Evaluating Service Mitigation Proposals for the MBTA Green Line Extension Construction Delay Using Simplified Planning Methods

by

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Abstract

This thesis reviews a select group of transit environmental mitigation proposals through the application of ridership estimation methodologies. In recent years, rider demands and environmental concerns have led many transit agencies to explore options for increasing service even within constrained budgets. Anticipated state and metropolitan area climate change mitigation strategies are likely to result in the need for further transportation system changes in many cities.

In response to environmental concerns raised during the construction of the Central Artery/Tunnel, Massachusetts committed to extending the Green Line light rail from its Cambridge terminal at Lechmere into Somerville and Medford. The Massachusetts State Implementation Plan requires that the Green Line be extended in two branches by the end of 2014. Massachusetts has delayed construction on the extension, and it must therefore undertake mitigation for the delay. Facing both financial constraints and pressure to increase service, transit agencies such as the MBTA need new ways to improve transportation systems with limited financial input and means by which to evaluate the impact of proposals.

Several mitigation proposals focusing on transit services in the Lechmere Station area are presented in this thesis. Increasing service on the Green Line to Lechmere is found to be a good first step towards improving service in Somerville. Proposals for increasing bus feeder service to and from Lechmere and the surrounding areas include both increasing service on existing routes and introducing new routes. Partnerships with existing private providers could also help decrease the costs to the MBTA of introducing a new route. In order to analyze the mitigation proposals, several methodologies are explored including area wide transportation planning models, direct demand (regression) models and comparison equations. A rail elasticity of demand with respect to service is calculated based on a prior MBTA system experience, while elasticities from literature are used for buses. In addition, a direct demand model is estimated for the MBTA bus network, and the results are compared to elasticity analysis. Regional planning models are found to be important for predicting system-wide responses but often are too detailed and expensive to use to evaluate every proposal. Instead, direct demand models can help with initial rankings of proposals, and service elasticities can help further examine expected ridership changes due to service improvements.

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1. Introduction

Public transit agencies must continually address the effect of changes in their regions including changing demographics, increasing ridership and mounting environmental concerns, all while dealing with growing budgetary constraints. System changes must constantly be considered and analyzed in order to adapt to regional changes. New Environmental Protection Agency (EPA) regulations requiring states to prepare plans to mitigate greenhouse gases are likely to result in further transportation system changes. System alterations can range from increasing information provision to adjusting frequencies, and from modifying existing services to creating new services. Methods for analyzing the impact of potential system changes are necessary for determining the best options to implement. This thesis investigates several sketch planning methods to predict the ridership impacts of small transit system changes in the context of mitigating the delay in building a new light rail line extension at the Massachusetts Bay Transportation Authority (MBTA).

1.1. Background and Motivation

One of the most significant changes the MBTA must address is the legal obligation to extend its Green Line light rail line north to the cities of Somerville and Medford. The extension has already been designed, but the extension will have significant impacts on the current transit system that should be addressed. In anticipation of implementing the extension, system operations and performance in the affected area can be studied and improved to build ridership ahead of the new extension. This was the focus of the work of Matt Shireman (2011). Once the extension opens, the bus system will also need to be integrated with the extended light rail line. Some bus routes may need to be adjusted or realigned, and some service frequencies may need to be altered.

In the immediate future, however, there is a need to address the recent delay in opening the extension. The extension of the Green Line was a requirement of the Central Artery/Tunnel project (the Big Dig) to offset the risk that improved travel time by auto would reduce transit use and lead to increased auto use congestion and air pollution. Since the extension was to have been opened by no later than 2011, the Massachusetts Department of Transportation

(MassDOT) agreed to a court settlement to open the extension by 2014 and to mitigate any further schedule slippage with added transit service of equal or greater value in offsetting auto vehicle miles traveled (VMT). Several of these mitigation considerations and options are the subject of this thesis. In order to properly address what should be done during this interim period, proposals must be considered and methods for examining the various proposals must be developed.

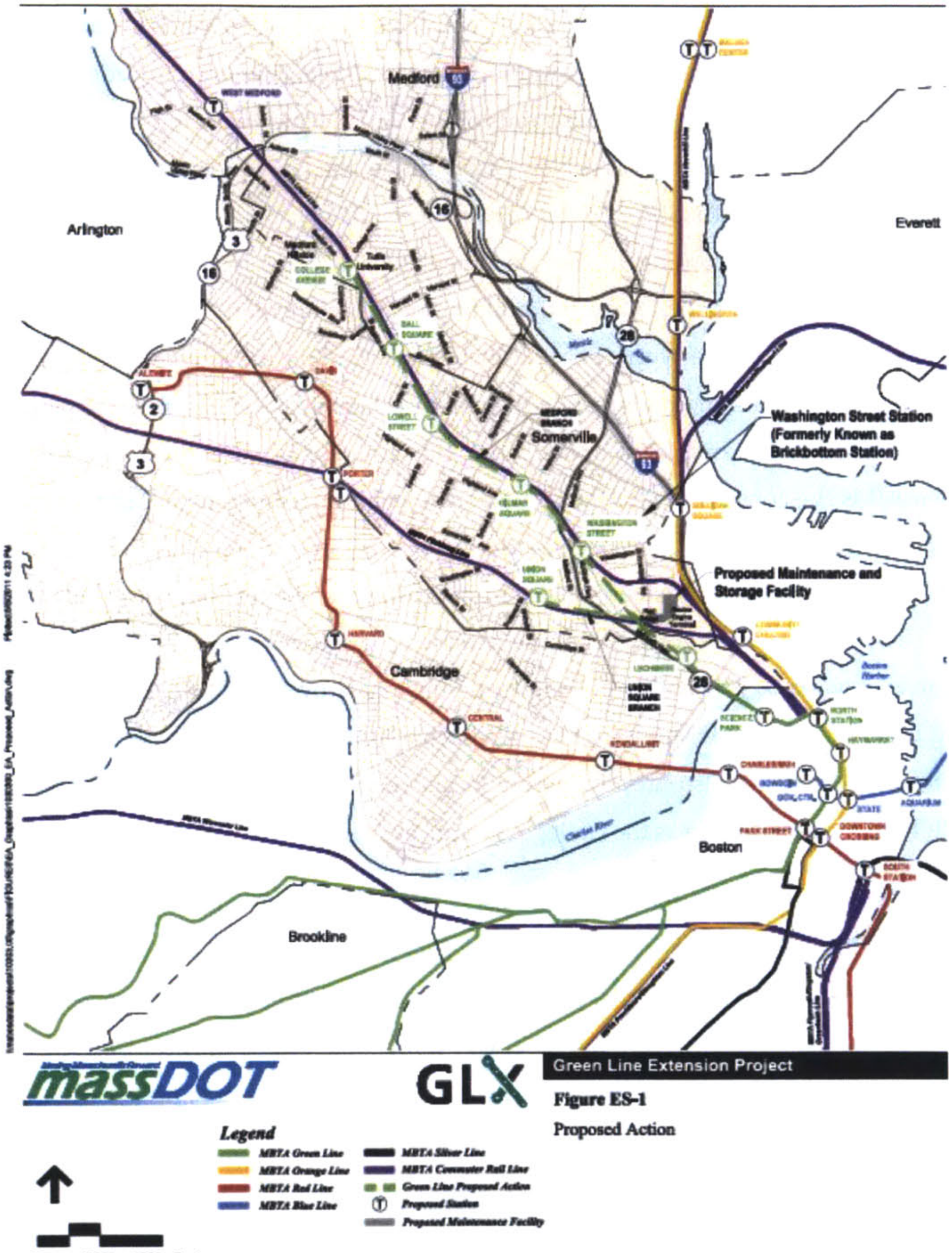
1.1.1. Mitigation Proposals

The Green Line Extension (GLX) is part of a commitment to increase public transit in response to a lawsuit related to the Central Artery/Tunnel project. The Massachusetts State Implementation Plan (SIP) has therefore been amended to include the following requirement:

> (j) Before December 31, 2014, construction of the following facilities shall be completed and opened to full public use:
>
> 1. The Green Line Extension from Lechmere Station to Medford Hillside;
> 2. The Green Line Union Square spur of the Green Line Extension to Medford Hillside (MassDOT, "Amendments", p. 2).

The current GLX design will extend the Green Line in two branches as outlined in the SIP. The "mainline" Medford Branch will operate along the existing MBTA Lowell Line commuter rail right-of-way, from the relocated Lechmere Station to College Avenue Station in Medford. The second branch will operate along the existing MBTA Fitchburg Line commuter rail right-of-way, from the relocated Lechmere Station to Union Square Station in Somerville. The two branches will be 3.4 miles and 0.9 miles, respectively. A map showing the existing system plus the proposed Green Line extension can be seen in Figure 1-1. In total, the extension will include the construction of seven new light rail stations: Lechmere replacement (relocated light rail and bus station), Washington Street, Gilman Square, Lowell Street, Ball Square, College Avenue, and Union Square. Additional project tasks include reconstructing bridge structures; constructing a vehicle maintenance and storage facility; changing and building signal, communication, and power systems; extending the Somerville Community Path (for pedestrians and bicyclists in the corridor); and acquiring new Green Line vehicles. Some of the tasks associated with the project, such as the Community Path extension, are not actually part of the SIP commitment but have been included in the project design.

Figure 1-1 Green Line Extension Map



Source: United States Department of Transportation Federal Transit Administration, Commonwealth of Massachusetts Department of Transportation. *Environmental Assessment (EA) and Section 4(F) Evaluation for the Green Line Extension Project Cambridge, Somerville and Medford, Massachusetts.* Executive Summary. October 2011

Although the SIP requires the GLX to be open to the public by the end of 2014, the project timeline from August 2011 included a project completion date of December 13, 2019 (MassDOT and Massachusetts Bay Transportation Authority, *Critical Path Schedule*). In order to deal with large project risks and the financial constraints of the MBTA which have inhibited access to U.S. Federal Transit Administration (FTA) New Starts funds, the GLX project is being broken into multiple phases. MassDOT's *SIP – Transit Commitments Monthly Status Report for December 2012* includes four phases. According to that document, Phase 1 involves widening two railroad bridges and demolishing a MBTA owned building near Lechmere in order to provide parking and staging areas for future work. Phase 2 includes extending the Green Line from the new Lechmere Station to Washington Street on the mainline branch as well as to Union Square. This phase is expected to be completed in late 2016 with testing, startup and full opening in early 2017. Phase 3 is the construction of the vehicle maintenance facility and storage yard, and it is scheduled to be completed about six months before the start of revenue service to College Avenue. Finally, Phase 4 will extend service from Washington Street Station to College Avenue Station. The plan is to have this final phase completed by July 2019. Risk evaluation suggests that there is only a 50% probability of completing this phase by June 2019 but a 90% probability of being done by July 2020 (MassDOT and Massachusetts Bay Transportation Authority, *Green Line Extension*). There are also proposals from local communities to achieve a further extension to Route 16 in the same phase as the College Avenue extension.

Given the delay in opening the GLX, MassDOT and the MBTA must undertake mitigation efforts. The SIP amendment states that "for delayed projects, [the Executive Office of Transportation] shall implement interim emission reduction offset projects or measures during the period of delay" (MassDOT, p. 4). These mitigation efforts must result in emission reductions greater than or equal to those of the initial project and be applied to "the transit ridership area of the delayed project" (MassDOT, p. 4).

The need for the GLX, and for interim mitigation, is augmented by other changes occurring in the Boston region. Anticipated development along the GLX corridor is expected to generate additional ridership on the Green Line. However, this development will likely be hindered by the delay, which will in turn cause a further delay in the establishment of ridership along the extension. Construction in the region will also increase the need for transit usage along the GLX.

In particular, the three year construction project on the Longfellow Bridge connecting Cambridge and Boston will reduce auto capacity across the river, eliminating all auto traffic along that bridge from Boston into Cambridge. This significant reduction in auto capacity will likely cause more people to take the Green Line as an alternative means of crossing the river.

In June 2012, MassDOT, with the help of the Central Transportation Planning Staff (CTPS), released a matrix listing 122 ideas and recommendations received from the public for interim mitigation measures for the delay of the GLX (121 new proposals plus a proposal to open the GLX in phases) (MassDOT, *Mitigation Ideas*, 2012; Peterson, 2012). The measures include projects broadly related to transit, vehicle policy, technology, research, parking, non-motorized modes, local improvements, land use, and fare policy. Based on MassDOT's qualitative assessment of the proposals, only 14% of the proposals were considered to have high emissions reduction potential (one or two on a five-point scale), and 32% were considered to have little or no emissions reduction potential (five or NA on a five-point scale). Of the proposals, 74% would impact the Cambridge/Somerville/Medford market impacted by the GLX path, and 66% would impact the Boston market. Almost all (88%) of the proposals were considered to have a high likelihood of being able to be implemented before 2015.

Since the mitigation is for a transit project, most of the proposals included on the MassDOT list would be implemented partially or entirely by the MBTA. The 17 proposals on the MassDOT list with the highest emissions reduction potential were exclusively transit or transit technology related, and the implementing entity would be the MBTA. The MassDOT list is not exhaustive and includes many proposals that cannot fulfill the SIP mitigation requirements due to timing, impact or other limitations such as operational or financial limitations. It is therefore important for the MBTA to investigate these and other possible mitigation projects to address the delay in the opening of the GLX and to determine which proposals they believe to be the most viable. Mitigation options that the MBTA could undertake include frequency and route adjustments for both bus and light rail routes.

The MassDOT list of mitigation ideas was constrained by the MBTA's financial situation and limited vehicle and operator availability. The proposals on the list relating to increasing rail or bus frequencies were restricted to the off-peak period. Due to the strong ridership impact potential of the peak periods, this constraint results in a list that is likely to make it impossible to achieve the required emissions reductions. While some of the MBTA's financial issues are expected to be resolved by the legislature, these actions will not help with the current vehicles constraint. Although the mitigation requirement addresses air quality impacts, transit ridership is treated as a proxy for emission reduction because the delay in project completion has also delayed the anticipated mid-term and long-term mode share impact as the ridership and land use mature.

While the scenarios considered by this research are specific to the Green Line Extension project, other transit agencies may have to go through a similar process when confronted with the demands of increased ridership and the need to address growing environmental concerns. On a statewide level, MassDOT Secretary and CEO Richard Davey announced a goal of tripling the share of statewide travel by transit, bicycling and walking. This goal cannot be met by improving transit within the MBTA system alone, so changes by other transit providers in the state will need to be considered. On a national level, many other cities are implementing air quality and climate change policies that will likely require transit changes. Additionally, as the EPA is required to issue regulations to reduce greenhouse gas emissions nationwide, many states are considering short and long term improvements in public transportation as an effective strategy to meet these new requirements. The types of proposals considered here and the techniques explored in this thesis to predict the ridership impact of transit improvements are likely to be useful to other agencies exploring system alterations.

1.1.2. Analysis Methodologies

The list of mitigation ideas released by MassDOT contained 122 projects, but it was not an exhaustive list of the possibilities for mitigating for the delay of the GLX, nor did it provide guidance on prioritizing the list for implementation. MassDOT said that the analysis provided with the matrix was "preliminary, qualitative assessments of the potential benefits and viability of the different ideas" and that the next step would be to formally analyze the proposals using the air quality modeling methodologies of the CTPS (MassDOT, *Mitigation* Ideas, 2012).

The key method available to CTPS is their regional demand model. Running the regional demand model for every possible mitigation proposal would be time consuming and costly. Given the time and monetary costs associated with running the large regional model, other methods could help save costs by doing initial analyses to limit the number of proposals that need to be tested using the regional model. These screening methods use transit ridership growth as a proxy for the capability of the proposed changes to reduce air pollution emissions.

Agencies in other cities considering transit system changes often face similar challenges in using a regional demand model that is time consuming and costly to use. Therefore other agencies would similarly be aided by the availability of alternative methods for the preliminary ridership analysis of service change options being contemplated.

1.2. Objectives

This research seeks to develop proposals of projects that the MBTA could undertake to mitigate for the delay of the Green Line Extension and to create easy-to-use analysis methodologies for determining the best proposals for further investigation and implementation. The mitigation ideas focus on the public transit system, particularly in the area of Lechmere Station where the GLX will begin. Proposals relate to both rail and bus services and range from the alteration of current services to the creation of new services. The proposals have been developed with consideration of the context of financial constraints and operator and vehicle availability limitations within the MBTA.

Two "sketch planning" analysis methodologies are used to examine the proposals. A comparison of the two methods helps determine the strengths and weaknesses of each method. It is expected that the analysis methodologies developed will provide alternative methods for the initial analysis of system changes and the determination of which proposals to prioritize for further work.

1.3. Research Approach

This thesis is arranged around several types of mitigation proposals. The potential analysis methodologies that would be applicable to each proposal are considered and the best methods are then applied and compared.

Since the issue at hand is a delay in changing light rail routing, potential changes to rail service is the first consideration. Bus routes in the study area are then considered for both service interval changes and then routing changes. For each proposal, the number of additional vehicles required is calculated in order to address limited vehicle and operator availability and as a major component of the costs associated with service. The impact on ridership is then calculated using a variety of methodologies.

Based on the ridership data available, two primary methods are used to predict the ridership impact of the proposals in this thesis. The first method of service elasticities builds directly upon current ridership to predict the response to a service alteration. The second method of applying a direct demand model uses current ridership and service information to specify a model that can then be applied both to changes to existing service and to the introduction of new services.

Both of the methods selected for this analysis are types of sketch planning models. To fully explore the possible mitigation opportunities, the MBTA should test as many options as possible. However, the limitations of the CTPS model make it unlikely that MassDOT and the MBTA will analyze as many proposals as would be ideal. These ridership estimation methods are intended to provide screening tools for the preliminary analysis of options prior to using the time and data intensive regional model typically used by the CTPS.

Table 1-1 summarizes three types of ridership estimation methods. This thesis seeks to provide an alternative to having to use a regional model such as that used by CTPS for analyzing all mitigation proposals available. To this end, elasticities are used as an example of a comparison equation approach and a direct demand model is used as an example of a regression model approach. These two alternative options can be used to compare amongst proposals in order to help determine which should be analyzed further using the CTPS regional model, and in some cases which should be implemented without further study.

Table 1-1 Ridership Estimation Methods Summary

Method	Description	Advantages	Disadvantages	Examples
Comparison Equations	Ridership comparisons to past experiences or existing routes based on a single explanatory variable.	Simple, fast calculations. Can potentially combine methods or make existing methods more robust.	Often rely on qualitative judgments. Most methods cannot capture more than one variable at a time.	Elasticities, individual or household trip rates
Regression Models	Regression based models of transportation system based on multiple explanatory variables.	Varying complexity levels. Can be designed to capture local effects.	Often best used for order-of-magnitude comparisons. May require large and/or complex data sets.	Direct demand models, route-level patronage model
(4-Step) Regional Model	Regional model using travel network and demand forecasting programs (ex. TransCAD, Cube, Emme).	Can capture full transportation system effects (multi-modal, network effects).	Complex to run. Planning unit of operating agency may not have direct access to model. Regional scale may not capture some local impacts.	MPO regional 4-step models

1.4. Thesis Organization

Chapter 2 reviews previous work on analysis methodologies for ridership responses to system changes with a focus on elasticities and other sketch planning models. Chapter 3 then discusses in further detail the methodologies considered for this thesis, including the data sources needed and used here. In particular, this chapter introduces trip rates and the creation of a direct demand model as an analysis methodology for examining the ridership impact of proposals. The following three chapters then discuss different types of mitigation proposals and the analysis methodologies that can be applied to the proposals to predict ridership. Chapter 4 focuses on light rail, proposing the extension of additional Green Line service to Lechmere and using elasticities to calculate the resulting change in ridership. Chapter 5 examines changes to existing bus routes and alternative ways to increase service on existing routes. Chapter 6 extends upon the previous chapter by applying the analysis methodologies to new bus routes. Two types of new bus routes are examined in Chapter 6: creation of a new cross-town route and providing public access to private routes. Finally, Chapter 7 will summarize the findings of the previous chapters, make recommendations for how the MBTA and MassDOT can use the results of this work, and suggest future work.

2. Literature Review

A key component of this thesis is the use of two transit ridership demand estimation methodologies. Before applying these methods, this chapter reviews previous literature on elasticities with a particular focus on the elasticity of demand with respect to service, and other sketch models with a particular focus on direct demand models. The concepts behind both methods are discussed, the findings of previous work are introduced, and select prior applications are presented.

2.1. Elasticity of Demand With Respect To Service

Elasticities measure the change in demand in response to a change in another feature of the transportation system. The other feature can be a measure of transit price or service, or even a measure related to another transportation mode. Elasticities can be applied to provide an estimate of the expected change in demand when a new service level is considered. In *Traveler Response to Transportation System Changes Interim Handbook,* Pratt et al. (2000) state that "when used with caution, elasticities provide a satisfactory means of quickly preparing first-cut, aggregate response estimates for a number of types of system changes" (p. A-1).

There are two main approaches for estimating elasticities: the experimental (or quasi-experimental) approach and the non-experimental approach. The experimental or quasi-experimental method relies on data from monitoring actual service changes and demonstrations. In comparison, in the non-experimental approach there is no actual change to be observed or the change is part of a historical time series analysis of annual data. Non-experimental methods can include time series analysis, aggregate direct ridership and modal split models, and disaggregate behavioral mode-choice models. While these latter methods may result in elasticity estimations, they do not always control for non-service changes and may not include changes in transit services (Lago, Mayworm and McEnroe, "Transit", 1981).

2.1.1. Elasticity Concept

At the most basic level, an elasticity measures the sensitivity of one variable to another. More specifically, an elasticity "tells us the percentage change that will occur in one variable in response to a 1-percent increase in another variable" (Pindyck and Rubinfeld, 2005, p. 32). In economics, the core concept of price elasticity looks at the sensitivity of quantity demanded to price changes. In transportation, elasticities typically measure the ridership response to fare or service changes.

A positive elasticity denotes a direct relationship, while a negative elasticity denotes an inverse relationship between the two variables being studied. For example, the elasticity of ridership with respect to route headways will be negative because as the headway increases ridership is expected to decrease. In comparison, the elasticity of ridership with respect to frequency of service will be positive because ridership is expected to increase with frequency increases.

Demand can also be considered elastic or inelastic with respect to a given parameter. If demand is elastic with respect to a parameter, a 1 percent change in the parameter will result in a greater than 1 percent change in demand and the absolute value of the elasticity will be greater than 1. If the reverse is true and a 1 percent change in the parameter results in less than a 1 percent change in demand, then demand is considered inelastic and the absolute value of the elasticity will be less than 1. In transportation, demand is inelastic to most system changes, including most service increases (Pratt et al., 2000).

There are four methods of calculating elasticity: point elasticity, arc elasticity, midpoint elasticity and shrinkage ratio. The different methods will give approximately the same results when the percentage change in price or service is small. However, the methods will result in different elasticities when large changes in price or service are examined.

Point elasticity is the method most directly related to the economics definition of elasticity and is described by the formula:

$$\varepsilon_{pt} = \frac{dQ}{dS} \times \frac{S}{Q} \qquad \text{2-1}$$

where ε_{pt} is the elasticity at service level S, and Q is the ridership demanded at that service level. Calculation of the point elasticity requires information about the functional relationship between service level and ridership which cannot be determined from limited empirical data. The point elasticity is therefore not generally used in calculating transit elasticities (Pratt et al., 2000).

Arc elasticity is the closest approximation of point elasticity. Arc elasticity has a logarithmic formula and can be further approximated by the midpoint elasticity, also referred to as the linear arc elasticity. The midpoint formula closely approximates the logarithmic arc elasticity formula except for when very large changes in the parameters are examined. The logarithmic arc and midpoint (or linear arc) elasticities are given by the following formulas:

Logarithmic arc elasticity: $$\varepsilon_{arc} = \frac{\Delta \log Q}{\Delta \log S} = \frac{\log Q_2 - \log Q_1}{\log S_2 - \log S_1} \quad 2\text{-}2$$

Midpoint (linear arc) elasticity: $$\varepsilon_{mid} = \frac{(Q_2-Q_1)}{(Q_1+Q_2)/2} \div \frac{(S_2-S_1)}{(S_1+S_2)/2} = \frac{(Q_2-Q_1)(S_1+S_2)}{(Q_1+Q_2)(S_2-S_1)} \quad 2\text{-}3$$

where Q_1 and Q_2 are the demand before and after the service alteration, and S_1 and S_2 are the service measures before and after. These two formulas are used in almost all elasticity calculations included in previous literature.

The final elasticity formula is for the shrinkage ratio, which is calculated using the formula:

$$\varepsilon_{sr} = \frac{Q_2-Q_1}{Q_1} \div \frac{S_2-S_1}{S_1} = \frac{\Delta Q/Q_1}{\Delta S/S_1} \quad 2\text{-}4$$

where Q_1 and Q_2 are the demand before and after, and S_1 and S_2 are the service measures before and after. This formula was previously used to report ridership response to transit fare changes (Pratt et al., 2000). However, most literature no longer reports the use of the shrinkage ratio concept because it generates asymmetric results for increases and decreases in service or price (Lago, Mayworm and McEnroe, "Transit", 1981; Pratt et al., 2000).

2.1.2. Service Quality Elasticity

Goodwin (1992) asserts that "empirical knowledge of the size and variability of travel demand elasticities has had an important effect on thinking about transport policy" (p. 155). A travel attribute with a low elasticity will be an ineffective lever for influencing demand. It is therefore important to understand the elasticity of demand with respect to service attributes in order to understand the impact that changes will have on ridership. Service quality is a key determinant of ridership and can include both time factors (travel time, service intervals, access/egress) and other non time factors (waiting environment, service reliability, vehicle quality, bus-specific issues) (Balcombe et al., 2004). The impact of some, but not all, of these service characteristics on ridership can be quantified by elasticity measures.

Less information is available about the effect of service characteristics on ridership than is available on the effect of fares. This is because it is more difficult to measure the impact of service changes. To begin with, there is no single measure of service quality. In addition, changes in service quality are often made incrementally, making it difficult to isolate and study the impact of the changes (Balcombe et al., 2004). Furthermore, service frequency changes are often made with other concurrent service alterations such as changes on other routes, implementation of clockface headways or improvements in passenger information provision, so that empirically derived elasticities reflect the combined impact and not purely the frequency change (Evans, 2004). Much of the data on service elasticities is dated, however recent findings "suggest that basic relationships between transit service level changes and impacts on ridership are remaining stable over time" (Evans, 2004, p. 9-3). At the same time, research has shown that fare elasticities have increased over time (Goodwin, 1992).

There are many service quality changes that can be made to affect ridership. Some of these changes include frequency changes, service hours alterations, frequency changes with fare changes, implementation of combined service frequencies (for example local plus express services), regularized schedules, information provision and reliability changes. Frequency, service hours and combined service changes directly impact waiting times. Changes to make schedules easier to understand or improve reliability can reduce both real and perceived waiting times and lower passenger anxiety, thus also increasing the attractiveness of service. Other changes, such as waiting environment or rolling-stock enhancements, aim to improve the conditions of the wait or in-vehicle time in order to improve the passenger experience.

Service intervals, in particular, are an important tool for affecting ridership in a system, and elasticities can be used to measure the impact of service interval changes on ridership. Service intervals can be characterized by headways, frequencies or vehicle-miles traveled. The analysis in the following chapters makes use of frequency or headway elasticities. Frequency and headway elasticities have comparable values and are often used interchangeably. However frequency elasticities are positive while headway elasticities are negative.

In the cases below, headway information is more readily available than vehicle-mile data. However, in some cases vehicle-miles operated is considered a good proxy as an aggregate indicator for a system. While headway or frequency elasticities work well for examining simple headway / frequency adjustments, vehicle-miles operated measures can be used to examine these changes as well as accessibility changes including changes in route density, area of coverage and hours of service (Lago, Mayworm and McEnroe, "Transit", 1981). Also, elasticity is a relative measure, so headway elasticity cannot be calculated for a new route, but a vehicle-miles elasticity for the full system can be calculated. When examining a fixed length route and fixed period of operation, vehicle-miles operated and headway elasticities should be proportional. However, a change in service hours can be reflected in vehicle-miles operated but not by a change in headway. Changes in route-length and network density can similarly be examined through the use of vehicle-miles operated elasticity, but any change in ridership may also be the result of the change in accessibility due to the route changes (Balcombe et al., 2004). Thus, headway and vehicle-mile elasticities have historically been comparable (Lago, Mayworm and McEnroe, "Transit", 1981), but other potential influences on ridership should be noted.

Service Interval Changes

In the second edition of *Traveler Response to Transportation System Changes,* Pratt and Copple (1981) warn that "any specific situation must be examined in terms of the particular urban form, population, travel patterns, and transportation systems involved" (p. 9). These differences in situations underlying service changes and the unique characteristics of individual routes result in a range of values for the elasticity of demand with respect to service intervals. In the updated version of Pratt and Copple's work, Evans (2004) calculates an average response to frequency changes of +0.5. This average is in line with Lago, Mayworm and McEnroe's (1981) headway elasticity average of -0.47.

The average demand elasticity calculated in previous literature is highly dependent on the choice of studies included in the calculation. Evans (2004) points out that although he provides an average elasticity of demand with respect to frequency of +0.5, this does not capture the grouping of recent individual estimates around +0.3 and +1.0, with the lower elasticities tending to be seen in urban cases and the higher ones seen in suburban cases and situations involving more comprehensive expansion programs. Balcombe et al. (2004) focused their review on the European experience and calculated a bus elasticity of demand with respect to vehicle-km of +0.38 in the short run and +0.66 in the long run.

A historical experience from the U.S. that is commonly used in literature is the Mass Transportation Commission of the Commonwealth of Massachusetts service improvement and fare reduction experiments of the early 1960s. This remains "the most comprehensive quasi-experimental data set on individual transit route frequency change impacts available" (Evans, 2004, p. 9-30). These experiments resulted in a median headway elasticity of -0.4 (-0.6 omitting depressed urban areas). Although these elasticities are in line with the average elasticity, they may be slightly understated due to the short duration of the experiments and the use of revenue as a proxy for ridership (Pratt and Copple, 1981; Evans, 2004).

In recognizing the grouping of recent elasticity calculations around two points, Evans (2004) began to recognize how the circumstances surrounding individual elasticity numbers can help establish elasticity breakdowns for different conditions. The data available is insufficient to determine if there is a significant difference between elasticities for service increases and service decreases, although none of the highest reported elasticities have been for service decreases (Evans, 2004). Instead, most of the variation in ridership responses can be attributed to differences in the pre-existing level of service, the time period during which service was adjusted, the geographic and demographic environment, or the time period examined.

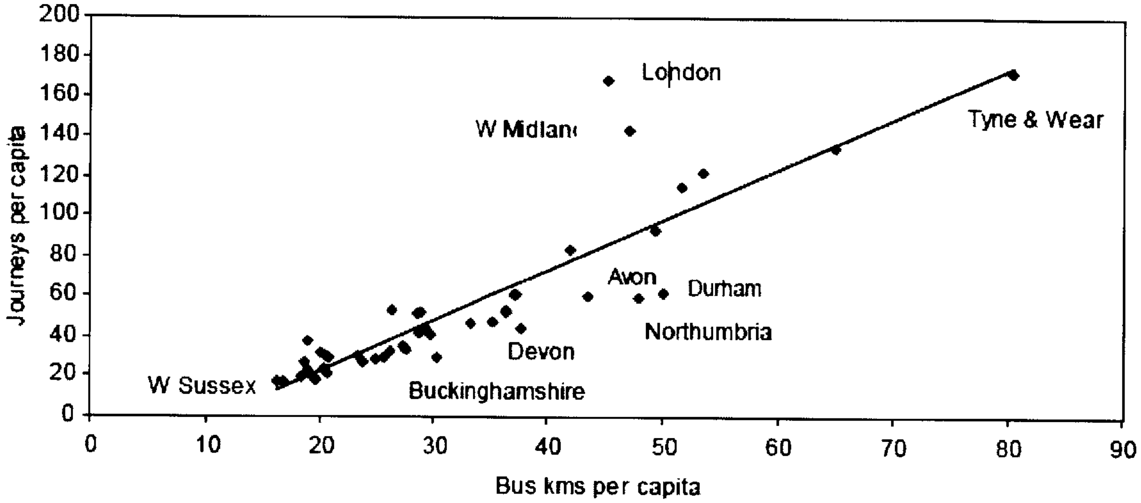
One of the most common breakdowns of elasticities is based on the pre-existing level of service. When initial service is poorer, increases in service will have a greater impact on ridership and the elasticity will be greater. Table 2-1 shows bus headway elasticities by service level from Lago, Mayworm and McEnroe ("Transit", 1981, p. 101). These numbers are commonly repeated in more recent research, including *Traveler Response to Transportation Planning* (Pratt and Copple, 1981; Pratt et al., 2000; Evans, 2004).

