Towards Regional Rail: Strategies for Service Transformation on the Worcester/Framingham Line

by

Devin Camille Wilkins

Submitted to the Department of Urban Studies and Planning
in partial fulfillment of the requirements for the degree of

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Abstract

Increasingly, the urgent threat of climate change has brought renewed focus to the efficiency of cities' transportation networks and the benefits of mode shift away from the private automobile and towards transit. Over the last three years, changes in journey patterns resulting from the social impacts of the COVID-19 pandemic have triggered questions about the future of public transit systems, and whether changes to established service delivery strategies and fare products are needed. In many ways, commuter rail as a service delivery strategy feels like a relic of a past time, as miles of track and a fleet of train sets sit virtually idle for most of the day until peak weekday commute hours.

The goal of this research is to explore the potential transformation of the Massachusetts Bay Transportation Authority (MBTA) Commuter Rail system into a so-called "regional rail" system. That is, a vast network of heavy rail that leverages its abundant track infrastructure to run high-frequency bi-directional service all day between major population centers in the region. The aim of regional rail service is to serve all members of society equally, not just white-collar commuters.

The Worcester/Framingham line is used as a case study, which runs from Boston's South Station through 44 miles of the Metro West corridor. Three post-pandemic demand scenarios are proposed and service simulation and schedule optimization tools are developed to generate service plans and policy recommendations that promote increased passenger demand in the near future. This analysis culminates in the proposal of a four-part investment plan for infrastructure and service on the line, culminating in a high-frequency service that serves riders only within the urban core, acting as a "second subway" to augment Boston's urban rail network.

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Acknowledgments

The past two years that I have spent at the Transit Lab have been some of the most rewarding, and the most challenging, of my life. Having spent almost the entirety of that life in sadly transit-deficient Texas before coming to MIT, I had a lot to learn about rail systems down to the very basics.

To that point, I owe an incredible thanks to the passionate transit advocates and railfans at Transit Matters who volunteer so much of their personal time to making our transit system better and who pointed me toward many potential strategies for improving commuter rail. Deserving of a special shout-out is Dave Perry, author of "Dave's Framingham-Worcester MBTA Commuter Rail Blog" which contains years of dutiful logs of every detail of the infrastructure and operation of the commuter rail line that became the subject of this thesis. It was nothing short of a blessing for me.

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Chapter 1

Introduction

Transportation is the largest source of greenhouse gas emissions in Massachusetts. With the progression of climate change starting to impact people's daily lives, the need for radical mode shift is apparent. The Massachusetts Secretary of the Executive Office of Energy and Environmental affairs has determined that the state's emissions must be reduced by 33% of 1990 levels by 2025, and 50% in 2030 [40]. According to 2022 MassDEP estimates, the state is only currently on track to reduces emissions by 34% by 2030 [40]. While personal vehicle electrification has attracted a lot of public attention, the widespread adoption of electric vehicles may take another 20-30 years and, further, is an insufficient solution to address the congestion and patterns of sprawl that strain other public resources. According to the INRIX Research 2018 Global Traffic Scorecard, Boston drivers already spend 164 hours each year in traffic. Further, the Massachusetts vehicle economy costs $64 billion [42] annually in the form of personal vehicle ownership costs, maintenance of roadways and parking facilities, collision injuries, congestion, and pollution. Of this, $35 billion is borne by the public in the form of state budgetary costs, social and economic costs. Transportation's contribution to climate change mitigation and social welfare must include a dramatic reduction in vehicle miles traveled (VMT) powered by investments in the state's public transit systems.

The Massachusetts Bay Transit Authority (MBTA) possesses a vast network of 14 commuter rail lines, spanning 398 miles of track, and serving over 80 communities and over 75% of the state's population. However, this important resource is not currently living up to its full potential, capturing only about 2% of person-trips made by this population on the average weekday in 2019. With train frequencies by line varying between 30 minutes and 1 hour during peak hours and 1 to 2 hours during off-peak, track infrastructure is very underutilized and existing service strategies do not adequately cater to demand patterns in the region and are unequipped for future growth. With hundreds of miles of commuter rail supplementing 69 miles of rapid transit, the Boston metropolitan area has a unique asset in legacy rail infrastructure that, if used strategically, could dramatically improve passenger rail service.

"Regional rail" is the name for a conceptual alternative to commuter rail which rejects 20th-century mobility assumptions that the system should primarily exist to serve suburban, white-collar, weekday commuter workforce. Regional rail emphasizes bi-directional, all-day frequent service that serves, for example, a part-time service worker who commutes late nights between suburbs as well as it serves a full-time office worker who commutes strictly during traditional AM/PM peaks on weekdays. Further, included in this vision is a transition to efficient, clean-energy electric rolling stock and infrastructure upgrades that ensure the system is physically accessible for all people.

The call for a movement away from commuter rail and towards regional rail has been ongoing since at least the 1980's [1,17]. In his 1984 work, Donald Eisele described regional rail as "the opposite end of the scale from commuter service" by providing a practical transportation service for all people at all times of day in both directions "rather than solely for the breadwinner". The idea is not only rooted in the past, in fact, it is gaining traction quickly. In 2016, Denver's Regional Transportation District (RTD) opened a 23-mile long fully-electrified service from downtown Denver to Denver International Airport at 15-minute frequencies which has since been praised by transit advocates for its frequency and reliability [35, 39].

Unfortunately, the MBTA commuter rail system has seen a decline in ridership since its peak in 2009. In fact, it was the only major commuter rail system in the nation to do so in the last two decades, having, in the same time period, increased its fares and operating costs more than any other comparable system [21]. Luckily, Massachusetts is at a unique time in its history for a major system transformation. The state's Commission on the Future of Transportation has emphasized the environmental need for transit, stating as one of its recommendations in its 2019 report the need to "move more people in fewer vehicles" to enhance the efficiency of the transportation system [43]. Massachusetts Governor Maura Healey's transportation plan acknowledges the shortfalls in current MBTA service and aims explicitly to expand commuter rail service frequency, rebranding it under the Regional Rail moniker. [43]. Locally, Boston Mayor Michelle Wu has consistently advocated for reduced fare pilots on commuter rail and for moving towards a regional rail system. On the federal level, post-pandemic stimulus spending aims to reinvigorate the country's aging infrastructure networks and transition the national economy toward a carbon-free, sustainable future. Specifically, the influx of funding from the Biden administration's Infrastructure Investment and Jobs Act (IIJA) provides Massachusetts with $4 billion in transportation formula funding towards major infrastructure investments.

Further, impending infrastructure changes in the region could create the right social environment for mode shift. The long-anticipated reconstruction of the Interstate 90 exchange at Allston will begin in the next 3 years and last for about 7 years, requiring lane closures that will cause significant traffic backups on the already crowded highway running through the Western corridor of Metro Boston. Because the interstate runs largely parallel to the Worcester/Framingham commuter rail line, this is an opportunity for the MBTA to attract displaced or frustrated highway users, especially taking advantage of the mitigation funds available from the project to reduce fares and increase service on the rail system. The feasibility of such a move is exemplified by the 2022 MBTA Orange Line shutdown incident which brought 14,000 new long-term riders to the commuter rail system following a temporary period of free inner-core fares [24].

To keep pace with economic investment in the corridor (notably Longwood, Boston Landing, and Worcester), especially in the biotechnology sector, regional rail can more efficiently connect so-called Gateway Cities to Greater Boston in ways that promote access to key destinations including jobs and education. Regional rail will also enable riders to take advantage of more affordable housing outside Boston's expensive urban core in growing transit oriented developments, like those expected to result from the MBTA Communites Act which mandated in 2021 that cities and towns served by the MBTA must zone a district of "reasonable size" for multi-family housing near MBTA stations [13].

Commuter rail was hit especially hard by the COVID-19 pandemic. As of April 2022, MBTA commuter rail ridership levels were just over half of what they were before the crisis. This is compounded by the fact that service levels, in terms of total number of daily trains, remain at around 90% of what they were pre-pandemic. More than ever, people are off-peak commuting, part-time commuting, and commuting to non-traditional locations like co-working spaces or coffee shops, yet new services have only been sparsely added to serve these patterns. With commuter rail still emphasizing unidirectional service towards and away from the core in the morning and afternoon peak hours respectively, riders who have fundamentally changed their journey patterns are shifting towards private vehicle transport.

A transformation of the passenger rail system to better accommodate potential customers in the region will likely provide economic benefits that far exceed the necessary investments as similar programs have at peer agencies. In 2007, Transport for London substantially upgraded some of its commuter rail services, dubbing these lines the London Overground (formerly called the Silverlink Metro), with a series of dramatic regional-rail-oriented changes. Namely, they implemented all-day 15-minute service (a 200% increase of train revenue miles), purchased new rolling stock, upgraded infrastructure, and integrated smartcard ticketing. In the 5 years following this transformation, the services saw a 400% ridership increase.

1.1 Research Motivation

In 2019, the MBTA and a number of other government stakeholders released a long-term plan called Rail Vision which explores the potential service and infrastructure expansion of the commuter rail system. Elaborating on goals outlined in the MBTA's 25-year strategic plan, Focus40, Rail Vision's goal was to identify, analyze, and model a number of potential service alternatives as well as evaluate the associated ridership and cost impacts. The end result of this report was a set of six "systemwide alternatives" or scenarios for the advancement of regional rail varying from low-investment, more immediate "higher frequency commuter rail" to "full transformation" which looked 20 years ahead to include major developments on the system like full electrification. The suggestions in these scenarios are presented in the form of general frequencies in terms of trains per hour and new fare structures. Following the release of Rail Vision, the MBTA Board released its first list of priorities and phasing of Rail Vision initiatives. "Phase 1A", as it was called, prioritizes the Providence, Fairmount, and inner Newburyport/Rockport lines as the first to receive additional service frequency as well as a modernization of infrastructure on the Worcester/Framingham line. As a whole, because the report's focus on the whole commuter rail system was necessarily so broad, it was unable to investigate the ground-level implications of its suggestions at a granular level or evaluate the impacts of individual infrastructure investments. Further, while the authors could not have predicted the impending COVID-19 pandemic, the plan nonetheless suffers from its inability to accommodate the impacts of this drastic shift.

This thesis seeks to expand on the work begun under Rail Vision, offering a deep-dive into the Worcester/Framingham Line as an example of how changes can be assessed and implemented system-wide. The Worcester/Framingham line was chosen as a case study for a number of reasons. The line is on the south side of the system and serves Boston's Western corridor, both of which have borne the heaviest ridership growth over the last several years and thus endured the heaviest stress on infrastructure and resources. It also connects greater Boston with two significant Gateway City destinations: Framingham/Natick and Worcester, and offers unique opportunities to improve rail access to key destinations with the addition of a new West Station at Allston and a connection to Kendall Square via the Grand Junction. The line also possesses unique infrastructure challenges in the form of single-tracking, low-level platforms, and long block lengths, and thus is ripe for upgrades. This line, however, is not considered in a vacuum, but within the context of the broader system at important transfer and terminal points. That is, the impacts on the line of a system-wide transformation are considered.

1.2 Research Objective

The objectives of the research are to explore a range of demand scenarios for the MBTA Commuter Rail Framingham/Worcester Line corridor and develop analytical tools to generate corresponding service plan recommendations which can both stimulate additional ridership on the line and accommodate it comfortably during the early, pre-electrification phases of a regional rail transition (present day - 2030). The service strategies tested will reflect goals outlined in the Rail Vision Plan while adjusting assumptions to conform to post-pandemic realities. This research will pay special attention to the potential efficacy of a high-frequency service which serves inner-core riders, defined in this work as Newton and Boston. A suite of useful tools is developed that will directly aid the MBTA and Keolis in planning service and prioritizing capital investment.

There are additional factors that are important in the implementation of such a plan but are outside of the scope of this thesis. While the storage of rolling stock can have major implications on operational capability, evaluation of potential new train storage and maintenance sites is also outside of the scope of this work, as plans for the use of recently acquired Widette Circle have not yet progressed, and will require time for engineering and construction. The North-South Rail Link and a possible extension from South Station to the airport require billions in investment and a long engineering and construction time. While they are important future possibilities that should not be precluded, they are beyond the scope of this thesis. Establishing a West Station to replace the function of Allston Depot which was closed when the Massachusetts Turnpike (I-90) was built, and establishing a West Station to North Station rail shuttle service via the Grand Junction are major near-term objectives of the Mayor of Boston, the Worcester Chamber of Commerce, the Senate president (who represents Framingham), and Kendall business interests, and are included in the current active planning of the Allston Multimodal Project. But because rail service to West Station can only begin upon completion of the Multimodal Project, it is not a focus of this thesis.

1.3 Data Sources

The data used in this thesis was obtained through public online records or received directly from the MBTA or its contracted operator, Keolis. From the public record, we obtain regional demographics, CTPS commuter rail counts, and economic data from sources including the ACS/Census, and the MAPC. Data which comes from non-publically available sources is described below. As much of the described ridership data is incomplete or otherwise flawed, gaps in information are filled with assumptions and corrective algorithms.

Ridership

In 2018, CTPS conducted a one-day full count of all boardings and alightings at each station on commuter rail services. Origins and destinations of riders can be inferred from an iterative proportional fit methodology. This provides a high-accuracy baseline to compare to the more comprehensive data source, the mTicket app. mTicket is a mobile app provided to customers by the MBTA exclusively for purchasing Commuter Rail tickets, for which the pay-per-use Charlie Card cannot be used. This data gives origin and destination information as well as time of ticket activation, but does not give train number or direction of travel. Lastly, onboard payment data supplements ridership information from the passengers who pay by cash or card onboard. Left out of all of this data is any customer who uses an employer-provided Perq pass or pays at a kiosk in the station.

Train Location

Automatic Vehicle Location (AVL) data is provided by Keolis and provides the latitude and longitude of a given train in approximately 30-second pings. A separate dataset provides the time at which audio announcements of station arrivals and departures are played, giving an approximation of station dwell times for each train.

Crew, Equipment, Incidents

A variety of daily operational reports from Keolis provide information on each daily train trip, including the number of crew scheduled for each trip, the length of the train consist, and a description of any major delay events that occurred.

1.4 Thesis Outline

Chapter 2 reviews the history of the MBTA Commuter Rail system and addresses how this history, including changes of ownership, parallel highway developments, and agency priorities, contributed to the unique infrastructure challenges of operations on the Worcester Line. Further, it details the status quo of infrastructure and operations on the line today.

Chapter 3 explores ridership on the Worcester Line utilizing mobile ticketing data and official ridership counts. This chapter also looks into demand projections from a prior study in the corridor and introduces a basic mode-choice methodology for creating three sketch-level future demand scenarios.

Chapter 4 focuses on the operational aspects of the line. An analysis of vehicle trajectory data and track infrastructure is performed to identify operational bottlenecks on the line and to assess how reliability and travel times are affected by congestion levels. This chapter introduces a time-based simulation tool that is used to predict trajectories for service patterns under infrastructure conditions not yet in existence.

Chapter 5 combines the demand and simulation tools introduced in previous chapters to evaluate the efficacy of various potential infrastructure investments in terms of capacity and ridership benefits.

Chapter 2

Worcester Line: Past and Present

2.1 The Worcester Line in the Past

The Worcester/Framingham line of the past looked a lot like the one of the present, with a few notable exceptions. Today, Worcester commuter rail trains run along the original alignment of one of the oldest rail lines in North America, and the first commercial rail line in Massachusetts, the Boston & Worcester railroad (later the Boston & Albany), which was opened in sections between 1834 and 1841. This railroad effectively introduced the idea of commuter rail, beginning commuter-oriented service to West Newton in 1834 at $60 for a season pass. What is now the entire above-ground portion of the Riverside D-branch of the MBTA's Green Line was once a commuter offshoot of this original rail line, and was known as "the Highland Branch" [23]. The Highland Branch

Figure 2-1: In October 1996, commuter rail service to Riverside was temporarily restored due to heavy flooding forcing a closure of the Green Line D Branch [http://photos.nerail.org/s/?p=1720]

started just West of present-day Lansdowne (known as Yawkey station until 2019) and rejoined the main line at a switch between present-day Control Point 11 and Auburndale station. This switch still exists, but the track is no longer accessible to commuter rail trains and remains blocked off by a gate.

Another significant rail link, the Grand Junction Railroad, was built between 1849-1856 and originally served to move freight between the busy docks of East Boston to freight yards in Somerville and eventually across the Charles River to Allston. This last expansion joined the Grand Junction to the Boston & Albany to form a major national freight link, though it never ran passenger service. Today, this segment is still used for regular freight service as well as transporting commuter rail and Amtrak equipment between the South Side and North Side lines and to maintenance facilities in Somerville.

At its height, the Boston & Albany line was four tracks wide all the way from Boston to Framingham, compared to today's two. In 1961, the four-track right-of-way was sold to the Turnpike Authority, and by 1965, the Turnpike was completed between Route 128 and Boston, eliminating two of the four tracks and demolishing existing stations in Newton, which were later rebuilt as low-level platforms only on the southern side of the tracks [36].

The MBTA first acquired trackage on the line in 1973, but only on the portion East of Framingham. Commuter service run by the MBTA didn't extend to Worcester until 1994, and even then had only very limited services during peak hours [8] The remaining trackage, from Framingham to Worcester, was not purchased by the MBTA from CSX until 2012. It has been operated by Keolis Commuter Services on behalf of the MBTA since 2014.

Trains today stop at many of the same stops they did during the Boston & Albany days, with a few extra additions. In 1988, Yawkey station (known today as Lansdowne) was added to provide convenient access to Fenway Park, and the Longwood Medical area. Between 2000 and 2002, four infill stations were added at Ashland, Southborough, Westborough, and Grafton. The newest station is at Boston Landing, which was opened in 2017 as an infill station between Lansdowne and Newtonville. The station was financed by footwear manufacturer New Balance as the company was constructing its $500 million mixed-used development one block away from where the station now stands. Additionally, four stations serving Newton Corner, Brook Street, Market Street, and the Allston depot were totally eliminated from the original line.

2.2 The Worcester Line in the Present

2.2.1 Infrastructure

As of today, the Worcester Line is double-tracked for all of its 46-mile length. Typically, the trains will utilize the northernmost track ("Track 2") to travel outbound and the southern track ("Track 1") to travel inbound. However, this is not always the case as rail tracks are bi-directional and trains sometimes must travel in opposite directions to what is typical. There are in total five grade crossings along the line where the trains interact with automobile traffic. There are 18 control points where movement between the two tracks is possible. Each of the two tracks is divided into 26 blocks, ranging in length from 0.4 miles to 5.6 miles (see Appendix A for exact boundaries and Track Diagram). Speeds on the line range from 10 miles per hour in the terminal to a height of 60-79 miles per hour on the remainder of the line.

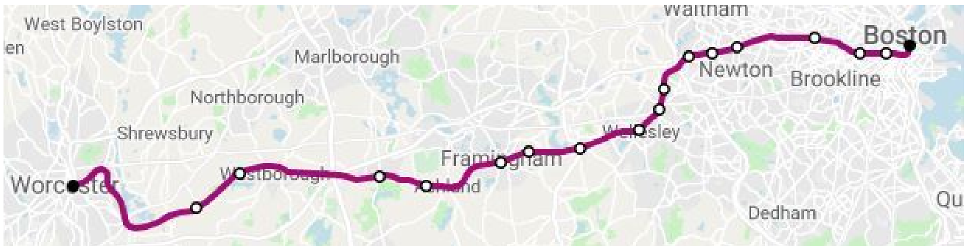


Figure 2-2: The 46-mile extent of the Worcester/Framingham Line

There are eighteen stations along the Worcester Line. It has three primary termini: Worcester to the West, South Station to the East, and Framingham at the approximate midpoint. The Worcester terminus can hold one train at a time at its single North-side platform and can store up to four trains on layover tracks. South Station consists of nine arrival/exit tracks and thirteen platform tracks shared among the nine south-side commuter rail lines as well as Northeast Corridor Amtrak trains and South Coast Rail trains. Currently, only three of the stations on the line have full high-level boarding platforms. Many of the stations on the line have low-level or mini-high platforms. Some stations in Newton and Worcester face unique operational challenges, such as having a platform on only one side of the tracks.

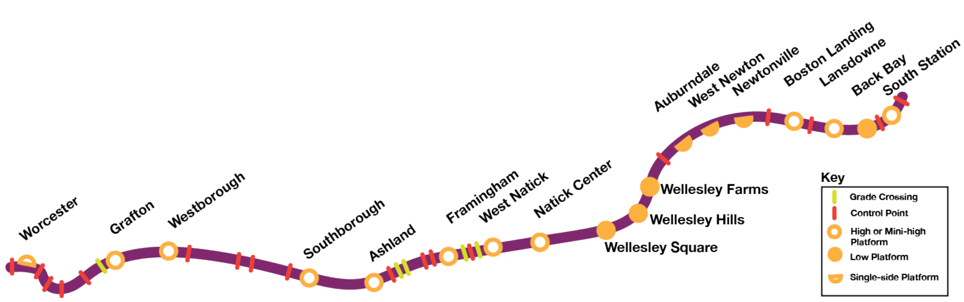


Figure 2-3: Current infrastructure on the line

2.2.2 Access

Commuter rail stations, like most transit, may be accessed by personal vehicle, cycling, or walking. Ease of access is thus limited by parking availability, bike lane, and pedestrian infrastructure. For those living outside of a cyclable distance or who are physically unable to do so could benefit from shuttle busses that transport passengers from their neighborhood to the commuter rail station, however, no such shuttle services are currently known exist. Of the fourteen stations that offer any private vehicle parking, six have utilization rates of 90% or above.

A 2020 work by Sevstuk et al. [49] evaluated the perceived walk and cycle buffers around commuter rail stations in the MBTA network. Because these commuter rail stations lacked desirable road conditions (low speed limits, flat elevation, low traffic volumes, sidewalks), protected bike lanes, and desirable mixed-use amenities, local residents' willingness to walk and cycle is well below the oft-referenced 0.5 and 1.5 miles respectively.

Signaling

Operations on the line are guided by an Automatic Block Signalling (ABS) system. Each block (50 in total) is protected by a signal which will display red when there is a train occupying this block or yellow when there is a train occupying the next block ahead. When faced with a red signal, trains must come to an immediate stop. When faced with a yellow signal, trains must reduce their speed. Due to the length

Table 2.1: Parking resources and utilization by station

Station	Spaces	Daily Rate	Monthly Rate	Utilization
South Station	210	$30	$445	unknown
Back Bay	N/A	N/A	N/A	N/A
Lansdowne	N/A	N/A	N/A	N/A
Boston Landing	N/A	N/A	N/A	N/A
Newtonville	N/A	N/A	N/A	N/A
West Newton	161	$4	$70	60%
Auburndale	35	$6	$105	89%
Wellesley Farms	190	$6	N/A	99%
Wellesley Hills	55	$6	N/A	100%
Wellesley Square	224	$6	N/A	62%
Natick Center	71	$7*	$69**	52%
West Natick	178	$6	$105	97%
Framingham	294	$4	$70	95%
Ashland	693	$4	$70	80%
Southborough	372	$6	$105	95%
Westborough	448	$6	$105	96%
Grafton	386	$4	$70	67%
Worcester	500	$15	$173	65%
* Town permit required ** Paid in annual sum $830				

Table 2.2: Bicycle and Pedestrian Infrastructure by Station

Station	Bike lane?	Bike Spaces	Sidewalk Condition	Classification
South Station	Yes	94	Good	-
Back Bay	Yes	85	Good	-
Lansdowne	Yes	10	Good	-
Boston Landing	No	Good	-	-
Newtonville	No	0	Good	-
West Newton	No	16	Good	-
Auburndale	No	16	Good	-
Wellesley Farms	No	25	Poor	-
Wellesley Hills	No	12	Good	-
Wellesley Square	No	12	Good	-
Natick Center	No	9	Good	-
West Natick	No	32	Fair	-
Framingham	No	37	Good	-
Ashland	No	18	Good	-
Southborough	No	8	Good	-
Westborough	No	6	Poor	-
Grafton	No	8	Good	-
Worcester	No	12	Good	-
* Town permit required ** Paid in annual sum $830				

of these signaled blocks which can be multiple miles long, in the most extreme case between Southborough and Westborough, a train may have to slow its speeds with almost 9 miles between itself and the closest train.

Dispatch

At South Station, trains from all lines may be assigned to any of the 13 platform tracks for passenger boarding and alighting. This assignment is planned in advance and executed by an Amtrak employee with the title "Train Master", but often changed ad-hoc to accommodate delayed trains. The signal interlocking to access South Station platforms is called "Tower 1" and functions as a Route-Lock-Route-Release system, meaning that a train moving through the interlocking claims every track segment and switch it uses for the entire time of the movement. Any other trains scheduled to make a movement that shares any of these claimed segments or switches must wait until the first train has completed its movement before entering the interlocking.

2.2.3 Rolling stock

All MBTA commuter rail locomotives are diesel-electric locomotives. The current models in use are the F40 (1987) and the HSP-46 (2014). These locomotives will typically pull a set of six bi-level cars which seat between 173 and 185 passengers each. They are able to accelerate at a maximum rate of 3.7 ft/s^2. The age of the F40 vehicles means that they are now reaching the end of their useful life, as the MBTA generally adheres to a 25-year life cycle for commuter rail equipment. However, in 2019, the agency completed an overhaul of much of the F40 fleet in order to extend the locomotives' lifespan by "up to 20 years" (2032). The F40 and HSP-46 fleets have a mean distance between failures of about 8,000 miles and 28,000 miles respectively by 2018 estimates [25].

Individual train sets are not assigned specifically to the Worcester Line. Rather, the MBTA makes use of interlining – moving train sets between routes – in order to optimize schedules and equipment availability. When the vehicles begin operations or need refueling or maintenance or end operations, they go to a maintenance yard. This includes Readville, Nevins, and the Amtrak Southhampton Street and Front Yards. Trains are not stored at the Southside Service and Inspection Facility, but may occasionally need to go there for non-revenue maintenance trips. In April 2023, the MBTA completed the purchase of Widett circle, a 24-acre storage and maintenance property near South Station, which should reduce need for layover in Hyde Park which is nine miles away.

