it would then be eligible to be contracted out to a private provider and would not require the use of the existing MBTA fleet.

7.3 Further Research

Over the coming months and years a larger ODX data set will accumulate. As changes are made to the bus network and other parts of the transit system, methods for post-hoc analysis should be developed to evaluate the effects of the changes. This analysis should be done at intervals after a change is made, such as 3 months, 6 months, and a year, since the full effects may take some time to develop. This will provide useful feedback on the methods developed here, particularly on some of the assumptions used to estimate how many riders will change their behavior given different types of changes in service.

The other type of analysis that will become possible is the longitudinal analysis mentioned in Section 4.2.3. The methods for this sort of analysis will be similar to those for a post-hoc analysis, as both will require comparing ODX data at different points in time to identify changes. With ODX data from multiple years rather than a single month, it will be possible to identify how travel in the region is changing over time, with respect to both recurring seasonal patterns and trends over several years. Understanding these trends will help service planners better anticipate future demand and help the network adapt as the region changes.

Further research should also expand the data sources that are used in the analysis to include other modes. In particular, finding sources for travel times and speeds for private vehicles could help identify parts of the system where transit travel times are especially slow compared to private cars. A source of origin and destination information for all modes could further enhance the analysis of transit service using ODX by identifying total travel demand and providing better data on which to base calculations of latent demand for transit. These data sources might include gaining access to the data from Google Maps or another mapping company or using the outputs from a calibrated regional travel demand model such as that used by CTPS.

By providing total travel times, including transfers, ODX provides an opportunity to look at reliability from a more customer-centric point of view. While the research presented here considers the overall travel times experienced by passengers, it does not compare these to the scheduled travel times or consider the variation in travel times among passengers or across time periods. These factors should be explored in future research.

Analysis of crowding and passenger turnover on individual routes could also be fruitful. Most bus service operates at a deficit and requires subsidy; that is, fares do not cover costs. ODX offers the ability to know how long each passenger rides the bus and what fare they pay, so the variations among routes and across time periods can be studied. Some routes may more than cover their costs during some time periods, particularly along busy stretches. If these routes can be identified using ODX, particularly those that more than cover costs in the off peak, it may help justify increasing service levels on those routes without cutting service elsewhere because doing so would have a net positive effect on revenue. This could help shift planners and other stakeholders away from the zero-sum approach to service planning that has stifled change in recent years.

Another avenue of further research that touches on policy, funding, and the political context of bus planning is to examine how ODX might be used as the basis for the assessments that cities and towns in the service area pay to support the MBTA. The new information that ODX provides on the exact locations of boardings and alightings would allow an assessment based on the number of passengers who board from within that city or town. A more complex assessment that included the number of passengers who travel in a typical commute pattern to the city or town could capture some of the economic development benefits generated for the municipality by MBTA service, which enables employees to commute to the municipality.

A potentially rich direction of future research is using ODX to better understand passengers' travel behavior. As mentioned above in Section 7.1.1, the results of this research indicate that not all riders choose the fastest or shortest route, whether the choice is due to mode preferences, preferring not to transfer, preferring shorter wait time even at the expense of greater in-vehicle time, the reliability of a particular route, or other factors. The ODX data set enables detailed study of how passengers travel through the system and could quantify these effects to help service planners better understand which improvements could have the most benefit.