Table 2-1 Bus Headway Elasticities by Service Level (Lago, Mayworm and McEnroe, 1981)

Original Service Level	Number of Observations	Elasticity	Standard Deviation
High (< 10 minute headways)	7	-0.22	0.10
Medium (10 - 50 minute headways)	6	-0.46	0.18
Low (> 50 minute headways)	10	-0.58	0.19
Aggregate Value	23	-0.44	0.22

The direct relationship between service level and ridership is further supported by Dargay and Hanly's (1999) finding a strong positive correlation between vehicle kilometers operated per capita and journeys per capita in English counties as can be seen in Figure 2-1 (qtd. in Balcombe et al., 2004).

Figure 2-1 Relationship Between Bus Vehicle-km and Bus Trips in English Counties (average 1987 to 1996) (Dargay and Hanley, 1999 qtd. in Balcombe et al., 2004)



The influence of initial service levels on elasticities can be seen with other breakdowns as well. Elasticities are generally greater during off-peak periods, when service levels tend to be lower compared to peak periods. Further breaking down time periods, Preston (1998) found service elasticities to be greatest in the evening and on Sundays (qtd. in Balcombe et al., 2004).

Similarly, rural areas that typically have lower service levels have been observed to have greater elasticities than metropolitan areas (Balcombe et al., 2004). However, when comparing metropolitan areas of different sizes, Balcombe et al. (2004) found that for European cities, small cities (population <500,000) had a vehicle-km operated elasticity of 0.33 compared to 0.49 for large cities. This difference is likely because large cities have more competition from other public transport modes making it easier for passengers to change between modes when bus service is adjusted. Also, large cities often have higher income levels which are associated with more elastic demand due to a higher value of time and more choice passengers that have the alternative of taking a private vehicle (Balcombe et al., 2004; Evans, 2004).

These differences in elasticities have important implications for policy and service changes. When looking to increase service, the greater elasticities in off-peak periods mean that there is likely to be a greater percentage increase in ridership if off-peak service is increased by a fixed percent as compared to when peak service is increased by the same percent. This is due to the lower initial frequencies and the greater level of discretionary travel during the off-peak. If the goal is to maximize the percent increase in ridership, service changes should therefore focus on the off-peak. However, if the goal is to maximize the nominal increase in ridership, the peak should be considered as well since there are more riders to begin with there, so even a smaller percentage increase in ridership in the peak is likely to result in a greater number of new riders compared to a larger percentage increase in off-peak ridership.

Another differentiation to take into account is short run versus long run elasticities. This distinction is important because there is a time lag in ridership response to service changes. It takes passengers time to assess the change in service and adjust their travel patterns. Some passengers may need to terminate old travel arrangements and make new ones based on a new mode or route choice (Evans et al., 2004). Long-run demand is typically more elastic than short-run as travelers are free to break old arrangements and adapt to changes in the long run. In the long run, consumers and firms may change locations and assets (including vehicles owned) that might otherwise be fixed in the short run (Oum, Waters and Yong, 1992). The first one to two years is typically considered the short run, around five to seven years is often considered the medium run, and as much as twelve to fifteen years is sometimes considered the long run.

Early research failed to distinguish between short, medium and long run impacts. Recent research has begun to make this differentiation, with long run elasticities being 50% to three times higher than short run (Goodwin, 1992). Balcombe et al. (2004) recommend a short run demand elasticity with respect to vehicle kilometers of 0.4 and a long run elasticity of 0.7 (Table 2-2), but they also quote Dargay and Hanley's (1999) short and long run elasticities of 0.4 and 0.8, respectively. When Mitrani et al. (2002) estimated a smoothed bus miles model the time lag parameter was set at 0.5, meaning that 90% of the impact of bus service changes occur in the first three four-week periods (qtd. in Balcombe et al., 2004).

Table 2-2 Service Elasticity by Range (Balcombe et al., 2004)

Run	Number of Measurements	Elasticity	Range	Standard Deviation
Short Run	27	0.38	0.10 to 0.74	0.135
Long Run	23	0.66	0.22 to 1.04	0.275

One differentiation that is not made in elasticity measures is in the source of new ridership. There are two possible sources of new or lost riders: mode shifts and new or discontinued trips. Evans et al. (2004) estimates that 10 to 20 percent of new trips generated by a service improvement are due to trips not previously made. Of trips that are attracted from other modes, "in general, one out of every two or three new riders drawn to transit service by frequency improvements would otherwise have driven an auto" (Evans et al., 2004, p. 9-5). In business districts, people who previously walked may also be attracted by frequency increases.

At the same time, changes to individual routes typically also divert some riders to or from other transit services. As a result, while service improvements on a route may generate new ridership along that route, some of those trips may result from reduced ridership on other routes rather than new trips within the system. This redistribution of trips within the system was experienced with a reduction of service in Toronto, Canada. When frequencies were reduced on a single trolley bus route within the system, system-wide ridership decreased by less than that individual route's ridership decreased. This suggests that since the city has a dense transit network, most of the ridership lost on that route merely shifted to other routes. Consequently, mode shifts away from transit and the reduction in total trips taken were both limited in the Toronto experience.

In some cases, shifting trips away from crowded routes or towards underutilized routes can be a good thing. This is the case within the MBTA system where diverting riders from the overcrowded Red Line may be a positive result of increasing ridership on the Green Line. If the goal of a service change is to generate new riders in the system, the diversion of existing riders may be an unintended consequence. However, in the case of the Red Line, diverting ridership from the overcrowded Red Line may permit additional new riders on the Red Line, thus still creating the desired environmental impact. When examining the elasticity of a service change on ridership for a single route, trip shifting within the system and the resulting impact on the system as a whole should therefore be considered.

Bus Routing and Coverage Changes

The elasticity discussion above was for service interval (headway/frequency) changes. Another way of adjusting service is by changing bus routing and coverage. This can be done through a number of changes including the extension or curtailing of existing routes, the introduction of new systems or routes, comprehensive service expansions, service restructuring, and service changes coupled with fare changes. These types of changes are often examined through elasticities with respect to vehicle-miles operated for the full system, or for the individual route for a route expansion, because elasticity measures are a relative measure as discussed above. Service expansions generally have a greater demand elasticity than frequency changes. The middle range of the demand elasticity with respect to regional bus miles of service is +0.6 to +0.9 (Pratt and Copple, 1981) or +1.0 (Pratt and Evans, 2004), with the average around +0.7 to +0.8 (Pratt and Evans, 2004). Elasticities at the upper end of the range often reflect the additional benefits of successful service restructuring.

Again, the work on elasticities for routing and coverage changes is old, but the limited recent findings suggest that the basic relationships between service and ridership have remained stable over time (Pratt and Evans, 2004). Routing and coverage changes can improve the efficiency, effectiveness, and reach of a system, but the success of new or modified routes "is very much a function of how they relate to local patterns and other elements of the transit system" (Pratt and Copple, 1981, p. 178; Pratt and Evans, 2004). More changes or combinations of changes (such as route or schedule changes simultaneous with the introduction of new vehicles) will result in greater elasticities. This is seen in the greater elasticities for comprehensive service expansions compared to changes to individual routes.

The impact of some types of service changes have been studied but not quantified into elasticities. New radial routes have been found to build up ridership approximately equal to that of other pre-existing routes with the same downtown orientation and serving areas with similar socioeconomic demographics (Pratt and Evans, 2004). New cross-town routes, on the other hand, have been found to frequently divert riders from other transit routes (Pratt and Evens, 2004). In many systems, the primary benefit of cross-town routes may be more in the improvement of connections within the system than in the production of new ridership within the transit system. Many bus routing changes will have the added benefit of improving transfers, which are highly penalized by passengers. Research cited by Pratt and Evans (2004) has suggested that passengers penalize transfers in the range of 12 to 15 minutes of in-vehicle travel time per trip in addition to the extra transfer wait time required. Transfer penalties are discussed further in Chapter 4.

Like frequency improvements, new or revised routes may draw ridership from other routes. In fact, this shift from other routes may be even greater in the case of new or revised routes than it is for some service changes on existing routes (Pratt and Evans, 2004). It is therefore important that the effect of new or revised routes "be examined in a system context in order to ascertain the net impact" (Pratt and Copple, 1981, p. 188).

Ridership may also take longer to respond to new routes than to frequency changes on existing routes. New bus routes typically take one to three years to develop their full patronage (Pratt and Copple, 1981; Pratt and Evans, 2004). This time lag in ridership response is an important planning consideration as there may be additional costs associated with maintaining service during this extended period of ridership development (Pratt and Copple, 1981).

Rail Frequency Changes

Compared to bus elasticities, limited information is available on rail elasticities. There is some quasi-experimental data available for rail, but it is primarily for commuter rail, not light rail (Evans, 2004). Similarly, there is little model based information available. There is also a discrepancy in the literature comparing service elasticities for rail and bus.

Much of the historical literature available suggests that rail ridership responses to service changes are generally comparable to bus (Evans, 2004; Lago, Mayworm and McEnroe, "Ridership", 1981). Lago, Mayworm and McEnroe ("Transit", 1981) quoted a commuter rail headway elasticity of -0.47 ± 0.14 based on quasi-experimental data. Furthermore, the elasticities were positively correlated with the original headway and off-peak elasticities were significantly greater than peak elasticities, just as they are for bus service. Evans (2004) looked at the results of the Massachusetts demonstrations (2 cases) examined by Lago, Mayworm and McEnroe plus an example from Philadelphia to find a commuter rail elasticity range of +0.5 to +0.9. Evans' results may have been impacted somewhat by simultaneous marketing efforts and fare adjustments in all three cases (off-peak fare incentives in Boston, fare increases in Philadelphia).

Non-experimental data is also limited for rail, but two successful studies of commuter rail in London resulted in a mean all-hours elasticity of demand with respect to headways calculation of -0.47 ± 11 based on four cases (Lago, Mayworm and McEnroe, "Transit", 1981). Clark (1997), on the other hand, was able to estimate reasonable models for bus and private vehicle, but found that the rail model had unusually high elasticities.

Other studies of European urban rail found that urban rail ridership may be more sensitive to service than bus ridership, but the evidence was limited to a small number of short run estimates (Table 2-3) (Balcombe et al., 2004). Balcombe et al. suggest the more elastic response of rail demand compared to bus demand may be due in part to the greater ability of rail services to appropriate bus ridership when service is improved while bus service is less likely to appropriate rail riders.

Table 2-3 Rail Service Elasticity (Balcombe et al., 2004)

Run	Number of Measurements	Elasticity	Range	Standard Deviation
Run Not Stated *	2	-0.49	-0.33 to -0.65	0.135
Short Run	3	0.75	0.22 - 1.04	0.275

* Based on headway

The only data available for rail rapid transit comes from London Transport and suggests that rapid rail has a lower elasticity of demand with respect to service than bus. London Transport (1993) calculated a miles operated service elasticity of +0.08 for London Underground, which is just under half the elasticity for London buses (qtd. in Evans, 2004). Evans (2004) says that "this general relationship is as would be expected, given the much higher overall service levels typical of rail rapid transit", but that it is "insufficient evidence to safely generalize" about the magnitude of the difference between bus and rapid rail elasticities since it is only one observation (p. 9-13). Mitrani et al. (2002) also recommended an elasticity with respect to unsmoothed train miles of +0.08 for London Underground and compared this number to an earlier recommendation by Kincaid et al. (1997) of +0.09 (qtd. in Balcombe et al., 2004). Mitrani et al.'s calculation is also based on the London Underground, so generalizations still should not be made based on this data. Mitrani et al. also calculated a cross-elasticity of Underground demand with respect to smoothed bus miles of -0.13, suggesting the mobility of riders between bus and rail modes. While the trends observed in London may give insight into expected responses in North America, differences in the systems make it difficult to apply European elasticities to North American systems.

Example of Elasticity Application

Stopher (1992) sought to examine ridership changes on bus routes due to changes in service. He compared two modeling alternatives: an elasticity based model and an econometric model based on socioeconomic and service data. For the elasticity model, Stopher used a model similar to the one developed by Parsons, Brinkerhoff, Quade & Douglas, Inc. for the Dallas Area Rapid Transit (DART) bus system. This spreadsheet model can estimate the impact of service and fare changes on a number of key metrics including ridership. This elasticity model goes beyond simply applying an elasticity number to a single route and instead allows for system-wide analysis by combining the impact seen on all routes across the system. The route level database utilized includes ridership, vehicle miles and vehicle hours, service characteristics, and fare information for each route. The database also contains information on unit costs per vehicle mile and per vehicle hour, and service and fare elasticities calculated based on other transit systems' experiences. This model is advanced in its use of applying different elasticities for each service period and route type as well as a step formula for applying the elasticities. The model can also examine the total impact of combinations of service changes. However, this model cannot be applied to a new route. The model also has limitations due to the data set used, including the fact that the elasticities were not calculated based on local examples and do not account for differences in residential and employment differences along the routes. The model also limits the size of the service change that can be examined (the elasticity is set to 1 for any change over 50% of the existing value) and inter-route impacts are not incorporated.

2.2. Other Sketch Planning Models

Ridership forecasts are commonly used by transit agencies when considering changes to their system. These forecasts can range from formal to informal, with varying levels of complexity. A 2006 Transit Cooperative Research Program (TCRP) report by Daniel Boyle surveyed transit agencies and found that the top reasons cited for preparing ridership forecasts were for a new route, major route changes, a new mode or type of service, for the next 5 or 10 years, or for the next fiscal year. The method used to produce the forecast depends on the change being analyzed as well as the time frame and the mode. The most common techniques are qualitative, including professional judgment and rules of thumb based on similar route analysis. Elasticities and four-step travel demand models are also common and are used by at least half of the agencies that responded to the survey.

The classic four-step area-wide transportation planning model is currently the most common complex quantitative method in use. In the case of the MBTA, the staff of the Boston Region metropolitan planning organization (MPO), the Central Transportation Planning Staff (CTPS), maintains a regional model and the MBTA commissions CTPS to run specific scenarios periodically. One of the key drawbacks to using a four-step model is the time and cost associated with running the model. The complexity of regional travel demand models makes them "in theory... the best tools for evaluating new transit services" (Marshall and Grady, 2006, p. 182). In reality, these models focus primarily on traffic counts and may lack detailed accuracy in modeling the transit network, for example by only using a subset of all bus stops (Marshall and Grady, 2006). Cervero (2006) discusses additional shortcomings of four-step models that have led researchers and transportation professionals to look for alternative methods for forecasting ridership. To begin with, the four-step model is not intended to estimate travel impacts on the neighborhood or local scale. The models are conducted using traffic analysis zones (TAZs), which vary in size from block groups to census tracts and therefore lack the detail to analyze small scale changes near stations and fail to capture local movements. In addition, not all variables impacting travel behavior are captured by the models, including land use. Feedback between travel and land use is also missing from four-step models. Another shortcoming discussed by Cervero is the mode choice specification, which often excludes non-motorized modes and does not account for transit oriented development (TOD).

Several attempts have been made to adapt or replace traditional four step models in order to address their shortcomings. Some of the methods seek to directly alter the four-step model. Examples of these methods are: the inclusion of auto ownership models, pre-mode choice models to estimate walk and bike trips, intra-zonal estimates to supplement trip distribution models, and re-specified mode-choice models. New model approaches are also being developed including disaggregate models and tour-based models, but these are still in the developmental phase (Cervero, 2006).

Alternative methods to traditional forecasting models are being used with increasing frequency to capture impacts missed by large-scale models and to "generate demand estimates quickly and economically" (Cervero, 2006, p. 288). This class of models is commonly referred to as sketch models. One example of this type of analysis is pivot point analysis, which typically uses current ridership as the basis for ridership forecasts (Marshall and Grady, 2006). Alternatively, pivot point analysis can use the outputs of other models and adjust for effects not accounted for in the initial model through post-processing of the results (Cervero, 2006). Based on the initial ridership numbers or estimates, forecasts can be calculated using elasticities or incremental adjustments. Elasticities can be calculated from historical data to capture the relationship between ridership and variables not typically included in other model formulations. Other changes can be captured by applying an incremental change in ridership. For example, an incremental change in ridership can be applied to account for an expanded service area due to the introduction of express service (Marshall and Grady, 2006).

2.2.1. Direct Demand Models

Direct demand models are a sketch modeling method with intermediate complexity between that of pivot point analysis and full four-step models. Direct demand models, also referred to as direct ridership models or off-line models, focus on station environments and service, and they do not consider the route or destination of the trip. Direct demand models forecast boardings or alightings at an individual stop "on the basis of the intensity of services flowing into it (e.g., frequency of buses), its surrounding environment (e.g., population densities), and its site features (e.g. presence of a bus shelter)" (Cervero, Murakami and Miller, 2010, p. 1). Direct demand models have been particularly favored for studying land use interactions with transportation and the impact of TOD due to the local nature of the data included.

Direct demand models have been developed for many rail networks in the United States. One drawback of this modeling approach is that when examining an individual rail system, the small sample sizes used often limit the number of variables that can be included in the model specification (Cervero, 2006; Cervero, Murakami and Miller, 2010). However, the key power of direct demand models is in providing order-of-magnitude insights for testing various system designs and land use scenarios. Cervero, Murakami and Miller (2010) call direct demand modeling "a fairly stripped-down, sketch-modeling approach that allows empirically informed estimates of patronage to be produced at a fraction of the cost" (p. 6).

Although sketch models are intended to be faster and less expensive than traditional four-step models, creating a sketch model for a particular location and situation can still be time consuming. As a result, TCRP commissioned a study in the early 1990s to create nationally applicable sketch ridership models for commuter rail and light rail. The models were then updated by Lane, DiCarlantonio and Usvyat in 2006. The authors' goal was to estimate a model that would be:

- applicable to a range of cities and projects
- easily used by planners with basic GIS understanding
- based on readily available, off-the shelf demographic and transportation data
- accurate within a reasonable margin of error.

Data was collected from MPOs and the 2000 Census Transportation Planning Package for 17 regions, 1,218 commuter rail and light rail stations, and 163 possible explanatory variables. Daily station boardings was used as the dependent variable and independent variables for station-area demographics (120 variables), station-specific transportation attributes (23 variables), corridor demographic characteristic (7 variables), and metro area demographic characteristics and transportation attributes (13 variables) were tested. The resulting commuter and light rail models used the natural log of daily boardings as the dependent variable and contained a constant plus 11 and 9 independent variables, respectively. The variables included in the 2006 models are shown in Table 2-4. Many of the headway variables were excluded because of concern about the direction of causality between headways and ridership, since headways can both affect and be affected by demand. The authors note that reverse causality "can yield a good-fitting model with significant variables but very poor predictive power" (Lane, DiCarlantonio and Usvyat, 2006, p. 205).

Location specific direct demand models have historically been estimated for fixed-guideway systems to analyze transit scenarios, particularly when TOD considerations needed to be included. Cervero (2006) gave three examples of direct demand models he developed for several situations in which TOD scenarios could not be properly captured by traditional four-step models.

In the case of Charlotte-Mecklenburg, a direct demand model was developed when the region's four-step model was determined incapable of forecasting the impacts of the TOD being discussed because the TAZs used were too large to capture local changes and land use variables were not included in the mode-choice model. In this case, no local data on fixed-guideway systems was available, so national data from the TCRP H-1 study was used. This is the same study that produced the two national models discussed above. Cervero believed the original TCRP model mentioned above was underspecified and should not be used in this situation. In particular, Cervero noted that the TCRP model did not include a measure of transit service levels. He therefore re-estimated the model including additional variables. Cervero's model had a better statistical fit than the original TCRP model, and post-processing was used to further adjust the model results. This direct demand model was successfully used along with a modified four-step model to help the city and county governments and voters make well informed decisions that eventually led to the construction of several fixed-guideway transit lines.

Cervero, along with Walters, also used a direct demand model in the San Francisco Bay Area when the board of directors of the Bay Area Rapid Transit (BART) system needed an analysis of a system extension faster than could be produced using the region's travel model. The board also wanted station by station ridership projections and an analysis of system characteristics that are not distinguishable in the regional model. In this situation, Cervero found that "regional modelers accepted the direct modeling approach as a credible basis for generating first-cut ridership estimates for alternative service and land-use scenarios" (p. 292). Furthermore, the consultant for the study later used the direct demand model to generate initial ridership predictions for heavy rail scenarios in Boise, Idaho, indicating that they believed the relationships in the model would hold even in a different city (Cervero, 2006).

A third direct demand model that Cervero discussed was estimated for the extension of St. Louis, Missouri's light-rail system, MetroLink. Again, direct demand modeling was used when the four-step model was thought to be unable to capture the impact of TOD. The direct demand model focused on capturing three types of transit submarkets: walk-on riders, feeder-bus riders, and park-and-ride riders. Variables pertinent to each of these submarkets were included in the model. While this model captured local experience, there was concern that the existing system did not have any TOD examples included in the analysis. As a result, the national TCRP model generated for Charlotte-Mecklenburg was also used to reflect TOD conditions more similar to those anticipated for the system extension. An average of the two models was ultimately used for the final ridership forecasts, which were found to be significantly higher than the local model.

Like the models discussed so far, most past direct demand models have been used to predict rail ridership. Cervero, Murakami and Miller (2010) extended the method to forecast ridership for bus rapid transit (BRT). Their model was developed to examine the ridership impact of upgrading a low-end BRT service to high-end BRT in Los Angeles County, California. Cervero, Murakami and Miller used ordinary least squares regression to estimate a final model that incorporates nine explanatory variables to predict average daily boardings and has an R-squared value of 0.952. The model was based on data on 22 candidate variables for 69 BRT stops in Southern California. The authors focused on interactive terms, something not seen frequently in prior rail direct demand models. The interactive terms used in this case were BRT specific and incorporated the interaction between operating on a bus-only lane and other variables in order to account for the quality of BRT service provided at a stop. The final model performed well and was able to capture the magnitude of the ridership impact of the planned changes to the BRT system with the addition of dedicated lanes. Still, the authors warn that the direct demand model is not a substitute for more data-intensive and statistically sophisticated models, but it does provide a useful initial ridership estimate and can be used to test the sensitivity of key explanatory variables.

2.2.2. Other Models

Marshall and Grady (2006) sought to develop a sketch model for the Washington, D.C. region that would be based on the MPO model structure and network, but that would not be controlled by the MPO and could therefore be modified without relying on the MPO. The model created was not a direct demand model, but it still made simplifications over the traditional four-step model approach. Data from the 2000 census was used because that data was recent and is "available in consistent form throughout the United States" (Marshall and Grady, 2006, p. 184). A key drawback of this data source is that the census data includes only work trips. Marshall and Grady's model estimates TAZ-to-TAZ mode shares using a simplified method for forecasting the growth in trips and then a series of binomial logit models to estimate mode splits. A key difference between the sketch model and the MPO model is the authors' inclusion of more detailed land use variables in the logit models.

As discussed above, Stopher (1992) considered the use of an elasticity based model, but he ultimately chose to use an econometric model to generate ridership forecasts for proposed service changes. Stopher's econometric model develops relationships between boardings and variables for residential and employment characteristics of the route service area and service levels. Although the model is based on census tract level data, the final output is ridership changes for the full route being analyzed. In order to get the differentiation between route types and service periods seen in the elasticity model, econometric models were developed for each subset of service type and period resulting in three separately estimated models for each boardings and alightings. Compared to the elasticity model, the econometric models are based on local data, incorporate both socioeconomic and service level data, and can treat routes as interdependent (with additional modifications not done by Stopher). It is also important to recognize that this model set, unlike the elasticity model, can be applied to new routes. On the other hand, the econometric models work at the census tract level, rely on databases that must be updated regularly, and are more complex than the elasticity based model. Stopher concluded that his econometric models could estimate the impact of service changes on ridership, but he did not test changing other features of the model, and the census tract basis of the socioeconomic data makes it possible that these models may not be sensitive to TOD and other land use changes.

Peng, Dueker, Strathman and Hopper (1997) take a different approach to ridership modeling using route-segments and focusing on the interrelationship between supply and demand of service and the interaction between competing routes. Peng et al. argue that single equation models, such as those discussed above, treat level of service as an independent variable and fail to recognize the supply side decision making process. Instead, the authors treat transit ridership and level of service as "both recursive and simultaneous" (p. 161). In addition, service improvements not only increase ridership on the given route, but they also reduce ridership on competing routes so that the net ridership change may be minimal. Peng et al. characterize three possible inter-route relations that must be considered: independent, complementary, and competing.

Peng et al. use route segments as determined by fare zones as the unit of analysis for their model. They note that some of the limitations caused by using route segment level analysis would be avoided with the use of a stop level model, but this would require more detailed data than was available at the time. The model estimated by Pang et al. consists of three equations: demand (ridership), supply (service) and competing routes. Separate models were estimated for five time periods (morning peak, mid-day, afternoon peak, evening, night) and two directions (inbound, outbound), with different variables used in different models in accordance with diverse travel patterns and influencing factors.

Consistent with their initial argument, Peng et al.'s model results show that service supplied positively affects transit ridership while being primarily determined by both previous year and current ridership. Service changes have both a synergistic impact (net change in ridership) and a competing effect (ridership reduction on competing routes). Peng et al. recommend the use of these simultaneous models for examining transit service and land use planning policies at the system level where the models would capture the difference between new ridership and the redistribution of riders. On the route level scale, these models could also be used to examine different service changes and even the introduction of new routes.

Table 2-4 Summary of Previous Direct Demand Models

Authors	Mode	Location	Variables in Final Model
Cervero (2006) (model: Cervero, 1998)	Light Rail	Charlotte-Mecklenburg County, North Carolina	constant, station in CBD, terminal station, park-and-ride, feeder bus services, catchment size (distance to next station), population density, service level, CBD employment and density interactive term, municipality
Cervero (2006) (model: Walters & Cervero, 2003)	Heavy Rail & Commuter Rail	San Francisco Bay Area, California	constant, station-area densities, catchment populations, service frequency, feeder bus services, parking, technology (heavy rail vs. commuter rail)
Cervero (2006) (model: Cervero, 2004)	Light Rail	St. Louis, Missouri & Illinois	constant, housing densities, mixed land use index, feeder bus services, parking supplies, terminal station, neighborhood vehicle ownership levels
Cervero, Murakami and Miller (2010)	Bus Rapid Transit	Los Angeles County, California	constant, number of daily metro rapid buses (both directions), number of perpendicular daily feeder bus lines (both directions), number of daily rail feeder trains, population density, distance to nearest BRT stop, full service BRT and feeder bus interactive term, full service BRT and feeder rail interactive term, full service BRT and parking capacity interactive term, full service BRT and total density interactive term
Lane, DiCarlantonio, Usvyat (2006)	Light Rail	11 U.S. cities	constant; bus present; parking; transportation center or rail trunk; CBD employment/metro area employment; typical commuter fare; average household size within 2 mi of station; CBD density if corridor connects to CBD; ln(employment within 0.5 mi of station); ln(households within 0.5 mi of station)
Lane, DiCarlantonio, Usvyat (2006)	Commuter Rail	8 U.S. cities	constant; parking; transportation center or rail trunk; speed to downtown (mph); time to downtown in minutes; midday headway in minutes; total stations on the entire CR network; population in the entire metropolitan area; ln(population within 2 mi radius); zero-car households/households with cars, within 2 mi of station; employment within 0.5 mi of station; distance to

2.3. Conclusion

This chapter summarized much of the existing literature on service elasticities and direct demand models. Sketch models such as these are intended to provide insights into ridership responses to changes without having to use regional models which are often more costly in terms of time, data and resource inputs.

Demand elasticities measure the percentage change in ridership in response to a percentage change in a service attribute. The focus of this thesis is the response to alterations in service levels, particularly in the form of headways or frequencies. There is a significant amount of literature on bus elasticities with respect to service intervals. Although several situational factors affect the elasticity of demand, one of the most common breakdowns of elasticities is by the initial service level. For this thesis, bus elasticities with respect to service intervals from past literature were selected. On the other hand, prior research on rail elasticities is limited, so this thesis uses an elasticity calculated based an experience with a recent MBTA rail service modification as described in subsequent chapters.

Direct demand models are more complex than elasticities and introduce additional variables into the analysis. These models are generally stop level based and include both service and stop environment variables. However, direct demand models, like elasticities, still do not usually incorporate destination information. Direct demand models have recently been used to predict ridership when it is considered important to include the impact of TOD and other land use variables that are often not captured by regional models. So far direct demand models have been developed for rail and more recently bus rapid transit, but this thesis seeks to expand this work to generate a direct demand model for the full MBTA bus system.

3. Ridership Estimation Methodologies

Transit ridership estimation methods can be roughly divided into three major types: comparison equations, regression models, and regional models. These methods are summarized in Table 3-1 (same as Table 1-1). Comparison equation methods estimate ridership by relying on previous experience tied to a single explanatory variable to predict future outcomes. Examples of comparison equation methods include elasticities which were discussed in Chapter 2 and will be applied in future sections, and trip rates which are discussed further in this chapter. Regression models can vary from single equation to multiple equation models capturing different levels of detail of a system through multiple explanatory variables. For this thesis, a direct demand model was estimated as discussed below. Another regression model approach by Peng et al. was discussed in Section 2.2. Finally, regional models such as the CTPS regional planning model for the greater Boston region make up the third major category of ridership estimation methods.

This thesis seeks to find simpler methodologies that can be applied prior to requiring a regional demand model which has several limitations as discussed in the literature review above. The remainder of this chapter first discusses the different ridership sources that were available to use in the analysis of the MBTA system and then provides further detail about methods used for the analysis in the subsequent chapters.

Table 3-1 Ridership Estimation Methods Summary

Method	Description	Advantages	Disadvantages	Examples
Comparison Equations	Ridership comparisons to past experiences or existing routes based on a single explanatory variable.	Simple, fast calculations. Can potentially combine methods or make existing methods more robust.	Often rely on qualitative judgments. Most methods cannot capture more than one variable at a time.	Elasticities, individual or household trip rates
Regression Models	Regression based models of transportation system based on multiple explanatory variables.	Varying complexity levels. Can be designed to capture local effects.	Often best used for order-of-magnitude comparisons. May require large and/or complex data sets.	Direct demand models, route-level patronage model
(4-Step) Regional Model	Regional model using travel network and demand forecasting programs (ex. TransCAD, Cube, Emme).	Can capture full transportation system effects (multi-modal, network effects).	Complex to run. Planning unit of operating agency may not have direct access to model. Regional scale may not capture some local impacts.	MPO regional 4-step models

3.1. Ridership Sources

A key component of predicting future ridership is having current ridership levels on which to base the estimates. There are several possible sources of current ridership data that are used in this thesis.

MBTA Ridership Master The MBTA maintains a Ridership Master file which compiles information from automatic fare collection (AFC) reports. This file only includes one number for total bus ridership across all routes. As a result, its use is limited for establishing base ridership for bus analysis and it is only used for rail analysis. Further information on this source is provided in Section 4.2.2.

