Mitigation of Passenger Effects of State of Good Repair Projects Using Automated Data Sources

by

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Abstract

Legacy urban rail transit systems in North America increasingly face challenges in maintaining their infrastructure to provide reliable, effective, and safe service and absorb future growth in cities, which makes scheduled service disruptions to implement State of Good Repair (SGR) projects imminent. Mitigating the impacts of these disruptions on passengers is important in order to maintain transit ridership in the face of competing transportation network company services. Transit agencies have access to large amounts of passenger and vehicle location data, which provide valuable information regarding passenger travel patterns and service levels.

This thesis presents a framework for incorporating passenger effects and their mitigation in planning for SGR project shutdowns using the data sources available to transit agencies, with relevant criteria for informing decisions proposed at each stage of the framework. The thesis focuses on passenger impact mitigation in two aspects: selection of work plan, and identification and planning of existing alternative services within the system.

From passenger travel patterns, the effects of a shutdown can be gaged, and the impact can be quantified in terms of additional passenger hours. This measure would vary by time of day, day of week, and season, and can be used to determine a shutdown work plan which is less disruptive to passengers. For a particular shutdown plan, connectivity within the transit system implies that some passengers could benefit by using alternative services on existing routes instead of station-to-station bus shuttles.

The proposed framework presents criteria for identifying such alternatives and passenger segments which could potentially benefit from them, assessing efficacy of the alternative service with respect to traditional bus shuttles, estimating operational requirements, and evaluating the mitigation benefit of an alternative. The implementation of the framework has been demonstrated for three case studies of recent shutdowns in the MBTA, using data sources available at the agency. Post-implementation evaluation of potential alternatives to shuttle service in two of these case studies shows substantial potential magnitudes of passenger benefit and proportion of passenger impact being mitigated.

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Chapter 1

Introduction

Urban rail public transit has been an integral component of transportation in many cities in the United States and North America for longer than a century. Beginning with streetcars on the New York and Harlem Railroad in 1832 and followed by significant investments in growing cities through the first decades of the 20^{th} century, transit agencies in several large North American cities developed and still operate legacy segments of both light and heavy rail. Among these, the Massachusetts Bay Transportation Authority (MBTA) has the distinction of operating 'America's first subway' which has become a segment of today's Green Line. Between 1897 and 1912, the underground segments of what are currently the Green, Orange, Blue, and Red lines were constructed, connecting to several streetcar and elevated rail routes. Over the span of the next century, the rail transit network grew and ebbed, undergoing several projects to add extensions and modify infrastructure, as well as several streetcar line closures, resulting in the network that the MBTA operates today.

A system operating aging infrastructure built decades ago has to cope with significant challenges completing the necessary repair and maintenance of its facilities and infrastructure. Major capital projects are necessary to achieve and maintain a State of Good Repair (SGR) in order to maintain the current infrastructure, continue operations and provide reliable service to passengers, and ensure safety in operations. Growing populations and economic activity in American cities also offer opportunities for transit agencies to increase ridership and hence enhancements are also needed for older systems to handle such ridership growth. In addition to this, legacy rail systems also need to be resilient in face of potential disruptions due to climate change.[1]

In light of such challenges, the MBTA has been steadily increasing its capital investment and the proportion allocated to SGR therein. Of the $875 million spent on capital investment in FY 2018, $720 million or roughly 82% was spent on SGR. This included $112 million spent on subway track, signal, and right-of-way (ROW) contracts. With an aim to eliminate the SGR backlog in the system (estimated to be roughly 7–10 billion dollars) over the next 15 years, the MBTA plans to step up yearly capital spending on SGR projects to more than $1.4 billion per year (2015 dollars, without inflation) between 2019 and 2023. Projects relating to the reliability and modernization of subway lines are planned in this period, spanning station improvements, track, ROW, bridge repairs, accessibility enhancements, and signalling system upgrades [3, 4].

Such projects often require shutdowns of stations or segments over extended time periods (in the form of either continual or intermittent shutdowns), which cause disruption in services as experienced and perceived by passengers. In order to provide efficient working conditions for construction activity, transit agencies typically provide construction 'windows' to shut down rail segments, often during less busy off-peak periods, weekends, or the summer season. Service is generally provided on the shut-down segments using replacement shuttle buses, which tend to be much slower in comparison to regular rail service (in addition to the inconvenience caused by new transfers). In a time when easy smartphone and internet access enables the use of applications like Uber and Lyft, it is likely that several passengers would switch modes during shutdowns. Such erosion of public transportation mode share in turn causes more congestion on streets which leads to further degradation in bus service. This creates the significant challenge of maintaining ridership, especially for disruptions which take place over prolonged periods.

A recent example of such ridership impacts of capital SGR projects is the SafeTrack project in Washington Metro. The stagnation and reduction in ridership since 2008 was

[1] A recent example of major service disruptions due to weather events is Hurricane Sandy, which in 2012 caused massive damage to the tunnels carrying the L train in the NYC subway system. This led to plans of shutdowns on segments of the line for at least 15 months [1]. As of March 2019, the plans for these shutdowns have been modified to provide continued service for passengers during weekdays [2]. In the MBTA system, flooding of the Muddy River at Kenmore has led to several planned and unplanned disruptions which are still intermittently occurring.

exacerbated by single-tracking, slow zones, and shutdowns which started in 2017. Despite service improvements after completion, the ridership still has been slow to recover. This has been attributed in part to insufficient passenger impact mitigation during the shutdowns on the agency's part, along with ease of accessing transportation network company options like Uber and Lyft [5, 6, 7, 8, 9, 10].

1.1 Motivation and Scope

The need to provide convenient and efficient service to passengers in face of several imminent shutdowns with the goal of maintaining public transportation ridership and meeting growing demand is the primary motivation behind this study. The insights gained by examining passenger travel patterns and vehicle data can help in finding opportunities for enhancing service in order to offset passenger inconvenience caused by the shutdown and also possibly increase passenger benefits for passengers not directly affected by shutdowns, who use other services running regularly.

Current practice involves providing enough capacity on bus shuttle service to replace the links being shut down: consequently, the capacity of the system is maintained while paying lesser attention to detailed passenger impacts. In the case of MBTA, the connectivity, complementarity, and redundancies of the rapid heavy rail, light rail, commuter rail, and frequent bus route network within and close to Downtown Boston offer potential alternatives (to replacement bus shuttles) which are already present in the MBTA system. In addition to providing faster alternatives than replacement shuttle buses and more direct connectivity for some directly affected passengers, utilization of such in-system alternatives for shutdown mitigation can lead to better service provision for some travelers not directly affected by the shutdown.

Because shutdowns have widespread effects on passengers which vary by time of day, day of week, and seasons, it is crucial to not only mitigate these effects, but also consider them in the planning and implementation process of SGR projects. Incorporation of metrics based on passenger impacts within the planning process can have benefits such as selection of less disruptive shutdown plans. For example, comparing plans with different construction windows might make it possible to reduce costs, the length of time of construction, and/or service disruption. Further, it may also be possible to reduce the overall replacement bus fleet size requirements (and thus costs) during shutdowns, or to serve more passengers with the same or marginally higher number of vehicles by implementing these alternatives. This means that, in additional to being beneficial to passengers, alternatives beyond replacement shuttles can also be more efficient — possibly even less costly — in terms of service provision.

To summarize the context presented above, this research deals with mitigating effects on passengers due to shutdowns for SGR projects by incorporating passenger impacts of shutdowns and utilizing and enhancing potential alternatives within the system. Using passenger and vehicle data, the effects of shutdowns and potential benefits and efficacy of these alternatives can be estimated. Significantly enhanced data availability because of automated data collection systems at agencies enables this effort. A common process is followed for various shutdown case studies presented in this research, which evolves into a revised generalized approach to plan for scheduled disruptions in the rail system.

1.1.1 Framework for SGR Service Planning

The variety of project types, plan requirements, locations, and passenger impacts of SGR shutdowns in the near future necessitates the need of a generalized framework to handle planning for a given shutdown. In order to move beyond merely substituting the capacity on the shutdown link with shuttle buses, the following objectives need to be achieved:

- Identification of feasible service alternatives to traditional bus shuttles
- Estimation of passenger impact or benefit in terms of travel and wait time metrics
- Providing input on modifying the reconstruction approach and the shutdown work plan based on passenger impacts (if applicable)
- Planning appropriate service levels on alternatives and bus shuttles
- Evaluation of multiple potential alternatives

The framework proposed with these objectives in mind is explained in detail in Chapter 3. This proposed framework utilizes data sources which include fare transaction data, vehicle location data, as well as any observed or inferred data on passengers' in-system origins and destinations as they vary spatially and temporally. Alternatively, wherever any kind of automated origin-destination data is available, the impacts of shutdowns and the demand on services can be estimated.

Because of its generalized nature, service planners employing this framework would have the flexibility to customize the process for particular shutdowns based on their specific local knowledge of ridership and operations. An example of such customization in terms of modification of bus route alternatives to the shuttle is presented for the Orange Line Forest Hills–Ruggles shutdown case study in Chapter 5.

1.1.2 Research Questions

Narrowing the scope of the study, some specific research questions as formulated below are explored in this study:

- Which passengers would be affected when different shutdown plans are considered, and what delays would they experience?
- How should in-system alternatives for mitigating a shutdown be identified?
- Which passengers could benefit from a given alternative, and to what extent?
- What are the operational requirements of a particular alternative?
- What is the overall benefit of an alternative to passengers compared to traditional replacement bus shuttle service, either as a substitute or as a complementary service?
- What is the 'best' alternative service plan for a given shutdown?
- How can operational impediments or passenger inconvenience in shuttle service be identified and rectified?

1.2 Approach

In the context of the planning framework and the research questions presented above, a sequential and flexible methodology has been implemented in this study. A summary of the study approach is provided below, while the implementation is explained in detail in the case studies as applicable. Refer to Section 3.2 for a detailed description of the more general framework. The data sources used in the MBTA case studies are described in detail in Section 2.3.

1.2.1 Overview of Methodology

To begin, the magnitude and the spatial and temporal distribution of trips affected by a given shutdown are estimated using in-system origin-destination data that was generated by an automated inference algorithm implemented at the MBTA that is known as ODX [11]. Based on identified passenger movements — link flows and transfers — within, through, and around the disrupted segment of rail links, the impact of a shutdown in a particular section of the rail network during particular times of the day, days of the week, and over various seasons of the year can be estimated.

The distribution of impacts along with knowledge of the various services within the system informs the identification of one or more alternative services for the shutdown. In the MBTA case, there exists a set of higher frequency bus routes and various commuter rail segments which form the basis for the identification of a candidate set of alternative routes.

Based on the identified alternatives and ODX data, different passenger segments based on unique combinations of trip origins and destinations are identified and their volumes over the time period of the shutdowns are estimated. Passenger segmentation is based on the various ways in which passengers with different origins and destinations could potentially use the proposed alternative(s). The examination of passenger segments could potentially provide feedback into the choice of alternatives to bus shuttles, depending on the specific case study.

After identifying the passenger segments, it is necessary to examine how effective the alternative(s) would be for these segments compared to riding the replacement bus shuttles.

By combining various vehicle location data sources like AVL for buses and TTR for rail, the distribution of travel times during particular times of the day, days of the week, and seasons are estimated. Since two of the case studies included here are post-implementation, location data for the bus shuttles was available, and actual on-ground shuttle travel times could be estimated. For planning in advance, however, the distributions of travel times can be sourced by querying online location services like Google Maps, studying the travel times of nearby parallel bus routes, or by running test shuttles prior to implementation.

The examination of the efficacy of the alternative for various segments answers two questions: whether there are significant travel time savings for a passenger segment using the alternative, and to what extent. If an alternative is equivalent or takes more time compared to the bus shuttle, it is not deemed to benefit that segment. For the segments for which the alternative is beneficial overall, because of variability in the travel times, it may not be faster for all the passengers. By comparing distribution of journey times by shuttle and by the proposed alternative(s), it is possible to estimate the probability of the alternative being faster for that segment. It should be noted that in almost all cases, it is likely that some minimal level of traditional station-to-station shuttles will be necessarily maintained to serve some disrupted passenger origin-destination segments.

The ridership on each of the segments can be assigned to the alternative by applying the respective probability of the alternative or the traditional shuttle being faster. In order to account for passengers not having knowledge of which path would be faster, and dropping out of the system completely during shutdown days, the ridership assigned to shift to the alternative is reduced by another factor.

The frequency required on the section is estimated based on the effective capacity required to handle the increased load resulting from the shift to the alternative. The distribution of run times for the alternative routes as well has the variation in headways at various stops are estimated from vehicle location data. These data are used for planning the operational characteristics like scheduled headways and fleet size requirements on the alternative route.

After setting cycle times to upper bounds of run times for the alternative (90^{th}–95^{th} percentile for buses), the frequency requirements and cycle times are used to calculate fleet size required to operate the alternative. This step also takes into account the increased fleet size requirements to provide effective capacity with the observed on-street variability in headways likely experienced by passengers.

From the estimates of in-vehicle travel time and changes in waiting and transfer time delays calculated from the various steps above, the overall passenger benefit for a particular alternative is calculated. This can be compared to the impact on the passengers that would be incurred using traditional shuttle buses due to the shutdown, and, by converting passenger hours to monetary values, to the costs of implementation of the alternative service.

1.2.2 Case Studies

The workflow of the framework above has been demonstrated for two case studies — namely, Longfellow Bridge (2016–17) and Forest Hills–Ruggles (2018). These required shutdowns of high-ridership segments of the network on weekends over extended periods of time and have been analyzed in detail to examine passenger impacts and the planning of and benefits from potential alternatives. Another major project studied here relates to repairs on the Green Line tunnel between Kenmore and Government Center stations, which is still in the planning phase, and presents an opportunity to consider passenger impacts in the planning of shutdown services beforehand. This case study focuses on comparing the passenger effects of various shutdown plans. In addition to these, two minor shutdown projects, namely the D Branch project on Green Line (on various segments between Riverside and Kenmore) (2018) and the North Cambridge shutdown on the Red Line (Alewife to Harvard) (2018–19), which were relatively limited in their impact or duration, have also been studied to gage affected passenger flows and examine recommendations for potential improvements in shutdown shuttle service provision. These are discussed in Appendix A.

1.3 Thesis Outline

Chapter 2 presents background on the MBTA rail network and discusses the commuter rail segments and bus routes which form an indicative (non-exhaustive) set of candidate alternatives to station-to-station bus shuttles during shutdowns. Chapter 3 describes a framework for using passenger and vehicle data sources in planning for mitigation of passenger effects of SGR project shutdowns, which involves estimation of passenger impacts of various shutdown plans, identification of alternatives, planning for replacement services, and estimating potential passenger benefits of these services. Chapters 4, 5, and 6 demonstrate the application of this framework to three different SGR shutdowns: the Longfellow Bridge segment on the Red Line, southern segments of the Orange Line, and the Green Line's Central Tunnel, respectively. Finally, chapter 7 summarizes the takeaways and recommendations from the earlier chapters, and concludes by discussing potential future work which could be based on this study.

Chapter 2

The MBTA Rail Network

2.1 Overview

The MBTA's urban rail network consists of three heavy rail lines (Red, Orange, and Blue Lines) and two light rail lines (Green Line and the Red Line's Ashmont–Mattappan Trolley). The Red Line (heavy rail) has two branches South of JFK/UMass station, one to Ashmont station and one to Braintree station. At Ashmont, passengers can transfer to/from the light rail line to Mattappan. The Green Line outside of Downtown Boston consists of four branches denoted as B, C, D, and E. The lines and branches converge from various neighboring cities into a dense and interconnected network in Downtown Boston, where the transfer stations between the lines (except Red and Blue Lines) are located. Fig. 2-1 shows the official MBTA schematic map, while Fig. 2-2 shows the rail lines and branches to scale.

On the 76.3 miles (122.8 km) of heavy rail and 51.0 miles (82.1 km) of light rail guideway across the rail system, a fleet of 432 heavy rail vehicles and 219 light rail vehicles carried 164 million and 62 million unlinked trips, respectively, in 2017. Of the $774 million capital expenditure in 2017, $252 million (32.6%) was spent on heavy and light rail systems and guideway construction and maintenance, while $87 million (11.3%) was spent on facilities and stations [12]. This includes expenditure on SGR projects (e.g., Longfellow Bridge repair and Southwest Corridor maintenance) as well as system expansion projects (e.g., Green Line Extension).

Figure 2-1: Official Schematic Map of the MBTA Rail and Bus Rapid Transit Network

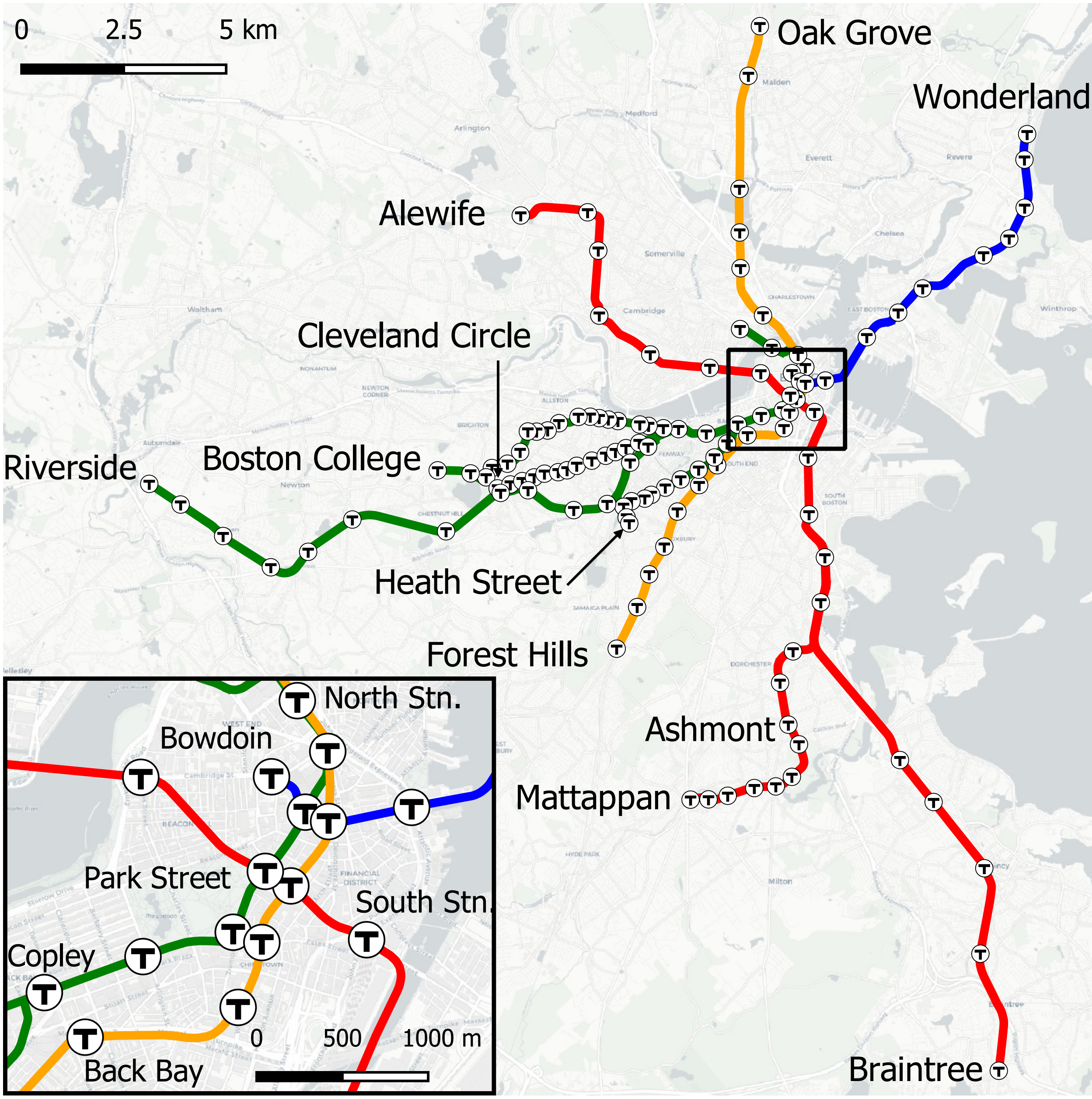


Figure 2-2: Map of the MBTA Network (to scale)

2.1.1 Rail Corridor Information

Grade of Corridor

The physical grades of the various rail segments are important factors in the SGR project work plan which has to be implemented along a particular corridor, particularly in terms of the nature of tasks required to be undertaken in a project, the staging and scheduling of tasks, feasibility of various kinds and time periods SGR-related disruptions, and routing of replacement shuttles. The three MBTA heavy rail lines (as well as the Green Line) mostly operate in tunnels in or close to Downtown Boston, and on corridors of various grades (on ground, elevated, and open cut) towards the peripheral areas.

The Green Line's B, C, and D Branches converge into the Central Tunnel at Kenmore station, and the E branch at Copley station. On the western side, the B, and C Branches run along streets with median reservations, the E Branch runs with median reservations partially, while the D Branch runs on along a corridor with dedicated right-of-way. The Ashmont-Mattappan line has dedicated right-of-way except two grade crossings at the Capen Street and Central Avenue stations. Figure 2-3 shows the grades along the various rail corridors.

Age of Infrastructure

In addition to the grade of the rail corridor, the age of the corridor also significantly determines the type and magnitude of tasks that need to be undertaken in an SGR project along that corridor. Older infrastructure generally needs projects on a larger scale in order to maintain a state of good repair. This is exemplified in the Longfellow Bridge case study, which was shut down in order to repair major structural deficiencies accounting for its construction in the early 20^{th} century.

The MBTA operates some of the oldest urban rail infrastructure in North America, with the Green Line tunnel between Park Street and Boylston stations being operational since 1897, and a large proportion of the remaining underground corridors being constructed by 1932. The Braintree Branch and Alewife–Harvard segment of the Red Line as well as northern and southern segments of the Orange line are more recent in construction. Figure 2-4 shows the year of construction of various segments of the MBTA rail network.

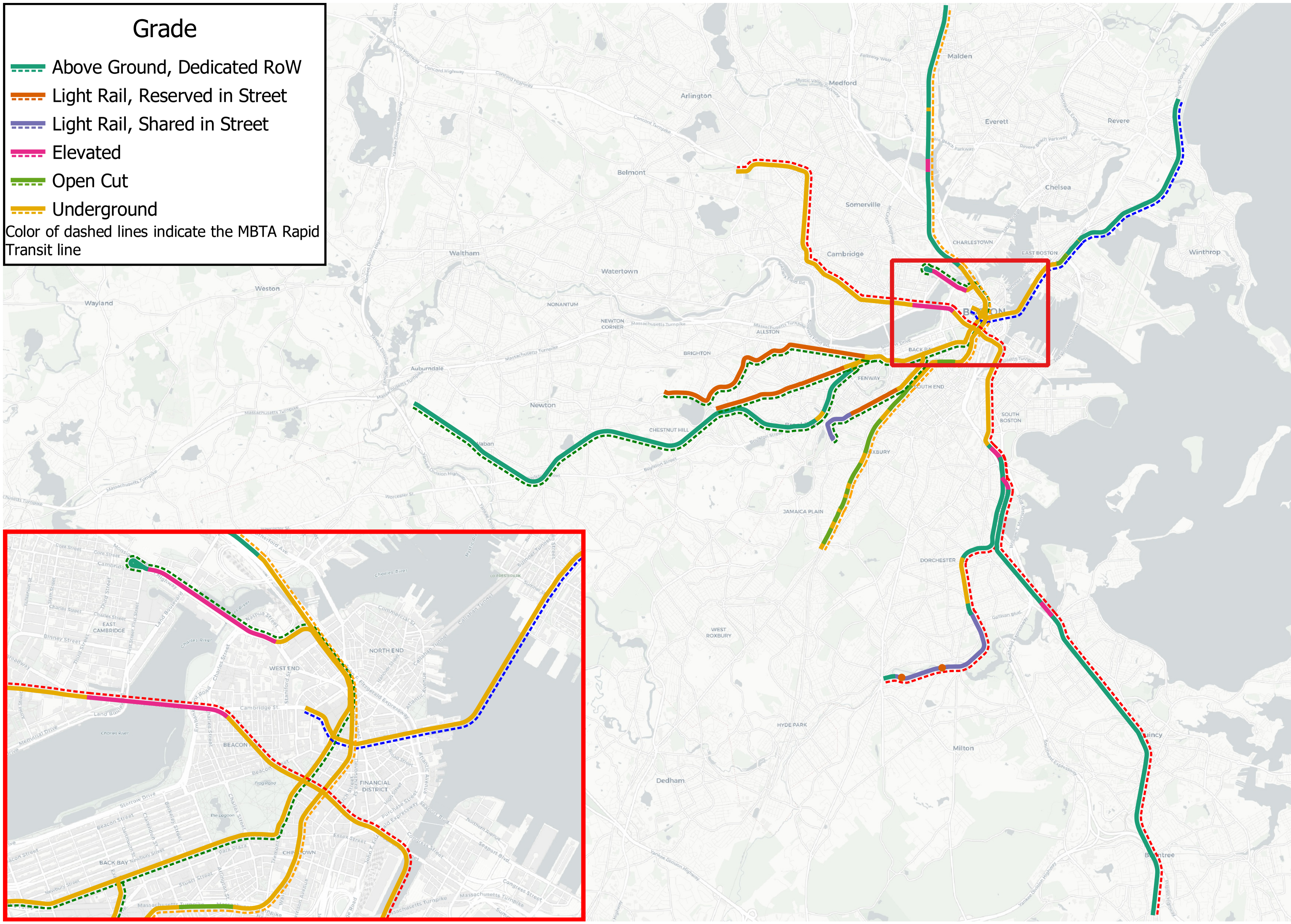


Figure 2-3: Grades of MBTA Heavy and Light Rail Track Segments

2.2 Systemwide Candidate Alternatives During Shutdowns

With SGR-related shutdowns in various parts of the rail network being imminent in the near future, it is helpful to examine other modes within the system, namely bus and commuter rail lines, to identify redundancies such that the MBTA could provide travel alternatives within the system to passengers. Being identified as potential candidate routes for SGR mitigation earlier, the service and infrastructure on these routes could be enhanced preemptively, which would, with appropriate information dissemination measures, make them more familiar to rail passengers as alternatives during shutdowns. Further, such a set of candidates can be useful to initialize future analyses of in-system alternative mitigation strategies. A non-exhaustive set of candidate commuter rail corridors and bus routes which could act as alternatives are described below.

2.2.1 Commuter Rail Corridors

Commuter rail lines in the MBTA are arranged in a similar fashion to the urban rail lines, wherein several branches serving peripheral cities and suburbs of Boston converge towards Downtown, terminating either at North Station or South Station. Because of this, heavy rail and commuter rail run along a shared corridor in several locations in the network, and connections between the two are available at some stations. Taking advantage of such connections, commuter rail shuttles can be operated between these stations to provide a faster alternative to bus shuttles for passengers during shutdowns. The MBTA could enhance infrastructure along these corridors, specifically in terms of double tracking and adding platforms to enable efficient bidirectional service and reduce track occupancy. These shared corridors and stations are shown in Fig. 2-5

On the northern side, the Orange Line shares its corridor with commuter rail tracks from Sullivan Square north. A commuter rail shuttle service between Malden Center and North Station could be an effective alternative for passengers traveling between northern portions of the Orange Line and the rest of the network during shutdowns along this segment. Similarly, for northern Red Line passengers, commuter rail connections at Porter (and potentially, Alewife, if an infill station is constructed) can provide an effective Downtown connection.

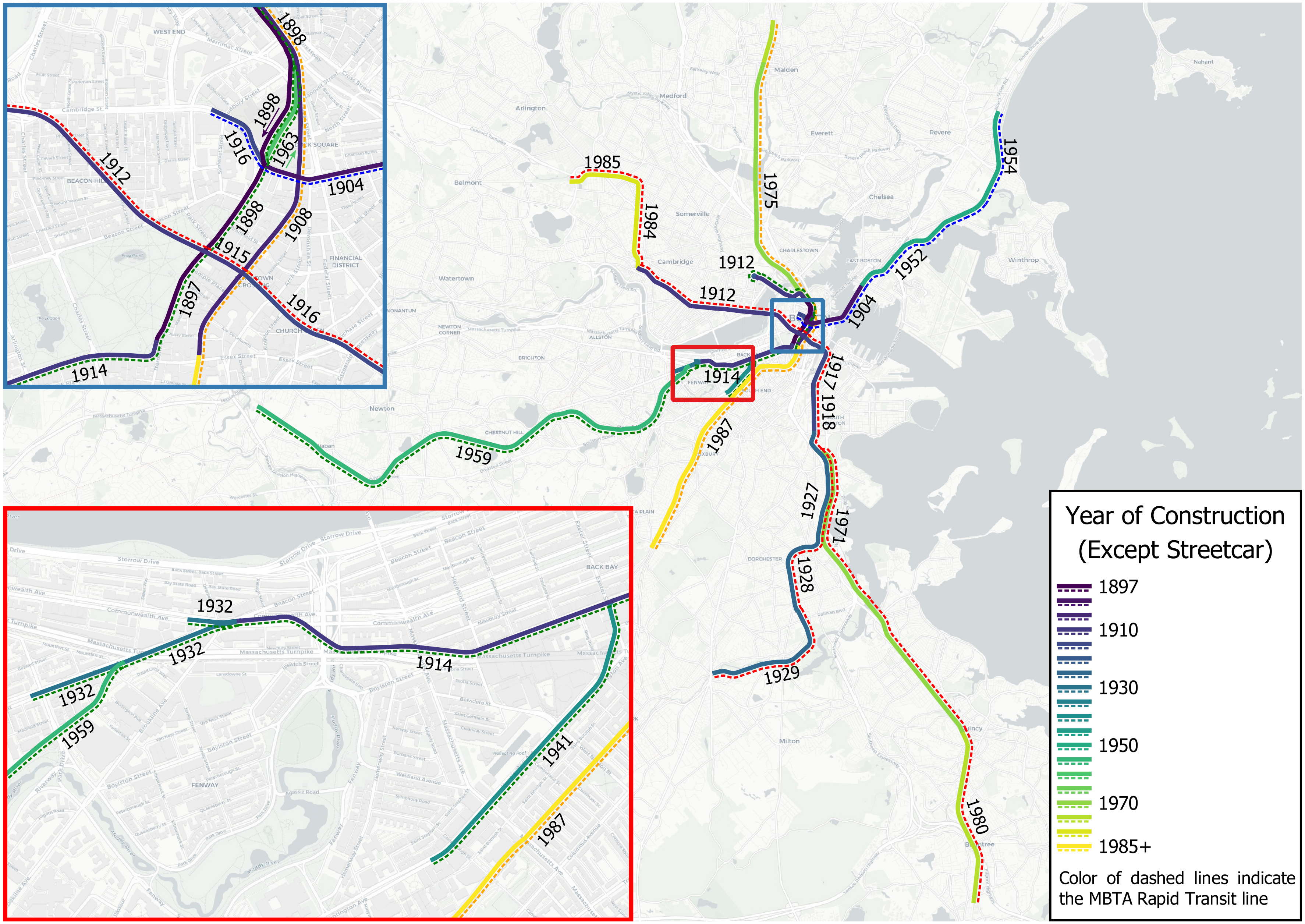


Figure 2-4: Year of Construction of MBTA Track Segments

On the southern side, the Forest Hills–Ruggles–Back Bay–South Station commuter rail corridor has been studied in detail as an alternative in Chapter 5. Similarly on the Red Line, and especially for Braintree branch passengers, commuter rail shuttles to South Station could help alleviate the inconvenience caused by substantially longer shuttle travel times during shutdowns in those segments.

2.2.2 Bus Routes

The numerous bus routes in the MBTA system which run in various directions and provide a large level of coverage in the Boston area lead to some bus routes which could potentially provide alternatives to station-to-station shuttle buses by enabling trips with fewer transfers. As such, bus routes which could potential be used by passengers as alternatives during shutdowns broadly fall into two topological categories: circumferential, and radial routes.[1] These are shown in Figs. 2-6 and 2-7, respectively.

Circumferential Routes

Some bus routes which run crosstown, that is, circumferentially without necessarily going into Downtown, offer possibilities for passengers to reach their destination more directly and avoid taking the shuttles on a path which goes through the Downtown transfer stations. Specifically in and around Boston, bus Routes 1, 47, and 66 connect various areas served by the southern and western parts of the rail network to Cambridge. Similarly, Route 91 connects Sullivan Square to Central Square, enabling northern Orange Line passengers a more direct route to Cambridge during Red/Orange line shutdowns.

Radial Routes

Numerous MBTA bus routes run closely along rail segments. During shutdowns in those particular segments, station-to-station replacement shuttles would also follow the same or similar path to these routes. In such a case, these routes can be effective alternatives to

[1] In addition to bus routes as alternatives to shuttle buses, bus routes can also be modified to serve as *complements* to shuttle buses (Chapter 5). This can be help reduce transfers in feeder-trunk networks.

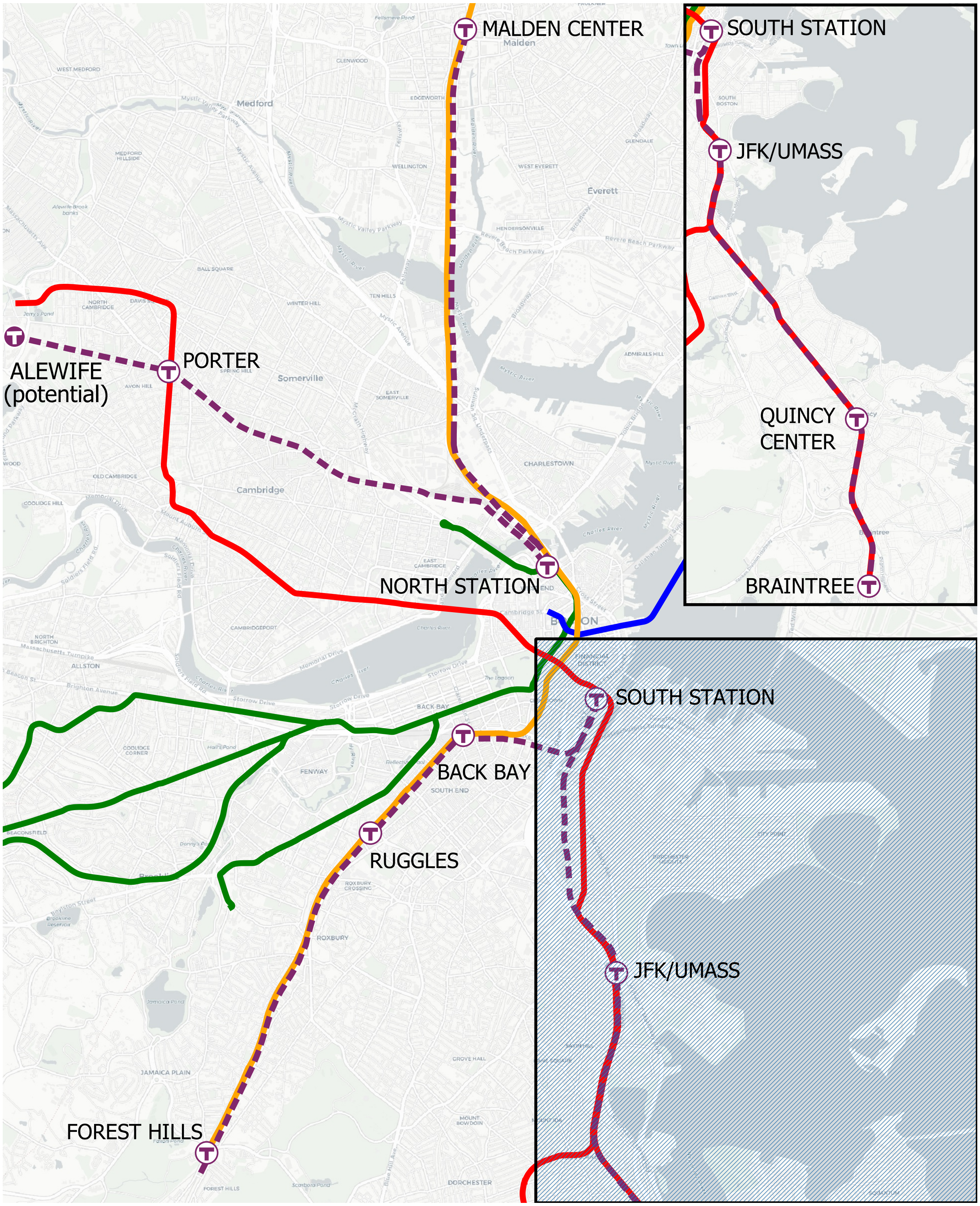


Figure 2-5: Potential Commuter Rail Alternative Segments

local station-to-station buses if service is extended to Downtown (if possible and feasible, as express service).

For example, Route 39 runs along the same street as the E Branch for all of the latter's overground segment. During Green Line shutdowns, this route can be extended to Downtown Boston so that E branch riders can get one-seat rides. Similarly, Route 92 connects Wellington, Assembly Row, and Sullivan Suqare to Downtown. Similar routes along other lines include 18 (Ashmont Branch), 27 (Mattappan Line), 210 and 230 (Braintree Branch) and 57 (B Branch).

2.3 MBTA Data Sources

Transit agencies continually generate large amounts of data about passenger movements (as a result of automated fare collection systems), and vehicles (for tracking and communicating real time movements). The data used in this study was queried from various automatically collected data sources, housed in multiple schemas on an SQL Database hosted on the MBTA Research Server. These schemas, and how the data within each schema was utilized, are described below (in alphabetical order).

APC: Bus Passenger Counts

A portion of the MBTA bus fleet has been equipped with an Automated Passenger Count (APC) system. These record not only the number of passengers boarding and alighting from the vehicle at each stop, but — due to the finer temporal resolution of location data (30 seconds) — also provide more accurate estimates of stop-to-stop travel times for bus routes in the regular service schedule. Hence in order to estimate the run time distribution on scheduled routes, APC can be used alongside AVL (described below). In this study, however, APC was primarily used to calculate average passenger loads on the buses at various stops along bus routes in order to estimate additional capacity needed on the routes in the respective case study.

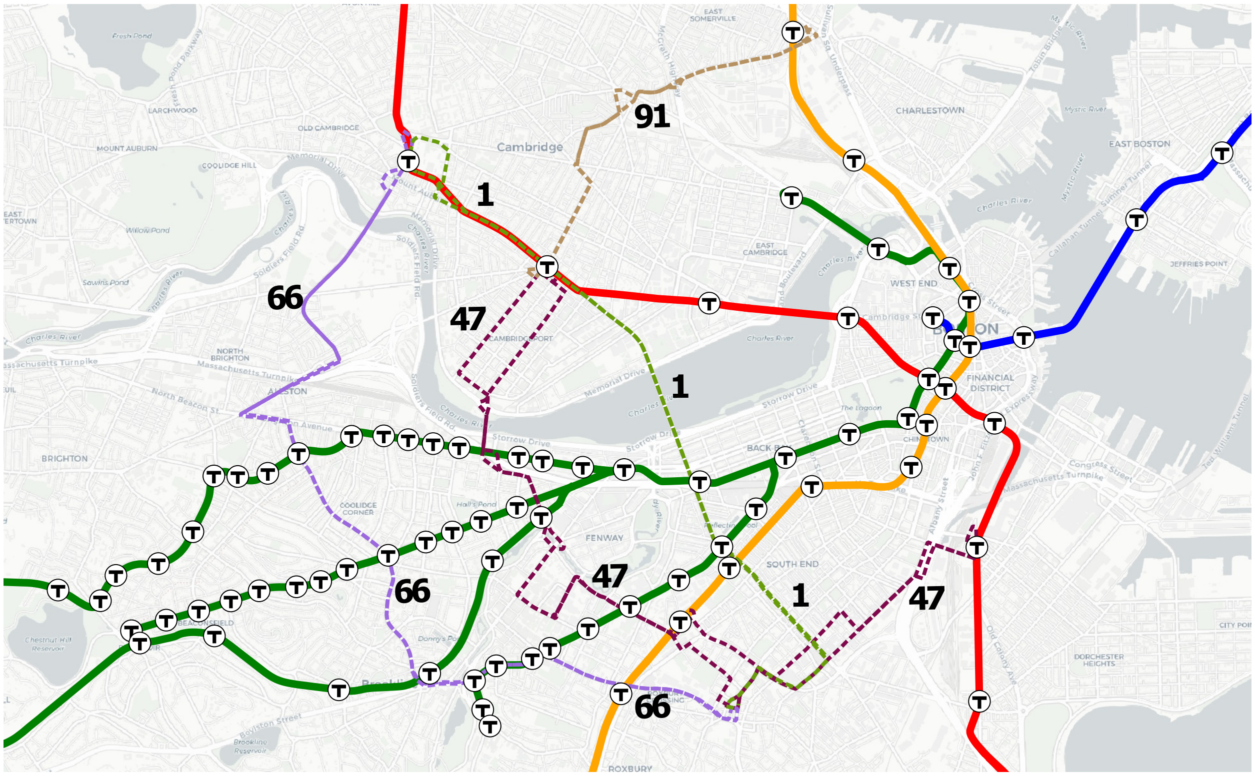


Figure 2-6: Circumferential Bus Routes Close to Downtown Boston

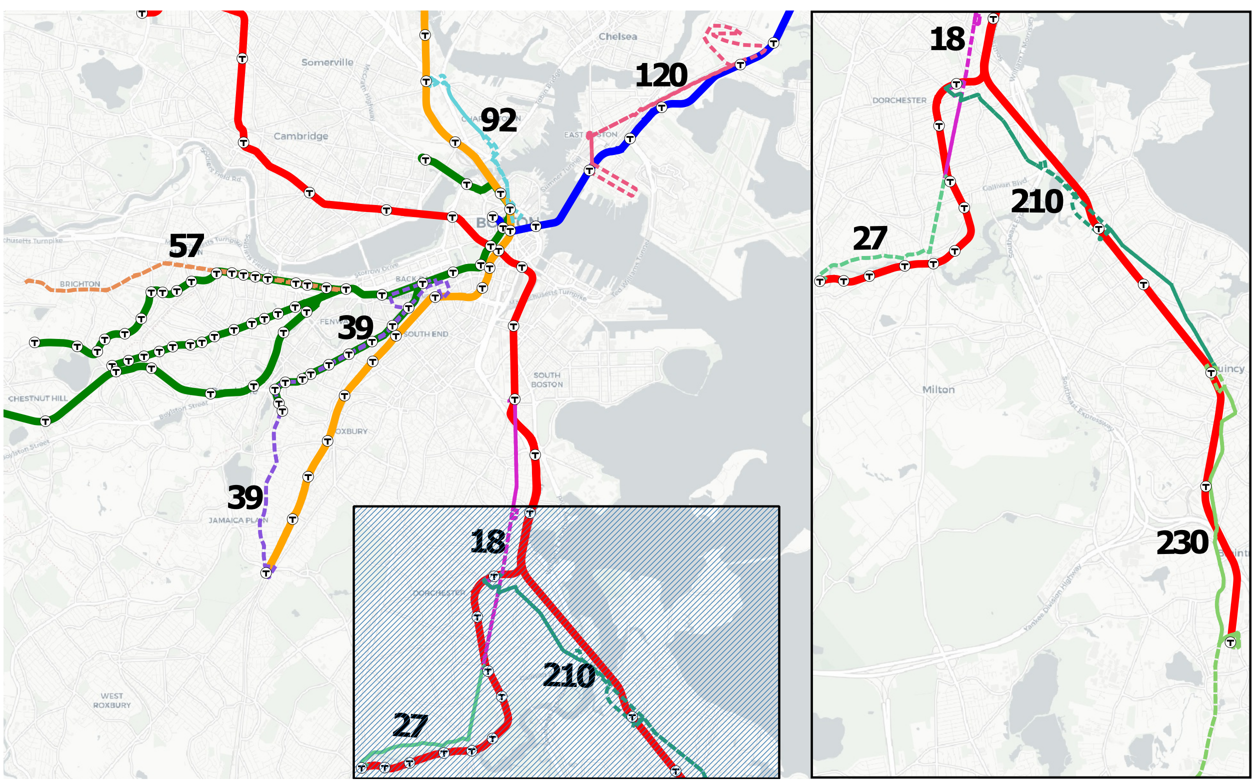


Figure 2-7: 'Radial' Bus Routes Running Roughly Parallel to Rail Corridors

AVL: Bus Location

Automatic Vehicle Location (AVL) systems consist of hardware and software which enable GPS tracking of bus locations. In addition to keeping track of fleet during operations, AVL systems can be used to announce stops on board and provide real time route arrival and delay information to passengers. In the MBTA, the AVL system on buses is based on 'heartbeats' which are location transmissions at 1 minute intervals. It also records in-vehicle announcements, vehicle stops, and doors being operated. Compared to APC, AVL equipment is much more widespread on MBTA buses, and hence AVL serves as a rich source for bus operations data.