Chapter 3

Demand in the Western Corridor

This chapter examines demand in the Western corridor alongside ridership on the Worcester line through the study years of 2018 to 2022 and looking forward to 2025. It begins with a conceptual review of the characteristics of commuter rail's ridership base and the way that changes in the corridor will likely alter that base in the next several years. Following that is an exploration of the ridership data used in this study, where fare collection information is used to quantify trends in past ridership over the study period. The remainder of this chapter explores the development of a demand tool used to anticipate, at a sketch-level, three possible scenarios for the demand for Worcester Line service following major impending changes to the market and to the service itself.

3.1 The Worcester Line Rider

Historically, perceptions of Commuter Rail have centered around its often perceived primary purpose to serve white-collar, 9-to-5 commuters from the suburbs to the business district, Monday through Friday. Though this has never been the exclusive audience of the mode, diversification of the demographics of its riders has been especially pronounced over the last five years. To provide the best insight into riders' patterns and motivations for travel, one should look at survey responses. Each year, the MBTA conducts a rolling survey of passengers, called the Systemwide Passenger Survey, aggregating and releasing the data to the public when a sufficient amount has been collected. A comparison of the 2015-2017 MBTA System-wide Passenger Survey to its 2022 equivalent provides a key look into the shifts in demographics and travel behaviors that have occurred within the study period.

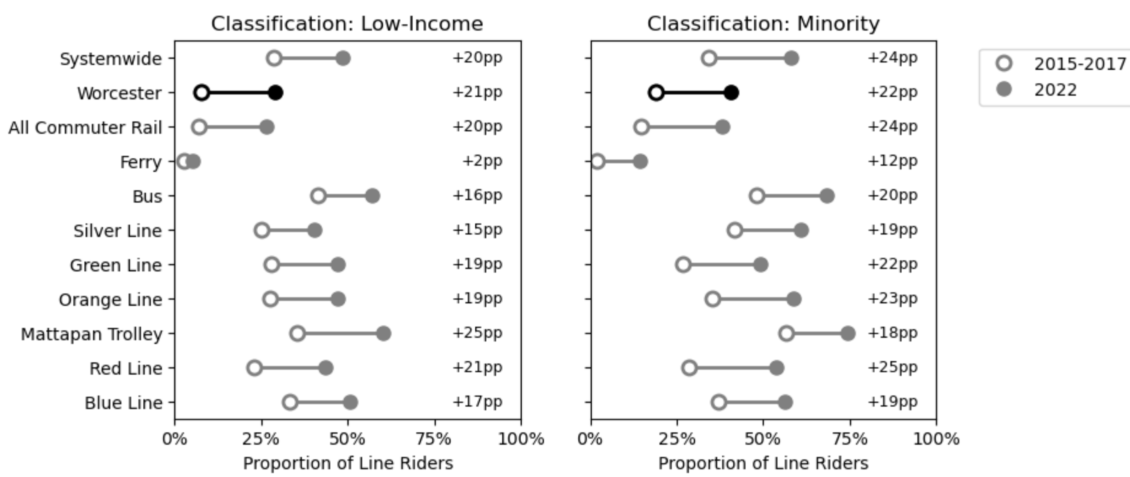
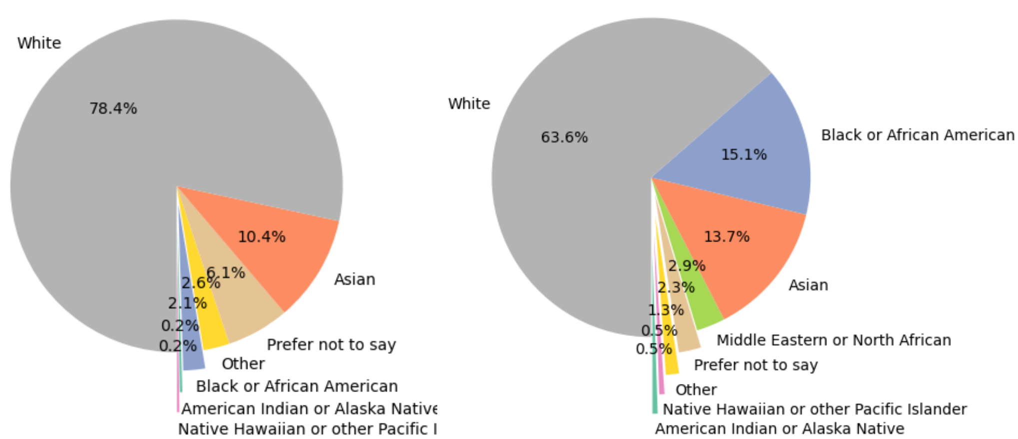


Figure 3-1: Proportion of riders identified as low-income by mode

In line with perceptions, Commuter Rail riders have a higher average income than those using other modes in the system, excepting Ferry service. However, between the 2015-2017 and 2022 survey reports, Commuter Rail saw an increase of 19.5 percentage points in its share of riders identifying themselves as low-income, now up to 26.3% (29.0% on the Worcester Line). Notably, the MBTA's Disparate Impact/Disproportionate Burden Policy increased the cut-off definition of low-income from \$43,500 to \$56,000 between the two survey periods though this is not the sole explanation for the shift. Some of this change may be attributable to the trend for low-income residents to move to the suburbs from Boston due to rising housing costs in the city [22].



(a) 2015-2017

(b) 2022

Figure 3-2: Racial composition of Worcester Line Riders

In a similar pattern of diversification, all modes in the system have seen substantial rises in riders self-identified as minorities, but Commuter Rail has had the most dramatic increase. On the Worcester Line,

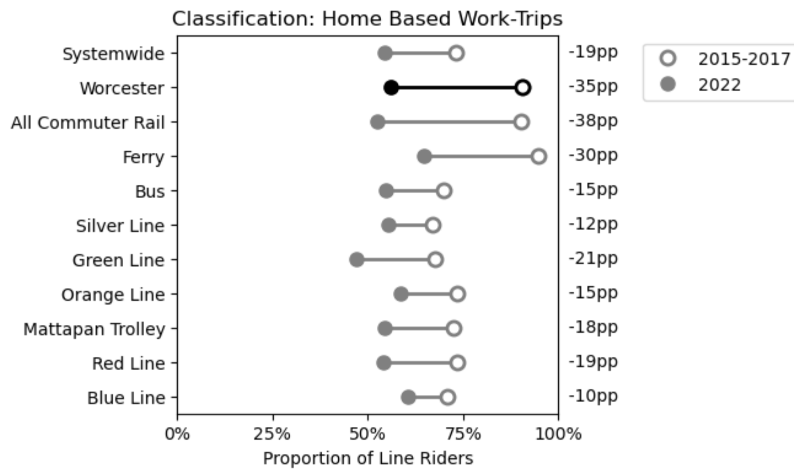


Figure 3-3: Trips purpose by mode

that proportion has jumped from 18.8% to 40.5%. The majority of this increase comes from Black and Asian riders, having risen 13.0 and 7.6 percentage points respectively. Though Black and Asian populations have been rising in the corridor, the mode's shift in demographics far outpaces the growth of those populations and likely demonstrates a significant shift in how the service is used [12]. To reaffirm that point, home-based-work (HBW) trips as a percentage of total trips have fallen dramatically on Commuter Rail, comprising only 52.4% of all trips in 2022 from 90.2% in 2015-2017. This is a more significant decrease than the average proportion of HBW trips across all MBTA modes (54.5% from 73.2%) and substantially less than the proportion of HBW trips on the Blue and Orange Lines (60.7% from 70.8% and 58.7% from 73.3% respectively). Further, the frequency of riders' trips has evolved from a predominance of 5 days a week travel to a much more even split towards lower frequencies such as 3-4 days per week or less than once per month.

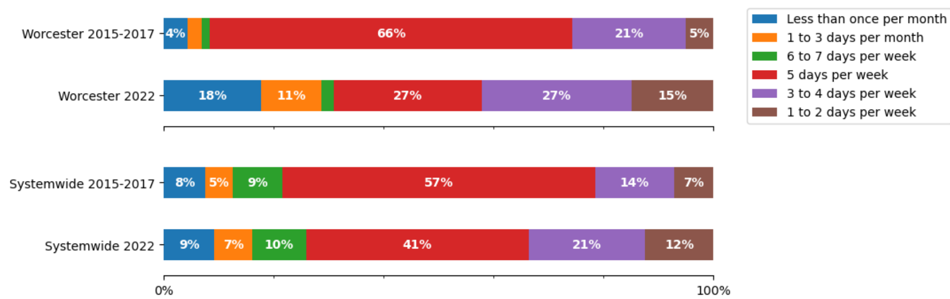


Figure 3-4: Trip frequency by year at the line and system levels

3.2 A Changing Landscape

Many factors influence the demand for a mobility service. The COVID-19 pandemic has changed the way many people travel and how often they do so, and new zoning policies and booming economic sectors are redistributing the housing costs and employment landscape across the region. In the midst of all this change, calls for corresponding changes to the MBTA Commuter Rail service delivery model are growing louder.

3.2.1 COVID-19 Impacts

Several phenomena have affected the shape of the total transportation trips market since the beginning of the COVID-19 pandemic State of Emergency declaration in March 2020. Certain major decisions such as residential moves, automobile purchases, and modified employment structures imply long-term effects, while factors like fear of disease transmission have mitigated and will likely continue to do so. As noted in Gkiotsalitis and Cats (2020) [20], previous global crises including SARS and the September 11th attacks in the early 2000's have not fundamentally altered travel patterns, outside of security and sanitation measures. Though many early avoiders of public transit during the pandemic feared transmission from contaminated surfaces and air inside transit vehicles, the Centers for Disease Control and Prevention (CDC) confirmed in April of 2021 that "each contact with a contaminated surface has less than a 1 in 10,000 chance of causing an infection" [18].

Though the number of people working from home full-time has decreased dramatically since Spring 2020, many retain at least partially remote work weeks. After conducting a longitudinal survey of U.S. residents between November 2021 and June 2022, Caros et al. (2023) found that 29.1% of work-hours were completed in the home during this time period and another 15.9% were completed from a so-called "third place", which could be a public space, co-working space, or a friend or family member's home [11]. The authors also found that commute trips to these third places were shorter on average than commute trips to traditional workplaces and more likely to be made on slower travel modes, like cycling and walking. Though these changes in commute behavior are explanatory of the drops in the trips market as a whole, transit agencies are still seeing falling demand that is disproportionate to the fall of the market itself. This is likely due to a mixture of lingering habits of avoiding public space during the COVID-19 pandemic as well as consequences of major decisions made during that time period, especially relating to vehicle ownership. Leveraging data from a map-based survey tool, Zheng et al. (2023) found that in the Greater Boston area "the absolute elasticity of travel time for transit has increased from -0.487 to -0.534 between pre-pandemic time and the fall of 2021, showing that people have become more sensitive to the travel time of commuting by transit" [52]. In 2022, Palm et al. found via analysis survey data that a car purchase explained the greatest variance in anticipated future transit use in Toronto and Vancouver, reflecting the 'stickiness' in travel habit changes [44] [47].

3.2.2 Population and Economic Shifts

All of the cities and towns in the Western Corridor housing a commuter rail station have seen population growth between 4 and 20% over the last ten years, with highest rates in towns furthest from Boston [19]. Though housing prices have increased in tandem, putting a strain on potential new residents, state policy has been introduced to mitigate this effect and ensure that continued growth is possible throughout the state. In 2021, the MBTA Communities Act was passed requiring local governments in so-called "MBTA communities", including every municipality with a commuter rail station, to increase zoning for multifamily housing near transit stops. While this mandatory up-zoning does not immediately translate into actual housing units, it will allow developers to construct these desirable properties, eventually increasing the market for commuter rail and reducing the average access times to stations.

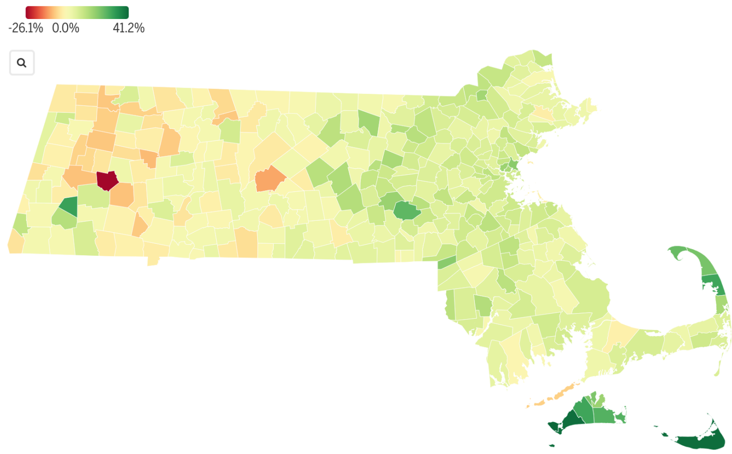


Figure 3-5: Change in population by Massachusetts town between 2010 and 2020 Census [19]

Economic sector growth is also shifting the way people travel in the corridor. Previously concentrated in Kendall Square and in the Longwood Medical Area, biotech laboratories have expanded into nearly every corner of Greater Boston, including the Metro West corridor (Figure 3-6) [10]. According to a Boston Globe report from August 28, 2022, public officials have recently approved the first biotech lab space in Wellesley [26]. Trends also indicate a shift away from downtown office spaces towards smaller office spaces spread throughout suburbs and exurbs, as companies try to accommodate the desires of employees accustomed to working from home [26]. Lastly, developments related to recreational activities may prompt more "reverse" and off-peak travel in the corridor. The WooSox baseball team, a Triple-A farm team for the Boston Red Sox, was recently relocated in 2021 from Pawtucket, Rhode Island to Worcester's new Polar Park stadium which was constructed within a few minutes' walk of the Commuter Rail Union Station.

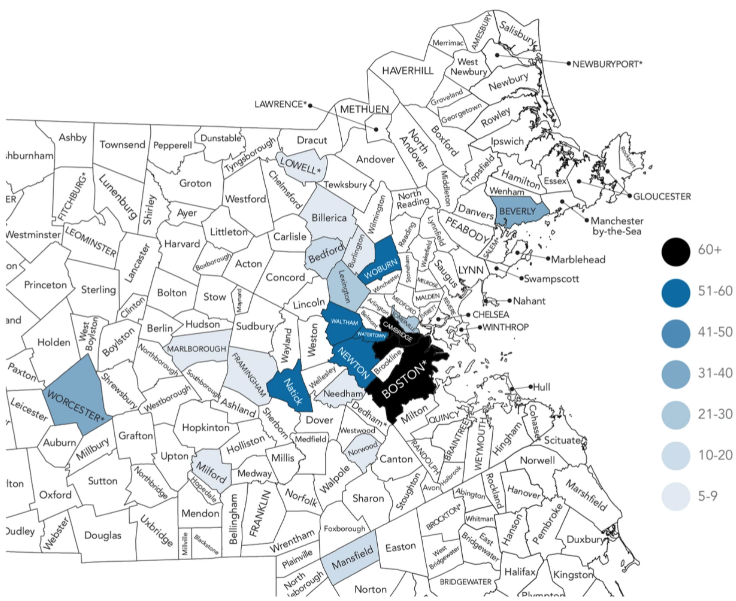


Figure 3-6: Number of companies enrolled as a member in the Massachusetts Biotechnology Council [32]

3.2.3 The Allston Multimodal Project

The Allston Multimodal project has been under design by MassDOT and its Design Team since 2014. Its stated goals are to improve the livability and connectivity of the Allston neighborhood, improve mobility and roadway safety, and replace the Allston Viaduct in order to reduce maintenance needs on the aging infrastructure. The chosen design alternative, the Modified At-Grade Option, includes plans for a new Worcester Line Station, West Station, to serve Allston and possible connections to Kendall Square and North Station via the Grand Junction Railroad. As reported on the public-facing project fact sheet, the project is anticipated to begin construction in the fourth quarter of 2023 and last between 6-10 years. Anecdotally, from stakeholders involved in the project, it is expected that the four-lane highway will reduce to 3 lanes during the construction work, equating to a 25% loss of capacity in the interchange for the one-mile length of the project. Beyond loss of physical lane capacity, delays caused by the bottleneck phenomenon are likely to further reduce flows. MassDOT has not yet made public any corridor studies performed to assess mitigation needs, making it difficult to anticipate exactly how significantly the project will affect travel times on the Interstate.

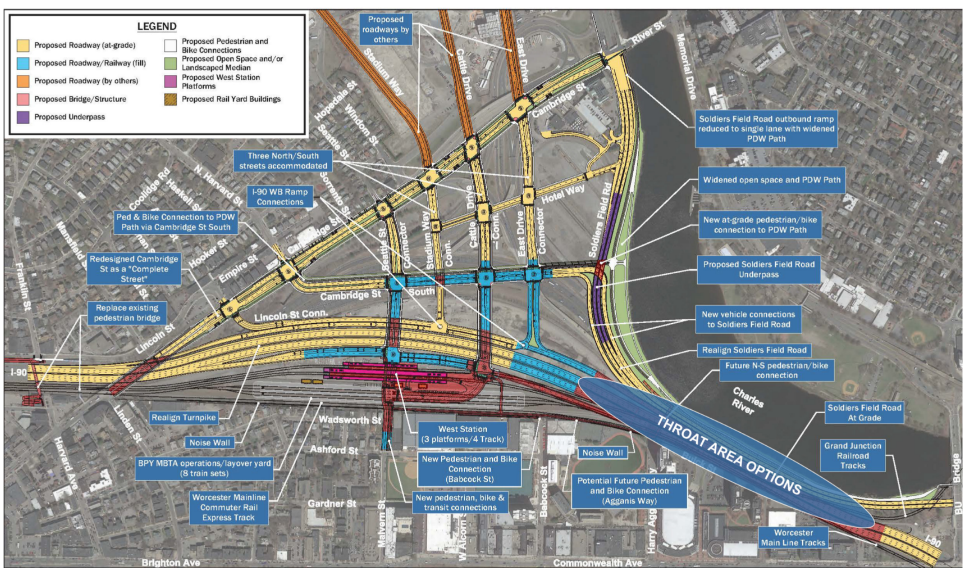


Figure 3-7: Allston Multimodal Project Features

3.2.4 Calls for Fare Reform

The construction period for the Allston Multimodal Project presents a unique opportunity to reduce fares as a pilot on the Worcester line. In fact, there is already significant political support for the idea; Massachusetts Senate President Karen Spilka of Ashland has stated that "any plan for this project must include increased reliability, frequency and affordability on the commuter rail during the construction and after if this is going to go forward" [15]. Representative Hannah Kane of Shrewsbury has also been vocal about the need for commuter rail fares to be competitive with the auto mode in the corridor.

Previous MBTA fare pilots show both the feasibility of such a program and the effective boosts to ridership it can provide. In December 2021, the Boston Transportation Department randomly selected 1,000 people who work in several Main Street districts in Boston to receive free $60 value MBTA passes [34]. Workers who received these passes took over four times as many transit trips (8.3 trips) as the control group (2 trips) in the first four weeks of the program. In a study of transit price elasticity under decreased fares, Liu et al. [30] calculated an elasticity of 2.52 when a decrease in average cost per journey of 6.7% led to an increase in total ridership of 12.1%. The authors point out that most of that ridership is not new riders, but rather current riders choosing to increase the number of trips they take. This could indicate that a possible fare policy reform will lead people to see the Worcester line as an option for more, shorter, trips. Further, given the recent demographic shift towards a significant proportion of low-income riders, high fares could be placing undue financial burden on those least able to afford it.

Inner Core fares are also an option to bring commuter rail payments more in line with subway fares. For a year beginning July 1, 2020, the MBTA conducted a fare pilot on the Newburyport/Rockport line in which riders at Lynn or Riverworks stations would only pay $2.40 rather than the typical $7 [48]. This was an attempt to move overlapping riders from the Blue Line (at capacity) to the Commuter Rail line (excess capacity).

3.3 Data Background and Assumptions

Fares on the MBTA Commuter Rail system are divided into 10 distance-based fare zones (Fig. 3-8). However, the Worcester Line only extends as far as zone 8. Many fare products are offered which provide levels of savings based on bulk-buying. Fare purchases for Commuter Rail can be made in advance at the station, onboard the train, or through the mTicket app.

The ridership data used in this thesis consists of 606,954 mTicket app activations spanning the five October months from 2018-2022. Additional data sources used to validate and make adjustments to this data include the CTPS 2018 One-day Commuter Rail Ridership Counts (accessed through a public database at mass.gov), and official daily ridership numbers provided by operator Keolis Commuter Services which are based on manual conductors' counts. Each dataset comes with

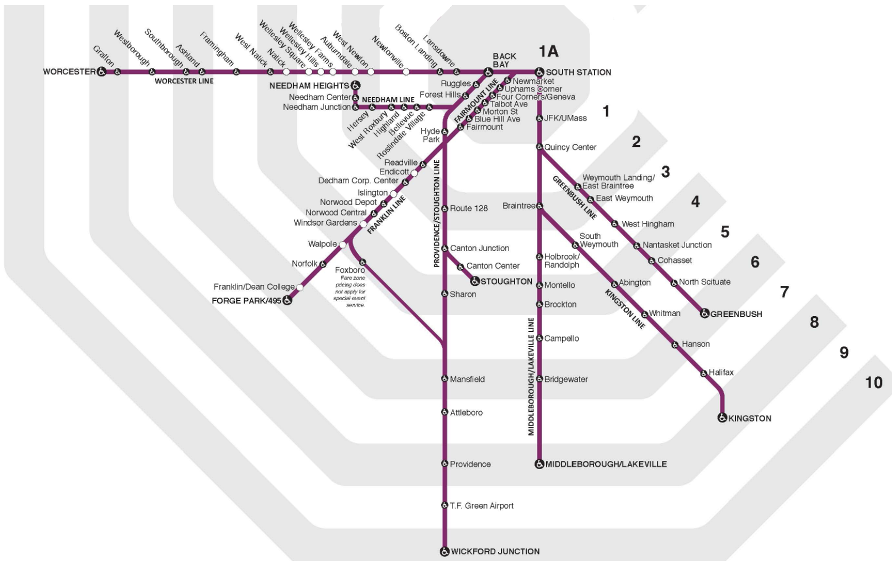


Figure 3-8: Commuter rail fare zones

unique weaknesses which are identified in this section. Taken together, and correcting for those weaknesses, a reasonably strong and reliable data platform is developed on which to build an analysis. Given the CTPS one-day count reported a total of 18,637 riders, and the average daily October mTicket trips totaled only 7,890 it is estimated that the mTicket data accounts for about 42% of all riders. The 58% of riders excluded are those paying in-person or onboard or using company-provided "Perq Passes" which are simply shown to a conductor rather than scanned by a machine.

3.3.1 Developing a Baseline: CTPS Commuter Rail Counts

The CTPS one-day count reflects boardings and alightings across all MBTA commuter rail lines collected between March and June of 2018 (with some recounts in September and October). Given the evidence that mTicket likely does not reflect the true travel behaviors of riders, this CTPS dataset, being a manual count, is used as an invaluable baseline for correcting the mTicket data later in the chapter.

Because this data gives passenger information as boardings and alightings, an iterative proportional fit methodology is used to infer an Origin-Destination probability matrix. Lacking an informative prior distribution (e.g. an on-board survey), the null base matrix is used. This method inherently provides a guess at passengers' true travel patterns and cannot be assumed to be completely accurate, as the method is equivalent to assuming that any passenger already onboard when the train arrives at a stop is equally likely to alight at that stop [33]. However, previous work by McCord et al. (2010) in estimating bus passenger origin-destination data from boarding and alighting information has found that the quality of the resulting matrices from a null base IPF procedure was "roughly similar to that of matrices derived from an onboard survey" [33]. To maximize possible accuracy, the IPF was conducted at the trip level, then each trip-level OD matrix was summed and consequently normalized to produce the full weekday probability matrix found in Figure 3-10.

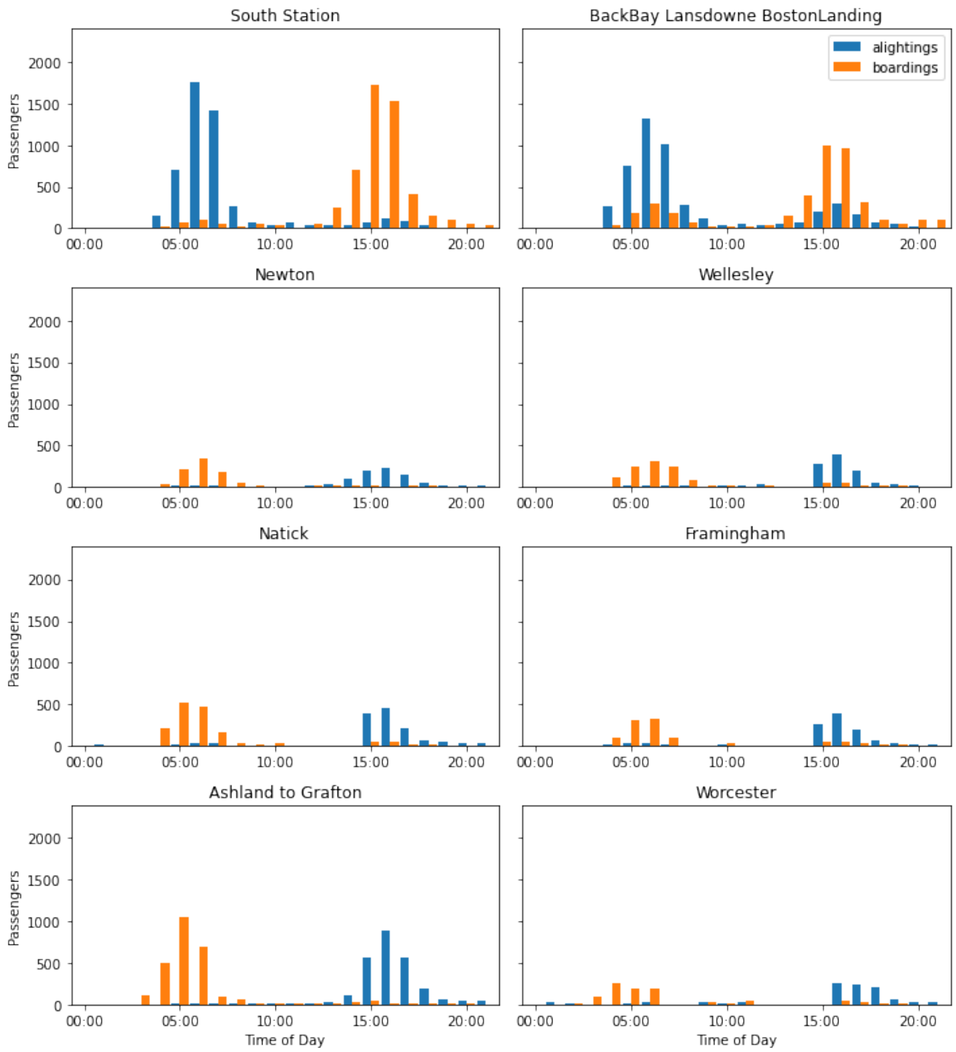


Figure 3-9: 2018 CTPS Counts boardings and alightings with time and geographical group

3.3.2 Analyzing the Status Quo: mTicket sales

mTicket is an app run by the MBTA exclusively for purchasing commuter rail tickets. Users of the mTicket app may purchase a ticket at any time by specifying an origin station and a destination station.