CTPS Ride Checks CTPS gathered ridership data for all bus routes over a period spanning from 2002 to 2009. For each route, checkers rode each scheduled inbound and outbound bus trip over a series of several days, counting the number of passengers both boarding and alighting at each stop. The data was then compiled into two summary files. The first file cumulates ridership over the full day, providing total boardings and alightings at each stop for the day. The second file cumulates ridership over the full route, providing the total boardings for each trip of the day. This second file also includes information about the maximum load, the headway, actual versus scheduled departure time, and actual versus scheduled running time. Although the data collected includes boardings and alightings at each stop for each trip of the day, the two file types saved by the MBTA and available for this thesis accumulate ridership either over the full day or over the entire route. As a result of this aggregation, data must be used either for the full day (without any time period distinction), or for the full route (without any stop level information). Although the trips checked for each route occurred during one schedule period, usually even within one month of each other, and typically occurred during the Fall and Winter time periods, the ride checks for the full system spanned over several years and therefore may be impacted by changing ridership patterns over time.

Automatic Passenger Counting (APC) The MBTA has automatic passenger counters on a portion of its fleet. These vehicles are rotated through different routes in order to provide APC data for as much of the system as possible. In the past, an emphasis was placed on collecting data for many of the routes in the GLX study area. The advantage of APC data over other ridership sources is that it counts all passengers equally, regardless of their interaction with the fare box. However, data collection is still incomplete, with some trips not accounted for and some routes missing altogether. Trips are particularly missing during the peak periods where the number of vehicles required makes it more difficult to ensure that each scheduled trip has been covered by APC during a time period. For this work, APC reports for the Fall 2012 schedule period were available. Although the MBTA intends to fill in missing trip data, this was not done in the reports used here.

Origin-Destination Matrices The final main ridership data source is origin-destination matrices created based on AFC data. Gordon (2012) established a methodology for inferring full journey origins, interchanges and destinations using AFC and automatic vehicle location (AVL) data. Gordon's methodology was initially created for London's public transit network managed by Transport for London (TfL) and implemented as a Java program. Gordon's methodology has since been used by Muhs (2012) and Schil (2012), who summarized his methodology and used it to analyze changes in travel patterns after a change in the system and to calculate passenger volumes on specific origin-destination pairs, respectively.

Gordon's method involves four main steps: origin inference, destination inference, trip linking and scaling (Muhs, 2012). London metro requires both tap-in and tap-out at fare gates, so rail origins and destinations were included in the AFC data already. Bus boarding locations were inferred by linking AFC time stamps and AVL data. Destinations were then assigned based on the user's next trip, assigning the alighting location to the closest bus stop on the route to the next boarding location. Gordon's methodology also linked consecutive journey segments using interchange parameters to infer full journeys for smartcard users. The results were then further scaled to represent all users of the public transportation network.

Gordon's methodology needs to be expanded to be applied the MBTA system. Since the MBTA rail system does not include tap-out, destinations had to be inferred for rail trips in a manner similar to buses. Furthermore, differences in the data collected by the two systems, particularly AVL data, required adapting the way some of the data was used. After altering the MBTA data for one weekday in April 2012 to resemble London data, over 99% of bus trip origins were inferred by the program. However, destination inference was excluded from this process. Unlike with the original London methodology, the scaling step was not applied to the MBTA data. Although the boarding inference rate for the MBTA data is high, not scaling the data means that the ridership totals are lower than actual and may have an unknown bias if undercounting does not occur equally throughout the system.

The MBTA uses an adjustment factor to account for trips not captured by AFC. The current adjustment factor for the bus system is 9.7% and is based on random counts done throughout the year for the National Transit Database (NTD). This factor can be applied to the results of the origin inference to account for undercounting, but this will not correct trips where the origins could not be inferred, or for unknown biases in undercounting or where origins were not inferred. It is also important to note that the origin inference was only conducted for one day of data, in this case Thursday April 26, 2012. This day is taken as representative of other weekdays during the time period.

Gordon's methodology was also applied to MBTA rail transactions (rapid transit plus surface portions of the Green and Silver lines) to create an origin-destination matrix using Microsoft Excel rather than Java. This methodology was applied to AFC data for September 23, 2010. Most origins were known based on the AFC location and rail destinations were inferred based on the next tap in the rail system. Destinations were inferred for 76% of all rapid transit transactions, or 90% of transactions from a fare card with multiple transactions. The resulting matrix was then scaled up to account for transactions where the destination could not be inferred or transactions where the origin line was known but not the specific station. In total, the matrix was scaled up by approximately 32% in order to match the total number of rapid transit transactions (Tribone, 2011).

3.2. Service Interval Elasticities

The application of elasticity formulas is a commonly used form of comparison equations. Both the concept and formulas for calculating elasticities were discussed in the literature review (Section 2.1). The magnitude of information available for several types of ridership elasticities including fare and service intervals and the simplicity of the elasticity formula makes these equations fairly simple to apply. One drawback of elasticities, however, is the need for an existing ridership base to which the elasticity number can be applied. When initial ridership data is not available, other methods must be used in order to estimate the initial or current ridership and then elasticities can be applied to adjust for further changes.

Two elasticities are used in this thesis. Both are ridership elasticities with respect to service intervals, but the first elasticity is for rapid rail while the second is for bus. For rail, there is insufficient information available to use a general elasticity number based on literature. Instead, an elasticity is estimated based on a previous experience in the MBTA system. The method used to estimate this rail elasticity is outlined in Section 4.2 and applied in Section 4.3.

More generalized information based on past experiences is available for bus elasticities. An elasticity range from previous research can therefore be applied for buses. Lago, Mayworm and McEnroe (1981) broke out ridership elasticities based on the initial headway before the service change (Table 2-1). Three levels of service were used: high (<10 minute headways), medium (10-50 minute headways) and low (>50 minute headways). The authors' calculations were based on a total of 23 cases. In order to have sufficient information for each service level, the aggregate values for the full day are used. The distinction between the three service levels is important because when headways are less than 10 minutes the service provided is typically referred to as walk-up service, and passengers are likely to behave differently than they would under scheduled service with longer headways. As mentioned in the literature review, while Lago, Mayworm and McEnroe published their work in 1981 based on earlier observations, there is a scarcity of more recent literature on service elasticities, and the more recent work suggests that the elasticity patterns have remained the same over time (Evans, 2004, p. 9-3). Other differences between situations observed, such as the urban versus suburban nature of a route, could also impact the elasticity. However, given the focus in this work on the MBTA system in the urban core, there is no need to consider the variation displayed in the suburban nature of the routes.

Given the range of experiences and elasticities in previous literature, a sensitivity range was applied to the base elasticity number used in this work for both the rail and bus elasticities. This additional analysis recognizes that the elasticities being applied are estimations and that additional factors could cause the true ridership elasticity to be higher or lower. For this thesis, a range of ±0.1 around the base elasticity was used. This is the same range that was used for the price elasticity sensitivity analysis in the MBTA fare increase and service reductions impact analysis (Central Transportation Planning Staff and Massachusetts Bay Transportation Authority, 2011). This range keeps the elasticities within the anticipated ranges but still allows for enough variation to see the impact of different elasticities.

All elasticity calculations included here use the mid-point arc elasticity formula. Equation 2-3 provides the midpoint approximation of the arc elasticity formula. Using the calculated rail elasticity or the Lago, Mayworm and McEnroe bus elasticities based on the initial headway before the service change, the predicted ridership can therefore be calculated using the following formula:

$$R_1 = \frac{(\varepsilon-1)H_0R_0-(\varepsilon+1)H_1R_0}{(\varepsilon-1)H_1-(\varepsilon+1)H_o} = \frac{(R_1-R_0)(H_0+H_1)}{(R_0-R_1)(H_1-H_0)} \qquad 3\text{-}1$$

where

ε = midpoint elasticity
H_0 = initial headway
H_1 = proposed headway
R_0 = initial ridership
R_1 = predicted ridership

The elasticity method for predicting ridership can be applied to the proposals to change rail and existing bus route service frequencies. The calculation of initial and adjusted headways and the sources of initial ridership are discussed for each proposal in the relevant sections below.

3.3. Trip Rates

In Boyle's (2006) survey of transit agencies, 80% of the respondents used rules of thumb or similar route comparisons to forecast ridership. Similar route comparison refers to the practice of predicting ridership on a route by comparing it to existing routes with similar characteristics and service. While this is a qualitative method that relies on the knowledge and judgment of the forecaster, the use of trip rates quantifies some of this analysis.

Trip rates compare the ridership along the route to the number of potential riders within walking distance of the route. Trip rates are typically calculated for a route or route segment as opposed to for a single stop or station. Calculating trip rates for route segments, as opposed to for single stops or full routes, accounts for the impact of having multiple routes along the segment. Overlapping routes on a segment could potentially result in both synergies and competition. The formulas for the route trip rate and the route segment trip rate are as follows:

$$Route\ Trip\ Rate = \frac{Ridership\ at\ All\ Stops\ Along\ Route}{Population\ in\ Route\ Catchment\ Area} \qquad 3\text{-}2$$

$$Route\ Segment\ Trip\ Rate = \frac{\sum_{i=1}^{n} Ridership\ of\ Route\ Segment\ Stops\ Served\ by\ Route\ i}{Population\ in\ Route\ Segment\ Catchment\ Area} \qquad 3\text{-}3$$

where the catchment area is defined here by a quarter mile radius around each bus stop along the route or segment, and n is the number of routes serving a route segment.

Fijalkowski (2009) used trip rates to support the recommendation that the Chicago Transit Authority (CTA) add bus service along 83rd Street in Chicago. Fijalkowski focused his analysis on three key routes for comparison. The first two routes examined were the two closest to the proposed route. These two routes, Route 79 and Route 87, have high ridership, provide connections to the Red Line, and run along corridors served by north-south buses that provide direct connections to downtown Chicago. The third line included in the analysis was Route 75 which was determined to be a good proxy for the proposed route. Route 75 is close to 83rd Street, provides the same Red Line connection, and has similar population densities, development patterns and roadway geometries as the proposed Route 83 corridor.

The trip rates calculated before the introduction of Route 83 and the trip rates predicted for after the introduction of the route are shown in Table 3-2. The initial trip rates for both Route 79 and Route 87 are relatively high due to high transit dependency rates in the area, high levels of service along the routes and the connection to the Red Line (Fijalkowski qtd. in Shireman, 2011). For the after analysis, the trip rate of Route 75 was applied to Route 83. Ridership adjustments were also made to Routes 79 and 87 to account for competition from overlapping catchment areas with the new Route 83. Although Fijalkowski predicted a slight decrease in ridership along Routes 79 and 87 due to competition from Route 83, their trip rates were actually predicted to increase. This increase in the trip rate occurred because the catchment areas would decrease (assuming non-overlapping areas) and the resulting catchment areas would generally be closer to the route and have higher ridership capture due to the shorter walking distance to bus stops.

Table 3-2 Trip Rates Before and After the Introduction of Route 83 (Fijalkowski, 2009)

	Before	After
Route 75	0.15	0.15
Route 79	0.33	0.46
Route 83	NA	0.15
Route 87	0.21	0.26

One important factor missing from the trip rate formula is service level. Fijalkowski accounted for service levels by selecting a proxy route with a similar service frequency to that proposed on the new route. Shireman (2011) further examined the correlation between service intervals and trip rates for MBTA bus routes. Shireman used the route segment trip rate equation above to calculate trip rates for 15 bus routes in the GLX study area defined for his thesis. He broke the routes into between one and ten segments each by dividing the routes at "route and node interchange points and other points where services are on the same street branch" (p. 169). His analysis utilized 2000 census data, APC data when available, and a combination of AFC and CTPS ride check data where APC data was not available. Inbound ridership from the start of service until 1pm was used in order to capture only the outgoing trip for each person and to not double count passengers by also capturing their PM return trip.

After calculating the trip rate for each route segment, Shireman plotted trip rates against the frequency of service. His results, shown in Figure 3-1, indicate a positive correlation between frequency of service and trip rates. Using all of the trip rates, Shireman determined that an increase of one trip per hour over the eight hour period from the start of service to 1pm "will result, on average, in an increase in the trip rate by 0.0064, which is 6.4 trips per 1000 residents." Given his findings of approximately 2,000-12,000 residents per route segment analyzed, this translates to an increase of 13-77 trips per segment in response to an increase of one trip per hour before 1pm. The correlation was even greater when route segments within walking distance of rapid transit stations were excluded - yielding a higher R-squared value and a steeper slope (Figure 3-2).

Figure 3-1 Relationship between Frequency of Service and Boarding Trip Rate – Inbound (Shireman, 2011, p. 170)

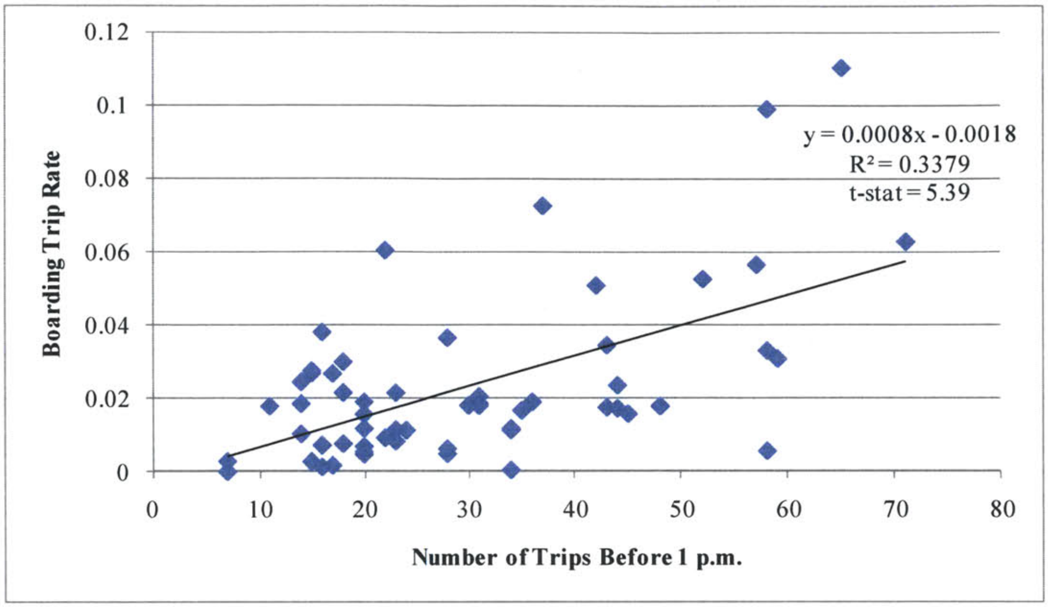
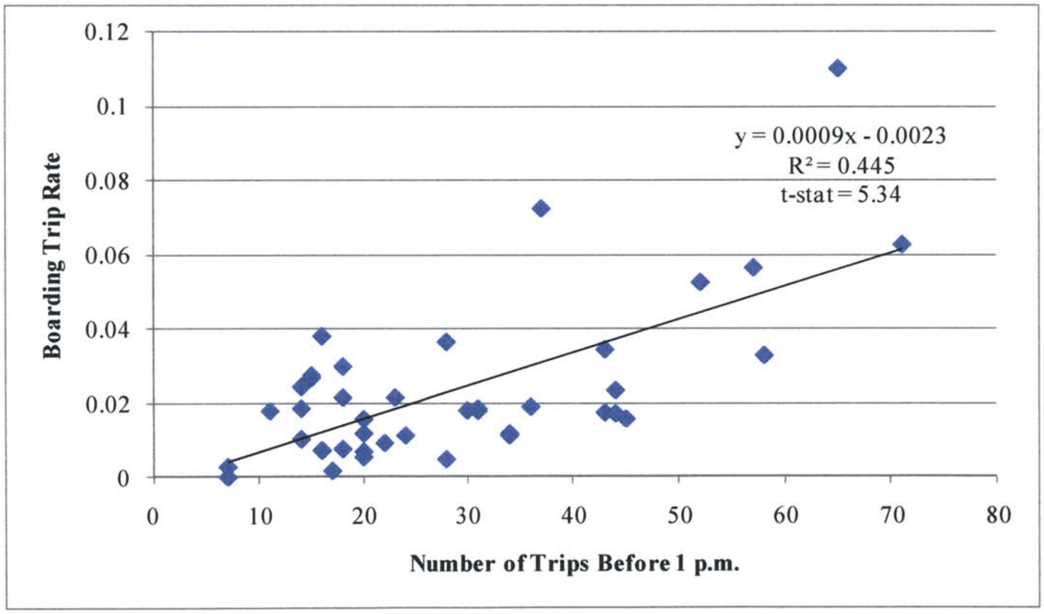


Figure 3-2 Relationship between Frequency of Service and Boarding Trip Rate – Inbound (excluding route segments that are within walking distance of a rapid transit station) (Shireman, 2011, p. 171)



Trip rates are a common method for estimating initial ridership levels on new routes and can provide important information on the performance of a route. However, there is still more work that can be done to make trip rate analysis more robust. Trip rates can be used to establish a baseline ridership number for a new route, but service frequencies must still be considered.

Therefore, when using proxy trip rates to estimate ridership for a new or existing route it is still necessary to adjust for service levels through the application of elasticities.

Choosing a trip rate proxy is typically a qualitative process. As seen in Fijalkowski's work, important considerations in choosing a proxy include population densities, development patterns, roadway geometries and route characteristics such as route length, running times, and connections to other routes, modes or key attractions. A future avenue of work could look at quantifying the selection of trip rate proxies using statistical methods. Further expansion of the work on trip rates could also look at other drivers of ridership levels as alternatives to population in the catchment area. In particular, ridership in some areas may be driven more by the attraction of employment opportunities in the area than by the trip generation of the population residing in the area.

Two formulas were provided above - one for a route trip rate and another for a route segment trip rate. Currently the definition of segments is open to interpretation. Another avenue for further consideration would be how to quantify and automate the selection of route segments. One way to chose route segments is based on fare zones, but not all systems use fare zones and the size of fare zones may vary even within a system. The use of route segments rather than full routes may have a significant impact on the trip rate as some routes may be long and go through areas with varying characteristics. This is often the case in the MBTA system where some routes may go through multiple neighborhoods and have several key locations along the route. Routes may also overlap with other routes for some segments. Depending on the level of overlap, routes along a shared segment may be independent, complementary or competing (Peng et al., 1997), which could have an impact on the resulting trip rates.

Given the need for further work in order to make the application of trip rates more robust and the selection of trip rate proxies more quantified, trip rate analysis was not applied in this thesis. Alternatively, a "direct demand" ridership model, which regresses ridership relative to individual bus stop characteristics and service levels, is developed in an attempt to provide a more robust method.

3.4. Direct Demand Models

Given the lack of generally applicable direct demand models for bus service, a new direct demand model was estimated for the MBTA system. This section discusses the process used to estimate this model. First the data collection process is discussed. Next, the estimation of the model is explained. Finally, the process for applying the model to the proposals in the subsequent chapters is outlined and a simple example is provided.

3.4.1. Data Collection

The first step in creating a new direct demand model for the MBTA system was to collect data on all bus stops within the system. The MBTA makes schedule and trip planning information available using the General Transit Feed Specification (GTFS) format. This data is available for download from the MBTA website and includes information on bus stop locations and route schedules. This information was used as the basis for identifying bus stops and calculating service level information. The GTFS data includes lists of all stops, routes, trips and stop times in the MBTA system. All of the GTFS tables can be connected to each other based on shared attributes. At the time of this work, the Summer 2012 GTFS feed was available.

Before starting the analysis, the stop time table was altered to set the pickup type and drop-off type to "not available" for the last and first stops of each trip, respectively. This is important for a later step when calculating service because trips into the last stop of a route should not be counted when examining service as passengers do not board there. Similarly, if alightings were to be examined, service departing the first stop of a trip should not be counted as no passengers would alight there.

After making this adjustment to the stop time table, the first step in establishing the model was to separate bus and rail stops and to identify bus locations. Using the GTFS tables, all stops associated with a route type of 3, meaning a bus route, were identified as bus stops. Similarly, all stops associated with a route type of 0 (street level rail) or 1 (underground rail) were identified as non-bus stops. For this analysis, stops associated with intercity rail and boat (commuter rail and ferries in the MBTA system) were excluded. Stops where pickup was not available (because it is the final stop of the route or for other reasons determined by the MBTA) were also excluded from these lists.

In most cases, the inbound and outbound stops for a route in the MBTA system are on opposite sides of the street and each has a unique stop identifier and a distinct latitude and longitude. However, when estimating a direct demand model the direction a passenger is traveling is not considered, so the inbound and outbound stops should be regarded as one joint location. In order to establish these joint "locations", buffers of 0.01 miles were created around each bus stop. Anywhere that these buffers intersect, the related stops were joined into one location. This was done regardless of the routes associated with the stops, assuming that any stops within 0.02 miles of each other would be close enough for passengers to easily travel between them and treat them as one effective location. The GTFS data included 7,834 unique bus stops which were then consolidated into 5,384 locations. All subsequent analysis was completed for locations rather than individual stops.

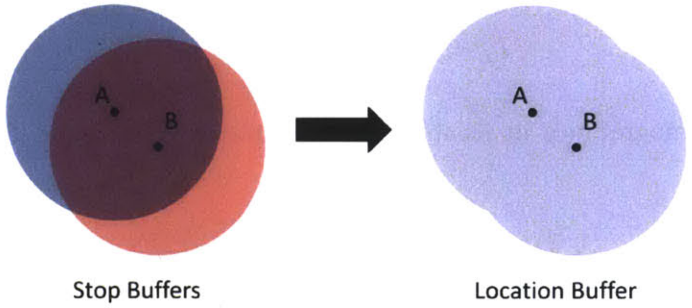
One concern with this location generation step is that stops might form chains when one stop is close to two unrelated stops. If this were to occur, it would be possible to end up combining several stops into one location even though some of the stops may not be near each other and are only linked by other shared stops within the location. It is assumed that this would rarely occur and even then the stops would all be relatively close together. One way to check for any significant chaining of stops is to look at the area of the resulting location buffer. Any locations including stops that are not close together would have a meaningfully larger buffer area than other locations. Doing this check for the MBTA locations suggests that there are not any locations with buffer areas large enough to cause concern about using this simplified method of establishing locations.

Once bus stop locations were established, data about the locations had to be collected. Given the vast number of bus stops, the list of variables considered was limited to features of the locations that could be determined from data readily available in digital form. The variables collected were prioritized and divided into three main categories: demographic information, geographic location information, and service characteristics.

For demographic information, census data was obtained for population, households and vehicle ownership, and Census Transportation Planning Package (CTPP) data was obtained for employment. In order to have demographic data from consistent years and analysis geographies, block group data from the year 2000 was used.

Demographics were calculated within a quarter mile buffer of locations using ArcGIS and PostgreSQL. Demographics were assumed to be distributed proportionally throughout block groups. Therefore, when a buffer intersected part of a block group, a portion of the demographics proportional to the intersecting area of the block group was applied. Two adjustments had to be made to the buffers when calculating the demographics. The first adjustment was to aggregate buffers for locations in order to get location demographics as opposed to individual stop demographics. An example of this aggregation is shown in Figure 3-3 where stops A and B are assumed to be part of the same location.

Figure 3-3 Stop to Location Catchment Area Generation



The second adjustment was to account for the overlap of location buffers. In the MBTA system, many locations are so close together that land may be within a quarter mile of more than one location. These locations may be either along the same or different routes. If the demographics were assigned to multiple locations, they would in effect be counted more than once. Lane, DiCarlantonio and Usvyat (2006) examined the impact of this potential double counting. The authors conducted correlation analysis between their independent variables (including demographic data) and their dependent variable of daily station boardings. This analysis included testing the difference between assigning geography exclusively to a single nearest station and assigning geography to all nearby stations. The authors found that assigning geography exclusively to a single nearest station, also referred to as using exclusive geographies, results in a better fit. Lane, DiCarlantonio and Usvyat point out that previous models such as those discussed in TCRP Report 16 often used overlapping catchment areas which could effectively double or triple count some demographics.

In this model, demographics in overlapping segments were split evenly between all overlapping catchment areas. Figure 3-4 shows an example where three locations (labeled A, B and C) all have segments of overlapping catchment areas (labeled 1-7). In this situation, the demographics in areas where two buffers overlap would have their demographics divided in two and split evenly between the two locations and the demographics in the segment where all three buffers overlap would be divided into thirds and split evenly between all three locations. As a result, the demographics for the three locations would be calculated as follows:

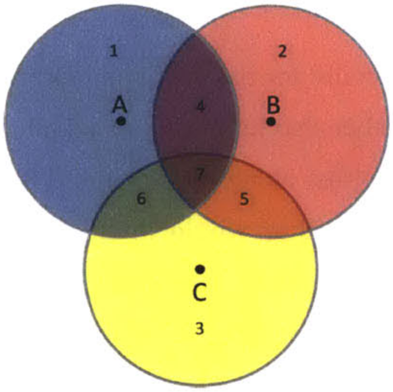
$$D_A = d_1 + \frac{1}{2}d_4 + \frac{1}{2}d_6 + \frac{1}{3}d_7 \quad \text{3-4}$$

$$D_B = d_2 + \frac{1}{2}d_4 + \frac{1}{2}d_5 + \frac{1}{3}d_7 \quad \text{3-5}$$

$$D_C = d_3 + \frac{1}{2}d_5 + \frac{1}{2}d_6 + \frac{1}{3}d_7 \quad \text{3-6}$$

where D_i is the demographics in location catchment area *i*, and d_j is the demographics in segment area *j*.

Figure 3-4 Overlapping Catchment Areas



Previous research, including that of Lane, DiCarlantonio and Usvyat (2006), has sometimes created exclusive geographies by splitting overlapping buffers and assigning all areas to only the closest station. This approach was not utilized here given the density of locations in the MBTA system. Some of the locations are close enough that passengers may choose between them and should therefore be split between the stops and not just assigned to the closest location. Also, in areas with dense transportation networks, limiting demographics to only the unique area around a location would result in some locations having very small catchment areas that would not properly represent the true demographics of the area from which passengers access the location.

Select geographic location information was also calculated in order to account for trends in stop characteristics that would be correlated between stops based on their location. Two key variables of this type were used. The first is the distance from the central business district (CBD). The latitude and longitude for the Government Center stop in the GTFS data was used as the CBD. Distances to the CBD were then calculated using the Haversine formula (Sinnott, 1984). This variable is intended to account for shared attributes of locations near each other as well as for trends in demographics and behavior based on distance from the CBD.

The second geographic location variable is distance to the nearest rail station. The non-bus stop closest to each bus stop was identified and the Haversine formula was used again to calculate the distance between the two stops. The average distance for all stops within each location was then calculated. This variable is intended to capture the two conflicting effects of a bus stop being located near a rail feeder station. The first effect is a potential increase in boardings near a feeder station due to passengers transferring from rail to bus to reach their final destination. Conversely, the second potential effect of being located near a rail station is that passengers may choose to walk to or from the rail station rather than taking a bus and having to transfer.

Finally, service information was obtained from the GTFS data. The data was limited to one weekday, July 25, 2012, from the data provided in order to get service characteristics for one representative weekday. Future work could expand the analysis to weekends and holidays and divide the data into periods such as peak and off-peak.

Only two key service variables were considered in this iteration of the model: bus trips and rail trips. When creating the lists of bus and non-bus stops, the number of stop times and trips associated with each stop was counted, excluding when the stop type was "not available". The trips for all stops within a location were aggregated to get total bus service. Rail stations that could serve as feeder stations to a location were determined based on if a non-bus stop was within a buffer distance of the location. Buffer distances of both 200 meters and 400 meters were tested, and the 200 meter buffer was ultimately selected. The trips for all non-bus stops within the buffer of each location were then aggregated to get the total feeder service.

The other data necessary to estimate a direct demand model is the dependent variable of current ridership. The origin inference results from the MBTA bus origin-destination matrix were used for this variable. The origin inference results identify both the route and stop for each trip, when possible. The boarding stop was not inferred for a small percentage of the trips with route information available. These trips were distributed along the route according to the distribution of the trips with inferred boarding stops. The boardings at each stop were then aggregated across all routes that serve the stop.

Many stops in the GTFS stop list had no inferred boardings. There are two reasons a stop may not have ridership associated with it. The first is that there were no boardings at the stop on the day examined. If this is the case, that stop should be included in the direct demand model with zero boardings. However, the other reason a stop may not have ridership associated with it is if that stop was not included in the origin-destination matrix output for some reason. In some cases, the inference method cannot distinguish between two consecutive nearby stops so the ridership was merely captured in the preceding or subsequent stop. In these cases, the stop with no ridership would ideally be excluded from the model. Since the correct reason for having no ridership at any given stop is unknown, all stops with zero ridership were included in the direct demand model estimation.

3.4.2. Model Estimation

Once all of the variables were collected and aggregated for each location, linear regression analysis was performed to estimate the direct demand model. The list of independent variables tested included demographic variables within a quarter mile buffer (population, households, households with and without vehicles, workers, income per capita), geographic location variables (distance to CBD, distance to rail, town), and service variables (bus trips, feeder rail trips within 200 and 400 meters). Various transformations of the dependent and independent variables were considered, including log and piecewise functions. A log-log regression was selected because of its higher explanatory power and the ease of interpreting coefficients as elasticities. On the other hand, with a logarithmic regression, the output must be transformed before it can be directly interpreted as ridership. The intercept was also forced to be zero (no intercept) based on the a priori assumption that a location with no people and service would have no ridership. The final regression estimation selected is shown in Table 3-3 below.

Table 3-3 Direct Demand Model Estimation Results
(dependent variable is log of ridership)

	Coefficient	Std. Error	t-Statistic	
Households with Vehicles	0.033	0.033	0.976	
Households without Vehicles	0.066	0.024	2.804	**
Workers	0.149	0.015	9.735	***
Income per Capita ($000s)	-0.645	0.038	-17.172	***
Distance to CBD (km)	-0.199	0.027	-7.350	***
Bus Trips	1.069	0.015	69.851	***
Rail Feeder Trips (1)	0.115	0.014	8.152	***

Summary Statistics

Adjusted R-squared = 0.882

N = 5,281

Note: (1) Excludes rail feeder trips at locations within 1.5km of the CBD

*Significance codes: 0 *** 0.001 ** 0.01 * 0.05 . 0.1 1*

The regression analysis began with a base model and other variables were tested and included or excluded based on the statistical significance, impact on the predictive power of the model and the impact on the coefficients. Variables for the number of households with and without vehicles were used in place of population and vehicle ownership variables. Initially population and vehicle ownership were tested separately, but it is possible with those two variables to get conflicting trends, for example where total vehicle ownership in a catchment area decreases but so does population, so the overall vehicle ownership relative to the population actually increases. As a result, these two variables were combined into the households with and without vehicles variables, which are exclusive groups.

Municipal level dummy variables were tested to see if inherent town specific behaviors and attitudes impacted ridership but the dummy variables were not easily interpretable and did not meaningfully change the coefficients and significance of the other variables so they were excluded.

Using the number of feeder trips versus using a dummy variable for the availability of a rail feeder connection was also tested. The two regression variations had similar coefficients on the other variables and similar adjusted R-squared values. Using the number of trips as opposed to a dummy variable allows for some additional variation between stops and can be interpreted as a cross elasticity. It should be noted, though, that there is not a lot of variation in the number of feeder trips in the data so caution should be exercised in interpreting the feeder trip variable as a cross elasticity.

Another variation of the feeder trips variable that was tested was the exclusion of feeder trips at locations within 1.5 kilometers of the CBD. This was done because it is expected that within the CBD the rail network is dense enough and the rail to bus transfer penalty high enough that rail feeders would not have as significant an impact on bus ridership .as seen elsewhere in the system. Furthermore, the density of the rail network in the CBD means that the number of rail feeder trips at some locations is disproportionate to that seen further away from the CBD, thus skewing the impact. In the final regression specification, excluding rail feeder trips at locations within 1.5 kilometers of the CBD results in only minor changes to the included coefficients including a slight increase in the coefficient on the feeder trip variable. The final selected regression therefore excludes feeder trips at locations within 1.5 kilometers of the CBD.