GTFS: Scheduled Services and Routes

GTFS stands for 'General Transit Feed Specification', which "defines an open-standard format for exchanging public transportation schedule, geographic and fare information" (`gtfs.org`). Many transit agencies around the world have GTFS feeds which are publicly available. While schedules and routes in the GTFS schema were not directly involved in the calculation of demand or efficacy of alternatives, they had various secondary uses like obtaining scheduled frequencies and cycle times for bus routes and linking vehicles to routes they served on particular days and times.

ODX: Origin, Destination, and Interchange Inference

The MBTA ODX inference algorithm is based on a method which was originally developed for London, which has a rail system with tap-ins and tap-outs, and a bus network where passengers only tap in [13, 14]. In Boston's case this model was modified [11] to incorporate the open rail system and the mixture of gated and un-gated stops on the Green and Silver lines. The ODX algorithm links Automated Fare Collection (AFC) data (passenger tap-ins) to vehicle location data (AVL and TTR) with certain assumptions in order to infer destinations and transfers.

A substantial number of trips do not have inferred destinations. On average, the rate of destination inference for various modes in 2018 ranged from approximately 60% for buses and Green Line to around 72% for heavy rail. Because of this, for the purpose of estimating origin-destination volumes, the non-inferred passenger destination data had to be assigned estimated destinations based on the distribution of inferred destinations.

During shutdown days, none of the trips passing through a shut segment have their destinations inferred. This is a consequence of the inference algorithm being unable to link passengers who don't have to tap into rail after getting off the bus shuttles. Furthermore, because the gates at stations that are not in service in both directions are open, there is no accurate estimate of tap-ins overall. Hence, it is not possible to reliably estimate passenger flows during shutdown days purely through AFC and ODX data. This makes the measurement of rail and shuttle ridership in order to study the actual passenger travel behaviour during a shutdown, and thus the estimation of impacts of shutdowns on ridership, very challenging.

TTR: Train Track-circuit Location

The TTR database records trains crossing circuits installed along the lengths of tracks across the subway system. Most heavy and light rail stations have associated circuits on the tracks which correspond to a train 'entering' the station, 'at' the station, or 'exiting' the station, depending on the distance to an adjacent station. TTR has a one-second temporal resolution, although its spatial resolution is restricted to discrete points along the track. For regular operations, 'at station' circuits are operational and can be used to measure station-to-station travel times accurately. However, in and adjacent to track segments which are shut down, the travel time estimates could need to be adjusted depending on whether or not the circuits record crossing trains properly.

Chapter 3

Framework for SGR Shutdown Planning

3.1 Background and Considerations

3.1.1 Current Process for SGR Shutdown Planning in the MBTA

The current process at the MBTA for planning rail shutdowns consists of a sequence of steps (outlined in Fig. 3-1) followed in the implementation of a capital project which requires dedicated rail access. Requests for Proposals (RFPs) are first sent out, which provide general guidelines for the nature of the project, tasks required to be undertaken, and timing for the project. These guidelines may incorporate the planners' background knowledge of passenger impacts of shutdowns beforehand.

Contractors are invited to propose the staging of work plans required to implement the project, along with cost estimates of their plan. A contractor is selected, and their work plan then moves on to the Access Committee within the MBTA for approval of the staging, and results in a detailed schedule on the segments to be shut down.

Based on the decided timing and location of the shutdown, service planners within the MBTA have to then plan for the replacement shuttle service based on the capacity which would be taken out, the ridership being affected, and vehicle and operator availability. This involves estimating fleet size, proportion of private and MBTA-owned buses, and overtime requirements. Finally, the shutdown is implemented based on the schedule and replacement shuttle plans.

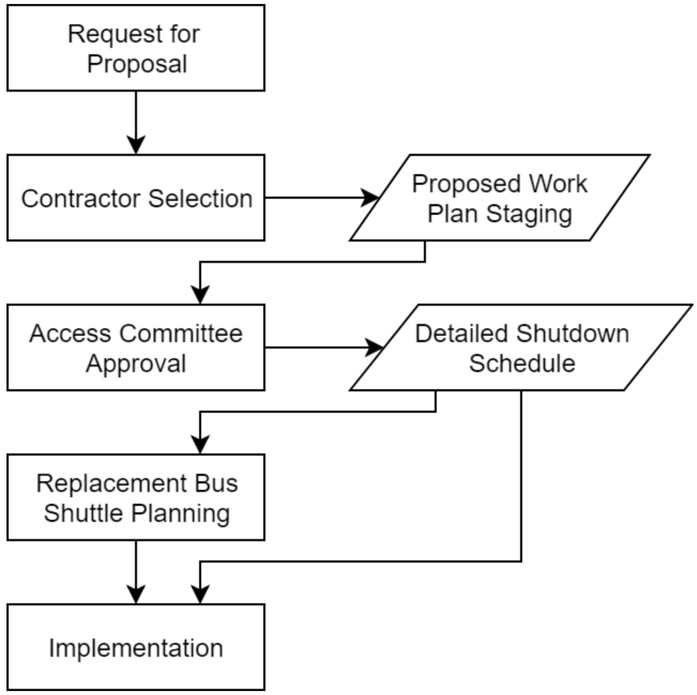


Figure 3-1: Summarized Current Workflow of SGR Project Planning at the MBTA

3.1.2 Shutdown Work Plan Schedule

The requirements of the specific tasks undertaken in an SGR project determine the length of each shutdown (overnight, early access, weekend, or continuous), number of shutdowns required, and the season and total duration of the project. Depending on the flexibility in the staging and implementation of these tasks, more than one work plan could be feasible for an SGR project — each with different costs and passenger impacts.

The advantages of one type of scheduling over another might vary in case of multiple feasible schedules. This makes it possible to incorporate passenger impacts of a project in order to influence the selection of a work plan which balances passenger inconvenience and construction costs. For example, it may be possible to reduce the overall duration of a shutdown substantially by choosing to implement a continuous shutdown instead of several weekend shutdowns, which may also be an attractive option for summer periods with lower demand, and operational requirements. The net impact on passengers may be lower for weekends, but from the passengers' perspectives, the certainty of a smaller, continuous disruption could be more favorable. On the other hand, it possible to take advantage of increased fleet availability during weekends and early access shutdowns.

3.1.3 Strategies for Scheduled Disruptions

Strategies like single-tracking, slow zones for peripheral works, and expressing and diversions on to other lines have been implemented during scheduled disruptions in some cities in North America. MBTA's rapid transit system faces the constraint of vehicle incompatibility and lack of interconnectivity between lines, which means that cars from one line cannot be diverted to be used on other lines (except among the branches of the Green Line). Single tracking is also difficult to implement with higher frequencies, and can constrict the construction process.

Instead, the current process for scheduled service disruption suspends all service on the link (the bi-directional rail link between two stations) or segment (a consecutive series of links) being shut down. This service is replaced by bus shuttles which travel between the stations in the link/segment facing the shutdown with two objectives: provide an equivalent magnitude of capacity on the shutdown segment, and minimize passenger waiting and transfer times at the stops where the switch between rail and replacement bus shuttles is made. Satisfying these objectives requires the implementation of very high frequency shuttle service. Bus shuttles require a longer travel time between stations than the rail service that is being replaced, and for segments with long links or several links, the increase in travel time due to the shutdown can be extremely high. In order to provide high frequency bus service along such segments, a large fleet size is required, adding to the cost of implementation.

3.2 Description of Framework

The modified framework for SGR planning can be summarized as: identifying redundancies within the transit network, and planning service on those alternatives during a shutdown based on the potential number of passengers who could benefit from the alternatives. Note that the alternative service is meant to absorb only some proportion of the flow on the shut links and, in most cases, cannot fully replace shuttle buses.

This framework can be used to inform decisions in the SGR shutdown planning and implementation process on two levels. First, in order to choose between contractors or multiple proposals of work plans provided by a contractor, the passenger impacts of the shutdown plan can be weighed against the costs associated with that plan and the impacts and costs of other plans. Second, at the service planning stage, by using passenger and vehicle data, planners can estimate the operational requirements for the shuttles and the alternatives, which may benefit both directly affected passengers and those on other routes which displace passengers could seek to use. These steps are meant to be a guideline for service planners and project managers to incorporate passenger impacts into the SGR mitigation planning process by utilizing the sources of data that are available at most agencies, and are flexible enough to accommodate specific knowledge about the network.

3.2.1 Overview of Modified Framework

Figure 3-2 represents the typical work-flow of the SGR rail shutdown service planning process in terms of the steps involved and the inputs and outputs at each step. The process begins by gaging the potential effects of a given shutdown in the system. This involves examining the spatial and temporal passenger travel patterns to gain insights about the impacts of the shutdown on passengers. Utilizing these insights combined with the planners' knowledge of the system, existing services which could be modified to benefit passengers during shutdowns are identified as candidate alternatives.

Based on the passenger origin-destination data, the segments of passengers which could benefit from a particular alternative are identified. Insights from this process also feed back into the identification of the alternatives. For the identified passenger segments which could benefit, a preliminary analysis of the efficacy of the particular alternative is performed. This involves comparing the probability and extent of the alternative being faster than taking replacement shuttle service for each of those segments. This analysis also gives information about the in-vehicle travel time savings for these passengers.

The demand from this segmentation, along with suitable assumptions about the extent of potential passengers shifting, is then translated to passenger flows along the links in the alternative. By estimating the service level requirements from this demand and the current service characteristics of the alternatives, modified operational parameters like scheduled headway and fleet size requirements for the alternative service as well as the shuttle service are generated.

The service planning steps also provide an estimate of the changes in waiting and transfer times that would result from its implementation. By combining all the time savings and weighing them with passenger volumes, the overall benefit to passengers from the alternative can be estimated.

3.2.2 Gauging the Effects of a Shutdown

Consider the rail network, which consists of several station-to-station links. Each of these links has the following attributes: station 1 (one end of the link), station 2 (other end of the link), direction (distinguishing it from the link in the opposite direction), line (line colors in the MBTA), branch (branch or trunk portion of a specific line, if applicable), and service type (heavy rail or light rail).

A shutdown in the system causes a segment — a set of consecutive links in both directions — to be taken out of the network. These links are usually on a single line and branch at a time. The trips impacted by a particular shutdown are all the trips which pass through these shut-down links: while passing through the segment, or while starting/ending their journeys or transferring within the segment. That is, of all the possible origin-destination (O-D) pairs, only those pairs where the path connecting them has at least one link in the shut segment are affected by a shutdown on that segment.

In a relatively simple rail system with a small set of possible transfer points, like the MBTA or D.C. Metro, most O-D pairs have only one feasible path connecting them. In the MBTA, the exceptions to this are the trips between stops on the Red Line and on the Blue Line. Since there exist no direct transfer stations between these two lines, passengers have to make two transfers, and take either the Green or the Orange line one stop in order to get on to the respective destination line. In networks like New York City Subway, where there are several path choices for a larger proportion of stop pairs, a detailed distribution of such path assignments would be required as an input in order to estimate the link loads and the affected ridership in case of shutdowns. This is to say that for O-D pairs with multiple feasible paths, only the proportion of trips passing through the path which has one or more links in common with the shut segment will be affected.

The ridership for each O-D pair can then be assigned to the links in the network, and

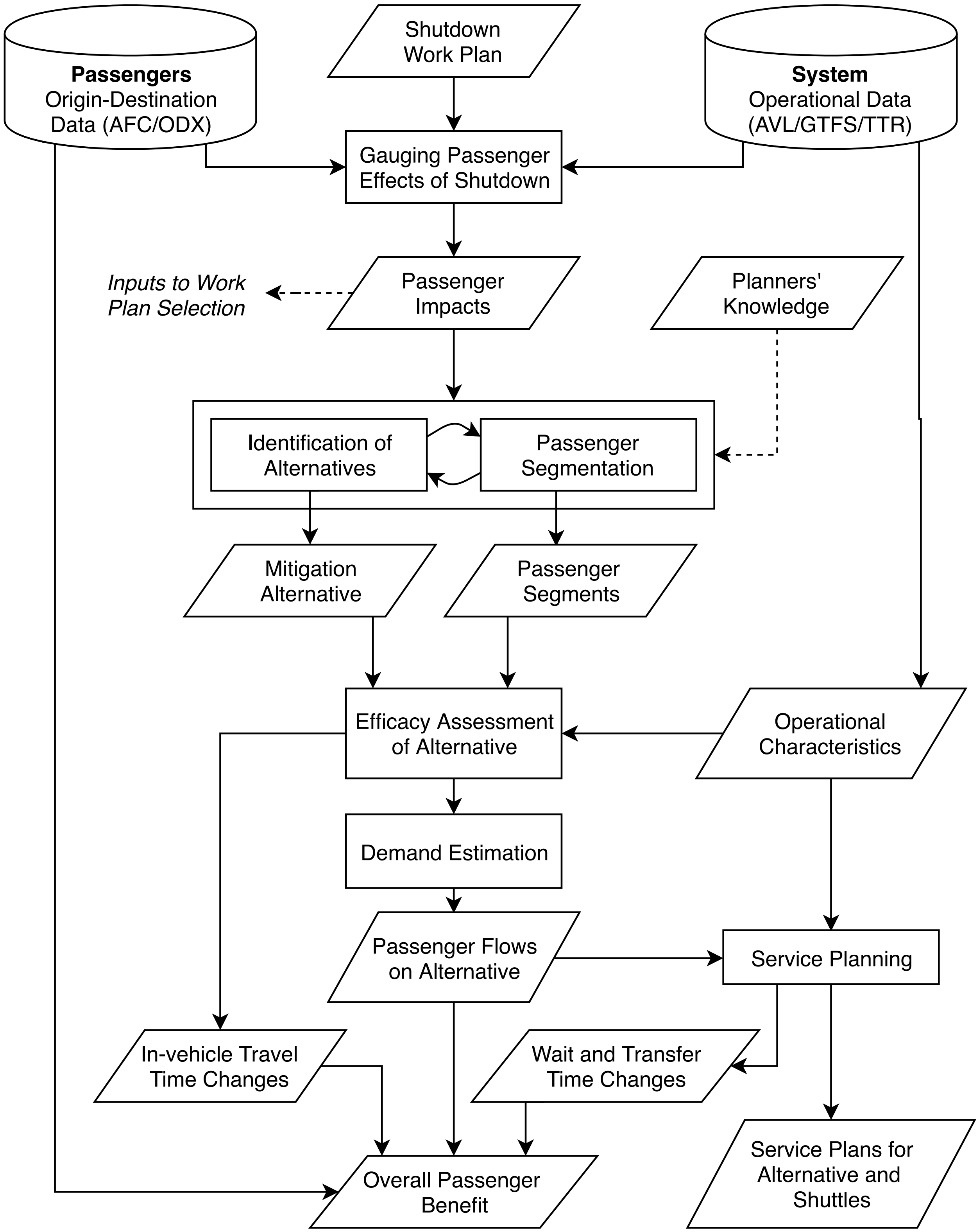


Figure 3-2: Detailed Workflow of Framework for SGR Mitigation Service Planning

aggregated to estimate flows on individual links in the shut segment in either direction:

$$f_{l_d} = \sum_{p \in P^d} \sum_{i} r_p^i$$

Here, P^d is the set of all possible O-D pairs p, which satisfy the following conditions:

- r_p^i is the number of trips for O-D pair p on the i^{th} feasible path (a set of consecutive links in a particular direction) x_p^i between the O-D pair p

- l_d is the link in question (among the set of all links L), in direction d, such that $l_d \in x_p^i$

If a given link l_d is part of a shut segment L^{shut}, then f_{l_d} is the passenger flow which would be disrupted. This flow estimate can be used for calculating net passenger travel time impact, and also for planning service on bus shuttles. If t_{l_d} is the average time it takes to traverse the link l in direction d during regular operations, and $t_{l_d}^{shut}$ is the average time the replacement bus shuttle takes to traverse the same link, then the overall travel time delay can be estimated as:

$$\Delta T^{travel} = \sum_{d} \sum_{l \in L^{shut}} \left(t_{l_d}^{shut} - t_{l_d} \right) \times f_{l_d}$$

In addition to this, a large segment of affected passengers have to face at least one additional transfer while using shuttle buses. The perceived inconvenience due to transfers and waiting for the shuttle or the train at the other end, could be weighed more compared to the addition to travel time. A term w^{trans}, which is generally greater than 1, incorporates the weight of the transfer delay, and can be multiplied to the delay due to transferring, ΔT^{trans}. This delay can be calculated by estimating the time it takes between the rail platform and the street at the start of the segment in a particular direction and the time between the street and the platform at the other end (and repeat in the other direction), and multiplying it by the number of passengers who have to make the respective transfers at the ends of the shut-down segment.

It is also possible to estimate ΔT^{wait}, the change in waiting time because of the shutdown at stations along the affected line. Like transfer delays, the waiting time delays are also weighed higher using a factor $w^{wait} > 1$. The components of additional waiting time (these can be either positive or negative) would be calculated differently for different segments of travellers, as applicable:

- Change in waiting time for the non-shutdown segments on the line due to decreased/increased operation frequencies on those segments
- Waiting time for added rail-to-shuttle and/or shuttle-to-rail transfer
- Reduced waiting time for passengers beginning a stage of their journey within the shut segment, because of higher frequency of shuttles

The weight factors w^{trans} and w^{wait} (with respect to travel time) usually range in value between 1 and 2.5. A report of the International Transport Forum [15] notes that while the generally accepted multipliers for wait and walk time in the United States are equal to 2, certain agencies (such as the NYC MTA) use a walking multiplier of 1.5 and a waiting penalty of 1.25. In a review of UK-based studies of value of time, Abrantes and Wardman [16] found that revealed preference (RP) surveys provided higher estimates of walking and waiting time weights compared to stated preference (SP) surveys. The mean RP multiplier for walking time was 1.84 (compared to 1.62 for SP and 1.65 overall), while that for waiting time was 2.32 (compared to 1.43 for SP and 1.70 overall). In this study, the values of the weights for waiting and transfer time have been set at 2.

The sum of the delays is the total delay: $\Delta T = \Delta T^{travel} + w^{trans}\Delta T^{trans} + w^{wait}\Delta T^{wait}$. Note that this is to be further aggregated over the specific days of the week and time periods during which the shutdown is to be implemented. Depending on the granularity of the O-D data, passenger flows in brackets as fine as 15-minute intervals have been estimated (for example, an internal rail flow tool developed at the MBTA), and can be aggregated while calculating overall effect. The travel time and service frequencies also vary depending on the time of day and day of week, and this information is readily available at an agency. This means that differing shutdown plans can be compared based on overall passenger impact, in addition to cost and duration.

It is possible to express passenger hour delay in monetary terms. Van der Hurk et al. [17] use average hourly wage rates — ranging from a minimum wage rate of \$8 to the average rate of \$32 per hour in Massachusetts — to make this conversion. As per USDoT guidelines, the value of travel time savings is taken as 50% of hourly median household income[18]. This allows for regional variations — for example, for the Boston-Worcester-Manchester (RI, MA, NH) Combined Statistical Area this value is estimated as \$18.80 [19].

Estimates of value of time (VoT) from transportation demand models can also be used to assign monetary value. This enables planners to use distinct transfer and waiting time monetary value conversions, instead of weighing the time delay with the w^{trans} and w^{wait} terms, while estimating the cost of such a shutdown on passengers. Having a monetary number on passenger impacts due to a shutdown can help decision-makers choose better shutdown work plans, as well as identify enhanced alternatives (which could require a higher expenditure) to trade off the estimated cost borne by the agency and the passengers.

3.2.3 Identifying Appropriate Alternatives

This is the most subjective step in the modified framework, wherein planners have a high degree of flexibility to select and/or modify existing bus or rail alternatives, or to come up with new routings, by applying specific domain knowledge about the system.

For a radially-oriented, Downtown-centered rail network, a shutdown along a peripheral segment would usually lead to impacts that are isolated, which means that the rest of the system is relatively unaffected, and that of all the trips affected by the shutdown, most trips are the ones which originate in/end in/pass through that peripheral segment. In such a case, alternatives which run parallel to the affected segment, especially if the ones offering connectivity to the Downtown, are relevant.

It may be possible that major trip producing/attracting locations are located in the peripheral parts of the network. In this case, even though the shutdown itself is isolated spatially, the effect is felt for a larger proportion of passengers across the system. In such a case, alternatives which offer more direct connectivity between the affected segment and other areas in the system (and not necessarily Downtown) are more relevant. This does not mean that increased Downtown connectivity would not be beneficial, but that there might be multiple feasible alternatives which could benefit different passenger O-D segments.

In some cases, it could be useful to examine passenger travel patterns at individual stops. This is especially important for feeder-trunk-style networks (as in the case of the MBTA), where suspending connectivity to a certain stop might impact passengers on several feeder services. Then, candidate alternatives could possibly be ones which alleviate the inconvenience of feeder-to-shuttle transfers.

The shutdown on a segment in or closer to Downtown could likely mean that the impacts are felt system-wide. In such a case, the choice set of potential alternatives can be large. This presents opportunities to implement multiple alternative services to mitigate this impact. It must be noted, however, that possibilities of multiple feasible alternatives, while more likely for Downtown shutdowns, are not exclusive to them.

Rider Segmentation Based on System Origins and Destinations

The choice of particular alternatives is influenced by (and in turn, influences) the number and distribution of passengers which have been identified as potentially benefiting from it. The affected (and in case they benefit, unaffected) passengers can be divided up into segments of riders based on their origin and destination stations, where each passenger segment could utilize the alternative in a different manner (that is, between different stops, or during different time periods). This also opens up the possibilities of specific interventions, alternatives, and mitigation strategies, which might be developed to serve demand between certain stop groupings within a larger rail corridor. Further, examination of passenger O-D patterns could also lead to new or refined alternatives being generated.

Specifically for the MBTA system, depending on the shutdown being examined, a small subset of alternatives from the ones listed in Chapter 2 may be feasible. In general, however, the selection of alternatives and corresponding rider segments to be examined for a shutdown could be based on the following features of the alternatives and ridership patterns in relation to the shut segment:

- Routes which offer passengers opportunities for reducing the overall number of transfers during shutdowns
- Bus/rail routes running along the shut rail segment, or running close-by and parallel to the segment

- Circumferential bus/rail routes enabling passengers to bypass the shutdown segments (i.e. connecting stations whose usual connecting paths would pass through the shut segment)

- Higher frequency bus routes

- Routes with spare capacity

- Routes serving major trip production/attraction locations affected by the shutdown

3.2.4 Estimating Demand on Alternatives

After having identified the O-D pairs affected by a shutdown and a set of available alternatives, a preliminary assessment of the efficacy of the alternatives is required. It is then possible to evaluate the usefulness of the alternative for each particular segment to estimate the demand which could shift to the alternative.

Assessment of Efficacy

Before assigning the demand which could use the identified alternatives, a preliminary assessment of whether the alternative could benefit the segments being examined, and to what extent it would do so, is necessary. This involves comparing the journey time on the traditional shuttles to that on the alternative. The path taken to travel between the origins and destinations for such segments via traditional shuttles could be replaced by the alternative for a particular segment of the path between the two stations.

Consider a hypothetical network as shown in Fig. 3-3. The thick, colored lines are the rail network, where the blue line is facing a shutdown (dashed line) between the stations D and E. A bus service (thin black line) offers connections to the rail network at stations B, C, and E through the respective corresponding bus stops B′, C′, and E′.

Passengers traveling from C to F have the option of either getting off at D and taking the bus shuttle between D and E, or of taking the alternative bus service between C′ and E′, before heading onwards to F. For this passenger segment, in order to assess efficacy of the alternative, the journey time between C and E (with the appropriate transfer penalties

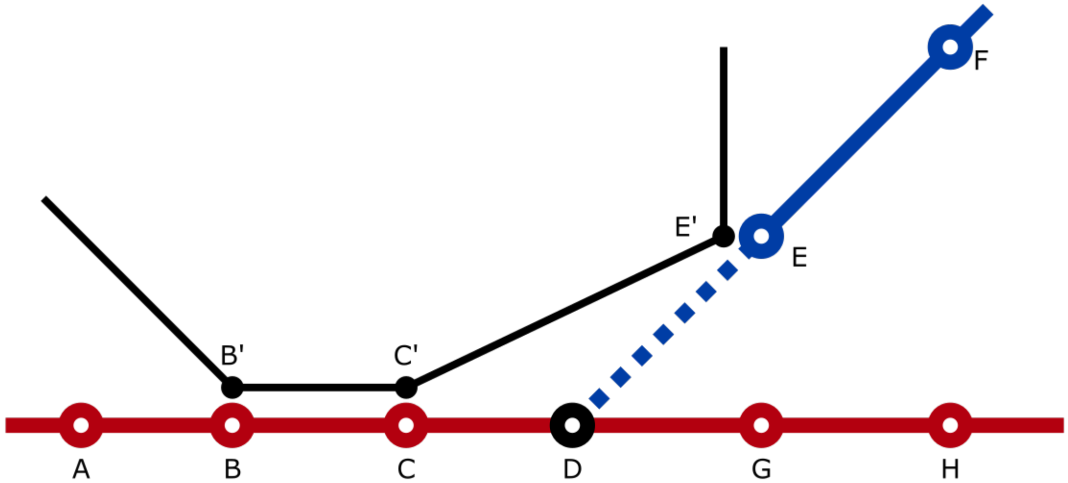


Figure 3-3: A Hypothetical Rail Network (Thick Red and Blue Lines) with a Shutdown (Dotted Link) and Alternative Bus Service (Thin Black Line)

included) can be compared for the rail and shuttle path and for the bus alternative, as this is the part of their path in which the passengers could benefit.

It may be possible that there are multiple possible paths which employ the alternative service for a particular passenger segment. In such a case, the more convenient path employing the alternative could be chosen for comparison to the shuttle service. In the hypothetical network, consider the passengers traveling between B and F. These passengers can either skip the red line altogether by getting on the bus at B′ and staying on it till E′, or they can travel on the red line to C and get on the bus at C′. Depending on the frequency of the bus route, and the time needed to travel between B and C, it may be more convenient for these passengers to get a one-seat ride all the way to E. On the other hand, for passengers traveling between A and F, if they were to use the bus as an alternative, they would necessarily have to transfer — either at B or at C. For these passengers, transferring to the bus at C reduces their overall travel time (assuming that rail is faster than bus between B and C), and is the more convenient path. The journey time on the potential paths via the bus alternative for all of the passenger segments (when multiple paths are possible for a segment, then the most convenient one) should then be compared to the journey time via traditional replacement shuttle service to see if the bus route is effective as an alternative.

Data Requirements

In order to assess the efficacy of an alternative in comparison to traditional shuttles, it is necessary to estimate the distribution of the time it takes in the common segment where the trajectories via shuttle service and the alternative diverge, as described above. For in-system alternatives, very detailed travel time distributions, as well as data about headways and their variability (and hence expected waiting time) at the stops can be obtained from vehicle location data (within the MBTA, AVL for buses and TTR for rail). By combining appropriate assumptions about time taken to transfer and the expected waiting time at stops, it is possible to estimate the distribution of journey time via the alternative on the segment being examined.

Estimating the distribution of time required on the disrupted service segments using traditional shuttles prior to implementation is not as straightforward. In this research, post-implementation data of shuttle vehicle location was used to measure the travel time by shuttle. However, in practice, such information may not be available beforehand. In such cases, travel time on shuttle can be estimated in multiple ways:

- Real-time web-based mapping service (e.g. Google Maps) queries for the vehicle path recorded over the span of a day

- Location data from buses which run on the same route segments as the shuttles, or close-by and parallel

- Running test shuttles on the route beforehand to estimate travel times

Of these, the last option is the most reliable one because it involves on-site measurements of runs akin to the shuttle operations. However, it is also the costliest option since it involves additional vehicle operation costs. In some cases of shutdowns being repeated on certain links, shuttle location data from the past can be accessed — it is thus helpful to maintain a record of shuttle run times. If commuter rail is a potential alternative, run times do not vary much, and current schedules can generally provide a reasonable estimate of the time involved.

Comparing Service Efficacy

The decision regarding whether an alternative can benefit a particular passenger segment is based on whether it is likely to be faster or more convenient for the passengers compared to taking the shuttle during particular times of the day and days of the week. Actual travel times for both bus and rail vary due to various on-ground conditions like dwell time delays due to boarding and crowding, traffic congestion, weather, and technical delays. This spread of travel time distribution has two implications: using the alternative will not necessarily always be faster than using the shuttle, and, when the median travel times are close, it cannot be ascertained whether the alternative is indeed a 'better' choice which could be more attractive to the passengers experiencing disrupted service.

From the vehicle location data available to agencies, it is possible to generate travel time distributions for each stage of the passengers' journeys via shuttle and via the alternative. Assuming independence of travel times for each stage and appropriate transfer/waiting times, the stage-wise travel times can be combined to estimate a distribution of journey times for the segment of the path which could be substituted by taking the alternative. These distributions can be combined using Monte Carlo simulations of sufficient size. In the post-implementation case studies considered here, the travel time of each trip is known, and samples of potential journey times were generated by linking actual trips for each segment's journey stages to create 'feasible' trajectories.

For example, consider the segment of passengers traveling from F to B in the hypothetical network in Fig. 3-3. For these passengers, the segment in their path on the traditional shuttle between E and B could be substituted by the bus alternative, and hence the time taken to traverse this segment via shuttle and via the bus alternative has to be compared. The travel times in the segments E–D (shuttle) and D–C (red line) along with transfer and waiting time at D can be combined to estimate a distribution of journey time via shuttle. Similarly, to estimate the distribution of journey time via the bus alternative, the transfer and waiting time at E can be added to the travel time distribution for the bus between E' and B'.

In order to test whether either of two independent random variables is stochastically larger than the other, the Mann-Whitney U test can be used, and it is suitable for continuous variables where (in contrast to a t test) no particular distribution needs to be assumed [20]. The test is based on a statistic U, which simply denotes the number of times one variable is larger than the other in every possible pairwise comparison between the two samples.

If two random variables X and Y (with n_x and n_y samples, respectively) have to be compared, then the total number of pairwise comparisons is $n_x n_y$. U_x denotes the number of times the variable X is smaller than the variable Y, and U_y denotes the opposite. Note that $U_x + U_y = n_x n_y$. Thereafter, there are several ways to test the null hypothesis that the distributions of these variables are equal. The one used by Mann and Whitney [20] is the global U statistic, which is $U = min(U_x, U_y)$. For given sample sizes n_x and n_y, one can compare the probability of obtaining a U not greater than the one calculated. If this probability is lower than the level of significance determined, then the null hypothesis that the distributions of the variables are equal can be rejected [21]. As a corollary, if the U obtained from the test is lower than or equal to the critical U_α value for a pre-determined level of significance, then the null hypothesis can be rejected.

This test can be utilized for comparing journey time distributions (refer Fig. 3-4). If the journey time (between the two stations for which the comparison is done) via the alternative for a given passenger segment is significantly lower than via traditional shuttles, then the segment stands to benefit from that alternative. Otherwise, if the time is not significantly different, or is greater for the alternative, these passengers would not benefit by switching and are not to be included while estimating ridership on the alternative.

Furthermore, for the segments which do have significantly shorter journey time, not all of the passengers would necessarily benefit all the time due to the variability mentioned above. In this case, it is possible to estimate a probability that the alternative would be faster for each segment, and it can be used as a factor to assign the ridership to the alternative. Consider n_{shut} samples of travel time through shuttles being compared to n_{alt} samples of travel time by the alternative. The proportion of times that the alternative travel time is lower can be calculated as:

$$P(T_{shut} \geq T_{alt}) = 1 - \frac{U}{n_{alt} \times n_{shut}}$$

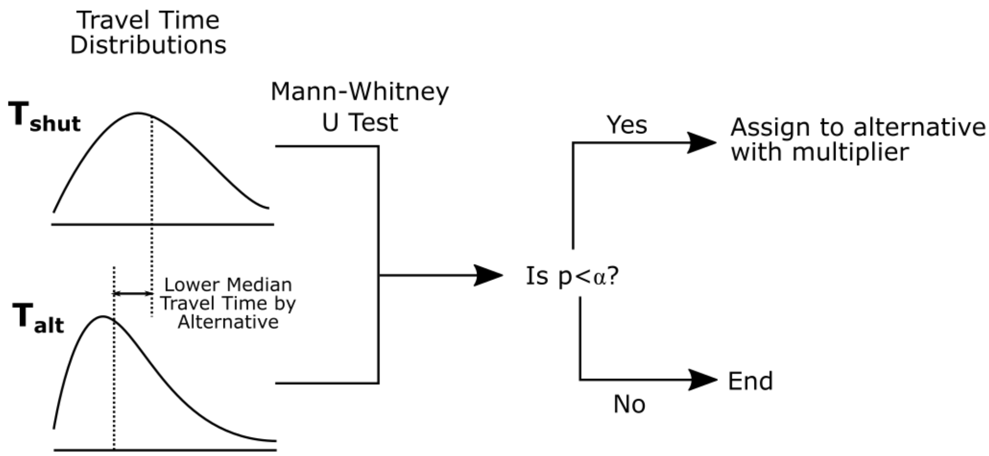


Figure 3-4: Application of Mann-Whitney U Test to Assign Passenger Demand to Alternative (Prior to Reducing Factor)

Assigning Ridership to Alternatives

The ridership on the passengers segments (which would benefit) can then be assigned to the alternative routes they would use. The number of trips for each O-D based segment weighed by the probability of the alternative being faster for that segment can be aggregated to estimate the potential demand changes on the services. Compared to logit-based path choice models which are traditionally used for trip assignment, this method of comparing distributions to assign ridership does not require prior estimation of model parameters and relies on targeting passenger segments which could benefit.

In practice, it is unlikely that every projected passenger (even after taking into account the probability of the alternative being faster) would actually end up switching to an alternative, because passengers often do not have perfect information while making their path decisions. Further, diversion to alternatives is more difficult to communicate than informing passengers of station-to-station replacement bus shuttles. This means that a significant proportion of passengers would stick to the default shuttle path in any case. In addition to this, some overall reduction in ridership can be expected because of passengers simply choosing to not ride the system during any shutdowns.

In order to account for this passenger behavior, and to avoid excessive costs of implementing the alternative service, the estimates of ridership which could potentially switch from the shuttle to the alternative should incorporate a 'reduction' factor in addition to the probability weights used above. A range of 50–75% for this reduction factor should be considered (75% being a conservative proportion to absorb demand on the alternative while eliminating any chance of passengers already using the alternative service experiencing crowding and degradation in service due to the shift) in combination with information dissemination strategies which could encourage more passengers to use the alternatives. Agencies can examine ridership changes through fare gate and vehicle passenger load data to estimate this factor, and track and study how it varies over different shutdowns. Such post-implementation insights can be used to choose a particular factor or range of factors for future projects.

3.2.5 Operational Requirements

With the potential shift to the identified alternative(s) being estimated, it is possible to assign this additional ridership to the alternative in question over and above the current ridership on the route. Service can be planned with reference to the segment on the alternative with the highest directional flow after assigning the shift ($f_{alt_d}^{max}$) for each particular time period. This step is followed by the estimation of the number of vehicles required to implement such a service with a certain frequency and cycle time.

Frequency Requirement and Headway Variability

In order to accommodate the potential shift to the alternatives, the service often needs to be enhanced to provide sufficient capacity. In case of bus alternatives, the planning capacity of each bus is known (in the MBTA system, each bus can hold roughly 54 passengers without unreasonable crowding [22]). Assuming one-hour time periods, this means that the frequency provided on the alternative during a particular time period should be at least $F_R = {}^{f_{alt_d}^{max}}/_{54}$ buses per hour.

For commuter rail alternatives, trains tend to accommodate a very large number of passengers, and hence the minimum frequency in implementation would be normally based on policy headways. A straightforward standard for policy headway is the regular operation headway on the line being shut down. For the MBTA, regular weekend headways on heavy/light rail are between 7 and 15 minutes, varying by line and branch.

In practice, the on-ground conditions which lead to variability in travel time as mentioned before also lead to variation of the headway experienced by the passengers. A common manifestation of this is the phenomenon of 'bus bunching', wherein a feedback loop of delays on a vehicle result in long gaps in headway which lead to crowding and further delays, to the extent that the vehicle behind it catches up and creates another long gap.

This means that even though the headway averaged over time might be close to scheduled headway, a large number of passengers who arrive at the stops for a delayed vehicle experience much longer headways, while a smaller number of passengers who turn up to board the following vehicle experience much shorter headways. This leads to the headway experienced from a passenger perspective being higher than the scheduled headway due to variability. From an operational perspective, because capacity is proportional to the frequency of service, a higher effective headway (i.e., lower effective frequency) experienced by passengers is indicative of a shortfall in effective capacity during implementation. The operational implications of such reduced effective capacity are discussed in the next section describing fleet size estimation.

Fleet Size Requirement for Effective Capacity Provision

Two operational characteristics of the alternative are necessary in order to estimate the number of vehicles required for operation:

- Cycle Time: During a particular time period, the cycle time for a route is the time scheduled for a vehicle to complete a round trip along the route added to a scheduled buffer time at each end of the route. It is common practice across public transit agencies to set the cycle time to an upper bound of the two-way running time distribution — usually between the 85^{th} and the 95^{th} percentile. This means that, after taking the variability of running times into account, most vehicles completing their trips have a buffer layover time at the terminals, which prevents the propagation of delays on to further trips that vehicle would make along the route [23, 24]. While planning alternative service for shutdowns, it is possible to examine the vehicle block schedules and realign cycle times to the upper bound of run times to reduce existing shortfalls or excesses in operations.

- Frequency: As discussed above, the frequency provision required during implementation is either based on the demand (existing and shifting in) or policy headways.

Maltzan [25] discusses in detail various equivalent formulations for effective headway in implementation and its translation to an 'additional vehicles required' metric, and this approach is summarized below. At a particular time of the day, let c be the cycle time based on upper bound of run times for the alternative route. If F_R is the hourly frequency required in that time period, then the headway required is $H_R = {}^{60}/_{F_R}$.

Under 'ideal' conditions during implementation with no variation in headways, the scheduled headway H_S would be the same as effective headway as experienced by passengers and H_E and can simply be set to the required headway H_R. Hence the number of vehicles required in ideal conditions (n) would be:

$$n = \lceil {}^{c}/_{H_S} \rceil = \lceil {}^{c}/_{H_R} \rceil$$

In reality however, as discussed before, headways in implementation are variable. The effective headway experienced by the passengers at a particular stop is related to the mean headway of operation as:

$$H_E = \widehat{\mu_H} \left(1 + \widehat{CV_H}^2\right)$$

Here, $\hat{\mu_H}$ represents the sample mean headway, and if $\widehat{\sigma_H}$ is the standard deviation of the sample headway, then $\widehat{CV_H}$ is the sample coefficient of variation of headways, estimated as $\widehat{CV_H} = {}^{\widehat{\sigma_H}}/_{\widehat{\mu_H}}$. By assuming that the mean headway in operation is equal to the scheduled headway (i.e., $\widehat{\mu_H} = H_S$), the scheduled headway and the effective headway at the critical stop can be related as:

$$H_E = H_S \left(1 + \widehat{CV_H}^2\right)$$

The coefficient of variation, and thus the effective headway, differs for different stops on the routes. The effective headway for the entire route can be estimated by weighing the effective headway at each stop with the number of passengers experiencing that headway. In this study, however, the value of the coefficient of variation at a 'critical' stop has been used for purposes of calculation. This is obtained by examining the stops along the route where passengers could switch to and board the alternative, and using the maximum directional $\widehat{CV_H}$ in either direction at any of those stops.