Appendix A

Additional Location Analysis Results

A.1 Kendall Square

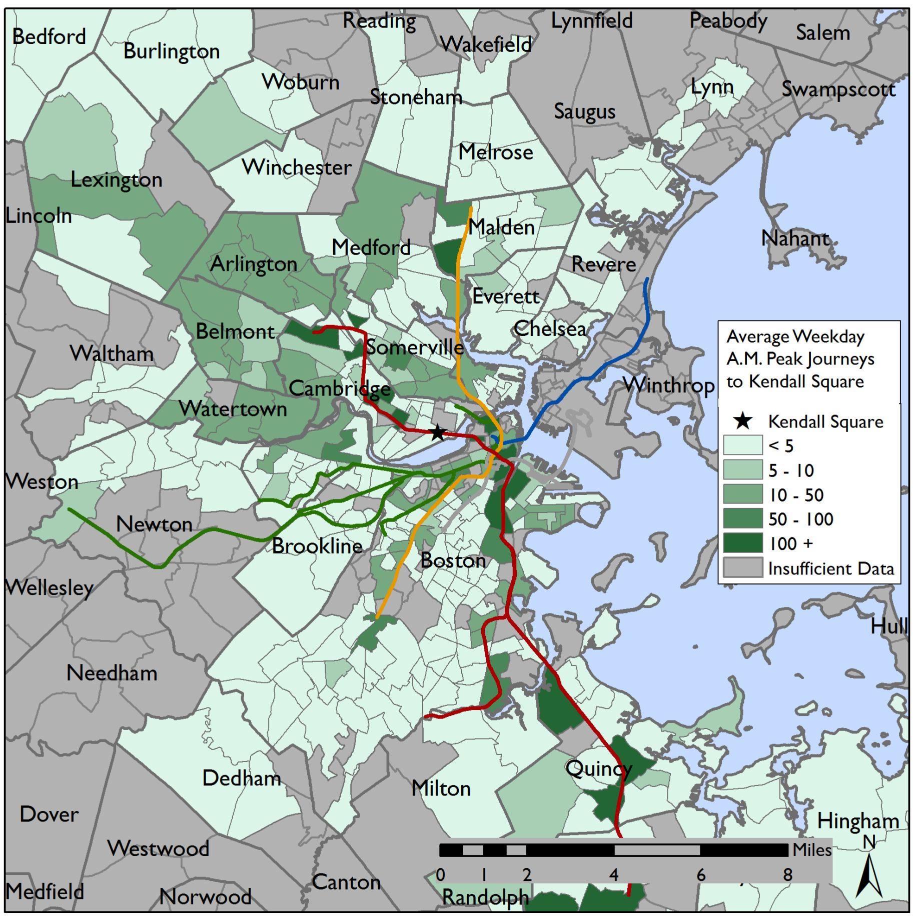


Figure A-1: Average number of weekday morning peak journeys to Kendall Square

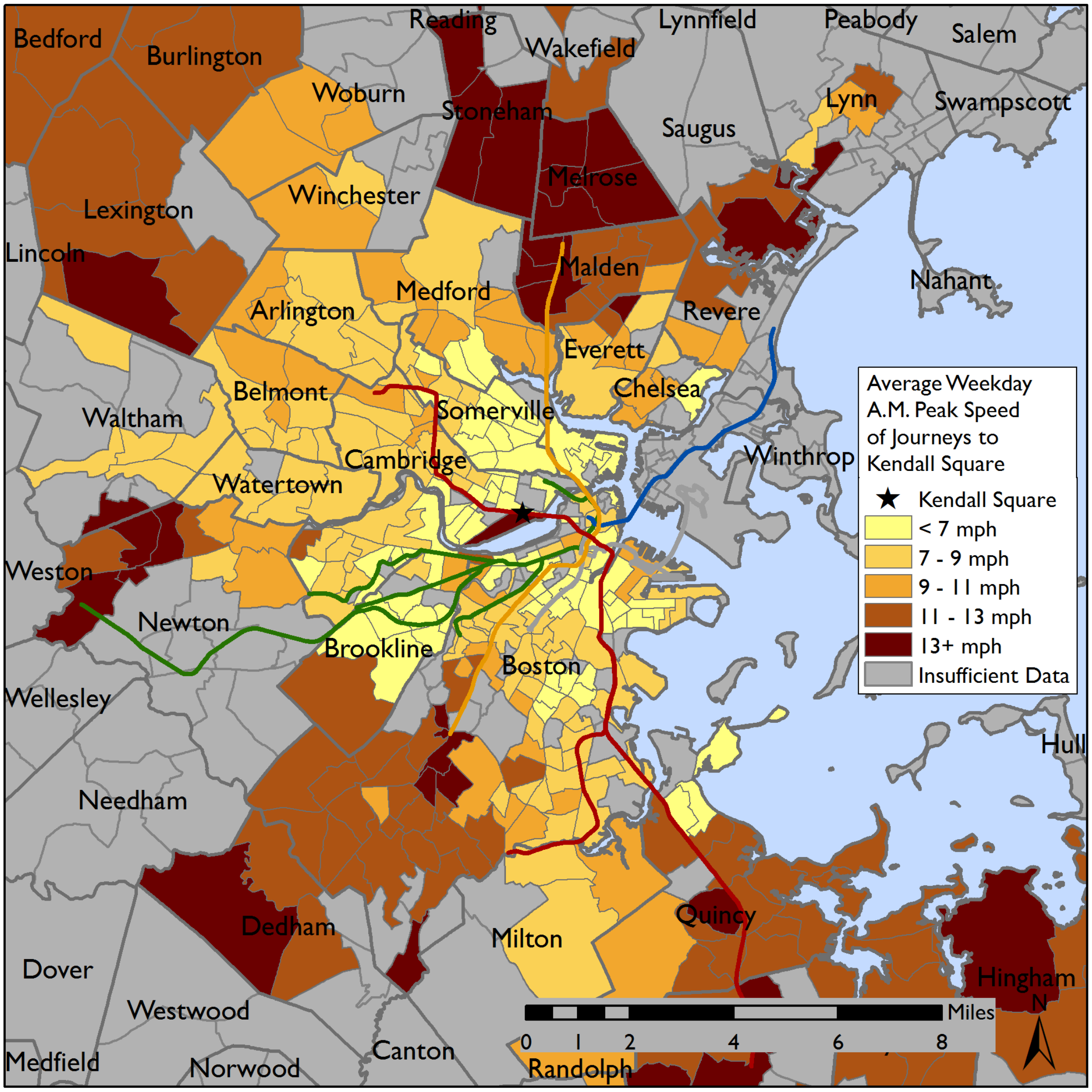


Figure A-2: Average weekday morning peak travel speed for journeys to Kendall Square