While the final regression selected includes only one variable each for income, bus trips and feeder trips, piecewise specifications were also tested. This was done because elasticities vary based on income and the initial service level. Ultimately, however, this piecewise formulation was not used due to concerns about over-fitting and interpretability of the results. Interaction terms were also tested, particularly between households without vehicles and bus trips and between bus trips and feeder trips. The interaction terms for bus and feeder trips were significant but did not change the overall results of the model, did not increase the adjusted R-squared, and made interpretation of the coefficients more difficult. The interaction terms were therefore excluded from the final model estimation.

An exponential term for bus trips squared was tested in the final model estimation in order to better capture the impact of bus service levels at a location. There were two main reasons for testing the inclusion of this exponential term. First, ridership is typically higher when service is greater, in particular when walkup service is provided (more than six trips per hour / less than ten minute headways on a particular route and direction). The second reason for including this exponential term was that when estimating the model without it, there were residuals, particularly at high ridership locations. Including a bus trips squared variable helps reduce the residual when estimating ridership at some of these locations. However, this variable was ultimately excluded from the final regression model selected because while it improved the ridership prediction accuracy at some of the key high frequency locations, it tended to overestimate the ridership at many stops. In testing the model on scenarios where service increased significantly, the model estimated with the bus trips squared term often over-estimated ridership at key locations. Instead, a scaling technique was used when applying the model to correct for these residuals. This scaling technique is described in Section 3.4.3.

The final logarithmic direct demand model estimation as seen in Table 3-3 includes households with and without vehicles, workers, income per capita (in $1,000s), distance to CBD (in kilometers), bus trips, and rail feeder trips for locations greater than 1.5 kilometers from the CBD. All of the coefficients have the anticipated signs and are in line with expectations. The variables for both households with and without vehicles have positive coefficients as any increase in population would be expected to increase ridership, but the significance and magnitude of the coefficient on households without vehicles is greater as this portion of the population is generally captive riders without the alternative of a private vehicle. The coefficient on workers is also positive and significant. It is interesting to note that the coefficient on workers is actually higher and more statistically significant than that of households with vehicles. Income per capita is also significant and has a negative sign, as expected. The expected sign of the distance to CBD coefficient was uncertain and turned out to be negative but small. This suggests that further from the CBD ridership is lower. There could be many reasons for this effect including the density of the transit network and other behavioral characteristics of neighborhoods outside the CBD.

Finally, both the bus and rail feeder trip coefficients are significant and positive. For a simple bus location that includes both stops in either direction for only one bus route, the bus trips coefficient of 1.07 can be interpreted as an elasticity of 0.53 for one-way service which is within the range seen in research. While the ability to interpret the bus trip coefficient as an elasticity can be useful, for this direct demand model based on locations it is difficult to use the bus trips coefficient as an elasticity because the number of bus trips at a location is a combined number for all stops, routes and directions within the location. When examining a change to one route and direction, the total percent change in trips for the full location would need to be calculated before applying the elasticity. As discussed above, care should also be taken when using the rail feeder trip coefficient as a cross-elasticity. Therefore, although this is a logarithmic equation, none of these coefficients are easily interpretable as elasticities.

Overall, the model has high predictive power with an adjusted R-squared of 0.88. One thing that may decrease the explanatory power of the model is the difference in the timing of the data sources. The ridership data is from the spring while the GTFS service data is from the summer when service is lower. This may contribute some amount of systematic error and decrease the overall explanatory power of the model. Similarly, the census data is taken from 2000 and may not reflect demographic changes since then. While these data source discrepancies would ideally be rectified for future work, the model still has high explanatory value as it is now.

3.4.3. Model Application

The advantage of a direct demand model is that it can be applied to any scenario, whether new routes or stops are created or if only existing service is altered. Before applying the model to new scenarios, however, it was applied to the existing system. Although the predictive power of the final chosen model estimation is high, the ridership prediction at individual stops was sometimes found to be meaningfully different than the true value. The final estimated model is unable to do a good job of simultaneously estimating ridership at both low and high ridership locations. As discussed above, piecewise functions and terms with bus trips squared were tested to improve the fit of the model. Regressions using only a subset of higher ridership locations were also tested but did not readily produce a better model. Further research should seek to develop a more refined model that can more accurately capture ridership at both high and low ridership locations.

Given that this direct demand model is intended as a stop level model, an adjustment was made to account for the initial residuals at current locations. For each current location, an initial adjustment ratio was calculated as the ratio of true to predicted ridership. In cases where current ridership was zero, the adjustment ratio for the total system was applied to that location. This resulted in an overestimation of system-wide ridership, so a second system-wide adjustment factor was applied to all stops to make total system ridership equal to the actual system ridership. The product of these two adjustment factors became the total adjustment factor for each stop. After applying adjustment factors to all locations, the total estimated system ridership was equal to the actual system ridership. This adjusted predicted current system ridership was used as the base case for the analysis of all proposals instead of the true ridership so that any predicted change ridership can be attributed to the proposed service change and not the error in the model.

An example of this initial estimation and adjustment process is provided in Table 3-4 and Table 3-5. Five locations are used in this example. In the first table, the data collected for the five locations is provided and Equation 3-7 is used to calculate the log of the ridership predicted. The initial predicted ridership is then calculated, the adjustment ratio is shown and the final adjusted ridership is calculated. Table 3-5 shows the calculation of the adjustment ratio seen in the previous table. In the table, the five locations have a total actual ridership of 127 passengers. However, the direct demand model estimates only 54.6 riders at these locations. The first adjustment is the actual ridership divided by the predicted ridership for each location. Location 4 has no actual ridership, so the full system adjustment ratio of 2.32 is used for that location. After applying these adjustment ratios, the total system predicted ridership is 154.6. A second adjustment ratio of 0.82 (calculated as the total system actual ridership divided by the adjusted ridership) is therefore applied to all locations to bring total system ridership back to 127. The product of these two adjustment ratios is the total adjustment ratio as highlighted in blue at the end of the table.

$$\begin{aligned}\ln(\text{ridership}) = {} & 0.033\ln(households\ with\ vehicles) + 0.066\ln(households\ without\ vehicles) \\ & + 0.149\ln(workers) + (-0.645)\ln(income\ per\ capita) \\ & + (-0.199)\ln(distance\ to\ CBD) + 1.069\ln(bus\ trips) \\ & + 0.115\ln\,(rail\ feeder\ trips)\end{aligned} \tag{3-7}$$

Table 3-4 Example Initial Model Application

		Model Inputs							Model Output			
Location	Current Ridership	Households with Vehicles	Households without Vehicles	Workers	Income per Capita (000s)	Distance to CBD (km)	Bus Trips	Rail Feeder Trips	LN of Ridership	Predicted Ridership	Adjustment Ratio	Adjusted Ridership
1	100	315	95	300	16.25	28	30	0	**2.5**	12.4	6.6	82.1
2	13	75	6	35	18.75	27	30	0	**1.9**	6.6	1.6	10.7
3	5	60	4	35	19.5	27	60	0	**2.6**	13.0	0.3	4.1
4	0	55	3	24	20	26	60	0	**2.5**	11.9	1.9	22.7
5	9	25	2	23	21	26	60	0	**2.4**	10.9	0.7	7.4
Total	**127**									**54.6**		**127.0**

Table 3-5 Example Adjustment Ratio Calculation

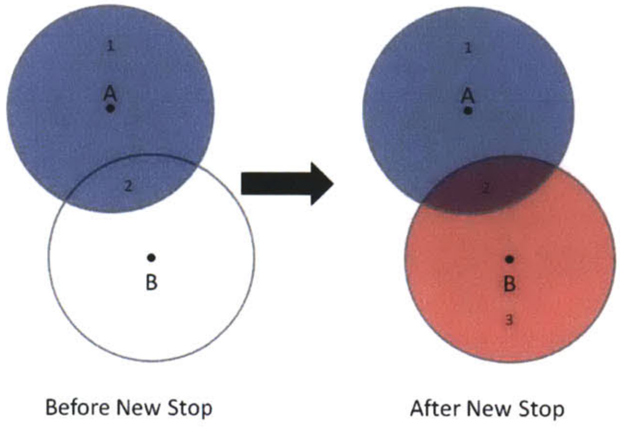
	Initial Ridership		First Adjustment		Second Adjustment		Total Adjustment Ratio
Location	**Actual Ridership**	**Predicted Ridership**	**Ratio**	**Adjusted Ridership**	**Ratio**	**Adjusted Ridership**	
1	100.0	12.4	8.07	100.0	0.82	82.1	**6.63**
2	13.0	6.6	1.98	13.0	0.82	10.7	**1.63**
3	5.0	13.0	0.39	5.0	0.82	4.1	**0.32**
4	0.0	11.9	2.32	27.6	0.82	22.7	**1.91**
5	9.0	10.9	0.83	9.0	0.82	7.4	**0.68**
Total	**127.0**	**54.6**	**2.32**	**154.6**	**0.82**	**127.0**	**1.91**

After calculating the adjustment ratios for all locations, there are two ways that the direct demand model can be applied to system change proposals. When no new stops are introduced and the proposed change is only a change in service at select locations, the change in trips can be added to the existing locations and the new predicted ridership calculated. In this case, all prior model inputs (other than bus trips) and the adjustment factors previously calculated can be used.

This process was used for applying the direct demand model to proposals for service changes to existing routes. In these cases, the current list of stops with bus trips on the route being studied was generated. The number of trips added to each stop on the route was calculated, summed by location, and added to the existing bus trip counts. The model was then applied to each location and the previously calculated adjustment factors were applied to get the predicted ridership after the service change. In these cases, the system ridership change will be the same as the change along the route because no other locations are affected, so only the change in ridership at locations along the study route is shown.

In contrast, when new stops are created, all variables must be recalculated for all locations because the catchment area of the new stops may overlap with existing locations and therefore change the demographics of existing catchment areas. This can be seen in Figure 3-5 where locations A and B have overlapping catchment areas. Initially the demographics of location A are equal to the sum of the demographics in segments 1 and 2. However, when location B is introduced into the system, the demographics in segment 2 must be split equally between locations A and B. The demographics for location A then become equal to the demographics in segment 1 plus one-half the demographics in segment 2.

Figure 3-5 Introduction of New Location



Due to the chance of overlapping catchment areas, for proposals involving new routes the variables were recalculated with an updated set of bus stops including the addition of any new stops. This process included the step to create locations in case any of the new stops were part of the same location as each other or existing stops. Location catchment areas and location specific variables were then recalculated in case any of the new locations overlap with existing location catchment areas. The creation of exclusive geometries for the updated location set will result in some previous locations having new variable values and therefore new predicted ridership values when the model is applied. The model must therefore be applied to all locations, not just locations along the proposed route. In order to determine the adjustment factor for each location, the old and new locations were matched and the total system adjustment factor was applied to new locations.

In Table 3-6 the same 5 locations from the previous example are used and a new stop is added along a new route. The previous location 5 and the new location 6 overlap as seen with locations A and B in Figure 3-4, therefore the model inputs for the locations must be recalculated. The adjustment factors calculated previously for each location are still used, and the total system adjustment factor is applied to the new location. Comparing this table with Table 3-4, it can be seen that the inputs for location 5 have changed as has the ridership estimation for that location.

Table 3-6 Example Model Application After Introduction of New Location

		Model Inputs							Model Output			
Location	Current Ridership	Households with Vehicles	Households without Vehicles	Workers	Income per Capita (000s)	Distance to CBD (km)	Bus Trips	Rail Feeder Trips	LN of Ridership	Predicted Ridership	Adjustment Ratio	Adjusted Ridership
1	100	315	95	300	16.3	28	30	0	**2.5**	12.4	6.6	82.1
2	13	75	6	35	18.8	27	30	0	**1.9**	6.6	1.6	10.7
3	5	60	4	35	19.5	27	60	0	**2.6**	13.0	0.3	4.1
4	0	55	3	24	20	26	60	0	**2.5**	11.9	1.9	22.7
5 (A)	9	21.3	1.7	19.6	21	26	60	0	**2.3**	10.4	0.7	7.1
6 (B)	0	50	5	22	20	27	75	0	**2.7**	15.2	1.9	29.1
Total	**127**									**69.5**		**155.8**

Unlike with service adjustments to existing routes, the impact of new route proposals must be looked at both at the locations along the route and in a system-wide context. Not all passengers along a new route will be new riders. Introducing new stops will impact the catchment area of existing stops and some riders who use the new service may be current riders who change their boarding locations. In the example used here, the new route at location 6 is estimated to generate 29.1 passengers, but the estimation of ridership at location 5 has decreased from 7.4 to 7.1 passengers, so the net change in system ridership is actually only 28.8.

In the chapters below, the direct demand model is applied to each proposal and the results are shown. Both the unadjusted and adjusted ridership estimations are presented although the adjusted numbers are used for comparison. For the full direct demand model based on the MBTA system, the first total system adjustment ratio was 1.98 while the second adjustment factor was 0.99. For a location with no actual current ridership, the total system ridership adjustment factor applied to the location was therefore 1.96. Again, applying the total adjustment factors to each location resulted in the predicted total system ridership being equal to the actual system ridership. The root mean square error was also reduced from 334 for the unadjusted ridership to just seven boardings after applying both adjustment factors. This means that on average the error in the ridership estimation for each location, after applying the adjustment factors, is only seven passengers.

The ridership change at only locations served by the routes being altered is shown. When new locations are introduced into the system for a new route, the change in full system ridership is also shown as it may not equal the change in ridership at locations with changed service. Due to overlapping catchment areas, some of the ridership generated at the new locations may come from ridership at existing locations and have no net impact on total system ridership. Therefore, in some cases the change in ridership for the full system and the change at only locations along the route being analyzed are both shown so that the two predicted changes can be compared.

At the same time, although the estimated ridership before and after each proposal is shown for locations along the study route, with a direct demand model it is difficult to isolate the ridership along an individual route. Direct demand models do not consider the destination of riders, and some of the increase in ridership at locations along the altered or new route may actually be additional riders on other routes at the location that benefit from an overall increase in service at the location. For mitigation purposes, the total change in ridership matters, not the route it is on, but ridership along the individual route may matter for planning purposes.

In order to account for the impact on other routes at locations, a portion of the change in ridership at locations along each study route is attributed to the route being altered proportional to the percent of total location trips attributed to that route. Given that it is still expected that most of the ridership impact will be seen on the route being altered, a sensitivity analysis is done on this calculation where the greater of the proportion of trips attributed to the study route or 75% of the change in ridership is attributed to the altered route. Table 3-7 provides an example of this distribution of the ridership change. In the example, 40% of the trips at the location are along the study route and the proposed changes result in an increase in ridership of 500 passengers. Using the first method of distribution, 40% of the 500 passengers are attributed to the study route for a total of 200 passengers, while the remaining 300 passengers generated by the service change are assumed to be along other routes serving the location. The second method assumes that a greater percent of the increase in ridership will be attributed to the altered route, so 75% of the ridership change is attributed to the study route for a total of 375 passengers. If the study route had accounted for more than 75% of the trips at the location then the second method of distribution would have resulted in the same distribution as the first method.

Table 3-7 Example Distribution of Ridership Change

				Distribution of Ridership Change			
				Method 1		Method 2	
Study Route Trips	Total Location Trips	Study Route % of Trips	Total Change in Ridership	Study Route	Other Routes	Study Route	Other Routes
90	225	40%	500	200	300	375	125

Both the nominal and percentage change in ridership are also shown for each proposal. Although the model is calibrated to make total system ridership equal to the actual system ridership in the base case, the direct demand model is not intended to be an accurate predictor of nominal ridership changes. As a type of sketch model, direct demand models are intended to be order of magnitude comparison tools and the nominal change in predicted ridership should not assumed to be the change in ridership experienced. Instead, the results of applying the model to different proposals should be used to help determine which proposals merit further investigation.

3.5. Conclusion

The following chapters discuss the application of service interval elasticities and a direct demand model to six different proposals including an increase in rail service in Chapter 4, an increase in service along existing bus routes in Chapter 5, and the introduction of new routes in Chapter 6. Details relevant to using the methods in specific scenarios are discussed in the appropriate chapters.

4. Green Line Extension to Lechmere

The planned Green Line Extension (GLX) will increase service to Lechmere by extending a second Green Line branch to Lechmere and beyond. The first proposal that is examined for mitigating the delay in opening the GLX is to increase Green Line service to Lechmere prior to the construction of the extension. Increasing service to Lechmere would help generate ridership patterns on the Green Line in anticipation of the GLX and would be complementary to the subsequent proposals to increase feeder bus services in the area.

This chapter discusses three options for increasing Green Line service to Lechmere. The vehicles required for the different options are calculated and the impact of new one seat ride opportunities is considered. A rail elasticity of demand with respect to service is calculated based on a prior experience within the MBTA system and then applied to the proposal to increase service to Lechmere. Finally, the bus direct demand model estimated for the MBTA system is used to evaluate the potential increase in bus ridership on connecting bus services due to transfers when additional rail service is provided at Lechmere.

4.1. Increased Service to Lechmere Proposal

Currently, only the E branch of the Green Line terminates at Lechmere. The planned GLX includes two branches, both operating at current E branch headways. In order to provide the intended headways on both the Union Square and College Avenue branches, a second Green Line branch will need to be extended to Lechmere and beyond. Figure 4-1 shows the current Green Line branches including all stops and available transfers to other rail lines.

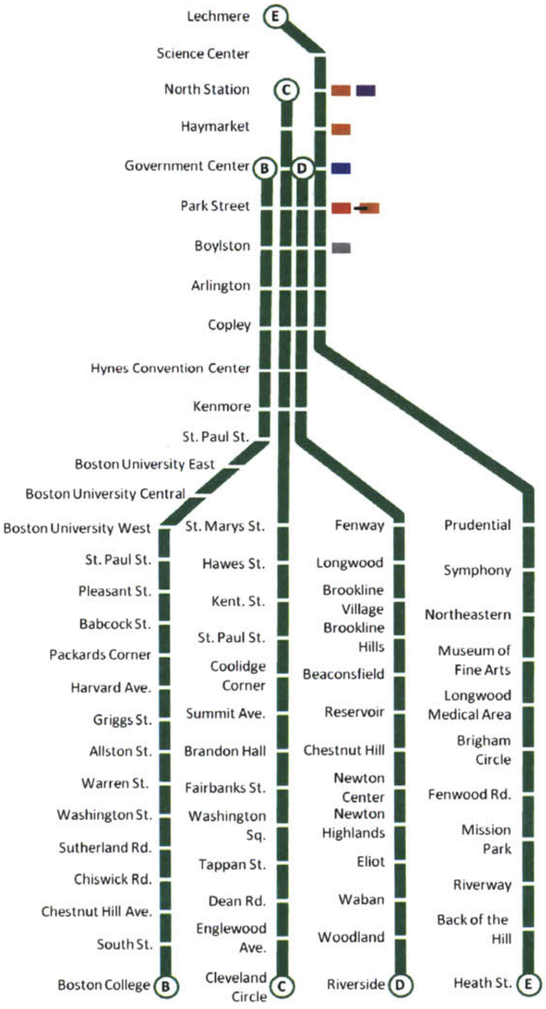
Although the extension is delayed, one means of mitigation would be to increase the frequency at Lechmere, as planned, by extending a second Green Line branch and turning both branches at Lechmere. This proposal would provide increased service at Lechmere (as well as Science Park and potentially North Station and Haymarket). Improved service at Lechmere would encourage greater use of this station and decreased headways may lessen the perceived unreliability of the E branch at Lechmere because wait times will be shorter. Ridership may also improve due to new one seat ride opportunities. Increased service at Lechmere would also encourage more use of the Green Line feeder bus routes.

The current GLX plan continues the E branch from Lechmere to Union Square and extends the D branch from Government Center to College Avenue. A key reason for choosing to extend the D branch is that it has its own right of way with no at grade crossings. This makes the D branch more reliable than other branches which include at grade crossings. Extending the D branch would also provide more capacity between Government Center and North Station. This segment is part of the congested Central Subway, which runs from Kenmore Station to North Station. While the Government Center to North Station segment is not the most congested portion of the Central Subway, more capacity is desired in this segment and the Government Center station is often extremely crowded. Extending the B branch from Government Center could also be considered. However, the B branch has the most variation in its run time throughout the day (Malikova, 2012), making the D branch a more reliable choice than the B branch.

Alternatively, the C branch could be extended from its current terminus at North Station. Extending the C branch would not provide additional capacity or increase train congestion in the Central Subway. The C branch already goes to North Station, so fewer trains and operators would be required to extend it further to Science Park and Lechmere than if the D branch was extended from Government Center. An alternative pattern could be introduced if the D branch were extended to Lechmere but the C branch cut back to end at Government Center, thus maintaining two branches in service between Government Center and North Station.

A third alternative for providing increased service at Lechmere would be to run a new route between Lechmere and Government Center. This shuttle loop could be operated using a single train car as opposed to the two or three car trains currently used on the Green Line branches. The advantage of this option is that it should reduce the number of train cars required compared to extending the C or D branches using two car trains. The disadvantage of this option is that all passengers on this loop would have to alight at Government Center and transfer to one of the main branches to travel any further along the line. All of the branches are available at Government Center so transfer waiting times should not be long, but Government Center is extremely crowded and is considered one of the worst transfer stations so transfers here are generally not preferred by riders (Guo, 2008). Forcing additional transfers at Government Center would only further exacerbate crowding at the station.

Figure 4-1 Current Green Line Routes



The MBTA currently has plans to renovate the Government Center station. The station is anticipated to be closed to passengers for two years during the renovation. Trains will still be able to run through the station, but passengers will not be able to board or alight there. The B and D branches that currently terminate at Government Center will need to either end at Park Street or be extended to Haymarket or North Station. If the D branch were to be extended to North Station as part of the construction mitigation, the number of additional trains required to extend the branch further to Lechmere would be less than the number calculated below. The

Lechmere - Government Center shuttle loop proposal would also need to be altered to have all passengers alight at Haymarket (but still turn at Government Center) or potentially to extend to Park Street (likely requiring additional trains). The impact of this construction is not included in the analysis of the proposals but should be considered when making a final decision on the implementation of any of the proposals. Given that changes will need to be made to the Green Line during the Government Center construction, this would be a good opportunity to extend additional service to Lechmere, thus getting ahead of the mitigation requirement and beginning the development of ridership patterns to Lechmere and beyond.

4.1.1. Number of Trains Required

A key factor in determining which branch to extend is the number of additional vehicles (trains and train cars) required. The peak periods are the most resource constrained in terms of both available train cars and available operators, so the vehicle requirements analysis will be most critical during the AM and PM peaks.

The number of trains required can be calculated using the simple formula

$$n = \left\lceil \frac{c}{h} \right\rceil \tag{4-1}$$

where

n = number of trains
c = cycle time
h = headway

The Green Line uses two car train sets in most cases, so the number of cars required will be twice the number of trains calculated. Currently the MBTA has been testing the use of 3 car train sets on some Green Line branches. The Fall 2012 schedule included the use of 3 car train sets for select trips on the B and D branches. If the D branch is extended, it is assumed that 3 car trains would not continue to be used. Otherwise, additional train cars beyond those calculated here would be required.

Headways and Cycle Times

All of the branches have unique headway schedules. Neither the C branch nor the D branch have the same headway as the E branch in every period, so either choice would require adjusting headways in some periods to achieve uniform headways at Lechmere. It is assumed the adjustment would be to make the new joint headway half the current E branch headway.

The internal MBTA schedule also differs from the public headway schedule published by the MBTA and available on the agency's website. While the internal schedule sets a time for each trip that can then be used to calculate the scheduled headway for each trip, the public headway schedule only provides a single headway for schedule periods that can be as long as 6.5 hours (the midday period is approximately 9:00AM - 3:30PM). Table 4-1 compares the internal and the public headway schedules.

Table 4-1 Internal vs. Public Schedule Headway Comparison – Weekday Schedule

		E branch		C branch		D branch	
Period	**Approx. Time**	**Internal**	**Public**	**Internal**	**Public**	**Internal**	**Public**
Early AM	Start - 6:30M	10		10		11	
AM Peak	6:30AM - 9:00AM	5	6	6	7	6	6
Midday	9:00AM - 3:30PM	8	8	10	10	10.5	11
PM Peak	3:30PM - 6:30PM	5	6	6.5	7	5.5	6
Evening	6:30PM - 8:00PM	9.5	10	6.5	7	10	10
Late Night	8:00PM - Close	13.5	14	13.5	14	13	13

The headways for the internal schedule in the table above are based on the Fall 2012 schedule. The minimum headway is used during the peak periods (to represent the peak of the peak) since this will be the constraining parameter in terms of the number of trains required. The current use of 3 car trains on the D branch during the peak periods results in a sequence of 5-6-7 minute headways for two 2-car train trips followed by a 3-car train trip during the peak of the peak. In these cases, the average headway of 6 minutes was used (5.5 minutes in the PM peak due to the inclusion of additional 2-car train trips with 5 minute headways). For the other periods, transitions between periods were general disregarded and the predominant or average headway was used.

Cycle times for each branch can also be calculated based on the Fall 2012 internal schedule. Based on the information in the schedule, the run time between any two stations for each trip and the layover time between any two trips can be calculated. The cycle time is the sum of the maximum run time and the minimum layover time for each period. The maximum scheduled run time is used because this will be the constraining unit in terms of requiring the maximum number of trains at this time. The minimum layover is used, though, because this is how long it actually takes to turn the vehicle at the terminal, and longer scheduled layovers could be shortened, if necessary, to save trains. Observed run times could also have been obtained from

Automatic Vehicle Identification (AVI) data. More information on the use of AVI and the related issues can be found in Malikova (2012).

Creating a Lechmere - Government Center shuttle loop or extending one of the other Green Line branches will result in new run times and layovers. The run time adjustments can be made based on the E branch run times between the relevant stations. For the shuttle loop, the run time is equivalent to the E branch Government Center - Lechmere run time. For the C branch, this means adding the E branch North Station - Lechmere run time in each direction to the current run times. For the D branch, this means adding the E branch Government Center - Lechmere run time in each direction.

The layover times must also be adjusted for two reasons: turning at different stations takes different amounts of time, and longer routes are often given more recovery time to ensure the next trip can leave as scheduled. For the Lechmere - Government Center shuttle loop, the layover is calculated as the sum of the layover at the two terminals. It is assumed that turning at Government Center will require 30 seconds and there will be no additional recovery time at that station. At Lechmere, the layover is taken as the greater of either the E branch percent of run time for the period applied to the shuttle run time or the current minimum layover at Lechmere for the day. The cycle time calculations for the shuttle loop can be seen in Table A-1 in Appendix A. The layover times calculated as a percent of run time are always rounded to the nearest half minute.

The C and D branches will have new terminal stations and be longer routes if extended. There are three possible ways to calculate the new layover time. The first looks at the current layover as a percent of the current run time and makes the new layover that same percentage of the new run time. The second method looks at the E branch layover as a percent of run time and makes the new layover that same percentage of the new run time on the extended route. The third option uses the current eastbound layover (since that direction will continue to turn around at the same station) and the E branch westbound layover at Lechmere. The results of the three methods, as well as the average layover for the methods, can be seen in Table A-2 in Appendix A. The subsequent analysis uses the average of these three layover calculation methodologies.

Additional Trains Required

Given the headways and cycle times for the shuttle loop and each of the current and extended branches, the number of trains required for each option can be calculated. Appendix A includes the different pieces of the trains required calculations. The C and D branches can be examined with the current routes and headways, with the current routes but the E branch headways, and with the extended routes and the E branch headways. The table below shows the results of using the extended routes and E branch headways. The average of the three methods discussed above for calculating the layover times is used. Appendix A also includes the trains required calculations using each method of layover calculation discussed above in order to show that the trains required does not differ by more than one train (two train cars) in any time period as a result of changing the layover time calculation method.

Table 4-2 Additional Trains Required Summary

	Loop	C Branch	D Branch
Early AM	2	1	2
AM Peak	5	6	8
MidDay	3	4	5
PM Peak	5	7	7
Evening	3	(2)	4
Late Night	2	0	2

If the C branch is extended, there is a decrease in the number of trains required in the evening period because the C branch has a greater frequency than the E branch in that period. Adjusting the C branch frequency to match the E branch headway in the evening saves four trains before extending the branch, but also means a decrease in service along this branch. Although the shuttle loop and the extension of the D branch both require adding trains along the same Lechmere - Government Center section, the D branch requires a greater number of additional trains because more trains are needed along the full route in order to increase the frequency of service along the entire route to match the E branch headways, not just to add trains to the extended section.

It is important to note at this point that the C and D branches use two (or sometimes three) train cars per train, so the number of cars required would be twice the number shown in Table 4-2 (or more when three car trains are used). In contrast, the shuttle loop could be operated using single car trains so it would only require the number of train cars shown in Table 4-2.

4.1.2. Transfers and One Seat Ride Opportunities

Another consideration in selecting the best option for increasing service at Lechmere is the connections made available by extending a particular branch. In this case, the major connections to other rail lines are all in the shared Central Subway section from Kenmore to North Station, so extending either branch would provide additional frequency from Lechmere and Science Park to these connections. However, unlike the C branch, extending the D branch would provide northbound passengers increased access to the commuter rail at North Station and the Orange Line at both North Station and Haymarket, assuming the C branch was not cut back to Government Center in response. Although these northbound passengers are not the focus of this mitigation proposal, these additional connections to the commuter rail and the Orange Line should be noted. The Orange Line transfer at Park Street is rather onerous and likely is not used by most riders, so providing additional transfer opportunities at other stations would improve some riders' transfer experiences while allowing other riders to avoid having to transfer at all in order to access the commuter rail at North Station.

Extending a second branch to Lechmere also provides more one seat origin-destination pairs along the Green Line. Table 4-3 provides an origin-destination matrix for the Green Line from the work of Tribone (2011). This matrix attributes all rail passengers that interact with the Green Line to the stations where they board and alight the Green Line, even if they transfer to or from another rail line. The new one seat origin-destination pairs that would be introduced by extending either the C or D branch to Lechmere are highlighted in blue. In addition to providing additional one seat rides to and from Lechmere and Science Park, extending the D branch would also provide a one seat ride between Haymarket or North Station and the surface portion of the D branch. Creating the Lechmere - Government Center shuttle loop does not provide any new one seat ride opportunities since it would only serve stations already along the E branch.

Table 4-3 Green Line O-D Matrix (full day, based on Tribone's model)

	Destination									
Origin	Lechmere + Science Park	Haymarket + North Station	Shared Stations (all Green Line branches)	Shared Stations (B, C, D branches)	B Branch Surface Stations	C Branch Surface Stations	D Branch Surface Stations	E Branch Surface Stations	**Total (all stations)**	**Origin % of Total Trips**
Lechmere + Science Park	8	1,708	2,525	171	92	77	137	352	**5,070**	**2.5%**
Haymarket + North Station	1,600	179	10,997	1,683	385	542	424	1,592	**17,403**	**8.5%**
Shared Stations (all Green Line branches)	2,655	10,418	49,897	10,462	7,909	4,596	8,260	9,110	**103,307**	**50.4%**
Shared Stations (B, C, D branches)	174	1,878	11,364	841	2,180	1,218	1,528	394	**19,577**	**9.6%**
B Branch Surface Stations	79	370	8,139	1,978	5,013	683	745	454	**17,461**	**8.5%**
C Branch Surface Stations	91	576	4,745	1,039	700	1,808	489	384	**9,831**	**4.8%**
D Branch Surface Stations	127	440	8,530	1,366	729	511	4,776	403	**16,882**	**8.2%**
E Branch Surface Stations	389	1,576	9,617	391	376	316	360	2,296	**15,321**	**7.5%**
Total (all stations)	**5,123**	**17,146**	**105,813**	**17,931**	**17,384**	**9,752**	**16,719**	**14,984**	**204,851**	**100.0%**
Destination % of Total Trips	**2.5%**	**8.4%**	**51.7%**	**8.8%**	**8.5%**	**4.8%**	**8.2%**	**7.3%**	**100.0%**	

It is difficult to determine the impact of a one seat ride based on the Green Line origin-destination matrix. More passengers travel between Lechmere or Science Park and the surface portion of the E branch than travel between Lechmere or Science Park and the surface portion of any of the other branches. However, attributes of each individual surface branch, and the trip generators and attractors along them, make it difficult to accurately determine ridership patterns due to one seat ride availability as opposed to the relative attractiveness of various origin-destination pairs.