The scheduled headways could to be set such that during implementation, the effective headway in practice (for that scheduled headway) would match the calculated headway required for absorbing the demand shift. This requires setting the scheduled headway $H_{S'}$:

$$H_{S'} = \frac{H_R}{1 + \widehat{CV_H}^2}$$

Hence the overall vehicle requirement for the alternative under variable headway conditions can be estimated as:

$$n' = \left\lceil \frac{c}{H_{S'}} \right\rceil = \left\lceil \frac{c}{H_R} \left(1 + \widehat{CV_H}^2\right) \right\rceil \approx n \left(1 + \widehat{CV_H}^2\right)$$

Compared to implementation under ideal conditions, this increased fleet size by taking into account headway variability is higher by a factor of approximately $\left(1 + \widehat{CV_H}^2\right)$. This metric incorporates the passenger delays due to the variation, and can be thought of as a 'maximum' fleet size necessary in order to provide sufficient effective capacity on the alternative to absorb the projected demand shifting to it. For services with very low headways (like shuttle buses), even smaller absolute variations in headway result in this factor being large. Hence, it can be capped to a certain percentage in order to limit excessive vehicle requirement estimates. In such cases, other interventions for maintaining headway regularity, such as improvements in dispatching and on-route headway control strategies, should be considered to provide enough capacity.

3.2.6 Passenger Benefits

For the ridership from various passenger segments which was assumed to shift to the new alternative in the earlier stages of the framework, the time savings $\Delta T_{shift}^{savings}$ can be estimated by combining the savings for each segment:

$$\Delta T^{savings}_{shift} = \sum_{d} \sum_{s_d} \left(t^{shuttle}_{s_d} - t^{alt}_{s_d} \right) r'_{s_d}$$

Here, s_d represents a particular segment of passengers (traveling in the direction d) which was assumed to benefit to some extent by shifting, r'_{s_d} represents the weighted proportion of riders in the segment assumed to shift, and $t^{shuttle}_{s_d}$ and $t^{alt}_{s_d}$ respectively denote the average time it takes via shuttle and via the alternative on the common stop-to-stop segment where substitution is possible for that particular rider segment.

It is possible to break down the overall time taken on the substituted segment into its components: in-vehicle travel time, waiting time, and transfer time. Similar to the use of weighted multipliers for waiting and transfer time in passenger impact analysis, the benefits of reduced number of transfers and/or reduced waiting time can also be weighed accordingly.

In addition to the riders which shift, some riders already using the alternative also stand to benefit from enhanced services on it. The time savings for these primarily arise in reduced waiting times: $\Delta T^{savings}_{pre} = w^{wait} \times r_{pre} \times {}^{(H_E - H_{E'})}/_{2}$, where the term in the parentheses represents the reduction in effective headway experienced by all the existing passengers (r_{pre}) on the route.

By combining the savings for the passengers who could shift to the alternative and for passengers already on the route $\Delta T^{savings}_{shift} + \Delta T^{savings}_{pre}$, a passenger hour metric can be calculated to judge the benefits of a particular alternative plan. This passenger hour metric can also be assigned a monetary value if necessary.

3.2.7 Considerations for Implementation

Adoption by Agencies

The framework proposed here seeks to incorporate passenger impacts within the planning process of SGR-related shutdowns. The organization of duties and responsibilities of project managers and planners differs from agency to agency. In general, this framework would require increased communication and coordination between project managers, contractors, service planners, and operations staff. Figure 3-5 describes a way various stakeholders can co-ordinate to plan shutdowns. During the earlier stages of planning, project managers could consult with both contractors and service planners to get their inputs (project task staging and costs from the contractors' side and passenger impacts of various shutdown scenarios from the service planners' side) in order to decide the specific work plan of the shutdowns. With that work plan in place, service planners can then identify feasible alternatives with inputs from operations, who would then be tasked with the implementation of shutdowns. The service planning process described earlier fits in as a subroutine with the work plan as an input and the impacts as its output. It is also important to incorporate insights from prior shutdowns to plan for future shutdowns. This is described in detail in below.

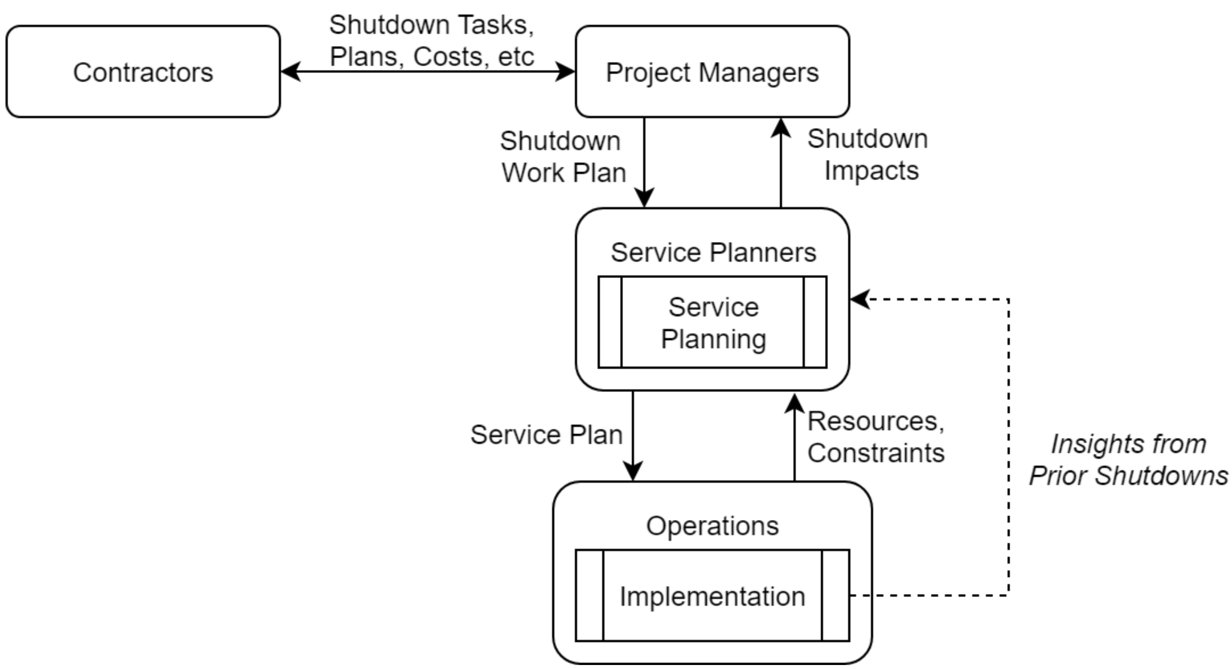


Figure 3-5: Example of Potential Workflow of SGR Project Planning to Incorporate Passenger Impacts

Costs and Funding of Alternative Mitigation Plans

Enhancing service on the alternative(s) requires additional expenditures, primarily for operator and fuel costs. From the crew and vehicle scheduling process within the agency, the additional costs incurred in order to provide enhanced service on the alternative can be estimated. In part due to added costs and complexities, agency stakeholders tend to show hesitation for enhancing service on already operational routes for shutdown mitigation.

The overall effectiveness of an alternative (and the subsequent decision of whether to implement the alternative) is based on cost of the project, the project's impacts on passengers, implementation costs of the alternative service, and benefits to passengers because of the alternative service. By default, the costs are in monetary terms, while the impacts and benefits of the alternatives can be estimated in terms of passenger hours. Although optional, converting these passenger hour units to monetary equivalents enables examination and comparison of the costs (of the project and of the alternative mitigation service), passenger impacts, and mitigation benefits to each other.

From the perspective of the costs borne by the agencies, there are short-term direct costs like those of operation of shuttle buses and its associated overhead, as well as revenue loss at fare gates during shutdowns. However, there are also indirect costs. The portion of passengers shifting to alternatives within the system without enhancement can lead to increased crowding and delays on those services. In addition to this, the passengers choosing not to make trips on the agency's system can still end up making those trips on automobiles (either personal vehicles or taxis/TNCs). The increased road congestion because of this causes system-wide negative effects. Inadequate mitigation of passenger impacts of sustained shutdowns has the danger of causing long range reductions in system ridership, and added congestion. Hence, the considerations for implementing a mitigation strategy should focus not just on costs to the agency, but also benefits to the passengers, extent of mitigation, as well as long-term impacts.

SGR projects are funded from a substantial pool of dedicated expenditure in the agency's budget. Some SGR projects tend to be very large in scale, and for these, compared to the costs of the project themselves, the costs of enhancing already existing service are very minor. This presents an opportunity to utilize some portion of these funds in order to improve alternative service for mitigating passenger effects, and could be undertaken through one or more of the following ways:

- Preemptively enhancing service on the routes during the off-peak and weekends, which could add redundancy in the system (for example, in the MBTA system, on the circumferential and parallel bus routes mentioned in Chapter 2), as a capital project under the SGR umbrella

- Establishing and/or reserving a dedicated fleet of vehicles to be used for implementing alternatives over the span of the next few years

- Adding conditions for mitigation alternative operations to the contracts with private operators while renewing them, or by modifying the contracts

Some possible service improvements (especially those for bus and shuttle routes) are not under the purview of the transit agency. The power to implement some of these solutions (like dedicated bus lanes, signal priority, and street network changes) that have the potential to significantly benefit passengers lies with municipal agencies, and hence collaboration with cities and towns for passenger impact mitigation is also of importance.

Information Dissemination

In addition to providing enhanced alternative service for mitigating SGR shutdown effects, the agency also needs to encourage the passengers who stand to benefit to actively utilize the alternatives. Since the passenger segments would already be known from the analysis, targeted information dissemination is possible at relevant stations/stops. This would primarily include posters and announcements informing passengers that there is more frequent/modified service on the alternative(s) available if they are going to particular stations/stops, how to access the alternatives, and popular trip production/attraction locations nearby.

Several passengers use web services (often smartphone applications) like the the agency's trip planner (if one exists), Google Maps, or Transit. These services have the flexibility to incorporate service changes on short notice, and can be used to inform passengers of available alternatives if they query a path which would be affected by shutdowns. In agencies Where passengers have opted for service alerts/notifications (in case of the MBTA, T-Alerts), such an interface could potentially be useful. With respect to systems with contact details associated with smart-cards, research has been done in identifying customer segments based on spatial-temporal travel patterns to provide customized information [26].

Post-Implementation Evaluation

Evaluation and analysis of each shutdown after implementation provides opportunities to implement improved future shutdown mitigation plans. This can be broadly divided into two aspects: operations and passenger behavior.

Records of crew and vehicle scheduling and costs, run times of shuttle trips, traffic conditions, improvements from interventions (e.g. inclusion of bus lanes), in addition to the data available from automated sources, can inform future planning of shutdowns. For example, from AVL and manually collected shuttle trip run time records, the distribution of time it takes for the shuttle buses to travel between each station-to-station link can be estimated. This can help identify bottlenecks in the shuttle service and opportunities of potential route changes and on-ground interventions.

To evaluate whether the alternative was effective in serving the demand which could benefit from it, sources like AFC databases can be used to infer individual passenger trajectories using the ODX algorithm. The difference of the tap-ins and transfers to the alternative at stops where passengers could shift during regular operations compared to during shutdown days also provides a rough measure of the number of passengers who ended up shifting.

Inside MBTA shuttle buses, APC counts during shutdowns have, thus far, been found to be imprecise and erroneous, and fixing this collection system for replacement shuttles is crucial for estimating the proportion of riders who use the shuttles. The difference between regular link flows and flow from passenger counts on the shuttles during shutdowns provides an estimate of the number of passengers who dropped out of the system, or switched to the alternative. Measures of passengers' willingness to use the system during shutdowns can be estimated. This enables testing and comparison of the effectiveness of various interventions for mitigating effects of rail shutdowns.

3.3 Summary

This chapter provides a detailed description of a proposed framework which seeks to address several pertinent questions which come up while planning services during SGR shutdowns. Relevant subjective and objective criteria have been introduced here in order to guide decision-making at various levels of service planning, and to some extent, in shutdown work plan selection.

Because of redundancies within the existing network, there may be alternatives to relying exclusively on replacement bus shuttles in order to mitigate disruption from SGR activity by absorbing passengers affected by SGR-related shutdowns. Choosing alternatives for shutdown mitigation and examining passengers who could potentially benefit from them requires making subjective decisions, based on planners' knowledge of the system, along with some insights from the impacts. The impacts of a shutdown and the benefits of potentially implementing an alternative mitigation plan can be quantified with the help of passenger and system data available to the agencies.

Because of differing duties and responsibilities, communication within various stakeholders is crucial in order to utilize these criteria for decision making. Agencies can also learn from prior shutdowns in order to better plan for upcoming shutdowns. Finally, during implementation, effectively communicating information about these alternatives to passengers is essential for these plans to be effective.

Chapter 4

Case Study: Longfellow Bridge

4.1 Background

The Longfellow Bridge, connecting Downtown Boston and Cambridge, was constructed between 1900 and 1907. The Cambridge Tunnel between Harvard and Park Street — the precursor to what is now the Red Line — was constructed between 1909 and 1912 [27, 28]. Due to its long history and construction methods, the bridge has already faced two major repair projects: in 1959 and 2002.

Because of substantial structural deficiencies, the most recent major repair project was undertaken between 2013 and 2018, and involved several weekends of shutdowns on the Red Line between Kendall and Park Street stations, with shuttle buses replacing rail service. Passenger and vehicle data from weekends in 2016 and 2017 have been used for this analysis. In these two years, shutdowns were implemented on 6 weekends spanning January, March, and July 2016, and 8 weekends between September and December 2017. In the near future, this same segment would need to be shut down for major repairs on the Red Line between Charles/MGH and Park Street stations, and the insights from examining the Longfellow Bridge repair project shutdown could be very valuable.

Van der Hurk et al. [17] studied the shutdowns on this bridge when they were undertaken in 2013. This study involved a mixed integer programming model to choose optimal shuttle lines (from an input set of shuttle lines), frequencies, and the fleet sizes for various services in order to maximize passenger benefit under operational budget constraints. After applying this model to the shutdown on the Longfellow Bridge, the following recommendations were presented:

- Shifting some buses from the replacement bus shuttle service to enhance service on bus route #1: This could lead to substantial benefits in waiting time, and subsequent total travel time reductions, for passengers traveling to Back Bay/Copley and west on Green Line or Orange Line via Route 1, while causing a slight negative wait time impact for the remaining bus shuttle passengers
- Adding a shuttle stop at Bowdoin station (refer Figure 4-1 for location of the station relative to the shuttle path): This would lead to a marginal increase in shuttle dwell time but an average of 9 min savings in travel time for passengers destined to Government Center, Blue Line, and the Haymarket/North Station area.

4.1.1 Bus Shuttle Service

The route of the bus shuttles traversed Kendall, Charles/MGH, and Park Street stations, crossing the Charles river between Cambridge and Boston on a reduced-capacity Longfellow Bridge, and making a loop around the Boston Common to travel back from Park Street towards Cambridge (Fig. 4-1). In order to make the shuttle service convenient for passengers by reducing waiting time at the end stations, the shuttles were operated at very high frequencies. This required the use of a large number of MBTA and/or private buses — between 60 and 85 vehicles on some weekends.

Before the repairs were completed, the speed of Red Line cars while passing through the bridge was restricted so that the average travel time during regular weekdays was approximately 5 minutes (solid lines in Fig. 4-2). During shutdowns, the shuttles took substantially longer to traverse the segment between Kendall and Park Street.

During most of Saturday and Sunday, the travel time for the shuttles was, on an average, at least 10 minutes in either direction. The outbound shuttles consistently took longer to travel along the segment compared to inbound shuttles: requiring more than 15 minutes on average for most part of the day, and more than 20 minutes in the afternoon peak periods. Figure 4-3 shows the distribution of the travel times in the entire segment compared to both

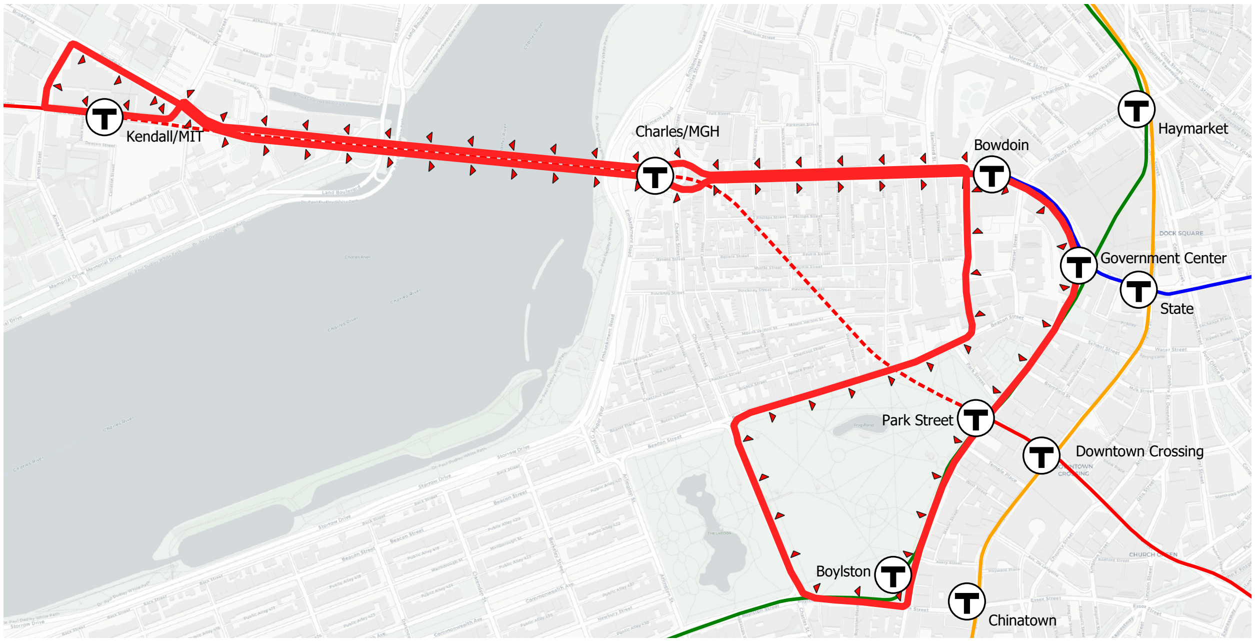
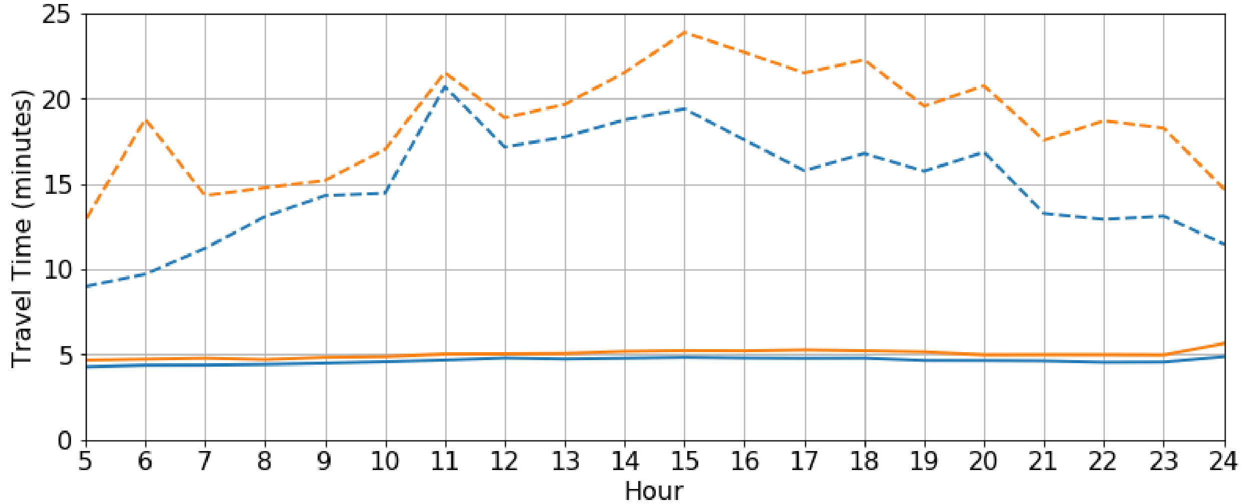


Figure 4-1: Map of MBTA Bus Shuttle Route During Longfellow Bridge Shutdowns

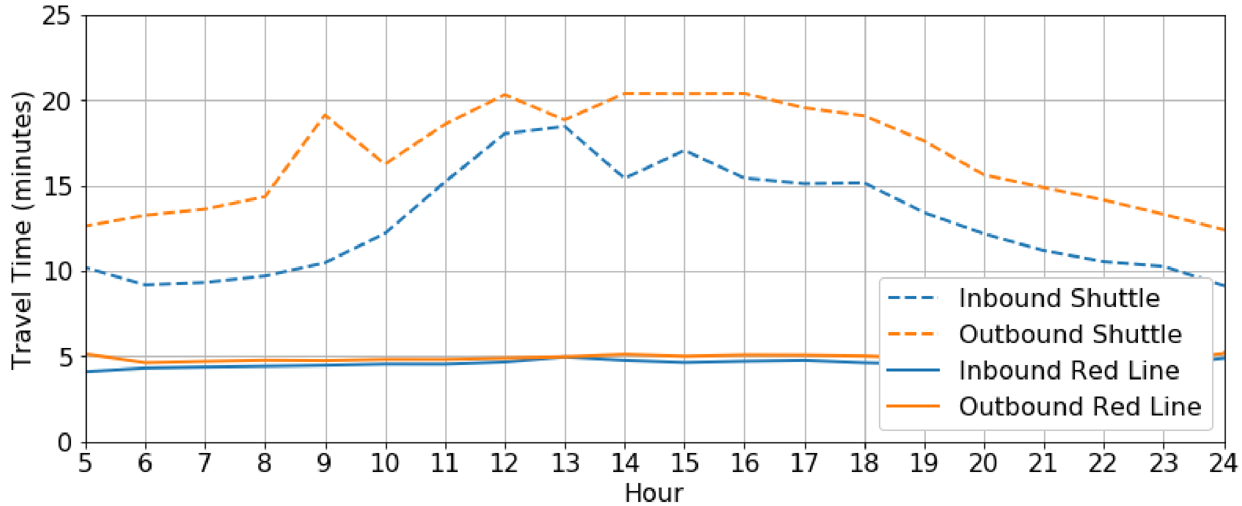
the links during the afternoon and early evening peak period of 3 pm – 8 pm. The whiskers represent 10^{th} and the 90^{th} percentile of the observed travel times.

The running time of the bus shuttles between Kendall and Charles/MGH in both directions are very similar, as seen by their medians and ranges. However, large discrepancies between the directions in the time between Charles/MGH and Park Street stations are also reflected in the overall travel time. This directional discrepancy can be attributed to the longer path (which went around the Boston Common) the vehicles took traveling outbound and, generally, more congestion on the Boston side of the river. This congestion is also reflected in the longer running times between Charles/MGH and Park Street on the Boston side compared to between Kendall and Charles/MGH.

The higher running time required between Charles/MGH and Park Street (compared to the other link) also suggests opportunities for improving shuttle service by altering its path in Boston, and because the path passes through congested streets like Cambridge and Tremont Streets, interventions like temporary dedicated bus lanes during shutdowns could help alleviate delays faced by passengers.

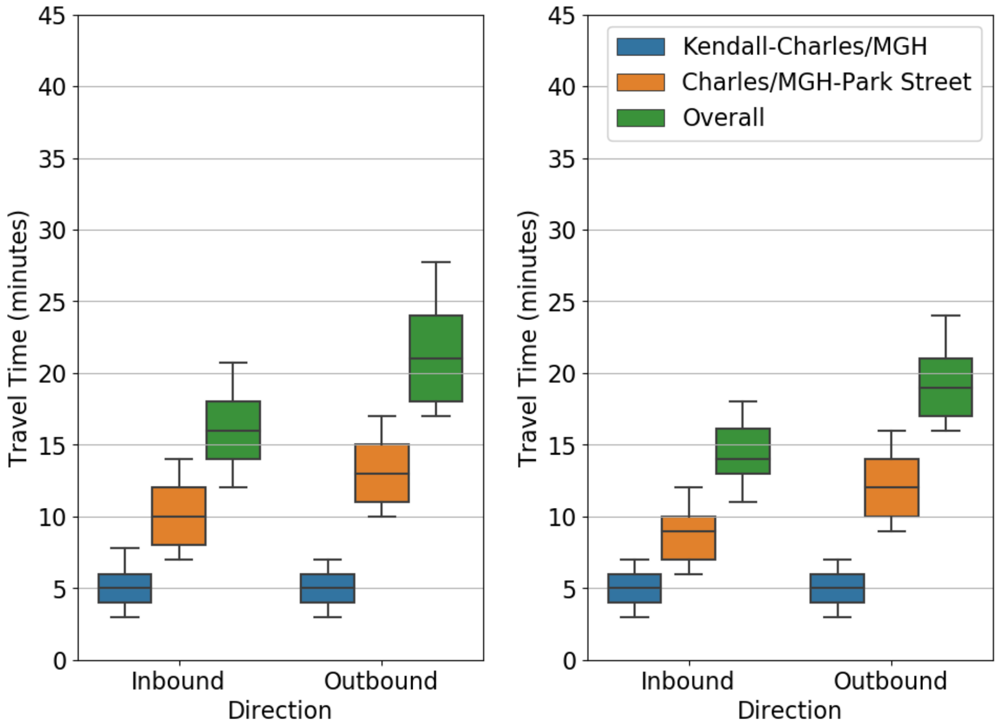


(a) Saturdays



(b) Sundays

Figure 4-2: Average Travel Times between Kendall and Park Street by Hour on Replacement Bus Shuttles and Regular Red Line Service



(a) Saturdays

(b) Sundays

Figure 4-3: Distribution Travel Times via Shuttle Between Kendall and Park Street by Link (3 pm–8 pm)

4.2 Analysis of Passenger Impacts

The Longfellow Bridge on the Red Line is an important connection between parts of Cambridge and Somerville to Boston and a few other cities to the South. In addition to several bus routes feeding in at various stations along the line, it also provides a commuter rail connection at Porter station, and park-and-ride rapid transit access at Alewife station. Similarly, the stations on the Boston side of the bridge can access key destinations like Kendall Square, MIT, and Harvard University while traveling northward.

These factors lead to the bridge being a vital link in the MBTA system, which means that a closure on this link affects a large number of heavy/light rail riders. This section presents analyses of passenger impacts on two levels — an analysis of the spatial distribution of impacts over various 'zones' in the system, and the aggregated temporal impacts for the riders passing through the shutdown segment on regular weekends.

4.2.1 Zonal Grouping of Stations

As described in Chapter 3, the 'affected' passenger flow comprises the passengers traveling between every origin-destination pair wherein the path connecting them shares links with the shutdown segment. The availability of detailed origin-destination data enables analysis at levels ranging from micro-scale station-to-station to macro-scale aggregate flow through the link.

It is also possible to do a meso-scale zonal analysis by grouping stations which share characteristics like location with respect to the shutdown, proximity to other stations, the lines being served at that stop, and alternative connection availability. The rationale behind this kind of grouping is that 'similar' stations are also similar in terms of impact of shutdowns. Thus, aggregating to the level of zones enables an examination of spatial patterns of the shutdowns while reducing the complexity in comparison to a disaggregate station-to-station analysis.

For the Longfellow Bridge shutdown, the stations have been grouped by taking into account some of the criteria above (Fig. 4-4). The zone denoted as DTN includes relatively densely located and interconnected Downtown stations of all the lines, bounded on the West by Massachusetts Avenue. This choice of delimiter on the West is also influenced by the alternative alternative identified for analysis: Bus route #1 (refer Section 4.3).

This DTN zone links the Northern Red Line zone (RLN) and Kendall and Charles/MGH stations to all the other zones. The radial segments of the Orange, Blue, and Green lines not in DTN are separate zones as per their directions. The remaining segments of the Red Line have been divided into three zones: the Trunk segment (denoted as JFK), and the Ashmont (including Mattapan line) and Braintree branches (RLA and RLB, respectively). Kendall and Charles/MGH stations are denoted as their own zones: KEN and MGH, respectively.

4.2.2 Zone-wise Impacts

Using the zones described above, average regular weekend zonal origin-destination flow matrices can be formed to examine the impacts of a shutdown. Table 4.1 shows the average Saturday zone-to-zone flows during non-shutdown weekends of 2016 and 2017 (for Sundays, refer to Table 4.2).

Of the roughly 318,000 heavy/light rail trips taken on the MBTA system on Saturdays, more than 63,000 or approximately 20%, pass through the Longfellow Bridge and are impacted during shutdowns. While the total number of trips is lower on Sundays (236,000 trips, out of which 47,000 pass through the bridge), the system-wide proportion of trips impacted is also very close to 20%. 93% of these trips cross the bridge structure to travel between Cambridge and Boston, while the other 7% of the trips are between Charles/MGH and the stations on the Boston side of the bridge.

On a zonal level, roughly 62–63% of the trips that originate or end at stations on the Cambridge side of the bridge (RLN and Kendall) are affected by the shutdown. For the other stations on the Red Line (excluding Park Street), roughly 18–20% of trips to/from these stations are affected. The effect on the Ashmont and Braintree branches is slightly lower (13–16%) than that on the Trunk portion of the Red Line (22–23%).

The effect on the outer portions of other lines is relatively modest, with between 5–7% of the trips originating/ending at the outer Blue, Green, and Orange Line stations being affected by the shutdown. The passengers traveling between Cambridge and zones on the western and south-western parts of the Green and Orange lines, along with some passengers

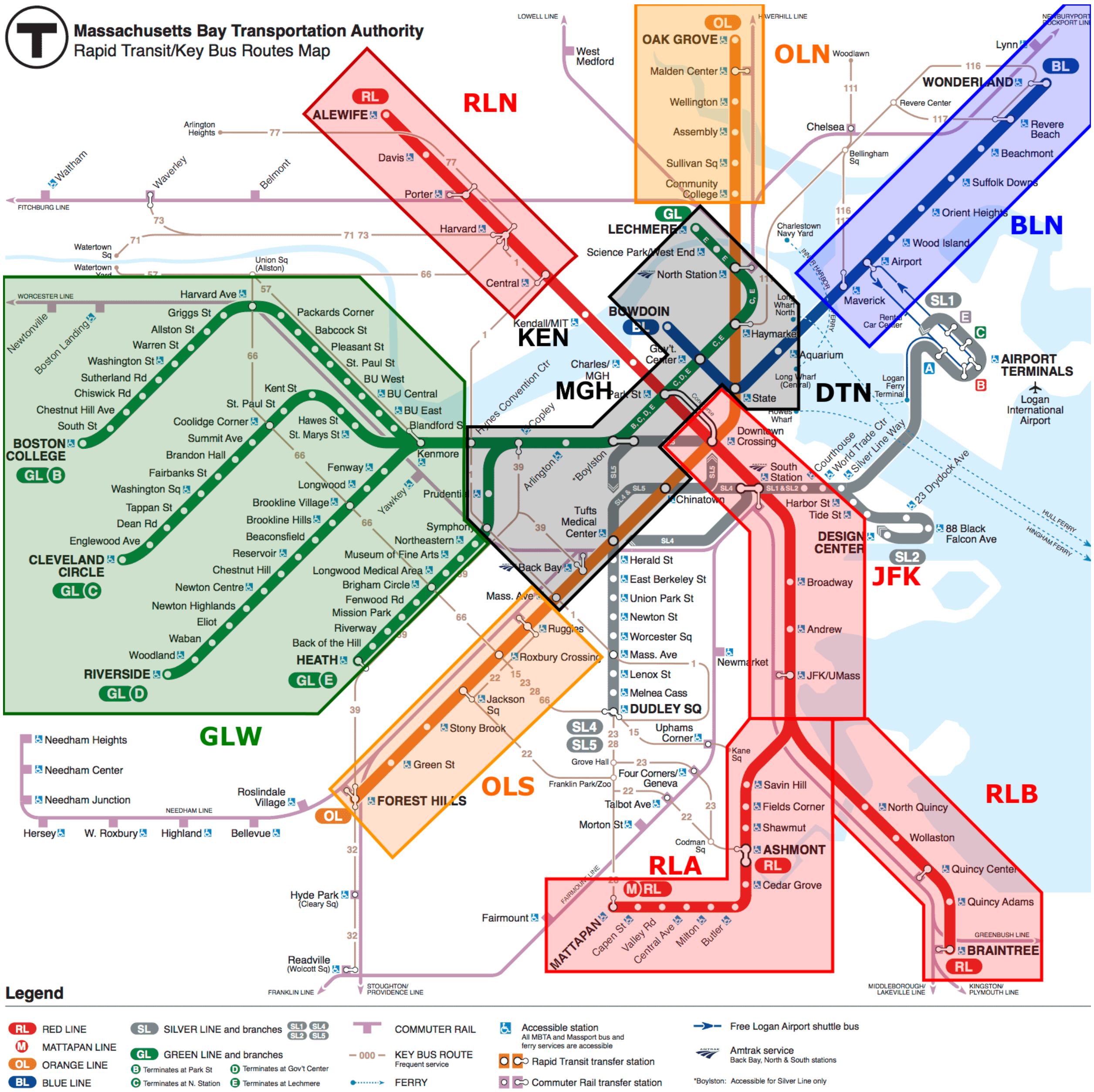


Figure 4-4: Zonal Grouping of Stations for Impact Assessment overlaid on the MBTA System Map

Table 4.1: Average Daily Zonal Origin-Destination Flows (thousands) (Saturdays, 2016-17)

Origins	Destinations												
	BLN	DTN	GLW	JFK	KEN	MGH	OLN	OLS	RLA	RLB	RLN	Total	Affected
BLN	6.20	13.22	1.27	0.66	**0.20**	**0.03**	1.47	1.09	0.26	0.23	**1.27**	25.91	**1.50**
DTN	12.73	27.52	17.51	5.15	**1.27**	**0.47**	9.71	8.19	1.98	3.14	**9.82**	97.48	**11.56**
GLW	1.43	20.58	15.89	1.11	**0.30**	**0.28**	1.15	0.19	0.46	0.85	**1.92**	44.15	**2.49**
JFK	1.21	5.24	1.35	5.97	**0.83**	**0.53**	2.57	2.65	3.12	3.79	**5.95**	33.21	**7.32**
KEN	**0.20**	**1.31**	**0.27**	**0.90**	—	**0.24**	**0.16**	**0.15**	**0.15**	**0.20**	2.34	5.93	**3.59**
MGH	**0.07**	**0.49**	**0.21**	**0.56**	**0.26**	—	**0.12**	**0.13**	**0.23**	**0.25**	**2.00**	4.31	**4.31**
OLN	1.25	9.34	1.01	2.98	**0.18**	**0.13**	4.04	1.67	0.31	0.35	**1.09**	22.34	**1.40**
OLS	1.13	8.39	0.19	3.11	**0.17**	**0.15**	1.86	4.12	0.21	0.20	**1.07**	20.60	**1.38**
RLA	0.31	1.98	0.43	3.26	**0.17**	**0.25**	0.36	0.21	1.67	0.45	**1.11**	10.20	**1.53**
RLB	0.28	3.08	0.79	4.02	**0.22**	**0.28**	0.39	0.24	0.46	1.79	**1.21**	12.76	**1.71**
RLN	**1.41**	**10.47**	**1.94**	**6.41**	2.46	**1.99**	**1.10**	**1.10**	**1.07**	**1.20**	12.35	41.50	**26.69**
Total	26.21	101.62	40.86	34.12	6.06	4.33	22.92	19.73	9.94	12.46	40.14	318.40	
Affected	**1.69**	**12.27**	**2.42**	**7.87**	**3.60**	**4.33**	**1.38**	**1.38**	**1.45**	**1.65**	**25.45**		**63.49**

Note: The cells in **bold** indicate that the segment of riders would be affected by the shutdown.

traveling between Cambridge and stations in DTN close to Mass Ave, could stand to benefit by using bus route #1 during the shutdowns.

4.2.3 Travel Time Impacts

Passengers traveling through the shut-down rail segments would have to incur substantial delays in travel time, as well as the inconvenience of added transfers and the resulting increase in waiting time. From origin-destination data, the flows of passengers which currently travel through a link, will face additional transfers, and will face changes in waiting time can be estimated.

For example, consider the passenger flows at Kendall Station going inbound during a shutdown (Fig. 4-5). The passenger flow southbound from stations in the northern segment of the Red Line (RLN) arrives at Kendall. Some of these passengers exit Kendall station as their destination. The passengers going further south have to transfer to the shuttle, and

Table 4.2: Average Daily Zonal Origin-Destination Flows (thousands) (Sundays, 2016-17)

Origins	Destinations												
	BLN	DTN	GLW	JFK	KEN	MGH	OLN	OLS	RLA	RLB	RLN	Total	Affected
BLN	5.26	9.77	1.07	0.49	**0.15**	**0.02**	1.21	0.89	0.19	0.17	**0.98**	20.19	**1.14**
DTN	9.62	19.65	13.43	3.68	**0.92**	**0.34**	6.86	5.81	1.36	2.06	**6.95**	70.68	**8.21**
GLW	1.18	15.28	13.11	0.91	**0.22**	**0.20**	0.92	0.14	0.35	0.67	**1.53**	34.52	**1.95**
JFK	0.96	3.79	1.25	4.71	**0.68**	**0.43**	1.93	1.90	2.32	3.12	**4.90**	25.99	**6.01**
KEN	**0.14**	**0.93**	**0.20**	**0.71**	—	**0.20**	**0.12**	**0.11**	**0.12**	**0.14**	1.79	4.47	**2.68**
MGH	**0.05**	**0.34**	**0.16**	**0.43**	**0.20**	—	**0.09**	**0.10**	**0.17**	**0.19**	**1.55**	3.28	**3.28**
OLN	0.95	6.16	0.77	2.07	**0.13**	**0.08**	2.82	1.22	0.21	0.24	**0.84**	15.49	**1.05**
OLS	0.87	5.70	0.14	2.10	**0.12**	**0.10**	1.36	3.01	0.14	0.15	**0.82**	14.52	**1.05**
RLA	0.23	1.32	0.33	2.32	**0.14**	**0.20**	0.24	0.14	1.12	0.34	**0.85**	7.22	**1.18**
RLB	0.21	2.01	0.65	3.00	**0.15**	**0.22**	0.27	0.18	0.33	1.37	**0.91**	9.30	**1.28**
RLN	**1.09**	**7.18**	**1.53**	**4.79**	1.86	**1.53**	**0.85**	**0.82**	**0.78**	**0.88**	9.42	30.72	**19.45**
Total	20.57	72.14	32.63	25.21	4.57	3.31	16.68	14.31	7.09	9.34	30.53	236.38	
Affected	**1.29**	**8.46**	**1.89**	**5.92**	**2.71**	**3.31**	**1.07**	**1.03**	**1.07**	**1.21**	**19.33**		**47.28**

Note: The cells in **bold** indicate that the segment of riders would be affected by the shutdown.

incur additional transfer and waiting times. On the other hand, the passengers beginning their trips at Kendall and going southbound can directly board more frequent shuttles at the beginning of their trips, and hence face a reduced waiting time at the origin. In a similar fashion, passenger volumes can be assigned and aggregated to estimate link flows, transfer movements, and passengers with reduced origin wait times northbound and at Charles/MGH and Park Street stations.

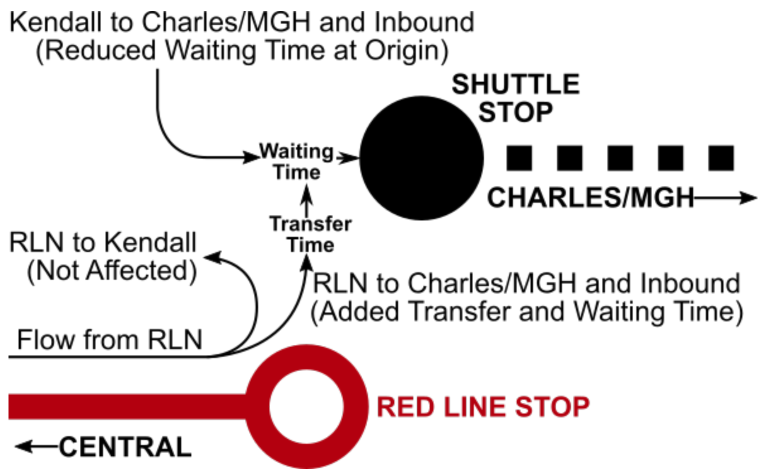


Figure 4-5: Example of Shutdown Impacts Faced by Various Passenger Movement Types: Kendall Station (Inbound)

Table 4.3 summarizes this break-down of the average daily volume of passengers affected by the shutdown by type of movement, as well as the number of passengers experiencing reduced waiting time because of the higher frequency of bus shuttles. These passenger volumes (estimated at the hourly level) were combined with estimates of changes in station-to-station travel time, along with appropriate transfer time and waiting time assumptions, as outlined in Table 4.4.

The average time required to transfer between the rail platform and the shuttle stop was assumed to be 1 min at Kendall and 1.5 min at Park Street. For the passengers who experienced reduced waiting time at origin, the waiting time for the shuttle buses was substantially lower than the expected waiting time on the Red Line during regular weekend (which is between 3.5 and 4 minutes). This reduction in waiting time, weighted by the number of passengers, offset some of the overall additional passenger hour waiting time impact arising from the other passenger movements.

Table 4.3: Average Weekend Daily Passenger Flows by Movement Type between Kendall and Park Street Stations (thousands)

Day	Direction	Link Flows		Added Transfers		Passengers with Reduced Wait
		Kendall–Charles/MGH	Chalres/MGH–Park Street	Kendall	Park Street	
Saturday	Inbound	30.14	29.94	28.82	10.97	3.35
	Outbound	28.83	28.63	27.51	10.42	20.48
	Total	58.97	58.57	56.34	21.30	23.83
Sunday	Inbound	21.95	21.74	20.24	8.10	4.17
	Outbound	21.75	21.52	20.03	8.30	14.97
	Total	43.70	43.26	40.27	16.40	19.14

The resulting passenger hour impact estimates (in units of thousands of passenger hours) are presented in Table 4.5. In terms of absolute passenger hours by type of delay, the additional travel time impact exceeds the additional transfer and waiting time impacts by a wide margin. The total in-vehicle travel time delay over the weekend is between 18,000 and 19,000 passenger hours, while the other two types of delays add up to approximately 5,600 passenger hours.