Destination

Origin	South Station	Back Bay	Lansdowne	Boston Landing	Newtonville	West Newton	Auburndale	Wellesley Farms	Wellesley Hills	Wellesley Square	Natick Center	West Natick	Framingham	Ashland	Southborough	Westborough	Grafton	Worcester	
South Station	0.00	1.45	0.32	1.31	1.35	0.80	0.60	0.95	0.81	1.77	1.89	2.61	3.50	2.89	1.79	2.14	1.35	3.66	29.17
Back Bay	0.30	0.00	0.21	0.71	0.61	0.34	0.25	0.39	0.37	0.80	0.86	1.07	1.62	1.15	0.75	0.89	0.56	1.56	12.45
Lansdowne	0.52	0.31	0.00	0.29	0.29	0.16	0.12	0.19	0.18	0.37	0.45	0.49	0.72	0.53	0.33	0.38	0.28	0.81	6.41
Boston Landing	1.40	0.77	0.40	0.00	0.06	0.03	0.02	0.03	0.05	0.10	0.10	0.04	0.10	0.01	0.01	0.01	0.01	0.07	3.22
Newtonville	1.20	0.75	0.32	0.04	0.00	0.01	0.01	0.02	0.01	0.03	0.03	0.02	0.03	0.01	0.01	0.01	0.01	0.03	2.55
West Newton	0.68	0.41	0.17	0.02	0.02	0.00	0.00	0.01	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.01	1.37
Auburndale	0.55	0.35	0.15	0.02	0.01	0.00	0.00	0.03	0.02	0.05	0.03	0.02	0.03	0.01	0.01	0.01	0.01	0.02	1.33
Wellesley Farms	0.77	0.48	0.21	0.03	0.02	0.01	0.01	0.00	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.01	1.60
Wellesley Hills	0.86	0.54	0.24	0.04	0.02	0.01	0.01	0.01	0.00	0.02	0.01	0.01	0.01	0.00	0.00	0.01	0.00	0.01	1.80
Wellesley Square	1.60	0.95	0.44	0.07	0.04	0.01	0.02	0.02	0.02	0.00	0.05	0.02	0.05	0.01	0.01	0.01	0.01	0.03	3.36
Natick Center	1.91	1.07	0.52	0.07	0.05	0.01	0.02	0.02	0.02	0.05	0.00	0.04	0.07	0.01	0.01	0.01	0.01	0.05	3.95
West Natick	2.64	1.50	0.59	0.05	0.02	0.01	0.01	0.02	0.01	0.03	0.03	0.00	0.05	0.02	0.01	0.02	0.01	0.05	5.07
Framingham	2.79	1.59	0.68	0.06	0.04	0.01	0.02	0.02	0.01	0.03	0.05	0.03	0.00	0.15	0.10	0.12	0.08	0.28	6.06
Ashland	2.72	1.42	0.55	0.03	0.01	0.00	0.00	0.01	0.01	0.02	0.02	0.01	0.07	0.00	0.02	0.03	0.02	0.06	5.00
Southborough	1.50	0.82	0.35	0.01	0.00	0.00	0.00	0.01	0.00	0.01	0.01	0.01	0.05	0.00	0.00	0.00	0.01	0.03	2.82
Westborough	2.20	1.15	0.44	0.02	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.06	0.00	0.02	0.00	0.02	0.07	4.05
Grafton	1.53	0.80	0.34	0.02	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.04	0.00	0.01	0.02	0.00	0.02	2.83
Worcester	3.43	1.96	1.03	0.07	0.02	0.00	0.00	0.03	0.01	0.03	0.03	0.03	0.18	0.02	0.05	0.04	0.02	0.00	6.96
	26.61	16.34	6.95	2.86	2.55	1.42	1.11	1.74	1.52	3.33	3.62	4.43	6.62	4.85	3.16	3.71	2.39	6.77	

Figure 3-10: 2018 CTPS count origin-destination probabilities after IPF procedure. The matrix is normalized to 100% to reflect percent likelihood of each passenger making a given paired trip

The user must then "activate" a purchased ticket before the conductor comes to scan it onboard the train. However, some passengers might activate the tickets long before they board the train or may not activate them until many minutes after boarding when they see the conductor comes around to scan. From riders' anecdotal evidence, it is also the case that many passengers ride without having their tickets scanned at all, and thus data about their trip is not collected. Officials at the MBTA estimated in 2019 that this current fare collection system has resulted in a loss of at least 4-8% of total commuter rail revenue or

$10-20 million [37].

Further, the data from the mTicket app does not explicitly give the trip number or trip time to which the passenger is linked. Rather, it contains the time the ticket was activated. The nature of purchasing tickets, whether one-way or round trip, by specifying an origin and destination station also leads to a number of phenomena that bias the data. As a result, on any kind of multi-trip ticket (Round Trip, Weekend Pass, Monthly Pass, 10-Ride), all trips will be recorded with the original origin and destination pairs entered. This means that many outbound trips will look like inbound trips, and vice versa. Further, subsequent uses of the pass may have different origins and destinations than the original ticket. For example, a Weekend Pass could be used on the Worcester/Framingham line on Saturday then for the Providence/Stoughton line on Sunday, or a Framingham to South Station multi-use ticket may be used to commute from Framingham to South Station one day, but then used to travel only to Newton the next. In the next paragraph, the process used to account for the inbound/outbound error is described. However, the data does not provide enough information to make similar adjustments for tickets that may actually correspond to a different set of origin-destination pairs, or to another line altogether.

Figure 3-11 demonstrates the origin-destination matrix of the raw mTicket data for all five study years. One can observe that the sum of inbound trip probability (59.1%), represented by the lower left triangle, is far greater than the sum of outbound trip probability (40.9%), rep-

Table 3.1: Data Counts from mTicket sales

Ticket type	2018	2019	2020	2021	2022	Total
mTicket Monthly Pass	47716	50753	1226	4421	4198	108314
mTicket Weekend Pass	6047	7244	2492	7179	8163	31125
Onboard Round Trip	6932	5792	596	2052	1416	16788
mTicket Flex Pass	N/A	N/A	1117	5501	6800	13418
mTicket One Way	1454	1682	265	1076	2590	7067
mTicket 10 Ride	1116	1251	48	358	0	2773
mTicket Round Trip	740	980	140	360	0	2223
Total	197279	214151	23807	73788	97929	

resented by the upper right triangle. This is likely because most users of the system live outside of Boston and commute inbound and thus they would purchase a ticket corresponding to the first trip of the day in the inbound direction.

Assuming that the customer activates her ticket at the approximate time of boarding the train, the activation time can be mapped to train arrival times in the automatic vehicle location (AVL) dataset (discussed further in Chapter 4). Given that the written origin point of the customer's journey may either actually be her destination point, we match the data in two ways. In the first case, it is assumed that the given origin and destination are accurate, and the activation time is matched to the nearest arrival time of a train at the origin station while traveling in the same direction noted on the ticket. In the second case, it is assumed that the given origin and destination are reversed, and the activation time is matched to the nearest arrival time of a

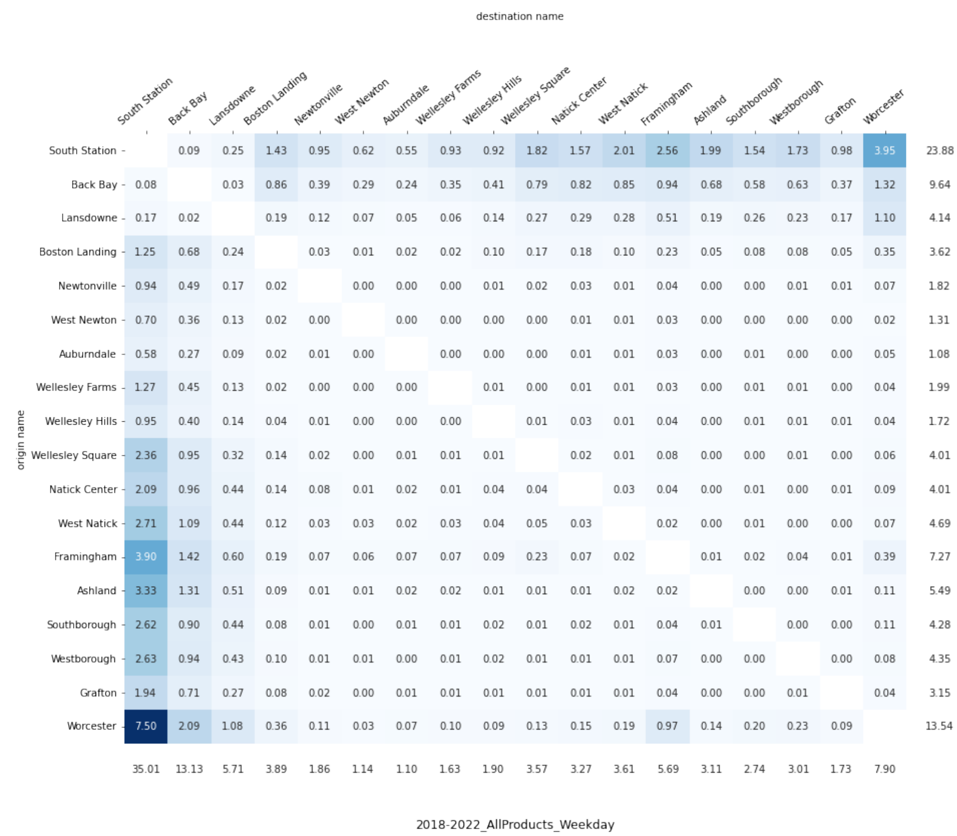


Figure 3-11: OD pair probabilities (in percent) from mTicket data before adjustment, all years

train at the given 'destination' station while traveling in the opposite direction noted on the ticket. Then, the two matches are compared. The closest match to the activation time is kept and assumed to be the true direction. If both matches are similar in accuracy, that is, within 15 minutes of one another, then a direction is assigned based on the time of day. A ticket activated between 4-10 am is marked inbound (method used for 3.5% of roundtrip tickets), a ticket activated after 4-10 pm is marked outbound (2.9%), otherwise the better of the two matches is still used. The procedure outlined above effectively accounts for this directional difference as shown in the origin-destination probabilites matrix below. As expected, about half (50.6%) of all round trip mTickets were reversed.

To investigate any further sources of bias, this corrected Origin Destination probabilities matrix for the 2018 mTicket data is then compared to the origin destination probabilities matrix created from the CTPS one-day counts. Figure 3-12 below represents the difference between these two matrices, where values in red indicate an underestimate in the mTicket data and values in blue indicate an overestimate. One can observe that the mTicket data greatly underestimates the reality of travel within the urban center while overestimating likelihood of travel to the outer metro area and beyond. Further, the mTicket data fails to capture patterns of travel that originate or terminate at Back Bay and Lansdowne, instead over-attributing these trips to South Station.

Lacking a sufficient wealth of observations to correct this bias at an origin-destination station pair level (some years have zero observed mTicket activations mapping from South Station to Lansdowne), we aggregate stops into three groups: Inner Core (South Station to Auburndale), Outer Metro (Wellesley Farms to Framingham) and Regional Cities and Towns (Ashland to Worcester). A linear scale factor is then applied to correct zone biases between the mTicket and CTPS data.

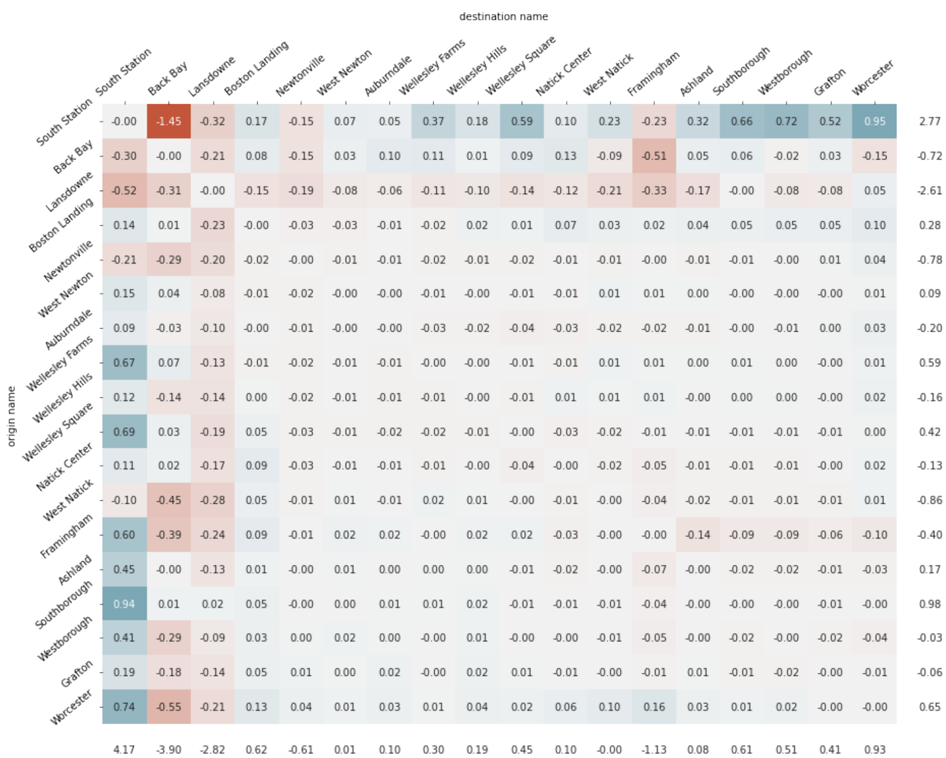


Figure 3-12: CTPS versus corrected mTicket OD probabilities difference matrix

3.4 Ridership Discussion and Analysis

Examination of the corrected mTicket dataset provides direct insight into shifts in travel behaviors on the Worcester Line during the study period. Since 2018, users have shifted away from a predominant use of multi-ride passes (10 Ride and Monthly Pass) towards single-use passes (One Way and Round Trip passes). This mirrors the trend of trip frequency reduction observed in the Systemwide Survey, likely indicating that multiride passes have lost the value per ride they once had when riders were using the line five days a week. To address this, the MBTA developed its Flex Pass option which allows for five days of unlimited round-trip travel over a 30-day period for 10% less than the cost of 10 individual one-way tickets. This option has seen rising popularity since its introduction and by 2022 exceeded the popularity of the 10 Ride and Monthly Passes. Another significant phenomenon is the resilience of weekend travel, observable in both Figures 3-13 & 3-14, which aligns with observed trends in the resilience of recreation travel [31]. Lastly, the most popular weekdays for commuter rail use are Tuesday, Wednesday and Thursday, with lower numbers on Monday and Friday. Though in line with perceptions about work from home schedules, this same pattern existed in the pre-pandemic years data as well.

To better understand how these ridership trends relate to the shape of the market as a whole, the mTicket observations can be compared to trips data for all modes in the corridor. Keolis Evolve is a 3-part study conducted from 2019 through 2022 to evaluate the potential market size of each MBTA Commuter Rail Line. Through analysis of millions of points of mobile location data, this study estimated the total trips happening in the corridor and determined a portion of these, called the "potential market", aggregated by spatial zone and time period, which either were or could have been taken on an MBTA Commuter Rail Line either in full or in part based on the origin/destination of the trip from cellular location data (Figs. 3-15 & 3-16). Temporally, tickets are grouped into four windows: AM Peak (6-9 AM), PM Peak (3-7 PM),

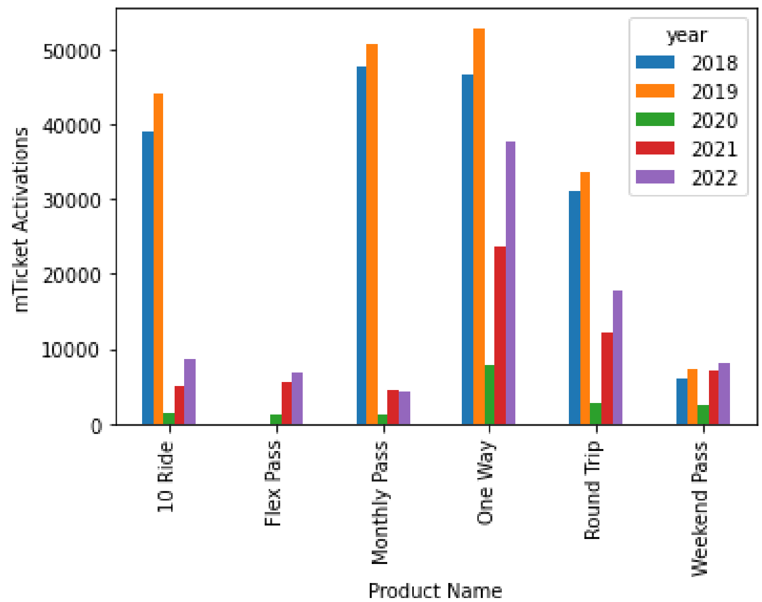


Figure 3-13: mTicket activations by product type and year

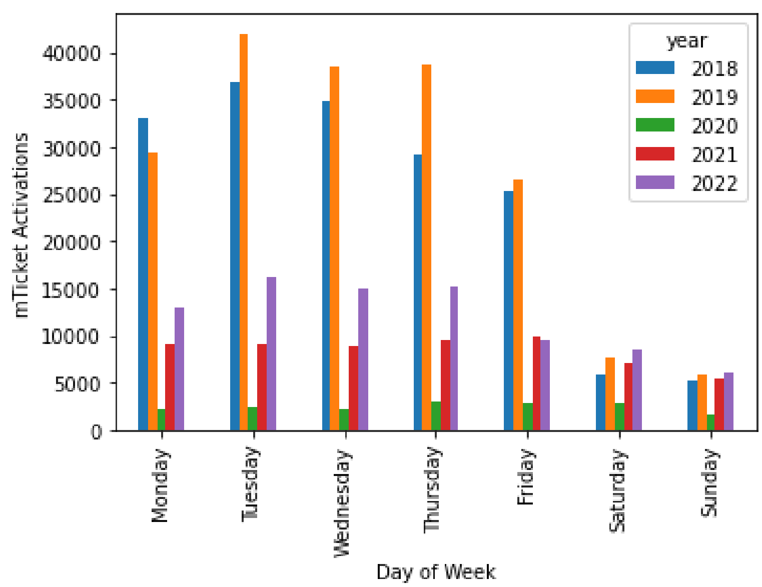


Figure 3-14: mTicket activations by day of week and year

Midday(9 AM - 3 PM), and Fringes(4-6 AM & 7-11 PM).

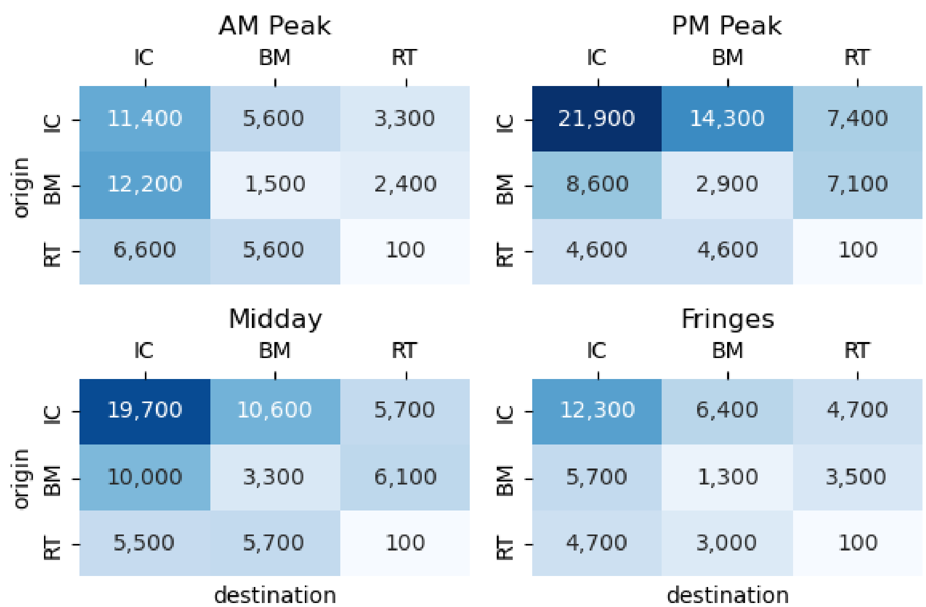


Figure 3-15: Keolis Evolve weekday trips market estimation (Fall 2018)

When overlaid with the mTicket ridership observations between zones, one can observe the market capture the Worcester Line has for each zone-to-zone pairing. Comparing 2018 (Figure 3-15) to 2022 (Figure 3-16), the market itself has proportionately shifted towards the Inner Core and Regional Cities and Towns and away from the Outer Metro while the proportionate share of transit trips borne by each zone has remained comparatively steady. However, the large market represented in Inner Core to Inner Core trips has been the least captured by commuter rail service, at less than 5% market share overall (Fig.3-17).

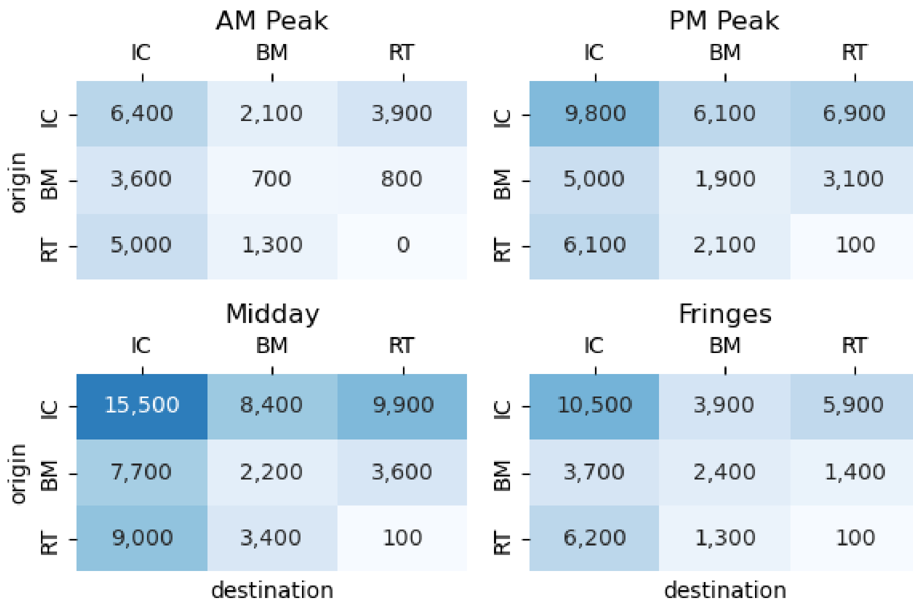


Figure 3-16: Keolis Evolve weekday trips market estimation (Fall 2022)

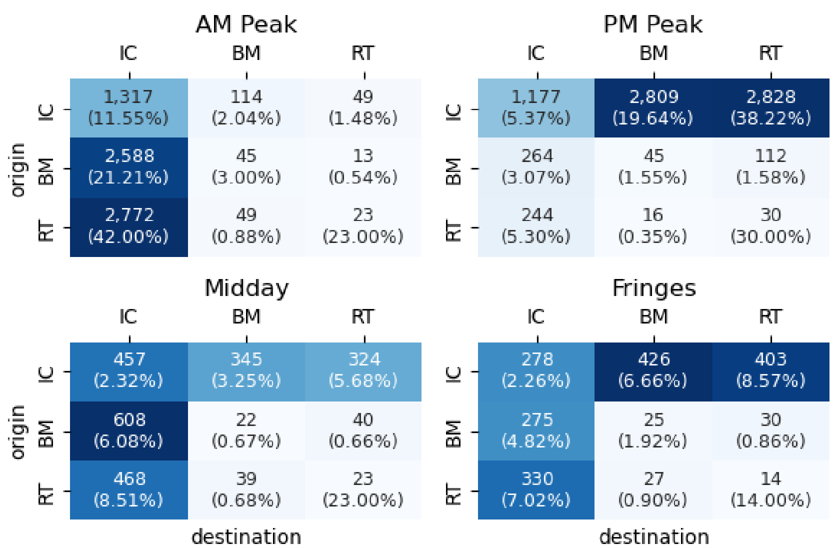


Figure 3-17: Observed ridership and percent market capture in 2018

3.5 The Demand Tool

The aim of this tool is to consider three possible scenarios for future demand for regional rail service in the Metro West corridor. In order to understand and represent riders' travel choices, a sketch-planning level demand estimation tool is developed. This procedure is not meant to provide accurate customer counts on a revenue-forecasting or capacity allocation level, nor advance the science of transit demand modeling. Those more detailed travel assignment models determined at the TAZ-level "are often insensitive to policy variables and the process is often too cumbersome and time-consuming to be used to test a wide range of transportation policy alternatives" [14]. In contrast, this tool is meant to provide a high-level outline of the possible trips market and commuter rail demand impacts of various environmental factors and transit policy choices. Those potential impacts are narrowed down into three main scenarios which can be examined and refined by a more detailed approach at a later time.