The benefits of a one seat ride in increasing ridership seem limited in this situation. The number of passengers riding between Lechmere or Science Park and the surface portions of the C or D branches is currently minimal. Only 4.2% of all passengers boarding at Lechmere or Science Park have destinations on the surface portions of the C or D branches (7.6% including stations shared by the B, C and D branches but not the E branch). The same percentage of passengers board at C or D branch surface stations and alight at Lechmere or Science Park. There is likely more regional trip generation and attraction along the surface portion of the D branch than the C branch because of the proximity of Longwood Station to the Longwood Medical Area.

Rather than using the Green Line origin-destination matrix to determine the benefit of a one seat ride, the concept of transfer penalties within the MBTA system can be used. Providing a one seat ride where it did not previously exist is equivalent to removing the transfer penalty. Appendix B discusses the work of Guo (2008; Guo and Wilson, 2004), who created several regression models to estimate the transfer penalty for rail to rail transfers within the MBTA system in Downtown Boston. Based on Guo's work, providing a one seat ride where a transfer was previously required is assumed to be equivalent to decreasing the headway by 8 - 12 minutes. This adjustment can be incorporated into the elasticity calculation below in order to include the impact of a one seat ride when extending one of the Green Line branches.

4.2. Service (Headway) Demand Elasticity Calculation

Despite the availability of literature on bus demand elasticities, very little information is available on rail service elasticities, particularly in the United States. TCRP Report 95 only quotes one study by London Transport using time series based estimates to find that the London Underground has a lower sensitivity to frequency changes than bus (Evans & Pratt, 2004). According to this study, the Underground has a miles operated service elasticity of +0.08, which is just under half the elasticity of London Buses. In contrast, TRL finds that urban rail may be more sensitive to service changes (as measured by a combination of vehicle kilometers and headways) than bus service (Balcombe et al., 2004). However, TRL also quotes a report by Mitrani et al. (2002) that calculated a significantly lower London Underground service elasticity. This same report also detected a small cross-elasticity of Underground demand with respect to bus miles.

Given the dearth of applicable rail elasticities in literature, evidence from MBTA experience is used to calculate a rail elasticity that can be used for the Green Line. Regression analysis of historical ridership on the MBTA Orange Line service was conducted to establish a rail elasticity. This elasticity was then applied to the Green Line. Additional adjustments were made to account for the fact that extending one of the Green Line branches to Lechmere would involve both a service frequency change and a network change.

4.2.1. Orange Line Single Person Train Operations

In 2010, the MBTA instituted single person train operations (SPTO) on the Orange Line. Some of the savings from the decreased operator requirements were used to increase service on the line. Service changes were only made to off peak periods due to train availability constraints during the peak. The resulting changes in service went into affect with the start of the summer schedule on June 26, 2010. The headway changes were as follows:

Weekdays:
- Afternoon service from 1PM - 4PM improved from every 9 minutes to every 8.5 minutes
- Evening service after 8PM improved from every 13 minutes to every 10 minutes

Saturdays:
- Service before 8AM improved from every 11-15 minutes to every 10 minutes
- After 6PM, service improved from every 13 minutes to every 10 minutes

Sundays:
- Before 10AM, service improved from every 15 minutes to every 12.5 minutes
- After 10AM, service improved from every 13.5 minutes to every 10 minutes.

Based on these changes, the impact of service frequency on ridership could be observed and calculated.

The Red Line also moved to single person train operations in 2012 and made some adjustments to the service schedule. However, other changes were made simultaneously on the Red Line so that any change in ridership cannot be directly attributed to a change in service for the purpose of calculating the service elasticity.

4.2.2. Data

The MBTA maintains a Ridership Master file which compiles information from Automatic Fare Collection (AFC) reports. Data contained in the file includes average daily ridership per month for weekdays, Saturdays and Sundays. Any day with a holiday schedule is reported separately and was excluded from the analysis presented here. The Ridership Master file breaks out ridership for each heavy and light rail line, buses, trackless trolley and the Silver Line. Prior to the availability of full AFC data in state fiscal year 2008 (July 2007 - June 2008), estimates of ridership were derived using a revenue-based approach (Guptill, 2011). In addition to providing the raw fare box ridership numbers, the MBTA's file makes adjustments for children and fare evasion, shared stations and transfers. The Central Transportation Planning Staff (CTPS) annually provides the MBTA with non-interaction factors and transfer rate estimates for the calculation of ridership adjustments. The analysis below was completed based on the Ridership Master as of October 18, 2012, which contains ridership data through June 2012 (select lines through July or August 2012). The data begins in January 2007, although some of the Silver Line data was not included until as late as October 2010.

Occasionally adjustments are made to the AFC reports that are not always reflected in the Ridership Master. One of the drawbacks of this file is that it focuses on weekdays and does not include all data or complete all of the adjustment calculations for weekends. In particular, the adjustment calculations are not done for the Silver Lines for weekends. All numbers as included in the Ridership Master as of October 18 were taken as given. The only modification made to the file data was to complete the Silver Line adjustment calculations for Saturdays and Sundays using the formulas provided for the weekday adjustments.

The other data needed for the elasticity analysis are measures of the service changes. Service and ridership patterns vary by period throughout the day, but the Ridership Master only provides daily ridership information. Therefore, a full day service change metric had to be established. An average daily headway was calculated before and after the implementation of SPTO for each weekdays, Saturdays, and Sundays. The headways provided for the Orange Line SPTO adjustment were used when available and the public schedule headways were used otherwise. When not available, early morning headways were set equal to the published late night headways. The headways provided with the implementation of SPTO do not always match the current published headways but were used regardless of current published headways. When a headway range was provided (Saturday mornings), the average value was used. Based on these calculations, average daily headways were calculated and the percentage change in service with the implementation of SPTO could be established (Table 4-4).

Table 4-4 Average Orange Line Daily Headway Before and After SPTO

	Average Headway Before (min)	Average Headway After (min)	% Change in Headway
Weekday	8.1	7.7	-5%
Saturday	11.3	10.0	-11%
Sunday	13.8	10.4	-24%

The Orange Line weekday MBTA internal timetable was also available for Spring 2010 and Spring 2011 (before and after the service change), and an analysis of the number of scheduled trips matches the 5% service change calculated using the method above. Ridership by time of day is available through AFC reports, but the historical data required for this analysis has been archived and was not available.

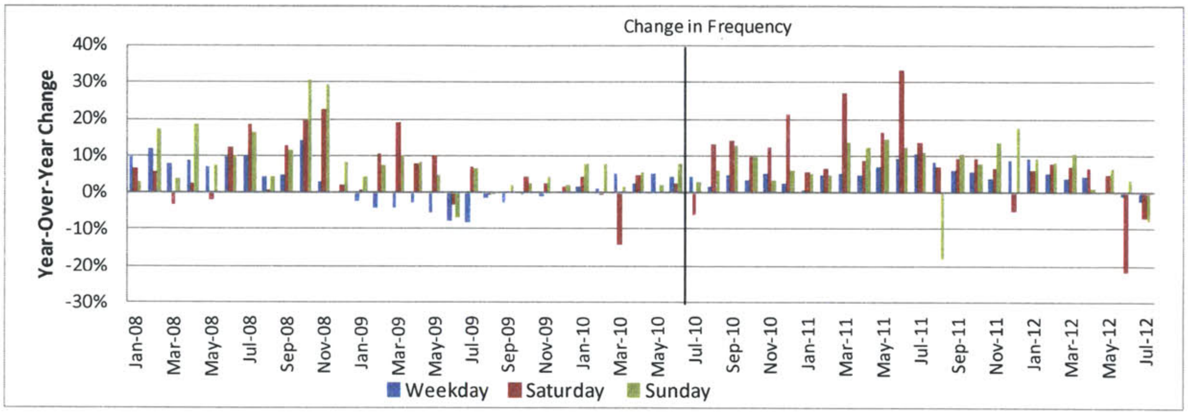
4.2.3. Initial Data Analysis

Before starting more advanced analysis, historical ridership data was examined to make sure that a pattern of growth due to the service change could be observed, in an attempt to distinguish system-level ridership growth due to exogenous economic factors from the ridership response to the service change. Ridership growth was examined for each line as well as for the sum of the system excluding the Orange Line. Select graphs and tables of the ridership growth can be found below and in Appendix C. The focus of the analysis was on two sets of comparisons: between different days, and between the Orange Line and the rest of the system. There were also two main time comparisons that were made: month-over-month changes and year-over-year changes.

Orange Line growth on different days (weekdays, Saturdays, Sundays) was observed to ensure that ridership growth was observed following the service change (Figure C-1). Since the different days had different magnitudes of service change, it was expected that the days would have slightly different growth patterns following the change. The difference between Orange Line growth and other lines was also examined to see where the Orange Line growth pattern differed from the rest of the system.

Month-over-month Orange Line ridership growth (Figure C-2) shows the strong influence of seasonality. The year-over-year change in ridership by month (Figure 4-2, also Figure C-3) accounts for seasonal patterns and shows growth patterns over time. Greater growth in Orange Line ridership was seen after the service change than before the service change. Strong statements about differences between the days cannot be made, but the largest growth is seen on weekends when the service changes were greater and applied to more of the day.

Figure 4-2 Year-Over-Year Change in Orange Line Ridership by Month



Although greater ridership growth can be seen in the Orange Line following the service change, the data must be normalized for system ridership to ensure that the growth is not due to a system-wide growth in ridership. Comparing Orange Line ridership growth to the growth in the rest of the system shows that following the headway change at the end of June 2010, the differential between Orange Line growth and system growth was greater than before the change, particularly on weekends (Table 4-5, also Table C-1 and Table C-2). Table 4-5 shows the comparison between the year-over-year growth in average annual Orange Line ridership and system ridership. The numbers in the table are the Orange Line percent growth less the system percent growth, so a positive number means Orange Line ridership increased more than system than ridership in the rest of the system. The greater Orange Line growth compared to system growth seen after the service change supports the premise that the service change led to increased Orange Line ridership. The ridership growth appears to be concentrated in the first year after the service change. This is reasonable given the size of the service change. The service changes to the Orange line were likely not significant enough to cause longer term impacts, such as people moving to areas along the line due to better service.

Table 4-5 Year-Over-Year Orange Line Average Annual Ridership Growth Compared to System Average Annual Ridership Growth
(system defined as bus, trackless trolley, light rail and heavy rail, excluding Orange Line)

	Weekday	Saturday	Sunday
07/08 - 06/09	3%	9%	9%
07/09 - 06/10	2%	3%	3%
07/10 - 06/11	3%	7%	6%
07/11 - 06/12	-1%	2%	4%

* Green = Orange Line ridership grew more than 5% more

4.2.4. Regression Analysis

The initial data analysis demonstrated that there is a connection between the service changes and the increased ridership on the Orange Line following the implementation of SPTO in 2010. Regression analysis was used to estimate the elasticity more precisely. Different regression models were evaluated based on whether the values of the coefficients seemed reasonable given expectations and if they were statistically significant.

The Ridership Master as of October 18, 2012 and the Orange Line average daily headways discussed above were used for the regression analysis. The log of ridership and headways were used so that the coefficient on the headway variable could be interpreted as the elasticity of demand with respect to service. Dummy variables were also created for the season and calendar year to account for seasonal trends and system growth over time. Several regressions were run for Orange Line ridership, starting with Orange Line service as the independent variable and adding in system ridership and other additional variables in subsequent regressions.

Additional variables tested but not included in the final regression model include dummy variables for the type of day, dummy variables for the year, and interaction factors between type of day and service. Different data set variations were tested as well, including using the full data range from 2007 through 2012, different combinations of weekday and weekend data, different definitions of the system for system ridership, and raw fare box numbers instead of adjusted ridership.

Initial regressions including dummy variables for the year showed that Orange Line growth was below the trend in 2007 and 2008. Removing these years still leaves sufficient data before and after the service change while removing unrelated growth patterns from the earlier data. This also results in more reliable data as earlier data reporting was not as consistent as current data reporting. Earlier periods also excluded Silver Line ridership data which was included in some model variations. Removing the 2007 and 2008 observations made the season dummy variables more statistically significant, suggesting that the regression was better able to attribute differences to a seasonal change rather than a general annual trend. The risk in removing these years of data and the year dummy variables is that the 2007 and 2008 coefficients showed that there are unidentified variables that impact Orange Line ridership that are not included in the regression. These variables may still be meaningful and are still not included in the final regression.

The impact of using adjusted ridership versus raw fare box numbers was also tested. Using unadjusted ridership numbers instead of the adjusted fare gate numbers does not have a large impact on the regression results. This makes sense because there are two major types of adjustments: shared station adjustments which primarily redistribute ridership throughout the system, and transfer and children & fare evasion adjustments which increase ridership proportionally throughout the system. While these adjustments affect the nominal ridership numbers, they do not have a large impact on the relationship between years and lines. These adjustments do have a slight impact on the year and season dummy variables though because the adjustment factors change each fiscal year while the dummy variables are for the calendar year.

The results of several regression models, including the final regression highlighted in blue, can be found in Table 4-6. The final regression includes Orange Line headway as a proxy for service, system ridership and season dummy variables. All of the regressions shown include data from January 2009 through June 2012 and define system ridership to include Red Line, Blue Line, Green Line, bus and trackless trolley.

Table 4-6 Orange Line Ridership Regression Results

Logarithmic Regression Results
Saturdays & Sundays, January 2009 - June 2012
Coefficient (t Statistic)

		1	2	3
		Service	**Service, System Ridership**	**Service, System Ridership, Season**
	Intercept	14.42	-0.51	-0.71
	Orange Line Headway	-1.29 (-7.71) ***	-0.34 (-8.15) ***	-0.33 (-8.36) ***
	System Ridership		0.97 (41.87) ***	0.98 (44.49) ***
Seasons	**Summer**			-0.02 (-1.51)
	Fall			0.03 (2.45) *
	Winter			0.02 (1.52)
	Adjusted R^2	0.41	0.97	0.98

N = 84

Significance codes: 0 *** 0.001 ** 0.01 * 0.05 . 0.1 1

Orange line service is the principal variable being examined here. The coefficient on this variable was expected to be significant and between negative one and zero. In the final regression, the Orange Line headway coefficient is statistically significant with a value of -0.33. This value is higher than that found in the London based research, but it is within the range of elasticities commonly cited for buses, including being in the middle of the Lago, Mayworm and McEnroe (1981) bus route headway elasticities for service less than 10 minutes (-0.22) and between 10 and 50 minutes (-0.46).

The system ridership variable is also important because it accounts for system-wide factors and changes other than the change in Orange Line headways. The system ridership coefficient was expected to be significant and close to 1.0. A coefficient close to 1.0 can be interpreted to mean that a change in system ridership results in an almost equal percentage change in Orange Line ridership, all else equal. This result would suggest that the model is able to properly account for the connection between system and Orange Line ridership. Different proxies for system ridership were tested, including with and without the Silver Line, and with and without bus and trackless trolley. The final regression model defines system ridership as the sum of ridership on the Red Line, Blue Line, Green Line, bus and trackless trolley. As anticipated, in the final regression the system ridership coefficient is nearly 1.0 and is statistically significant.

The last set of variables included in the final regression is dummy variables for the seasons. Previous examination of the data showed strong seasonality in the ridership, so it is not surprising that there would be a seasonal impact. The fact that the season coefficients are significant means that the Orange Line seasonal pattern in ridership is different than the pattern seen in the rest of the system and therefore cannot be accounted for solely through the inclusion of system ridership. It is important to include these variables to determine whether the impact of seasonal variation in Orange Line ridership is significant or should otherwise be attributed to changes in either the system ridership or the Orange Line service change. The season coefficients in the final regression are small, and only the fall coefficient is statistically significant. This finding is consistent with other regression estimates conducted.

The regressions above were run using data for both Saturdays and Sundays. By not including any type of day dummy variables and assuming that travel patterns are the same on Saturdays and Sundays, more variation in service can be included, allowing for a better estimation of the coefficient. However, failure to distinguish between Saturday and Sunday may result in some of the differences between the two days being falsely attributed to the differences in headway. Weekdays were excluded because the service change was minimal (5% decrease in headway). Weekdays also have a greater differentiation between peak and off-peak ridership which cannot be accounted for with the full day data available.

The final regression model defines system ridership as the sum of rail (Red, Blue and Green Lines), bus and trackless trolley ridership, but additional models tested other variations including omitting bus and trackless trolley, and including Silver Line. These minor changes to the definition of system ridership did not have a significant impact on the regression results. The final regression includes bus and trackless trolley because of the strong connection between the services in the MBTA network. The Silver Line is excluded because data was not available for some of the lines prior to 2010, making the data inconsistent when the Silver Line is included. However, even when Silver Line ridership counts on their own are excluded, Silver Line fare box data (when available) factors into the calculation of the adjusted bus ridership and transfers. This impact of the Silver Line ridership was not altered when using the data, but its impact is minimal.

4.3. Green Line Elasticity Application

Based on the rail elasticity of -0.33 calculated from the Orange Line SPTO service change experience, the change in Green Line ridership due to extending a second branch to Lechmere can be analyzed. Again, Tribone's model can provide weekday ridership data for any time period. Sensitivity analysis was also conducted using a range of ±0.1 around the base elasticity. As mentioned in Section 3.2, this same sensitivity range was used for price elasticity calculations during the MBTA fare increase and service reductions impact analysis (Central Transportation Planning Staff and Massachusetts Bay Transportation Authority, 2011), and this range allows for variation while keeping the elasticity within the anticipated range.

Elasticities were applied to two time periods: all day and AM peak, where AM peak is defined as 6:30AM to 9AM. The key ridership for this proposal is the ridership to and from Lechmere and Science Park. If the D branch is extended, ridership increases could also be expected at North Station and Haymarket. It is assumed that the extension would result in twice the current frequency of service at Lechmere and Science Park throughout the day.

4.3.1. One Seat Ride Adjustment and Ridership Segmentation

Before the calculated elasticity could be applied to the Green Line, adjustments had to be made to account for different passenger experiences. As discussed in Section 4.1.2 and Appendix B, providing a new one seat ride opportunity is equivalent to decreasing the headway by about 8 - 12 minutes on the Green Line. This perceived benefit of a one seat ride is greater than the expected waiting time given the current E branch headway. This has implications for a passenger waiting for a train to or from Lechmere or Science Park. If a passenger has a choice between two branches but only one of the two options will provide a one seat ride, the transfer penalty is great enough that the passenger would rather wait for the one seat ride, even if that means not taking the first train to arrive at the station. In order to reflect the benefits of new one seat ride opportunities and the choice of passengers to wait for a branch that provides a one seat ride, the ridership boarding and alighting at Lechmere and Science Park must be segmented for the elasticity calculation. The segmentation of passengers is shown in Table 4-7 for the AM peak and Table 4-8 for the full day.

When extending the C or D branches, there are three possible categories that riders can belong to. The first category is riders who currently have both their origin and destination on branches served only by the E branch. These riders will not experience any service change. The E branch headways will remain the same, so if a passenger boards along the surface portion of the E branch, their headway will not change. If a passenger boards at Lechmere or Science Park and alights at an E branch surface station, they will continue to wait for an E branch train in order to avoid having to transfer.

The second category is passengers who are boarding or alighting at stations served by the extended branch but not the E branch. These passengers will benefit from the addition of a new one seat ride opportunity. Before extending the second branch, these passengers had to take both the E line and an additional branch. Their new headway is the E branch headway because these passengers will wait for the extended branch in order to avoid a transfer. In addition, these passengers no longer need to transfer, so the removal of the transfer penalty decreases their perceived headway by an additional 8 - 12 minutes.

Finally, passengers going to stations served by both the E branch and the extended branch will not benefit from a new one seat ride opportunity. However, they will experience an improvement in service since they can take the first train to arrive, regardless of what branch it is.

A similar segmentation of riders can be done for the Lechmere - Government Center shuttle loop. Again, passengers who have both their origin and destination at stations served only by the E branch will not experience any change. All other passengers will experience a doubling of the frequency of service. Passengers who are going to a station served by the shuttle can take the first train to arrive and will therefore experience an increase in service. At the same time, all passengers going to a station not served by the E branch or the shuttle will be forced to transfer. These passengers had to transfer before, so they do not experience a new transfer penalty, but they do experience an increase in service because they can take either branch to North Station, Haymarket or Government Center to transfer.

Table 4-7 Segmentation of Current Ridership - AM Peak

Based on current ridership with origin or destination at Lechmere or Science Park

If Extend C Branch		
	Origin	**Destination**
1. E branch	99	86
2. C branch	48	55
3. Either	987	844
Total	**1134**	**985**

If Extend D Branch		
	Origin	**Destination**
1. E branch	99	86
2. D branch	66	50
3. Either	969	849
Total	**1134**	**985**

If Use Loop Shuttle		
	Origin	**Destination**
1. E branch	99	86
2. Either	1035	899
Total	**1134**	**985**

Table 4-8 Segmentation of Current Ridership - All Day

Based on current ridership with origin or destination at Lechmere or Science Park

If Extend C Branch		
	Origin	**Destination**
1. E branch	360	397
2. C branch	247	265
3. Either	4462	4460
Total	**5070**	**5123**

If Extend D Branch		
	Origin	**Destination**
1. E branch	360	397
2. D branch	308	301
3. Either	4401	4425
Total	**5070**	**5123**

If Use Loop Shuttle		
	Origin	**Destination**
1. E branch	360	397
2. Either	4709	4725
Total	**5070**	**5123**

4.3.2. Elasticity Application

In order to run the elasticity calculation, a weighted average change in service was calculated based on the segmentation of riders. Based on the weighted average headways before and after the provision of additional service at Lechmere and Science Park, the MBTA rail elasticity calculated above can be used to estimate the change in ridership. In addition to the sensitivity analysis for the elasticity used, a range can be applied to the transfer penalty savings to see how sensitive ridership changes are to this assumption. The tables below show the elasticity calculations including the sensitivity range and assuming the transfer penalty is equivalent to eight minutes of headway time. The tables in Appendix D provide additional results including the transfer penalty sensitivity analysis.

Table 4-9 Green Line Ridership Elasticity – AM Peak (Transfer Penalty = 8min)

	Origin			Destination		
	Extend D Branch	Extend C Branch	Loop Shuttle	Extend D Branch	Extend C Branch	Loop Shuttle
Initial Ridership	1,134	1,134	1,134	985	985	985
Initial Headway	5.0	5.0	5.0	5.0	5.0	5.0
New Weighted Average Headway	2.4	2.5	2.7	2.4	2.4	2.7
Projected Ridership						
Low Elasticity (e = -0.23)	1,334	1,324	1,299	1,155	1,157	1,129
% Change	*17.6%*	*16.7%*	*14.6%*	*17.2%*	*17.4%*	*14.6%*
Midium Elasticity (e = -0.33)	1,432	1,416	1,379	1,238	1,242	1,198
% Change	*26.3%*	*24.9%*	*21.6%*	*25.6%*	*26.0%*	*21.6%*
High Elasticity (e = -0.43)	1,538	1,516	1,464	1,328	1,333	1,272
% Change	*35.6%*	*33.7%*	*29.1%*	*34.8%*	*35.3%*	*29.1%*

Table 4-10 Green Line Ridership Elasticity – All Day (Transfer Penalty = 8min)

	Origin			Destination		
	Extend D Branch	Extend C Branch	Loop Shuttle	Extend D Branch	Extend C Branch	Loop Shuttle
Initial Ridership	5,070	5,070	5,070	5,123	5,123	5,123
Initial Headway	7.8	7.8	7.8	7.8	7.8	7.8
New Weighted Average Headway	3.9	4.0	4.2	3.9	4.0	4.2
Projected Ridership						
Low Elasticity (e = -0.23)	5,904	5,860	5,828	5,955	5,946	5,881
% Change	*16.5%*	*15.6%*	*15.0%*	*16.2%*	*16.1%*	*14.8%*
Midium Elasticity (e = -0.33)	6,311	6,244	6,194	6,360	6,347	6,247
% Change	*24.5%*	*23.2%*	*22.2%*	*24.2%*	*23.9%*	*22.0%*
High Elasticity (e = -0.43)	6,749	6,655	6,586	6,797	6,777	6,638
% Change	*33.1%*	*31.3%*	*29.9%*	*32.7%*	*32.3%*	*29.6%*

The D branch results in the greatest change in ridership in almost all cases. This makes sense since extending the D branch creates the most new one seat ride opportunities (8.2% of all Green Line trips have destinations on the surface portion of the D branch compared to 4.8% for the C branch). In contrast, the Lechmere – Government Center shuttle loop does not create any new one seat ride opportunities and results in significantly lower ridership increases.

The actual anticipated ridership impact could be even greater than the nominal change seen in the tables above due to AFC undercounting boardings. In the MBTA Ridership Master file, a fare gate shortage of 5.1% is applied to the fare gate count to adjust for children and fare evasion. Applying this additional adjustment factor to the results in the tables above does not impact the percent changes but does increase the nominal ridership increase.

A weakness of the elasticity analysis above is that the ridership information is based solely on weekdays while the elasticity calculation is based on weekends. Previous experiences suggest that bus elasticities are different on weekdays and weekends, and it is reasonable to assume the same would hold true for rail. These results could also be overstating the expected impact since off-peak elasticities are being applied to peak ridership, when peak elasticities would be expected to be lower.

For bus routes, the elasticity is generally recognized to vary based on the initial headway. If the same trends occur for rail as with bus, the longer headways on the Orange Line would result in a greater elasticity than the Green Line would experience with shorter headways. For buses, a distinction is made between walk-up service (under 10 minute headways) and scheduled service (over 10 minute headways). The Orange Line weekend headways used to calculate the rail elasticity were all ten minutes or more while the Green Line weekday headways are all 10 minutes or less, with the exception of late night headways of 13.5 minutes. This distinction is not expected to be as meaningful for rail since all MBTA rail service operates as walkup service with published schedules providing headways and not arrival or departure times. These differences between the Orange Line and the Green Line suggest that the elasticity calculations above may serve as an upper bound on what should be expected.

On the other hand, some additional rider benefits are not captured by this analysis and may result in additional ridership generation. The C and D branches would have changes in their frequency if extended to Lechmere. These changes would be experienced by all riders along the route, not just riders going to or from Lechmere and Science Park. In most cases, this would mean an improvement in service on these branches. The one exception is the C branch in the evening when current headways are shorter than the E branch headways and therefore service on the C branch would be decreased during this time period. Extending the D branch or implementing the Lechmere - Government Center shuttle loop would also increase service at North Station and Haymarket, so increased ridership would be expected to and from these stations as well. Given the higher current ridership at North Station and Haymarket, increasing service at these stations would have a greater impact with an possible ridership increase of over 2,000 passengers each boarding and alighting at these stations.

Although different transfer penalties are tested here, differences between passengers and their individual sensitivities to the transfer penalty are not accounted for. The current lack of information along the Green Line about when the next train will arrive and, when appropriate, what its destination will be may cause some passengers to take the first train to arrive, regardless of its destination. Passengers might take the first train to arrive even if it is not the a branch that provides a one seat ride to their destination because they do not know if the wait for the one seat ride will be longer than the time saved from avoiding a transfer. This means that at Lechmere and Science Park more passengers will benefit from the increased service than suggested by the analysis above because some of the passengers assumed to wait for a specific branch may take the first branch to arrive, even if it results in a transfer. However, these passengers will not benefit from the removal of a one seat ride if the first train to arrive is not on the correct branch. Providing real time arrival information would remove the uncertainty around when the next train will arrive. Real time arrival information would complement the service increase by allowing passengers to make informed decisions on when to take the first train to arrive versus waiting for the next train if it will be on a branch that would remove a transfer penalty.

4.4. Direct Demand Model Application

Although the direct demand model generated for the MBTA bus system is not applicable to rail stations, rail feeder trips are an input into the bus model and therefore impact the estimated bus ridership. The impact of a change in rail service on rail ridership cannot be analyzed by the direct demand model used here, but the magnitude of the impact on bus ridership (through transfers) can be estimated. In the bus direct demand model developed for the MBTA bus system, only feeder trips at stations greater than 1.5km from the CBD are included. Along the portion of the Green Line being examined (between Government Center and Lechmere), only Lechmere is more than 1.5km from the CBD. This means that the impact of the service increase at Lechmere can be estimated but the impact at Science Park, North Station and Haymarket cannot.

In order to apply the bus direct demand model to increased service on the Green Line, the number of rail feeder trips at Lechmere as calculated from the GTFS data was assumed to double. The change in bus ridership at the bus transfer location at Lechmere Station was estimated to be an increase of 166 passengers, or 8.3% of current ridership (Table 4-1). This number only includes the impact on passengers boarding at Lechmere. It can be assumed that there would also be an equal increase in boardings at other locations by passengers with destinations at Lechmere due to passengers transferring to the Green Line at Lechmere, but this direct demand model does not consider destinations and therefore cannot capture this additional ridership impact.

Table 4-11 Direct Demand Model Results - Double Frequency of Green Line at Lechmere

	Bus Riders at Lechmere Locations		
	Before	**After**	**Change**
Unadjusted Ridership	220	238	18 (8.3%)
Adjusted Ridership	2,006	2,172	166 (8.3%)

4.5. Conclusion

The GLX will increase service to Lechmere, extending a second Green Line branch to Lechmere and beyond. One way to mitigate the delay in opening the GLX would be to increase service to Lechmere prior to the construction of the extension. Increasing service to Lechmere would help generate ridership patterns that would decrease the anticipated time lag between the opening of the GLX and the development of ridership along the extension. Synergies would also exist between increased service on the Green Line to Lechmere and increased feeder bus service as discussed in subsequent chapters, resulting in more transfers and increased ridership on both modes.

There are three ways Green Line service to Lechmere (and Science Park) could be increased: extending the D branch from Government Center (as planned for the GLX), extending the C branch from North Station, or creating a new Lechmere - Government Center shuttle loop. Depending on the proposal, these three options would require between five and eight additional trains during the peak periods in order to double the current Green Line frequency to Lechmere. This peak train requirement is an upper bound, and fewer vehicles would be required during some periods of the day. Some of the proposals would also increase service at other stations (North Station and Haymarket) and provide new one seat ride opportunities along the Green Line.

Given the lack of rapid rail elasticity information in the United States, an elasticity for the MBTA system was estimated based on the service changes made on the Orange Line when single person train operations were implemented in 2010. Based on this experience, a ridership elasticity with respect to headway of -0.33 was calculated. Applying this elasticity to the three proposals to increase Green Line service to Lechmere and using a sensitivity range of ±10% results in an estimated ridership increase of approximately 15-36% in the AM peak and 15-33% for the full day. For the AM peak, this equates to about 300-750 additional passengers boarding and alighting at Lechmere and Science Park and about 1,500-3,350 additional riders over the full day. Using the bus direct demand model created for the MBTA system also predicts an additional 8% increase in bus boardings at Lechmere when Green Line service is increase.

5. Existing Bus Routes Service Increase

Before considering the creation of new routes, the MBTA could consider altering existing routes in the study area in order to maximize ridership. Alterations to existing routes could take advantage of already established bus stops, routes, and trip patterns, thereby requiring less time and resources than creating new routes which would require attracting passengers to new bus stops and patterns. Methods for improving service on existing routes include scheduling changes (increased frequency, implementation of clockface schedules) and non-scheduling changes (improved information provision, bus stop upgrades).