By assuming waiting and transfer time multipliers of 2, the overall delay estimate sums up to roughly 29,000–30,000 passenger hours over an average weekend. During a weekend shutdown, when a larger proportion of trips are not work-based (compared to weekdays), USDoT income-based value of passenger time of \$18.80/hr [19] probably should be scaled down. By using a reduced rate range of \$12–\$15, the monetary equivalent of an average shutdown weekend's passenger impact can be assigned a value of \$350,000–\$450,000.

4.3 Alternative for Mitigation: Bus Route 1

Building upon the analysis of impacts that passengers have to face during shutdowns, this section presents a demonstration of identification of an alternative (bus route # 1) to bus shuttles, estimation of the demand which could potentially benefit by using this alternative, and the operational requirements for the alternative to absorb a portion of the shift.

Table 4.4: Transfer Time and Waiting Time Assumptions used in Impact Assessment by Movement Type at Kendall and Park Street Stations (minutes)

Day	Direction	Station	Transfer Type	Transfer Time	Waiting Time
Saturday	Inbound	Kendall	Rail–Shuttle	1	1
		Park Street	Shuttle–Rail	1.5	3.5
	Outbound	Kendall	Shuttle–Rail	1	3.5
		Park Street	Rail–Shuttle	1.5	1
Sunday	Inbound	Kendall	Rail–Shuttle	1	1
		Park Street	Shuttle–Rail	1.5	3.75–4
	Outbound	Kendall	Shuttle–Rail	1	3.75–4
		Park Street	Rail–Shuttle	1.5	1

Note: The ranges in waiting time reflect variations in scheduled frequencies.

Table 4.5: Average Weekend Passenger Impacts of Longfellow Bridge Shutdown by Day, Direction, and Type (thousand passenger hours)

Day	Direction	In-vehicle Travel Time	Transfer Time	Waiting Time	Subtotal: Trans. and Wait	Total (weighted)
Saturday	Inbound	5.39	0.75	0.86	1.62	8.62
	Outbound	5.77	0.72	0.86	1.58	8.94
	Total	11.16	1.47	1.73	3.20	17.56
Sunday	Inbound	3.23	0.54	0.65	1.19	5.62
	Outbound	4.05	0.54	0.71	1.25	6.54
	Total	7.28	1.08	1.36	2.44	12.17
Weekend (Total)		18.44	2.55	3.09	5.64	29.72

4.3.1 Route 1 as an Alternative

As mentioned earlier, the Longfellow Bridge serves as a vital link between Cambridge and Downtown Boston, enabling connections between northern stations on the Red Line and stations on the Orange and Green lines. Within the MBTA system, bus routes 1, 47, CT2, and 66 also run in a circumferential fashion between Cambridge and Boston.

Of these, Route 1 (Fig. 4-6) is the most relevant as an alternative to the Red Line during shutdowns of the Longfellow Bridge. It is the easternmost route and runs the closest to Downtown Boston — between Harvard station and Dudley Square, along Massachusetts Avenue for most of its route — and connects Harvard and Central stations on the Red Line to Hynes Convention Center and Symphony stations on the Green Line and Massachusetts Avenue station on the Orange Line. Through these three stations, Route 1 allows passengers coming from/going to the western segments of the Green Line branches and southern segments of the Orange Line to easily transfer to a direct connection to Cambridge. On the Boston side, other stations like Kenmore, Copley, Northeastern University, Prudential, and Back Bay are accessible within a 10–12 minute walk to Route 1 stops along Massachusetts Avenue.

In addition to rail connections, Route 1 also serves major trip generators/attractors like Harvard University, MIT, Fenway Park, Northeastern University, and Boston Medical Center. Being a Key Bus Route within the MBTA system, it currently offers a relatively high frequency (10–12 minute headways) on the weekends.

4.3.2 Estimation of Demand Shift

The choice of alternatives for a particular shutdown is deeply interlinked with passenger segments which could potentially benefit by modifying/enhancing that alternative. This consideration goes both ways. The rationale behind the identification of Route 1 described above includes rail stations served as well as actual passenger origin/destination locations. In return, with the route being specifically identified as an alternative, it is possible to perform detailed analysis of the passenger segments which could benefit from it, and the extent to which these passengers benefit. This extent of benefit further affects the potential volume

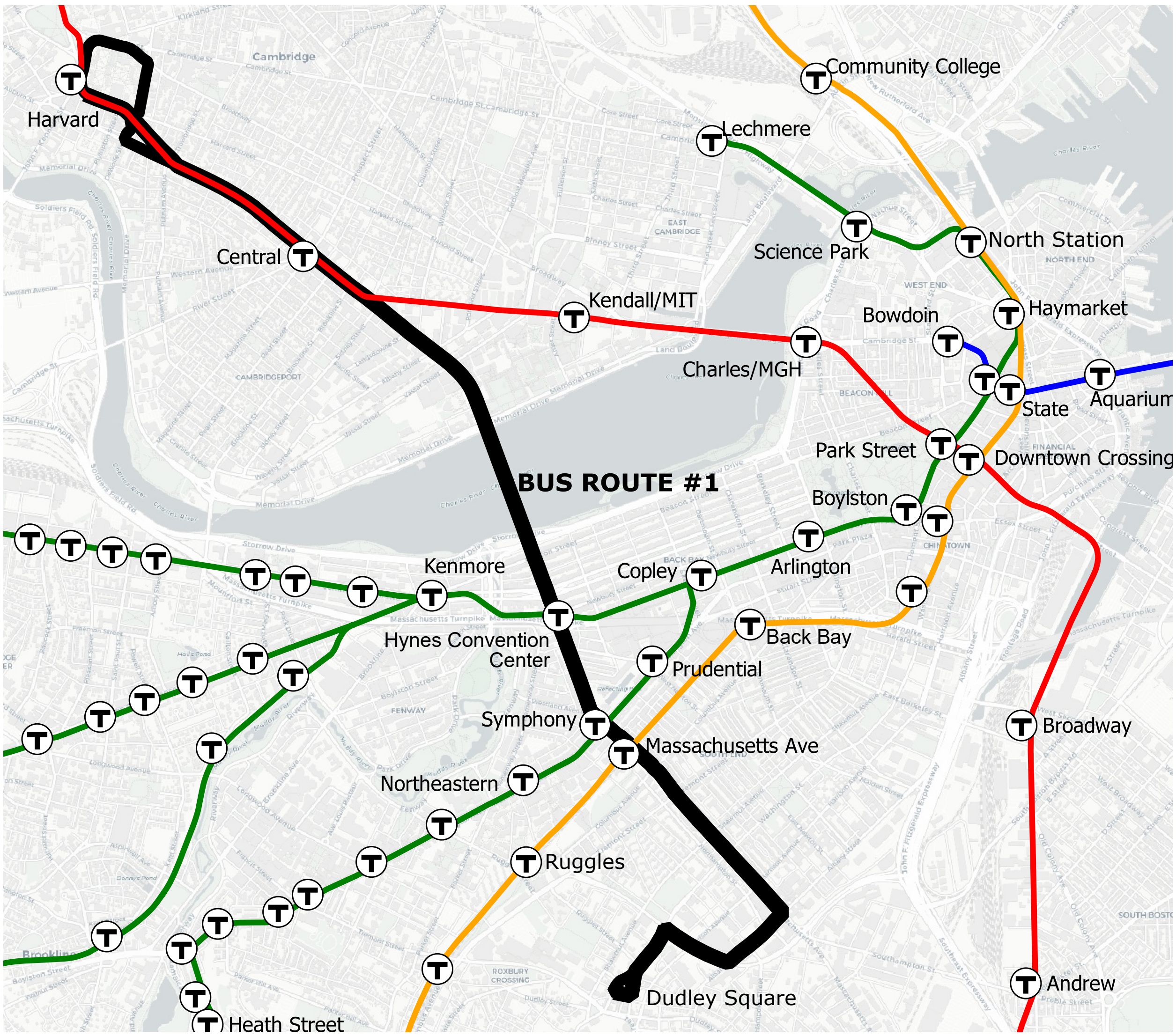


Figure 4-6: Map of Bus Route #1 with MBTA Rail Connections

of demand which could shift, and the resulting operational requirements.

Potential Passenger Segments Using Route 1

The characteristics of the passenger segments which could potentially benefit by shifting to Route 1 have been outlined in Table 4.6. The trip ends (i.e., origins and destinations) of the segments are distinguished based on whether they are served by Route 1, accessible by a short walk from Massachusetts Avenue, or require a transfer between rail and Route 1.

Passengers in each segment travel from one station in the Cambridge area to one station in the Boston area (or vice versa). The 3 zonal trips ends on the Cambridge side and the 11 on the Boston side give a total of 33 passenger segments which could potentially benefit. The trip ends on the Boston side have been broadly classified on the basis of which line/branch other than Red Line would be part of their trajectory. For instance, someone traveling between Harvard station and Northeastern University would take the E branch from Park Street after using the Red Line or the shuttle. On shutdown days, if they were to use Route 1, they would reach Northeastern by getting off at Symphony Station.

Tables 4.7 and 4.8 present estimates of average weekend trips between the trip ends described above going inbound and outbound, respectively. The passenger volumes on these segments (in both directions) add up to more than 14,000 trips on Saturdays, and more than 10,000 trips on Sundays — roughly 22% of the affected passengers.

Trips with one of their ends at Harvard or Central have the benefit of skipping the Red Line entirely and eliminating two transfers, and some of these trips can also get a one-seat ride from their origin/to their destination in Boston. These trips make up roughly 60% of the passenger segments being considered here, and 13% of the overall affected trips. Harvard is the single largest trip end (either on the Boston side or the Cambridge side), and the large volume of passengers traveling inbound from the Harvard terminal compared to outbound has the added benefit of increased likelihood of finding seats on the Route 1 buses.

Efficacy Assessment and Demand Shift

Passengers in each of the 33 passenger segments considered above could benefit by using Route 1 as an alternative to different degrees. In order to evaluate the extent of benefit, the

Table 4.6: Trip Ends of Passenger Segments Potentially Benefiting from Route 1 during Longfellow Bridge Shutdowns

Area	Broad Station Grouping	Trip Ends	Served by Route 1	Rail–Route 1 transfer	Walk from Mass. Ave.
Cambridge	Northern Red Line	Alewife, Davis, Porter		✓	
		Harvard	✓		
		Central	✓		
Boston	B, C, D Branches (via Hynes)	Hynes	✓		
		Copley			✓
		Fenway			✓
		Other B, C, D		✓	
	E Branch (via Symphony)	Symphony	✓		
		Prudential			✓
		Northeastern			✓
		Other E		✓	
	Southern Orange Line (via Mass. Ave.)	Massachusetts Avenue	✓		
		Back Bay			✓
		Other Southern Orange		✓	

difference in journey time these passengers would experience by using Route 1 was estimated. In order to compare the distribution of journey time via Route 1 and journey time via the shuttles, sets of potential feasible trajectories for the two path choices were constructed. This methodology is described below:

Assumptions The following assumptions about the trajectories were used for comparing journey time efficacy:

1. Copley, Kenmore, Prudential, Northeastern, and Back Bay stations are within 10-12 minute walks from Massachusetts Avenue. The passengers traveling to/from these stops were assumed to walk between the station and Massachusetts Avenue at the end/beginning of their journeys (instead of traveling one stop on rail to Mass. Ave. and adding a transfer to their trip).

Table 4.7: Average Weekend Daily Passenger Volumes on Segments which could Potentially Switch to Route 1 (Southbound from Cambridge towards Boston)

Destinations	**Origins**							
	Saturday				**Sunday**			
	Central	Harvard	Red North	Total	Central	Harvard	Red North	Total
Green BCD	357	844	819	2020	280	612	546	1438
Kenmore	135	301	306	742	111	225	226	562
Copley	210	546	592	1347	164	391	386	941
Hynes	135	301	306	742	111	225	226	562
Subtotal (1 to Hynes)	838	1991	2023	4852	667	1452	1385	3503
Green E	61	121	127	309	61	107	96	264
Northeastern	15	36	37	88	15	29	27	71
Prudential	45	149	134	328	33	103	92	229
Symphony	25	67	83	176	19	46	47	112
Subtotal (1 to Symphony)	146	374	381	901	128	284	263	675
Orange South	280	485	382	1147	230	342	284	856
Back Bay	65	160	157	382	47	100	99	246
Mass Ave	40	89	96	225	29	60	61	151
Subtotal (1 to Mass. Ave.)	385	734	635	1754	306	502	445	1253
Total	1369	3100	3039	7507	1101	2238	2093	5432

Table 4.8: Average Weekend Daily Passenger Volumes on Segments which could Potentially Switch to Route 1 (Northbound from Boston towards Cambridge)

Origins	**Destinations**							
	Saturday				**Sunday**			
	Central	Harvard	Red North	Total	Central	Harvard	Red North	Total
Green BCD	354	652	768	1774	281	484	523	1288
Kenmore	94	188	256	538	82	149	192	422
Copley	221	444	527	1191	170	320	355	846
Hynes	94	188	256	538	82	149	192	422
Subtotal Hynes to 1	763	1472	1807	4042	615	1102	1262	2978
Green E	78	130	137	345	73	112	103	288
Northeastern	16	36	36	88	17	27	26	70
Prudential	58	152	150	359	44	116	110	269
Symphony	24	60	84	167	19	44	47	109
Subtotal Symphony to 1	177	378	406	960	153	298	286	737
Orange South	307	438	372	1117	262	321	274	856
Back Bay	75	130	156	361	59	99	109	267
Mass. Ave.	34	46	63	144	25	34	42	101
Subtotal Mass. Ave. to 1	416	614	592	1622	346	454	425	1225
Total	1356	2464	2804	6624	1113	1855	1972	4940

2. On the Cambridge side, all passengers traveling to/from Harvard are assumed to completely skip the Red Line, and ride Route 1 all the way to/from Harvard.

3. The distribution of journey times via Route 1 is independent of the distribution of journey times via the shuttle buses.

Assumptions 1 and 2 reduce the complexity of the problem by reducing the set of feasible paths for comparisons for some passenger segments (for example, riding rail one stop and transferring to Route 1 vs. walking to Mass. Ave. to get to Route 1 both being possible alternative paths to the shuttle path). These are based on convenience to passengers in terms of seating availability and reduction in transfers, as discussed earlier.

Method From the AVL (bus) and TTR (rail) data sets available at the MBTA, the time point at each station/stop for a vehicle on a scheduled trip along a particular route can be extracted. This gives the time it takes for a vehicle to travel between two stations/stops. The travel time data for shuttle buses is not as easily available. By geo-fencing around shuttle stop locations, the arrival and departure time of a shuttle vehicle at a stop can be estimated. The location and the resulting vehicle trip travel time data give sets of vehicle trajectories along each route. Knowing the path taken for a particular choice (between Route 1 and shuttle) of travel between two stops, it is possible to construct a set of feasible trajectories.

For example, consider the calculation of journey time distributions for the passengers traveling between Porter and Northeastern, as shown in Figure 4-7. The path by shuttle has the segments: Porter–Kendall on Red Line, Kendall–Park Street on the the shuttle, and Park Street–Northeastern on the E branch. The corresponding path via Route 1 would be: Porter–Central on Red Line, Central–Symphony on Route 1, and a 6 minute walk to Northeastern. The segment of the path being substituted in this case is Central–Northeastern, and any benefit to the passengers is located in this substituted segment. Hence the difference in journey time in this section should be examined.

For each Red Line arrival at Central, the next Route 1 arrival inbound can be linked to it, with the time taken for the bus to reach Symphony being known. Adding 6 minutes to the arrival of that bus at Symphony gives an estimate of arrival time at Northeastern.

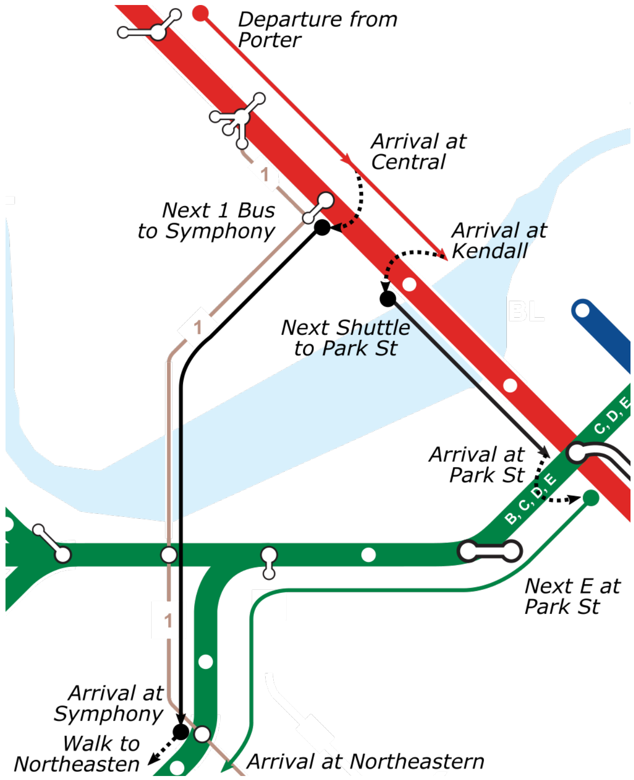


Figure 4-7: Example of Trip Linking to Estimate Journey Time for Efficacy Assessment

The time difference between the arrival at Central and arrival at Northeastern is the journey time estimate by Route 1. Similarly, for the same Red Line arrival at Central, its arrival at Kendall is also known. By linking the next shuttles departing within a particular threshold (in this case, 3 minutes) to this arrival, and then further linking the next E branch train going outbound, the journey time for this arrival via shuttle can also be estimated.

This results in samples of journey time by Route 1 and of journey time by shuttle. Similarly, for other segments, such journey time samples were generated based on their particular trajectories to estimate a distribution of journey time (Refer Appendix B). Mann-Whitney U Test was performed on the distributions in order to check whether either journey time is stochastically larger than the other (as described in Section 3.2.4). If the journey time by Route 1 is found to be significantly shorter than the shuttle, then the ridership of that segment in the particular hour is assigned to Route 1, based on an assignment 'factor', which is simply the proportion of times Route 1 was faster than taking the shuttle.

Results Figure 4-8 shows the results of comparing journey time distributions for passengers traveling inbound from Cambridge towards Boston. Each column of plots represents the origins of the segments, while each row represents the broad grouping of the stops on the Boston side based on which stop along Route 1 the passengers would get off. The lines in the plots are the proportion of times the journey time by Route 1 (for a particular destination) is found to be faster than the journey time by shuttle over the span of a day (and consequently, is the factor used for assigning passengers to Route 1). The closer this proportion is to 0.5, the less likely it is that Route 1 is effective as an alternative to shuttles for that passenger segment.

For most of the trips originating at Central and Harvard, Route 1 is the faster alternative to the shuttle. This is especially applicable to destinations on Massachusetts Avenue. A dip in the efficacy of Route 1 is generally observed during the middle of the day, which corresponds to increased on-street travel times due to congestion. Compared to Harvard, trips originating from Central are more likely to experience lower journey time via Route 1. This is because of the longer time that trips originating in Harvard have to spend between Harvard and Central on the Route 1 buses compared to Red Line. In case of Alewife, Davis, and Porter, the requirement of a transfer at Central adds to the overall time required to reach to the destination. This, added to the assumptions of walking to the destinations for some stops on the Boston end, leads to generally lower likelihoods of Route 1 being faster, compared to passengers originating from Central.

The segments traveling to the destinations reachable with a walk on the western side of Massachusetts Avenue fare better than the ones on the eastern side (for example, passengers traveling to Kenmore are more likely to benefit than those traveling to Copley). This is because for the eastern destinations, the time taken between Park Street and that station on the Green Line is lower compared to that for western destinations, making the shuttle more attractive in comparison. Segments with destinations directly on or very close to Massachusetts Avenue fare better than the ones where a walk or transfer after alighting from Route 1 is required.

For northbound journeys from Boston towards Cambridge, Route 1 generally tends to be much more effective than for southbound journeys (Fig. 4-9). This can be attributed to the longer time taken by the shuttle buses while going outbound, leading to a higher number of samples where Route 1 is indeed faster. This high degree of efficacy underscores the large potential benefit to passengers by shifting to Route 1, and the need of planning service on it in order to accommodate large potential shifts.

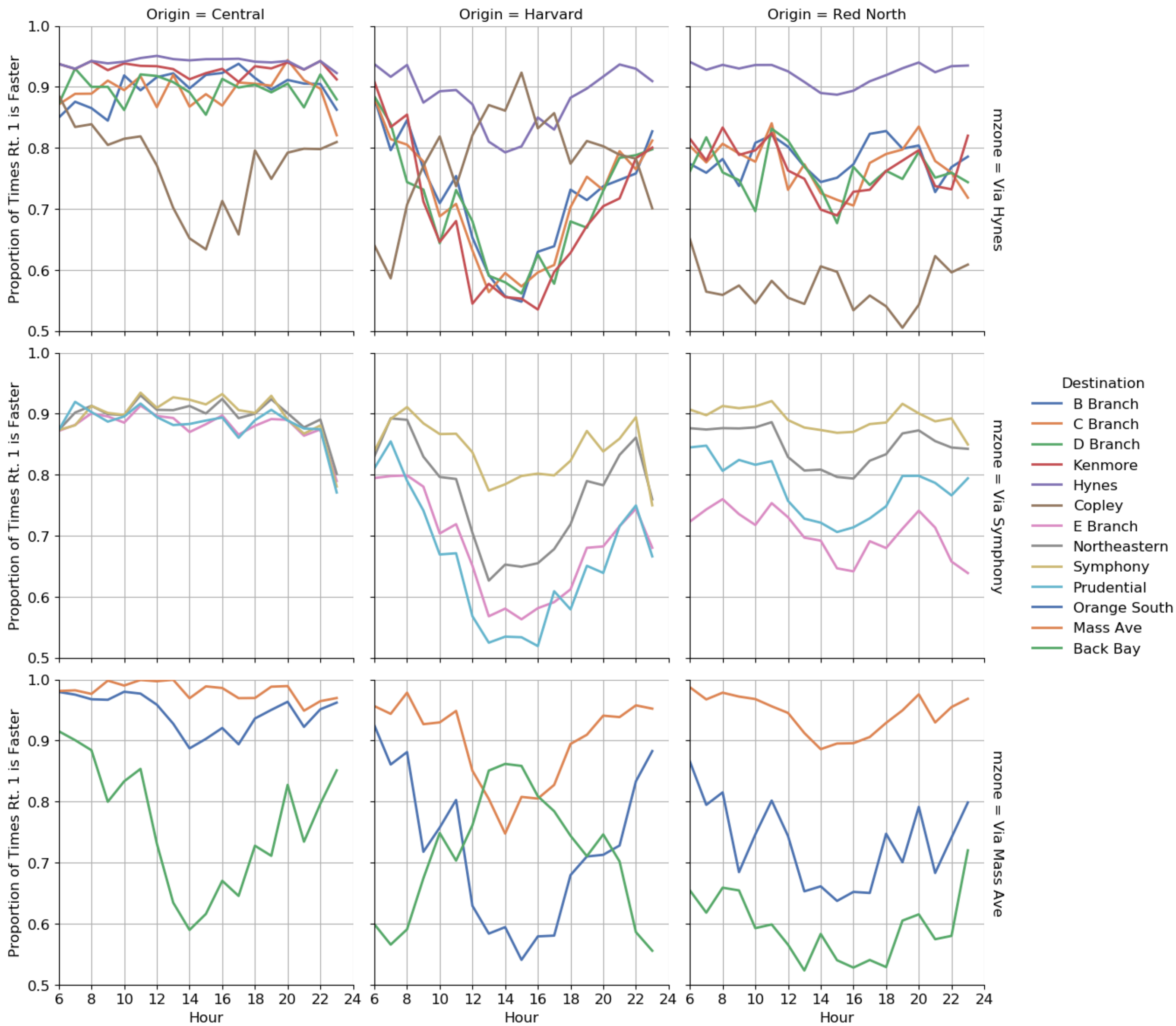


Figure 4-8: Proportion of Times Route 1 is Faster than Shuttles for Each Origin-Destination Pair (Southbound from Cambridge towards Boston)

4.3.3 Analysis of Operational Requirements

Based on the assessment of efficacy of Route 1 as described in the section above, potential passenger volumes which could shift to the bus route are assigned. In addition to the proportional journey time assignment factors, a factor of 75% was also multiplied to account for passengers not being aware of Route 1 as an alternative, sticking to the default shuttle paths, or choosing not to take trips on the MBTA system during shutdowns. As discussed above, Route 1 is especially effective for outbound passengers, and hence these larger volumes would determine the capacity and fleet size requirements.

Capacity Requirements

The northbound demand shift on to Route 1 is generally found to be larger than southbound, and is considered as the critical demand for planning purposes. These northbound segments would be loaded cumulatively at or beyond Hynes Station (since they are presumed to first get off at Central). This means that the projected passenger loads at Hynes needs to be examined for the capacity requirement analysis.

From APC passenger load data, the average hourly loads on the buses at Hynes can be estimated. Existing excess capacity on the weekend on buses which aren't full can absorb a portion of the shift. In addition to this, during the daytime, additional buses would be required to provide capacity for absorbing the remainder of the shift. Figure 4-10 provides estimates of excess available capacity (blue bars) and additional capacity required (orange bars) on weekends based on the volumes of passenger segments over the span of the day. This can be translated to an overall frequency/headway requirement (black line) during implementation. On Saturdays, the peak frequency required corresponds to approximately 6 minute headways, while on Sunday, 7–8 minute headways in implementation would sufficiently absorb the potentially shifting demand.

Run Times and Cycle Times

Route 1 runs along Massachusetts Avenue, which is an arterial road handling large volumes of traffic. This causes variability in the time required for the bus vehicles to run from one

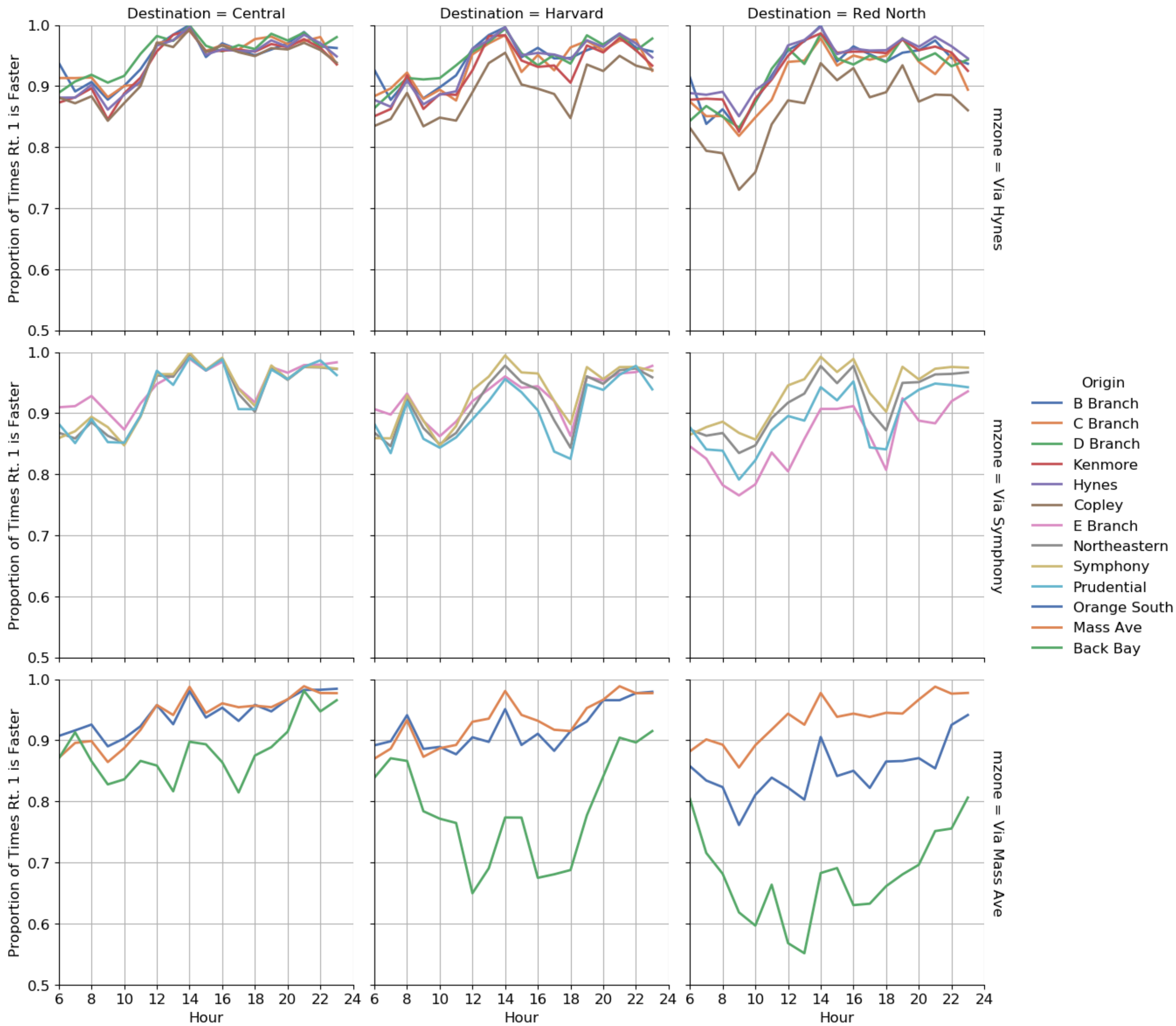
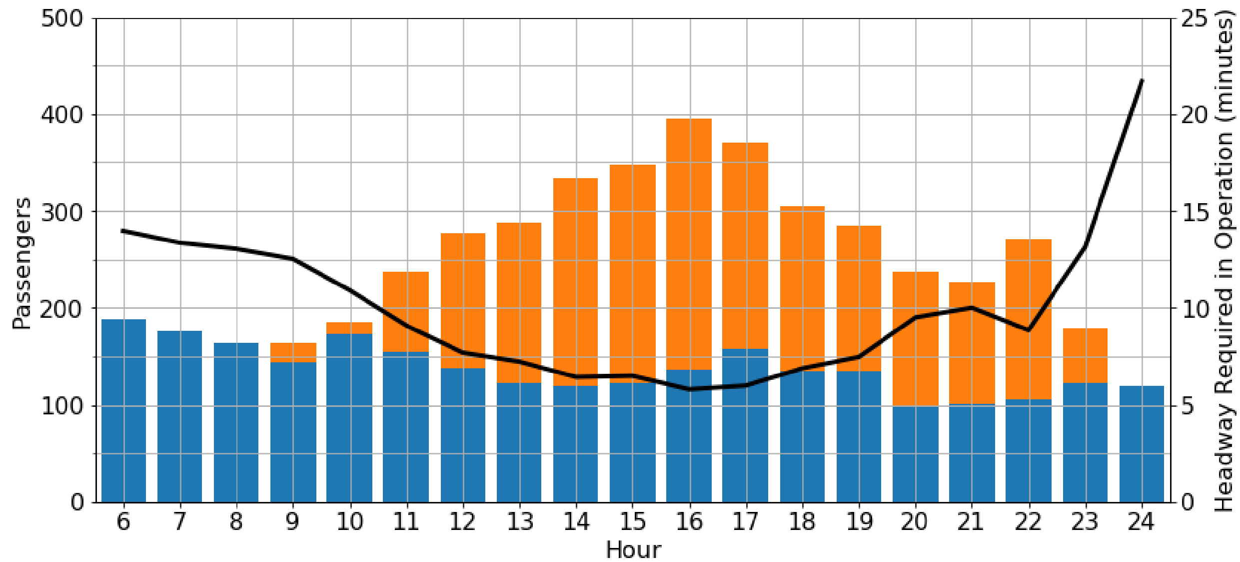
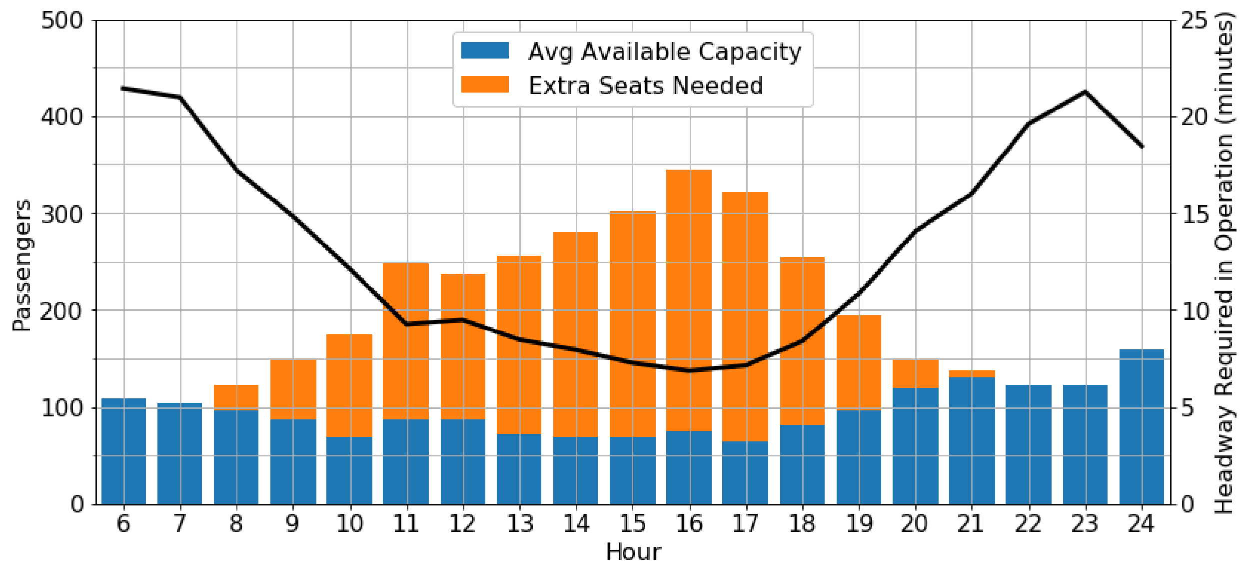


Figure 4-9: Proportion of Times Route 1 is Faster than Shuttles for Each Origin-Destination Pair (Northbound from Boston towards Cambridge)



(a) Saturdays



(b) Sundays

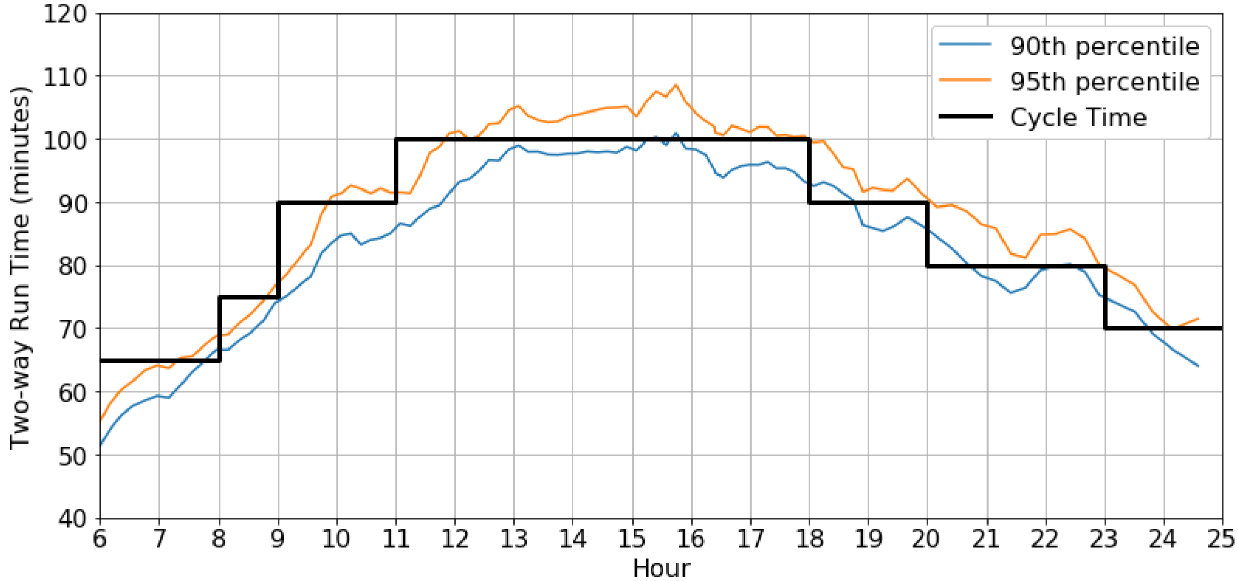
Figure 4-10: Excess Hourly Seating Capacity Available at Hynes, Additional Seats Required to Absorb 75% Shift, and Overall Headway Required in Implementation end of the route to the other. Standard service planning practice takes this into account by providing buffer layover times at the terminals, i.e., time between a bus's scheduled arrival and next departure. The combined scheduled cycle time is set to an upper threshold of the two-way run time during that particular time period. Figure 4-11 shows the observed 90^{th} and 95^{th} percentile run times for Route 1, and the corresponding cycle time (set based on these upper thresholds) used for the fleet size requirement calculation, which follows.

Headway Variability and Fleet Size

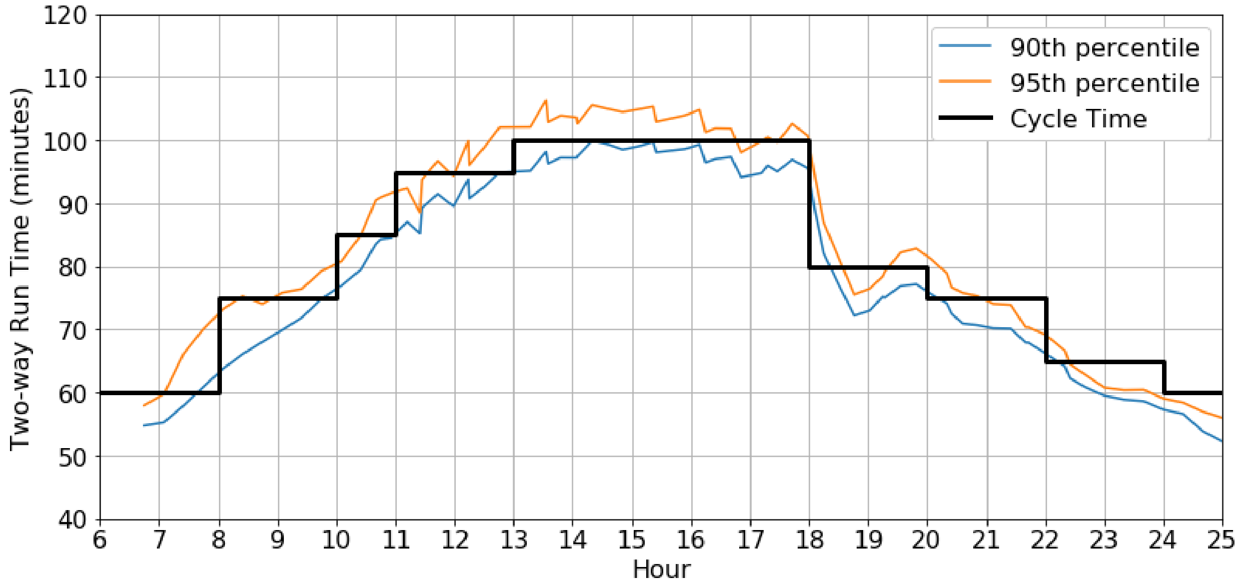
In addition to variable run times which affect the delays and travel times that passengers experience, on-street conditions as well as crowding cause variations in headways as experienced by passengers. This causes the effective capacity in implementation to be lower than planned capacity. Hence, in order to take this drop in effective capacity into account, the schedule has to be set with additional buffer capacity, leading to an increased fleet size requirement to provide improved frequency, reducing the waiting time experienced by passengers.

As outlined in Section 3.2.5, the additional fleet size requirement can be estimated by scaling up with a factor of CV^2, where CV is the coefficient of variation of headways at the critical stop. Figure 4-12 shows values of the square of observed coefficient of variation of headways on Route 1 at Hynes going northbound. Note that because the mean headways on Sundays are higher and traffic is generally lighter, the corresponding CV^2 values are generally lower compared to Saturdays. During the daytime on Saturdays, an additional 30–40% more vehicles are required when compared to the fleet size that would be required if there were no variation of headways. Similarly, on Sundays, a vehicle fleet larger by roughly 15–20% compared to 'ideal' headway conditions would be required.

With the cycle time (c), headways required (H), and the variation in headways (CV) being estimated, the fleet size requirement after taking into account run time variability and headway variability can be calculated as $\left\lceil \frac{c}{H_R}\left(1+CV^2\right)\right\rceil$. The results of these calculations are shown in Fig. 4-13. Currently, in the afternoon peak period, 10–11 vehicles are operational on Saturdays, and 6–7 vehicles on Sundays. Accommodating 75% of the potential shift requires reducing scheduled afternoon/evening peak headways to 4 minutes on Saturdays and 5.5 minutes on Sundays, which would, in implementation, translate to the



(a) Saturdays



(b) Sundays

Figure 4-11: 90$^{\text{th}}$ and 95$^{\text{th}}$ Percentile Two-way Run Times for Route 1 on Weekends with Estimated Cycle Times required 6 minute 'effective' headways on Saturdays and 7 minute headways on Sundays due to variability, thus ensuring provision of the required effective capacity. In consonance with the recommendations by Van der Hurk et al. [17], these buses could be sourced from the large fleet of buses used to operate the shuttle service, and would cause marginal negative impacts for the remaining shuttle passengers.