The tool is built in two parts. Firstly, factors affecting overall travel demand in the corridor are used to scale the size of the available market. Secondly, factors that affect the distribution of these trips across different modes are then used in a simple mode choice model to estimate which of these trips in the market the Worcester Line could expect to capture. A summary of all these factors is presented in Table 3.2 and a more detailed explanation is offered in the following sections.

Table 3.2: Scenario Factors

Factor	Internal/ External	Market/ Mode Choice	Scenario 1	Scenario 2	Scenario 3	Description
Population Growth	External	Market	90%	100%	110%	Refers to percent of projected growth realized
COVID-19 Impacts (Market)	External	Market	70%	85%	100%	Refers to percent of pandemic-era market recovery in loss areas
COVID-19 Impacts (Transit Value)	External	Mode Choice	120%	100%	100%	Refers to value of transit time in relation to auto time
Allston Construction	External	Mode Choice	0%	10%	20%	Refers to increase in auto travel time
Fares	Internal	Mode Choice	No change	Inner core fares	Half-price fares	
Service	Internal	Mode Choice	0-365%	0-365%	0-365%	Refers to percent increase from 2018 service levels

3.5.1 Scaling the Market

All projections begin with a 2018 baseline daily corridor trips (made on any mode) between each origin zone o and destination zone d as assumed from Keolis Evolve research and illustrated in Figure 3-17. The first step of the demand tool is thus to apply linear scale factors to each of these zonal submarkets based on factors that will influence the size of the overall market (Eq. 3.1). These factors are general population growth trends and the impacts of COVID-19 on non-traditional travel patterns.

$$M2025_{o,d,P} = M2018_{o,d,P} \cdot PGF_{o,d} \cdot CIF_{o,d} \tag{3.1}$$
$$\text{where} \quad PGF_{o,d} = \text{Population growth factor}$$
$$CIF_{o,d} = \text{COVID-19 impact factor}$$

Population Growth Trends

The population growth trends used are sourced from the University of Massachusetts Donahue Institute (UMDI), produced with support from Massachusetts Secretary of the Commonwealth and the Massachusetts Department of Transportation. Given that data is available for the years 2010 and 2020, linear interpolation is used to estimate 2018 population levels in each township. Population estimates for 2018 and population projections for 2025 were then aggregated to the zonal level, thus allowing one to obtain the average growth rate in the zone.

Because demand must be scaled as an origin-destination pair, the zonal growth factors are applied accordingly. For the AM Peak (6-9 AM) market, trips are scaled by the growth of their origin. For PM Peak market (5-9 PM), trips are scaled by the growth of their destination. For mid-day and fringe (before the AM peak and after the PM peak) markets, trips are scaled by an average of the growth rates between the origin and destination. If this model were used at a more granular level, the market scaling should take into account data about trip purposes as proportions of each sub-market. That is, if trips between the Inner Core and the Outer Metro in the mid-day period consist predominantly of people who live in the Outer Metro returning home from a trip to the inner core, this number should be proportionately stronger scaled by the outer metro growth rate than the inner core growth rate.

The three scenarios thus reflect three possible cases for the realization of UMDI-predicted growth. In the first scenario, projections are assumed to be an overestimation of reality, so it is assumed that all markets will experience a growth rate of 90% of what was predicted. In Scenario 2, the full growth rate is used. In the optimistic Scenario 3, the projections are assumed to be surpassed, and a growth rate of 110% of that predicted is used.

COVID-19 Market Impacts

As of Fall 2022, the impact on the overall trips market caused by COVID-19 currently rests at an overall 70% of what it was pre-pandemic. However, this trend is not universally applicable in all zonal pairs. The markets which have actually grown rather than shrunk since 2018 are not modified in any of the scenarios. However, markets which are still performing under pre-pandemic levels are presumed in scenario 1 to remain at the level of recovery in terms of trips per capita that they stand at today. In scenario 2, these markets are presumed to recover half of their loss. In scenario 3, the markets are presumed to fully recover back to their 2018 per capita trips levels.

3.5.2 Mode Choice

Having accounted for market impacts, the scaled data for each scenario is used as an input to a simple mode choice logit model in order to predict what share of the new market the Worcester Line could possibly capture. The model is primarily bimodal, deciding between auto and Worcester Line modes. The model is shown in Equation 3.2 where P_T is the proportion of the market captured by the Worcester Line for the given origin and destination zones and time period (o, d, P), av is the value of the auto mode, tv is the value of the Worcester Line mode, and $c1$ is the calibration factor between the auto and Worcester Line modes (value = 0.18). However, for the Inner Core to Inner Core trips, the Green Line mode must also be considered, as it is a serious competitor for potential customers (Equation 3.3). All the factors considered here are significantly aggregated to be represented by only these three zones. Therefore, a representative station-pair is selected for each of the nine combinations (Figure 3-18).

$$P^t_{o,d,P} = \frac{1}{1 + e^{c_1 \cdot (av_{o,d,P} - tv_{o,d,P}}} \quad (3.2)$$

$$P^t_{o,d,P} = \frac{1}{1 + e^{c_1 \cdot (av_{o,d,P} - tv_{o,d,P})} + e^{c_2 \cdot (gv_{o,d,P} - tv_{o,d,P})}} \quad (3.3)$$

where gv is the value of the Green Line mode and $c2$ is a calibration factor between Worcester Line and Green Line modes (value = 0.1). In the logit model, the calibration factors determine the spread of the diversion curve along the x-axis. This represents the market's relative sensitivity of modal choice to the difference in values of each mode. The factors present in this model, being less than 2, imply that the market for transit in the Western Corridor is relatively insensitive to these costs [14].

The value of each mode (av,tv,gv) for each origin-destination zonal pair (o,d) and time period (P) is equal to the sum of its costs. These costs come in the form of monetary buy-in, like gasoline or transit fares, as well as time costs from travel and access. The methodology for determining each of these costs is detailed in the following section.

Cost

For the auto mode, cost-per-mile metrics are taken from AAA's yearly Your Driving Costs report which includes cost of depreciation, finance, registration, insurance, fuel, and maintenance. AAA reports these average costs per mile in three categories based on the intensity of car usage: 10,15, or 20 thousand-miles-per-year drivers. For this model,

	Inner Core	Outer Metro	Regional Cities
Inner Core	Back Bay - Newtonville	Back Bay - Natick Center	Back Bay - Westborough
Outer Metro	Natick Center - Back Bay	West Natick - Wellesley Hills	Natick Center - Westborough
Regional Cities	Westborough - Back Bay	Westborough - Natick Center	Southborough - Grafton

Figure 3-18: Representative stations for zone pairings

these three categories are broadly assigned to the three regions, Inner Core, Outer Metro, and Regional Cities and Towns, respectively. This assumption is based on the fact that drivers living further from the Boston urban core travel significantly more miles per year on average, as confirmed by the Massachusetts Travel Survey [28]. In the base year, 2018, AAA reported that the average cost-per-mile for the auto mode was 51, 59, and 75 cents for each of the usage categories respectively [2]. Four years later in 2022, AAA reported the same costs to be 70, 72, and 76 cents [3]. Parking costs at one's destination do go unaccounted for in this assumption, and since auto parking data is not used in this study, the model may understate the true cost of an auto commute.

For the Commuter Rail mode, costs come as upfront fare costs. Used for input to the mode choice model is the fare between the representative stations for the given zone pair. Green Line costs were calculated as the rapid transit fare only.

For Scenario 1, the fares are assumed to be equal to the 2022 levels. In Scenario 2, an Inner Core fare of $2.40 is enacted through Auburndale, while the other zone fares remain unchanged. In Scenario 3, the fares are all assumed to be half of 2022 levels, excepting Zone 1A which is already equivalent to subway fare.

Access Time

Access time for the Commuter Rail and Green Line modes are inferred from responses to the 2015-2017 and 2022 Systemwide Passenger Survey. Though access times are not given on a station-specific level, they are assumed to scale upwards from 5 to 15 minutes from the Inner Core outwards. This factor remains constant in all three scenarios.

Headway

For Commuter Rail headway estimates, GTFS schedules were utilized to estimate headways for each zonal pair during the peak and off-peak periods, ranging from thirty minutes to two hours. Because headways are not consistent throughout the whole zone, as, for example, the three Newton stations within the Inner Core face frequent stop-skipping, a metric which will be referred to as *effective service frequency* (in trains per hour) is developed according to Equations 3.4 & 3.5 for each origin-destination zonal pair in each time period. This effective frequency devalues trains that skip stops, by dividing the actual possible trip combinations that could be made on the train by the possible trip combinations that could be made on an equivalent local service. Effective service frequency is then converted to the correct format for the mode choice model, an *effective headway*, with Equation 3.6.

$$ESF_{o,d,P} = \frac{1}{l_P} \cdot \sum_{t \in P} \frac{s_o^t \cdot s_d^t}{S_o \cdot S_d} \quad \forall o \neq d \tag{3.4}$$

$$ESF_{o,d,P} = \frac{1}{l_P} \cdot \sum_{t \in P} \frac{(s_o^t)(s_o^t - 1)}{(S_o)(S_o - 1)} \quad \forall o = d \tag{3.5}$$

where s_o^t = number of stations in origin zone o visited by train t

s_d^t = number of stations in destination zone d visited by train t

S_o = total number of stations in origin zone o

S_d = total number of stations in destination zone d

l_P = length of the time period P in hours

$$EH_{o,d,P} = \frac{60}{ESF_{o,d,P}} \tag{3.6}$$

For the Green Line, peak and off-peak headways were taken from MBTA archive schedules [6, 7], found to be 6 minutes during peak and 8-11 minutes off-peak respectively for both the 2018 and 2022 years. Because the Green Line does not regularly employ skip-stop or express service types, no modification is made.

For all three scenarios, effective service frequency is assumed to increase by between 0-365% depending on the origin zone, destination zone, and time period as reflected in Figure 3-19 (see Chapter 5 for determination), corresponding to the timetable developed for the first major service increase possible under current infrastructure limitations.

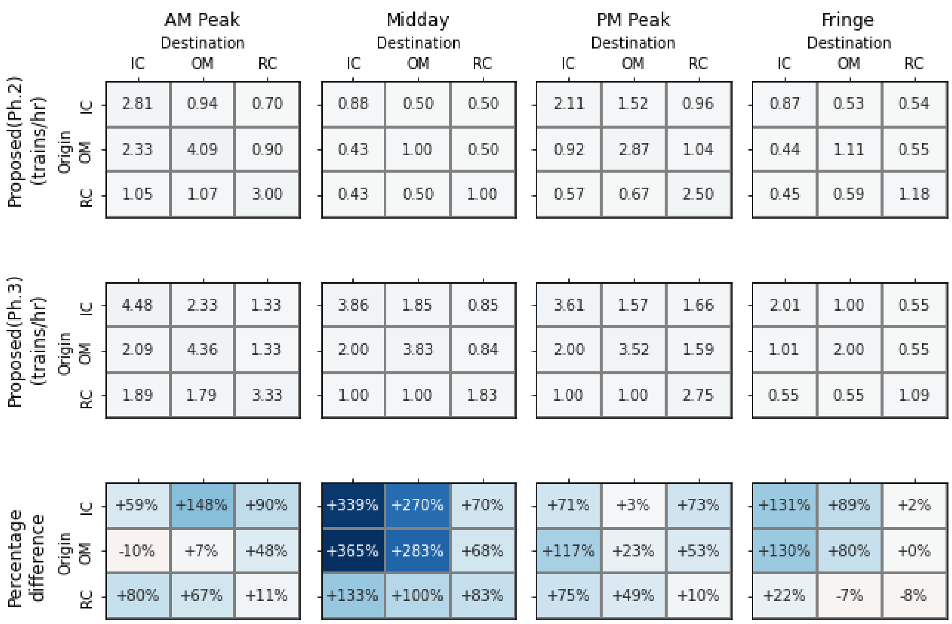


Figure 3-19: Phase 1 Service Increase

In-vehicle time

For the commuter rail mode, GTFS schedules were utilized to determine in-vehicle time for each set of representative stations. For the Green Line, in-vehicle travel time is pulled from between Newton Centre and Copley, the nearest stations to our representative Inner Core to Inner Core stations, for an assumed travel time of 28 minutes. For the auto mode, historic travel times between the representative commuter rail stations were obtained from the Bing Maps API for peak and off-peak periods. In Scenario 1, auto travel times are expected to remain unchanged. In Scenario 2, Allston Multimodal Project construction is anticipated to increase corridor travel times for auto by 10%, and in Scenario 3, construction is anticipated to increase corridor travel times by 20%. In reality, these increases would likely not be uniform across all trips but rather be greater for short trips and less for longer trips, however this simplifying assumption was used.

3.5.3 Calibration

The model, while useful, is high-level and imperfect. the calibration constant in Equations 3.2 and 3.3 was selected by minimizing the sum of the prediction errors of all zone pairings and time periods, shown in Tables 3.3 & 3.4. The AM and PM peak periods are much more reliably predicted than off-peak periods. This model is unable to capture many phenomena of user behavior, including mode loyalty which may explain the ridership that the line maintains even in the off-peak when the auto mode is considerably faster and more inexpensive.

Period	Predicted Riders	Observed Riders	error
AM Peak	7767.08	6970.0	797.08
Fringes	381.04	1808.0	-1426.96
Midday	709.99	2326.0	-1616.01
PM Peak	8138.53	7525.0	613.53

Table 3.3: Sum of the error in ridership predictions by Period

Origin	Destination	Predicted Riders	Observed Riders	error
IC	IC	4205.63	3229.0	976.63
	BM	3573.83	3694.0	-120.17
	RT	2063.47	3604.0	-1540.53
BM	IC	3804.68	3735.0	69.68
	BM	139.46	137.0	2.46
	RT	433.19	195.0	238.19
RT	IC	2487.42	3814.0	-1326.58
	BM	283.44	131.0	152.44
	RT	5.52	90.0	-84.48

Table 3.4: Sum of the error in ridership predictions by OD pair

3.5.4 Scenario Summary

The results of the market scaling and mode choice process are aggregated into the three scenarios below. The first scenario reflects a sluggish return. That is, population growth lags, COVID-19 effects linger, and I-90 reconstruction has yet to begin. Nevertheless, dramatic service increases will raise average daily ridership to almost 30,000 daily weekday passengers. In the second scenario, some demand boosts are seen from intial stages of the construction work as pandemic effects fade, prompting an average weekday ridership of almost 49,000 riders. Lastly, Scenario 3 paints an optimistic view of the future in which external factors and internal actions bring dramatic levels of demand to the line, beyond the current capacity of the service.

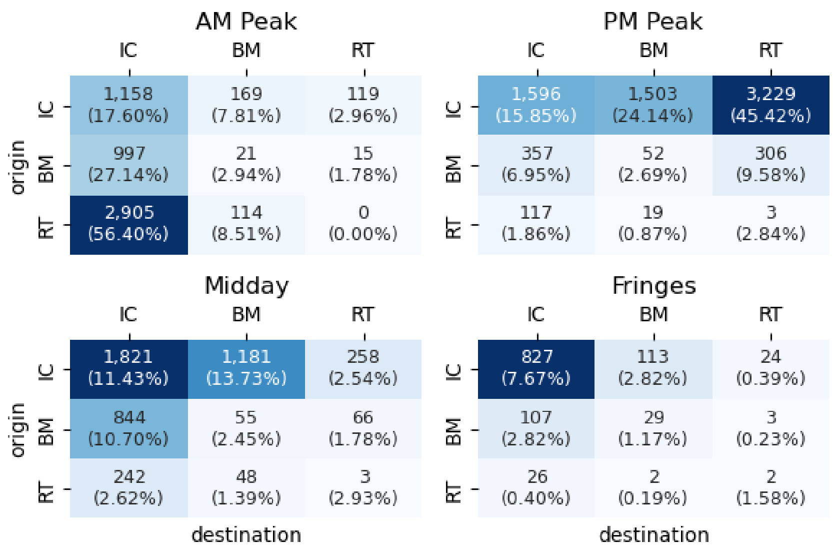


Figure 3-20: Expected ridership by period of day for Scenario 1

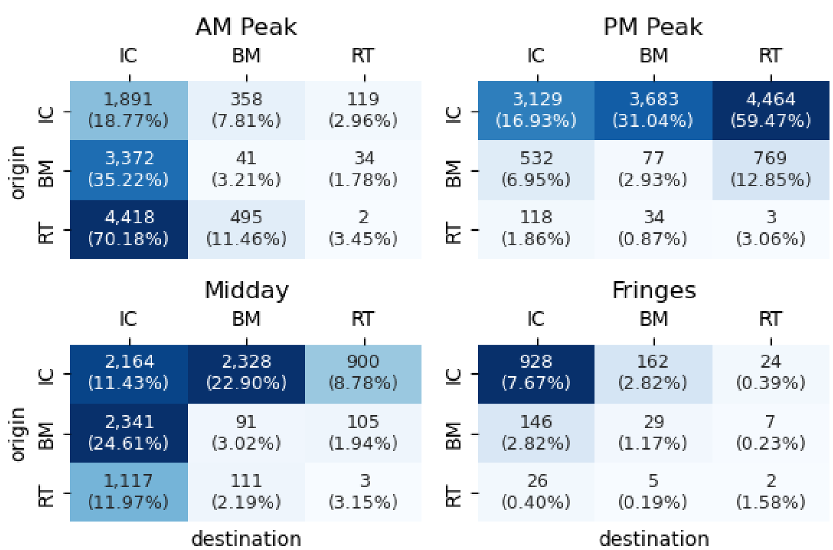


Figure 3-21: Expected ridership by period of day for Scenario 2

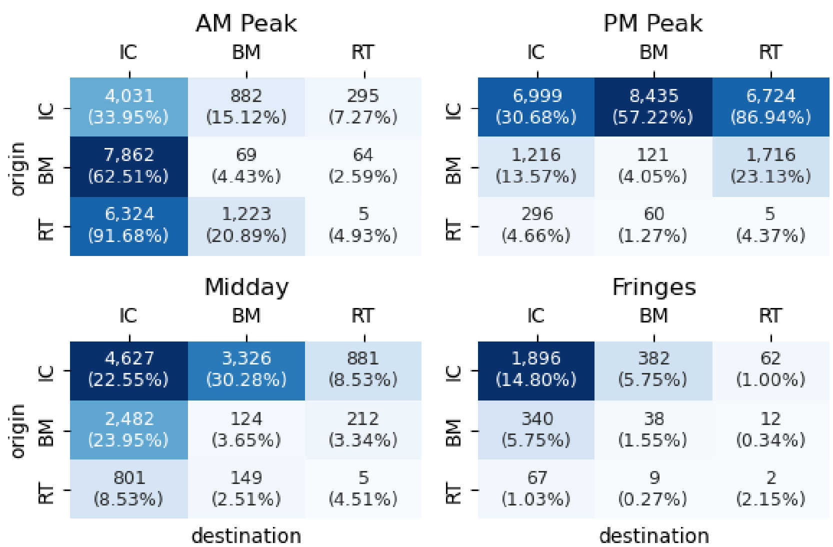


Figure 3-22: Expected ridership by period of day for Scenario 3

Chapter 4

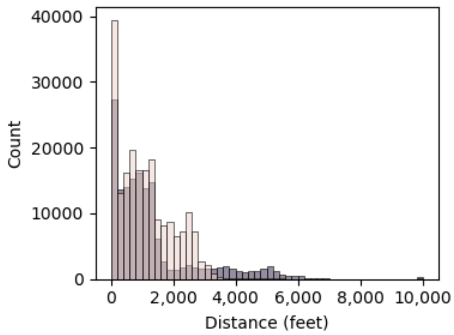
Service Supply

Commuter rail's extensive track mileage requires a mix of local, express, and skip-stop services to serve its user base effectively. This variety of offerings provides many operational challenges for the agency as mixed route types must compete for the use of the tracks. This competition is further exacerbated under the unique conditions present on the Worcester Line, which necessitates shared use of tracks by inbound and outbound trains at some segments along the line. A challenge also unique to Commuter Rail when compared to other rail modes is that the line contends with interference from freight trains and Amtrak Lake Shore Limited service.

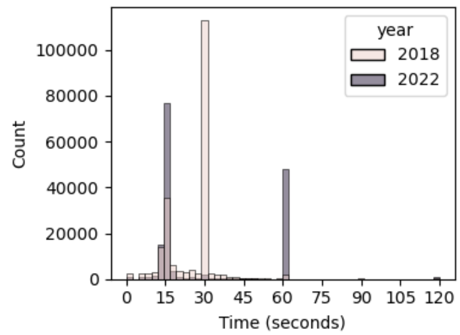
This chapter aims to characterize the service offered on the Worcester Line during the study period, analyze how effectively that service has been delivered, and quantify the total amount of service possible under the current infrastructure. Further, this chapter discusses Worcester Line service as it relates to the stated ideals of the MBTA and of Rail Vision, understanding that service is not exclusively guided by quantitative measures of passengers per hour efficiency but is also informed by social ideals to serve its constituents equally in a way they deem fair and acceptable.

4.1 Data Background and Assumptions

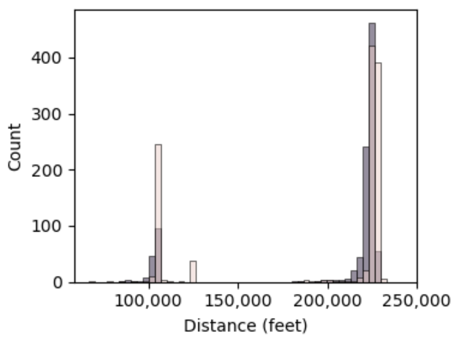
To analyze past service on the Worcester line, data sources used include Automatic Vehicle Locations (AVL) and General Transit Feed Specifications (GTFS). For commuter rail, AVL data comes as heartbeat GPS pings data which triggers a train to log its location every 30 seconds on average regardless of whether the train is stopped or in motion. Because these pings can be triggered at any point on the train's journey, they can easily provide errors of up to 60 seconds when estimating any given dwell time or interstation travel time. In 2022, Keolis Commuter Service changed the way this AVL data is logged. In the newer data, the GPS pings are recorded either 15 or 60 seconds apart whereas in 2018 pings were consistently recorded every 30 seconds (Figure 4-1). The reader should be aware of the potential impact this variation in the data may have on the resulting analysis.