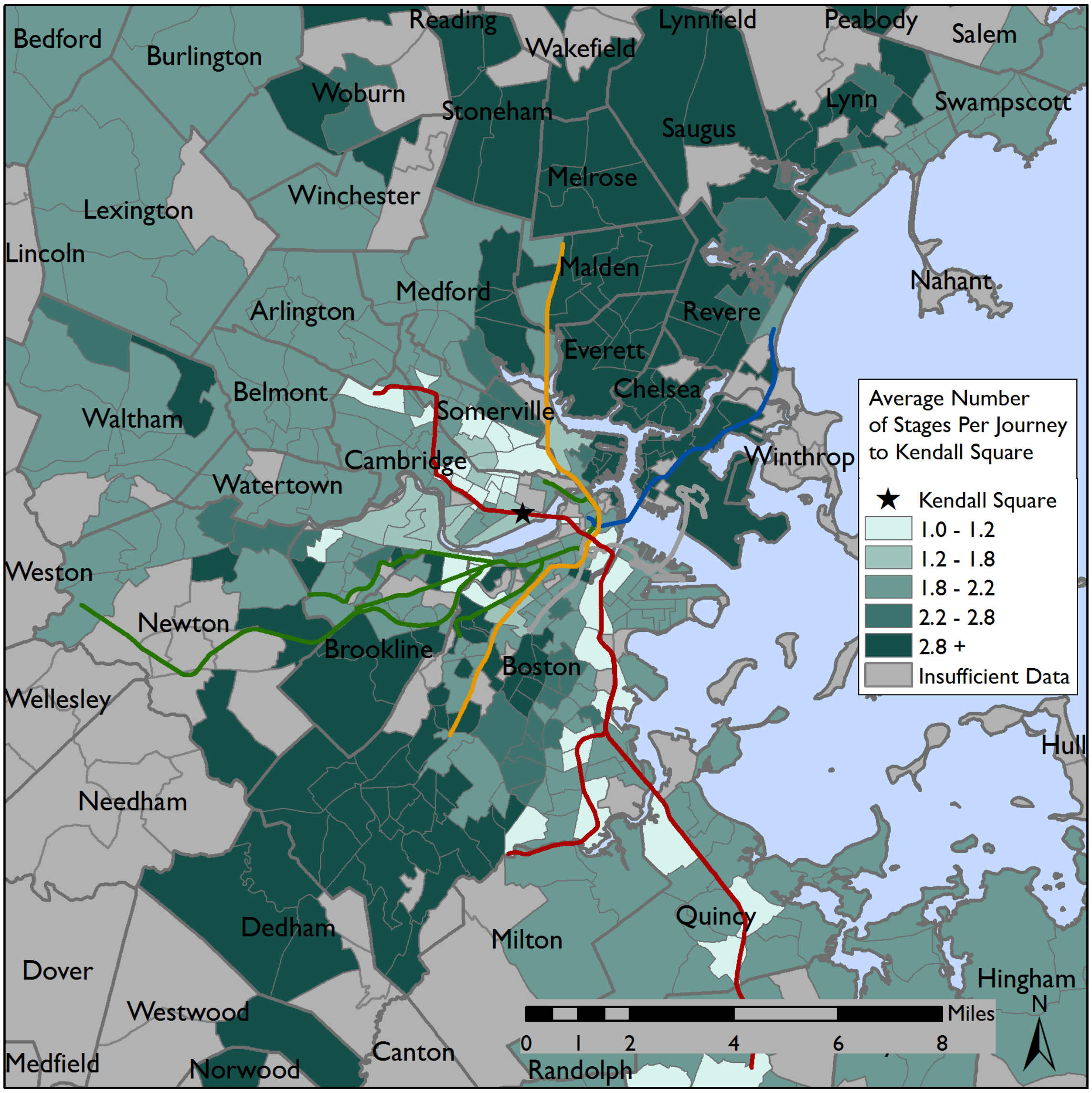


Figure A-3: Average number of stages for journeys to Kendall Square

A.2 Longwood Medical Area

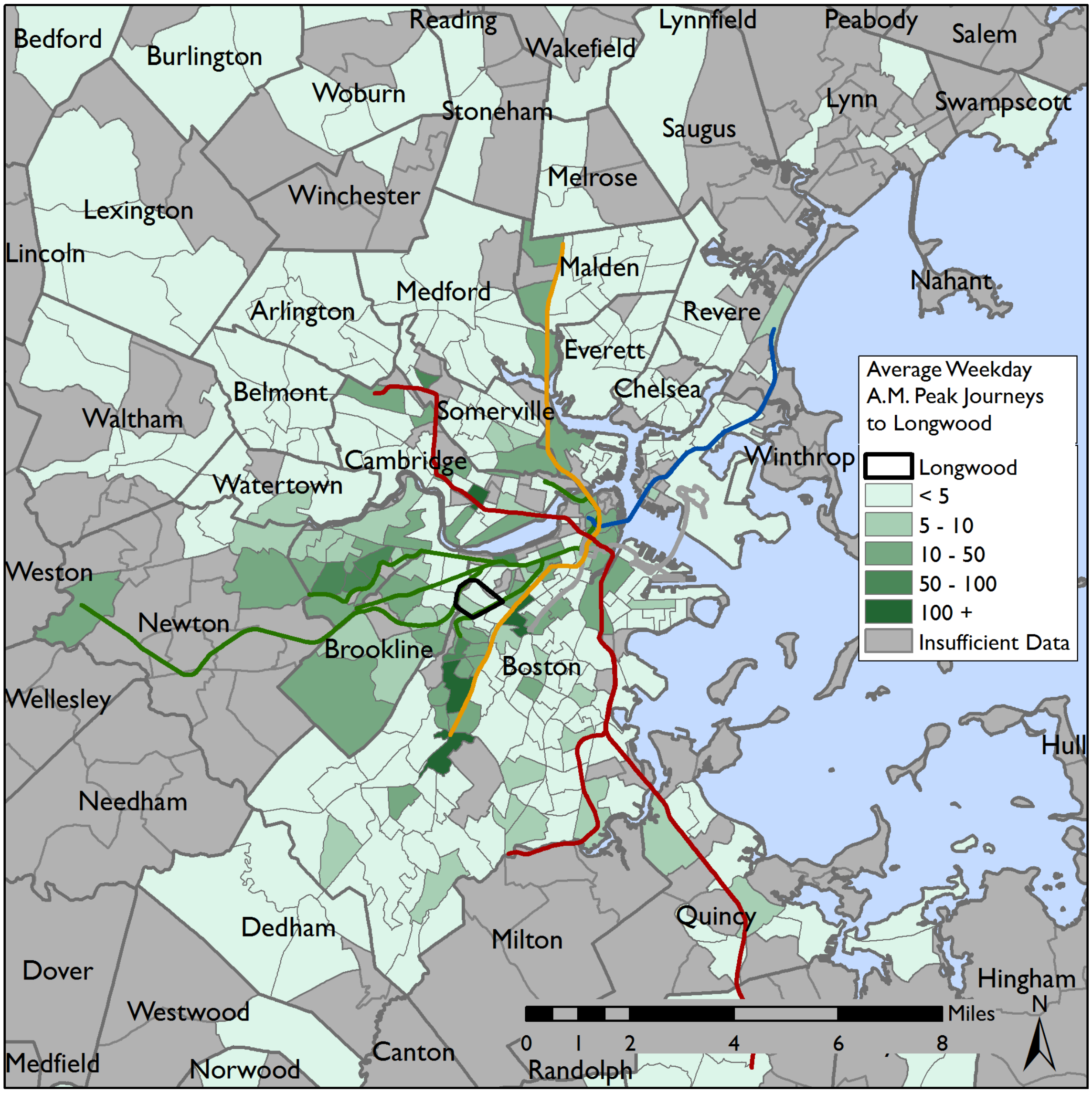


Figure A-4: Average number of weekday morning peak journeys to Longwood Medical Area