The focus of the proposals presented here is on scheduling changes. Routes serving Lechmere Station are selected because the GLX will eventually provide more options from this station and the proposal in Chapter 4 would increase Green Line service to this station. Increasing bus service to and from Lechmere Station would provide increased transfer opportunities and hopefully induce more ridership on the Green Line and along the future GLX corridor. The first proposal presented in this chapter is to increase frequency along Route 88, while the second proposal seeks to create a short variant of Route 87 in order to increase service along a portion of the route while minimizing vehicle and operating cost increases.

In the sections below, each route is described and the proposed changes are discussed. The number of additional vehicles required under each proposal is calculated as a proxy for costs associated with the change and to allow for a measure of the efficiency of the proposals by looking at the impact generated per additional vehicle required. The peak period vehicle requirement is used because these periods are generally the most demanding of resources. Applying the peak period vehicle requirements to the full service period can be taken as an upper bound on the vehicle requirement for the full day. Finally, the anticipated change in ridership is calculated using two different methodologies. First elasticities are applied to existing ridership and then the direct demand model created for the MBTA bus system is used to calculate the predicted change in ridership.

5.1. Route 88 Service Improvements

Route 88 is one of the four routes with a terminus at Lechmere Station. Route 88 runs from Clarendon Hill to Lechmere via Highland Avenue. According to the public schedule, the route has 16 minute headways in the AM peak and 20 minute headways in the PM peak. The schedule also quotes a running time of four minutes from Clarendon Hill to Davis Square (with a connection to the Red Line) and 14-18 minutes from Davis Square to Lechmere Station. Key attractions along the route include Teele Square, Davis Station, Somerville Hospital, Somerville High School and City Hall, as well as connections to both the Red and Green Lines.

The path of Route 88 in the inbound direction begins at the Clarendon Hill busway which is near the intersection of Alewife Brook Parkway and Broadway. The route proceeds east along Broadway until Teele Square and then turns onto Holland Street and goes south to Davis Square where connection to the Red Line is available. After Davis Square, the route continues on Elm Street before taking a left onto Cutter Avenue and then a Right onto Highland Avenue. The route continues on Highland Avenue past Somerville Hospital, Somerville High School and City Hall. Finally, the route turns onto the McGrath/Monsignor O'Brien Highway and takes that until arriving at Lechmere Station. Along this path, Route 88 makes stops close to many of the future GLX stations. The route stops at Lechmere, but it also has stops within walking distance of the Union Square, Lowell Street, Gilman Square and Washington Street (Brickbottom) stations.

On weekdays, Route 88 operates between 5:16am and 1:19am. The route has the following approximate printed headways: AM Peak – 16 minutes, Midday – 30 minutes, PM Peak – 20 minutes, Night – 35 minutes, Saturday – 20 minutes, and Sunday – 40 minutes. There are also two variations of this route that operate only a few trips each day. One variation provides additional service between Clarendon Hill and Davis Square during the AM peak. The other variation provides additional trips from Somerville High School to Clarendon Hill on weekday afternoons. The work in this chapter assumes that no changes would be made to the two minor variations of the route.

Given its high correspondence with the GLX route, Route 88 is a good candidate for increased service as a mitigation proposal. In addition to increased frequency, another way to improve service on this route could be the implementation of clockface headways. Clockface schedules are where buses always arrive at the same time each hour, for example at 10 minutes, 30 minutes and 50 minutes after each hour (Webster and Bly, 1980 qtd. in Evans, 2004).

The existing operating headways (those used in the internal schedule as opposed to the printed public schedule) as well as the new headways under this proposal are shown in Table 5-1. In order to increase the headway and allow for clockface headways, this proposal increases service from 14 minute headways in the AM peak and 18 minute headways during the PM peak to 10 minute headways during both periods. This not only provides increased service but also allows for clockface headways and consistent frequencies during the AM and PM peak periods. The other key ridership period is midday where current headways are 30 minutes and the proposal analyzed below is to increase service to 20 minutes. Late night headways are also proposed to decrease from 35 minutes to 30 minutes, both increasing service and allowing for a clockface schedule. Shorter 15 minute headways during both the midday and late night periods could also be considered to provide a more consistent, higher level of service throughout the day, although this alternative is not evaluated here.

The early morning and evening periods have a less regular schedule currently. These periods are often used as "ramping periods" where service gradually increases from the start of service to the peak frequency, or service declines as the PM peak period ends and the schedule adjusts to late night service levels. As the key time periods of the day all have increased service, these periods are assumed to also receive a 20% increase in service. The elasticity formula discussed below looks at the change in headway not the nominal change, so for these two final periods a percent change is used rather than trying to determine a single headway.

Table 5-1 Route 88 Initial and Proposed Headways

Period	Initial Headway	Proposed Headway	Proposed Change
Early AM	-	-	-20%
AM Peak	14.0	10.0	-29%
Mid Day	30.0	20.0	-33%
PM Peak	18.0	10.0	-44%
Evening	-	-	-20%
Late Night	35.0	30.0	-14%

5.1.1. Number of Vehicles Required

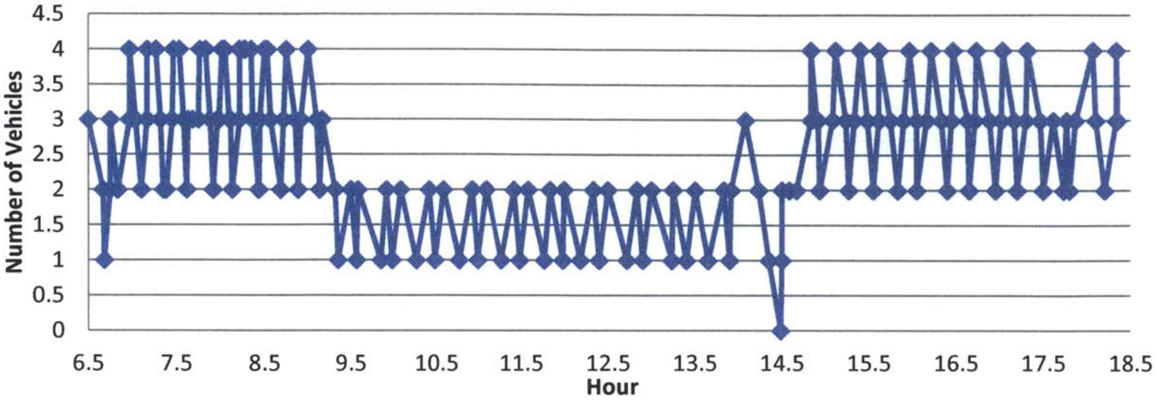
As was done for the rail service increase proposed above, equation 4-1 can be used to calculate the number of vehicles required for a route. This equation is $n = \left\lceil \frac{c}{h} \right\rceil$ where n = number of vehicles, c = cycle time, and h = headway. When a route service interval change is being contemplated, a key consideration is the change in the number of vehicles (and therefore also operators) required. The need for additional vehicles and operators comprises a significant portion of the cost of increasing service.

Since vehicle and operator availability concerns are greatest during the peak period, the vehicles required calculations were completed for these periods. Also, frequencies are typically the greatest during the peak periods therefore requiring the most vehicles at these times. As mentioned above, applying the peak period vehicles required throughout the day can be used as an upper bound for the number of vehicles required for the full day. The vehicles required calculations could also be conducted for off-peak periods using the same procedures and data sources as were used for the peak periods. The rapid transit schedule defines the morning rush hour as approximately 6:30am to 9:00am and the evening rush hour as approximately 3:30pm to 6:30pm. This same time period definition was applied to the bus schedules.

Current and predicted vehicles required can be calculated using the information included in the AVL report. For this analysis, AVL data was obtained for one week (weekdays only) during the Winter 2011/2012 schedule, from March 19 to March 23, 2012. For Route 88, the two minor variants of the route were excluded because they provide additional service at the Clarendon Hill end of the route during the peak periods and do not provide service to Lechmere.

For the existing service, the current number of vehicles being used to operate the route can be determined from the schedule information included in the AVL data. A graph of the number of active vehicles each day by time of day shows that four vehicles are currently being used to operate the route during the peak periods. Figure 5-1 shows the vehicles in operation for one day on the main variant of Route 88 during the AM peak, midday and PM peak periods. The graph includes only the active time, not layover time, which helps explain the short periods of time during which fewer vehicles are in operation while some of the vehicles are between trips.

Figure 5-1 Route 88 Vehicles Operated (AM peak, midday and PM peak)



The AVL data can also be used to calculate the number of additional vehicles required by the proposal to increase service. The two key inputs for the vehicles required equation are cycle time and headway, both of which can be calculated based on the AVL data. For each half trip, meaning a terminal to terminal trip of the route in one direction, the AVL report records the scheduled time the bus should be at key time point locations as well as the actual time the bus arrived and departed each point. From this information, both the scheduled and actual run times between any two timing points can be calculated. The cycle time can then be set as the 90th or 95th percentile of the observed running times. At the same time, the headway can be determined based on the included schedule information.

Based on the time point crossing data in the AVL report, the observed end to end running time for each half trip was calculated. Each trip was classified into a time period based on the trip's scheduled departure time from the beginning terminal. The running time was calculated as the difference between the departure time from the first stop and the arrival time at the final stop. Any trip with a run time less than or equal to zero was excluded assuming a negative run time implies that the AVL was not working properly. Once the observed run time for each half trip was calculated, the 50th percentile run time was found for each direction, and all trips with run times greater than twice the 50th percentile were removed. It is assumed that any trip with a run time more than twice the 50th percentile run time was an exception and was likely subject to a onetime event that extended the run time.

Next, the 95th and 90th percentile run times in each direction were calculated. These run times in both the inbound and outbound directions were added together to calculate the cycle time. The impact of using the 90th versus the 95th percentile of run times as the cycle time was determined to have a minimal impact on the vehicles required calculation, and the 90th percentile was used for all calculations.

Headways were calculated based on the schedule times included in the AVL data. The preceding headway, meaning the time between each trip's departure time from the terminal and the previous trip's departure time, was used. Headways are not constant throughout each period therefore judgment was used to determine the predominant headway during each time period. The headways determined for each time period are shown in Table 5-1.

If service during the AM and PM peaks is increased to 10 minute headways and the 90th percentile of the observed running times is used as the cycle time, 6 vehicles would be required to operate Route 88 during both the AM and PM peak periods. This means that increasing service would require an additional two vehicles in the peak periods (Table 5-2). Using the 95th percentile of running times may result in the need for an additional vehicle in the PM peak in order to operate the proposed ten minute headways. Interlining could be used to possibly reduce the total number of vehicles required in the system beyond the number required for each route independently. If the full number of vehicles required without interlining were to be provided, the headways could be reduced further or additional reliability could be provided given the excess recovery time generated with the additional vehicles.

Table 5-2 Route 88 Vehicles Required Calculations

	Cycle Time(1)	Headway	Number of Vehicles	Change in Vehicles
Before				
AM Peak		14	**4**	
PM Peak		18	**4**	
After				
AM Peak	57.2	10	**6**	**+2**
PM Peak	58.9	10	**6**	**+2**

(1) Cycle time set as the 90th percentile of observed running times

5.1.2. Elasticity Application

Given that existing ridership information is available for Route 88, both the elasticity and the direct demand model approaches can be applied to estimate the ridership impact of this proposal. The analysis of this proposal focuses on the impact of only the service interval change and not the implementation of a clockface schedule. However, providing an easily remembered clockface schedule would likely further increase ridership. The impact of clockface schedules has not been calculated previously, but "anecdotal evidence is reported of appreciable gains in ridership when schedules have been reorganized to give simple 'clockface' timings" (Evans, 2004, p. 9-16).

As discussed above, the Lago, Mayworm and McEnroe (1981) bus ridership elasticities with respect to service were chosen for this analysis. The current scheduled Route 88 headways are always between 10 and 50 minutes, which means that the medium service level elasticity of -0.46 should be applied. Two different ridership sources were tested and compared: the origin-destination matrix and APC. The APC results were found to support the findings of the calculations based on the origin-destination matrix, therefore only the origin-destination matrix based results are shown here.

Ridership for the full route can be obtained from the bus origin-destination matrix data. All trips attributed to this route had an inferred origin stop and therefore no scaling of non-inferred origins was required. Trips were assigned to a time period based on the boarding time rather than the time the bus left its initial terminal. This may cause a slight disconnect between the bus schedule time periods and the ridership time periods. However, given the length of the route and the need to adjust service gradually between periods this should not have a meaningful impact on the analysis. The ridership analysis also does not distinguish between the variants of the route. In order to adjust for this, ridership at stops along the two variants during the periods they operate were separated out and the change in headway at these stops was adjusted to account for only changing the headway along the main variant of the route. Table 5-3 displays the combined elasticity results for each time period and the full day using the medium service level elasticity and a sensitivity range of ±0.1 as explained in the methodologies chapter.

Table 5-3 Route 88 Elasticity Calculations
(based on the origin-destination matrix ridership data)

	Early AM	AM Peak	Mid Day	PM Peak	Evening	Late Night	**All Day Total**
Initial Ridership	110	901	1,232	677	253	404	**3,577**
Initial Headway (main variant)	-	14.0	30.0	18.0	-	35.0	
New Headway (main variant)	-	10.0	20.0	10.0	-	30.0	
% Change	*-20.0%*	*-28.6%*	*-33.3%*	*-44.4%*	*-20.0%*	*-14.3%*	
Projected Ridership							
Low Elasticity (e = -0.36)	119	1,012	1,416	832	274	427	**4,081**
% Change	*8.3%*	*12.3%*	*15.0%*	*22.9%*	*8.3%*	*5.7%*	***14.1%***
Midium Elasticity (e = -0.46)	122	1,045	1,473	882	280	434	**4,235**
% Change	*10.8%*	*16.0%*	*19.5%*	*30.3%*	*10.8%*	*7.3%*	***18.4%***
High Elasticity (e = -0.56)	125	1,080	1,531	935	287	440	**4,397**
% Change	*13.3%*	*19.8%*	*24.3%*	*38.1%*	*13.3%*	*9.0%*	***22.9%***

Increasing Route 88 service in each period of the day by 14–44% along the main variant (a weighted average of roughly 28%) results in an all day ridership increase in the range of approximately 14–23% (504–820 new passengers) based on the elasticity estimation approach. The nominal change in ridership would actually be greater than that shown in the table above because the origin inference data used does not scale for AFC undercounting. If the 9.7% adjustment factor discussed in Chapter 3 is applied to the all day totals to account for AFC undercounting of boardings, the projected ridership percent change would be the same but the resulting total ridership would be 4,477–4,824 (553-900 more passengers than currently). Another factor that may serve to increase these estimates is the change from scheduled to walk-up service. While the elasticity used is based on the initial headway, providing walk-up service during the peak periods may also result in an additional boost in ridership.

5.1.3. Direct Demand Model Application

The direct demand model can also be applied to estimate the ridership impact of increased service on Route 88. In order to do this, service levels at all stops along the route need to be adjusted and the ridership before and after the change estimated to see the increase in ridership attributed to a change in service.

According to the GTFS data, all stops associated with Route 88 have 46, 49, 51 or 54 trips in either direction during an entire weekday. The GTFS data does not distinguish between variants of a route, but analysis of the stops and trip counts suggests that five trips along one of the Route 88 variants have been included in the trip count for the stops with 51 and 54 trips. Removing these 5 trips results in each stop having either 46 or 49 trips, with the difference being whether the stop is along the inbound or outbound direction of the route. After removing the five variant trips, it is assumed that service would increase by approximately 30% at all stops. This increase is approximately the total daily increase in proposed trips from Table 5-1, above, and after rounding to the nearest full trip this equates to 14 additional outbound trips and 15 additional inbound trips.

As described in Section 3.4.3, the additional trips were then summed by location and added to the current trip count at those locations. The direct demand model was then applied to all affected locations. No changes to the independent variables of any other locations occurred, so no other independent variables needed to be calculated and the model only needed to be applied to affected locations. The results of the direct demand model for the locations along Route 88 are shown in Table 5-4. The "before" number is the ridership predicted by the direct demand model based on the current inputs while the "after" number is the prediction based after incorporating the new service levels. The adjusted ridership numbers include the application of the location adjustment ratios discussed in Section 3.4.3.

Table 5-4 Direct Demand Model Results - 30% Increase in Route 88 Service

	Route 88 Locations		
	Before	After	Change
Unadjusted Ridership	2,763	3,143	380 (13.8%)
Adjusted Ridership	8,753	9,757	1,004 (11.5%)

The results of the direct demand model suggest that there would be an 11.5% increase in ridership at locations along Route 88 if service were to increase by approximately 30%. The AFC undercounting factor should also be applied to the nominal change, resulting in an adjusted ridership increase of 1,101 passengers. The results of the direct demand model fall slightly below the range of the percent increase seen in the sensitivity analysis of the elasticity calculations. However, the nominal increase in ridership predicted by the direct demand model is higher than that seen in the elasticity calculations.

Some of the difference in the nominal change in ridership predicted by the elasticities and direct demand models can be reduced by considering that the direct demand model does not distinguish between routes at a location. Overlapping routes at a location may be competing or complementary. When routes at a shared location run parallel to each other along a shared segment, they may compete for riders and some of the increase in ridership seen at the location may be along the other routes at the location that benefit from an overall increase in service at the location. At the same time, when routes at a shared station run perpendicular to each other they may be complementary, with increases in service along one of the routes leading to increased transfers between the routes. In these synergistic cases, some of the increase in ridership seen at a station with increased service may be along these other perpendicular routes rather than the route being studied, although this would be expected to be a smaller portion of the ridership than with the competing routes.

For mitigation, the air quality impact is what is important and it does not matter what route the ridership increase is along. However, for the purposes of examining the impact of proposals in this thesis it is useful to distinguish the ridership increase along the study route from the increase on other routes at shared locations. Section 3.4.3 discussed two methods for distributing the predicted ridership increase across routes at a location. If the increase in ridership at Route 88 locations is distributed amongst routes at the locations according to the distribution of the total number of trips across routes, 52% of the total ridership increase (520 passengers or 570 passengers after adjusting for AFC undercounting) would be along Route 88. If the Route 88 share of the increase in ridership is taken as the greater of the Route 88 percent of trips or 75%, 76% of the total increase in ridership (758 passengers 832 passengers after adjusting for undercounting) would be attributed to Route 88. This alternative range of additional Route 88 passengers is more similar to the ridership increase predicted by the elasticity analysis.

The ridership impact predicted by both the elasticity calculations and the direct demand model can be provided with only an additional two vehicles required during the resource constrained peak periods. These peak periods would have a significant ridership increase to support the provision of additional resources. Overall, this proposal provides a substantial ridership increase with minimal additional resource requirements. Transfers to the Red Line and Green Line could generate additional system ridership, and proximity to future GLX stations could help with the early generation of development and ridership patterns in these areas.

5.2. Route 87 Short Variant

Route 87 is another route with a terminus at Lechmere Station. Route 87 runs from Arlington Center or Clarendon Hill to Lechmere with headways of 22 minutes in the AM peak and 20 minutes in the PM peak. According to the public schedule, the route has a running time of 9-11 minutes from Arlington Center to Davis Square, 7-9 minutes from Davis Square to Union Square and finally 7-10 minutes from Union Square to Lechmere Station, for a total run time of 23-30 minutes. Key attractions along the route include Teele Square, Davis Station and Union Square, as well as connections to both the Red and Green Lines.

The path of Route 87 from Arlington Center in the inbound direction begins at the Broadway and Massachusetts Avenue stop. The route goes south-east along Massachusetts Avenue, takes a left onto Franklin Street and then a right onto Broadway which it takes until the Clarendon Hill busway. From Clarendon Hill, the route proceeds east along Broadway until Teele Square and then turns onto Holland Street and goes south to Davis Square where connection to the Red Line is available. This portion of the route runs parallel to Route 88. However, past Davis Square Route 87 continues south along Elm Street to a stop only a block from the Porter Square Red Line station. The route then turns onto Somerville Avenue which turns into McGrath/Monsignor O'Brien Highway (again parallel to Route 88) until ending at Lechmere Station.

On weekdays, Route 87 operates to Clarendon Hill between 5:10am and 1:18am. The service period to Arlington Center is slightly shorter, with the first trips arriving and departing the station at 6:18am and 6:30am, respectively, and the last trips arriving at and departing the station at 7:49pm and 7:51pm, respectively. The route has the following approximate printed headways: AM Peak – 22 minutes, Midday – 30 minutes, PM Peak – 20 minutes, Night – 35 minutes (to Clarendon Hill), Saturday – 30 minutes, and Sunday – 40 minutes.

Route 87 has stops at several key locations, including connections to the Red Line at both Porter Square (with a short walk) and Davis Square. Given the length of the route, increasing service along the entire route would have much of its impact outside of the GLX area and would entail a significant cost increase. Figure 5-2 and Figure 5-3 provide the inbound and outbound passenger flow profiles for Route 87 based on the CTPS ride checks conducted during Winter 2006. The three highlighted stops in each figure correspond with Davis Square, Porter Square and Union Square. Many passengers boarding prior to Davis Square in the inbound direction use the route primarily for access to the Red Line at Davis Square rather than for connecting to the Green Line.

Figure 5-2 Route 87 Load Profile - Inbound

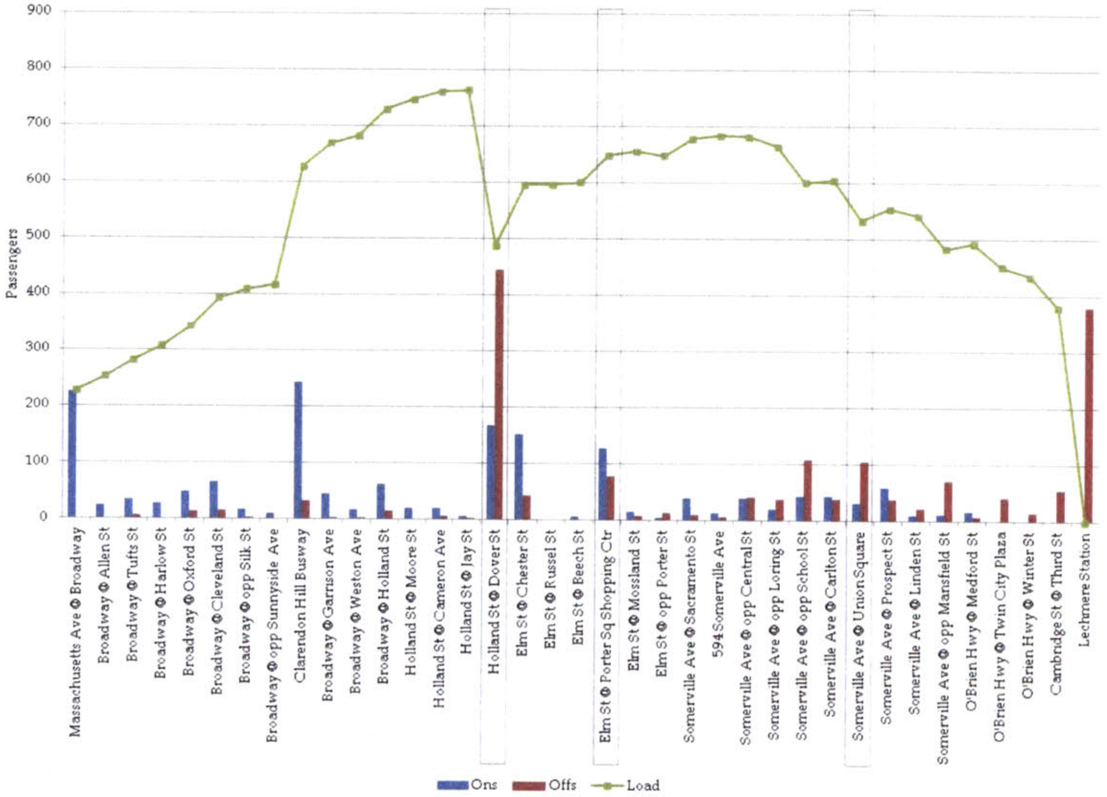
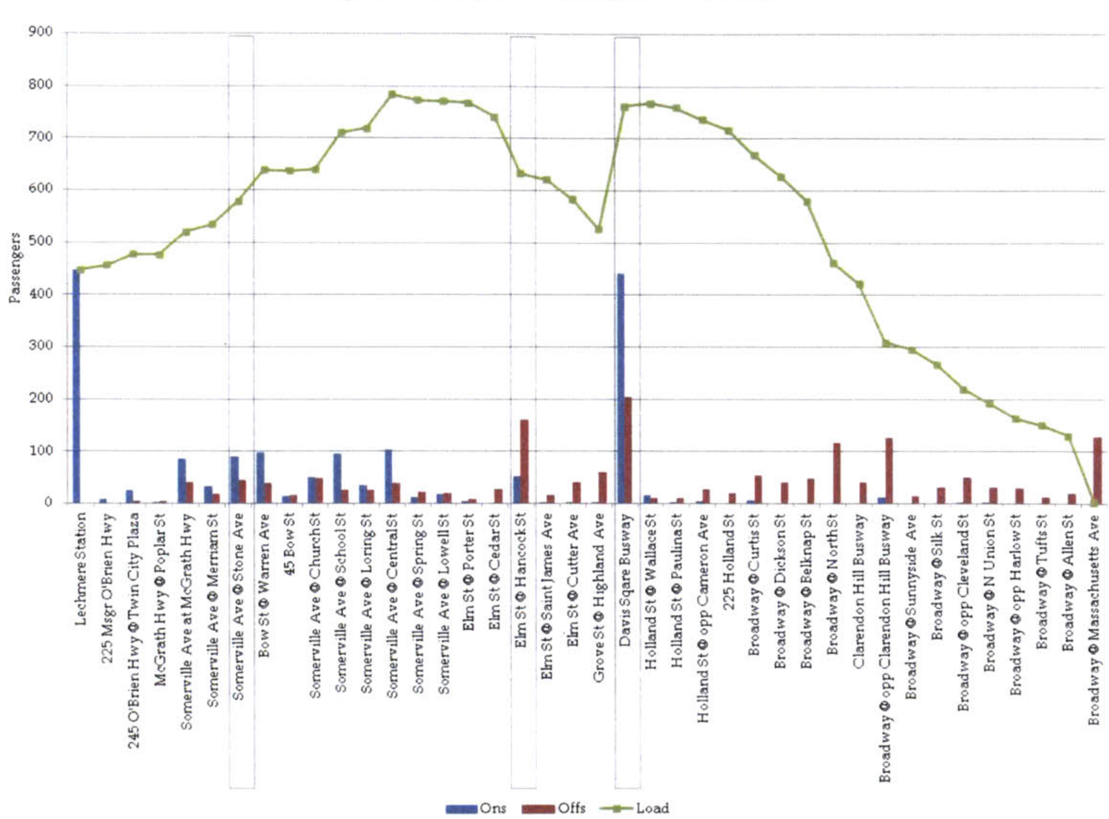


Figure 5-3 Route 87 Load Profile - Outbound



Rather than increase service along the full route, Route 87 is a good candidate for proposing increased service along only part of the route by creating a short variant with service between Lechmere and Union Square. This would provide increased service from the Green Line at Lechmere to Union Square near the future site of the Union Square Station of the GLX. Increasing service along this portion of the route would provide more service at Lechmere and help to generate ridership along what will eventually be the GLX, thus decreasing the time lag in the impact of the extension. The route could also potentially be adjusted slightly from the full Route 87 path in order to take passengers closer to the future GLX station at Union Square, although that option is not analyzed here. The city of Somerville is also considering changing the one-way road patterns near Union Square which could allow for new route path opportunities in the area.

Currently the Union Square area is served by several bus routes that provide access to the Red Line at different locations, the Orange Line at Sullivan Square, and the Green Line at Lechmere (via Route 87). These different bus routes provide several options to leave Union Square and access the rest of the MBTA system. However, given the irregularity of service along these routes and the need to transfer from rail to bus, it is difficult to access Union Square from the greater Boston area. Providing more service on the Green Line to Lechmere and on Route 87 from Lechmere to Union Square would make this trip a more viable option and therefore increase access to Union Square.

The proposed route analyzed below closely follows the Route 87 path. Leaving Lechmere, the route would take McGrath/Monsignor O'Brien Highway until the highway underpass. After taking a left onto Medford Street, the route would take a right onto Somerville Avenue. The route would then continue on Somerville Avenue, taking Bow Street just past Union Square. After the outbound stop at Bow Street and Warren Avenue, the route would turn left back onto Somerville Avenue instead of right as the full route does. This would take the short route back onto the Route 87 inbound path along Somerville Avenue, past the Somerville Avenue and Union Square stop, to McGrath/Monsignor O'Brien Highway and back to Lechmere Station.

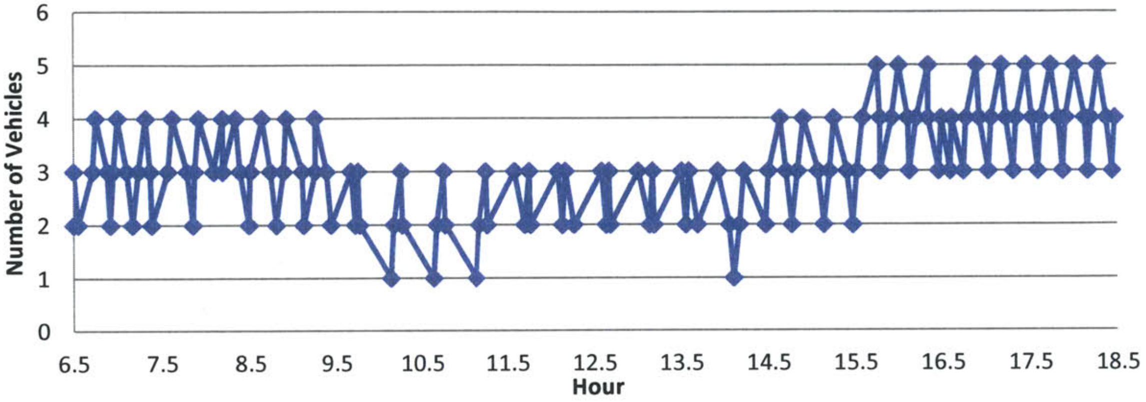
It is proposed that both the full Route 87 and the Route 87 Short variant would operate in a coordinated schedule with 18 minute headways each during the AM and PM peak periods for a combined headway of 9 minutes at Lechmere and Union Square. This schedule is based on the frequencies currently being operated during the AM peak. Another option would be to provide 20 minute headways on each variant for combined ten minute headways. This latter option would require fewer vehicles while providing the additional benefits of clockface headways and potentially a more reliable schedule. There is currently a discrepancy between the public printed schedule and the operated schedule. While the public may experience 18 minute headways in the AM peak and 17 minute headways in the PM peak, the schedule presented to the public says the headways should be 22 and 20 minutes in the AM and PM peak, respectively, so providing reliable 20 minute headways during both periods may not be perceived as a decrease in service to most passengers.

5.2.1. Number of Vehicles Required

The current number of vehicles being used to operate Route 87 during the peak periods can be determined from the AVL data as was done for Route 88. Figure 5-4 shows the number of vehicles in operation along Route 87 during the peak and midday periods for one weekday.

According to this analysis, four vehicles are required in the AM peak currently and five vehicles are required during the PM peak. Interlining is currently being used on this route to help minimize the number of vehicles required.

Figure 5-4 Route 87 Vehicles Operated (AM peak, midday and PM peak)



The run and cycle times for the 87 Short variant can also be calculated based on the AVL data for Route 87 using a similar procedure to that described above for Route 88. However, because AVL records times at key points only, the run times for the variant must be inferred. Route 87 Short follows the path of Route 87 between Lechmere and Somerville Avenue at Bow Street. There is a timing point at Lechmere as well as one near Union Square in each direction. In the outbound direction, the timing point is at Somerville Avenue and Stone Avenue, just before the Bow Street fork. The timing point in the inbound direction is slightly further north-west at the Somerville Avenue and Union Square stop, which is just before the intersection with Washington Street and Webster Avenue. The next timing point east of Union Square is at Somerville Avenue and Stone Street in both directions. The observed run times between Lechmere and Union Square can be taken directly from the full Route 87. The run time for the turn made between the outbound and inbound Union Square stops is assumed to be a fraction of the run time between the Union Square timing points and the Somerville Avenue at Central Street timing points in each direction, proportional to the distance traveled relative to the distance between the two timing points. In the outbound direction, the route travels approximately 43% of the distance between the timing points, so 43% of the outbound running and cycle times are assigned to this segment. In the inbound direction, the distance from the end of Bow Street to the Union Square timing point is 33% of the distance between the timing points, so a proportional fraction of the running and cycle times is used.