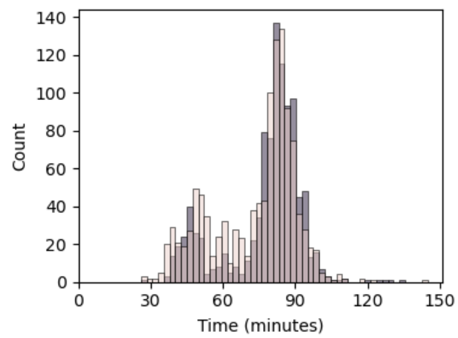
(a) Distance traveled between pings



(b) Time between pings



(c) Total distance time by each trip



(d) Total traveled time by each trip

Figure 4-1: AVL Data Summary

4.2 Service in the study period

Comparing the beginning and end of the study period (Figures 4-3 and 4-4) the spread of service types offered by the MBTA on the average weekday remained largely the same. This offering includes local services of both full-length and a short-turn at Framingham, and one local-express service that serves Boston and the Regional Cities and Towns zone. A true express service is also offered, branded "Heart to Hub" by the MBTA, which ran only from Boston to Worcester in

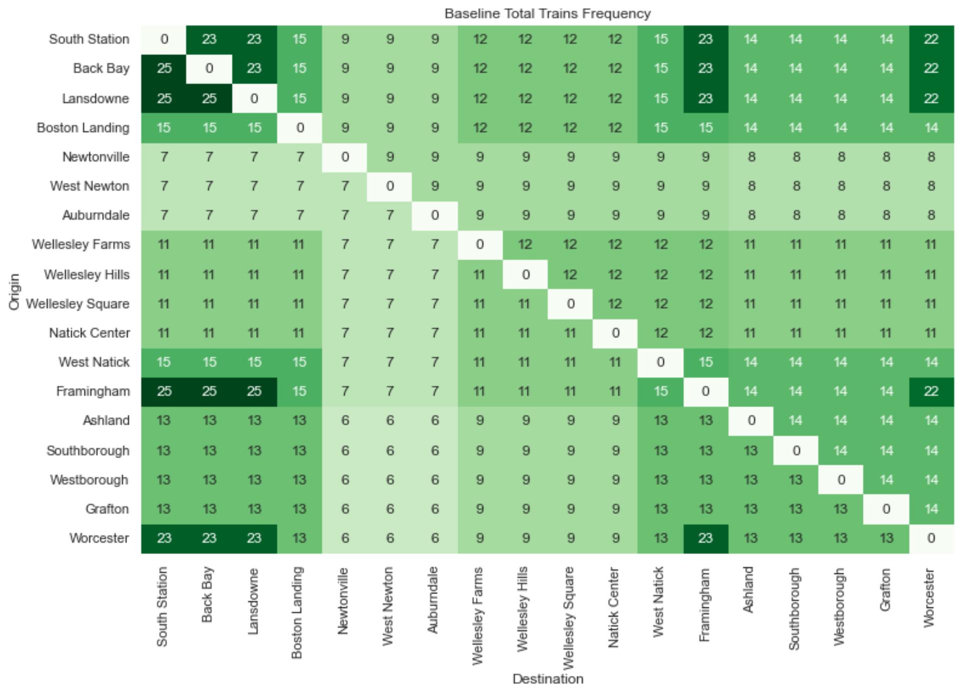
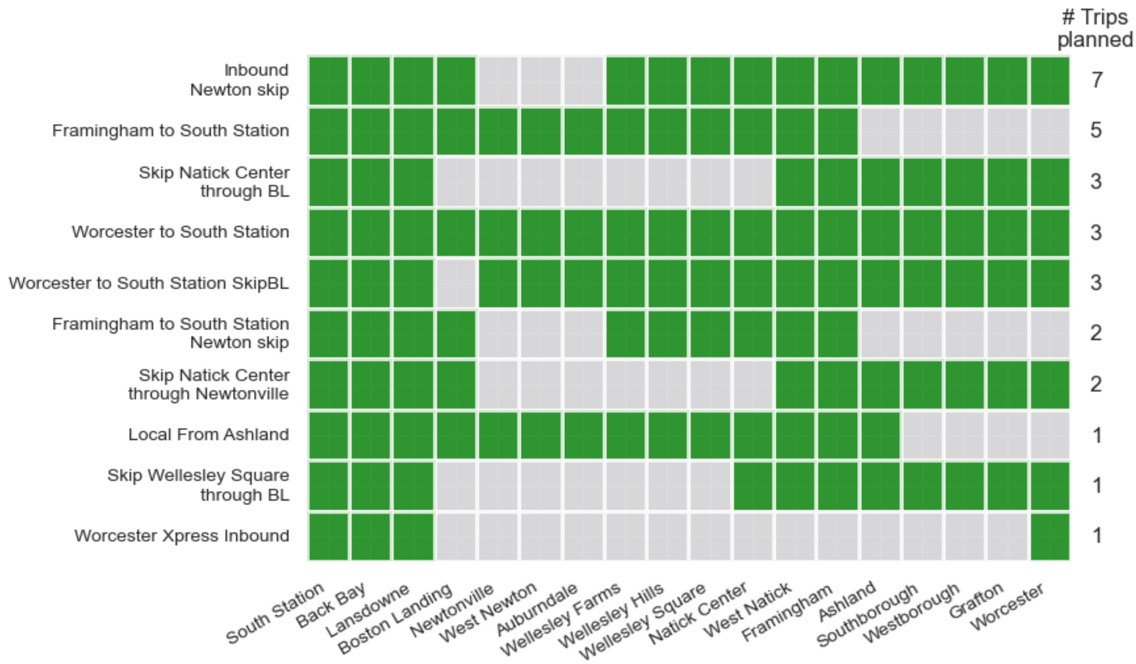


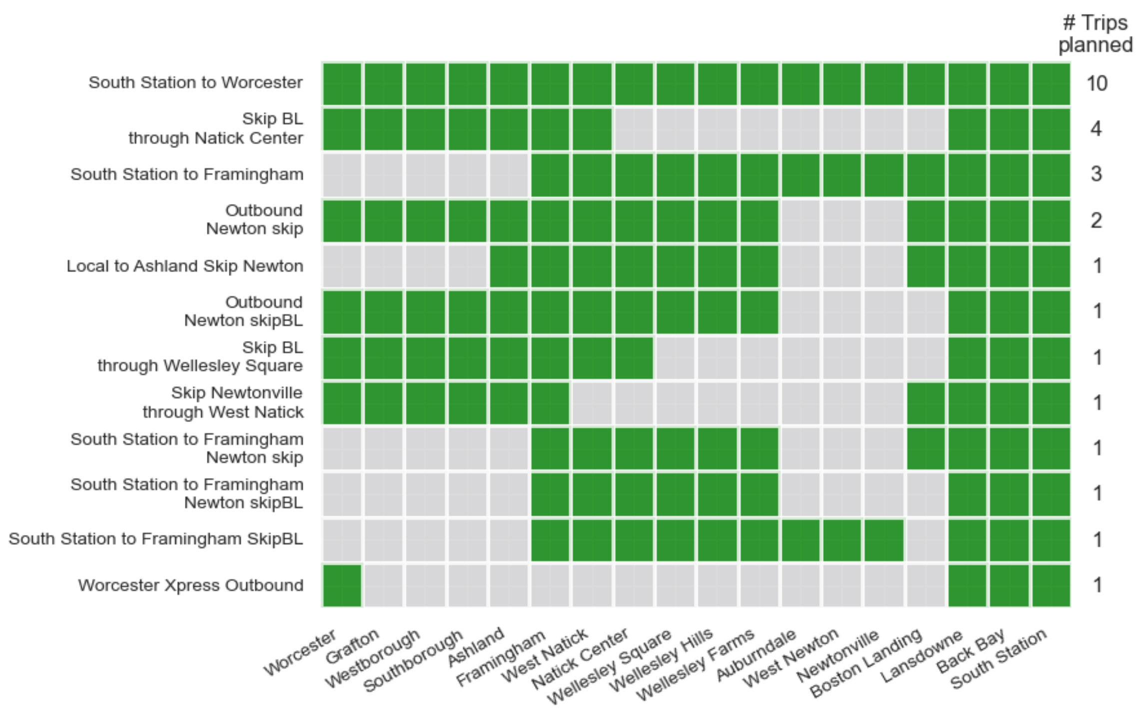
Figure 4-2: Total Daily Trains in October 2022

2018 (referred to here as "Worcester Xpress") but includes a stop at Framingham as of 2022. Further, alternate versions of all local services are offered which skip the three stations located in Newton in order to avoid conflicts on the single-tracked section ("Newton Skip" and "South Station to Framingham Newton Skip"). From 2018 to 2022, the overall number of daily services dropped from 55 trips to 48 trips and the proportion of local trips which skip the Newton stations has increased from 41% to 48%, further decreasing service to these stations, though distributing the service they do receive more equally between inbound and outbound. A full summary of the number and characteristics of each service type is demonstrated in Figure 4-3. During October 2018, as Boston Landing was a recently opened station, it was still being skipped on a number of the services offered, so there appears to be more diversity in service offerings during this time.

In the same time period, the service has equalized throughout the day, deemphasizing high frequencies during the peak and allotting more service to mid-day as shown in Figure 4-5. Though the average headways in the Inner Core were as low as 16 minutes in 2018 and 22 minutes in 2022, these headways do not account for the stop-skipping at Newton and thus only apply from Lansdowne inwards. While all-day bidirectional service is a tenet of regional rail, this shift falls short of fulfilling its goals as it comes at the expense of longer headways during the peak.

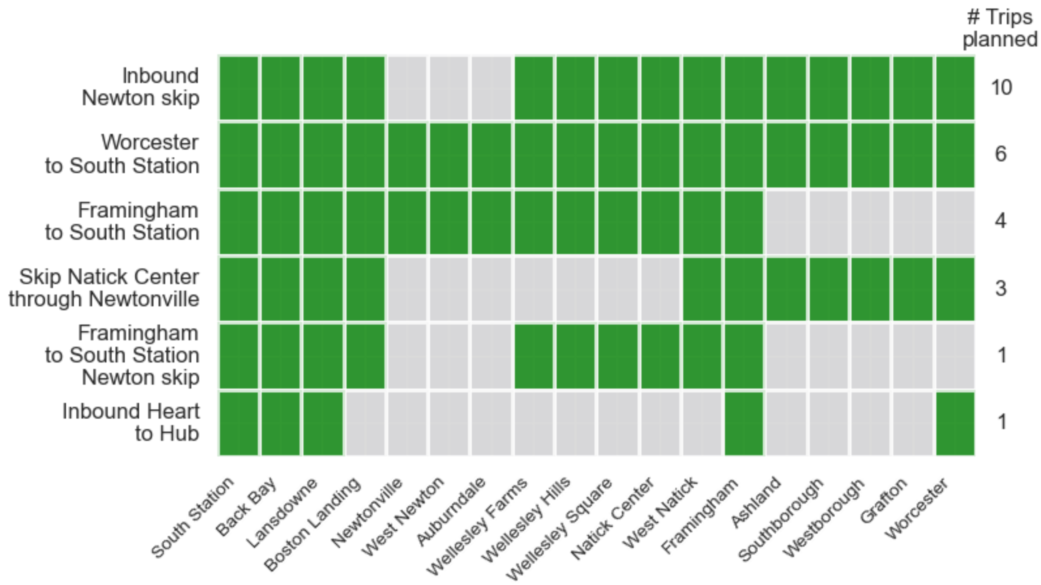


(a) Inbound

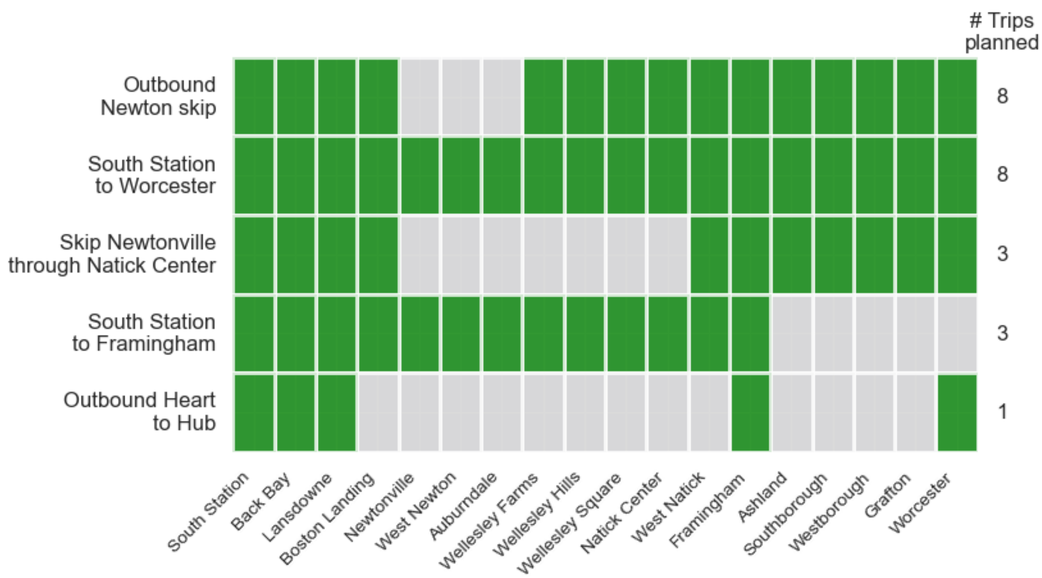


(b) Outbound

Figure 4-3: Daily schedule in 2018 on a weekday by direction



(a) Inbound



(b) Outbound

Figure 4-4: Daily schedule in 2022 on a weekday by direction

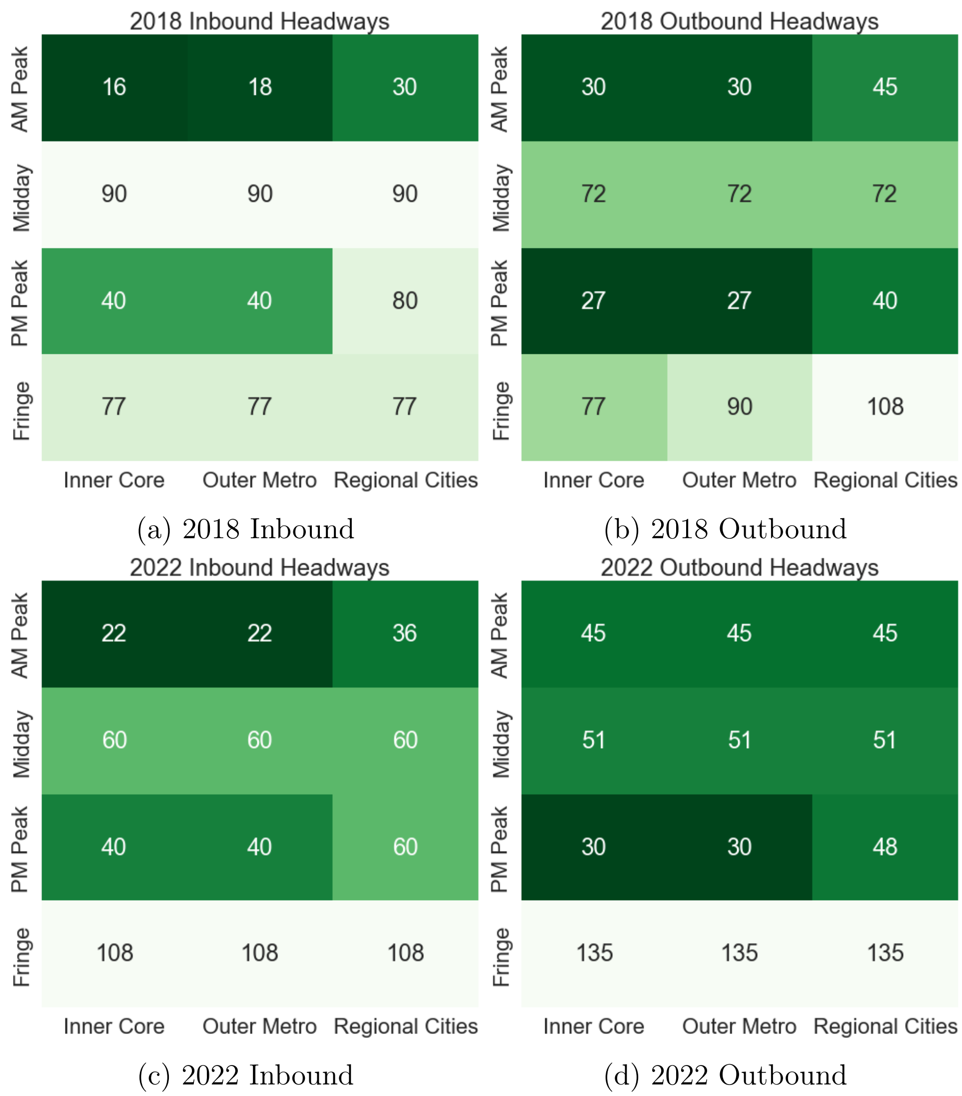


Figure 4-5: Average headways by at the line and system levels

4.2.1 Run Time

Run time effects can be felt in travel time between stations and dwell times at stations. Travel time is found to vary dramatically for trips of the same service type at different times of the day, reaching heights during peak times in the direction of travel. In Figure 4-6, the 2018 trajectory data for four trains of the service Skip BL through Natick Center during the AM Peak (501 and 503) and PM Peak (521 and 523). On average, the run times of each period of the day were 67.23 (SD = 3.58) and 80.01 (SD = 5.21), respectively (4.1). As expected for outbound services, the PM peak trains have a longer run time and collect the majority of their comparative delay during dwell times at West Natick and Framingham. Somewhat less expected, the late morning train also collects significant delays traveling in the same section between Ashland and Southborough, indicating congestion or other phenomena that require further attention in that segment.

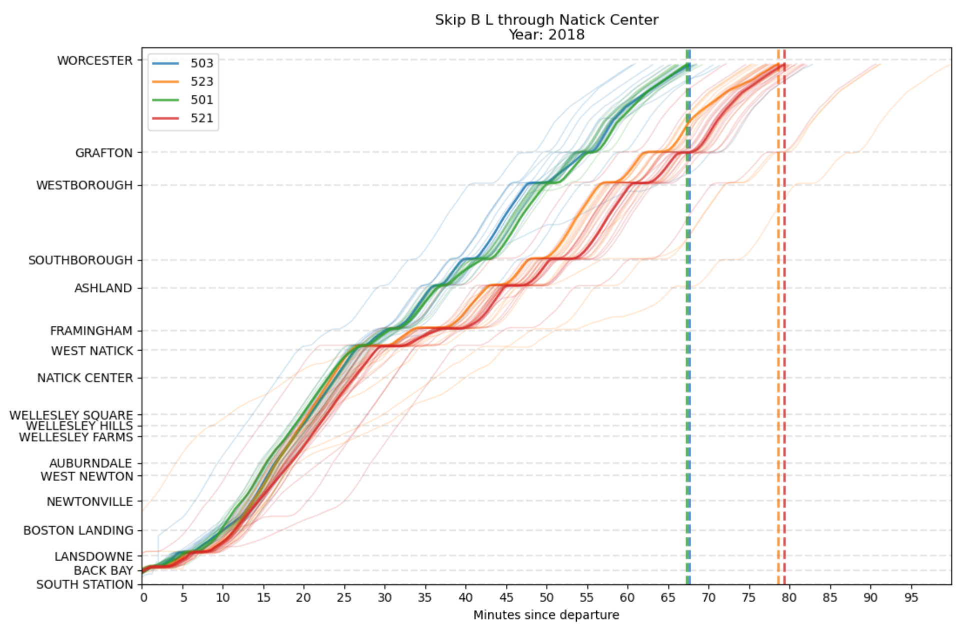


Figure 4-6: Compared run time of train in service Skip BL through Natick Center in 2018

	Travel Time				Total Dwell Time		
	count	median	mean	std	count	mean	std
AM Peak	33	67.23	67.23	3.58	19	7.82	2.09
PM Peak	38	79.07	80.01	5.21	38	21.31	3.54

Table 4.1: Service indicators for Skip BL through Natick Center in 2018

4.2.2 Dwell Time

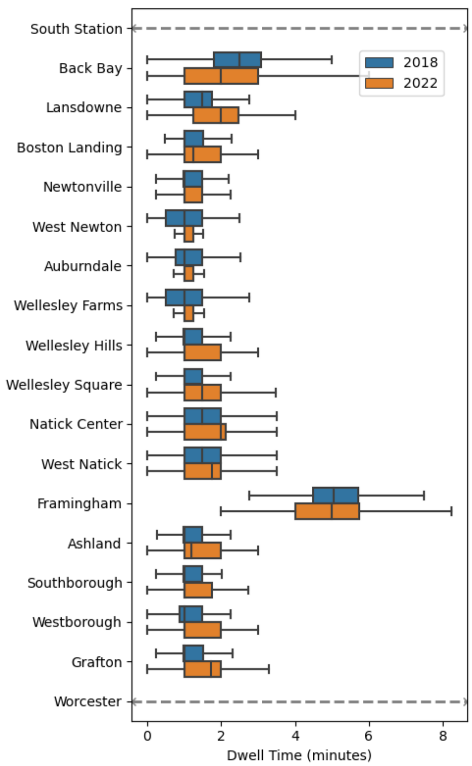
Figure 4-7 reflects dwell time values obtained from the stop triggers data, as it can provide a finer level of resolution than the GPS pings data used in run time analysis. These values are shown averaged across all years from 2018-2021. In line with observations in the run time data, the largest source of dwell time is felt at Framingham station, especially in the inbound direction. Dwell times are also typically higher and more variable near the Inner Core for outbound trains and near the Outer Metro and Regional Cities for inbound trains, suggesting explanatory power for number of passenger boardings or track congestion.

Table 4.2: Travel Time by Route name - Outbound

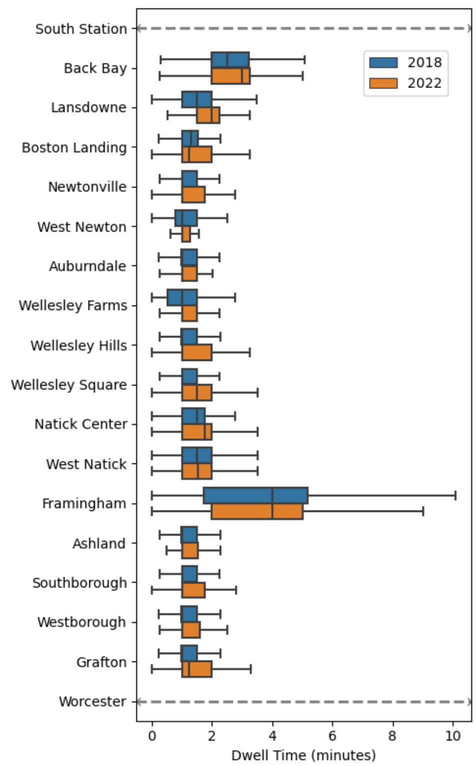
	Travel time (min)					
	2018			2022		
Route type	count	mean	std	count	mean	std
Local to Ashland Skip Newton	19	48.07	3.34	–	–	–
Outbound Heart to Hub	–	–	–	18	61.0	3.06
Outbound Newton skip	37	83.22	5.21	126	84.0	7.13
Outbound Newton skip Boston Landing	20	77.65	3.38	–	–	–
Skip B L through Natick Center	75	75.67	8.45	–	–	–
Skip B L through Wellesley Square	14	83.25	6.77	–	–	–
Skip Newtonville through Natick Center	–	–	–	49	74.5	6.35
Skip Newtonville through West Natick	20	65.71	3.6	–	–	–
South Station to Framingham	66	51.87	7.64	61	47.0	3.53
South Station to Framingham Newton skip	21	38.53	3.21	–	–	–
South Station to Framingham Newton skip BL	18	37.04	2.86	–	–	–
South Station to Worcester	233	84.18	7.74	221	84.25	6.94
Worcester Xpress Outbound	21	60.4	5.38	–	–	–

Table 4.3: Travel Time by Route name - Inbound

	Travel time (min)					
	2018			2022		
Route type	count	mean	std	count	mean	std
Framingham to South Station	103	50.55	6.49	76	45.38	3.96
Framingham to South Station Newton skip	44	41.06	4.53	20	40.0	1.61
Inbound Heart to Hub	–	–	–	20	60.0	9.45
Inbound Newton skip	140	82.98	6.73	179	84.0	5.13
Local From Ashland	20	60.08	5.55	–	–	–
Skip Natick Center through BL	57	78.25	4.79	–	–	–
Skip Natick Center through Newtonville	40	75.56	7.44	52	76.0	5.6
Skip Wellesley Square through BL	20	73.05	7.42	–	–	–
Worcester Xpress Inbound	22	60.8	8.39	–	–	–
Worcester to South Station	120	87.56	5.49	168	87.62	7.93
Worcester to South Station Skip Boston Landing	54	88.02	7.81	–	–	–



(a) Inbound



(b) Outbound

Figure 4-7: Dwell Times by Direction and Year

4.3 Simulation Tool

Rail simulation is particularly complex because of its many inter-operating components [16]. The simulation structure presented within this chapter is based on previous simulation work in the Transit Lab, including SimMETRO, designed for MBTA Red Line operations [27, 53] and LightSim, designed for evaluation of train protection systems on the MBTA's Green Line. The adapted form presented here varies in its capability to simulate stop-skipping behavior, perform crossovers at control points, and interact with other services at terminal stations.

4.3.1 Assumptions

Information about block length, block speed, and signal location comes from a track chart provided by the MBTA. There is no historical data kept or guidance provided for which track a given train is meant to be on at a given time. Therefore, it is assumed that a train only travels on the atypical track for the minimum extent required to complete an opposite-track maneuver.

This tool simulates a fixed block system, assuming that trains are unable to move forward on a block with a red signal, and thus that simulation of safety systems like Positive Train Control (PTC) is not necessary. When a train receives a yellow signal, it proceeds through the remainder of the block at a limited speed of 40 miles per hour as established by the Northeast Operating Rules Advisory Committee (NORAC), or at current speed if the posted speed is lower.

4.3.2 Structure

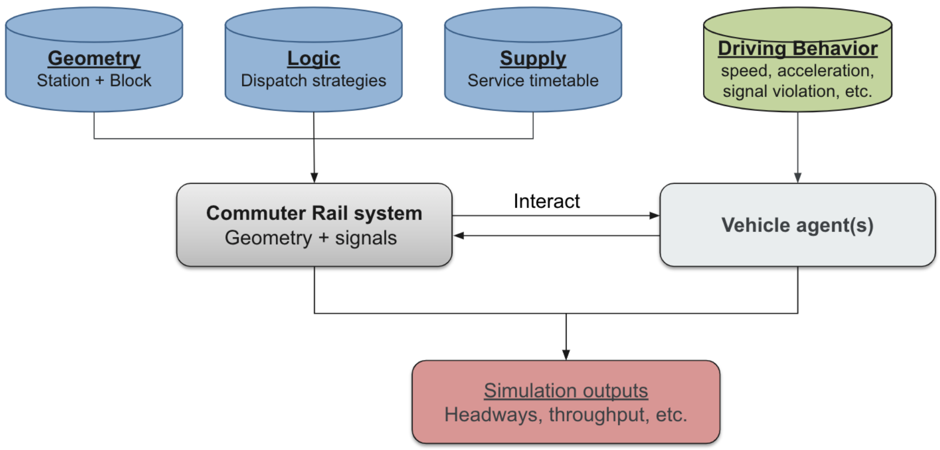


Figure 4-8: Structure of the RRSim tool

The structure of the simulation is a microscopic, agent-based stochastic simulation model. The simulation model is designed for performance analysis, operations planning, evaluation of infrastructure upgrades, and evaluation of real-time control strategies. The model simulates fixed-block signaling systems. Vehicle agents (train sets) move through the network using an assumed constant acceleration and deceleration rate. At each timestep, trains are assumed to be in one of nine possible logical states (Table 4.4), each of which is defined by its own set of speed, acceleration, and dwell behaviors, and may transition between them if the necessary conditions are met.

Table 4.4: Vehicle States

State	Description
Prepare to pull in	The train waits at a station before beginning its daily service
Dwell at station	The train is stopped at a station along its route
Free move	The train moves at its free flow speed
Constrained move	The train moves at a reduced speed because of a yellow signal
Decelerate to stop at red	The train slows to a stop when approaching a red signal
Stop at red	The train is stopped at a red signal
Move and stop at station	The train slows to a stop when approaching a station
Turnaround	The train changes direction at the terminal station
Ready to pull out	The train waits at a station before beginning its next trip

4.3.3 Validation

The model developed was validated against AVL data discussed in section 1. Specifically, speeds and dwell times are aligned with 2022 observations under the assumption that these longer run times are necessary for reliable service with an aging train fleet. The ability of the model to emulate variance in the dataset is limited, as its primary purpose is to simulate an expected average service delivery to use as input for schedule planning. Future work adapting this simulation tool as a basis for testing incident response scenarios is encouraged.

4.4 Capacity Assessment

Capacity must be thought of not only in terms of spacing between trains on the same track (determined by block length and speed) but also in terms of competition for use of a track. That is, single-tracked sections can support fewer trains than double-tracked sections.