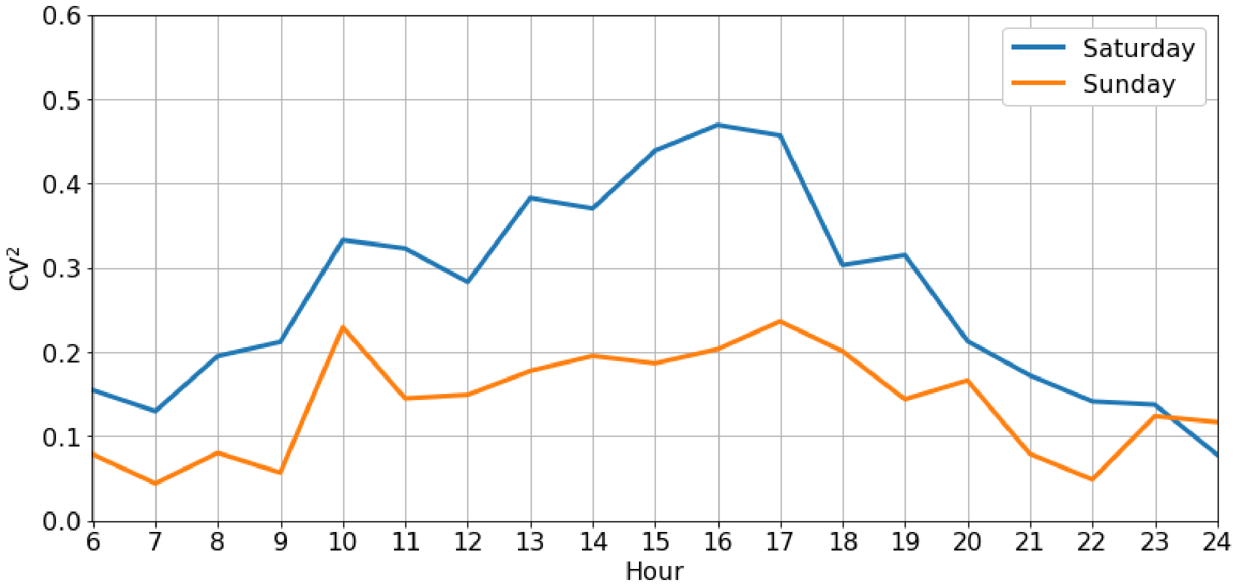
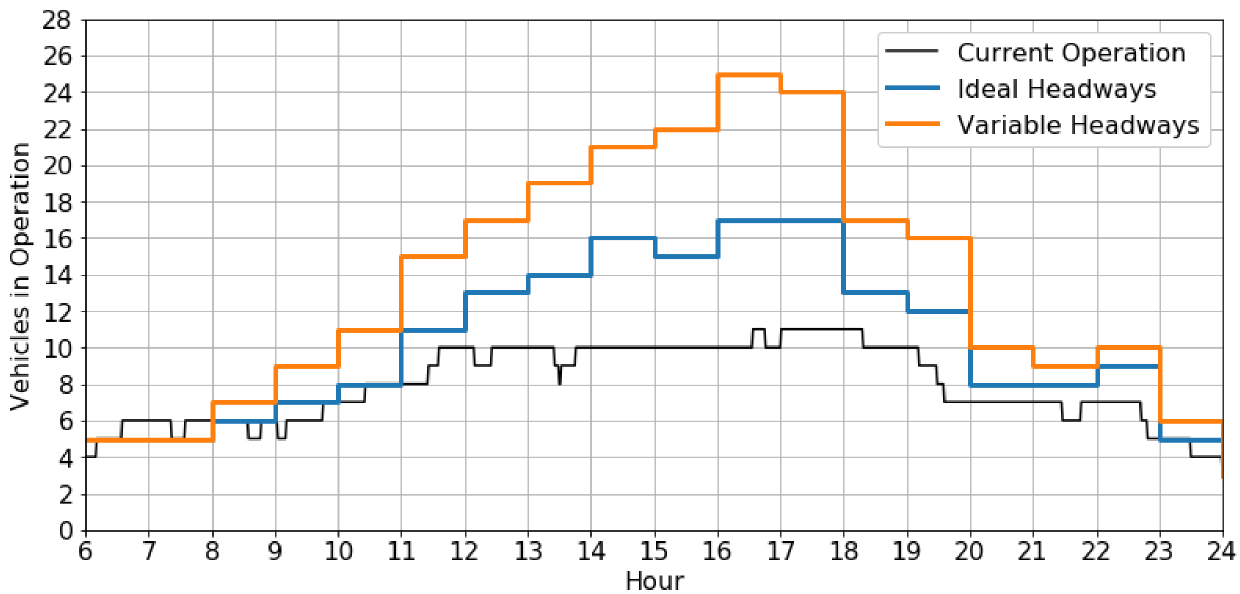


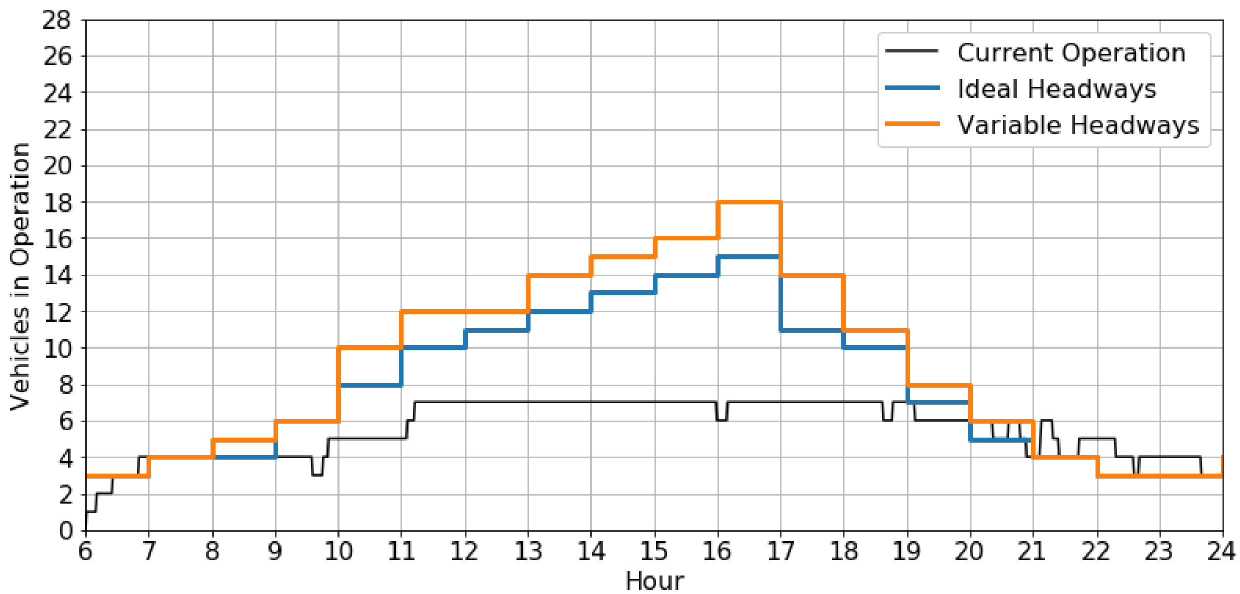
Figure 4-12: CV^2 of Route 1 Headway Observed at Hynes Outbound

4.3.4 Passenger Benefits

The efficacy assessment of Route 1 involved constructing samples of potential trajectories for various passenger segments. Although the comparison of efficacy was performed on the basis of overall journey time, it also makes it possible to estimate the benefits to passengers in terms of in-vehicle travel time. The time taken to transfer from bus to rail and to walk between Route 1 and the stops close to Massachusetts Avenue (if applicable), is assumed to be fixed. The waiting time for Route 1 is based on the effective headway calculated while estimating operational requirements. The segments which have reduced number of transfers via Route 1 consequently also have a reduction in waiting time at those transfer stations. These waiting times have been assumed to be half the scheduled rail headway. The segment-wise passenger assignment to Route 1 can be used to infer potential volumes of passengers



(a) Saturdays



(b) Sundays

Figure 4-13: Current Fleet Size in Operation and Estimated Overall Hourly Vehicle Requirement to Accommodate 75% of Potential Shift experiencing these changes in various components of travel time.

Passengers currently riding Route 1 on regular weekends would benefit indirectly by enhancing service on this bus route, resulting in reduced waiting times. The volume of these passengers can be estimated from ODX/AFC data. Similarly, by assuming a slight reduction in frequency on the shuttle service caused by diverting buses to Route 1, the waiting time impact of that for passengers who are not assigned to shift to Route 1 was estimated. In the shuttle service case, it was assumed that the average waiting time increases by 30 seconds.

The estimates of overall passenger hour benefits of Route 1 as an alternative in comparison to the shuttle service are shown in Table 4.9. Positive numbers indicate a net benefit, while negative values in the cells indicate added inconvenience. The benefits/impacts have also been broken down based on whether the passengers would use Route 1 inbound or outbound, already use Route 1, or would stay on the shuttles.

The benefit to passengers who shift while traveling northbound on Route 1 compared to southbound is substantially higher. The longer outbound shuttle travel time causes this substantial difference in two ways: a larger difference in the in-vehicle travel times for the segments, and an increased likelihood of passengers on each segment finding Route 1 to be faster, the latter of which influences volume assignment.

Several segments have been assumed to walk between Route 1 and their origins/destinations close to Massachusetts Avenue. This leads to a high negative passenger hour impact in terms of additional walking required. The ratio of added inconvenience due to walking compared to benefit due to reduction in in-vehicle travel time is roughly 20%.

However, this additional inconvenience due to walking is offset to a considerable extent by reductions in transfers and waiting time. The overall added inconvenience is approximately 21% of that caused by walking on Saturdays, and approximately 38% on Sundays. For the passengers who could shift to Route 1, the changes in waiting time are meager despite the fewer number of transfers. This is because compared to buses, rail tends to be more frequent, especially for stations like Kenmore, Hynes, and Copley, which are served by three or more different lines and serve as major origins/destinations on the Boston side. The benefit of reduction in transfers is reflected in the larger value of transfer time benefit.

Using the waiting/walking weighting multipliers of 2, the overall potential benefit is estimated at approximately 1,750 passenger hours on Saturdays and 1,100 on Sundays. This corresponds to 9–10% of the overall passenger delay impacts of the Longellow Bridge shutdowns being mitigated by enhancing Route 1.

Table 4.9: Benefits of Route 1 as a Mitigation Alternative Compared to Existing Shuttle Service (assuming 75% of potential trips shifting) (passenger hours)

(a) Saturdays

	Inbound Segments	**Outbound Segments**	**Current Route 1 Passengers**	**Red Line Shuttle Users**	**Total**
In-vehicle Travel Time	500	1414	-	-	1915
Transfer Time	88	132	-	-	220
Waiting Time	20	39	466	-435	90
Walk Access/Egress	-104	-286	-	-	-389
Subtotal: Transfer, Wait, and Walk	5	-115	466	-435	-80
Total (weighted)	510	1184	931	-870	**1755**

(b) Sundays

	Inbound Segments	**Outbound Segments**	**Current Route 1 Passengers**	**Red Line Shuttle Users**	**Total**
In-vehicle Travel Time	360	982	-	-	1343
Transfer Time	70	104	-	-	175
Waiting Time	-15	-12	366	-321	18
Walk Access/Egress	-94	-218	-	-	-312
Subtotal: Transfer, Wait, and Walk	-38	-126	366	-321	-119
Total (weighted)	284	730	733	-643	**1105**

4.4 Discussion

Because the Longfellow Bridge is a vital link in the MBTA rail system, a shutdown on the bridge causes widespread passenger impacts, in addition to revenue loss and increased operating costs of shuttles to the MBTA. The operating costs of buses shifted on to Route 1 would not differ significantly from the costs involved while operating those same buses as shuttles. There is, however, an overhead associated with modifying the crew and vehicle schedules of Route 1. If 75% of the passengers who could benefit from shifting to Route 1 do end up shifting, the impacts of the shutdown could be reduced by 9%. Given the overall scale of the impact, this a significant degree of potential mitigation.

4.4.1 Observed Ridership Changes

Red Line

The ODX algorithm does not infer the destinations of any trips which pass through a rail segment being shut down. Fare gates at Kendall and Park Street are also open on shutdown days, which means that there is no reliable source of passenger volumes at these stations. The effect on ridership can be gauged to a certain extent by examining passenger tap-ins at other stations.

Figure 4-14 shows the differences in tap-ins at all the stations along the Red Line except Kendall, Charles/MGH, and Park Street (that is, all the stations where AFC data was reliably available). The day has been divided into four time periods, and the box plots show the distribution of combined tap-ins at all the stations during regular and shutdown Saturdays. On average, the number of passenger tap-ins fell by roughly 10% on shutdown weekends compared to regular weekends. This drop was especially prevalent in the stations north of Kendall, and those along the trunk portion of the Red Line between Downtown Crossing and JFK/UMass, ranging between 12–17% over the span of the day. This reduction points to a fall in overall ridership during shutdowns, as passengers seek other routings or modes to make their trips. The reduction in Red Line ridership was accompanied by an increase in passengers routing themselves on to Route 1, as described below.

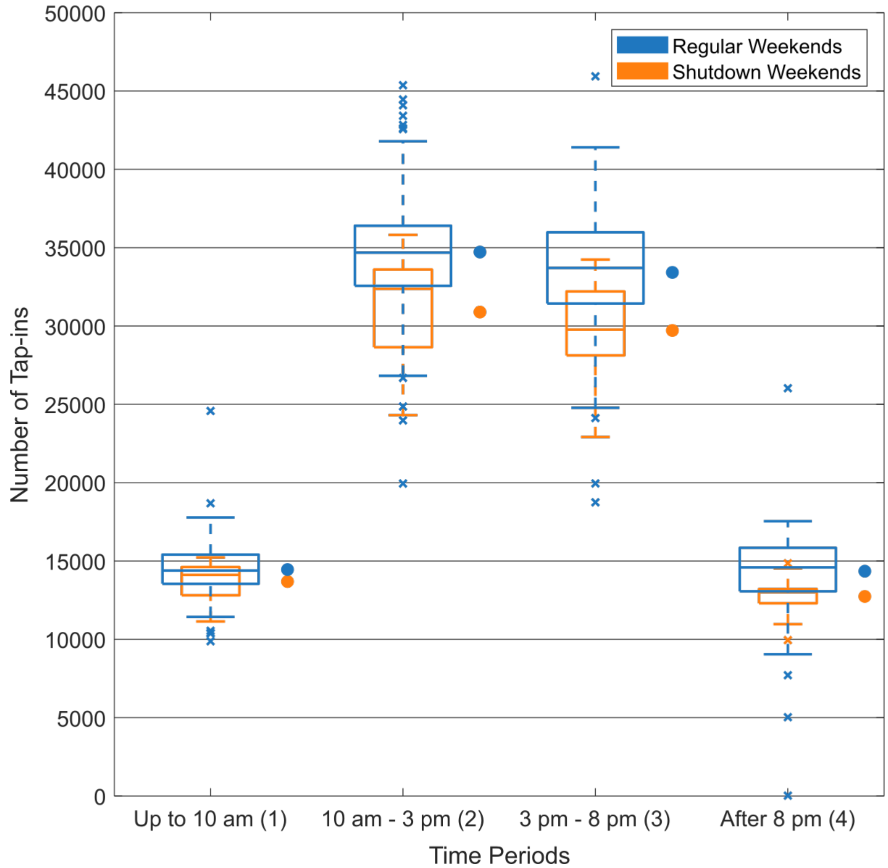
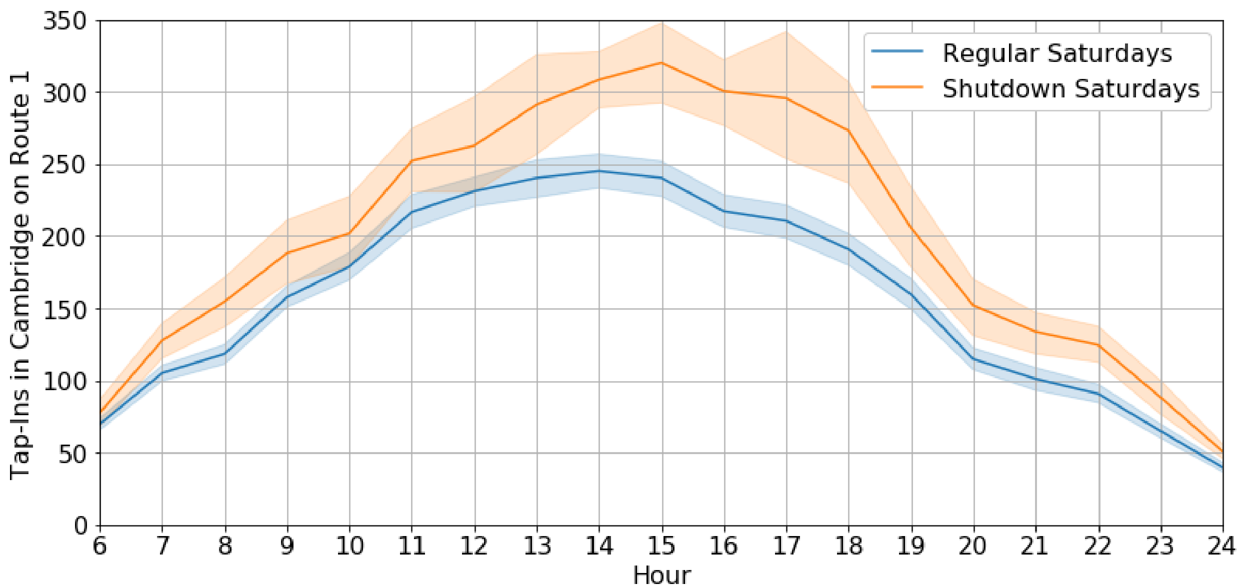


Figure 4-14: Distribution of Daily Tap-ins at Red Line Stations (Regular vs Shutdown Saturdays)

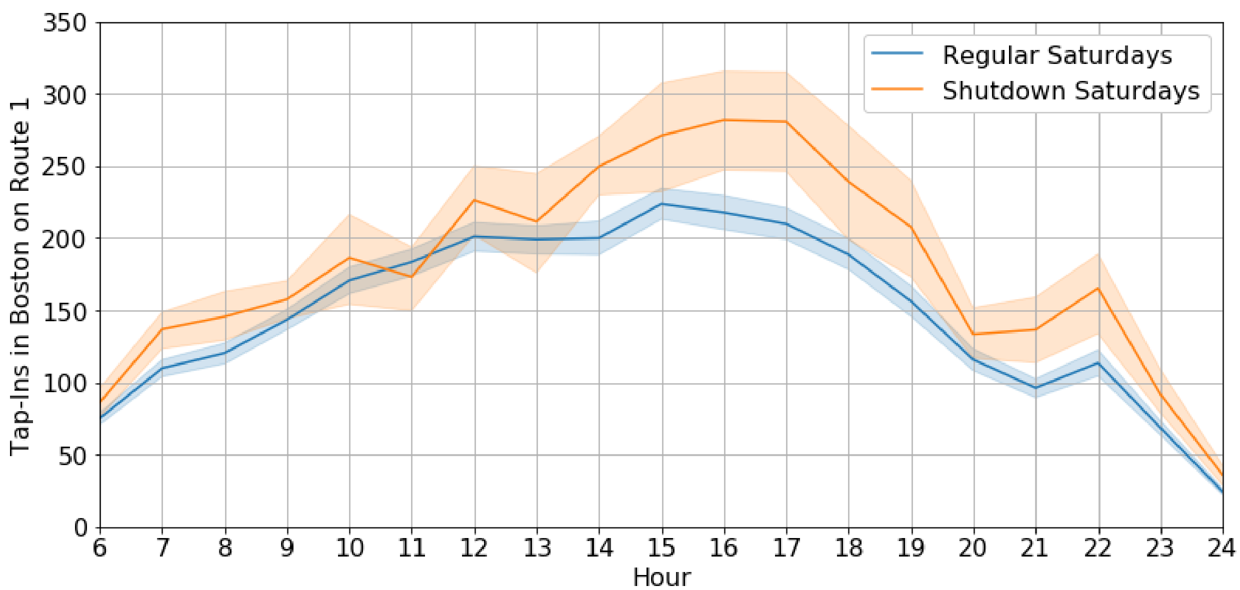
Route 1

From the AFC tap-ins on buses, it is possible to examine the change in ridership during shutdowns. Assuming that this change in ridership is due to passengers shifting to Route 1 without any change in weekend service, the change can be related to the potential demand which could be served by Route 1. Figure 4-15 shows the inbound tap-ins in Cambridge and outbound tap-ins in Boston during regular and shutdown Saturdays. There is a noticeable increase in the average number of tap-ins during shutdowns.

Between 50 and 70 additional passengers per hour tap in in either direction. This translates to 15–17% of the weighted ridership on the various segments which could switch to Route 1. Even with no service enhancements in place, the increase is fairly notable. This proportion can be improved by making passengers aware of alternatives which could be beneficial to them, and providing sufficient capacity to absorb this shift.



(a) Inbound in Cambridge



(b) Outbound in Boston

Figure 4-15: Observed Changes in Tap-ins on Route 1 During Shutdowns

4.4.2 Considerations for Implementation

Future Shutdowns

Repair work along the Red Line segment between Charles/MGH and Park street station is being planned for the near future. The same Kendall–Park Street segment would have to be shut down or handle single track operations in such a case, because of the location of switches along the line. While the exact work plan is still being planned, the MBTA can use ODX to assess passenger impacts of various work plan scenarios (like single tracking or complete segment shutdown) over different times of days, days of week, and seasons and incorporate these impacts while deciding on a plan. Along with the impacts on passengers, the effectiveness of Route 1 as an alternative to bus shuttles or single track work would differ considerably for weekday or early access work, and these need further examination.

Information Dissemination

For many passengers in the network, the choice of an alternative being present may not be obvious, which makes it necessary to nudge some passengers towards utilizing alternatives being enhanced. The segmentation of passenger and efficacy assessment by segment leads to opportunities for targeting these segments with appropriate information dissemination.

For example, posters like the ones in Figure 4-16 can be placed at station and within the trains running along the respective branches. Additionally, arrival information for Route 1 can be placed at the platform level at stations along Massachusetts Avenue. Train announcements for passengers while approaching these stations could also remind them of the possibility of using Route 1.

MBTA's existing opt-in alert system is called T-Alerts, where passengers can choose to receive text alerts about service changes and status for lines/routes of their choosing. This can be especially helpful for targeted information provision. Finally, since a vast number of people use trip planning software/applications like Google Maps and Transit, the MBTA could collaborate with these companies to suggest alternative routes to passengers.

Route 1 Service Improvements

The distribution and variability of headways and run times over the span of the day along Route 1 are critical factors determining the resources required to operate the route to provide sufficient capacity. With passengers potentially choosing Route 1 as an alternative to the shuttle buses, the capacity required, and consequently, the MBTA resources required to operate it would increase. By improving reliability along the route, it is possible to use fewer resources in order to provide the same level of service. The MBTA could hence work with

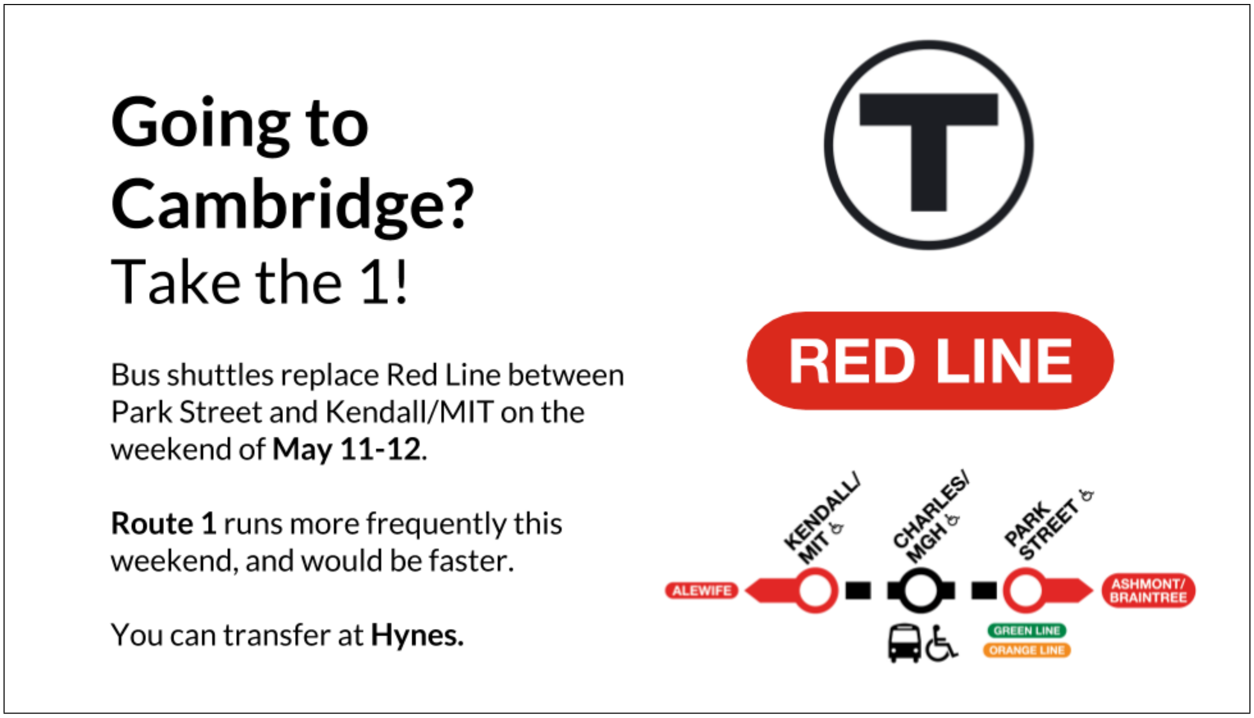


Figure 4-16: Example of Poster for Information Dissemination Along B/C/D Branches

the cities of Boston and Cambridge to implement reliability improvements like dedicated lanes and transit priority along Massachusetts Avenue. These improvements would also help increase reliability and reduce resource requirements during regular weekends.

Shuttle Service Improvements

This chapter examined the potential of Route 1 as an alternative to the bus shuttles. Some insights gained here point to the inefficiencies within the shuttle operations, namely, the longer route the shuttles take outbound, and congestion the buses face in Downtown Boston. The delays caused by these can be somewhat alleviated, making the shuttle more efficient, and as an added benefit, reducing the amount of resources required to enhance Route 1, and the overall resources needed to mitigate the shutdown.

Routing of Shuttle In case of the Longfellow Bridge shutdowns, the extra time it takes for the shuttle to go outbound from Park Street to Charles/MGH due to its circuitous path leads to very high travel times in that direction. An alternative to routing the shuttle around the Boston Common is to turn the buses on to West Street and then on to Washington Street before heading back to Cambridge Street through Court Street (Fig. 4-17). This is a much shorter route in comparison, and additionally would serve Downtown Crossing, State, and Government Center Stations. It also takes advantage of the Washington Street pedestrian zone, which reduces likelihood of the shuttles being delayed by congestion. Alternatively, routing the shuttle through Essex Street, and then via Chauncy, Arch, Milk, and Washington Streets can also reduce the length of the shuttle path (albeit to a smaller extent) while serving Boylston, Chinatown, State, and Government Center stations.

Other Improvements The shuttle path between Charles/MGH and Park Street runs along Cambridge and Tremont Streets, which are major streets in Downtown Boston. The congestion along these streets means that the large number of shuttle buses operating on them face very long travel times. During a Longfellow Bridge shutdown, providing temporary bus lanes on these streets would make a faster path for shuttle buses. This would reduce the requirement of vehicles and costs of operating the shuttle service.

The work for the upcoming shutdowns is specifically located between Charles/MGH and Park Street stations. Hence, before starting shutdowns, the MBTA could add switches North of Charles/MGH station, so that shuttles would not need to travel from Boston into Cambridge. The reduction in travel time would mean that fewer buses would be required to operate this shuttle service during shutdowns.

Adding stops along the shuttle route at other Downtown stations could serve many more passengers while causing slight inconvenience due to added travel time to the others. Since the shuttle buses currently run by Bowdoin station, adding Bowdoin as a stop would add to the convenience of passengers transferring between the Red and Blue Lines.

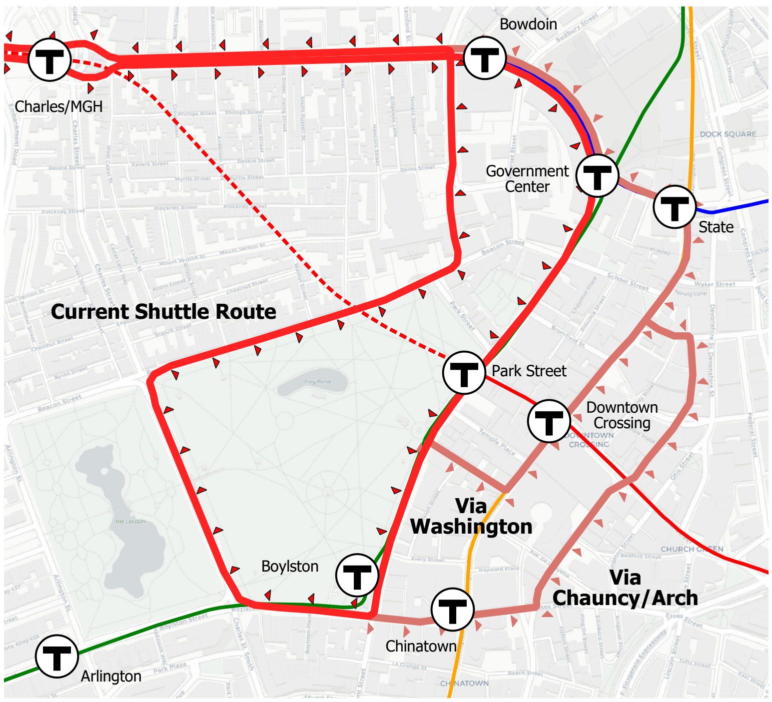


Figure 4-17: Alternative Routings of Longfellow Shuttles Outbound

Chapter 5

Case Study: Southern Orange Line

5.1 Background

The Southwest Corridor which carries the Orange Line and Providence/Stoughton, Needham, and Franklin commuter rail lines between Tufts Medical Center and Forest Hills was constructed over an eight-year period between 1979 and 1987, with some construction towards the northern end of the section beginning earlier in 1968. This replaced the Washington Street Elevated which, prior to this, ran between Chinatown (then Essex) station and Forest Hills [29].

Forty years after construction, over the Summer and Fall of 2018, sections of the Orange Line between Forest Hills and Ruggles were shut down over several weekends for track and minor structural repairs. Similar to the Longfellow Bridge repair project, station-to-station shuttle buses replaced Orange Line service in this section. This chapter focuses on two possible service modifications which could alleviate part of the inconvenience caused by the shutdowns by utilizing the redundancies in capacity and infrastructure available on this corridor:

- Continuation of buses terminating at Forest Hills as shuttles till Ruggles

- Commuter rail shuttles between Forest Hills and Ruggles, Back Bay, and South Station

5.1.1 Bus Shuttle Service

The station-to-station replacement shuttles travelled along a route which ran parallel to the Orange Line tracks, usually on its Eastern side (Fig. 5-1). At Stony Brook and Jackson Square stations, the route crossed over the rail tracks and back on Boylston and Centre streets, respectively, which provide access to the headhouses at those stations. On Saturdays, up to 50 buses were in operation to implement this shuttle service.

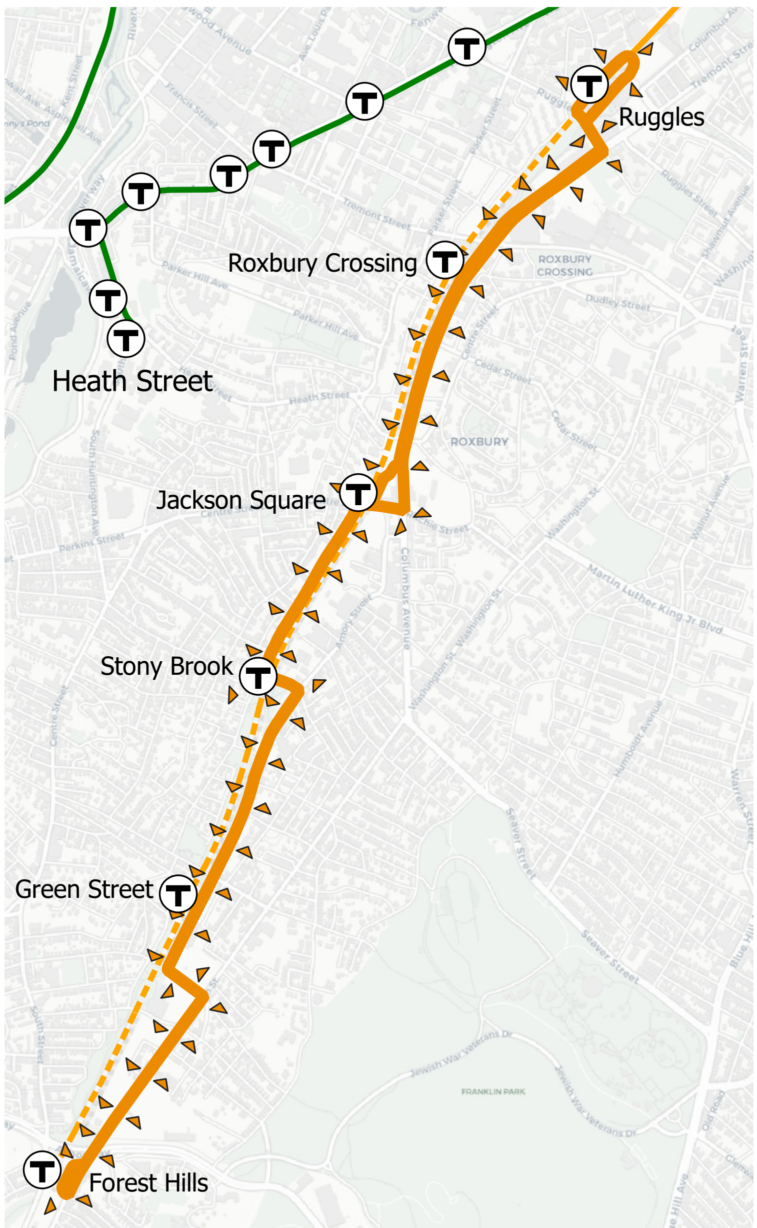
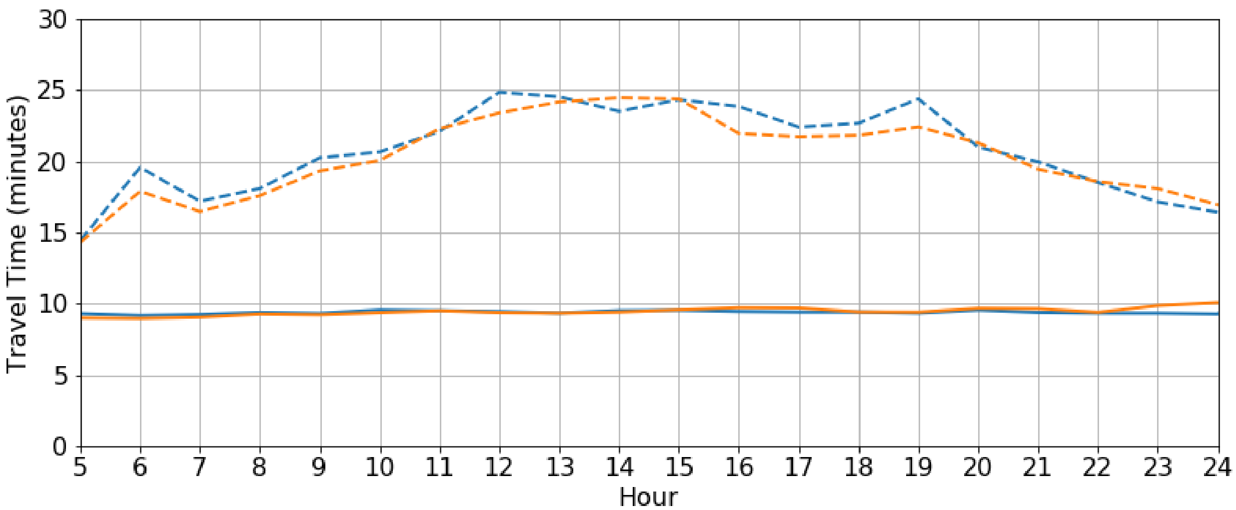
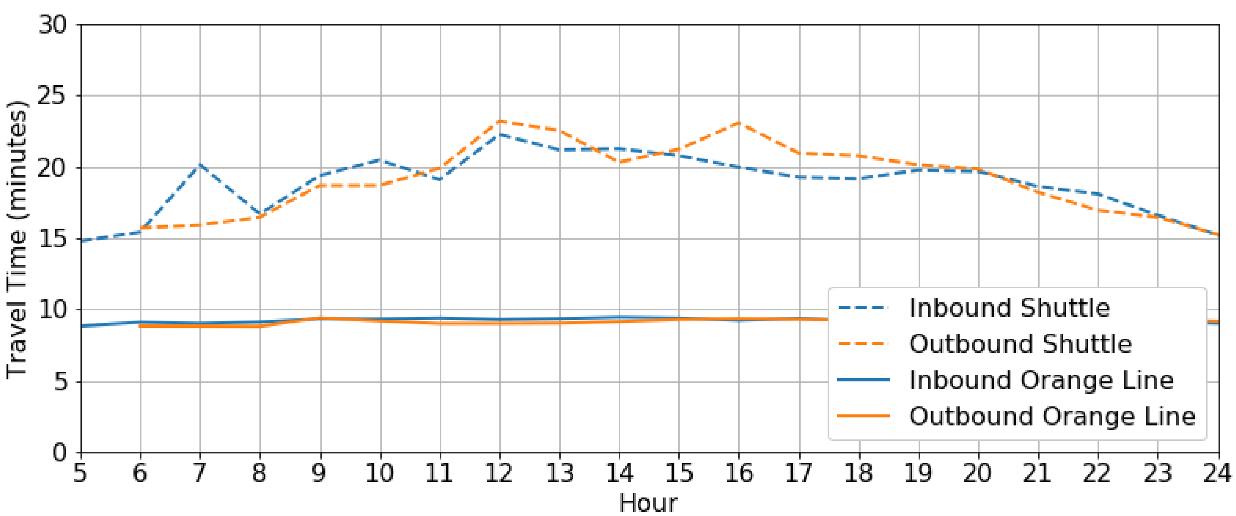


Figure 5-1: Route of Orange Line Replacement Shuttles Between Ruggles and Forest Hills

The regular travel time between Forest Hills and Ruggles by Orange Line on weekends is between 9 and 10 minutes. On the other hand, the 5th percentile travel time for the shuttle varied between 11 and 19 minutes over the day in either direction, while the average travel time was 15–25 minutes between Forest Hills and Ruggles (Fig. 5-2). The travel times for the shuttle going inbound vs. outbound are not significantly different.



(a) Saturdays



(b) Sundays

Figure 5-2: Average Travel Times between Forest Hills and Ruggles by Hour on Replacement Bus Shuttles and Regular Orange Line Service

5.2 Analysis of Passenger Impacts

5.2.1 Zonal Grouping of Stations

In order to examine the distribution of impacts of shutting down the section between Forest Hills and Ruggles across different parts of the MBTA rail network, it was divided into several 'zones' as depicted in Figure 5-3. All the stations from Forest Hills to Roxbury Crossing have no rail service during shutdown and are grouped into the zone labelled OLS, while stations from Ruggles to Chinatown are in the OLM zone. Stations along the Red Line have been grouped into three zones: RLN between Alewife and Charles/MGH, RLD for Park Street, Downtown Crossing, and South Station, and RLS for the remaining stations on the southern side. The Blue Line has been grouped into one zone: BLN. The Green Line branches and trunk till Boylston are denoted as GLW, while Lechmere and Science Park have been grouped into the zone GLN. The northern section of Orange Line between Community College and Oak Grove are in the OLN zone, while Haymarket and North Station are grouped as OLD.

5.2.2 Zone-wise Impacts

Tables 5.1 and 5.2 show the number of trips traveling between each of the segments mentioned above. The affected trips make up approximately 10% of all weekend trips in the network. Out of all the affected trips, 10–11% of trips are made within the OLS section, i.e. between two stops which have no rail service during a shutdown. Approximately 29% of the affected trips are made between OLM and OLS zones.

The Forest Hills–Ruggles shutdowns are located within a peripheral section of the rail network in the MBTA, and hence the effects of these shutdowns are felt only for trips which originate in/end in that section. In order to access every other zone (except OLM), passengers traveling to/from the southern stops must do so via Downtown. These trips which need to pass through Downtown together make up a majority of the affected trips: 60–61%. As a consequence, the connectivity between the southern stops and Downtown is a crucial consideration passenger mitigation during the shutdowns.