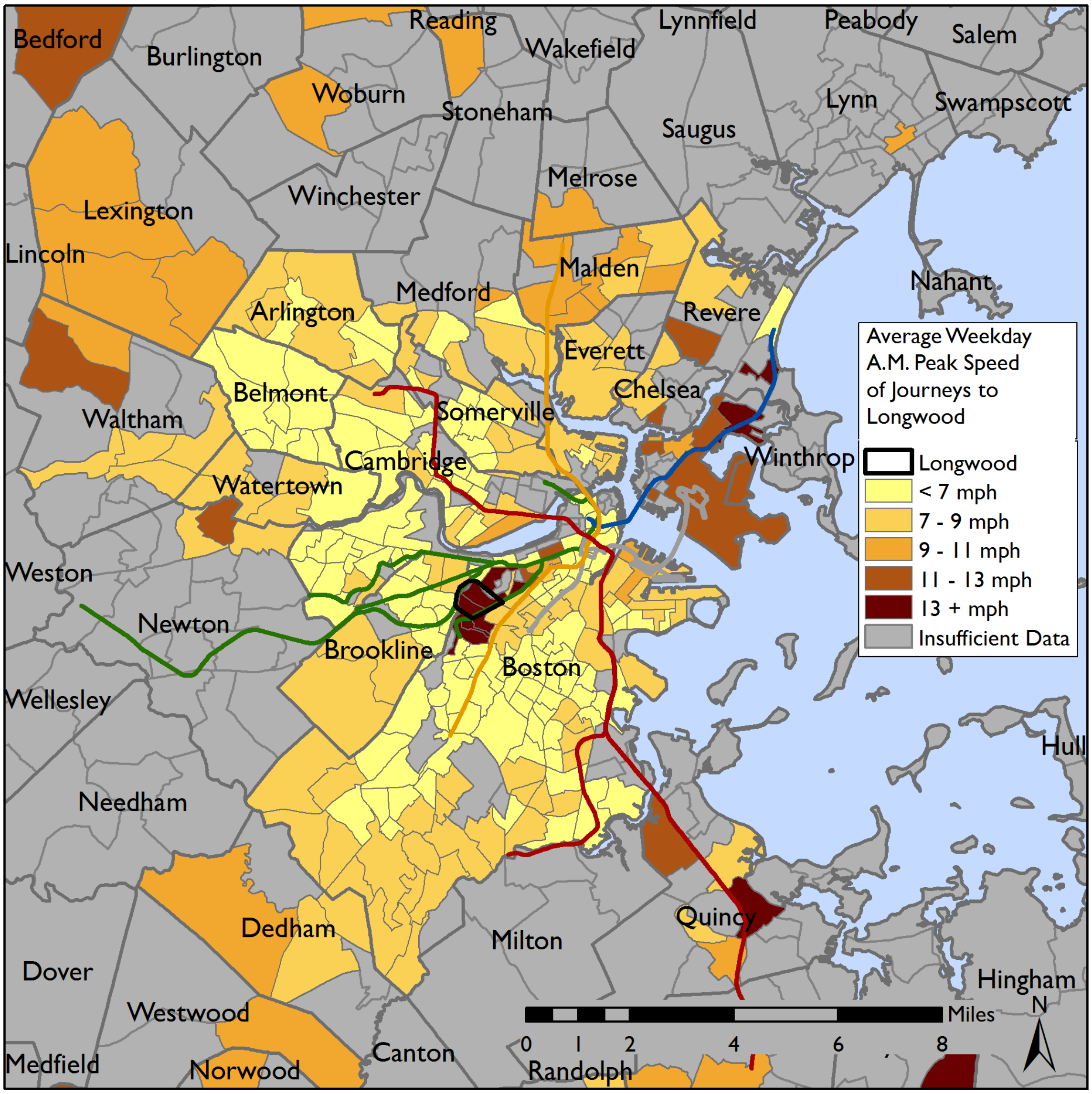


Figure A-5: Average weekday morning peak travel speed for journeys to Longwood Medical Area