Each service type allowed on the Worcester Line was simulated in RRSim, allowing the exact time window that each block is occupied to be known. These so-called "block occupation matrices" are then extracted where both the block the train is on and the block behind it are considered occupied such that trains are never scheduled to encounter slow blocks/yellow signals. To create block occupation matrices, 95th percentile dwell times from distributions presented in (ref) are used in order to prevent issues related to standard delay events.

On the Inner Core segment, between South Station and Riverside, the capacity is complicated by some long block lengths as well as the 5.7-mile single-tracked segment between control points CP-6 and CP-11. The inbound and outbound trains alone are limited to a ten-minute headway by a pair of blocks spanning 3.6 miles between Back Bay and Newtonville (Figure 4-9). After considering the effects of the effectively single-tracked 3.6 mile section which trains must traverse for 10 minutes on average to serve the Newton stations, the bidirectional capacity is 3 trains per hour in each direction, or a 20-minute headway. However, because this frequency would require very precise staggering to achieve, a more realistic headway is 25 minutes in each direction or 2.4 trains per hour.

Figure 4-9: Capacity diagram

On the Outer Metro segment, between Riverside and Framingham, the capacity is determined to be six trains per hour, limited by block length as there are no single-tracked portions in this section. The limiting blocks are a 5.2 mile segment spanning from the block signal at mile 18.1 and CP-21 at mile 21.3 which takes 9 minutes to transverse.

Finally, on the Regional Cities segment, the frequency is mediated both by the longest block lengths on the route as well as by the single-tracking necessitated by a single-side platform at Worcester's Union Station. The transversal time of the competitive segment and the approach block together is nine minutes. Thus, this section limits headways to 20 minutes in either direction. Further, the outbound and inbound trains alone are limited to 17 and 23 minute headways respectively due to differences in signal block length on the northern and southern tracks. The southern (inbound) track limiting blocks span 10.8 miles from CP-28 at mile 28.2 to CP-39 at mile 39.0 and the northern track limiting blocks span 9.3 miles from CP-33 at mile 33.3 to CP-42 at mile 42.6 (Figure 4-9).

This assessment of capacity sets a baseline for the frequency that is possible on the line today using only additional train sets and labor hours. Universal headways of 25 minutes are achievable with current infrastructure across the entire Worcester Line. This quantification does present a simplified explanation of the capacity in terms of the ability to support bidirectional, local service. In reality, express service introduces complexity because of its shorter travel times and its ability to perform passing maneuvers in certain circumstances. This nuance is explored further in Chapter 5.

Chapter 5

Investment Phases

The analysis in this chapter addresses the classical railway planning problem at both the strategic and tactical levels, considering the impact of long-term infrastructure planning decisions on day-to-day service scheduling and equipment allocation realities. A logical flow of infrastructure investment phases is proposed to guide the transition of the Worcester Line from traditional Commuter Rail to a Regional Rail service, then a corresponding timetable, equipment allocation, and ridership projection is presented for each investment phase.

In deciding this order of investments, emphasis was placed on feasibility, prioritizing short-term projects that can make a significant immediate impact over more time-intensive investments that are unlikely to be achievable before major reconstruction work on the Allston Multimodal Project begins. Because the exact construction timelines of each project are unknown as they have not been brought fully through the design and funding process, basic estimates of construction time are used to arrive at the order presented here.

5.0.1 Methodology

In order to fulfill one of the major goals of Rail Vision, to "match service with growth and changing needs of the region", emphasis is placed on timetables that increase bi-directional all-day service to align with the expanding non-traditional commute and leisure travel patterns established in Chapter 3. Further, Inner Core service is prioritized as this market is under-served in comparison to the Outer Metro and Regional Cities and Towns zones.

In developing the timetables, qualitative factors relating to regional fairness and passenger experience held as much priority as quantitative measures of capacity utilization. Though express services present complex operational challenges which negatively impact the provision of service to intermediary communities [46], commuters who use the Heart to Hub service have come to rely on the continued existence of this service which reduces their journey times by over half an hour. Former Worcester Mayor Joseph Petty has even referred to the express service as "critical to the continued transformation of Worcester's economy" [38]. For this reason, every phase presented here commits to the provision of at least one Heart to Hub and one Local-express (Skip Newton through West Natick) in both the AM and PM peaks. To address the existing service inequities experienced by the town of Newton, all existing service types which skip the Newton stations were eliminated. Beyond presenting a more fair version of the service in which communities are not punished for a lack of proper infrastructure outside of their control, this change simplifies the user experience on the line as a whole. Excepting a handful of express services, passengers can board any Worcester Line train they see without worrying about their stop being passed by. To further simplify the passenger experience, regular interval (otherwise known as clock-face) schedules are honored all day except where modifications are strictly necessary to accommodate express services. Regular interval service instills confidence that the system is well-planned and reliable and reduces passengers' costs of acquiring information on train departure times [51]. Valuing the extended service hours established in 2021 which proved popular with Commuter Rail's user base ([29]), all schedules maintain a wide span of service beginning at 4 AM in each direction, and the last train departing around 11 PM in each direction.

The shared nature of Commuter Rail right-of-way also necessitates accommodation of third party services, specifically Amtrak Lake Shore Limited (LSL) service. Today, the service has one daily service in each direction. The outbound LSL departs Boston at 12:50 PM and the inbound LSL arrives at South Station at 8:32 PM.

The general process of developing schedules then proceeds according to three fundamental steps.

1. Maximize clock-face bidirectional local service frequency in the Inner Core

2. Determine and implement desired frequency to Outer Metro and

Regional Cities and Towns zones

3. Add Amtrak Lake Shore Limited and commuter express services where possible without disrupting local trains schedule. Eliminate local trains to accommodate express and Amtrak trains where necessary

To determine the maximum possible frequency of bidirectional local service in the Inner Core, an optimization model is implemented which takes the constraints of the fixed-block signalling system into account. The model presented below builds off a formulation of the Train Timetabling Problem (TTP) developed by Brännlund et al., in which the authors model block signalling with a binary decision variable x^r_{it} to signify whether a train r occupies a block i at time t, specifying that the sum of x^r_{it} over all t must be no greater than 1 and thus that no more than one train may occupy a signalled block at any one time [9]. With a slight variation, the model developed uses a simpler decision variable, x^r_t (a binary variable equal to 1 if a train of service type r begins its journey at time t). This simplification treats the block occupation times of the entire service types as predetermined input matrices to the problem itself, collectively referred to for all routes and possible start times as y^r_{bst} in constraint equation 5.2. These input matrices are developed for hypothetical infrastructure realities using the simulation tool introduced in Chapter 4. An example matrix is reflected in Figure 5-1 for an outbound local train, where the green cells represent the occupation of block b at time s, showing the train skipping between non-consecutive blocks to serve the three Newton stations on the opposite track. The objective of the model is then to maximize the total number of inbound and outbound local trains within an hour (Eq. 5.1), requiring an equal amount of each (Eq. 5.3). The output from the model is a timetable of inbound and outbound local clock-face services from which the determination of proper offsets is possible. For example, the model may determine that 30 minute bidirectional clock-face headways are possible in which the outbound service leaves its first station on the 1st and 30th minute of each hour and the inbound service at the 11th and 41st minute of each hour.

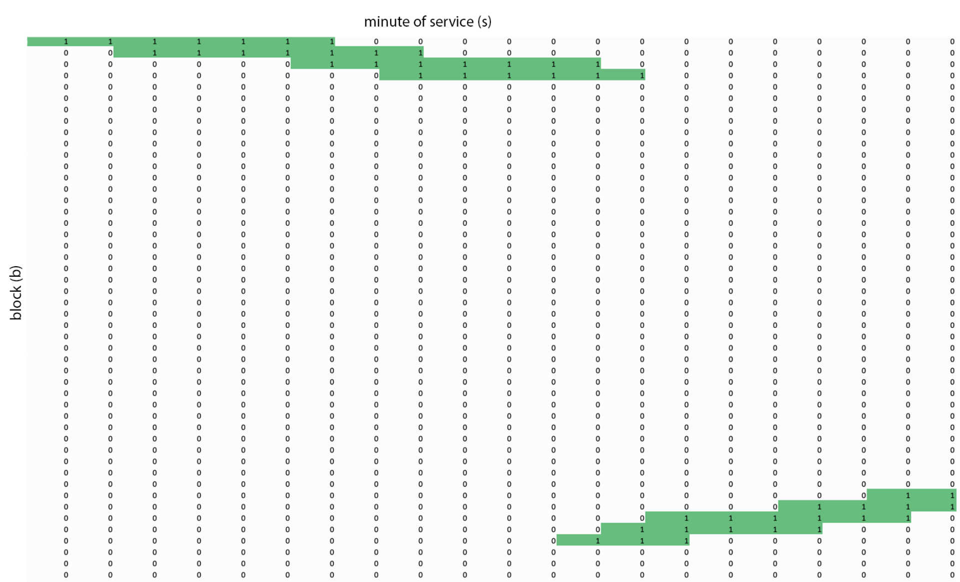


Figure 5-1: Block occupation matrix

$$\max \quad \sum_{t=1:60} x_t^{local_{IB}} + x_t^{local_{OB}} \tag{5.1}$$

$$\text{s.t.} \quad \sum_t \sum_r x_t^r * y_{rbst} \leq 1, \ \forall b, s \tag{5.2}$$

$$\sum_{t=1:60} x_t^{local_{IB}} = \sum_{t=1:60} x_t^{local_{OB}} \tag{5.3}$$

Estimating Fleet Size

After the schedule is created, the number of train sets necessary to fulfill the planned service can be estimated with another optimization model which minimizes the number of train sets (Eq. 5.4) constrained by the conservation of flow of trains within the network (Eq. 5.5) given the demands of the schedule (Eq. 5.6 & Eq. 5.7). That is, the model enforces that the sum of trains at each terminal station at each time step is equal to the sum of trains at the terminal station in the previous time step minus any departed trains plus any arrived trains. The output is then a value of the number of trains needed to service a given schedule and which terminus each should begin at for the day. Because fleet size minimization is a separate single-objective optimization problem from the timetable development, the result is not guaranteed to be the absolute minimum fleet required to achieve a similar total level of service. Such a guarantee would require a more complex dual-objective optimization problem to consider the variables of fleet size and departure times simultaneously.

$$\min \quad \sum_{w \in W} v_0^w \tag{5.4}$$

$$\text{s.t.} \quad v_{s+1}^w = v_s^w + \sum_{r \in r_{D_w}} x_{s-T_r}^r - \sum_{r \in r_{O_w}} x_{r,s}, \ \forall s, w \in W \tag{5.5}$$

$$x_t^r = 1, \ \forall r, t \in \text{schedule} \tag{5.6}$$

$$x_t^r = 0, \ \forall r, t \notin \text{schedule} \tag{5.7}$$

where

T_r : Total travel time of route r

W : Set of terminal stations

Estimating Ridership Benefits

The initial dramatic increase in ridership expected to result from an immediate service enhancement without new infrastructure investment (Phase 1) as outlined in the next section, was used in the mode choice model developed in Chapter 3 to create three no-build potential demand scenarios for 2025.

In subsequent investment phases, additional service increases will be more moderate in comparison, made possible via the gradual elimination of constraints on track capacity, or enabling of passing maneuvers and short-turn services. Thus, these ridership changes are appropriate to be scaled with a simple service elasticity. As identified by Voith in a study of the SEPTA Commuter Rail system in Pennsylvania, long-run rail service elasticities of 0.36 for peak service and 1.89 for off-peak service were utilized [50]. This elasticity is applied cumulatively, each subsequent phase builds off the ridership level of the one before it.

5.0.2 Phase 1: Immediate Service Enhancement & Upgrades to Worcester Line Platform

The first proposed investment phase reflects the increases to service that are possible today without new infrastructure, except the assumption of the imminent completion of the center platform at Worcester as part of the Worcester Union Station Improvements project. This project will replace the current low-level north-side-only platform and eliminate the need for competition on the north track at the terminus. After this project is complete, inbound and outbound trains will no longer need to compete for track use in the approach to the platform and will be able to simultaneously arrive at and depart from Union Station which provides significant scheduling flexibility [4]. The benefits of this change will become especially pronounced in subsequent phases after block lengths are shortened to increase the capacity in the Regional Cities and Towns zone. As established in Chapter 4, the primary limiting factor in Phase 1 is track capacity linked to long block lengths and single-side platforms at the Newton Stations and Worcester.

The service types allowed as input to the optimization model for this phase (Fig. 5-3) are a subset of the service offered on the line today with Newton-skipping services removed. The resulting timetable reflected in the trajectory diagram (Figure 5-4) proves that even with a limited

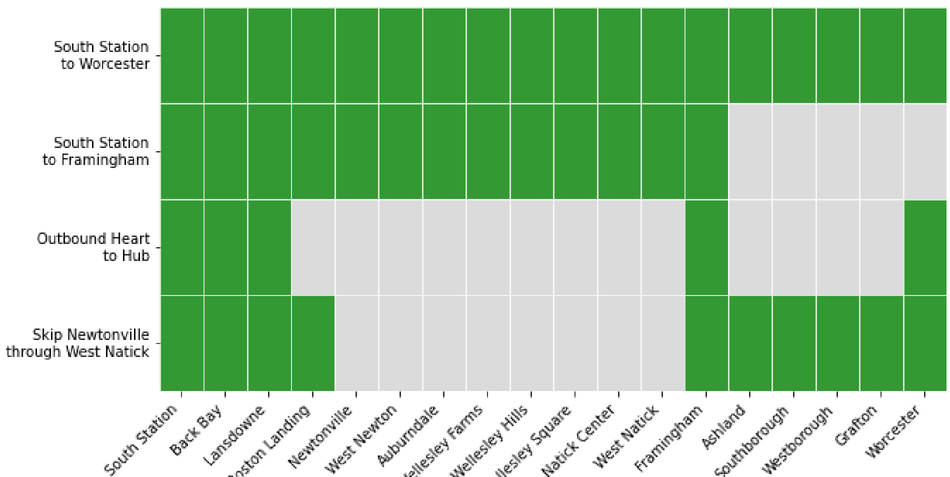


Figure 5-2: Phase 1 Service Type Offering

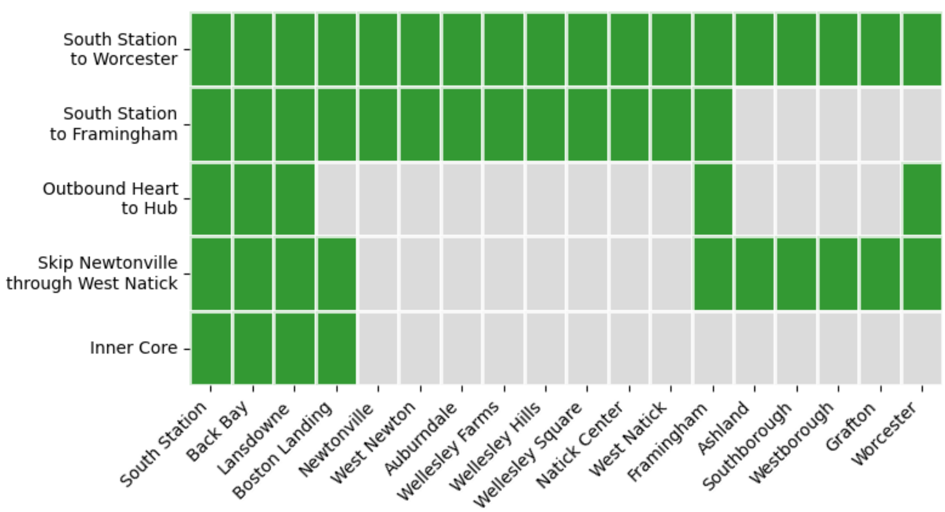


Figure 5-3: All proposed Service Type Offering

palette of service types, dramatic improvement in service quantity is feasible. This timetable is defined by an underlying bi-directional local service that runs every 30 minutes within the Inner Core and Outer

Metro zones and hourly to the Regional Cities and Towns zone during the off-peak (30 minutes during peak). While this underlying clock-face service is the goal, sacrifices of some of these regular-interval services are necessary to accommodate Heart to Hub and Local Express services. Specifically, two inbound and one outbound service during the AM Peak, two outbound services during the PM peak, and one inbound and one outbound service during off-peak hours cannot be fulfilled due to track capacity conflicts. Using the *effective service frequency* metric introduced in Chapter 3, Figure 5-5 shows increases in service by zone pair and time period. These changes range from near-zero change in the peak periods to 365% increase in service in the mid-day. These results are as expected, as the AM peak period is the most difficult to add additional frequency into as all the trains running during this period, even express services, are competing for the use of the south side track. In contrast, express services on the outbound track during the PM peak do not have to use the south side track for any reason, thereby reducing comparative conflict.

As explained in detail in Chapter 3, the service increases reflected in Figure were used to calibrate the three demand scenarios, 5-3, and as discussed prompt a significant overall ridership increase of 0-300% depending on the scenario, as only one part of the suite of factors considered in the mode choice model. The projected ridership for each demand scenario across each phase is summarized in (Fig. 5-13). The estimated number of required train sets is 12, an increase of 3 from the estimated 9 currently devoted to the line.

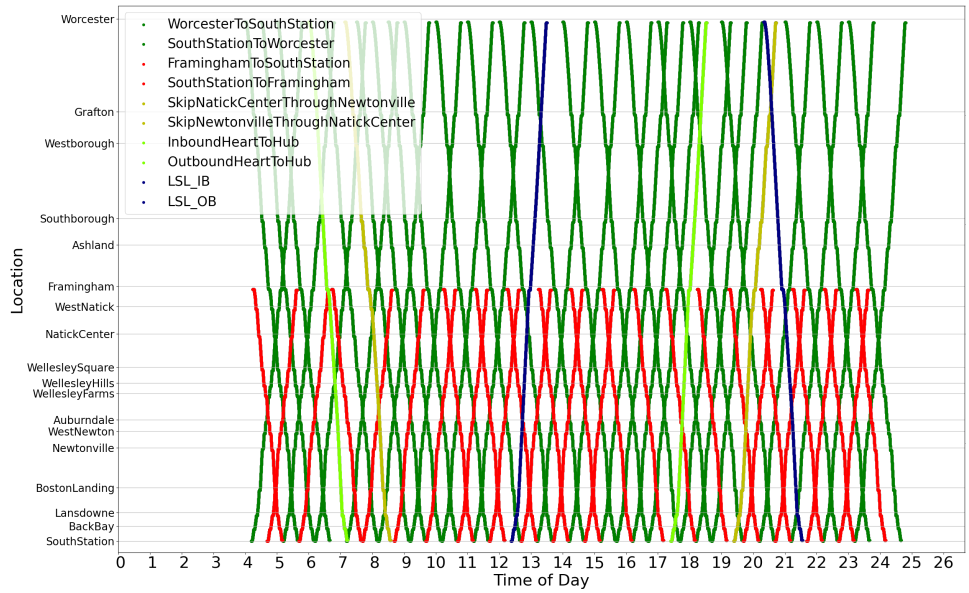


Figure 5-4: Phase 1 Proposed Timetable

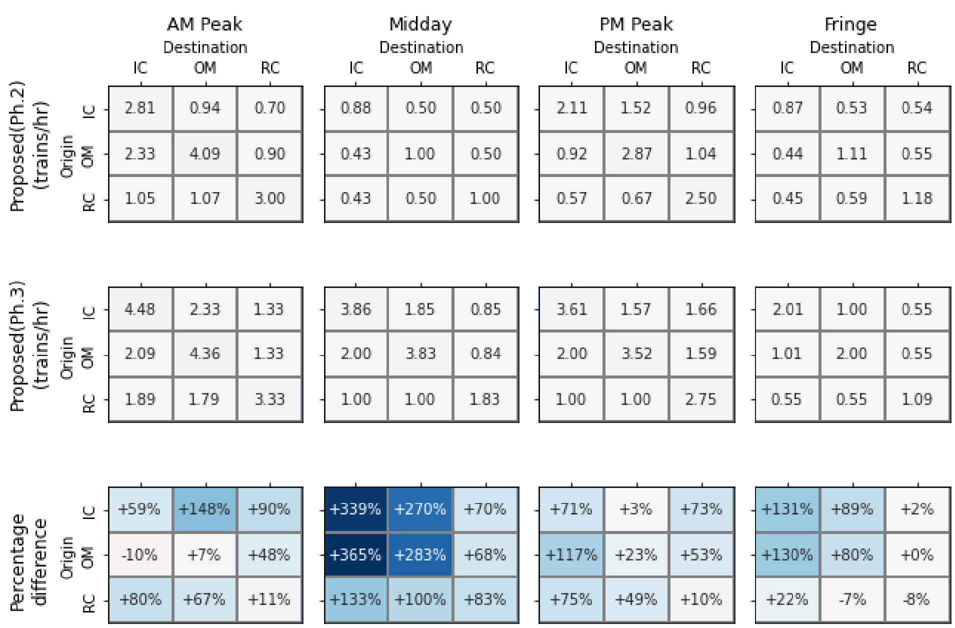


Figure 5-5: Phase 1 Effective Service Increases

5.0.3 Phase 2: Re-signalling

The re-signaling phase, defined by the subdivision of long signal blocks, is suggested as the first infrastructure investment on the line as signaling is less time and resource-consuming than major infrastructure work like rebuilding track or platforms and can be completed with intermittent overnight and weekend closures. Metro-North installed a complete Centralized Train Control (CTC) system on the Danbury line over the course of 3.5 years with no major service interruptions [41]. During the MBTA's own installation of Positive Train Control (PTC) on its commuter rail system, the Worcester Line required the installation of 34 Wayside Interface Units at 21 locations, which began in May 2018 and completed in August 2020 requiring only periodic weekend closures [5].

Further, this phase is key to the effectiveness of all subsequent phases, as block lengths are currently the primary limiting factor on the capacity of the Outer Metro and Regional Cities and Towns segments of the line. To avoid any capacity limitations from block lengths, any current signal blocks longer than half a mile in the Inner Core or 1 mile in the Outer Metro and Regional Cities zones are subdivided into smaller blocks until they meet this maximum length. This change targets 112 locations, expanding the total number of signaled blocks from 50 to 162.

The resulting timetable after this phase (Fig. 5-6), assuming the same underlying regular interval service and desired express and Amtrak service as in Phase 1, produces minor service gains compared to Phase 1 (Fig. 5-7), and the corresponding minor ridership increase, as outbound express services are able to coincide closely with outbound local services and perform a passing maneuver while the local service is visiting the Newton stations on the opposite track. However, inbound service does not gain any comparable benefit.

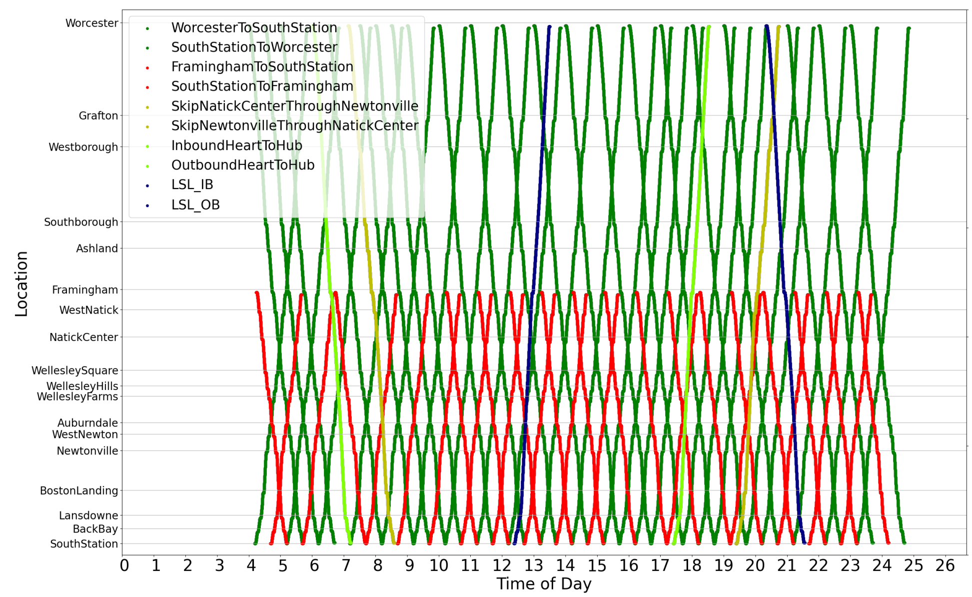


Figure 5-6: Phase 2 Proposed Timetable

A modest ridership increase of 4-4.5% from Phase 1 is expected from this project alone, while the number of train sets is expected to remain the same because the service increases would be off-peak.

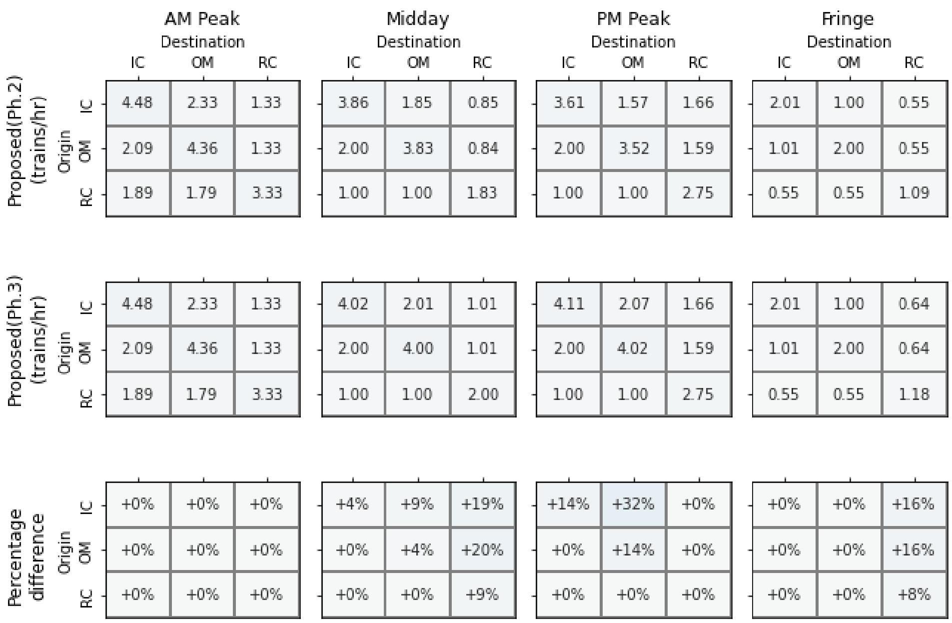


Figure 5-7: Phase 2 Effective Service Increases

5.0.4 Phase 3: Newtonville Platform

The Newton Commuter Rail Stations Accessibility Improvements project is currently in the Design Development phase. As it stands, this project aims to build high-level, fully-accessible, double-side platforms at Newtonville, West Newton, and Auburndale where low-level single-side platforms currently exist. As of the virtual public meeting on October 13, 2021, the agency maintained plans to build all three of these improvements simultaneously. However, the agency is now considering a consolidation approach wherein only one or two of these stations would receive this improvement. This approach aims to combat inflating costs of the project.