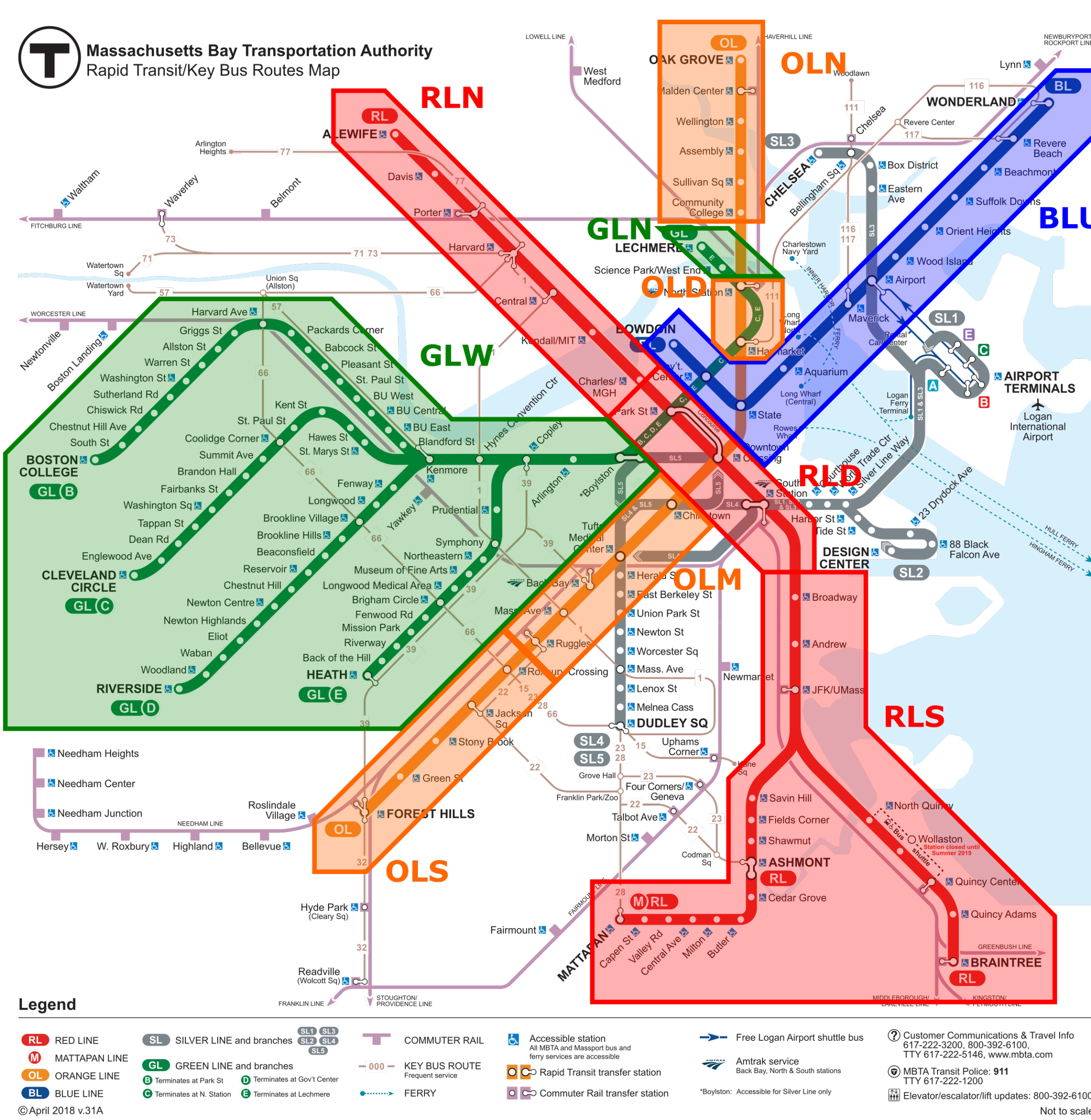


Figure 5-3: Zonal Grouping of Stops for Impact Assessment overlaid on the MBTA System Map

Table 5.1: Average Daily Zonal Origin-Destination Flows (thousands) (Saturdays, June-September 2017)

Origins	**Destinations**											
	OLS	OLM	OLD	OLN	RLD	RLN	RLS	BLU	GLN	GLW	Total	Affected
OLS	**3.36**	**5.30**	**1.63**	**1.76**	**2.83**	**1.32**	**0.67**	**2.33**	**0.07**	**0.17**	19.44	**19.44**
OLM	**4.47**	1.76	1.53	3.84	1.15	0.95	0.99	2.18	0.03	0.24	17.14	**4.47**
OLD	**1.53**	1.23	0.27	3.66	1.12	1.99	1.41	1.01	0.69	4.13	17.04	**1.53**
OLN	**1.53**	4.54	3.41	3.49	2.71	1.49	1.09	2.66	0.07	1.68	22.66	**1.53**
RLD	**2.35**	0.96	1.05	2.41	1.21	10.59	9.72	1.53	0.41	5.11	35.34	**2.35**
RLN	**1.18**	0.65	2.07	1.38	11.98	22.17	5.16	2.50	0.18	6.12	53.40	**1.18**
RLS	**0.65**	0.73	1.41	1.07	10.12	5.24	9.12	1.36	0.21	4.06	33.97	**0.65**
BLU	**1.91**	1.83	0.57	2.46	1.01	2.69	1.48	17.68	0.73	7.52	37.87	**1.91**
GLN	**0.21**	0.03	0.67	0.32	0.58	0.28	0.34	0.94	0.34	1.54	5.25	**0.21**
GLW	**0.35**	0.01	4.03	2.12	5.59	5.76	4.11	8.28	1.39	37.50	69.14	**0.35**
Total	17.53	17.03	16.64	22.51	38.30	52.48	34.09	40.46	4.13	68.07	311.23	
Affected	**17.53**	**5.30**	**1.63**	**1.76**	**2.83**	**1.32**	**0.67**	**2.33**	**0.07**	**0.17**		**33.61**

Note: The cells in bold indicate that the segment of riders would be affected by the shutdown.

5.2.3 Travel Time Impacts

The origin-destination flows of the passengers affected by the shutdown have been translated to the various types of passenger movements in Table 5.3. Consistent with a peripheral section in a Downtown-centered network, the flow builds up going From Forest Hills towards Ruggles. The passenger flows in each of these links face a significantly higher travel time in the shuttle compared to the time it takes to traverse that section on the Orange Line.

During shutdowns, most of these passengers would face an additional transfer between the Orange Line and the replacement shuttles at Ruggles. Because shuttles generally run at a higher frequency than rail, passengers who begin their journeys at stations served by shuttles would also experience a reduction in waiting time. The number of passengers who face reduced origin waiting time in the outbound direction is much lower than inbound; this is because most affected outbound passengers would not experience the shutdown at the origin of their trips. Table 5.4 summarizes the impact due to the shutdown over a weekend in

Table 5.2: Average Daily Zonal Origin-Destination Flows (thousands) (Sundays, June-September 2017)

Origins	**Destinations**											
	OLS	OLM	OLD	OLN	RLD	RLN	RLS	BLU	GLN	GLW	Total	Affected
OLS	**2.80**	**3.91**	**0.94**	**1.35**	**1.95**	**1.11**	**0.51**	**1.81**	**0.04**	**0.12**	14.53	**14.53**
OLM	**3.43**	1.47	0.86	3.15	0.83	0.71	0.77	1.73	0.02	0.20	13.15	**3.43**
OLD	**0.97**	1.01	0.18	2.29	0.80	1.31	0.77	0.67	0.42	2.86	11.26	**0.97**
OLN	**1.18**	3.48	1.88	2.62	1.93	1.16	0.80	1.97	0.04	1.30	16.37	**1.18**
RLD	**1.75**	0.90	0.71	1.90	1.07	8.65	8.04	1.27	0.28	4.48	29.04	**1.75**
RLN	**0.99**	0.67	1.16	1.13	9.14	17.76	4.25	1.90	0.10	4.96	42.05	**0.99**
RLS	**0.51**	0.70	0.71	0.81	7.65	4.31	6.99	1.00	0.12	3.29	26.08	**0.51**
BLU	**1.58**	1.82	0.33	2.04	0.68	2.03	1.10	14.54	0.49	5.81	30.41	**1.58**
GLN	**0.14**	0.02	0.39	0.23	0.39	0.21	0.25	0.74	0.29	1.24	3.89	**0.14**
GLW	**0.26**	0.01	2.64	1.77	4.55	4.75	3.47	6.58	1.06	34.26	59.35	**0.26**
Total	13.61	13.98	9.80	17.27	28.98	41.98	26.95	32.20	2.85	58.52	246.13	
Affected	**13.61**	**3.91**	**0.94**	**1.35**	**1.95**	**1.11**	**0.51**	**1.81**	**0.04**	**0.12**		**25.35**

Note: The cells in bold indicate that the segment of riders would be affected by the shutdown.

the form of overall increased passenger hours in the various types passenger movements. The overall travel time impact on passengers of the shutdown over a weekend is approximately 9,500 passenger hours. Most of the impact is due to added travel time within the shuttle compared to Orange Line, while the added time associated with transfers and the consequent waiting are smaller in comparison.

The transfer time impact calculation assumed the time required for the transfer to be approximately 30 seconds. The average waiting time for Orange Line was assumed to be half the headway for the particular day and time period in the weekend. The overall additional transfer and waiting delay is approximately 1,100 passenger-hours. By using the weighting multipliers of 2 for these delays, the overall passenger impact is estimated to be approximately 11,500–12,000 passenger-hours. By using a reduced rate range of \$12–\$15 similar to the Longfellow Bridge case study, the monetary equivalent of an average weekend shutdown's passenger impact can be assigned a value of between \$138,000 and \$180,000.

Table 5.3: Average Weekend Daily Passenger Flows by Movement Type Between Forest Hills and Ruggles Stations (thousands)

Day	Direction	Link Flows					Rail-to-shuttle Transfers at Ruggles	Passengers with Reduced Waiting Time
		Forest Hills–Green Street	GS–SB	SB–JS	JS–RC	Roxbury Crossing–Ruggles		
Saturday	Inbound	7.16	8.81	10.71	13.17	14.44	13.60	15.60
	Outbound	6.11	7.89	9.91	12.13	13.32	12.52	1.99
	Total	13.27	16.71	20.62	25.30	27.76	26.12	17.59
Sunday	Inbound	5.29	6.39	7.60	9.43	10.33	9.64	11.27
	Outbound	4.77	5.99	7.32	8.98	9.89	9.22	1.66
	Total	10.06	12.39	14.92	18.41	20.22	18.85	12.94

Abbreviations: GS = Green Street, SB = Stony Brook, JS = Jackson Square, RC = Roxbury Crossing

Table 5.4: Average Weekend Passenger Impacts of Orange Line Shutdown by Day, Direction, and Type (thousand passenger hours)

Day	Direction	Travel Time	Transfer Time	Waiting Time
Saturday	Inbound	2.76	0.11	0.33
	Outbound	2.82	0.10	0.09
	Total	5.57	0.22	0.42
Sunday	Inbound	1.97	0.08	0.24
	Outbound	1.98	0.08	0.07
	Total	3.95	0.16	0.32

5.3 Alternative for Mitigation: Commuter Rail Shuttles

On its southern side, between Forest Hills and Back Bay, the Orange Line shares right-of-way with three more tracks. These tracks carry Amtrak trains and the Franklin, Needham, and Providence line commuter rail trains. Forest Hills, Ruggles, and Back Bay stations are served by both Orange Line and commuter rail. These direct connections on a shared right-of-way mean that it is possible to run shuttles along the commuter rail tracks between Forest Hills, Ruggles, Back Bay, and South Station, providing faster rail-based connectivity (compared to bus shuttles) to numerous passengers, substantially reducing their journey time.

In a 2018 article in Commonwealth Magazine, Finlan, Fairchild, and Aloisi [30] recommended these shuttles as an alternative. They highlighted several benefits to passengers traveling to/from Forest Hills, including faster service, reduced transfers, and better access to Downtown. Based on preliminary calculations, they estimated four trains sets required to run a shuttle service with 12-minute headways – equivalent to the current weekend Orange Line headways. This section presents a detailed analysis of the commuter rail alternative primarily with respect to estimation of potential demand shift and the resulting benefit in terms of mitigation of the effects of the shutdown between Forest Hills and Ruggles on passengers.

5.3.1 Estimation of Demand Shift

The direct and non-stop connection between Forest Hills and Ruggles on commuter rail means that passengers traveling the entire section as part of their journeys (i.e. having Forest Hills as one end of their journey and Ruggles and stops beyond it as the other end) are most likely to find this alternative useful. Passengers traveling to/from Green Street, Stony Brook, Jackson Square, and Roxbury Crossing would not be able to use this alternative, and would still need to use the shuttles.

Potential Passenger Segments for Shift

Table 5.5 summarizes the various passenger segments traveling to/from Forest Hills. Based on which commuter rail station these segments would travel to/from to utilize the alternative, the segments have been grouped into three broad groups. For example, someone traveling from Harvard to Forest Hills could take the Red Line to South Station and board a commuter rail shuttle.

Some of these passenger segments can get a one-seat ride between Forest Hills and their other trip end, and would not have to endure an additional shutdown-induced transfer. In Downtown Boston, the commuter rail connects to South Station instead of Downtown Crossing. Because of this, passengers traveling between Forest Hills and the portion of Red Line north of South Station would face a slight addition in travel time because of the added South Station–Downtown Crossing link in their path. On the other hand, someone traveling between Forest Hills and South Station/southern portion of Red Line would experience a reduced travel time by eliminating that link in their path.

Table 5.5: Trip Ends of Passengers Traveling to/from Forest Hills Potentially Benefiting from Commuter Rail Shuttles

Commuter Rail Station Used	**Trip End**	**Reduced Transfer**	**SS–DC Travel Time**
Ruggles	Ruggles		
	Massachusetts Avenue		
Back Bay	Back Bay	✓	
	Other Orange/Green/Blue		
South Station	South Station	✓	-
	Red South	✓	-
	Park Street/DC	✓	+
	Red North	✓	+

Abbreviations: SS = South Station, DC = Downtown Crossing

Potential Shift to Commuter Rail

Figures 5-4 and 5-5 show the average hourly ridership on the passenger segments described above in the inbound and outbound directions on Saturdays and Sundays, respectively.

During the day time (9 am – 6 pm on Saturdays and 10 am – 7 pm on Sundays), there is a consistent directional ridership of more than 450 passengers per hour on Saturdays, and more than 350 on Sundays.

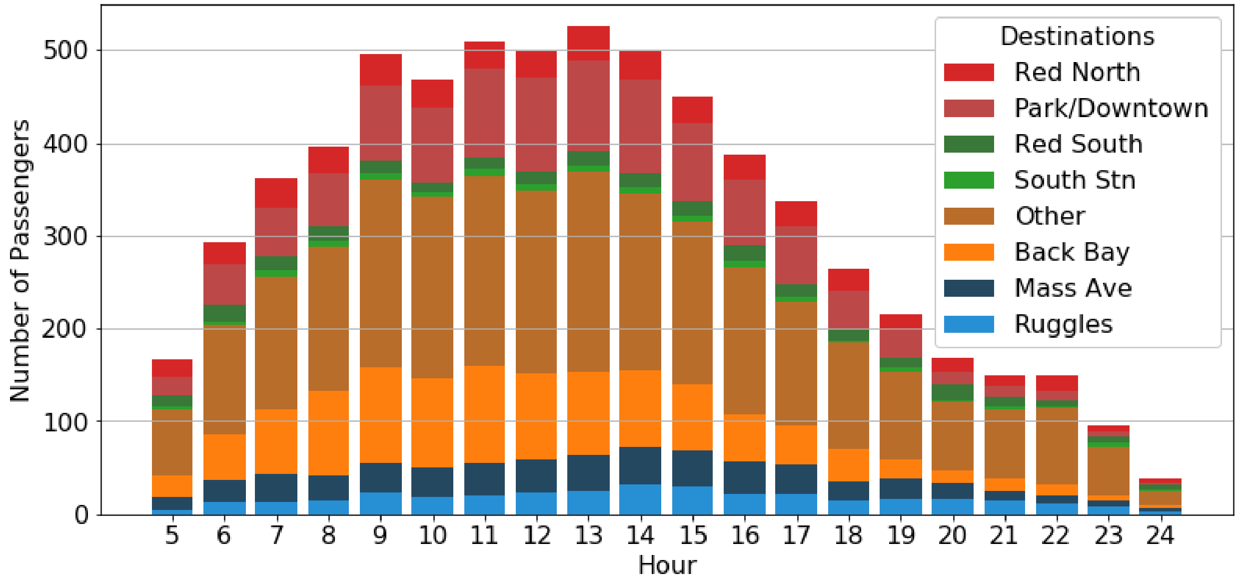
For all of these passengers, the commuter rail alternative would lead to substantial reductions in travel time within the Forest Hills to Ruggles segment. Compared to the average of 15–25 minutes it takes via bus shuttles (11–19 minutes at the minimum), the commuter rail trains can cover this section in 5 minutes. Passengers traveling between Forest Hills and Back Bay/South Station as part of their trajectory can accrue additional travel time savings.

In contrast, there would be marginal increases in waiting time (compared to bus shuttles) for commuter rail shuttles, and in travel time for the Red Line passengers traveling to/from stations in the section north of South Station. However, the degree of these increases is minor compared to the in-vehicle travel time savings the passengers could experience. Hence, in terms of passenger assignment, it can be assumed that the commuter rail alternative would be faster for all of these passengers.

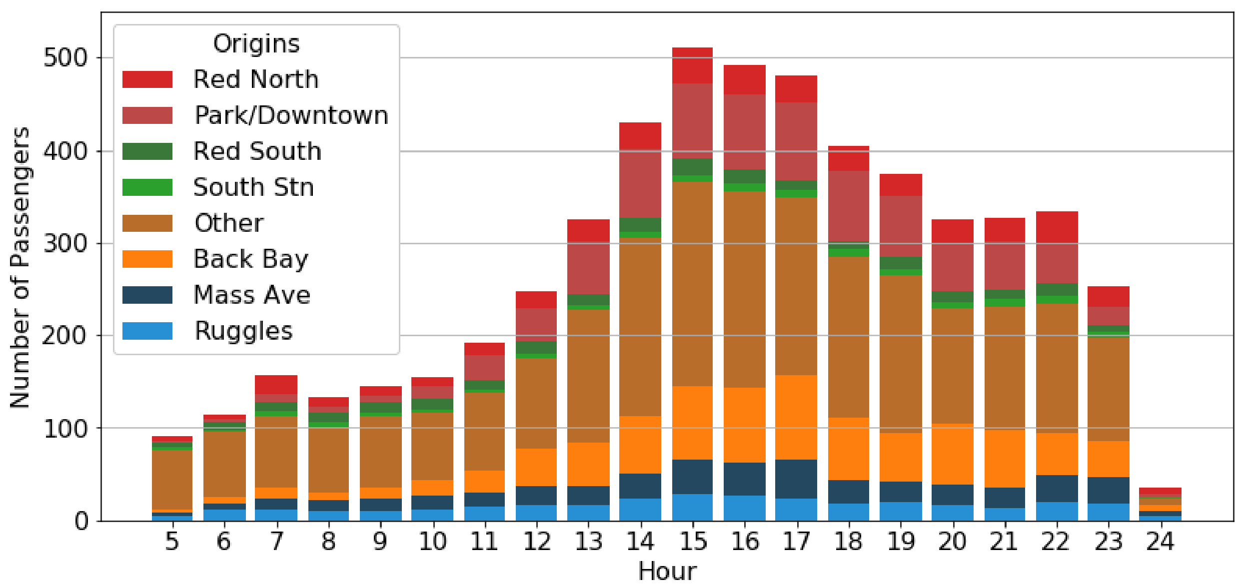
Ridership on Bus Shuttles

Although a commuter rail shuttle alternative would benefit the passengers traveling between Forest Hills and stations beyond Ruggles, the passengers traveling within the Forest Hills–Ruggles segment would still need to use the bus shuttles. Additionally, there would be some passengers who could benefit from the commuter rail shuttles but still ending up using bus shuttles. The frequency required in this case would be dependent on capacity, and not on policy headways. To account for this, 25% of passengers traveling between Forest Hills and Ruggles and beyond were assumed to stay on the bus shuttles.

The resulting maximum passenger flows on the bus shuttle by day of week and direction are presented in Fig. 5-6. Compared to the volumes of passengers who could switch to the commuter rail shuttles, the volume of passengers on the bus shuttles is larger. Of the approximately 34,000 daily affected trips on Saturdays, for example, 13,000 are made between Forest Hills and stations beyond Roxbury Crossing and could use the commuter rail shuttles. The rest of the passengers would still require shuttle buses.

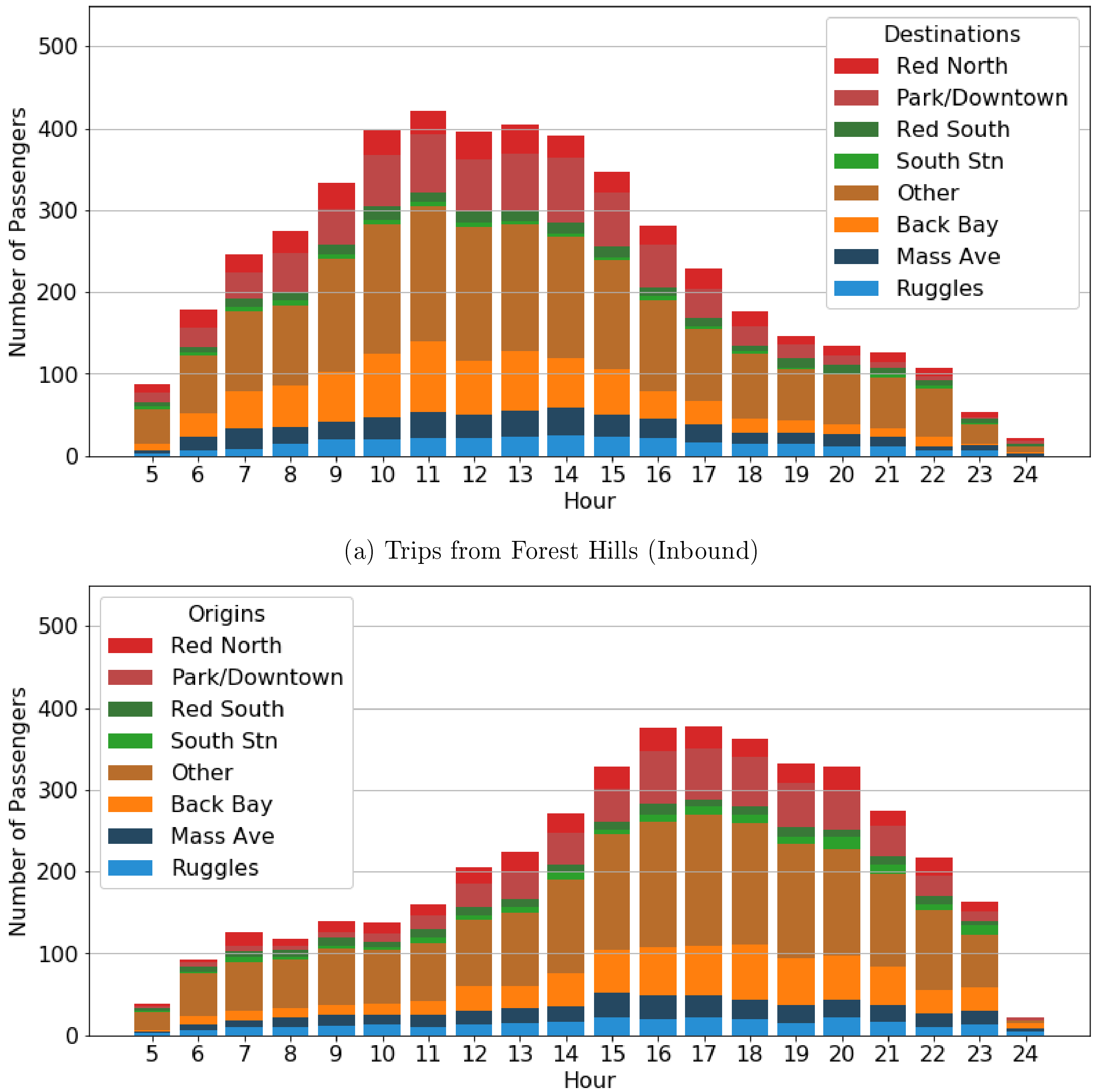


(a) Trips from Forest Hills (Inbound)



(b) Trips tp Forest Hills (Outbound)

Figure 5-4: Average Hourly Ridership by Passenger Segment for Commuter Rail Shuttles (Saturdays)



(a) Trips from Forest Hills (Inbound)

(b) Trips tp Forest Hills (Outbound)

Figure 5-5: Average Hourly Ridership by Passenger Segment for Commuter Rail Shuttles (Sundays)

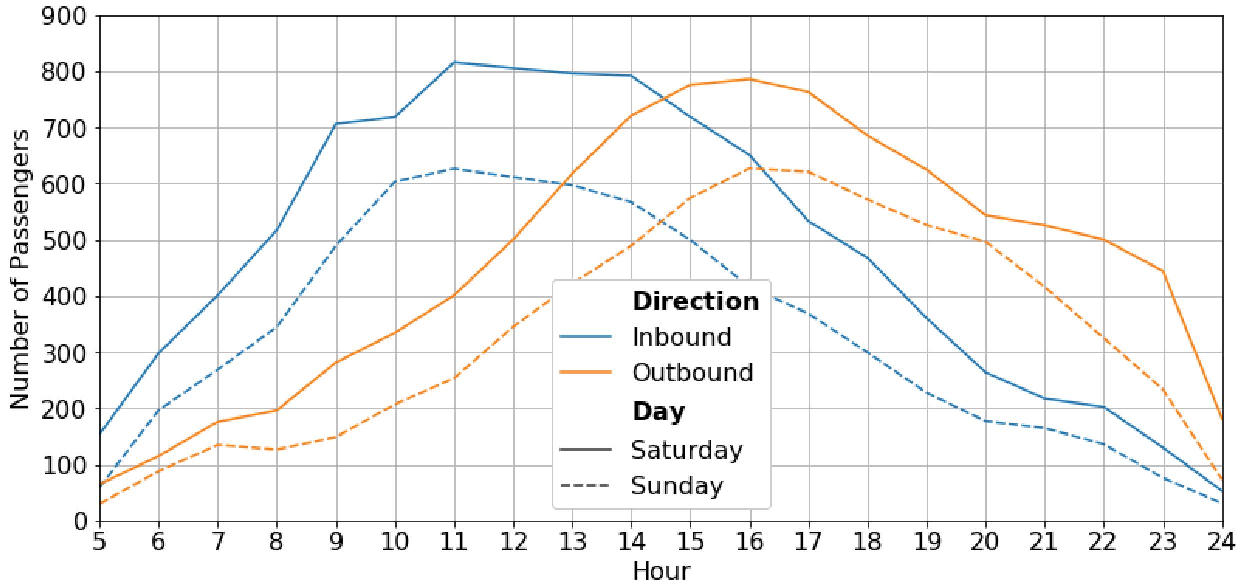


Figure 5-6: Maximum Hourly Passenger Flow on Bus Shuttle (Commuter Rail Shuttle Alternative)

5.3.2 Analysis of Operational Requirements

Commuter Rail

Commuter rail trains consist of multiple cars which together can carry several hundreds of passengers at a time. A single commuter rail train can provide more capacity than the maximum hourly passenger demand which could shift to it. This necessitates planning of fleet size for commuter rail shuttles not on the basis of capacity, but on the basis of policy headways. Orange Line currently runs on 9–11 minute headways on Saturdays and 11–13 minutes on Sundays. Hence, the policy headways can be set to 10 minutes on Saturday and 12 minutes on Sundays, to match the disrupted service for these passengers.

Trains do not have to face congestion, crowding impacts, and variation in headways the same way buses do. This is especially true on weekends, when other commuter rail lines and Amtrak generally run less frequently, thus freeing up track capacity for the commuter rail shuttles. The one-way run time between Forest Hills and South Station can been estimated to be the scheduled run time of 15 minutes. Assuming layovers of 10 minutes at either end, the overall cycle time can be assumed as 50 minutes. For 10 minute Saturday headways, 5 train sets are only just enough with the assumptions above, hence 6 sets could accommodate some slight unavoidable variability in implementation. On Sundays, 5 train sets could suffice.

Shuttle Buses

The 90$^{\text{th}}$ and 95$^{\text{th}}$ percentile estimates of two-way run times for shuttles in the Forest Hills–Ruggles segment are shown in Fig. 5-7. On Saturdays, the peak period upper bound of two-way run time ranges between 50 and 60 minutes. For most of the afternoon and evening on Sundays, it is lower than 50 minutes. The thicker black like indicates the cycle times used for estimating fleet size, based on these upper bounds.

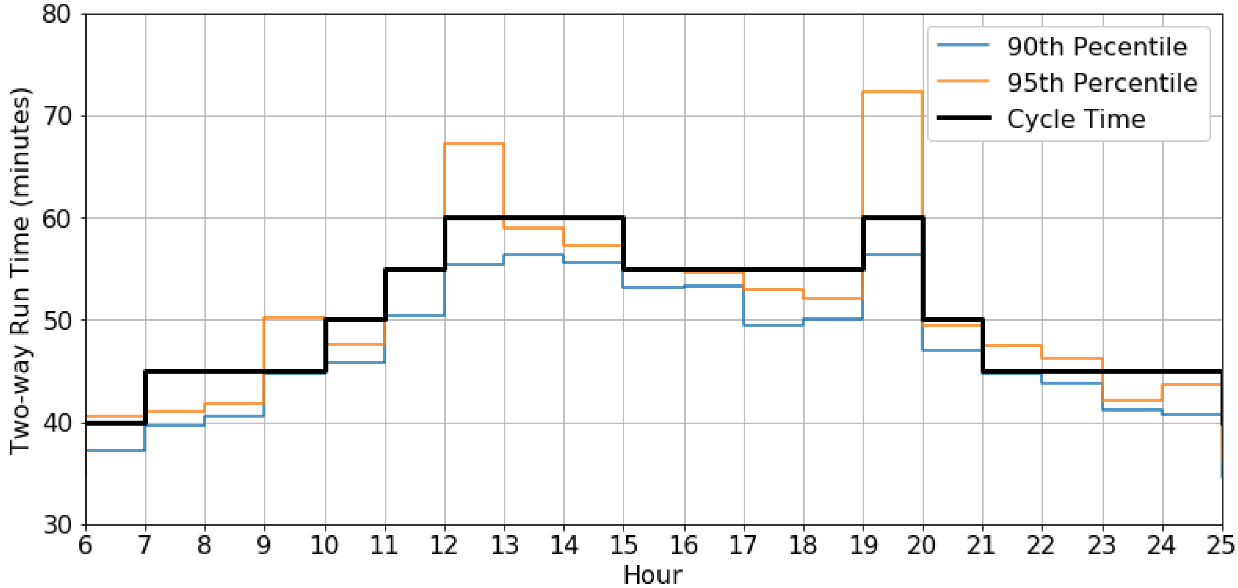
From the maximum demand estimates along the shuttle route, the minimum frequency required in operation for shuttles to provide the required capacity can be calculated. This translates to a headway requirement of approximately 4 minutes on Saturdays, and approximately 5 minutes on Sundays. This is lower frequency than the current shuttle operation. Consequently, the size of fleet required to run this service is also lesser.

The current shuttle headways are very low (roughly 2–3 minutes on average), and hence smaller variations in headways are relatively large compared to mean headways, causing very high estimates of coefficient of variation. In order to get a reasonable estimate of maximum fleet size, the additional vehicle required metric (which is calculated as $1 + CV^2$, where CV is the coefficient of variation of headways) was capped at 1.5.

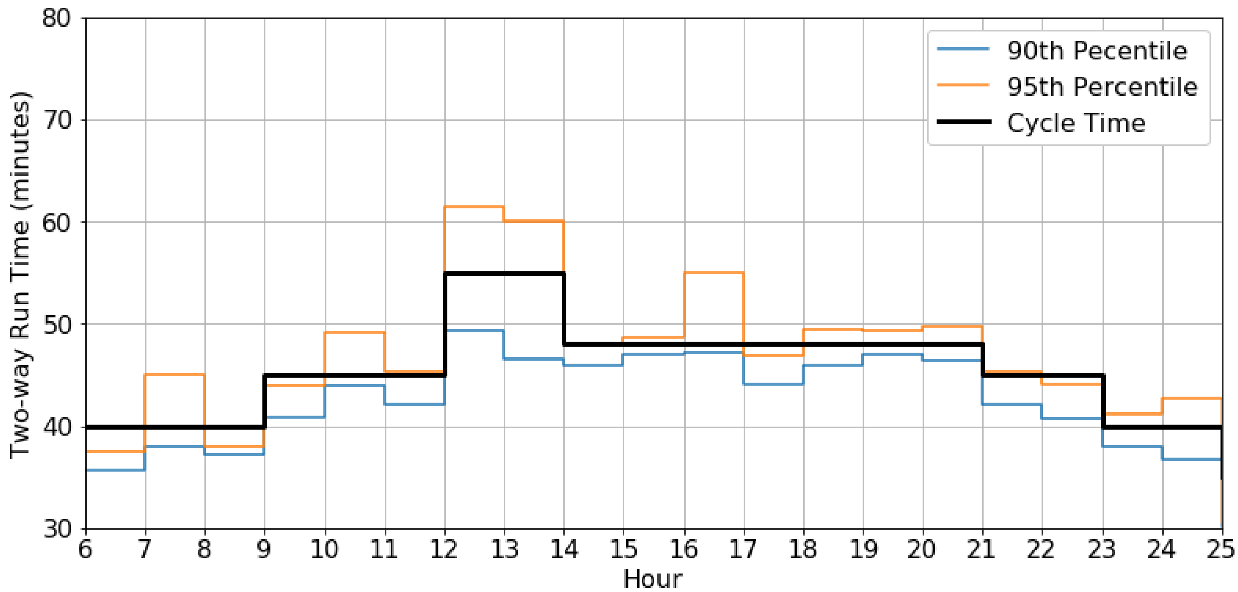
Implementing commuter rail shuttles can substantially reduce the requirement of vehicles on the bus shuttle fleet. For example, on Saturdays, this requirement is reduced by roughly half: from 50 vehicles in operation at present to 24. Figure 5-8 shows the results of the headway and fleet size requirement calculations.

5.3.3 Passenger Benefits

The extent to which the commuter rail alternative could mitigate effects on passengers during shutdowns between Forest Hills and Ruggles is presented in Table 5.6. The potential of the commuter rail alternative lies in the substantial in-vehicle travel time reduction in trains compared to buses. This is reflected in the magnitude of the various components of the benefits. More than 2,200 passenger hours on Saturday and 1,400 passenger hours on



(a) Saturdays



(b) Sundays

Figure 5-7: 90^{th} and 95^{th} Percentile Two-way Run Times for Orange Line Replacement Shuttles on Weekends with Cycle Times

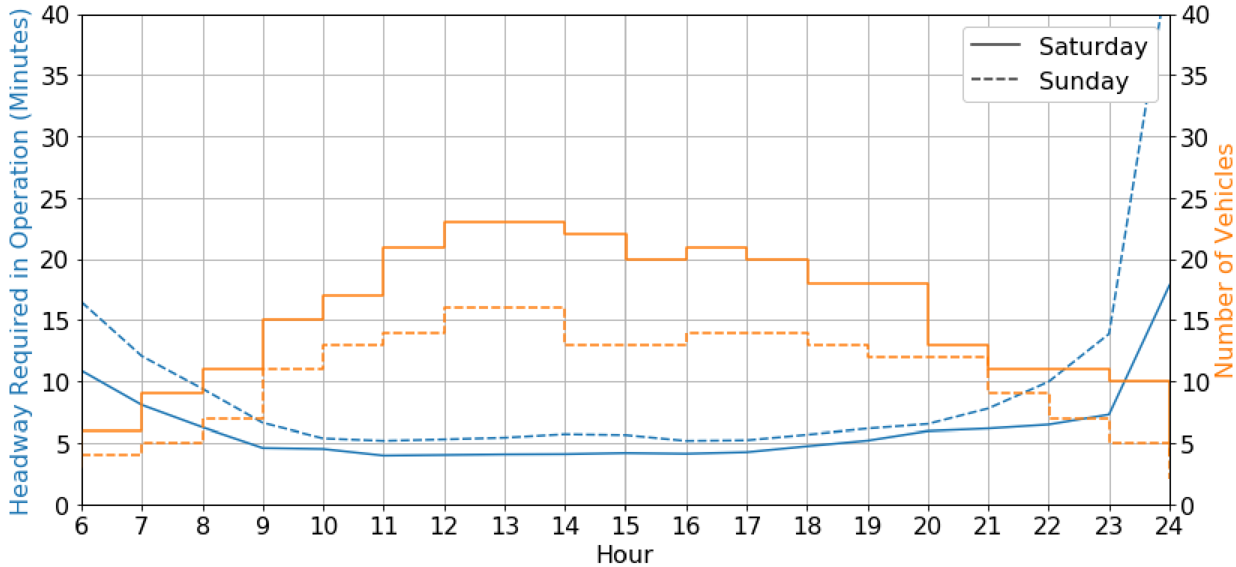


Figure 5-8: Headway Required in Operation for Orange Line Shuttles and Vehicle Requirement (Commuter Rail Shuttle Alternative)

Sunday could be saved by passengers using the commuter rail alternative. This corresponds to a reduction of almost 45% of the impact on passengers' in-vehicle travel time.

In comparison, if the bus shuttle frequency were to be reduced to serve the remaining demand, the passengers still using the shuttle buses would experience slightly higher waiting times on average. This would add up to roughly 290 additional passenger hours on Saturdays and 380 on Sundays. By weighing changes in waiting and transfer time which the commuter rail shuttle alternative could lead to, the overall passenger benefit arising out of this alternative over the weekend can be estimated as slightly more than 3,000 passenger hours. This represents a potential to mitigate approximately 26% of the overall impact of the shutdown. If the bus shuttle service was to remain unchanged and the commuter rail shuttle was added, up to 32% of overall passenger hours could be saved.

5.4 Alternative for Mitigation: Bus Route Continuation

Forest Hills acts as a major multi-modal hub in the MBTA network, with numerous bus routes which serve southern neighbourhoods of Boston terminating there, enabling transfers on to the Orange Line. Between 40 and 60% of passengers tapping in at Forest Hills transfer

Table 5.6: Benefits of Commuter Rail Shuttle Alternative Compared to Existing Shuttle Service (passenger hours)

(a) Saturdays

	CR Shuttle Passengers		Bus Shuttle Passengers	Total
	Inbound	Outbound		
In-vehicle Travel Time	1116	963	-	2078
Transfer Time	11	11	-	22
Waiting Time	42	26	-144	-76
Subtotal: Transfer and Wait	53	37	-144	-54
Total (weighted)	1222	1037	-289	**1970**

(b) Sundays

	CR Shuttle Passengers		Bus Shuttle Passengers	Total
	Inbound	Outbound		
In-vehicle Travel Time	737	691	-	1428
Transfer Time	8	10	-	18
Waiting Time	8	1	-190	-181
Subtotal: Transfer and Wait	16	10	-190	-163
Total (weighted)	770	711	-380	**1101**

(c) Weekend (total)

	CR Shuttle Passengers			Bus Shuttle Passengers	Total
	Inbound	Outbound	Total		
Total (weighted)	1991	1784	3739	-669	**3071**

from these buses. This feeder catchment nature of Forest Hills means that on shutdown weekends, these passengers would have to add another transfer to a trip which is possibly already long. Mitigation efforts could be targeted towards these passengers with the aim of reducing the number of required transfers.

Several low-frequency local and key/high-frequency bus routes feed into Forest Hills (Fig. 5-9). This presents an opportunity to continue the buses on these routes as shuttles between Forest Hills and Ruggles. The passengers on these buses would then not need to get off at Forest Hills to get on a different shuttle bus, eliminating a transfer. It would also mean that the bus could pick up the passengers waiting at Forest Hills (since it serves as a shuttle). The capacity offered by these bus routes could augment the shuttle buses, and possibly offset some of the vehicle requirements for the shuttle service.

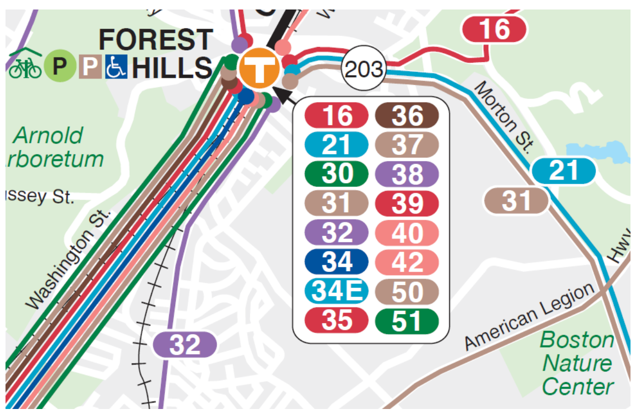


Figure 5-9: Bus Routes Serving Forest Hills (Source: MBTA System Map)

For this analysis, the relatively frequent bus routes with their northern terminus at Forest Hills have been considered. Routes 31 and 32 offer 12–13 minute frequencies on Saturdays and 15–20 minute frequencies on Sundays, while 34/34E buses together serve Forest Hills 3–4 times an hour on weekends. Of these two, only Route 34 has been considered for estimating fleet size, because the longer route and consequently higher cycle times for 34E would lead to unreasonably large vehicle requirements for enhancing services.

Figure 5-10 shows the hourly capacity available on buses on these routes arriving at Forest Hills on the weekend compared to the peak link load which needs to be served by replacement shuttle buses. In the daytime, roughly half of the hourly passenger load can be accommodated in these buses, which means that they can substitute for a large portion of the vehicle requirement for the shuttle service. Another possibility is to enhance frequencies on these regular routes such that there are enough buses serving Forest Hills which can continue and entirely substitute the shuttle service to Ruggles. Accordingly, two operational 'scenarios' of continuing the buses on the routes as shuttles have been considered for analysis:

Scenario 1: Continuation to Ruggles while maintaining current weekend frequencies to substitute part of shuttle bus requirement

Scenario 2: Continuation to Ruggles by enhancing frequency on the regular routes to completely substitute shuttle bus service

5.4.1 Operational Requirements

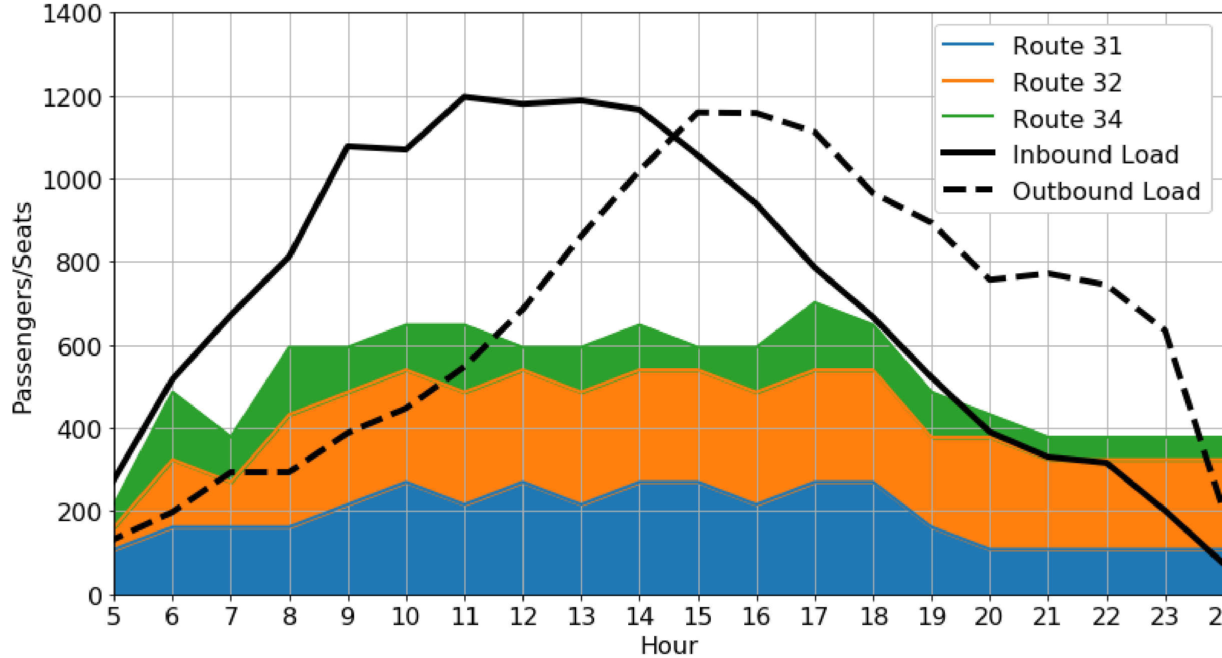
Capacity and Frequency

Scenario 1: The frequencies of the bus routes would stay the same. However, since these continued routes would be able to complement the shuttle service, the capacity and the consequent frequency of the shuttle-only service can be reduced. This would lead to a reduction in vehicle requirement on the shuttle-only service.