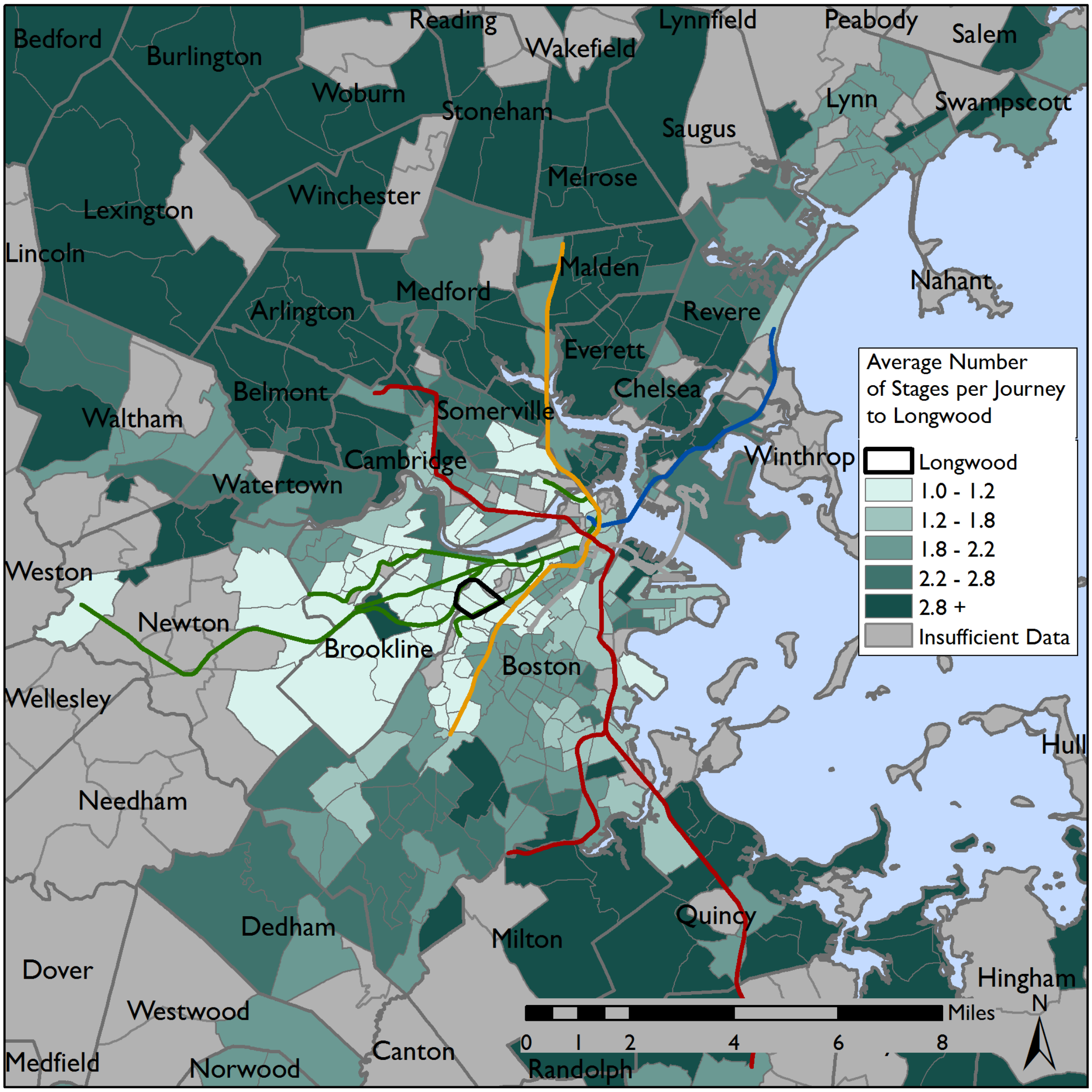


Figure A-6: Average number of stages for journeys to Longwood Medical Area

A.3 Roxbury, Dorchester, and Mattapan Study Area

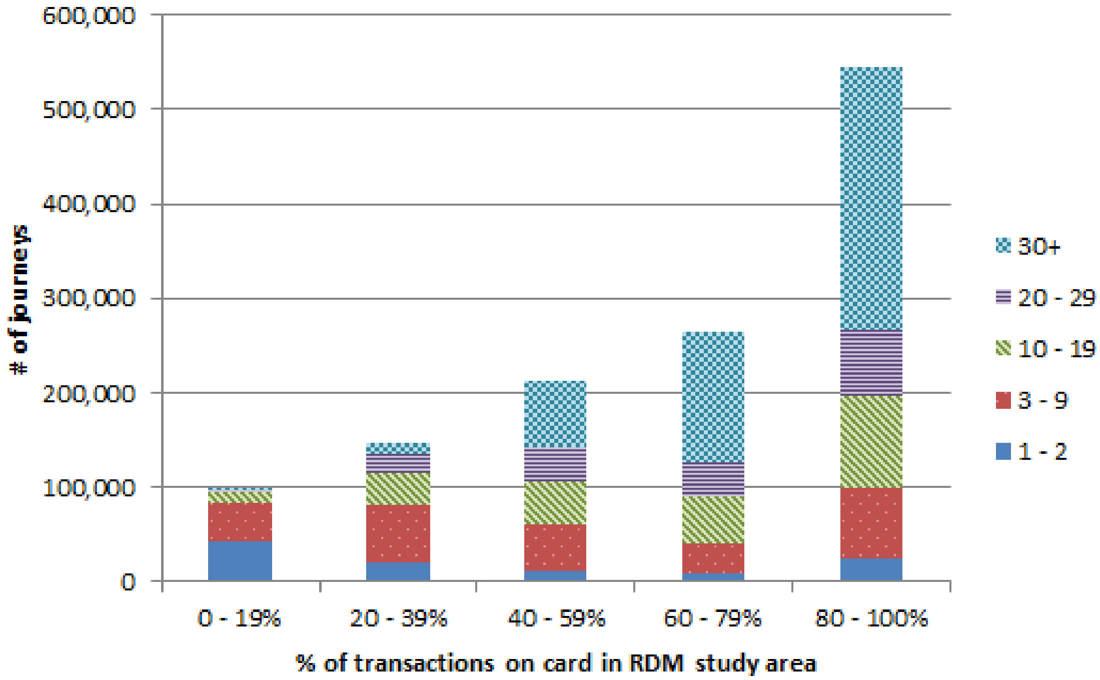


Figure A-7: Number of journeys per farecard at the RDM study area, as a % of all journeys