Considering the significant number of options available for Newton, and understanding that maintaining a robust set of Inner Core stations is important for a vibrant "subway-like" service in this segment, the approach proposed here values immediate improvement in the short term while keeping long-term options open. A policy is desired that would allow service to Newton to resume on the north track as soon as possible, alleviating undesirable constraints on service caused by the single-side platforms. Therefore, the construction of a single *temporary platform* on the north side of the tracks at Newtonville is proposed as a transitional phase, to be replaced with a permanent platform at a later date. This would require temporary suspension of service to the West Newton and Auburndale Stations in both directions, the latter of which is proposed to re-open as Riverside station in Phase 4. Currently, at the Lynn station on the Newburyport/Rockport MBTA Commuter Rail Line, a temporary platform is being constructed while the station undergoes renovations. As of July 2023, the platform had not begun its construction yet has been slated for completion by Spring 2024, indicating the project can be completed in significantly less than a year [45]. Understandably, this move could cause backlash amongst Newton residents and elected officials who have come to expect that they will receive three full station upgrades. The plan proposed here does not rule out this option, rather, it prioritizes the fastest possible improvement in service frequency for the under-served area while the construction plans for permanent platforms in Newton are finalized.

This infrastructure phase will mark the end of any need to coordinate movements between the inbound and outbound tracks and thus, the use of the optimization model to create schedules is less critical because the minimum headway as a result of track capacity would be arbitrarily small. Rather, scheduling decisions are primarily concerned with desired frequency and equipment availability, as all trains must still go at least as far as Framingham before they are able to turn around.

The resulting timetable proposed after this change (Fig. 5-8) is characterized by an underlying regular interval service of 20-minute headways in the Outer Metro and Inner Core zones and 40 minutes to the Regional Cities and Towns zone (20 minutes during peak) with none of the regular interval service within the Outer Metro/Inner Core requiring cancellation.

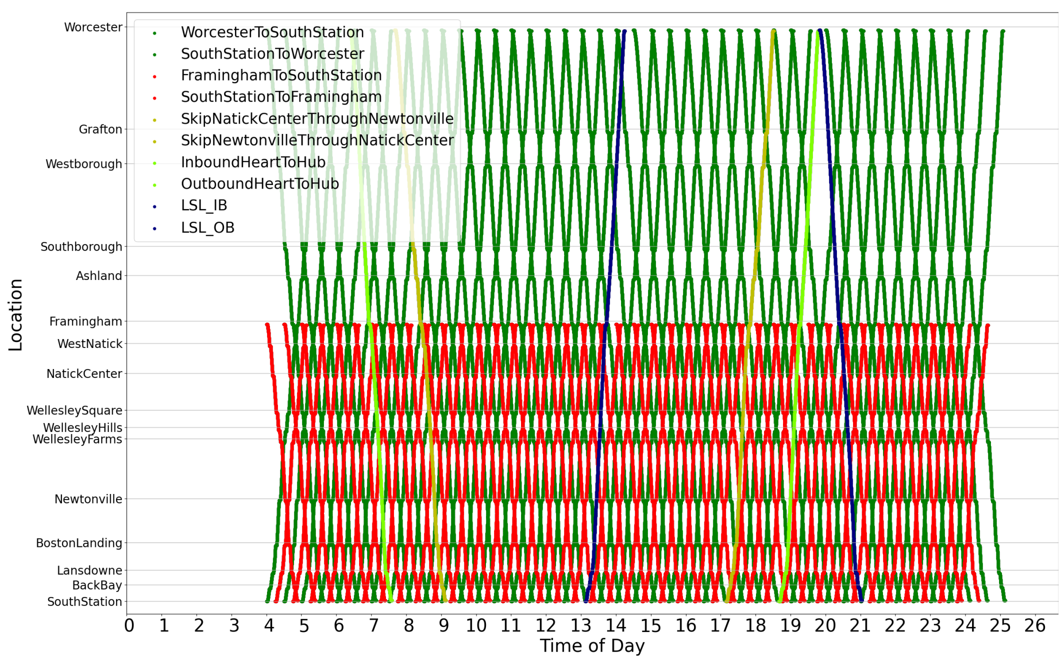


Figure 5-8: Phase 3 Proposed Timetable

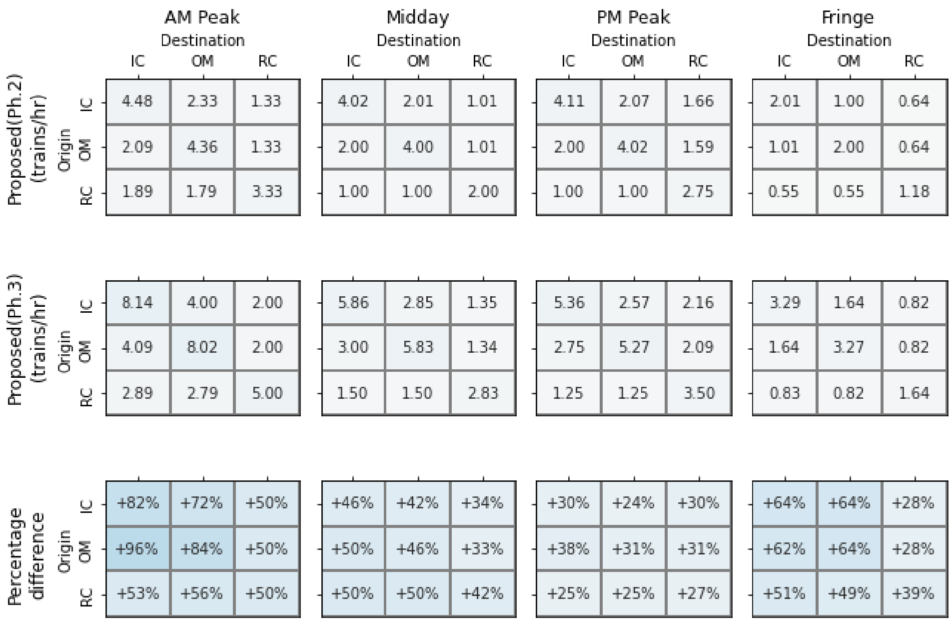


Figure 5-9: Phase 3 Effective Service Increases

Corresponding ridership increases are expected at 37-40% over Phase 2 levels, and 15 total train sets are expected to be required.

5.0.5 Phase 4: Riverside Spur and Platform

As introduced in Chapter 2, there is existing track infrastructure leftover from the Boston & Albany Railroad which branches off the Worcester Line after modern-day Auburndale station towards the Green Line's Riverside station. Given the agency's past ability to reopen this spur under the major 1996 flood event, the investment needed to reopen this spur for short-turn Inner Core service, both in terms of time and capital is expected to be minimal.

Though the creation of a platform at Riverside will take more time than the initial reopening of the turning track, this project will restore service to the area of Newton previously served by Auburndale station, which would be closed in Phase 3. In alignment with the stated Rail Vision goals to "improve connectivity throughout the region", the new station would offer a direct transfer to the Green Line's D Branch, providing invaluable integration with the city's transit network at large.

The proposed timetable (Fig. 5-11) is identical to that proposed for Phase 3, except for the addition of an additional Inner-Core-only service which turns at the reopened Riverside Spur, bringing headways in the Inner Core down to a subway-like 10 minutes. Eventually, this will provide service to Riverside Station though that will likely come significantly later (Fig. 5-10).

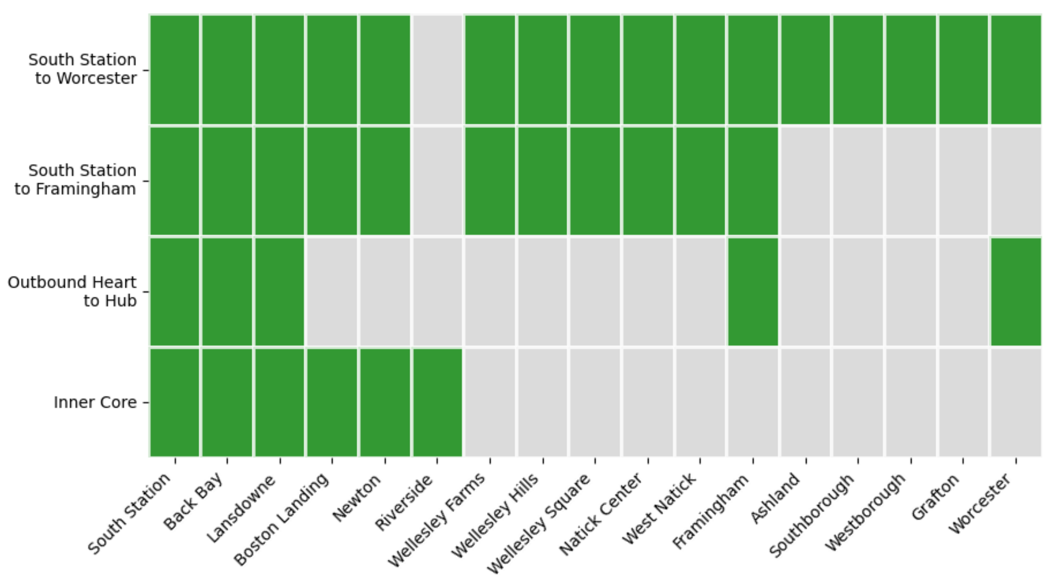


Figure 5-10: Phase 4 Service Types

Corresponding ridership increases from the Inner Core market alone

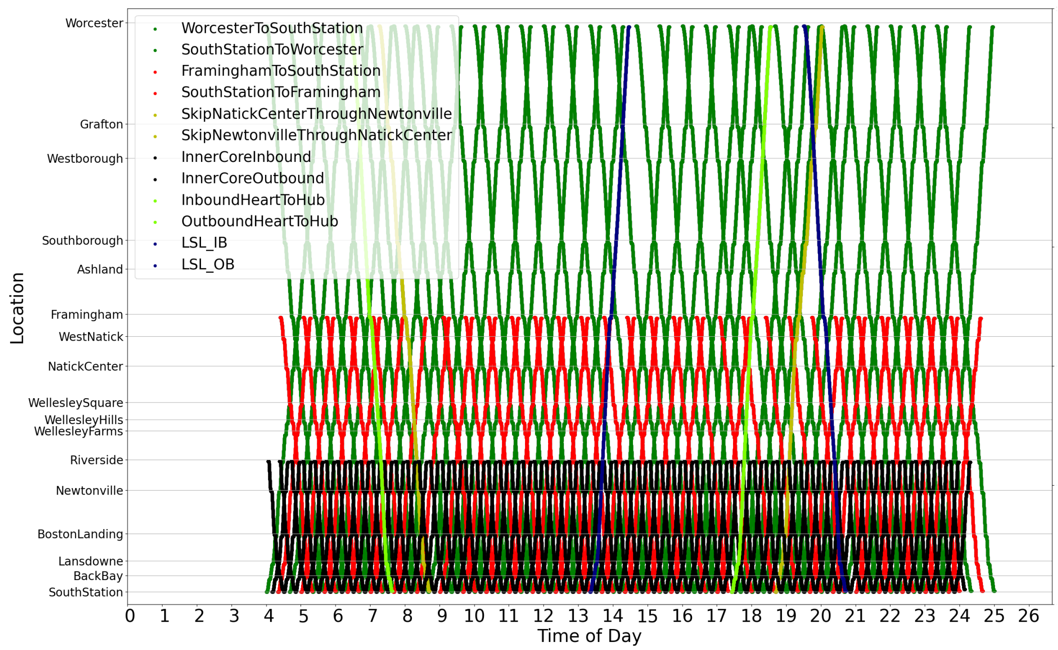


Figure 5-11: Phase 4 Proposed Timetable

are expected at 35-43% over Phase 3 levels, and 17 total train sets are expected to be required.

Proposed(Ph.2) (trains/hr)

	AM Peak			Midday			PM Peak			Fringe		
Origin \ Destination	IC	OM	RC	IC	OM	RC	IC	OM	RC	IC	OM	RC
IC	8.14	4.00	2.00	5.86	2.85	1.35	5.36	2.57	2.16	3.29	1.64	0.82
OM	4.09	8.02	2.00	3.00	5.83	1.34	2.75	5.27	2.09	1.64	3.27	0.82
RC	2.89	2.79	5.00	1.50	1.50	2.83	1.25	1.25	3.50	0.83	0.82	1.64

Proposed(Ph.3) (trains/hr)

IC	16.14	4.00	2.00	11.86	2.85	1.35	11.36	2.57	2.16	6.56	1.64	0.82
OM	4.09	8.02	2.00	3.00	5.83	1.34	2.75	5.27	2.09	1.64	3.27	0.82
RC	2.89	2.79	5.00	1.50	1.50	2.83	1.25	1.25	3.50	0.83	0.82	1.64

Percentage difference

IC	+98%	+0%	+0%	+102%	+0%	+0%	+112%	+0%	+0%	+99%	+0%	+0%
OM	+0%	+0%	+0%	+0%	+0%	+0%	+0%	+0%	+0%	+0%	+0%	+0%
RC	+0%	+0%	+0%	+0%	+0%	+0%	+0%	+0%	+0%	+0%	+0%	+0%

Figure 5-12: Phase 4 Effective Service Increases

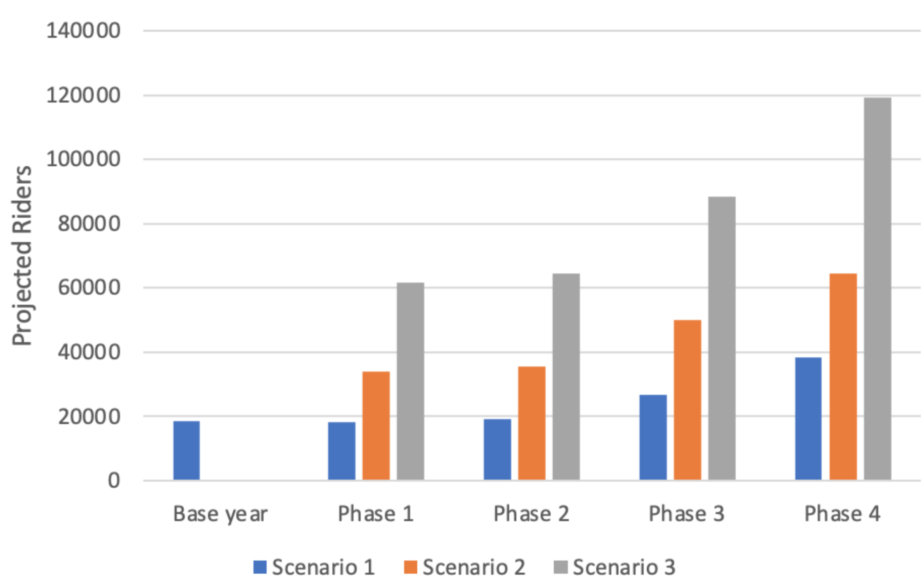


Figure 5-13: Cumulative Projected Ridership

Chapter 6

Conclusion

6.1 Summary of Findings

This work analyzed the potential for the high-frequency, bidirectional service which characterizes the concept of regional rail to boost ridership on the Massachusetts Bay Transportation Authority (MBTA) Worcester/Framingham Commuter Rail line. Focus was placed on short-term goals that will enable the transition between present-day diesel commuter service and fully electric regional rail that may be decades in the future. This analysis took place in three parts: an evaluation of potential demand for regional rail service, a survey of existing operational challenges and bottlenecks with current infrastructure and rolling stock, and a proposal for a four-phase infrastructure investment path which selected a suite of projects intended to be complete before major reconstruction work begins on the Allston Multimodal Project.

Throughout the work, special attention is paid to improving service in the Inner Core region. The market of trips in this zone that could be completed on the Worcester Line, but are not, due to high fares or unfavorable headways is vast yet currently overlooked. The MBTA stands to strongly benefit from increased attention to this short corridor which can bring an abundance of riders into the city whilst expending very minimal operational resources. Further, this Inner Core market will only grow vastly larger once the reconstruction period begins. For this reason, emphasis is placed on the complete follow-through of the recommendations proposed here. The replacement of Auburndale with a Riverside stop is key, as even with improved frequency to Newtonville, the elimination of service to West Newton and Auburndale may fail to attract enough drivers from the urban area to transit to offset the loss of capacity on Interstate-90 during the lengthy reconstruction period in Allston. Shifting drivers from the Inner Core is of benefit not only to Inner Core residents, but provides regional benefit to the suburban, exurban, and intercity auto travelers who would experience less congestion in their auto commutes. By focusing on improved signaling, upgraded accessible stations, eliminating the complication of the existing single-side Newton stations, and allowing short-turn service and a Green Line connection at Riverside, the limited rolling stock available in the near term can be used more intensively to attract as many riders as possible, mitigating the regional congestion problem, as well as pleasing Newton interests.

6.1.1 Discussion of Demand in the Western Corridor

Chapter 3 characterized the demand landscape in the Boston Metro West Corridor. First looking to survey data from the MBTA Systemwide Passenger Survey conducted before the pandemic (2015-2017) and present day (2022), show major shifts away from home-based-work trips (90% to 55%), and towards low-income riders (8% to 29%), and minority riders (19% to 41%) who are primarily Black and Asian. Additionally, Worcester Line riders are choosing to ride less frequently. Before the pandemic, 66% of riders used the line 5 days per week compared to 27% after.

In line with understanding of post-pandemic travel behaviors, an analysis of mTicket data during the study period revealed a strong shift away from multi-ride passes such as 10-Ride and Monthly passes towards single-use passes like the One Way and Round Trip offerings. A new pass type designed to accommodate the flexible future of work, the 5-Day Flex Pass, has steadily increased popularity since its inception to capture over 8% of the mTicket sales in 2022 surpassing the Monthly Pass option. Compared to real corridor demand data across all modes, the Worcester Line has achieved the greatest market capture in the AM and PM peak periods and between the Regional Cities and Towns zone and the Inner Core, capturing 42% and 38% of the market in the morning and evening peaks in the base year (2018), respectively. The Inner Core-to-Inner Core trips market is the largest by far, yet has the lowest market share of any of the zone pairings. This indicates that the agency should cease to continue the operation of skipping the three Newton stations on a majority of trips except in express service types and focus on offering more short-turn service which would more efficiently allocate resources to where the market for the service is. Through the demand tool developed in the chapter using a series of environmental and policy-driven input factors, three scenarios are generated for the potential future of demand on the line. In the most pessimistic case, a total of 18,330 Worcester Line trips are expected in 2025 versus 61,742 in the most optimistic case.

6.1.2 Discussion of Service Supply

An analysis of GTFS data during the study period reveals a complex system of as many as 12 different service types on a single day, each stopping at a different combination of stations along the line. In the analysis of automatic vehicle location (AVL) data, travel times for services of the same type were found to vary significantly based on time of day by as much as 15 minutes on average. This time was not all attributable to additional dwell, indicating track congestion as a possible factor. The most common place to accumulate delay on the route was between West Natick and Framingham stations, indicating the need for further analysis in this area.

A capacity assessment of the block signaling infrastructure confirms that the single-sided platforms at Newton are the single greatest inhibitor of high-frequency local bidirectional service, as the competitive segment takes up to 13 minutes to be traversed by a train. Another limiting factor on the current infrastructure is the long block lengths of up to 6 miles, especially in the Regional Cities and Towns zone.

6.1.3 Discussion of Investment Phases

Chapter 5 proposed a four-step sequence of investments to improve service delivery on the Worcester Line. Weekday service timetables were generated for each phase, based on a service-maximizing optimization model which considered signal block constraints. In the first phase, service is estimated to increase the most in the midday off-peak period (+68% - +365%) and increase the least in the AM Peak (-10% - +148%). The infrastructure is able to support bidirectional headways of 30 minutes when not met with interference by capacity-intensive express services. The second phase proposes thorough resignaling work to shorten block lengths that will not provide very significant immediate benefits to service and ridership but proves necessary to reap the benefits of subsequent phases. Phases 3 and 4 solve the problem of the Newton bottleneck by suggesting a temporary platform on the north track at Newtonville and eventually reopening Auburndale as Riverside station. In all, these investments are expected to return a ridership increase of between 210% and 651% of base year ridership levels depending on the demand scenario which eventually plays out over the next several years.

6.2 Limitations and Future Work

6.2.1 Data Limitations

Ridership data available today in the form of mTicket mobile app records and onboard conductor counts is drastically insufficient in accurately estimating the number of riders on the system and what paths they take through it due to the inconsistency associated with conductor fare collection as well as reporting faults with the mTicket app itself. It is strongly recommended that data in the form of automated passenger counts (APC) continue to be pursued.

6.2.2 Limitations regarding demand forecasts

This thesis uses a very basic sketch-level model to estimate market growth in the corridor and each resident's mode choice. Future work focusing on the nuance of the demand patterns in the area could greatly benefit our understanding of the transportation needs of its residents. Specifically, the state should explore using mitigation funding from Allston Multimodal Project construction to monitor resulting ridership responses to the disruption and improve the prediction of mode shift potential during other construction disruptions. Though this thesis is not primarily concerned with access, its effects are indisputable. It is recommended that the reader supplements this work with the 2020 report by Sevstuk et al. [49], *Transit Access: Improving walking and biking to commuter rail stations in Greater Boston.*

6.2.3 Limitations regarding schedule generation

In Chapter 5, an optimization model was developed as an aid to generate timetables for commuter rail service. Because this model is based on the Event Scheduling Problem and not the more complex Periodic Event Scheduling Problem (PESP), it requires a lot of input and iteration from the user to obtain a regular-interval timetable. Future researchers looking to advance this method should look into the PESP and also consider a bi-objective function to minimize fleet requirements at the same time.

6.3 Future Work

This thesis looked at short-term transitional solutions over the next few years while the MBTA Commuter Rail system still operates with diesel locomotives. The full transition to regional rail is a vast and incredibly complex set of solutions that must take place at a network scale.

6.3.1 Electrification

Though this work focused on the transition into regional rail that can be achieved in the present day under limited resources, and with diesel locomotives, the improvements in reliability and acceleration times that come with electrification will completely change the strategy for service delivery in the network. Further research into this area is strongly encouraged.

6.3.2 Terminal Operations

Arguably the most pressing factor standing in the way of regional rail today is the capacity at South Station terminus. Though the South Station Expansion project has been proposed to alleviate bottlenecks in the Tower 1 interlocking, this construction is unlikely to move forward due to space constraints. Given that MBTA/Amtrak dispatch operations at South Station are led primarily by a handful of experts without the use of computer-aided technology, there is likely a lot of room to improve operational efficiency without any construction work at all. Strategies for maximizing train throughput in terminal stations would be an immense push forward for the regional rail concept in Massachusetts.

6.4 Policy Recommendations

6.4.1 Timeline

To restate an urgent point, the projects outlined in Chapter 5 are intended to be implemented in the very near-term with the expectation that they can be completed before major reconstruction begins on Interstate-90 at Allston. This thesis does not advocate for the permanent closure of West Newton station. Rather, it aims to offer short-term solutions while construction plans are finalized to restore full rightful service at all the town's stations. The best chance for a significant mode shift away from private automobiles and towards regional rail relies on the existence of regional rail as an appealing alternative in the next three years. Thus, it is in the agency's best interest to complete infrastructure investments that could alleviate capacity restrictions on the line as soon as possible. However, in the worst case that any of the outlined projects are not able to be completed in the time window before I-90 reconstruction begins, they should be either delayed or completed at off-revenue times such that there is no construction on the line which slows or eliminates service.

6.4.2 Fares

A reduction in Commuter Rail fares, especially after work on the Allston Multimodal Project begins, is strongly recommended. This construction event provides a unique opportunity to pilot a fare reduction and test its effect on ridership. It is also recommended that the MBTA pursue the integration of commuter rail fares with Charlie Card and transfer credits to promote the idea that regional rail is an extension of the urban rail network.

6.4.3 Access

Adding additional bike storage at rail stations, where many currently number in the single digits (see Chapter 2), is a low-cost and potentially high-impact intervention that will improve access to stations. As transit-oriented development accelerates in coming years in conjunction with the MBTA Communities Act, the agency can anticipate the growing need for first and last-mile access solutions as part of a robust, multi-modal transportation system.

While many users who live further from stations choose to travel by car, many potential riders are excluded from the service for not having this reliable form of access. Shuttle bus services that provide motorized access to stations for those who live further from stations and may not have daily access to a private vehicle are strongly encouraged to attract ridership and ensure regional equity.

Further, all low platforms, especially at the major urban station Back Bay should be considered for reconstruction to high-level platforms, both to make the system more accessible for riders with physical disabilities and to reduce dwell times.