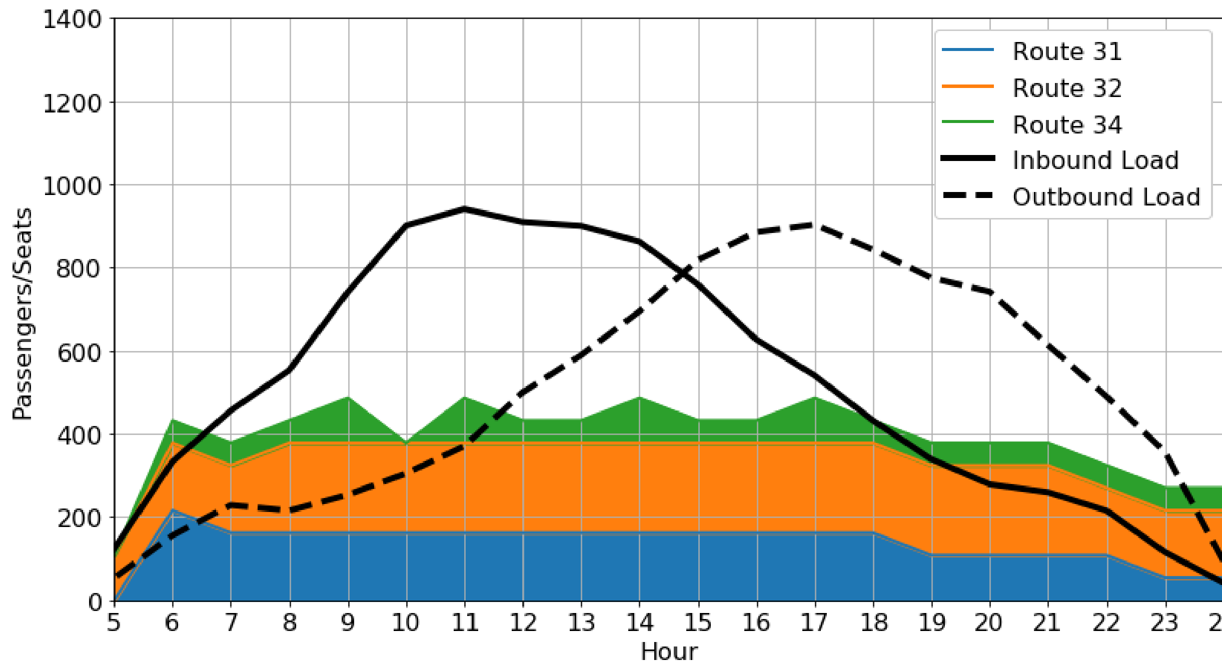
Scenario 2: In order to substitute shuttle buses entirely, the hourly frequency for the three routes should add up to provide enough capacity to handle the maximum hourly loads in the Forest Hills–Ruggles segment as shown in Fig. 5-10. This translates to a minimum combined frequency on these routes of 23 per hour on Saturdays and 18 per hour on Sunday during the respective days' peak load periods. This can be roughly divided in a 2:2:1 ratio similar to the proportions of the current frequencies on the three selected routes.

Run Times and Cycle Times

Estimates of the upper bounds of two-way run times for the bus routes with continuation are shown in Fig. 5-11 (dotted lines). These were obtained by adding the 90^{th} percentile run times of the bus routes to that of the shuttle service between Forest Hills and Ruggles. Accordingly, the cycle times for the extended bus route service were set (solid lines).

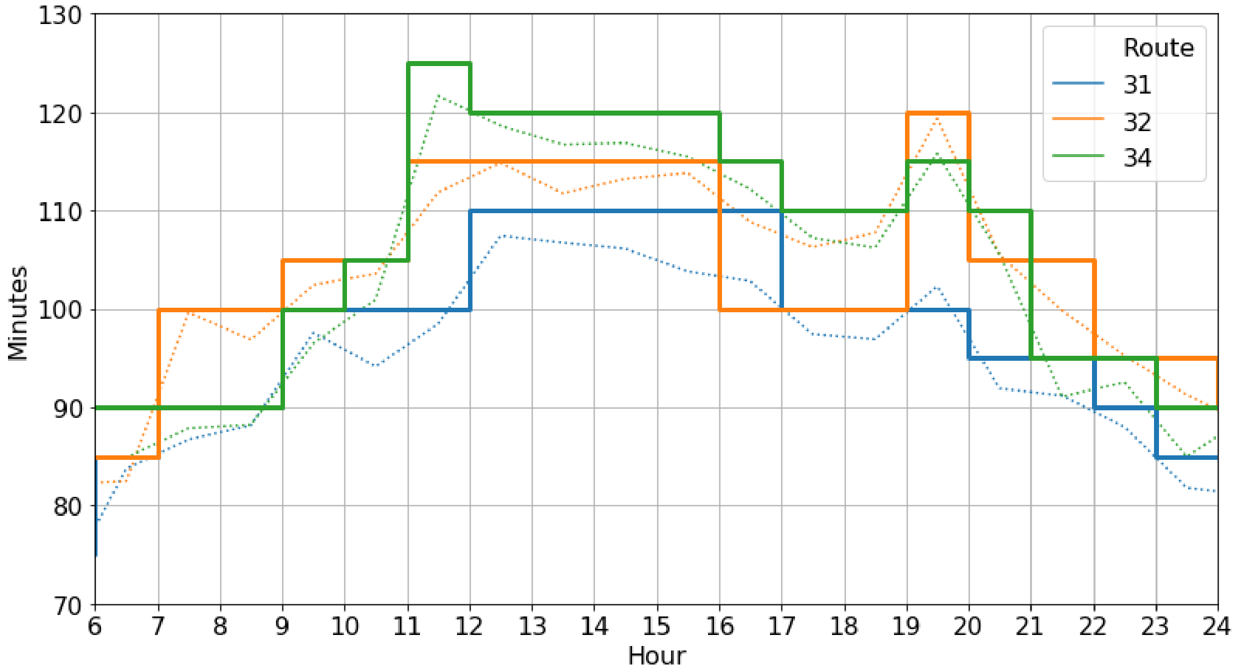


(a) Saturdays

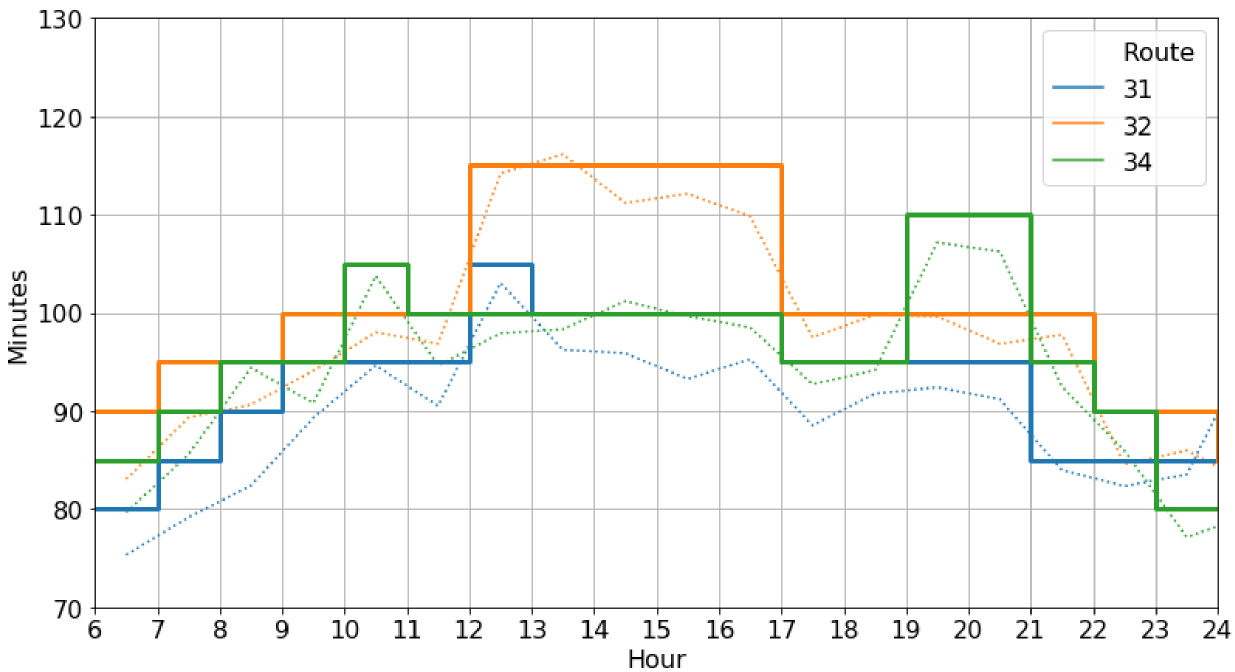


(b) Sundays

Figure 5-10: Hourly Capacity on Buses Arriving at Forest Hills and Maximum Directional Load on Shuttles between Forest Hills and Ruggles



(a) Saturdays



(b) Sundays

Figure 5-11: Combined 90th Percentile Two-way Run Times for Routes 31, 32, and 34 Continued as Shuttles till Ruggles, with Estimated Cycle Times

Fleet Size

With the cycle time for each of the bus routes with continuations being set, it is possible to estimate the number of vehicles which would be required to implement such extended routes at the headways in each scenario. Figure 5-12 shows the factor with which maximum fleet size required (compared to fleet size under perfect/ideal headway conditions) was estimated. This was calculated as the minimum of 0.5 and the square of coefficient of variation (CV) of headways (i.e., a maximum of 0.5). On Saturdays, the large variability of headways on Route 31 and 32 causes the square of CV to exceed 0.5. This points to a need of additional interventions in order to improve headway reliability and provide a more efficient and reliable service.

The fleet size required for each service was calculated based on its cycle time and headways. Fig. 5-13 shows the combined number of vehicles required for continuation of Routes 31, 32, and 34 (and for Scenario 1, shuttle service). The requirements under ideal and variable headways, respectively, represent the 'minimum' and 'maximum' fleet size needed to provide service at the required capacities. For Scenario 1, the maximum fleet size required over a Saturday (which is the busier of the two days) is 49 buses, which is less than the 63 buses in operation for all the four services (3 regular routes and the shuttle) at present. For Scenario 2, the maximum fleet size over a Saturday is 63 buses, which is equivalent to the current number of buses in operation. This means that utilizing the capacity offered by bus routes to augment the shuttle can lead to more efficient utilization of resources, which would also very much benefit passengers who use just the regular bus routes, which is not possible with the current shuttle operations.

5.4.2 Passenger Benefits

The benefits of implementing the bus route continuation till Ruggles are two-fold: passengers who would have to transfer to the shuttle could eliminate the transfer at Forest Hills, and in the case where frequencies are enhanced, all the passengers who use these bus routes would experience reductions in waiting time. The aggregated estimates of these benefits are presented in Table 5.7.

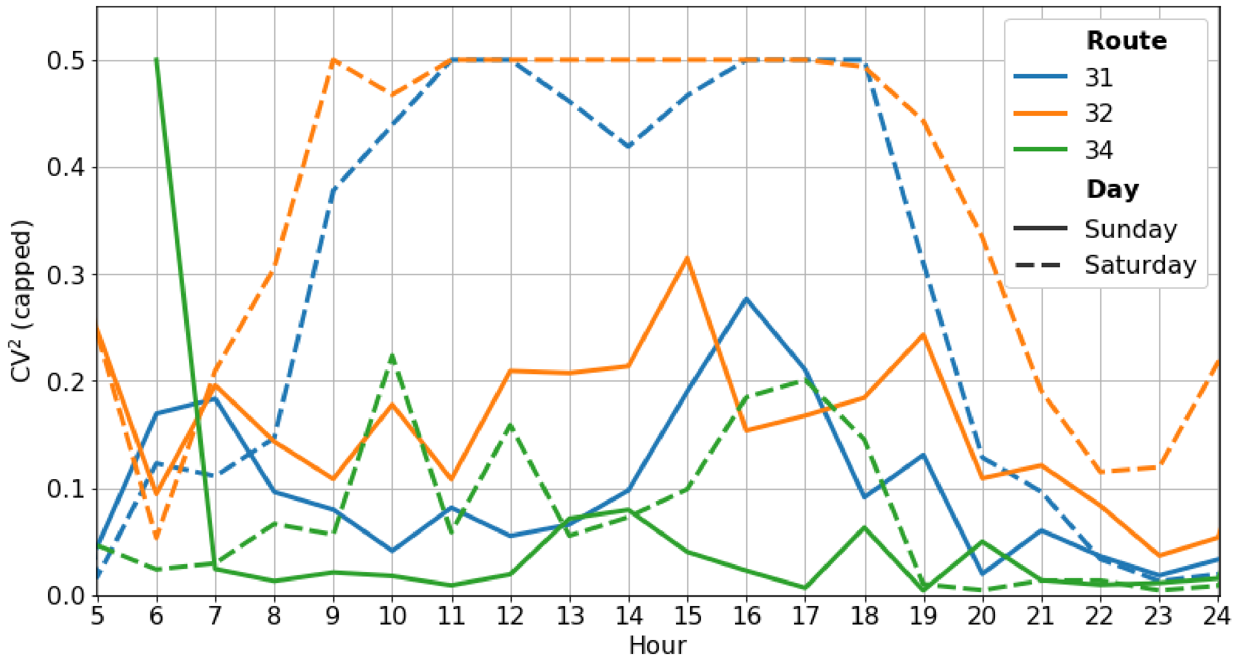


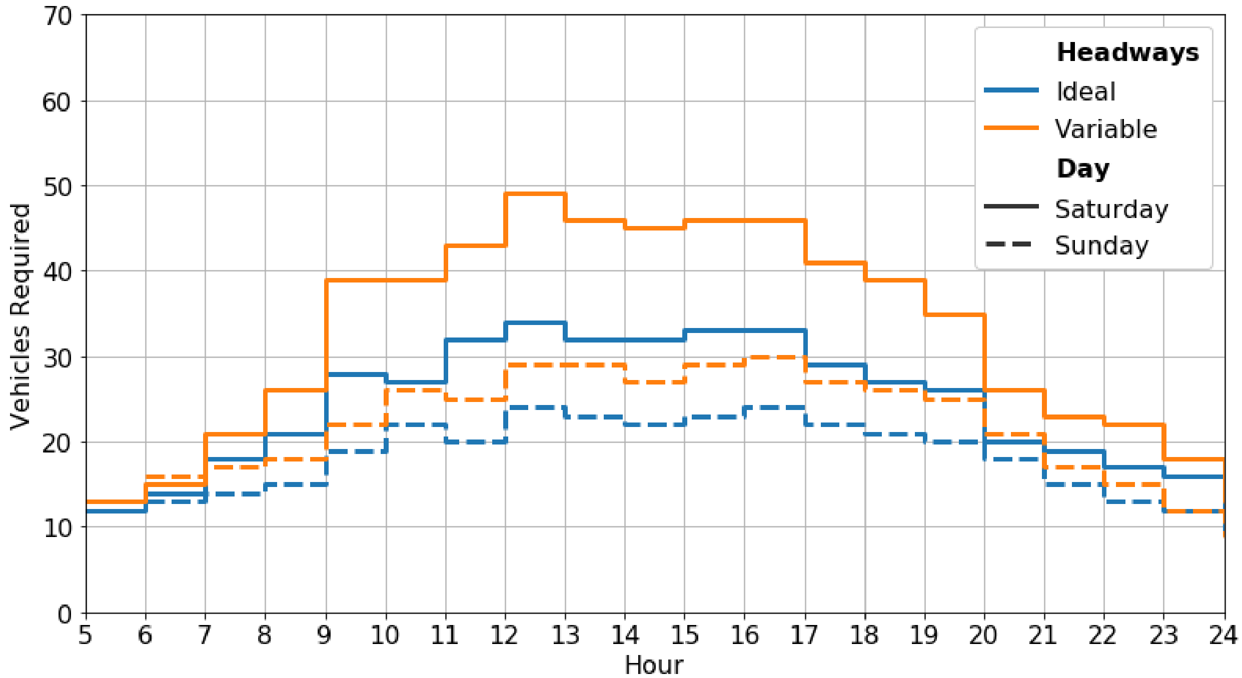
Figure 5-12: Additional Vehicle Requirement Factor for Routes 31, 32, and 34: Headway CV^2 Observed at Forest Hills Capped at 0.5 (Inbound)

The benefit of removing transfers inbound adds up to approximately 150 passenger hours over the weekend. This represents roughly 2–3% of the overall impact of the shutdown. In the outbound direction, it is unlikely that most passengers would get on a bus which at Forest Hills would continue as the desired bus route of their next stage. The maximum possible savings outbound (i.e., in case every passenger at Ruggles gets on to their desired bus route) would be similar in magnitude, although they are not included in benefit calculation presented here.

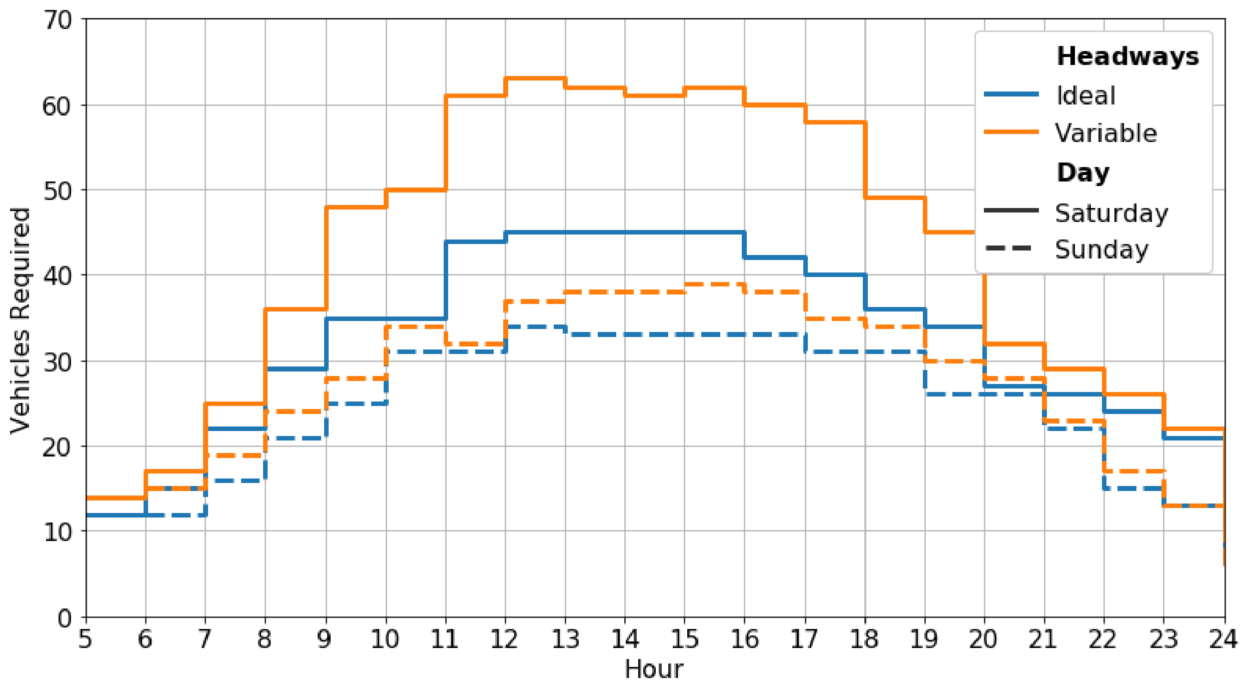
With enhanced frequencies, the potential waiting time savings for all the passengers who use these routes add up to more than 1,600 passenger hours over the weekend. With a weighing factor of 2 for waiting time savings, this represents a 28–29% portion of the impact of the shutdown by utilizing the existing resources at the MBTA.

5.5 Discussion

Two potential alternatives for passengers during shutdowns of the Forest Hills–Ruggles have been studied here. Commuter rail shuttles would be an alternative to the bus shuttle service



(a) Scenario 1: Bus Continuation at Current Frequency



(b) Scenario 2: Bus Continuation at Enhanced Frequency

Figure 5-13: Hourly Total Fleet Size Requirement for Bus Route Continuation Scenarios

Table 5.7: Benefits of the Two Bus Continuation Scenarios Compared to Existing Shuttle Service (passenger hours)

			Saturdays		**Sundays**	
			Scenario 1	Scenario 2	Scenario 1	Scenario 2
Passengers Transferring at Forest Hills	**Waiting Time**	Inbound	64		60	
		Outbound	53*		53*	
	Transfer Time	Inbound	14		11	
		Outbound	12*		10*	
All 31, 32, 34 Users	**Waiting Time**	Inbound	-	421	-	323
		Outbound		446		349
Total			**78**	**946**	**71**	**743**
Total (Weekend)			Scenario 1: **149** Scenario 2: **1689**			

* Maximum possible benefit, not included in total calculations

for several passengers, and reduce their in-vehicle travel time to a large extent. Bus routes continued between Forest Hills and Ruggles as shuttles, on the other hand, would not be an 'alternative' to the shuttle service in the sense of replacing shuttles for some passengers, but present an opportunity to use existing vehicle fleet resources to better serve passengers.

Both of these (commuter rail shuttles and bus continuation with enhanced frequencies) could potentially generate passenger benefit which would be a large proportion of the impact of the shutdown. While the commuter rail shuttle would directly improve several affected passengers' in-vehicle travel time, the bus continuation alternative would improve service for a large number of passengers while benefiting a relatively small proportion of riders affected by the shutdown.

In terms of operational requirements, both of these alternatives require some degree of service modification. The commuter rail alternative can be implemented with a small number of train sets, but train operation costs are usually much higher than bus operation costs. Further, this could possibly involve new operating contracts, and scheduling to avoid track occupancy conflicts. For example, just after 11 am on Saturdays, two Amtrak trains traveling in opposite directions are simultaneously traveling between Ruggles and Back Bay. This means that one of the two western tracks would have an Amtrak train running in addition to the commuter rail and shuttles. The shuttle scheduling would need to account for such conflicts. In order to minimize the interference of a train stopped at Forest Hills on incoming trains, the commuter rail shuttles can use the switch between Forest Hills and Roslindale Village. Since the shuttle service would serve the same stops as the Needham branch does, the latter can be run with added cars in lieu of the shuttle during the particular time of each hour it is scheduled. This would alleviate scheduling conflicts of the shuttle service with the Needham branch.

On the other hand, the large reduction in the number of buses required to operate the shuttle service would lead to a decrease in operational costs on the bus shuttle service. For the bus continuation alternative, the vehicle requirements and operating costs would not change by much. However, the vehicle and crew scheduling would need to be revised because of the extended paths. Further, modifications in dispatching would be required to coordinate bus arrivals and departures such that reasonable effective capacity is available for the buses to continue as shuttles between Forest Hills and Ruggles.

Because these two alternatives are broadly distinct in terms of the passenger segments which could benefit, it is possible to implement both alternatives in order to combine the benefits experienced by passengers. In terms of operational requirements, the reduction in fleet size requirement for the bus shuttle service from the commuter rail alternative can help offset some of the vehicle requirement for the bus continuation alternative.

The implementation of any of these alternatives, or of their combination, would require informing passengers of the option being made available to them, so that they can benefit from it. The commuter rail shuttle alternative can be communicated to passengers at the stations across the system, and especially at Orange and Red Line stations. Finlan, Fairchild, and Aloisi [30] provide a sample of the kind of posters which could be used to disseminate information for such an option (Fig. 5-14). The bus continuation alternative would require announcements by the operators to passengers on Route 31, 32 and 34 buses pulling into Forest Hills informing passengers that the vehicle would continue as a shuttle on to Ruggles.

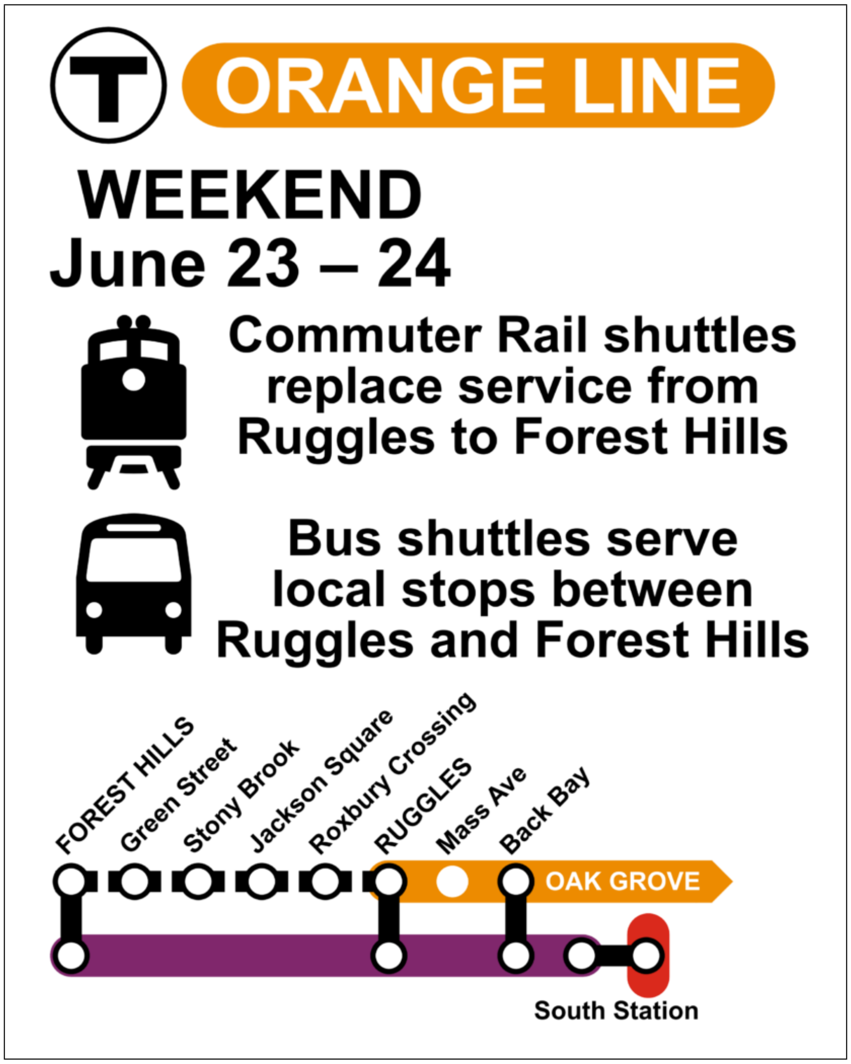


Figure 5-14: Example of Poster for Information Dissemination About Commuter Rail Shuttles (Source: Finlan, Fairchild, and Aloisi [30]).

Chapter 6

Case Study: Green Line Central Tunnel

6.1 Background

MBTA's Green Line currently operates within what was North America's first subway infrastructure, the Tremont Street Subway. The segment between Haymarket and Boylston was operational by 1898. By 1914, this was connected to the Boylston Street Subway, which ran West through to the Kenmore Square incline. Arlington Station was opened along this corridor in 1921. The Blandford Street and St. Marys Street inclines, which currently accommodate the B and C branches, respectively, were opened in 1932. On the northern side, Haymarket station was relocated in 1971. Scollay Square station was structurally modified and renamed as Government Center in 1963, and underwent reconstruction most recently between 2014 and 2016 with a complete shutdown of the station [29].

Given the age of these tunnels, SGR projects relating to track and signal upgrades are being planned in the near future to improve reliability and accommodate the new Green Line fleet, as well as extensions to the Green Line to Somerville and Medford. The Green Line has a very large coverage, and shutdowns of the Central Tunnel, which connects all the branches to Downtown Boston and the other MBTA lines, would have widespread impact on passengers. Being in the planning phase, this project presents an opportunity to utilize insights from current passenger travel patterns and vehicle data to compare shutdown plans in terms of disruption, and to plan alternatives for the imminent shutdowns.

6.1.1 Potential Work Plans

Based on the nature of the project, when multiple work plans are feasible, there are likely to be trade-offs between cost of the project, overall duration, resources like operators and fleet, as well as inconvenience as experienced by passengers. Furthermore, the requirements of the staging of specific project tasks which might need to be undertaken would also dictate the length of shutdown required at that stage.

The construction work plan for the Green Line Central Tunnel project has not yet been finalized, although discussions have mentioned the choice of either weekday early access shutdowns or complete segment shutdowns. In addition to this, there are options of shutting down the entire tunnel between Kenmore and Government Center, or shutting down parts of it at time. For the analysis of impacts, two shutdown periods — full day vs. 'early access' (9 pm – end of service) — and three shutdown location scenarios — Kenmore to Copley, Copley to Government Center, and the entire Kenmore to Government Center tunnel — have been compared.

6.1.2 Shuttle Service Requirements

Traditional replacement shuttle services are planned with the aim of replacing the capacity on the links which are being shut down. The capacity required on a segment at a particular time of the day should be sufficient to handle the maximum passenger flow through any link within that segment in either direction. The regular weekday demand between different station pairs is known from ODX data. By assigning this to the network, link flows can be estimated.

The frequency of bus shuttles require to substitute rail service can then be estimated. The tunnel is a crucial segment in the network — connecting Green line branches to Downtown and other lines — and consequently, large volume of passengers could be affected by shutdowns in it. Because of this, vehicles with larger capacity could be used to provide shuttle service.

Figure 6-1 compares the headway required for various scenarios of weekday shutdowns. The blue lines indicate the headway required when the segments closer to Downtown Boston are shut down, either as a part of the full segment shutdown, or a Copley–Government Center shutdown. Replacing these links would generally require a higher frequency shuttle service compared to when only the Kenmore–Copley segment is shut down (orange lines).

Dashed lines show the headway required when operating the articulated buses which can accommodate up to 79 passengers, while solid lines represent regular 40-seater buses which can accommodate up to 54 passengers. The large flow volumes mean that during peak period, a very high frequency of shuttle service is required, which is reflected in the 'dips' down to 1–2 minute headway requirements close to 8 am and 5 pm. Compared to the peak periods, the early access period (shaded in blue) requires relatively lower frequencies. This makes an early access shutdown less constrained than full-day shutdowns (which include peak periods) in two ways: more spare vehicles available for operating relatively lower frequency services.

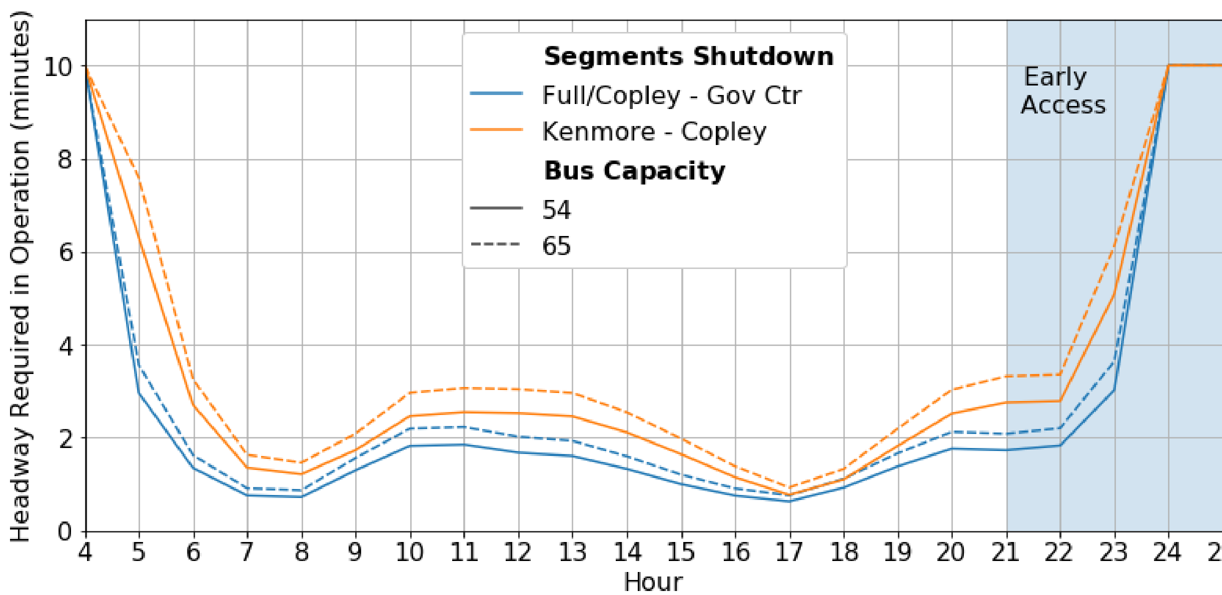


Figure 6-1: Shuttle Headway Requirements for Location of Shutdown and Shuttle Bus Capacity (Capped at 10 Minutes)

6.2 Analysis of Passenger Impacts

The impacts of shutdowns can be broken down into components: in-vehicle travel time, waiting time, and transfer time. The shuttle service is not yet implemented, and hence the average travel time along each station-to-station link on the shuttles for various times of the day was estimated from Google Maps. This was compared with the time it takes on Green Line for each link, and the difference combined with the passenger flows on the link during the particular time of the day to get an estimate of the in-vehicle travel time impacts of the various shutdown plans.

In addition to estimating link loads, the assignment of trips from ODX to the network can also be used to estimate the number of passengers who would incur additional transfers or experience changes in waiting time at various stages of their journeys. The average time impact per passenger for the additional transfers was assumed to be 30 seconds. Comparing the shuttle headway requirements calculated above to the scheduled headway of the various lines, changes in waiting time due to additional transfers and higher frequency of the shuttle were calculated at various stations. These transfer and waiting time changes were then combined with the corresponding number of trips on each kind of passenger movement at the various locations as applicable. These were then weighed with a factor of 2, combined with the in-vehicle travel time impact, and aggregated to estimate the overall passenger hour impacts for the particular shutdown plan. The results of these estimations are shown in Table 6.1, which compares shutdowns over various segments and time periods of the day.

6.2.1 Impacts by Shutdown Location

For shutdowns over the same time periods but across different parts of the Kenmore–Government Center rail segment, the in-vehicle travel time impact depends on which links are being shut down. Accordingly, the effect of the entire segment being shutdown on passengers' in-vehicle travel time is the sum of those for the Kenmore–Copley and Copley–Government Center segments.

The overall number of additional transfers that passengers experience in any of the three shutdown cases are similar in magnitude, with the full segment shutdown leading to a fewer overall number of transfers required. This is because the stations in the Trunk also serve major trip generators, and with the full segment being shut down, many such trips would need to only up to one transfer to their journey (on a high-frequency shuttle route) instead of two. Consequently, the overall waiting time impact due to these transfers is lower. As a result of such trends in transfer-related delays, a shutdown of the entire segment has a lesser impact than the the sum of the impacts of shutting down sub-segments within it.

This information can be incorporated while deciding the staging of shutdowns. For example, if a particular task in the work plan of the project can either be completed by shutting down each smaller segment one day at a time, or by shutting down the entire segment over a day, project managers can use the knowledge of impacts, and choose the latter option, which is less disruptive to passengers overall and require fewer shutdowns.

6.2.2 Impacts by Period of Shutdown

Another dimension of choice when it comes to choosing a shutdown plan is the period of day during which the shutdown could be implemented. On weekdays, early access shutdowns, which do not disrupt either of the peak or daytime base demand, would have only 8–10% of the impact compared to full-day shutdowns. For replacement service implementation, another advantage of early access shutdowns, as mentioned before, is the greater availability of bus resources. On the other hand, the relatively shorter time period for each shutdown could mean that more days of shutdowns would be required for the same task. In such a case, comparing the passenger impacts of fewer full-day shutdowns to those of more early access shutdowns, can help project managers in deciding the shutdown work plan.

Connectivity to Downtown and other lines is a crucial aspect of mitigating any shutdown in the Green Line Central Tunnel. The analysis below demonstrates the identification of alternatives for one of the several possible shutdown options, namely full-day shutdowns between Copley and Government Center, as well as assessment of their potential efficacy for various passenger segments, potential shift, and capacity requirements for the 5–6pm evening peak period.

6.3 Alternative for Mitigation: Orange Line

In and around Downtown Boston, the Orange Line runs roughly parallel to the Green Line. On the northern side, Boylston, Park Street and Government Center on the Green Line are all merely one block away from Chinatown, Downtown Crossing, and State stations, respectively, on the Orange Line. Towards the other end of the segment, Back Bay is

Table 6.1: Passenger Impacts of Green Line Central Tunnel Weekday Shutdown by Location and Period (passenger hours)

Shutdown Location		**Kenmore-Copley**		**Copley-Gov. Ctr.**		**Full Segment**	
Shutdown Period		Full Day	Early Access	Full Day	Early Access	Full Day	Early Access
IVTT	Eastbound	3,222	281	3,431	336	6,652	617
	Westbound	2,788	173	4,346	207	7,134	380
	Total	6,010	454	7,776	543	13,786	996
Waiting	Eastbound	626	83	580	103	379	44
	Westbound	837	135	699	88	342	81
	Total	1,463	218	1,279	191	721	126
Transfer	Eastbound	369	33	356	37	318	22
	Westbound	390	33	375	28	340	29
	Total	759	66	731	65	658	51
Subtotal: Wait + Transfer		2,223	284	2,009	256	1,380	177
Total (weighted)		10,455	1,022	11,795	1,054	16,546	1,350

accessible by a 5 minute walk from Copley station. This means that during shutdowns between Copley and Government Center, the Orange Line segment between Back Bay and State could be alternatively used by some passengers.

Passenger Segments

More specifically, the following passenger origin-destination segments could switch to the Orange Line (along with the stations at which they would switch to the Orange Line while traveling inbound):

1. Passengers traveling between the B/C/D branches and Charles, Kendall, Northern Green/Blue/Orange Line stations, or Southern Red Line stations: at Back Bay

2. Passengers traveling between Boylston station and Northern Green/Blue/Orange Line stations: at Chinatown

3. The segment of passengers who usually transfer between the Red and Blue lines via Green Line: at Downtown Crossing

Of these, passengers in segment 2 can very conveniently use the Orange Line because it is only one block away. Passengers in segment 3, would easily be able to use Downtown Crossing and the Orange Line to transfer between the Red and Blue lines. Hence it is assumed that these passengers will almost always take the Orange Line as an alternative. However, for the B/C/D Branch passenger segments, the efficacy of Orange Line with respect to traditional shuttles needs to be compared. Table 6.2 shows the number of passengers in each of these O-D based segments during the PM peak hour of 5–6 pm.

Table 6.2: Average Volume of Passengers on Segments Who Could Use Orange Line (Weekday, 5–6 pm)

Passenger Segment Trip Ends		**Northbound**	**Southbound**
Green BCD	Blue North	221	155
	Lechmere–Haymarket	286	316
	Orange North	167	131
	Kendall-MGH	45	177
	Red South	394	409
	Subtotal	**1112**	**1189**
Boylston	Blue North	49	23
	Lechmere–Haymarket	59	45
	Orange North	8	5
	Subtotal	**116**	**73**
Red	**Blue**	**142**	**76**
Total		**1370**	**1337**

Efficacy Assessment

While assessing efficacy of alternatives with respect to shuttles in the planning phase, travel time data for special services like shuttles is usually not available. In this case, there is no single bus route which travels along or close to the segment. In such a case, the distribution of travel times for comparison can be estimated from other sources.

For the purpose of demonstration in this hypothetical case, the range of typical travel times was obtained from Google Maps queries, and the distribution was assumed to be a skewed normal distribution with mean equal to the average of the range from Google Maps, standard deviation of 4 minutes and a skewness parameter of 2. When planning shuttle service, it is also possible to run test shuttle buses to gather this data, or to set up queries to collect travel time samples in real time over the span of several days, which would provide empirical travel time distributions.