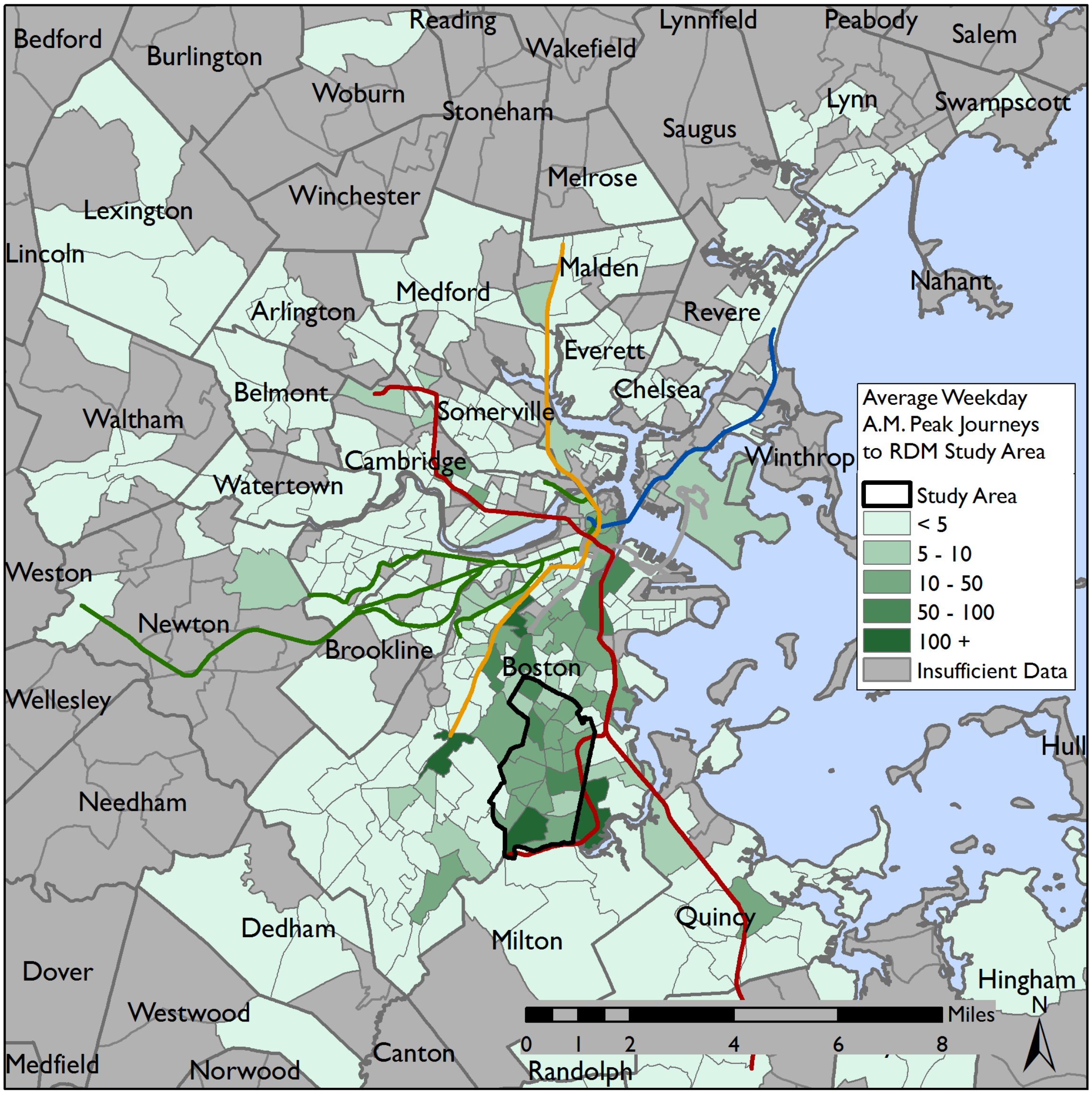


Figure A-8: Average weekday morning peak journeys to the RDM study area

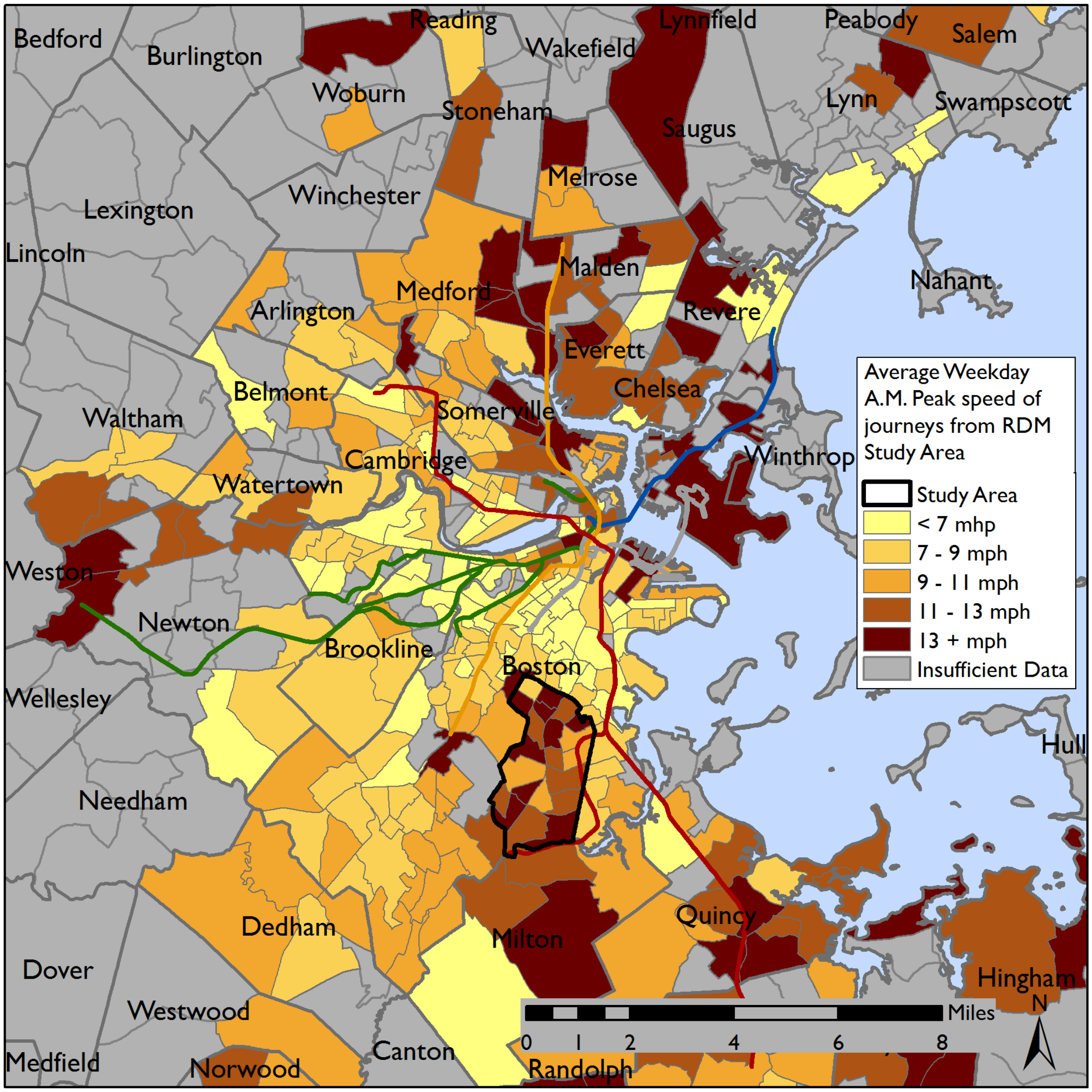


Figure A-9: Average weekday morning peak travel speed for journeys from the RDM study area

Bibliography

A Better City (2009). The Urban Ring: Connecting the spokes. www.abettercity.org/transportation/urbanring.html.

A Better City (2015). South Boston Waterfront sustainable transportation plan progress report. abettercity.org/docs%20starting%206.30.2015/2015.08.17%20SB%20Revised%20Progress%20Report.pdf.

Barry, J., Freimer, R., and Slavin, H. (2009). Use of entry-only automatic fare collection data to estimate linked transit trips in New York City. *Transportation Research Record: Journal of the Transportation Research Board*, (2112):53–61.

Belcher, J. (2015). Changes to transit service in the MBTA district 1964 - 2015. www.transithistory.org/roster/MBTARouteHistory.pdf.

Breitrose, C. (2015). Arsenal owners seek new zoning regulations. *WickedLocal Watertown*, August 27, 2015. watertown.wickedlocal.com/article/20150827/NEWS/150826942.

Bridj (2015). Greater Boston service area. www.bridj.com/greater-boston-service-area. Accessed 9/14/2015.

Bruun, E. (2007). *Better Public Transit Systems: Analyzing Investment and Performance*. American Planning Association.

Cambridge Community Development Department (2013). Kendall Square Central Square planning study: Kendall Square final report 2013. www.cambridgema.gov/cdd/projects/planning/k2c2.

Central Transportation Planning Staff (2010). 2008-2009 MBTA systemwide passenger survey report. www.ctps.org/2008_09_mbta_survey.

Central Transportation Planning Staff (2012). Potential MBTA fare increase and service changes in 2012: Scenario 3 impact analysis.

Chapleau, R., Chu, K. K. A., and Allard, B. (2011). Synthesizing AFC, APC, GPS and GIS data to generate performance and travel demand indicators for public transit. In *Transportation Research Board 90th Annual Meeting*, number 11-2894.

Charles River Transit Management Association (2015). EZRide overview. www.charlesrivertma.org/ezride-shuttle. Accessed 9/14/2015.

Chow, W. (2014). Evaluating online surveys for public transit agencies using a prompted recall approach. Master's thesis, Massachusetts Institute of Technology.

Chu, K. K. A. and Chapleau, R. (2008). Enriching archived smart card transaction data for transit demand modeling. *Transportation Research Record: Journal of the Transportation Research Board*, (2063):63–72.

Cipriani, E., Gori, S., and Petrelli, M. (2012). Transit network design: A procedure and an application to a large urban area. *Transportation Research Part C: Emerging Technologies*, 20(1):3–14.

Clarke, B. H. (2003). *Streetcar Lines of the Hub: The 1940's Heyday of Electric Transit in Boston*. Number 23. Boston Street Railway Association.

Devillaine, F., Munizaga, M., and Trépanier, M. (2012). Detection of activities of public transport users by analyzing smart card data. *Transportation Research Record: Journal of the Transportation Research Board*, (2276):48–55.

Dullea, M. (2015). Personal communication.

Dumas, R. A. (2015). Analyzing transit equity using automatically collected data. Master's thesis, Massachusetts Institute of Technology.

Dunga, N. (2015). MBTA moves toward privatizing some bus routes. *The Boston Globe*, August 20, 2015. www.bostonglobe.com/metro/2015/08/19/mbta-exploring-privatization-bus-routes-including-late-night-service-union-president-says/Cl5hjyben3c2H6aQEpsDZL/story.html.

Dungca, N. (2015). MBTA shopping for new rail cars. *The Boston Globe*, January 11, 2015. www.bostonglobe.com/metro/2015/01/11/mbta-asks-for-bids-new-trains/4ysvEHYBytvtjV0tWEPjwJ/story.html.