Appendix A

Service Analysis Tables

Table A.1: Travel Time by Route name - Inbound

	Travel time (min)					
	2018			2022		
Service	count	mean	std	count	mean	std
Framingham to South Station	103	50.55	6.49	76	45.38	3.96
Framingham to South Station Newton skip	44	41.06	4.53	20	40.0	1.61
Inbound Heart to Hub	–	–	–	20	60.0	9.45
Inbound Newton skip	140	82.98	6.73	179	84.0	5.13
Local From Ashland	20	60.08	5.55	–	–	–
Skip Natick Center through BL	57	78.25	4.79	–	–	–
Skip Natick Center through Newtonville	40	75.56	7.44	52	76.0	5.6
Skip Wellesley Square through BL	20	73.05	7.42	–	–	–
Worcester Xpress Inbound	22	60.8	8.39	–	–	–
Worcester to South Station	120	87.56	5.49	168	87.62	7.93
Worcester to South Station Skip Boston Landing	54	88.02	7.81	–	–	–

Table A.2: Total Dwell Time by Route name - Inbound

	Total Dwell Time (min)					
	2018			2022		
Service	count	mean	std	count	mean	std
Framingham to South Station	102	18.01	5.35	76	16.56	4.04
Framingham to South Station Newton skip	44	11.37	3.52	20	10.93	2.54
Inbound Heart to Hub	–	–	–	20	10.5	6.95
Inbound Newton skip	140	20.09	5.29	179	24.0	6.0
Local From Ashland	20	21.02	6.31	–	–	–
Skip Natick Center through BL	57	18.38	2.92	–	–	–
Skip Natick Center through Newtonville	40	15.46	3.56	52	20.9	5.17
Skip Wellesley Square through BL	20	15.02	6.76	–	–	–
Worcester Xpress Inbound	22	6.76	4.47	–	–	–
Worcester to South Station	120	22.08	5.07	169	27.0	7.58
Worcester to South Station Skip Boston Landing	54	22.78	7.97	–	–	–

Table A.3: Travel Time by Route name - Outbound

	Travel time (min)					
	2018			2022		
Service	count	mean	std	count	mean	std
Local to Ashland Skip Newton	19	48.07	3.34	–	–	–
Outbound Heart to Hub	–	–	–	18	61.0	3.06
Outbound Newton skip	37	83.22	5.21	126	84.0	7.13
Outbound Newton skip Boston Landing	20	77.65	3.38	–	–	–
Skip B L through Natick Center	75	75.67	8.45	–	–	–
Skip B L through Wellesley Square	14	83.25	6.77	–	–	–
Skip Newtonville through Natick Center	–	–	–	49	74.5	6.35
Skip Newtonville through West Natick	20	65.71	3.6	–	–	–
South Station to Framingham	66	51.87	7.64	61	47.0	3.53
South Station to Framingham Newton skip	21	38.53	3.21	–	–	–
South Station to Framingham Newton skip BL	18	37.04	2.86	–	–	–
South Station to Worcester	233	84.18	7.74	221	84.25	6.94
Worcester Xpress Outbound	21	60.4	5.38	–	–	–

Table A.4: Total Dwell Time by Route name - Outbound

	Total Dwell Time (min)					
	2018			2022		
Service	count	mean	std	count	mean	std
Local to Ashland Skip Newton	19	13.52	3.22	–	–	–
Outbound Heart to Hub	–	–	–	18	8.63	2.46
Outbound Newton skip	37	21.57	4.75	126	19.23	5.07
Outbound Newton skip Boston Landing	21	13.25	3.98	–	–	–
Skip B L through Natick Center	71	17.03	7.19	–	–	–
Skip B L through Wellesley Square	14	24.49	7.6	–	–	–
Skip Newtonville through Natick Center	–	–	–	49	19.82	6.1
Skip Newtonville through West Natick	20	10.0	2.64	–	–	–
South Station to Framingham	65	21.03	5.07	61	18.5	3.7
South Station to Framingham Newton skip	21	9.57	1.75	–	–	–
South Station to Framingham Newton skip BL	19	6.78	2.54	–	–	–
South Station to Worcester	232	20.06	6.72	222	23.31	5.56
Worcester Xpress Outbound	20	4.12	2.31	–	–	–

Table A.5: Travel Time by Period of Day - Inbound

	Travel time (min)					
	2018			2022		
Service	count	mean	std	count	mean	std
AM Peak	270	68.44	14.45	190	64.69	16.69
Fringe	172	75.45	14.81	137	76.97	13.99
Midday	110	90.08	6.61	142	84.62	16.30
PM Peak	161	60.48	21.43	150	67.20	20.37

Table A.6: Total Dwell Time by Period of Day - Inbound

	Total Dwell Time (min)					
	2018			2022		
Service	count	mean	std	count	mean	std
AM Peak	270	17.16	7.32	191	17.94	7.73
Fringe	168	15.02	4.41	142	15.62	7.58
Midday	110	20.36	8.35	142	22.80	8.94
PM Peak	159	15.07	6.80	150	18.00	7.07

Table A.7: Travel Time by Period of Day - Outbound

	Travel time (min)					
	2018			2022		
Period	count	mean	std	count	mean	std
AM Peak	164	59.79	15.15	110	74.68	11.68
Fringe	169	73.91	20.86	133	80.11	10.41
Midday	121	74.62	23.11	169	75.60	24.70
PM Peak	224	63.90	25.55	206	61.30	20.70

Table A.8: Total Dwell Time by Period of Day - Outbound

	Total Dwell Time (min)					
	2018			2022		
Period	count	mean	std	count	mean	std
AM Peak	150	11.94	5.81	106	16.35	7.80
Fringe	151	13.18	8.96	124	18.51	7.56
Midday	115	15.09	10.11	169	16.70	9.29
PM Peak	226	18.60	7.91	206	15.18	8.39

Table A.9: Travel Time by Train Number - Inbound

		Travel time (min)					
		2018			2022		
Service	Train Nº	count	mean	std	count	mean	std
Framingham to South Station		**103**	**50.15**	**6.49**	**76**	**45.69**	**3.96**
	582	23	48.51	9.13	18	45.32	3.19
	584	18	52.05	4.28	18	46.78	5.44
	586	19	51.64	2.87	19	47.68	3.62
	588	21	53.95	4.96	–	–	–
	596	22	45.41	5.08	21	43.29	1.42
Framingham to South Station Newton skip		**44**	**41.17**	**4.53**	**20**	**39.72**	**1.61**
	592	23	44.03	2.86	20	39.72	1.61
	594	21	38.04	3.93	–	–	–
Inbound Heart to Hub		**–**	**–**	**–**	**20**	**62.21**	**9.45**
	552	–	–	–	20	62.21	9.45
Inbound Newton skip		**140**	**83.96**	**6.73**	**179**	**84.41**	**5.13**

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Table A.9 – *Continuation of previous page*

		Travel time (min)					
		2018			2022		
Service	Train Nº	count	mean	std	count	mean	std
	510	20	89.76	8.49	–	–	–
	514	–	–	–	19	89.45	4.83
	518	20	88.17	7.9	21	87.01	5.1
	520	22	85.58	3.36	19	87.06	3.22
	522	–	–	–	10	83.55	4.93
	524	–	–	–	21	86.55	2.72
	526	20	82.84	5.2	17	84.29	3.66
	528	21	78.52	3.34	17	82.35	2.81
	530	20	79.83	4.46	18	85.53	3.92
	532	18	80.03	13.08	–	–	–
	534	–	–	–	20	78.82	3.53
	536	–	–	–	17	78.0	2.01
Local From Ashland		**20**	**61.81**	**5.55**	**–**	**–**	**–**

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Table A.9 – *Continuation of previous page*

		Travel time (min)					
		2018			2022		
Service	Train Nº	count	mean	std	count	mean	std
	590	20	61.81	5.55	–	–	–
Skip Natick Center through BL		**57**	**78.93**	**4.79**	**–**	**–**	**–**
	504	18	76.71	3.41	–	–	–
	506	17	80.04	4.84	–	–	–
	508	22	79.87	5.27	–	–	–
Skip Natick Center through Newtonville		**40**	**78.13**	**7.44**	**52**	**77.04**	**5.6**
	502	–	–	–	17	72.49	2.92
	504	–	–	–	17	76.6	4.65
	506	–	–	–	18	81.76	4.6
	522	20	79.04	6.39	–	–	–
	524	20	77.23	8.44	–	–	–
Skip Wellesley Square through B L		**20**	**75.74**	**7.42**	**–**	**–**	**–**

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Table A.9 – *Continuation of previous page*

		Travel time (min)					
		2018			2022		
Service	Train Nº	count	mean	std	count	mean	std
	502	20	75.74	7.42	–	–	–
Worcester Xpress Inbound		**22**	**63.96**	**8.39**	**–**	**–**	**–**
	552	22	63.96	8.39	–	–	–
Worcester to South Station		**120**	**87.53**	**5.49**	**168**	**88.88**	**7.93**
	500	18	87.76	1.93	20	84.17	2.02
	508	–	–	–	17	88.69	2.98
	510	–	–	–	21	95.61	10.76
	512	21	92.15	3.47	9	87.03	7.14
	514	2	88.5	0.33	–	–	–
	516	3	86.04	0.8	9	89.91	6.07
	532	–	–	–	15	88.5	7.89
	534	17	83.79	8.14	–	–	–
	1500	4	86.69	5.09	4	86.5	5.07

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Table A.9 – *Continuation of previous page*

		Travel time (min)					
		2018			2022		
Service	Train Nº	count	mean	std	count	mean	std
	1502	3	92.26	6.08	4	90.69	3.95
	1504	4	93.83	5.04	5	93.4	4.04
	1506	3	84.43	1.04	4	85.81	4.07
	1508	4	86.29	5.89	3	95.25	11.7
	1510	3	90.27	2.88	5	90.95	7.93
	1512	3	87.05	1.08	3	89.25	1.25
	1514	4	85.25	7.72	5	84.45	1.46
	1516	3	82.43	3.02	5	86.2	1.75
	2500	2	83.83	1.06	4	80.5	5.57
	2502	4	86.71	2.5	4	86.25	3.66
	2504	3	91.3	5.54	4	87.62	3.15
	2506	4	86.54	3.77	5	95.39	19.31
	2508	3	81.95	2.02	4	96.31	18.69

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Table A.9 – *Continuation of previous page*

		Travel time (min)					
		2018			2022		
Service	Train Nº	count	mean	std	count	mean	std
	2510	3	87.92	1.16	4	84.62	1.16
	2512	3	89.7	6.46	4	89.5	1.29
	2514	4	85.21	0.49	5	86.95	3.52
	2516	2	78.51	0.11	5	84.2	1.48
Worcester to South Station Skip BL		**54**	**89.35**	**7.81**	**–**	**–**	**–**
	514	18	95.95	8.27	–	–	–
	516	17	88.83	4.26	–	–	–
	536	19	83.57	4.45	–	–	–

Table A.10: Total Dwell Time by Train Number - Inbound

		Total Dwell Time (min)					
		2018			2022		
Service	Train Nº	count	mean	std	count	mean	std
Framingham to South Station		**102**	**17.63**	**5.35**	**76**	**16.59**	**4.04**
	582	22	15.46	5.19	18	16.84	3.16
	584	18	18.81	4.17	18	17.9	4.34
	586	19	20.06	2.16	19	18.78	4.0
	588	21	21.76	5.44	–	–	–
	596	22	12.79	3.37	21	13.26	2.1
Framingham to South Station Newton skip		**44**	**11.92**	**3.52**	**20**	**11.48**	**2.54**
	592	23	13.79	2.98	20	11.48	2.54
	594	21	9.88	2.91	–	–	–
Inbound Heart to Hub		**–**	**–**	**–**	**20**	**11.63**	**6.95**
	552	–	–	–	20	11.63	6.95
Inbound Newton skip		**140**	**21.01**	**5.29**	**179**	**23.17**	**6.0**

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Table A.10 – *Continuation of previous page*

		Total Dwell Time (min)					
		2018			2022		
Service	Train Nº	count	mean	std	count	mean	std
	510	20	27.2	5.24	–	–	–
	514	–	–	–	19	24.3	4.7
	518	20	23.23	5.79	21	25.4	5.37
	520	22	24.24	3.43	19	26.63	4.16
	522	–	–	–	10	24.38	5.33
	524	–	–	–	21	27.18	2.31
	526	20	20.04	2.48	17	23.91	4.52
	528	21	16.78	2.13	17	24.18	4.15
	530	20	16.36	2.31	18	23.84	7.01
	532	18	17.69	4.63	–	–	–
	534	–	–	–	20	17.66	3.76
	536	–	–	–	17	13.64	3.05
Local From Ashland		**20**	**22.91**	**6.31**	**–**	**–**	**–**

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Table A.10 – *Continuation of previous page*

		Total Dwell Time (min)					
		2018			2022		
Service	Train Nº	count	mean	std	count	mean	std
	590	20	22.91	6.31	–	–	–
Skip Natick Center through BL		**57**	**18.96**	**2.92**	**–**	**–**	**–**
	504	18	18.57	2.23	–	–	–
	506	17	18.96	3.38	–	–	–
	508	22	19.29	3.12	–	–	–
Skip Natick Center through Newtonville		**40**	**16.84**	**3.56**	**52**	**21.49**	**5.17**
	502	–	–	–	17	16.97	2.71
	504	–	–	–	17	21.57	3.85
	506	–	–	–	18	25.69	4.49
	522	20	16.94	3.08	–	–	–
	524	20	16.75	4.07	–	–	–
Skip Wellesley Square through BL		**20**	**17.48**	**6.76**	**–**	**–**	**–**

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		Total Dwell Time (min)					
		2018			2022		
Service	Train Nº	count	mean	std	count	mean	std
	502	20	17.48	6.76	–	–	–
Worcester Xpress Inbound		**22**	**8.24**	**4.47**	**–**	**–**	**–**
	552	22	8.24	4.47	–	–	–
Worcester to South Station		**120**	**22.3**	**5.07**	**169**	**27.45**	**7.58**
	500	18	21.46	1.86	20	21.2	2.96
	508	–	–	–	17	28.38	2.95
	510	–	–	–	21	33.23	11.44
	512	21	26.07	3.39	9	26.48	4.7
	514	2	24.86	0.74	–	–	–
	516	3	23.11	1.03	9	28.36	4.88
	532	–	–	–	15	27.18	7.12
	534	17	15.77	5.04	–	–	–
	1500	4	22.33	4.47	4	28.67	2.05

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Table A.10 – *Continuation of previous page*

		Total Dwell Time (min)					
		2018			2022		
Service	Train Nº	count	mean	std	count	mean	std
	1502	3	30.17	7.79	4	28.95	3.64
	1504	4	28.9	2.64	5	30.67	3.57
	1506	3	21.52	1.8	4	28.91	3.21
	1508	4	22.32	3.1	3	32.18	12.44
	1510	3	24.04	2.88	5	29.51	7.69
	1512	3	23.76	0.93	3	27.41	2.12
	1514	4	20.87	3.16	5	24.08	1.77
	1516	3	15.74	1.09	5	23.46	3.18
	2500	2	20.83	0.26	4	25.18	5.85
	2502	4	23.69	3.6	5	22.03	11.4
	2504	3	27.57	3.32	4	27.07	2.86
	2506	4	23.39	4.59	5	36.11	14.58
	2508	3	21.71	2.29	4	34.8	11.92

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Table A.10 – *Continuation of previous page*

		Total Dwell Time (min)					
		2018			2022		
Service	Train Nº	count	mean	std	count	mean	std
	2510	3	21.83	0.97	4	23.32	4.23
	2512	3	26.56	6.46	4	24.75	3.95
	2514	4	19.58	0.9	5	25.55	1.37
	2516	2	15.28	0.82	5	22.2	3.03
Worcester to South Station Skip BL		**54**	**20.85**	**7.97**	**–**	**–**	**–**
	514	18	26.66	3.36	–	–	–
	516	17	24.84	5.25	–	–	–
	536	19	11.77	4.01	–	–	–

Table A.11: Travel Time by Train Number - Outbound

		Travel time (min)					
		2018			2022		
Service	Train Nº	count	mean	std	count	mean	std
Local to Ashland Skip Newton		**19**	**48.52**	**3.34**	**–**	**–**	**–**
	589	19	48.52	3.34	–	–	–
Outbound Heart to Hub		**–**	**–**	**–**	**18**	**60.65**	**3.06**
	551	–	–	–	18	60.65	3.06
Outbound Newton skip		**37**	**84.28**	**5.21**	**126**	**83.79**	**7.13**
	501	–	–	–	19	79.45	5.6
	503	–	–	–	16	78.31	4.99
	505	–	–	–	20	80.26	5.14
	507	–	–	–	11	87.1	4.22
	509	19	82.87	5.55	19	85.58	5.02
	511	–	–	–	11	87.11	11.42
	513	–	–	–	20	87.64	5.82

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Table A.11 – *Continuation of previous page*

		Travel time (min)					
		2018			2022		
Service	Train Nº	count	mean	std	count	mean	std
	517	–	–	–	10	89.42	6.1
	525	18	85.77	4.51	–	–	–
Outbound Newton skip Boston Landing		**20**	**76.42**	**3.38**	**–**	**–**	**–**
	505	20	76.42	3.38	–	–	–
Skip B L through Natick Center		**75**	**74.75**	**8.45**	**–**	**–**	**–**
	501	18	71.32	9.78	–	–	–
	503	19	67.48	4.66	–	–	–
	521	22	79.48	3.38	–	–	–
	523	16	80.73	7.07	–	–	–
Skip B L through Wellesley Square		**14**	**85.03**	**6.77**	**–**	**–**	**–**
	519	14	85.03	6.77	–	–	–
Skip Newtonville through Natick Center		**–**	**–**	**–**	**49**	**76.08**	**6.35**
	523	–	–	–	15	77.93	8.88

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Table A.11 – *Continuation of previous page*

		Travel time (min)					
		2018			2022		
Service	Train Nº	count	mean	std	count	mean	std
	525	–	–	–	15	77.15	4.41
	527	–	–	–	19	73.78	4.65
Skip Newtonville through West Natick		**20**	**66.65**	**3.6**	**–**	**–**	**–**
	507	20	66.65	3.6	–	–	–
South Station to Framingham		**66**	**53.52**	**7.64**	**61**	**47.32**	**3.53**
	591	24	53.95	10.8	21	46.5	2.34
	593	21	55.08	5.89	20	48.06	3.97
	595	21	51.46	3.65	20	47.43	4.06
South Station to Framingham Newton skip		**21**	**38.59**	**3.21**	**–**	**–**	**–**
	587	21	38.59	3.21	–	–	–
South Station to Framingham Newton skip BL		**18**	**36.68**	**2.86**	**–**	**–**	**–**
	583	18	36.68	2.86	–	–	–
South Station to Worcester		**233**	**85.77**	**7.74**	**221**	**85.78**	**6.94**

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Table A.11 – *Continuation of previous page*

		Travel time (min)					
		2018			2022		
Service	Train Nº	count	mean	std	count	mean	std
	511	19	82.99	3.62	–	–	–
	513	15	81.38	4.19	–	–	–
	515	21	89.95	13.31	19	92.92	9.42
	517	20	92.84	8.66	–	–	–
	519	–	–	–	20	90.52	7.41
	521	–	–	–	17	85.86	5.71
	527	22	83.78	4.25	–	–	–
	529	18	83.15	11.07	15	85.12	8.88
	531	18	82.69	7.78	19	88.24	4.69
	533	12	83.6	5.16	17	83.13	3.79
	535	18	84.78	8.17	19	82.28	3.22
	537	16	90.26	9.0	17	82.16	2.35
	1501	3	79.44	6.55	4	81.05	2.7

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Table A.11 – *Continuation of previous page*

		Travel time (min)					
		2018			2022		
Service	Train Nº	count	mean	std	count	mean	std
	1503	4	90.93	9.08	5	79.8	1.64
	1505	2	81.21	1.4	4	83.88	3.07
	1507	4	87.85	1.79	3	85.42	4.64
	1509	3	82.79	1.52	5	90.71	12.11
	1511	3	83.24	0.8	3	86.42	4.63
	1513	3	89.91	4.77	5	86.05	5.49
	1515	3	82.11	2.22	5	87.65	4.14
	1517	2	87.47	7.61	5	81.75	1.75
	2501	4	85.06	6.69	4	80.5	3.94
	2503	3	84.27	2.46	4	81.19	4.2
	2505	4	82.23	0.5	5	81.9	2.31
	2507	3	83.44	0.61	4	87.06	9.41
	2509	2	81.9	0.38	4	84.69	3.72

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Table A.11 – *Continuation of previous page*

		Travel time (min)					
		2018			2022		
Service	Train Nº	count	mean	std	count	mean	std
	2511	3	87.78	9.5	4	88.25	9.0
	2513	4	84.19	2.44	5	84.78	12.79
	2515	2	82.22	0.65	5	87.6	6.66
	2517	3	91.79	9.15	4	83.12	2.32
Worcester Xpress Outbound		**21**	**58.85**	**5.38**	**–**	**–**	**–**
	551	21	58.85	5.38	–	–	–

Table A.12: Total Dwell Time by Train Number - Outbound

		Total Dwell Time (min)					
		2018			2022		
Service	Train Nº	count	mean	std	count	mean	std
Local to Ashland Skip Newton		**19**	**13.73**	**3.22**	**–**	**–**	**–**
	589	19	13.73	3.22	–	–	–
Outbound Heart to Hub		**–**	**–**	**–**	**18**	**8.45**	**2.46**
	551	–	–	–	18	8.45	2.46
Outbound Newton skip		**37**	**21.23**	**4.75**	**126**	**19.64**	**5.07**
	501	–	–	–	19	18.3	7.58
	503	–	–	–	16	20.33	3.46
	505	–	–	–	20	22.03	4.05
	507	–	–	–	11	20.65	2.57
	509	19	19.32	5.22	19	18.66	5.12
	511	–	–	–	11	18.31	4.17
	513	–	–	–	20	18.42	3.24

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Table A.12 – *Continuation of previous page*

		Total Dwell Time (min)					
		2018			2022		
Service	Train Nº	count	mean	std	count	mean	std
	517	–	–	–	10	20.9	7.65
	525	18	23.24	3.24	–	–	–
Outbound Newton skip Boston Landing		**21**	**13.03**	**3.98**	**–**	**–**	**–**
	505	21	13.03	3.98	–	–	–
Skip B L through Natick Center		**71**	**15.21**	**7.19**	**–**	**–**	**–**
	501	14	8.4	1.23	–	–	–
	503	19	8.03	2.19	–	–	–
	521	22	22.31	3.01	–	–	–
	523	16	19.94	3.85	–	–	–
Skip B L through Wellesley Square		**14**	**24.47**	**7.6**	**–**	**–**	**–**
	519	14	24.47	7.6	–	–	–
Skip Newtonville through Natick Center		**–**	**–**	**–**	**49**	**19.48**	**6.1**
	523	–	–	–	15	21.5	7.79

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Table A.12 – *Continuation of previous page*

		Total Dwell Time (min)					
		2018			2022		
Service	Train Nº	count	mean	std	count	mean	std
	525	–	–	–	15	20.55	6.19
	527	–	–	–	19	17.04	3.37
Skip Newtonville through West Natick		**20**	**10.81**	**2.64**	**–**	**–**	**–**
	507	20	10.81	2.64	–	–	–
South Station to Framingham		**65**	**21.21**	**5.07**	**61**	**18.28**	**3.7**
	591	23	20.13	4.75	21	17.13	3.56
	593	21	23.82	6.11	20	18.89	3.88
	595	21	19.8	3.06	20	18.87	3.55
South Station to Framingham Newton skip		**21**	**9.58**	**1.75**	**–**	**–**	**–**
	587	21	9.58	1.75	–	–	–
South Station to Framingham Newton skip BL		**19**	**6.63**	**2.54**	**–**	**–**	**–**
	583	19	6.63	2.54	–	–	–
South Station to Worcester		**232**	**21.49**	**6.72**	**222**	**23.93**	**5.56**

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Table A.12 – *Continuation of previous page*

		Total Dwell Time (min)					
		2018			2022		
Service	Train Nº	count	mean	std	count	mean	std
	511	19	17.34	2.71	–	–	–
	513	15	19.59	4.53	–	–	–
	515	21	26.25	13.62	19	24.17	4.76
	517	20	28.13	7.52	–	–	–
	519	–	–	–	20	24.62	4.9
	521	–	–	–	17	23.37	7.14
	527	22	20.93	4.14	–	–	–
	529	19	18.8	6.39	15	25.36	8.25
	531	18	19.36	3.64	19	26.0	5.66
	533	12	18.38	2.1	17	23.82	4.91
	535	17	18.98	2.53	19	22.36	4.2
	537	16	22.12	7.15	17	21.8	2.9
	1501	3	19.86	0.75	4	19.71	2.59

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Table A.12 – *Continuation of previous page*

		Total Dwell Time (min)					
		2018			2022		
Service	Train Nº	count	mean	std	count	mean	std
	1503	4	26.91	7.58	5	18.39	3.04
	1505	2	16.77	1.07	4	25.92	3.43
	1507	4	20.85	2.21	3	24.27	4.05
	1509	3	18.52	0.48	5	27.71	4.85
	1511	3	22.46	1.57	3	25.87	4.51
	1513	3	23.98	4.44	5	28.2	4.42
	1515	3	19.37	0.33	5	27.7	5.85
	1517	2	20.72	2.4	5	22.38	1.65
	2501	4	18.39	1.19	4	22.87	7.63
	2503	3	19.35	1.27	5	16.85	8.9
	2505	4	19.15	1.08	5	22.65	2.98
	2507	3	20.98	2.24	4	27.77	6.63
	2509	2	17.73	1.84	4	24.62	1.29

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Table A.12 – *Continuation of previous page*

Service	Train Nº	Total Dwell Time (min)					
		2018			2022		
		count	mean	std	count	mean	std
	2511	3	27.4	9.07	4	23.75	7.27
	2513	4	20.87	1.43	5	25.91	6.97
	2515	2	19.64	3.71	5	23.0	5.96
	2517	3	31.28	11.46	4	23.88	3.47
Worcester Xpress Outbound		**20**	**4.23**	**2.31**	**–**	**–**	**–**
	551	20	4.23	2.31	–	–	–

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