For this proposal, headways in the AM and PM peak are set the same using the current AM peak headway of 18 minutes. This would not impact the number of vehicles required for the full route. Table 5-5 shows the calculation of the vehicles required to operate the short variant during the peak periods based on the run time calculations just described and setting the cycle time as the 90th percentile of the observed round trip run times. The vehicles required equation calls for rounding up the number of vehicles required. However, in this situation rounding down to one vehicle required in each the AM and PM peak periods makes more sense. Prior to rounding, the number of vehicles required is just over 1 and is based on an approximate cycle time calculation. The use of the 90th percentile of run time as the cycle time can also be adjusted. Decreasing layover times slightly and possibly using interlining should allow the MBTA to operate the short variant using only one vehicle. The remainder of the work here assumes that the short loop would be operated by a single vehicle during the peak periods.

Table 5-5 Route 87 Short Vehicles Required Calculations

Period	Cycle Time(1)	Headway	Number of Vehicles
AM Peak	18.9	18	**2 (1)**
PM Peak	20.8	18	**2 (1)**

(1) Cycle time set as the 90th percentile of observed running time

The goal of the new Union Square loop is to increase service between Union Square and Lechmere. Creating even joint headways between the full and short variants of the route would provide better, more regular, service for customers at stops along the shared segments. In the AM and PM peak, even joint headways of nine minutes would also put this segment in the category of walk-up service, which has significant benefits for riders and often results in greater ridership. Even ten minute headways could also be operated with the same number of vehicles and would provide the additional benefits of a clockface schedule. Some adjustments would need to be made to running time assumptions and the location of layover time in order to create even headways at both terminals of the short loop. This would require that the vehicle be able to hold along the turn at Union Square, which may not be possible along the path currently being considered. An alternative to creating even headways at both terminals would be to focus on the primary direction of travel during each time period and create even joint headways in that direction while having irregular headways in the alternate direction.

5.2.2. Elasticity Application

Once again, the Lago, Mayworm and McEnroe (1981) bus ridership elasticities with respect to service and the current ridership levels derived from the origin-destination matrix can be used to calculate the estimated ridership with this service adjustment (and checked using APC ridership). The current Route 87 headways are always between 10 and 50 minutes which means that the medium service level elasticity of -0.46 should be applied. The full route headways are assumed to remain at the current levels except in the PM peak where the headway is set at 18 minutes to match the AM peak. This minor increase in headway along the full route in the AM peak likely will not be felt by passengers given the irregularity of the operated schedule and the higher printed headway. It is proposed that the short loop operate at the same headway as the full route at all times, resulting in a 50% decrease in the headway during all periods (with a slightly lower total change in the PM peak).

Elasticity calculations were applied to the ridership data based on inferred origins from the bus origin-destination matrix. As with Route 88, all trips attributed to this route had an inferred origin stop and therefore no scaling of non-inferred origins was required. The stops that would be included in the Lechmere - Union Square loop were separated out for this analysis. In the outbound direction, only passengers getting off at stops along the short variant would have the option of taking either route and would therefore experience the increase in headway. Since the destination inference is not complete, the CTPS ride check data was used to determine that only about 20% of passengers that board along the outbound portion of the proposed Route 87 Short variant also alight along that portion of the route. Therefore, the elasticity calculation was applied to all inbound passengers and 20% of outbound passengers boarding at stops along the proposed route.

The results of the elasticity calculations using the medium service level elasticity and a sensitivity range of ±0.1 are shown in Table 5-6. The impact of increasing headways from 17 minutes to 18 minutes on the rest of Route 87 between Union Square and Arlington Center during the PM peak is assumed to be negligible and is not calculated here.

Table 5-6 Route 87 Elasticity Calculations
(based on the origin-destination matrix ridership data)

	Early AM	AM Peak	Mid Day	PM Peak	Evening	Late Night	**All Day Total**
Initial Ridership	8	46	129	80	23	35	**320**
Headway % Change	*-50.0%*	*-50.0%*	*-50.0%*	*-47.1%*	*-50.0%*	*-50.0%*	
Projected Ridership							
Low Elasticity (e = -0.36)	10	59	164	99	30	44	**405**
% Change	*27.3%*	*27.3%*	*27.3%*	*24.9%*	*27.3%*	*27.3%*	***26.7%***
Midium Elasticity (e = -0.46)	10	63	175	106	32	47	**433**
% Change	*36.2%*	*36.2%*	*36.2%*	*33.0%*	*36.2%*	*36.2%*	***35.4%***
High Elasticity (e = -0.56)	11	67	188	113	34	50	**463**
% Change	*45.9%*	*45.9%*	*45.9%*	*41.6%*	*45.9%*	*45.9%*	***44.8%***

Adding a short loop to double frequency along Route 87 between Lechmere and Union Square would result in a 27-45% increase in ridership at affected stops (85–143 additional passengers) for the full day based on boardings from the origin-destination matrix. As with the Route 88 calculation, a 9.7% adjustment factor should be applied to the nominal change in ridership to account for AFC undercounting. The resulting total ridership after applying this adjustment factor would be 444–508 passengers per day (93–157 additional passengers). The elasticity number used is set based on the initial headway, but the elasticity is greater when walk-up service is provided. In this situation, the joint headway would be less than 10 minutes, and therefore it would provide walk-up service for passengers that can use either route. Having walk-up as opposed to scheduled service may increase ridership along the route.

5.2.3. Direct Demand Model Application

The direct demand model developed for the MBTA bus system can also be applied to predict the ridership change in response to the creation of a Route 87 short variant. To do this, the change in the number of trips at each stop along the route must be determined. Since the direct demand model does not take into account what route a trip is on or the direction of the trip, the change desired is the change in total trips at the location. As with the Route 88 application, the current number of trips is based on the GTFS data. The list of all stops along Route 87 was obtained and the stops along the proposed Lechmere - Union Square loop were identified. The number of Route 87 trips at each stop was determined and it was found that each stop had either 45 current trips (if along the outbound portion of route) or 48 trips (if along the inbound portion of the route). All stops along the proposed short variant were assumed to get twice the number of trips, so the number of additional trips at stops along the short route was set equal to the current Route 87 trips. Again, this analysis did not incorporate the effect of the minor decrease in scheduled frequency along the full route in the PM peak. The number of additional trips was then summed by location and added to the total current trip count at these locations. The direct demand model could then be applied to these locations. The results of the model for the locations on the proposed Route 87 short variant are shown in Table 5-7.

Table 5-7 Direct Demand Model Results - Introduction of Route 87 Short Variant

	Route 87 Short Locations		
	Before	After	Change
Unadjusted Ridership	947	1,345	398 (42.0%)
Adjusted Ridership	3,190	4,258	1,068 (33.5%)

The results of the direct demand model suggest there would be a 33.5% increase in ridership at stops along Route 87 between Lechmere and Union Square where service would double with the introduction of a short route variant. The predicted nominal increase should be even higher given the AFC undercounting. The estimated percent change in ridership is in the middle of the range found using elasticity analysis. However, the nominal increase in ridership is significantly greater than that predicted by the elasticity analysis, even on the upper end of the sensitivity range.

After accounting for the fact that some of the ridership increase may actually be on other routes at shared locations, the nominal ridership increase predicted on Route 87 is still higher in the direct demand model than in the elasticity calculations. Based on the proportion of trips by route at each location, 53% of the change in ridership would be attributed to either variant of Route 87 for a total of 569 riders (624 riders after adjusting for AFC undercounting). Assuming the ridership impact would be greater on the altered route than on other routes so that the maximum of the Route 87 proportion of total location trips or 75% of the ridership change is attributed to Route 87, the ridership increase on Route 87 would be 843 passengers (925 passengers after adjusting for undercounting).

These results suggest that, at least in this case, the elasticity and direct demand model applications are comparable on a percentage change basis but not a nominal change basis. The direct demand model used here does not incorporate destinations. In this situation, the short route variant being proposed offers access to very few destinations in the outbound direction. The elasticity analysis was able to account for this limitation of the proposed route by applying the elasticity to only a portion of the current outbound passengers. This comparison of the two methods suggests that in specific situations where the limited destinations offered by the route being studied impacts the route's ability to generate ridership, the direct demand model may overestimate nominal ridership change. On the other hand, the elasticity calculation may fail to capture some of the network effects offered by the route. In the case of the Route 87 short variant, some passengers may currently take competing routes to Union Square (either from Lechmere or other rail feeder stations) and are therefore not included in the base ridership but would switch to Route 87 after this change. Given the relative strengths and weaknesses of applying each of the elasticity and direct demand model methods to this proposal, using an average of the two nominal ridership predictions could be considered, such as was done in the MetroLink situation discussed in Section 2.2.1.

Although the ridership impact of creating a short variant of Route 87 between Lechmere and Union Square would be limited, it should still be considered as a mitigation option. This proposed route would only require one vehicle and would serve the same area as the Union Square branch of the delayed GLX. Increasing service between Lechmere and Union Square would help decrease the time lag in developing ridership and land use patterns in the Union Square area after the opening of the GLX.

Extending the short variant past Union Square to Porter Square was also considered. This alternative would likely require one additional vehicle beyond the one required for the Union Square option in the peak periods, but it would also have a greater ridership impact. Extending the short loop to Porter Square would provide a connection from Lechmere to the Red Line at Porter Square, but the benefits of this variant would extend beyond the GLX area that is the focus of the proposal to create a loop to Union Square.

5.3. Conclusion

The proposal to increase service on Route 88 by 14-44% throughout the day would have a meaningful impact on ridership with minimal additional vehicle and operator requirements. The additional service could be operated using two vehicles during the peak periods. According to elasticity calculations, the daily ridership on the route could be expected to increase 14-23%

with the change, which equates to approximately 550-900 passengers. The use of a direct demand model supports the elasticity findings on the percentage increase, although it does not provide a reliable nominal ridership estimation. Additional post processing of the direct demand outputs to distribute the ridership change between the different routes at shared locations results in a more comparable nominal ridership increase estimation.

The proposal to create a short variant of Route 87 that would double frequencies between Lechmere and Union Square would require only one additional vehicle during the peak periods, thus minimizing costs, but the ridership impact would not be as significant as increasing service along the entirety of Route 88. Elasticity calculations estimate that the ridership increase resulting from the implementation of the Route 87 short variant would be about 27-45% or in the range of about 100-150 new passengers. The direct demand model predicts a similar percentage change in ridership, but - as with the Route 88 analysis - the direct demand model estimates a greater nominal increase in ridership of about 1,170 passengers. In this case, the elasticity method is better able to adjust for the limited current ridership, and potentially limited new ridership, benefiting from the proposed route which serves only few destinations in the outbound direction. At the same time, the elasticity method does not capture the network effects that contribute to a higher ridership estimation using the direct demand model. In this situation, neither estimate can confidently be called the "best" estimate, and using an average of the two estimates could be considered.

Overall, increasing service on Routes 87 and 88, either along the full route or only part of the route as in the Route 87 proposal, would provide greater transfer opportunities at Lechmere and help generate ridership along the future GLX corridor. Both proposals could be operated without significant vehicle and operator impacts. The Route 88 proposal appears to provide greater ridership benefits, although there is currently a focus on developing the Union Square area which would benefit more from the Route 87 proposal. Analysis of these service increase scenarios also showed that using simplified elasticity calculations and applying a direct demand model could result in similar percent ridership change predictions, although the direct demand model generally predicts a somewhat higher nominal change in ridership. The nominal change in ridership estimated by the direct demand model may overestimate the actual expected change in a system, due to nearby complementary and competing services to similar destinations. Therefore the percentage change is a better indicator of impact and nominal ridership changes should primarily be used to compare between applications of the direct demand model to different service proposals. Additional post processing of the direct demand model results can generally help to distinguish the anticipated impact on the specific route of interest.

6. Creation of New Bus Routes

While increasing service on current bus routes can have an incremental impact on ridership, introducing new service can potentially have an even greater impact. This chapter analyzes the introduction of three possible routes into the MBTA system. The first new route proposed is a cross-town route that would provide access from Lechmere to new key destinations not currently accessible with a one seat ride. To avoid vehicle constraints, this service could be contracted to a private operator. A possible additional way to increase ridership quickly could be to partner with private operators in the area to provide public access to services already being operated. Two potential partnership routes are explored here: the M2 and the EZRide.

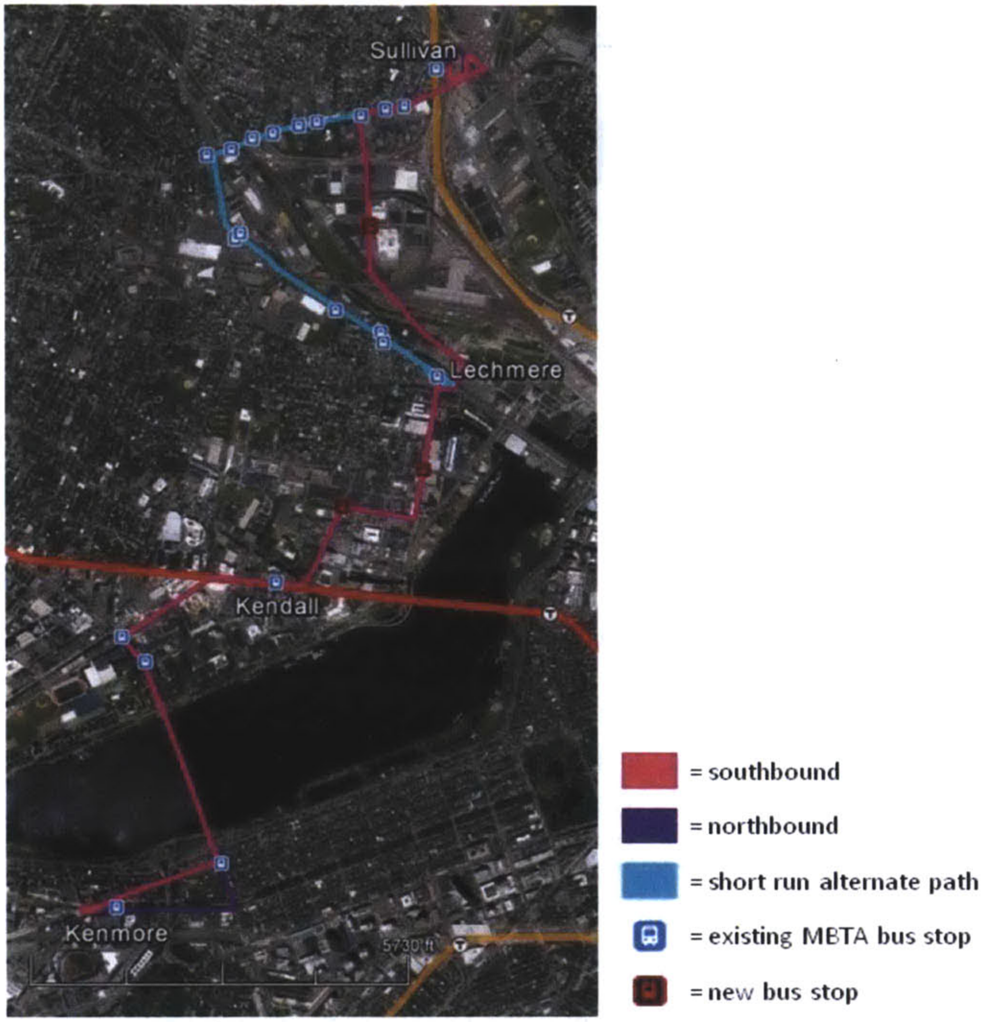
For each of the three proposals discussed here, the route path and service levels are first described. The number of vehicles required is then calculated, when appropriate. Finally, the potential ridership is estimated using the direct demand model described in Section 3.4. The last section of the chapter summarizes the findings of the new route analysis and the recommended priorities for future work and analysis.

6.1. New Cross-Town Route

The MBTA bus system has many radial routes with a few key cross-town routes. Only a limited number of bus routes cross the Charles River which separates Boston from Cambridge, Somerville and Medford. In particular, there are no bus routes that link Lechmere with Boston, making the Green Line E branch the only direct cross-river connection. Therefore, a new route is proposed connecting Sullivan, Lechmere, Kendall/MIT and Kenmore stations. These are all key locations with significant ridership generators and attractors.

The proposed route is shown in Figure 6-1 and described in greater detail later in this section. The route would begin at Sullivan Station, which is a major transfer station. Connection to the Orange Line is available at Sullivan as well as connections to many bus routes. The next key location would be Lechmere Station. Currently there are no buses that directly connect Lechmere and Sullivan. From Lechmere, the next key location on the route would be Kendall Square. Transfer to the Red Line is available at Kendall/MIT. Although other routes provide access from Lechmere to the Red Line at Davis and Porter, for passengers going inbound to Boston, accessing the Red Line at either of those stations would require back tracking. Kendall/MIT is also a significant trip generator and attractor as it is on the Massachusetts Institute of Technology campus and is an important corporate and research center. From Kendall, the route would run across the MIT campus and would then cross the river using the Massachusetts Avenue Bridge to Beacon Street and then to Kenmore Square. Kenmore Station provides connections to the B, C and D branches of the Green Line as well as several bus routes. Although both Lechmere and Kenmore are on the Green Line, at present they are on different branches and therefore using the Green Line to travel between these stations requires a transfer at one of the busy central subway stations. Extending the C or D branch to Lechmere as proposed in Chapter 4 would provide a one seat ride on the Green Line between Lechmere and Kenmore stations but not between other locations along the proposed route. None of the four key locations along the proposed route are currently connected by a one seat ride using either MBTA light rail or bus routes.

Figure 6-1 Proposed New Cross-Town Route



The new route is proposed to operate with the weekday headways in Table 6-1. Ten minute headways are proposed for most of the day. These headways are intended to make this a walk-up service rather than a scheduled service and to minimize wait time for transfers from the rail connections at key points along the route. Longer headways are provided at the beginning and end of the day to allow for ramping up service, to make the proposal more financially feasible, and to better align service levels with other services offering reduced frequencies at the beginning and end of the service period.

Table 6-1 Proposed New Cross-Town Route Weekday Headways

Period	Time	Headway
Early Morning	5:30 AM - 6:30 AM	15
AM Peak	6:30 AM - 9:00 AM	10
Midday	9:00 AM - 3:30 PM	10
PM Peak	3:30 PM - 6:30 PM	10
Evening	6:30 PM - 8:00 PM	10
Late Night	8:00 PM - 12:40 AM	20

The proposed new cross-town route is referred to here as the CT4, following the example of the three existing MBTA cross-town routes. The existing cross-town routes seek to link key locations, serve limited stops, and only operate on weekdays. Although this new route is referred to as the CT4, since it is intended as mitigation it could be contracted out to a private operator. In addition to relieving the need to find or purchase vehicles to operate the route, contracting out operations of the route would make it easier to discontinue the route if it is found to generate less ridership than anticipated or if mitigation is no longer required.

The majority of the path for the proposed route is based on roads used by segments of current bus routes (including Routes CT1, 1, 86, 87, 91, and the EZRide Shuttle), particularly when entering and exiting the busways at the key stations. The path is also derived from the EZRide path and the combined CT2/CT3 route proposed by MASCO. One key difference between this proposed cross-town route and existing MBTA routes is in its use of Inner Belt Road. The short term version of the route would take Cambridge Street to Washington Street to McGrath/Monsignor O'Brien Highway in order to access the existing Lechmere Station bus stop. This is similar to the path taken by existing routes entering and exiting Sullivan and Lechmere Stations. However, in the long run the route would make use of an extended Inner Belt Road, taking a new bridge over the train tracks in order to connect to an extended North Point Boulevard and access the relocated Lechmere Station. This new alignment makes use of the planned new bridge and provides transit service in this previously unconnected area. Despite the advantages of the long term route design, it is dependent on new construction. Since the new construction is not expected to be completed until 2016, a short term alternative path is proposed that makes use of existing roadways. The analysis presented here focuses on the short term alternative that requires minimal alterations to road alignments and construction thereby making it more rapidly implementable.

The other key difference between the proposed route and existing routes is in the path taken near Kendall Station. 1st Street is used to connect Lechmere and Kendall. This street is currently used by the EZRide Shuttle and is part of both a MASCO route proposal and proposals being considered for a proposed Urban Ring. Closer to Kendall, Binney Street can be used to connect the route from 1st Street to 3rd Street. Currently, one way roads require that vehicles make extra turns and go in loops in order to navigate the Kendall Square area and properly access Kendall/MIT Station. In order to avoid this, it is proposed that a bus-only cut through be created through the small median at the intersection of Broadway and Main Street. This would allow for a bus-only connection between 3rd Street and Main Street and access to Kendall Station from 3rd Street in both directions without having to take Binney Street further or create a long loop using Ames Street to avoid one way streets in the area.

All current MBTA stops along the proposed route would be served. Additional stops would need to be added along Inner Belt Road (only in the future proposal), 1st Street, and Binney Street, where currently no MBTA bus stops exist. The proposed stops would be: Inner Belt Road at 3rd Avenue, 1st Street at Charles Street, and Binney Street at 3rd Street. All existing and new stops along the route are shown in Figure 6-1 with new stops in red. The detailed path of the proposed route in each direction is as described in the following paragraphs.

In the southbound direction, the proposed cross-town route would begin at Sullivan Station. The bus would exit onto Mafia Way and take Cambridge Street until it turns into Washington Street and then take McGrath/Monsignor O'Brien Highway to Lechmere. In the long run, the path would turn off of Cambridge Street onto Inner Belt Road and take Inner Belt Road to North Point Boulevard and the relocated Lechmere Station. After exiting the Lechmere busway, the route would take East Street to Cambridge Street. After a left onto 1st Street, the route would continue on until taking a right onto Binney Street. The route would then take a left onto 3rd Street. After crossing Broadway, the path would cut through the median at the intersection of Broadway and Main Street to access Main Street and the Kendall/MIT Station stop. From Kendall, the route would take a left onto Vassar Street and then another left onto Massachusetts Avenue. After crossing the Harvard Bridge, the route would turn right onto Beacon Street. Just past Kenmore Station, the route would take a left onto Commonwealth Avenue to enter the Kenmore Station busway.

The route would generally be the reverse in the northbound direction, except at Kenmore Station. Exiting the Kenmore Station busway, the route would take a left onto Beacon Street and then a left onto Commonwealth Avenue. The route would then take Commonwealth Avenue until it takes a left onto Massachusetts Avenue. After crossing the Harvard Bridge on Massachusetts Avenue, the route would take a right onto Vassar Street and a right onto Main Street. From Main Street, the route would cut through the median again to access 3rd Street, take a right onto Binney Street, and a left onto 1st Street. Under the existing conditions, the path would then take a right onto Cambridge Street and then take East Street to McGrath/Monsignor O'Brien Highway and the Lechmere bus stop. Exiting Lechmere, the path would again take McGrath/Monsignor O'Brien Highway to Washington Street and then Cambridge Street. In the long run, rather than taking McGrath/Monsignor O'Brien Highway, the route would take the bridge connecting North Point Boulevard to Inner Belt Road and then take a right onto Cambridge Street before turning into Sullivan Station.

6.1.1. Number of Vehicles Required

After establishing the proposed path of the CT4 route, the number of vehicles required can be estimated. Unlike with the existing routes above, observed running times cannot be used to calculate the number of vehicles required. Instead, an approximation method was used that combines information about observed running times and Google Maps predicted travel times for comparable existing routes. This analysis was done for the short term alternate path discussed above that does not take Inner Belt Road. It is assumed, however, that the necessary work would be done to allow buses to cut across the median at the intersection of Broadway and Main Street near Kendall Square.

Routes 87 and 88 were used as comparables for the CT4 run and cycle time analysis. The predicted travel times from Google Maps were collected and the observed running times from AVL data were analyzed. The 50th percentile of observed running times was used as the run time and the 90th percentile was used as the cycle time. Separating inbound and outbound service for each of the two routes resulted in four observation points. It was then assumed that for each route and direction any difference between the Google Maps travel time and the 50th percentile of the observed running times in each direction was due to dwell time. This simplification attributes any differences in run time throughout the day to dwell time, so dwell time becomes a proxy for traffic as well. Recovery time is taken as the difference between the 90th and 50th percentiles of observed running times.

After collecting all of the data for the existing routes, the estimated dwell time per stop and recovery time as a percent of run time were calculated. The average and maximum of the four observations of dwell time and recovery time percent for each the AM and PM peak were calculated. These values were then applied to the proposed CT4 route stops and Google Maps predicted travel time to get the CT4 estimated run time, cycle time and estimated vehicles required (Table 6-2 and Table 6-3).

Table 6-2 CT4 Cycle Time Estimation

		Google Maps	AM Peak Observed				PM Peak Observed			
	Number of Stops	Travel Time	50th Percentile	90th Percentile	Recovery % of Run Time	Dwell Time per Stop (sec)	50th Percentile	90th Percentile	Recovery % of Run Time	Dwell Time per Stop (sec)
Existing Routes										
88 - IB	27	16	24.5	31.4	28.3%	19	24.9	28.1	13.1%	20
88 - OB	27	13	21.6	25.8	19.6%	19	26.9	30.8	14.5%	31
87 - IB	34	18	35.5	42.1	18.7%	31	30.8	35.1	14.0%	22
87 - OB	36	20	28.8	33.3	15.8%	15	34.9	40.0	14.6%	25
Average					**20.6%**	**21**			**14.0%**	**24**
Maximum					**28.3%**	**31**			**14.6%**	**31**
Proposed Route - Average of Existing Statistics										
CT-4 IB	18	22	28.3	34.1	20.6%	21	29.3	33.5	14.0%	24
CT-4 OB	16	20	25.6	30.8	20.6%	21	26.5	30.3	14.0%	24
Total CT-4	**34**	**42**	**53.8**	**64.9**			**55.9**	**63.7**		
Proposed Route - Maximum of Existing Statistics										
CT-4 IB	18	22	31.3	40.1	28.3%	31	31.3	35.8	14.6%	31
CT-4 OB	16	20	28.2	36.2	28.3%	31	28.2	32.3	14.6%	31
Total CT-4	**34**	**42**	**59.5**	**76.3**			**59.5**	**68.2**		

Table 6-3 CT4 Vehicles Required Calculation

Period	Cycle Time	Headway	Number of Vehicles
Average			
AM Peak	65	10	**7**
PM Peak	64	10	**7**
Maximum			
AM Peak	76	10	**8**
PM Peak	68	10	**7**

The analysis in the tables above suggests that 7 or 8 vehicles would be required to operate the proposed CT4 route during the peak periods. The estimated cycle time in the PM peak is shorter than in the AM peak when using either the average or maximum statistics from the existing routes. Typically this is not the case and PM peak running times are longer. The reason for this inversion might be the low recovery as a percent of run time calculated for the existing routes in the PM peak. This number is both significantly below the AM peak observed percentage and lower than expected. Setting the PM peak recovery time as a percent of run time equal to the AM peak percentage results in 7 vehicles required in the average case and 8 vehicles required in the maximum case for both the AM and PM peak periods.

This analysis was done for both the AM and PM peak periods since these are the most resource constrained, but it could also be expanded to other time periods. Other methods were also explored, including using average speeds. Applying speeds observed on the comparable routes to the CT4 route distance resulted in longer run and cycle time estimations. When using the average speed from the existing route comparables, the same number of vehicles is required despite the higher cycle time estimation, but when using the maximum of the comparables' statistics one additional vehicle beyond those in Table 6-3 would be required in both the AM and PM peak.

The analysis above also does not incorporate the impact of varied loads on dwell time. The analysis here assumes an average dwell time across all stops. However, if the proposed route is expected to have similar ridership to the existing routes but spread across fewer stops with boardings particularly concentrated at a few key stops, then it is reasonable to expect more boardings per stop and longer dwell times on the new route.

This analysis suggests that seven or eight vehicles would likely be required to operate the proposed route during the peak periods, but additional analysis would need to be done prior to implementing the route to establish the vehicle schedule. The number of vehicles required is shown as both an indication of anticipated costs. One way to possibly avoid the large vehicle requirements for operating this route would be to contract out operations of this route.

6.1.2. Direct Demand Model Application

For a new route such as the proposed CT4 route, elasticity analysis cannot be applied because there is no base ridership from which to project. One way of estimating ridership for this new route is by applying the direct demand model that has been estimated for the MBTA bus system. In order to do this, updated service level inputs must be calculated for all locations affected by the introduction of the new route. The CT4 also requires the introduction of a few new stops into the system therefore locations must be regenerated and location variables recalculated in case overlapping catchment areas with the new locations result in a change to the independent variables of existing locations.

As discussed in Section 3.4.3, it is difficult to isolate the predicted ridership on the new route, but the estimated impact on location and total system ridership is valuable for comparing between different proposals. Table 6-4 shows the impact of adding the proposed CT4 route as estimated by the direct demand model. Only the impact at CT4 locations is shown because the difference between the impact at these locations and the total system net impact is minimal. Adding the CT4 is estimated to add about 8,400 riders at CT4 locations after applying the location adjustment factors. This is a 2.2% increase in total system ridership. Further adjusting for AFC undercounting would bring the ridership increase estimation up to about 9,200 additional passengers. It should be recognized that this is not intended as an accurate prediction of the ridership expected if CT4 service were to be introduced, but it does provide an order of magnitude indication of the ridership impact. The main power of this tool is in comparing between proposals.

Table 6-4 Direct Demand Model Results - Creation of CT4 route

	CT4 Locations		
	Before	**After**	**Change**
Unadjusted Ridership	3,434	6,408	2,974 (87%)
Adjusted Ridership	14,035	22,413	8,378 (60%)

The change in ridership seen in Table 6-4 should not automatically be assumed to all be on the new route as opposed to on other routes at those locations that benefit from greater combined headways at the location. Although it is anticipated that not all riders along the new route would be new entrants into the system, the CT4 route does not run parallel to any other services for significant portions of the route making it possible that it would have less of a competitive relationship with existing routes and take only a small portion of its riders from existing ridership on other routes. On the other hand, the proposed CT4 route is likely complementary to some routes, so some of the observed increase in ridership may be due to increased transfers to and from other routes at shared locations.

The two methods outlined in Section 3.4.3 can be used to estimate the CT4's share of the ridership impact. Based on the route's proportion of total trips at all locations along the route, the ridership on the new route would be approximately 4,300 passengers after adjusting for AFC undercounting, or 47% of the total increase. Assuming that a minimum of 75% of the ridership increase would be on the new route would suggest that the ridership on the CT4 would be about 7,100 passengers after adjusting for undercounting, or 77% of the total impact at locations along the route. Using the 75% lower bound seems reasonable given the minimal overlap between the CT4 and other routes at the CT4 locations. At the same time, for air quality calculations for mitigation 100% of total system ridership change is what matters, regardless of what route the change is attributed to.

The proposed CT4 route would generate significantly more ridership than the proposed changes to existing bus routes as analyzed in the previous chapter. According to the direct demand model, establishing CT4 service at the proposed headways would result in a 2.2% increase in system ridership. The change in ridership at CT4 locations is significantly higher than the ridership increases estimated due to the proposed increases in service on Routes 87 and 88. However, the additional vehicle requirements are greater and more work would be required to establish the route (including additional onetime costs such as those for creating new bus stops and the Kendall Square bus-only access lane) or contract out the route than to just make changes to existing services.