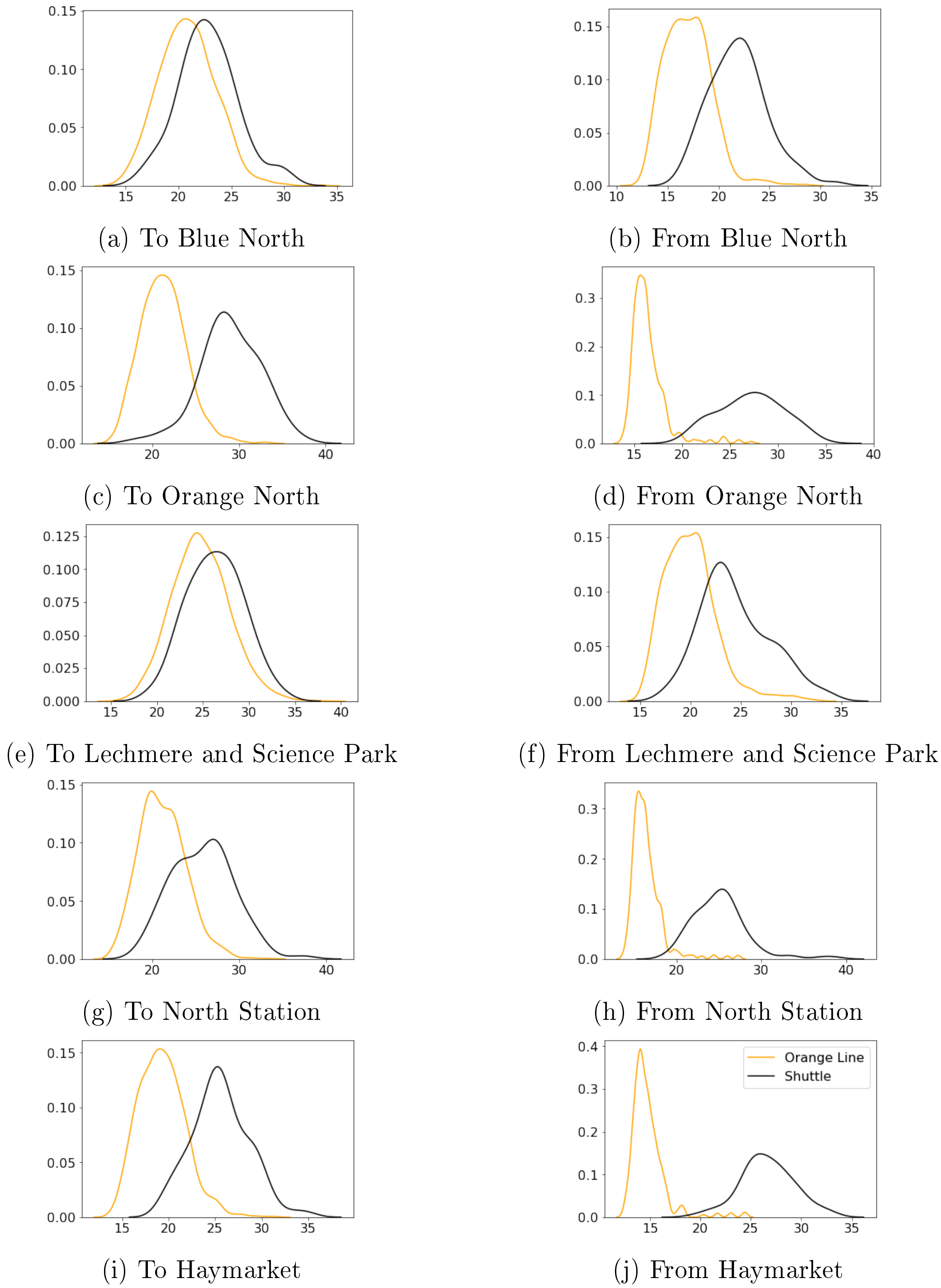
The travel time distributions for currently operational bus and rail routes were obtained from AVL and TTR data. Waiting times were assumed to be uniformly distributed between 0 and the corresponding headway for each service, while time taken to walk or transfer was assumed to be fixed. Based on the potential trajectory of the passengers of each particular segment via the bus shuttles and via Orange line, 100 random draws from the corresponding distributions were combined to generate a sample of journey times. The journey time distribution via shuttle and via Orange Line were then compared using the Mann-Whitney U Test to check whether the alternative could potentially be faster for each segment, and the proportion of times it could be faster was calculated as $1 - {}^{U}/_{10,000}$.

The results for this procedure are shown for different passenger segments in Figures 6-2 and 6-3. The left column in either figure indicates northbound trips from the Green Line branches while the right column indicates southbound trips to the branches. The travel time distributions via Orange Line (orange curves) are in most cases noticeably lower than by shuttle, albeit by varying degrees, and except for the passengers traveling between the Green Line branches and Kendall or Charles/MGH stations.

Capacity Requirements

The proportions of times that the Orange Line is faster for each segment were multiplied to the number of passengers in that segment to assign the changes in flow due to shifting passengers to the Orange Line, along with a reduction factor within the 50–75% range. The resulting changes in link flows on the Orange Line are shown in Fig. 6-4.

During the evening peak period, the Haymarket–North Station northbound link is the one with the highest load. With passengers shifting due to shutdown, the maximum increase in



(a) To Blue North

(b) From Blue North

(c) To Orange North

(d) From Orange North

(e) To Lechmere and Science Park

(f) From Lechmere and Science Park

(g) To North Station

(h) From North Station

(i) To Haymarket

(j) From Haymarket

Figure 6-2: Comparisons of Journey Time Distributions for Various Passenger Segments via Orange Line vs Shuttle between Copley and Government Center link flow would occur in Downtown. Consequently, the Downtown Crossing–State link would handle the highest passenger flow, which would increase by roughly 200–250 passengers, to approximately 7200 passengers per hour.

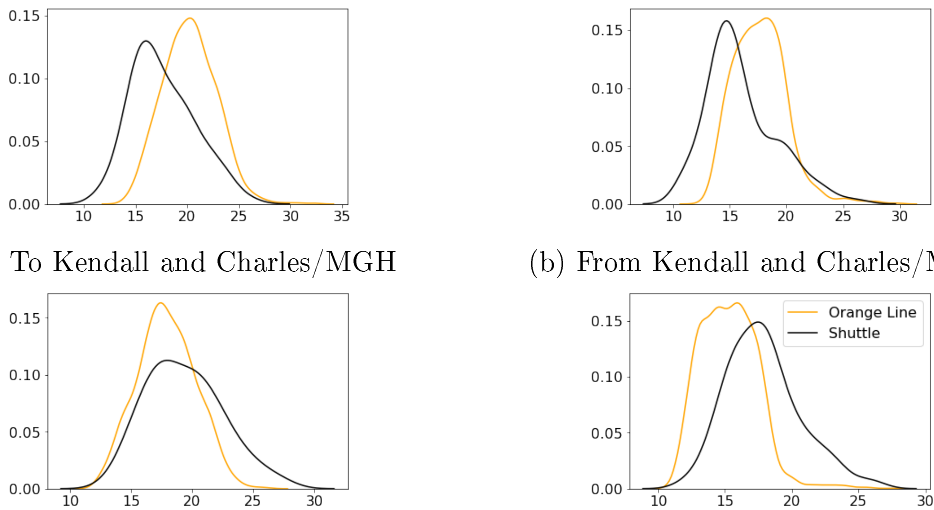
At present, the Orange Line is scheduled to run at 6 minute headways in the PM peak period. Six-car trains carrying 131 passengers per car [22] can hence serve a maximum link flow of 7,860 passengers per hour during this period. This means that, assuming ideal operations, the Orange Line currently has sufficient capacity to absorb this shift. The near-capacity conditions during the PM peak also underscore the need of maintaining reliable headways in order to ensure sufficient capacity. The track and signal upgrades taking place as part of other SGR projects, and a new fleet of Orange Line cars being introduced into service will help achieve these reliability goals in the near future and provide additional capacity with more frequent service.

6.4 Bus Alternatives

6.4.1 Route 1

Similar to the case of Longfellow Bridge shutdowns in Chapter 4, disruption of services in the Green Line's Central Tunnel would mean that the rail connection between northern stations in Cambridge and stations in the western portions of the Green Line would be suspended. In this case, Route 1 could serve to provide this connectivity, thereby also reducing loads on the shuttles. The passenger segmentation in such a case would also be similar to the Longfellow Bridge case study; the only change being the assumption that passengers traveling to/from Copley would stick with the shuttles which are readily available there. Passengers going to/coming from the branches would transfer at Hynes or Symphony stations as applicable, which are directly served by Route 1. These segments together add up to approximately 330 passengers in the 5–6pm peak hour.

A range of increase in frequency required for Route 1 can be roughly estimated by assuming capacity required to serve 50–75% of this potential shift. In this case, it translates to a frequency increase of 4–5 buses per hour, which means that the headway would need to be



(a) To Kendall and Charles/MGH
(b) From Kendall and Charles/MGH
(c) To Red South
(d) From Red South

Figure 6-3: Comparisons of Journey Time Distributions for Various Passenger Segments via Orange Line vs Shuttle between Copley and Park Street

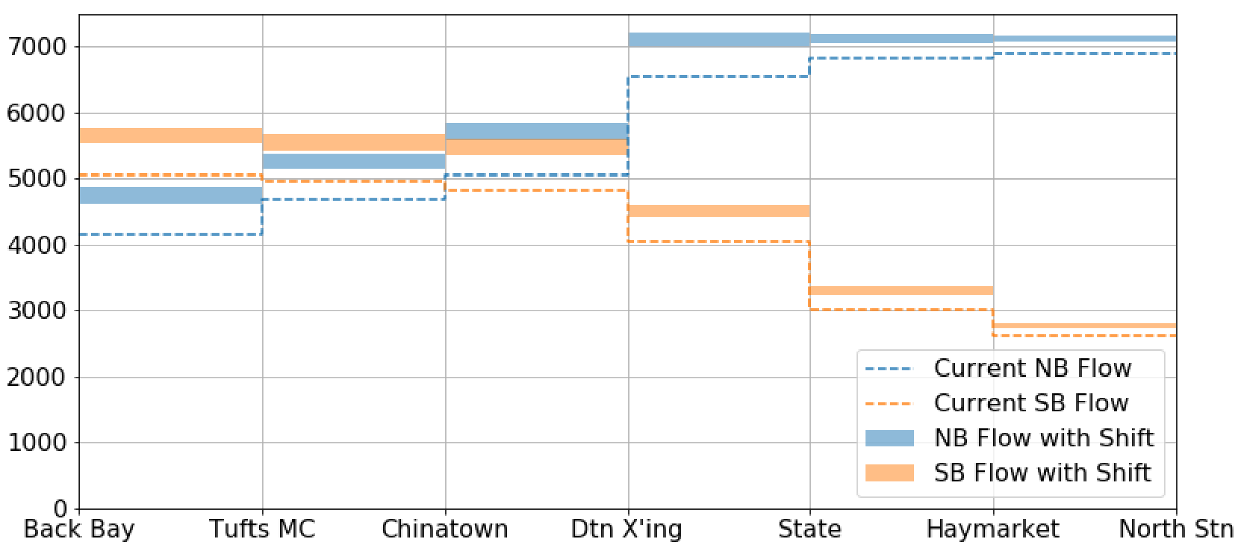


Figure 6-4: Increase in Average Evening Peak Hour Link Flow on Orange Line due to Passengers Shifting During Green Line Shutdowns

lowered to 5 minutes (compared to the currently scheduled 9 minute peak headway) during implementation. Detailed efficacy assessment by segment can also be performed similar to Chapter 4, by estimating journey time distributions on potential passenger segment paths.

6.4.2 Route 39 (Extended to Haymarket)

Route 39 is designated as a key bus route in the MBTA system, and runs on the same path as the E branch between Heath Street and Massachusetts Avenue. Extending this route from its current Downtown terminus in Back Bay to the Haymarket bus stop would mean that during the times when links between Copley and Government Center are shut down, the extended bus route could provide one-seat rides to a several E branch passengers to Downtown destinations and transfer stations to other lines.

On an average weekday, this corresponds to a maximum increase in flow of approximately 750 passengers in the segment between Copley/Back Bay and Prudential, going westbound. During regular operations, the E branch generally provides faster and more frequent service along the shared corridor, which means that more passengers prefer to use rail instead of the route 39 buses. Consequently, the buses carry only 11–12 passengers in this segment. Further, the fleet along this route consists of 60′ articulated buses which can carry more passengers than regular 40′ buses. This means that there currently exists spare capacity on Route 39 even during peak periods.

Similar to the Route 1 case above, the required frequency increase can be roughly estimated by considering that 50–75% of these passengers would shift. This translates to up to 3 additional buses per hour on this route, which corresponds to reducing the headway from the current 10 minutes to 6–7 minutes.

6.5 Summary

In contrast with the Longfellow Bridge and Southern Orange Line case studies,this chapter focuses on demonstrating the use of parts of the SGR mitigation framework in *pre-implementation* planning of a shutdown. The impacts of various shutdown work plan scenarios can be quantified based on passenger flow data. This information can be used along with other aspects of the plan, such as costs and staging requirements, in order to potentially select a shutdown work plan which would be less disruptive in terms of passenger inconvenience. Project managers would in such a case act as an interface between service planners and contractors, to decide a 'best' work plan.

The efficacy assessment of the Orange Line alternative demonstrates how, prior to a shutdown, passenger and vehicle location data can be combined in order to judge whether and to what extent an alternative can be effective for certain segments. When post-implementation data about shuttle service from prior shutdowns is not available, alternative sources can be used to estimate the travel times.

Chapter 7

Conclusion

Several North American legacy urban rail transit systems are facing upcoming challenges in terms of maintaining their infrastructure in a state of good repair in order to provide efficient, reliable, and safe service to passengers, maintain ridership, and accommodate new growth in cities. This motivates the need for a framework that agencies can utilize to plan for shutdowns necessary in order to implement SGR projects. Generalizability and flexibility is important in this case, since transit systems differ in terms of their coverage, ridership, topology, operational constraints, and institutional contexts.

Such a framework which uses data sources available at agencies to incorporate passenger effects into the SGR shutdown planning process, and specifically in service planning of alternatives to traditional station-to-station bus shuttles, has been presented in this thesis, with case studies of recent SGR project shutdowns in the MBTA rail network used as examples to demonstrate the potential use of this framework. At various stages of this framework, criteria which could inform decision making within this process have been established.

This chapter summarizes the framework and case studies, presents resulting recommendations which the MBTA could implement to better serve passengers during shutdowns, and concludes with potential future work and research which could build upon this framework.

7.1 Summary and Findings

7.1.1 Framework for SGR Shutdown Planning

Chapter 3 began by presenting background of the current fairly standard process that agencies like the MBTA use in order to plan replacement shuttle service. The shutdown work plan is based on the staging and requirements of different works within the project. The planning workflow is generally sequential and siloed in nature, with various agency stakeholders working on specific tasks within their domain based on the inputs they get.

The proposed modified framework for SGR shutdown planning utilizes the large amounts of automated passenger and vehicle data that transit agencies have available. This information can be potentially used in the planning process on two 'levels'. First, passenger origin-destination flows can be used to gage the impact of a shutdown at a specific location and time period. Such impact assessment could be useful while scheduling or staging shutdown work plans.

The second use of automated data relates to pre-existing routes and services within the system which could act as in-system alternatives to replacement shuttle service. By using insights about the impacts of a shutdown, along with knowledge of the network, planners can identify potential alternative bus/rail routes through which some passengers could enjoy a more convenient trip during a shutdown compared to taking bus shuttles. This is followed by assessing the efficacy of the alternative, estimating demand on various services, and planning service in order to accommodate this demand.

Criteria for Informing Decisions

The large amount of data available with the agencies needs to be condensed into suitable information in order to make decisions regarding shutdown and service plans at various stages of the framework. Accordingly, the following criteria have been explored in this research:

- Passenger Impact: This is the effect of a particular shutdown plan in terms of additional passenger hours spent by passengers compared to regular rail service, and is composed of additional in-vehicle travel time and transfer time, and changes in waiting time.

Transfer and waiting time changes can be weighted with respect to in-vehicle travel time, and the overall passenger impact can be expressed in monetary terms if needed. This is useful when deciding shutdown plans based on passenger impacts.

- Identification of Alternatives and Potentially Benefiting Passengers: The decision at this stage is subjective, and depends on the availability of alternative routings within the particular system. In general, however, routes which could offer passengers the opportunity to reduce their inconvenience in terms of travel time or transfers can be identified by planners based on their knowledge of the system and impacts of the shutdown.

- Efficacy of an Alternative: For a given O-D segment, a portion of the path between the origin and destination via bus shuttles can be substituted by the alternative being examined. In this portion, the distribution of journey time by bus shuttles can be compared to the alternative. A Mann-Whitney U test can then be used to decide if the alternative is indeed faster.

- Mitigation Benefit of an Alternative: Similar to quantification of the passenger impact of a shutdown, the potential savings in in-vehicle travel time, transfers, and waiting times can be estimated for a given alternative in terms of passenger hours. This also allows the agency to determine the degree to which the impact of a shutdown can be mitigated by a given alternative.

7.1.2 Case Studies

Three case studies of shutdowns over different time periods and parts of the MBTA network were examined for the purpose of demonstrating the implementation of this framework. Two of these case studies (namely, the Red and Orange Line shutdowns) examine shutdowns after their implementation, using the framework to identify potential alternatives and their efficacy compared to observed bus shuttle service, while the third one demonstrates the use of the framework for incorporating passenger effects and alternative efficacy analysis in the planning stage of a shutdown. These case studies have been summarized below:

1. Longfellow Bridge: Bus Route 1 was examined as an alternative to bus shuttles between Kendall and Park Street stations. Several passenger origin-destination segments traveling between northern parts of the Red Line and western parts of the Green and Orange lines could find Route 1 to be faster. For future Red Line shutdowns along this segment (for example, when repairing the viaduct between Charles/MGH station and the portal towards Park Street), service on Route 1 can be enhanced by shifting some buses from the shuttle service to the bus route. Roughly 9–10% of the passenger hour impact of the Kendall–Park Street shutdowns can be potentially mitigated this way.

2. Southern Orange Line: Two alternatives for the shutdowns between Forest Hills and Ruggles stations on the Orange Line were studied: Forest Hills–Ruggles–Back Bay–South Station commuter rail shuttles, and the option of continuing northbound bus routes at Forest Hills as shuttles till Ruggles. Both of these alternatives can help mitigate the impact of the shutdown to a large extent (25–30%). Further, it is possible to combine both of these alternatives, since in terms of operational requirements and certain passenger markets served, they are complementary.

3. Green Line Central Tunnel: This project is currently in the planning phase, which presents an opportunity to incorporate passenger impacts at this stage. Weekday shutdown plans differing in location of shutdowns and time of day were compared in terms of their daily passenger hour impact. Project managers can use these insights in consultation with contractors to decide a 'best' shutdown work plan.

   With the shutdowns being close to Downtown Boston, several alternatives could be feasible. The efficacy of Orange Line between Back Bay and Haymarket as an alternative was examined based on journey time distributions observed from AVL/TTR data, and estimated from Google Maps's directions service. The current capacity on the Orange Line is found to be sufficient, but the potentially increased passenger load due to passengers using the alternative underscores the need to maintain reliable service. Further, two bus alternatives — Routes 1 and 39 — can also serve other passenger segments during shutdowns, with appropriate frequency enhancements.

7.2 Recommendations and Next Steps

A set of recommendations for the MBTA to explore and implement with regards to mitigating impacts of SGR-related shutdowns is presented below. These have been divided into two categories: a more general set of recommendations which could be helpful to a larger set of shutdowns in the span of the coming few years, and recommendations for the specific case studies considered here.

7.2.1 SGR Shutdown Impact Mitigation

Adoption of Framework

The research in this thesis estimates potential operational requirements and passenger mitigation benefits from the data sources available at the MBTA. As discussed in Chapter 3, increased involvement of and inputs from service planners and operations staff within the SGR project planning process would allow the selection of plans which are 'better' from a passenger perspective. Translating the overall framework into mitigation of impact to the fullest extent possible requires implementation of the alternative services, along with enhanced communication with passengers to encourage them to use the alternatives.

Testing Shutdown Mitigation Interventions

Within the context of the accelerated budgetary allocation for SGR projects, there are ample upcoming opportunities to test and implement in-system alternatives to bus shuttles. Initially, this can be achieved through implementation pilots over portions of the project duration, such that replacement service with the alternative(s) can be compared to traditional bus shuttle service. Testing alternative services during shutdowns over various locations and time periods can help MBTA gain insights into what kind of alternatives are effective in terms of passengers' reaction to various implementation and information dissemination mechanisms, and how feasible they are to implement. Beginning to test such strategies as early as possible would generate a bank of knowledge within the MBTA which can be very useful for later shutdowns. This also requires additional emphasis on post-implementation evaluation of shutdown mitigation services.

An important metric for measuring passenger behavior during shutdowns (including response to agency mitigation measures) is passenger volumes on vehicles and links. At rail stations with shutdowns, fare gates are usually kept open. As a result, very little if any passenger data is collected. Perhaps fare gates could continue to accept passenger taps during shutdowns, but the back end fare collection system could be modified to eliminate the fares at such stations during shutdowns. Inside replacement shuttle buses, APC passenger volumes are often found to be unreliable. The underlying technical causes of this problem should be examined and rectified in order to regularly and reliably measure passenger volumes on shuttles.

System-wide Enhancements

It is likely that shutdowns in different parts of the MBTA system could employ the same routes as alternative service. For example, in both the Longfellow Bridge case study and the Green Line Central Tunnel case study, Route 1 is an alternative which can benefit several affected passenger segments traveling in similar ways. This points to the identification of some routes and corridors, service along which could be preemptively enhanced (perhaps using SGR funding) so that they are able to absorb the volumes of passengers shifting to them during shutdowns. A candidate set of such routes and corridors has been presented in Chapter 2.

Dedicated SGR Mitigation Resources

The scale of the overall MBTA SGR project scope warrants a dedicated pool of resources in terms of fleet and operations staff, which would reduce the dependence on the resources required for regular operations in other parts of the system. This availability of dedicated resources would also open up the possibility of many different kinds of shutdown work plans being feasible to implement; that is, there would be more flexibility on the MBTA's side to choose a less disruptive plan. In addition, the MBTA could also coordinate with cities and towns so that infrastructure for maintaining reliability of bus services (for example, dedicated bus lanes, restricted curb access for TNCs, and transit priority at signals) along key/frequent corridors can complement the enhanced level of bus service provided by the

MBTA.

7.2.2 Case Study-Specific Recommendations

Longfellow Bridge

The Red Line segment between Kendall and Charles/MGH stations would be shut down again in the near furure for repairing the viaduct between Charles/MGH and the portal to Park Street. This presents an opportunity to potentially implement some of the following recommendations:

- Enhancing frequency on Route 1 on weekends by shifting 15 buses from shuttle service to Route 1
- Adding a crossover on the Red Line North of Charles/MGH station so that during shutdowns trains can travel from Alewife through to Charles/MGH
- Adding a shuttle stop at Bowdoin station
- Modifying the bus shuttle route to serve additional stations in Downtown Boston
- Bus priority measures like dedicated lanes and signal priority along Cambridge and Tremont Streets in Boston for shuttle buses, and Massachusetts Avenue for Route 1

It must be noted that the major repairs between Charles/MGH and Park Street in the near future may require a more intensive and disruptive shutdown plan than the weekend closures implemented during the Longfellow Bridge repair project. In such a case, new analysis would be required, where the framework and recommendations presented in this study would serve as a reference.

Southern Orange Line

The maintenance project along the Southwest Corridor was completed in October 2018. Further shutdowns along the southern Orange Line segment would take place in the near future have not been discussed or planned. However, some steps would help passengers during regular service and potential future shutdowns:

- Reliability improvements along bus routes 31 and 32
- Identifying potential commuter rail shuttle corridors throughout the MBTA network, and implementing commuter rail shuttles on shutdown weekends where applicable and feasible
- When service to Forest Hills is suspended as part of a future shutdown, continuing buses as shuttles between Forest Hills and the station where Orange Line service restarts

Green Line Central Tunnel

- Incorporating passenger impacts in shutdown work plan staging and selection prior to implementation
- Testing and implementing one or a combination of the following mitigation strategies:
  - Extending Route 39's northern end from Back Bay to Haymarket in order to augment bus shuttle service between Copley and Government Center
  - Enhancing service on Routes 1 and 39 and Orange Line during weekdays to handle passengers shifting, including capacity and reliability improvements

7.3 Future Work

As mentioned above, imminent future SGR-related shutdowns in the MBTA and other transit systems provide opportunities to test and implement this framework. The subjective criteria within the framework are meant to accommodate generalizability in face of the differences in various urban rail systems. Research on shutdowns in different transit systems could compare the implementation of these criteria and seek to establish more objective criteria in place of subjective ones. In particular, studying passenger behavior in response to implementation of mitigation strategies can help refine criteria like the reduction factor for passenger assignments to alternatives, or even revise objective criteria, like passenger hour estimates of passenger impacts and mitigation benefits, or the thresholds for assessing the effectiveness of alternatives for passenger segments. Further, passengers' response to different interventions for passenger impact mitigation can be studied.

The process of estimating and measuring various criteria introduced in this framework can be automated, and be implemented as a set of tools which could inform and support decisions at various levels. In particular, for the impact and benefit assessment and alternative efficacy assessment steps in the framework, automation can significantly help service planners in gaining insights. The advantage of such tools is also that they can implement relatively tedious tasks like efficacy assessment by passenger origin-destination segment on a wider scale (network-wide assessment instead of assessing a select group of passenger segments) and finer resolution (station-to-station instead of grouping stations by convenience). One limitation of this research is that passenger origins and destinations are only known at the station level. Future research could expand the pool of data sources beyond the ones available at agencies to base mitigation strategies on passengers' actual origins and destinations instead of just the stations they travel to and from. Such toolkits (e.g. mobile phone-based trip information collection applications or surveys for a sample of passengers) could also automate data collection processes when necessary.

It must be emphasized that MBTA is now planning to undertake SGR activities at a much more intense scale, with the likelihood of simultaneous disruption on multiple lines, and a risk of cumulative and escalating ridership impacts. It would be beneficial to identify the full set of SGR actions being planned, consider more than one scenario for the sequencing of SGR activities in order to minimize adverse impacts, and develop suitable mitigation strategies for those impacts which are unavoidable. The case studies show that these tools can help mitigate adverse impacts of individual projects, but to apply them to an entire program of projects will require careful advance planning.

Appendix A

Application of ODX for Shuttle Service Improvements

It may not always be possible to implement alternatives to replacement bus shuttles. This could happen when no potential alternative services exist, or identified alternatives have been assessed as infeasible in terms of passenger time savings or operational costs. In such cases, origin-destination data available to agencies can still be used to identify potential shuttle service modifications so that passengers can be served better. Two such examples of shutdowns in peripheral parts of the MBTA network have been described below.

A.1 Green Line D Branch

This project involves track and signalling upgrades between Beaconsfield and Riverside stations, which requires weekend early access shutdowns. Compared to other Green Line branches, the D branch is much longer, with stops being spaced farther apart, so that bus shuttles have to travel relatively longer on potentially circuitous paths to offer replacement service.

The regular weekday passenger flow along this D branch segment at the beginning of the early access period (evening) was obtained from ODX data and is shown in Fig. A-1. The outbound load (blue) is higher on weekday evenings compared to the inbound load (orange). Within this segment, three stations stand out relatively in terms of number of passenger ons and offs: Riverside, Newton Center, and Reservoir. Approximately 100, 75, and 115 passengers respectively get on or off at these stations. A majority of the passengers getting on/off at these stations travel to/from outside the segment.

This means that running some shuttles express between Reservoir, Newton Center, and Riverside can provide these passengers faster service. This is especially true for Riverside passengers, who currently have to endure the entire shuttle route. As such, in addition to the 8 buses required to operate station-to-station shuttles between Brookline Hills and Reservoir at the D branch's current 11 minute headways, 5–6 buses could be used to operate the Brookline Hills–Reservoir–Newton Center–Riverside express shuttle at the same frequency.

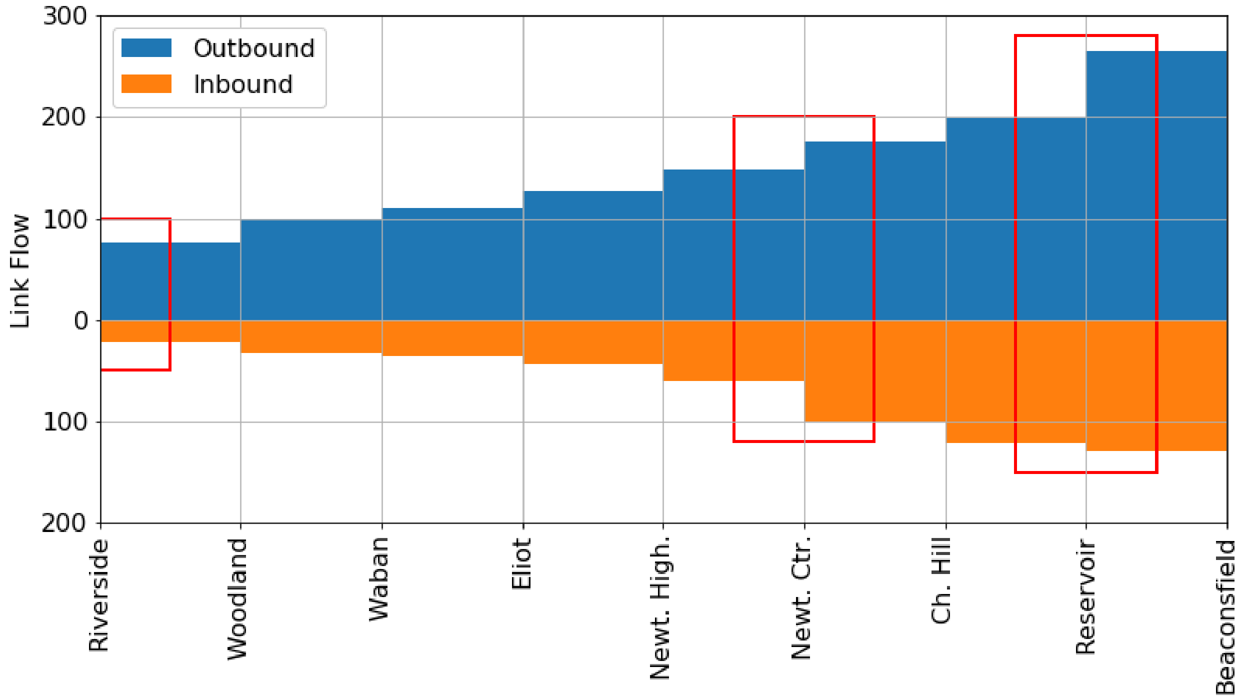


Figure A-1: Average Weekday Passenger Flow Along D Branch by Direction (9–10 pm)

A.2 Northern Red Line

As part of a project to maintain floating slabs beneath the tracks, the underground segment of the Red Line between Harvard and Alewife underwent shutdowns over several weekends in 2018 and 2019, with station-to-station shuttle buses replacing service. While Harvard and Porter stations are both located on Massachusetts Avenue, Davis and Alewife stations are located away from it and on opposite sides of this major artery. This causes the path between Alewife and Davis to be long and circuitous.

In an article in the Commonwealth Magazine, Ofsevit [31] proposed a modified shuttle service which could potentially be both convenient for passengers and cost-efficient for the MBTA to run. Under this modified shuttle service, two shuttle bus routes would be employed: one would connect Harvard to Porter and Davis stations, while another would connect Harvard to Alewife directly.

The reasoning behind this recommendation was that majority of the passengers traveling in this segment pass through it to/from the rest of the network. In such a case, more direct connectivity for most Alewife passengers and shorter cycle times for the shuttle routes for all Northern Red line passengers would lead to substantial passenger benefit.

This argument can be examined by using ODX data. Hourly passenger demand in the segment on Saturdays has been shown in Figure A-2, broken down based on origin-destination segments. The solid and dashed lines show the demand for trips between Davis/Porter and stations south of this segment, and Alewife and stations south the segment, respectively. These trips greatly outnumber the volume of passengers traveling between Alewife and Davis/Porter stations, which are depicted as dotted lines. Thus, it appears that the suggested split of the shuttle route into two routes has significant merit from the perspective of passenger convenience.

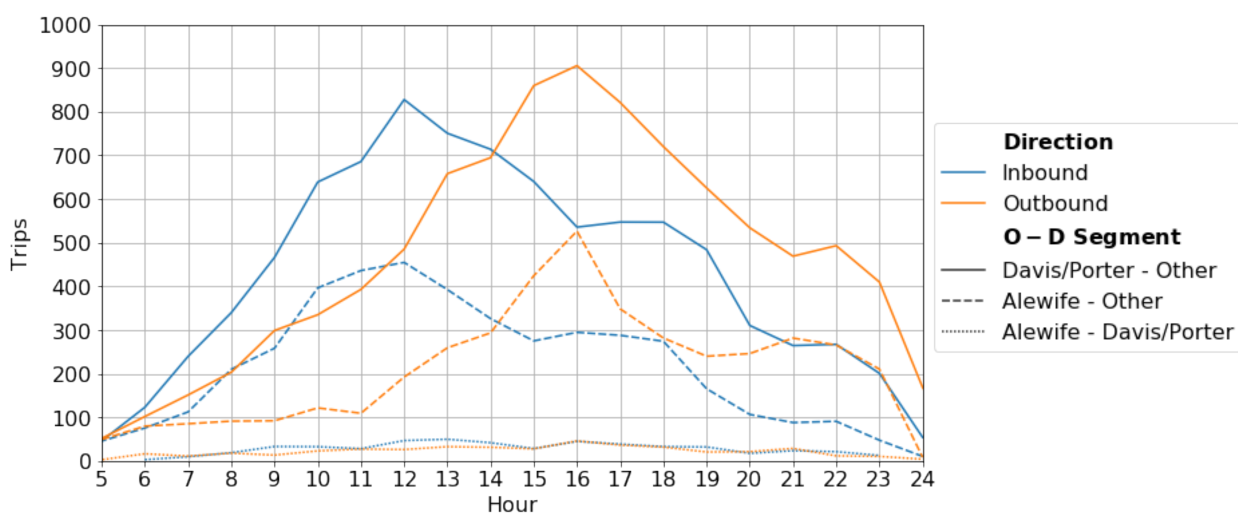


Figure A-2: Average Saturday Hourly Trips to/from Alewife, Davis, and Porter Stations

Appendix B

Longfellow Bridge: Journey Time Distributions

Figures B-1 and B-2 show the cumulative distribution of journey times by Route 1 (solid lines) and traditional bus shuttles (dashed lines) for the various passenger segments considered for analysis in the Longfellow Bridge Case for the afternoon peak period on Saturdays, for southbound and northbound journeys, respectively.

The journey times for each passenger segment are the time required on the segment of the path which would be substituted if the passengers were to use Route 1 as alternative. For example, for the segment of passengers traveling from northern Red Line stations to Northeastern University, the passengers using Route 1 are assumed to get off at Central, take the Route 1 bus to Symphony, and walk to Northeastern. When traveling via shuttles, they stay on till Kendall, take the shuttle to Park Street, and then take E branch to Northeastern. Hence the segment of their path between Central and Northeastern is substituted, and the journey time distribution from Central to Northeastern via shuttle and via Route 1 is compared. The plots are arranged by which stops on Route 1 various segments would get on and off. The Mann-Whitney U test is used to compare the distributions via shuttle and via Route 1 for each segment (the dashed and solid lines, respectively, for each color).

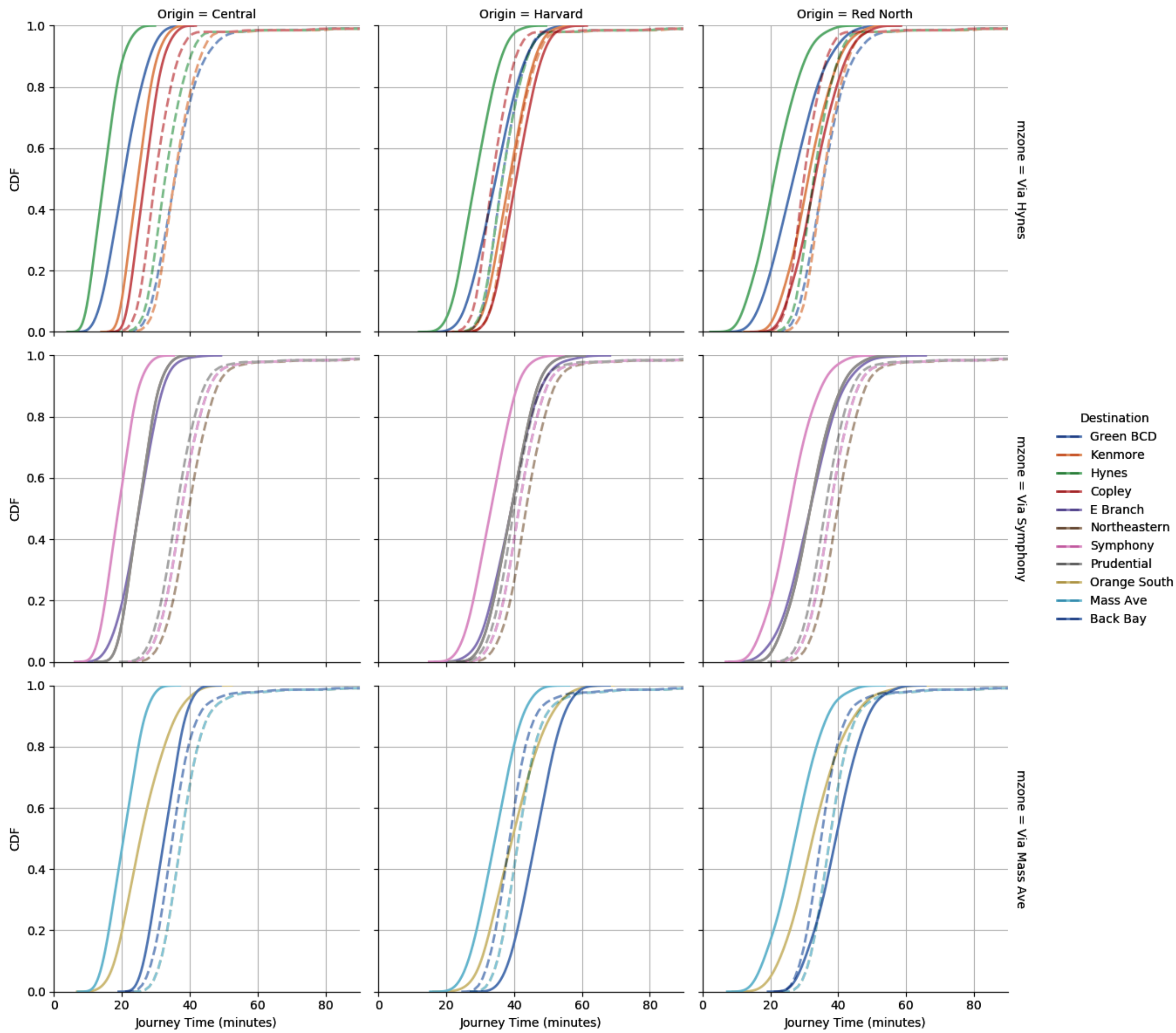


Figure B-1: Southbound Journey Time Cumulative Distribution (Saturdays, 2pm–6pm)

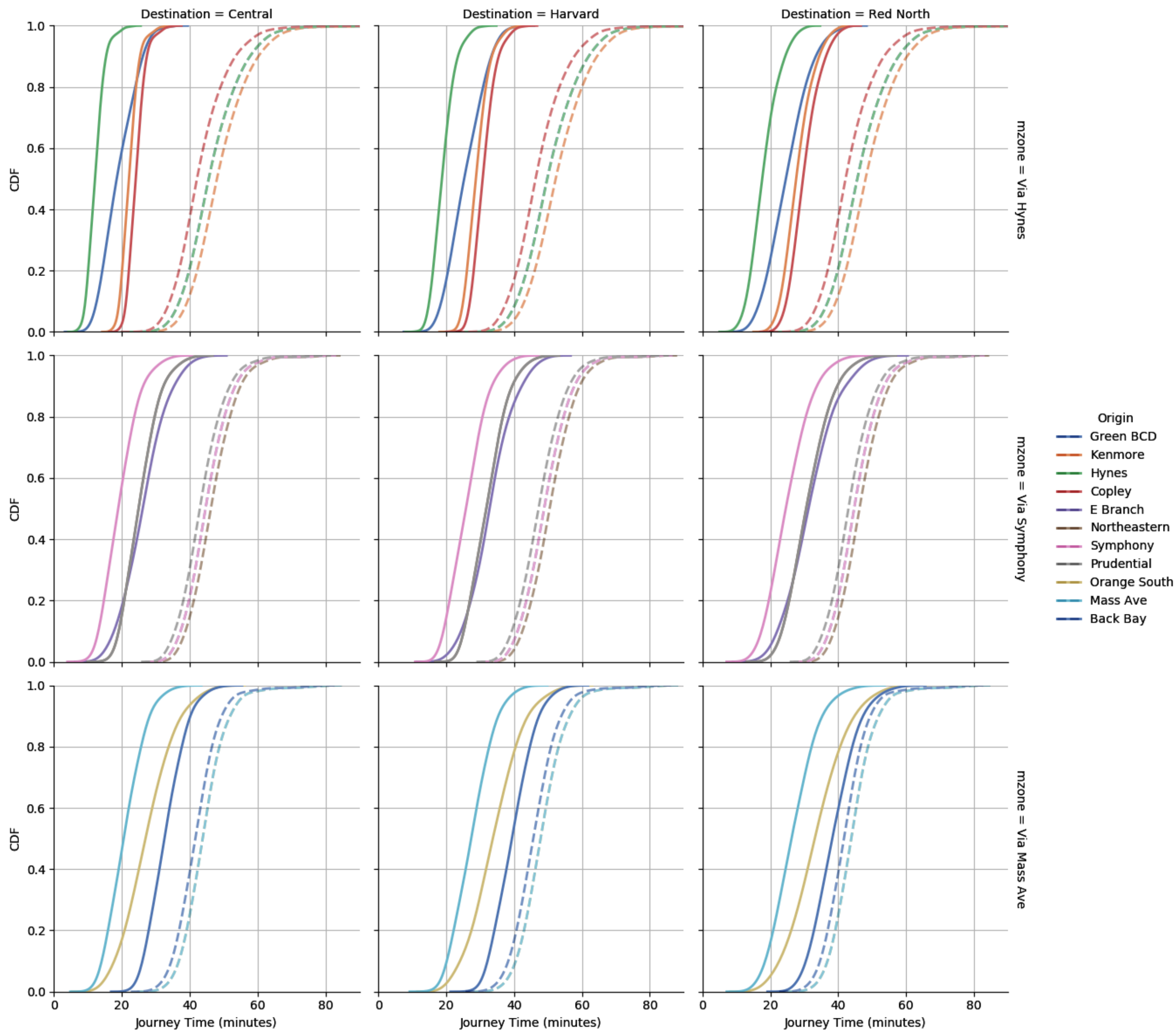


Figure B-2: Northbound Journey Time Cumulative Distribution (Saturdays, 2pm–6pm)

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