Editorial Board (2015). Time for MBTA to change its bus map. *The Boston Globe*, April 14, 2015. www.bostonglobe.com/opinion/editorials/2015/04/14/time-for-mbta-change-its-bus-map/kUN5xxHnG5c7xIcZlnYjiO/story.html.

Farahani, R. Z., Miandoabchi, E., Szeto, W., and Rashidi, H. (2013). A review of urban transportation network design problems. *European Journal of Operational Research*, 229(2):281–302.

Farzin, J. (2008). Constructing an automated bus origin-destination matrix using farecard and global positioning system data in São Paulo, Brazil. *Transportation Research Record: Journal of the Transportation Research Board*, (2072):30–37.

Federal Transit Administration (2012). Circular FTA C 4702.1B Title VI requirements and guidelines for Federal Transit Administration recipients. www.fta.dot.gov/documents/FTA_Title_VI_FINAL.pdf.

Federal Transit Administration National Transit Database (2013). TS2.1 - Service data and operating expenses time-series by mode. www.ntdprogram.gov/ntdprogram/data.htm.

Feijo, S. (2015). All eyes on Volpe: Huge plans leave Cambridge councillors feeling rushed. *WickedLocal Cambridge*, June 30, 2015. cambridge.wickedlocal.com/article/20150630/NEWS/150639795.

Francis, B. (2015). Personal communication.

Furth, P. G., Hemily, B., Muller, T. H., and Strathman, J. G. (2006). *Using archived AVL-APC data to improve transit performance and management.* TCRP Report 113. Transportation Research Board.

Gascoigne, J. (2015). Development and operations of EZRide shuttle. Presentation to Cambridge Transit Advisory Committee. www.cambridgema.gov/~/media/Files/CDD/Transportation/transitcommittee/2015/trans_cmte_EZRide_20150204.ashx?la=en.

Gordon, J., Koutsopoulos, H., Wilson, N., and Attanucci, J. (2013). Automated inference of linked transit journeys in London using fare-transaction and vehicle location data. *Transportation Research Record: Journal of the Transportation Research Board*, (2343):17–24.

Gordon, J. B. (2012). Intermodal passenger flows on London's public transport network: Automated inference of full passenger journeys using fare-transaction and vehicle-location data. Master's thesis, Massachusetts Institute of Technology.

Gordon, M. and van der Hurk, E. (2014). Longfellow Bridge shuttle alternatives. Memorandum. Massachusetts Institute of Technology.

Gordon, M. A. (2015). Developing strategies for resource-constrained transit growth through increased private sector involvement. Master's thesis, Massachusetts Institute of Technology.

Goulet-Langlois, G. (2015). Exploring regularity and structure in travel behavior using smart card data. Master's thesis, Massachusetts Institute of Technology.

Gray, G. E. and Hoel, L. A. (1992). *Public Transportation.* Prentice-Hall, Inc, 2nd edition.

Gu, Z., Kladeftiras, M., Mohammad, S., and Xuto, P. (2014). Improving transportation access to the South Boston Seaport District. Master's thesis, Massachusetts Institute of Technology.

Gutiérrez de Quevedo Aguerrebere, C. (2012). Redesigning and improving the efficiency of bus transit networks using automatically collected data: The case of Gipuzkoa, Spain. Master's thesis, Massachusetts Institute of Technology.

He, L. and Trépanier, M. (2015). Estimating the destination of unlinked trips in public transportation smart card fare collection systems. In *Transportation Research Board 94th Annual Meeting*, number 15-4344.

Jaffe, E. (2015). How the microtransit movement is changing urban mobility. *Citylab.com*, April 17, 2015. www.citylab.com/commute/2015/04/how-the-microtransit-movement-is-changing-urban-mobility/391565/.

Kamfonik, D. and Block-Schachter, D. (2014). Quantifying the impacts of a commuter benefits program: The MBTA Corporate Pass program case study. In *Transportation Research Board 93rd Annual Meeting*, number 14-4065.

Kamfonik, D. E. (2013). Quantifying the current and future impacts of the MBTA Corporate Pass program. Master's thesis, Massachusetts Institute of Technology.

Lee, S. G. and Hickman, M. (2014). Trip purpose inference using automated fare collection data. *Public Transport*, 6(1-2):1–20.

Maltzan, D. (2015). Using real-time data to improve reliability on high-frequency transit services. Master's thesis, Massachusetts Institute of Technology.

Marr, B. (2015). How big data and the internet of things improve public transport in London. *Forbes.com*, May 27, 2015. www.forbes.com/sites/bernardmarr/2015/05/27/how-big-data-and-the-internet-of-things-improve-public-transport-in-london/.

Massachusetts Bay Transporation Authority (2008). Final 2008 service plan: Bus, rapid transit, and boat service changes and service delivery policy modifications. www.mbta.com/uploadedfiles/About_the_T/T_Projects/T_Projects_List/Final_2008_Service_Plan.pdf.

Massachusetts Bay Transporation Authority (2009). Program for mass transportation. www.ctps.org/mbta_pmt.

Massachusetts Bay Transporation Authority (2015). Capital investment program FY2015-FY2019. www.mbta.com/uploadedfiles/About_the_T/Financials/FINAL%20FY15-19%20MBTA%20Capital%20Investment%20Program.pdf.

Massachusetts Bay Transportation Authority (2010). Service delivery policy. www.mbta.com/uploadedfiles/About_the_T/T_Projects/T_Projects_List/2010ServiceDeliveryPolicy.pdf.

Massachusetts Bay Transportation Authority (2014a). MBTA system map 2014-2015. www.mbta.com/schedules_and_maps/system_map/.

Massachusetts Bay Transportation Authority (2014b). Ridership and service statistics, 14th edition. www.mbta.com/uploadedfiles/documents/2014%20BLUEBOOK%2014th%20Edition.pdf.

Massachusetts Department of Transportation (2012). Roxbury-Dorchester-Mattapan transit needs study. www.massdot.state.ma.us/rdm/downloads/RDMReport_0912.pdf.

Massachusetts Department of Transportation (2014). The GreenDOT report: 2014 status update. www.massdot.state.ma.us/GreenDOT/GreenDOTReport.aspx.

Massachusetts Executive Office of Transportation (2009). Route 28X bus enhancements project TIGER discretionary grant application. www.massdot.state.ma.us/portals/20/docs/28X_TIGER_Application_-_Narrative.pdf.

McCord, M., Mishalani, R., Goel, P., and Strohl, B. (2010). Iterative proportional fitting procedure to determine bus route passenger origin-destination flows. *Transportation Research Record: Journal of the Transportation Research Board*, (2145):59–65.

Medical Academic Scientific and Community Organization (2015). Shuttle information. www.masco.org/directions/shuttle-information. Accessed 9/14/2015.

Metropolitan Area Planning Council (2012). Growing station areas: The variety and potential of transit oriented development in metro Boston. www.mapc.org/tod.

Metropolitan Area Planning Council (2014). Population and housing demand projections for metro Boston. www.mapc.org/projections.

MIT News Office (2015). MIT presents Kendall Square Initiative to Cambridge planning board. *MIT News website*. news.mit.edu/2015/mit-presents-kendall-square-initiative-plan-cambridge-planning-board.

Munizaga, M. A. and Palma, C. (2012). Estimation of a disaggregate multimodal public transport origin–destination matrix from passive smartcard data from Santiago, Chile. *Transportation Research Part C: Emerging Technologies*, 24:9–18.

Nassir, N., Hickman, M., and Ma, Z.-L. (2015). Activity detection and transfer identification for public transit fare card data. *Transportation*, (42):683–705.

Nassir, N., Khani, A., Lee, S., Noh, H., and Hickman, M. (2011). Transit stop-level origin-destination estimation through use of transit schedule and automated data collection system. *Transportation Research Record: Journal of the Transportation Research Board*, (2263):140–150.

Pelletier, M.-P., Trépanier, M., and Morency, C. (2011). Smart card data use in public transit: A literature review. *Transportation Research Part C: Emerging Technologies*, 19(4):557–568.

Pincus, K. S. (2014). Analysis of the 2012 Massachusetts Bay Transportation Authority fare increase using automated fare collection data. Master's thesis, Massachusetts Institute of Technology.

Poftak, S. (2015). Thoughts on the route 28X failure. *The Pioneer Institute*, November 20, 2009. pioneerinstitute.org/news/thoughts-on-the-route-28x-failure/.

Pollack, S. (2012). *Hub and Spoke: Core Transit Congestion and the Future of Transit and Development in Greater Boston*. Urban Land Institute. www.mbta.com/uploadedfiles/About_the_T/Panel/HubandSpoke.pdf.

Reiss, J. (2015a). Watertown group pushing for non-T transit. *The Boston Globe*, May 28, 2015. www.bostonglobe.com/metro/regionals/west/2015/05/28/watertown-group-pushing-for-non-transit/CiYCAOA2IHSllLNG481fYI/story.html.

Reiss, J. (2015b). Watertown zoning officials approve 'Linx' project. *The Boston Globe*, July 28, 2015. www.bostonglobe.com/metro/regionals/west/2015/07/28/watertown-zoning-officials-approve-linx-project/L9dpiLecEk6UcfyHBM4GXL/story.html.

Rosen, J. C. (2013). Evaluating service mitigation proposals for the MBTA Green Line extension construction delay using simplified planning methods. Master's thesis, Massachusetts Institute of Technology.

Sanborn, G. (1993). *A Chronicle of the Boston Transit System Including a Log of Incidents Affecting the MBTA*. State Transportation Library.

Sánchez-Martínez, G. (2015). Personal communication.

Scharfenberg, D. (2015a). Baker names 5 to MBTA fiscal control board. *The Boston Globe*, July 17, 2015. www.bostonglobe.com/metro/2015/07/17/baker-names-mbta-fiscal-control-board/JmMsv6PPD02e6KzOgO2VyH/story.html.

Scharfenberg, D. (2015b). State budget shakes unions. *The Boston Globe*, July 9, 2015. www.bostonglobe.com/metro/2015/07/08/new-state-budget-big-defeat-for-labor/dhIDQjYNxSpCTs4qVJm1LI/story.html.

Shireman, M. T. (2011). Using automatically collected data for bus service and operations planning. Master's thesis, Massachusetts Institute of Technology.

Southwick, C. (2016). Title to be determined. Master's thesis, Massachusetts Institute of Technology. Forthcoming.

Stewart, A. F. (2014). Visualizing urban accessibility metrics for incremental bus rapid transit projects. Master's thesis, Massachusetts Institute of Technology.

The Arsenal on the Charles (2015). Transportation and parking. thearsenalonthecharles.com/campus-info/transportation-parking/. Accessed January 2, 2016.

Tribone, D. (2013). Making data matter: The role of information design and process in applying automated data to improve transit service. Master's thesis, Massachusetts Institute of Technology.

Tribone, D., Block-Schachter, D., Salvucci, F., Attanucci, J., and Wilson, N. (2014). Automated, data-driven performance regime for operations management, planning, and control. *Transportation Research Record: Journal of the Transportation Research Board*, (2415):72–79.

VHB (2015). *South Boston Waterfront Sustainable Transportation Plan.* A Better City. `abettercity.org/docs/2015.01.15%20SBoston%20Waterfront_Full_Report_PB.pdf`.

Viggiano, C. A. (2013). Bus user behavior in multi-route corridors. Master's thesis, Massachusetts Institute of Technology.

Wallack, T. and Weisman, R. (2013). 1,900 new jobs, $9.5m tax break for Athenahealth. *The Boston Globe*, June 25, 2013. `www.bostonglobe.com/metro/2013/06/24/athenahealth-plans-add-jobs-watertown-exchange-for-tax-credits/el8H1k1VhY9BAifrCWWDdP/story.html`.

Wang, W. (2010). Bus passenger origin-destination estimation and travel behavior using automated data collection systems in London, UK. Master's thesis, Massachusetts Institute of Technology.

Wang, W., Attanucci, J. P., and Wilson, N. H. (2011). Bus passenger origin-destination estimation and related analyses using automated data collection systems. *Journal of Public Transportation*, 14(4):7.

Williams, E., Pollack, S., and Billingham, C. (2014). Measuring transportation equity: Commute time penalties by race and mode in greater Boston. In *Transportation Research Board 93rd Annual Meeting*, number 14-4849.

Woodward, C. (2015). Wynn outlines proposed changes to Everett casino. *The Boston Globe*, October 29, 2015. `www.bostonglobe.com/metro/2015/10/29/somerville-files-another-lawsuit-against-casino-planed-for-everett/Cm6ihUBiXbJ1y4ImEWx5FL/story.html`.

Zhao, J. (2004). The planning and analysis implications of automated data collection systems: Rail transit OD matrix inference and path choice modeling examples. Master's thesis, Massachusetts Institute of Technology.

Zhao, J., Wilson, N. H., and Rahbee, A. (2006). Estimating rail passenger trip origin-destination matrix using automatic data collection. *Computer-Aided Civil and Infrastructure Engineering*, 22:376–387.