6.2. Providing Public Access to Private Routes

The first proposal in this chapter was the introduction of an entirely new route. Another means to avoid the equipment capacity constraints faced by the MBTA is to contract out services. There are currently several private operators running services throughout the MBTA system that overlap with and add to the MBTA network. Some of these private services are for members only, while others are open to the public for a fee. An alternative way for the MBTA to expand their bus route network would be to work with some of these private operators to increase public access to private routes, particularly by providing MBTA fareboxes (or CharlieCard readers) on the private vehicles. Although coordination with the private operators would be necessary and may entail some costs, by making use of routes already being operated, the MBTA would not need to spend effort and resources designing and scheduling the routes.

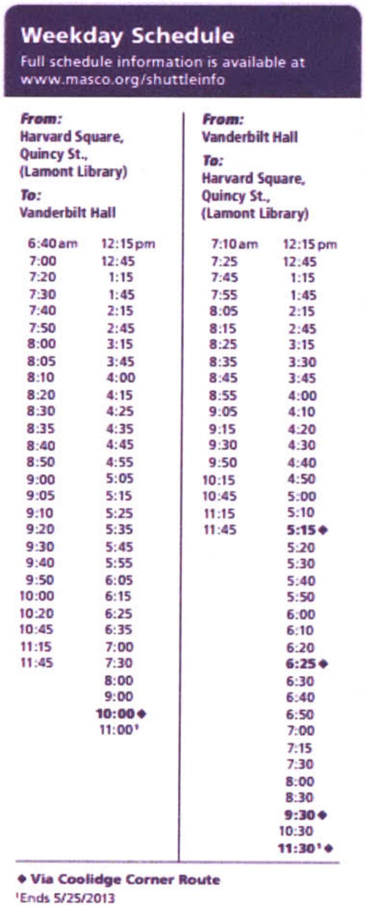
Furthermore, by not directly operating the routes, the MBTA is able to provide additional service without requiring additional vehicles or operators. Another advantage of outsourcing the operation of routes to private operators is that if the MBTA wants to stop providing the service because it does not generate considerable new ridership or because mitigation is no longer necessary, it would be easier to end the partnership with the private provider than to discontinue an MBTA operated route.

This section discusses providing public access to two private routes: MASCO's M2 shuttle and the EZRide. For each service, the current operations of the route is described and then the direct demand model is used to estimate the impact of incorporating the routes into the MBTA network.

6.2.1. M2

The M2 Shuttle is operated by MASCO and provides service between Harvard Square in Cambridge and the Longwood Medical and Academic area (LMA) in Boston's Fenway area. A map of the M2 and the weekday schedule are provided in Figure 6-2. The weekday M2 operates between 6:40am and approximately midnight with headways as low as five minutes during the peak and up to one hour at night. There is also limited Saturday service, but no Sunday service. The route has a one-way run time of approximately 25 minutes with ten stops in the Harvard Square to Vanderbilt Hall (LMA) direction and 13 stops in the Vanderbilt Hall (LMA) to Harvard Square direction. Most of the stops make use of MBTA bus stops, and many stops are by request only.

Figure 6-2 M2 Route and Schedule



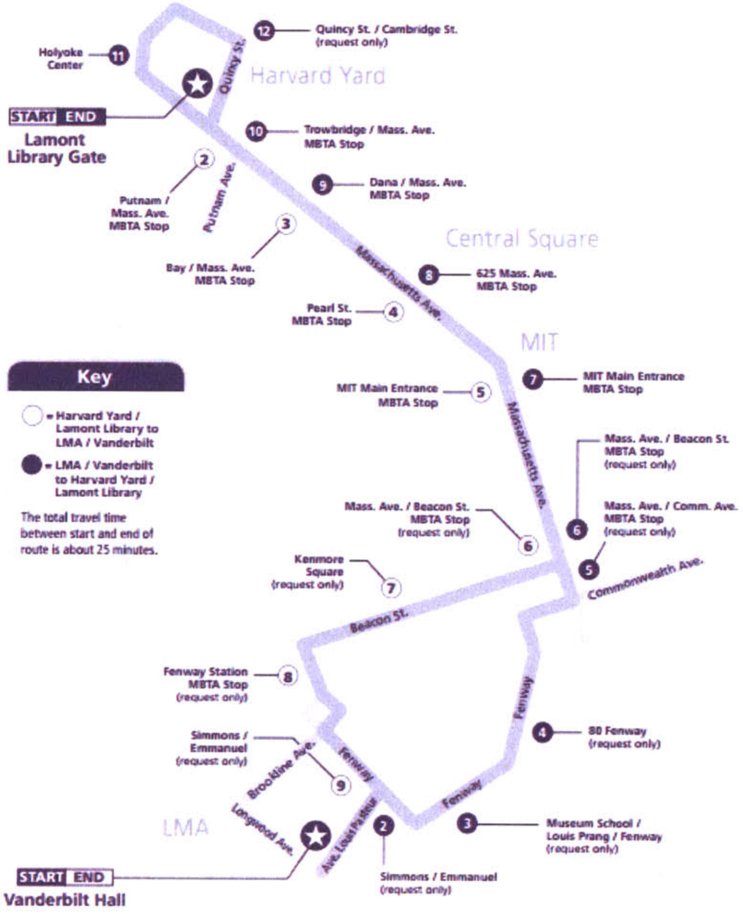
Weekday Schedule

Full schedule information is available at www.masco.org/shuttleinfo

From: Harvard Square, Quincy St., (Lamont Library) *To:* Vanderbilt Hall		*From:* Vanderbilt Hall *To:* Harvard Square, Quincy St., (Lamont Library)	
6:40am	12:15pm	7:10am	12:15pm
7:00	12:45	7:25	12:45
7:20	1:15	7:45	1:15
7:30	1:45	7:55	1:45
7:40	2:15	8:05	2:15
7:50	2:45	8:15	2:45
8:00	3:15	8:25	3:15
8:05	3:45	8:35	3:30
8:10	4:00	8:45	3:45
8:20	4:15	8:55	4:00
8:30	4:25	9:05	4:10
8:35	4:35	9:15	4:20
8:40	4:45	9:30	4:30
8:50	4:55	9:50	4:40
9:00	5:05	10:15	4:50
9:05	5:15	10:45	5:00
9:10	5:25	11:15	5:10
9:20	5:35	11:45	**5:15◆**
9:30	5:45		5:20
9:40	5:55		5:30
9:50	6:05		5:40
10:00	6:15		5:50
10:20	6:25		6:00
10:45	6:35		6:10
11:15	7:00		6:20
11:45	7:30		**6:25◆**
	8:00		6:30
	9:00		6:40
	10:00◆		6:50
	11:00[1]		7:00
			7:15
			7:30
			8:00
			8:30
			9:30◆
			10:30
			11:30[1]◆

◆ Via Coolidge Corner Route

[1] Ends 5/25/2013



Source: www.masco.org/directions/m2-cambridge-harvard-shuttle

The majority of the M2 route runs along Massachusetts Avenue between Harvard and Beacon Street/Commonwealth Avenue. This section of the route parallels the MBTA's Route 1, essentially providing an express service. Route 1 is often overcrowded and is prone to bus bunching, so it could benefit from this additional service. Harvard students in certain programs as well as university officers and staff can ride the M2 shuttle for free. The general public can also ride the shuttle for $3.25 per ride, but they must purchase tickets or a Crimson Cash card in advance from one of the M2 ticket offices. This is a difficult process that limits public use of the service.

As with the proposed CT4 route, predicting the impact of accepting MBTA fares and payment methods on the M2 - therefore essentially introducing it as an MBTA bus route - can be estimated using the direct demand model for the MBTA bus system.

Many of the M2 stops are identified as being MBTA bus stops. In a few cases, the M2 has a distinct stop location in which case a new stop identity was created for the direct demand model. This was done for the stops at Kenmore Square, Vanderbilt Hall, Museum School, and 80 Fenway. There is also an M2 stop at Quincy Street and Cambridge Street, but this is a by request only stop a short block away from the end terminal, so it was excluded for this analysis assuming it is primarily used as an alighting stop and rarely as a boarding stop. Since new stops were identified, locations had to be regenerated and variables based on catchment areas were recalculated.

The number of trips added with the introduction of M2 service at each location was based on the weekday schedule. According to the schedule, the span of service is being shortened starting at the end of May, eliminating the last trip of the day in each direction. Therefore these trips were excluded from the trip count. Several evening trips also take a different route (Coolidge Corner Route) and skip key stops along the route, particularly several stops along Massachusetts Avenue, and were therefore also excluded from the trip count for all stops. Ideally the M2 schedule would be coordinated with the Route 1 schedule in order to provide even headways at shared stops, which could potentially have a slight affect on the number trips provided, but this was not incorporated into this analysis.

Table 6-5 provides the estimates for the full system impact and the impact on only the locations including M2 stops. Providing public access to the M2 using MBTA fares and payment methods results in an increase in ridership at M2 locations of approximately 2,200 passengers (2,400 passengers after adjusting for AFC undercounting), and an estimated 0.4% increase in system-wide ridership. The difference between the total system nominal ridership change and the ridership change at locations along the M2 is more pronounced than with the introduction of the CT4. A combined increase of about 2,200 riders is estimated for the M2 locations and yet only about 1,650 new riders are estimated to enter the system (about 2,200 and 1,800 passengers, respectively, after adjusting for AFC undercounting), suggesting that almost 25% of the ridership increase at the M2 stops would be coming from other locations within the MBTA system.

Table 6-5 Direct Demand Model Results - Public Access to M2

	Full System			M2 Locations		
	Before	After	Change	Before	After	Change
Unadjusted Ridership	193,449	194,140	691 (0.4%)	2,156	3,120	965 (44.7%)
Adjusted Ridership	383,962	385,613	1,651 (0.4%)	5,478	7,672	2,194 (40.1%)

As noted with the previous proposals, the direct demand model does not consider what route a trip is on, so additional work must be done to estimate what portion of the increase in ridership at M2 locations would be on the M2 versus other routes at shared locations. In this case, the M2 competes with Route 1 and the CT1 for a large portion of the route, so it is possible that some of the estimated increase in ridership might be an increase in Route 1 or CT1 ridership due to increased total service at shared stops. At the same time, some of the M2 ridership may be taken from current Route 1 or CT1 ridership. Distributing the total ridership change to the different routes proportional to the share of trips at each location suggests that 41% of the ridership, or about 1,000 passengers after adjusting for undercounting would be riders on the M2 route. Using 75% of the change at each location as a lower bound, the M2 would capture 80% of the impact, or about 1,900 passengers after adjusting for AFC undercounting. This analysis suggests that significant ridership would be generated on the M2 but that there would also be additional ridership generated on other routes at shared locations.

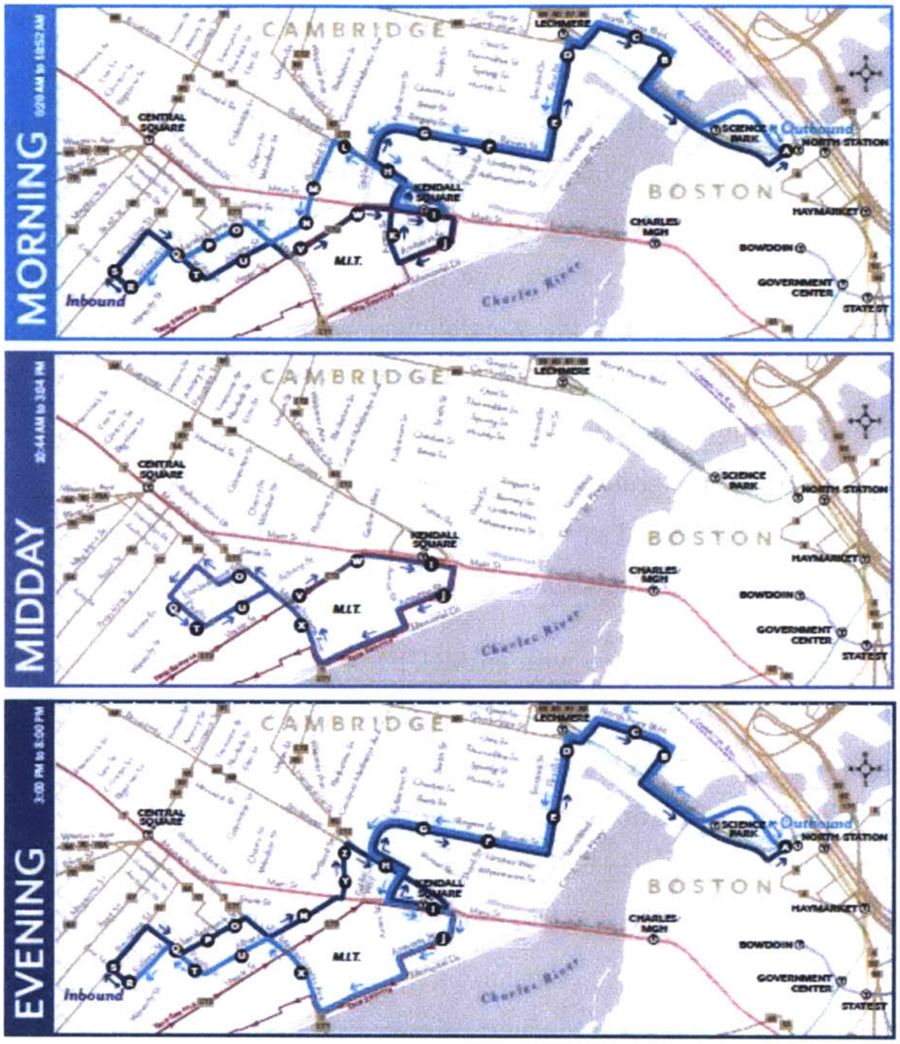
For mitigation, the distinction between M2 ridership and new ridership generated on other routes is not important because the overall air quality impact is what matters. At the same time, some of the M2 ridership predicted by the direct demand model may be current M2 passengers who will continue to use the service for free. These passengers will not generate new revenues or air quality benefits. There may also be some additional M2 ridership beyond that predicted by the direct demand model due to passengers who use the M2 because it is free and convenient but would not pay to use an equivalent public service and are therefore not captured by the model. No detailed current M2 ridership information was available for comparison, but casual observations of the route suggest that there is currently sufficient capacity remaining on the route to accommodate additional public ridership.

6.2.2. EZRide

The EZRide Shuttle is operated by the Charles River Transportation Management Association (TMA). The route maps and schedule are provided in Figure 6-3. The shuttle runs between 6:20am and 8pm. Morning service (start of service until approximately 10:45am) operates with an eight minute headway during the peak and a ten minute headway otherwise. The midday schedule (10:45am to 3pm) has a 20 minute headway, and the evening schedule (3pm until end of service) has a nine minute headway. The morning and evening routes operate between Cambridgeport and North Station via Kendall Square, including a stop near (but not at) Lechmere Station. According to the Charles River TMA website, the outbound running time is 23-26 minutes and the inbound running time is 26-30 minutes on the morning and evening routes. The midday route is significantly more limited and creates a loop from Kendall Square through MIT's main campus and part of the northwest campus which houses several school offices and dormitories. The midday route has an 8-10 minute running time in each direction.

The EZRide Shuttle is currently free with an MIT ID or a sticker from one of the participating member institutions. The member institutions are primarily companies in the Kendall Square area. All other passengers can pay a cash fare of $2 ($1 for students, seniors and persons with disabilities) to ride the shuttle. Unlike the M2 shuttle, the EZRide route actually appears on the MBTA bus system map. The fare is also more comparable to the MBTA bus fare, although MBTA fare cards are not accepted and free transfers to MBTA services are not permitted.

Figure 6-3 EZRide Routes and Schedules



Time Period	Time	Headway
Morning	6:20am-10:52am	8-10 mins
Midday	10:44am-3:04pm	20 mins
Evening	3:00pm-8:00pm	9 mins

Source: www.charlesrivertma.org/program_ezride.htm

Once again, the direct demand model can be applied to estimate the impact of introducing MBTA fares and fare payment methods to the EZRide thereby incorporating it into the MBTA system. The same method was used as for the other proposals, with new stops being identified, locations and catchment area variables being calculated, and new trips being added to the relevant locations. The trips to each location were determined based on the printed schedule, including variants that start or end at Kendall/MIT rather than North Station.

Table 6-6 provides the results of applying the direct demand model to the introduction of the EZRide into the MBTA system. A ridership increase of about 2,300 passengers (about 2,600 passengers after adjusting for AFC undercounting) is predicted at EZRide locations. In comparison, the net impact on system ridership is only about 1,700 passengers (about 1,900 passengers after adjusting for undercounting), which is a 0.4% increase in total system ridership. As with the M2, the net system ridership impact is less than the increase at EZRide locations. This suggests that some of the ridership along the route would likely be made up of existing riders coming from other routes in the system.

Table 6-6 Direct Demand Model Results - Public Access to EZRide

	Full System			EZ Ride Locations		
	Before	After	Change	Before	After	Change
Unadjusted Ridership	193,449	194,480	1,031 (0.5%)	846	2,048	1,202 (142.1%)
Adjusted Ridership	383,962	385,669	1,707 (0.4%)	1,511	3,851	2,340 (154.9%)

Even at EZRide locations, some of the predicted increase in ridership may be on other routes at shared locations. Again, the two methods discussed in Section 3.4.3 can be used to distribute ridership amongst the routes at locations along the EZRide route. Unlike with the routes examined above, the EZRide primarily operates at locations not shared with other routes and therefore a greater portion of the predicted ridership impact is attributed to the study route than seen previously. Based on the EZRide's proportion of total trips at each location, 88% of the ridership increase would be attributed to the EZRide, for a route ridership of approximately 2,300 passengers after adjusting for undercounting. Attributing a minimum of 75% of the ridership increase to the EZRide increases the estimated ridership on the route to approximately 2,400 passengers after adjusting for undercounting, or 94% of the increase at the affected locations.

The direct demand model results can be compared to the actual EZRide ridership levels from the Charles River TMA for October and December 2011. Excluding the Columbus Day school holiday, average daily ridership in October was 2,141 passengers, and the average daily ridership for the December through the 22nd was 2,041 passengers. This comparison suggests that after post processing to adjust for the distribution of ridership changes amongst routes at shared locations, the direct demand model did a good job at predicting EZRide ridership. This actual ridership data can also be used to look at capacity. North Station in the AM Peak is assumed to be the peak load location. Boardings at this station in the AM peak are fairly variable, with the peak boarding seen to be as high as 60 passengers for one peak trip per day, but other trips typically have in the range of 30-50 boardings per trip. The schedule at the time of this data also had ten minute headways as opposed to the current eight minute scheduled headways. This suggests that there is some capacity for additional ridership on the route. If capacity during the peak of the peak is a concern, provisions could be written into the contract to provide for additional service during this period if necessary.

As with the M2, there may be some EZRide ridership not captured by the direct demand model because the model does not capture the effect of fares. Some current EZRide passengers may use the EZRide because it is free but would not use it if they had to pay. The actual ridership data available does not distinguish between member and paying passengers, but ridership patterns appear to confirm that a good portion of the observed ridership at certain times is students traveling between the MIT dormitories and campus or around the MIT campus. These passengers likely are not captured by the direct demand model. This proposal also introduces the most new locations into the system and therefore is the most affected by the assumption of applying the system-wide adjustment factor to the ridership predicted at new locations.

6.3. Conclusion

The introduction of new routes can be analyzed using the direct demand model estimated for the MBTA bus system, but elasticities cannot be applied due to the lack of initial ridership levels at some stops.

The proposed new CT4 route would provide connections between key locations that are currently not accessible to each other with a one seat ride. Providing a frequent walk-up level of service would produce an estimated 2.2% increase in system ridership. This is the greatest ridership increase seen in any of the proposals examined. However, this ridership impact would also come at the highest cost, requiring seven or eight vehicles throughout most of the day. Contracting out the operations of the route is an alternative way to provide the CT4 service while eliminating the need for the MBTA to provide these vehicles. Given the need for mitigation and the high potential impact of this route, the MBTA should start planning and implementing this route. The CTPS regional planning model should also be applied and the results compared to the direct demand model and to ridership data collected after implementation of the route.

Increasing service by providing public access to private routes rather than introducing new routes is another alternative way to provide better service without increasing the number of vehicles required in the system. The two private routes considered are the M2 and the EZRide. There could still be some costs associated with paying MASCO or the Charles River TMA for operating the routes, but no MBTA vehicles or operators would be required.

Using the direct demand model, accepting MBTA fares and payment methods on the M2 and EZRide would each result in an estimated 0.4% increase in system ridership. However, the net ridership increase in the system is less than the ridership increase predicted at locations along the study routes. This implies that a portion of the increase in ridership at the route locations is coming from neighboring locations. This net system-wide impact should be considered when evaluating the addition of new services, especially for air quality impact for mitigation purposes.

Although the direct demand model predicts a similar system ridership change when the M2 and EZRide routes are introduced into the system, the EZRide is expected to have greater route ridership. The direct demand model only predicts ridership at the location level, not the route level, so two methods were applied to distribute ridership changes to routes at joint locations. Based on this analysis, even though the M2 and EZRide result in similar ridership gains at locations along the routes, a greater portion of the ridership increase would be attributed to the EZRide than would be attributed to the M2. This seems reasonable because the EZRide has less overlap with existing services while the M2 runs parallel to other MBTA routes, including Route 1 and the CT1. For the air quality measures required for mitigation, this difference between ridership increases on the study route and ridership increases on other routes is not important. However, this impact could have operational implications and possibly revenue effects depending on how the contracts with the private operators are written.

7. Summary and Conclusions

With the legal obligation to undertake mitigation for the delay in constructing and opening the Green Line Extension (GLX), the MBTA has the difficult task of increasing service while operating under resource (peak hour vehicle and operator) constraints. This thesis examines three types of mitigation proposals for the delay of the GLX. In order to analyze the different proposals, two ridership estimation methodologies are applied, as appropriate.

The first proposal looks at several ways to increase Green Line service to Lechmere, the current terminal where the extension will begin. The next set of proposals includes two options for increasing service along existing bus routes. Both Routes 87 and 88 have terminals at Lechmere and operate near some of the future GLX stations. Increasing service on Route 88 is examined while increasing service along only a portion of Route 87 is considered. The last set of proposals entails introducing new service into the MBTA system. The proposed new CT4 cross-town route would offer high frequency service and create connections between key stations. Finally, adding MBTA fare collection equipment on two existing private routes in order to increase public access to these routes is proposed and analyzed.

The two ridership prediction methodologies utilized in this thesis are elasticities and a direct demand model. The rail elasticity of ridership with respect to service was calculated based on a previous experience of rail frequency adjustments within the MBTA system. In contrast, the bus elasticity was selected based on previous literature due to the greater availability of data and prior analysis of bus elasticities. A bus direct demand model for the MBTA system was developed based on available data due to the lack of a generally applicable bus direct demand model. Elasticities were applied to the first two types of proposals (increased rail service and increased service on existing bus routes), while the direct demand model was applied only to the latter two (increased service on existing routes and the introduction of new routes).

The remainder of this chapter summarizes the findings of these analyses and recommends follow-up actions on the implementation of the different mitigation proposals and the use of the two methodologies. Suggestions are then provided for avenues of future research.

7.1. Findings and Recommendations

7.1.1. Ridership Estimation Methodologies

Two ridership estimation methodologies were utilized in this research: elasticities and a direct demand model. Table 7-1 highlights some of the key advantages and disadvantages of each of the two methods. The methods have several contrasting advantages and disadvantages. The results of the two models are not necessarily intended to be compared to each other, and there are times when it might be more appropriate to use one versus the other.

Table 7-1 Comparison of Elasticity vs. Direct Demand Model Approaches

Elasticities	Direct Demand Model
Advantages	
• Precedent for use (people are familiar with definition & comfortable with use) • Quick and easy application • Easy interpretation • Availability of research and data on previous experiences (but not always comparable) • Can account for different levels of initial service • Can add adjustments for other characteristics of service	• Can be applied to new routes • Based on current data and observations • Captures some interaction between routes because location based • Testing changes to existing routes is simple (introducing new routes requires data collection) • Multiple variables used in model can be expanded to look at impact of other system characteristics • Can incorporate land use impacts and TOD
Drawbacks	
• Requires current ridership levels as an input • Must be based on past experiences (or time series data) • Judgment required in selection of elasticity • Looks at impact on a single route, not network • Use of single arc elasticity may not be applicable to large changes in service • Single variable to predict ridership is not always realistic	• No generally applicable bus models exist - creating a new model is time and data intensive • Destinations not generally considered • Sketch model – to be used for comparison of options, not actual prediction of anticipated results • Location based - interpretation of results on individual routes is difficult • Limited by quality and availability of data • Availability of data may limit model estimation –manual data collection required for some variables
Uses	
• Best for examining small changes to existing routes	• Best for comparing between scenarios that include the introduction of new stops or services

There is abundant current research on elasticities and they are commonly used to examine the impact of minor system changes. Even when there is insufficient research on elasticities, such as in the case of rail service elasticities, previous system experiences can be used to calculate an elasticity as was done in Chapter 4. Fare and service elasticities are frequently used in many types of transportation analysis. Furthermore, it is relatively intuitive to understand the definition and interpretation of elasticities. As such, may transportation analysts are quite comfortable using elasticities for the analysis of proposed service changes.

The availability of previous research on elasticities provides numerous values of service elasticities, although a level of personal judgment is required in each specific application. The formula for applying an elasticity with a sensitivity range is fairly straightforward and can be done with a simple excel model. Different elasticities can be selected to account for differences in starting service levels, time periods, urban vs. suburban routes and other service characteristics. However, typically the availability of comparable cases in research means that only one of these characteristics can be accounted for at a time. In this research, the selection of elasticities was based on the initial service level. Future work could look to build a more complex model that can adjust for other characteristics as well.

Elasticities are a popular method for estimating the impact of service changes due to their ease of use. However, there are several limitations to their use. A key limiting factor is that initial ridership levels are required to apply elasticities. For this reason, elasticities could not be applied to all of the proposals in this thesis. As mentioned above, judgment is also required to select the "best" elasticity, and often average elasticities found in the literature are derived by combining past experiences with different underlying situations. Another limitation is that a basic elasticity formula is intended to look at one route at a time and does not incorporate network effects. Finally, arc elasticities are generally most applicable to small changes. Some of the proposals here seek to have a meaningful impact by increasing service by as much as 50% in order to provide walk-up service. In these cases, the arc elasticity may no longer be applicable. In moving from scheduled to walk-up service, typical service elasticities may need to be modified.

Overall, the availability of relevant elasticity measures and the simplicity of application make elasticities a powerful tool for first-cut ridership estimation. Elasticities can easily be altered to fit different routes and are comparable across the system. However, when initial ridership levels are not available another method must be used. In this thesis, direct demand models were tested as an alternative.

Direct demand models have the advantage of being applicable in more situations, including the introduction of new stops and routes, but they have the disadvantage of being generally more difficult to estimate and interpret. Direct demand models are a type of demand models known as sketch models, and are intended primarily to be used to compare between scenarios and not necessarily to produce accurate estimations of individual impacts. Unlike elasticities, direct demand models are developed based on cross-sectional current data and observations rather than historical longitudinal experiences and time series data. Importantly, the variables included in the model can incorporate more factors simultaneously than with a single elasticity equation. The base model typically includes demographic information and basic service information, but the variable list can be expanded to include other system characteristics. For example, Cervero, Murakami and Miller (2010) estimated a direct demand model that captured the effect of special bus rapid transit service characteristics such as dedicated lanes. Another reason for using direct demand models is the ability to incorporate the impacts of land use and transit oriented development that are rarely captured in other demand models.

Currently, few direct demand models have been estimated. In particular, there are no generally applicable bus route direct demand models. This means that a situation specific model must be developed in each case, such as was done for the MBTA bus system in this thesis. The development of a direct demand model can be time and data intensive. The quality of the model is dependent on the quality and availability of data. For example, the model estimated above uses census block group level data from 2000 because smaller geographic breakdowns and more recent census results were not available for all of the key variables. The model has the ability to add many other variables, many of which were considered and discussed in past literature, but the inclusion of these variables depends on the ability to assemble or infer automated data for all stops included in the model.

Once the model is estimated, though, testing changes to existing routes is fairly straight forward. Estimating the impact of introducing a new route usually requires adding new stops to the system and requires some additional work, but no initial ridership information is required. Another advantage of direct demand models is the ability to test the combined impact of several changes, although this was not tested for the proposals discussed in this thesis. On the other hand, it is difficult to differentiate the impact of a change on a single route because the model is location based. At any given location, the total change in ridership can be calculated but the ridership is not specifically attributed to an individual route or direction. This issue was addressed in this thesis by distributing ridership to routes based on the number of trips operated. Furthermore, most direct demand models are origin based only and do not consider the destination of riders. The lack of consideration given to destinations was seen to be a concern in the case of the proposal to create a short variant of Route 87 serving a limited number of destinations. In this situation the direct demand model may overestimate the nominal ridership impact of a route with limited destinations. On the other hand, the direct demand model is able to capture network effects that may increase ridership but are missing from the elasticity calculation.

Ultimately, direct demand models are most useful when studying the introduction of new stops or routes. When looking at minor changes to individual existing routes, applying an elasticity is the most efficient method for estimating ridership changes. The creation and application of direct demand models is more difficult and time intensive than elasticities, but they are applicable in more situations. Direct demand models are useful for comparing between different scenarios in order to determine priorities for further work. Any significant destination factors must still be considered outside of the model. The results of elasticities and direct demand models are not intended to be compared to each other, so while elasticities may be more easily applied to existing routes than direct demand models, a direct demand model must be used when new routes are also being considered.

7.1.2. Mitigation Proposals

Six unique proposals were presented for mitigating the delay in opening the GLX. The chapters above describe the proposals and the application of elasticities and the direct demand model, as appropriate, to predict their effectiveness. Table 7-2 summarizes the results of the analysis methodologies for the mitigation proposals.

Table 7-2 Comparison of Mitigation Proposals

				Full Day Predicted Ridership Increase			
				Elasticity	Direct Demand Model		
Proposal	Additional Vehicles Required in Peak	Half Trips Added to DRM	# of Affected Locations	Affected Locations	Affected Locations	Full System	Considerations
Rail: Green Line Increased Service [1]							
Loop: Lechmere - Government Center	5	162	2	760 - 1,520 (15% - 30%) [2]	170 (8%) [3]	170 [3]	- Pre-generate patterns for future GLX - Limited by vehicle availability constraints (fewer vehicles are required during other periods of the day) - Transfer potential with bus services at Lechmere
C Branch Extension	6-7	162	2	790 - 1,590 (16% - 31%) [2]	170 (8%) [3]	170 [3]	
D Branch Extension	7-8	162	2	830 - 1,680 (16% - 33%) [2]	170 (8%) [3]	170 [3]	
Bus							
Route 88 increased service	1 - 2	29	43	500 - 820 (14% - 23%)	1,000 (11%)	1,000	- Significant ridership increase with minimal vehicle requirements - Makes use of existing operations - Minimal network benefits - not provide new OD pairs - Help pre-generate ridership in GLX corridor
Route 87 Short loop (Lechmere - Union Square)	1	93	14	85 - 140 (27% - 45%)	1,070 (33%)	1,070	- Significant ridership increase with minimal vehicle requirements - May not experience full predicted ridership increase because many passengers have destinations beyond Union Square - Minimal network benefits - not provide new OD pairs, but increases access to Union Square - Pre-genrate GLX ridership. encourage Union Square development
New CT4 route [1]	7 - 8	198	27	NA	8,380 (60%)	8,380	- Most significant ridership impact predicted - High vehicle and operator costs - Creates key OD links currently not in network
Providing public access to the M2	0	105	17	NA	2,190 (40%)	1,650	- Minimal costs (no vehicle / operator costs) - Minimal revenues, but increased service for passengers - Coordination required with private operators - Potential legal and technological issues with putting MBTA fareboxes on private vehicles
Providing public access to the EZRide	0	125	26	NA	2,340 (155%)	1,710	

Notes: (1) Ridership along the Green Line to Lechmere and the proposed CT4 would likely be higher than predicted due to the disruption of auto traffic across the river during the Longfellow Bridge reconstruction. Synergies would also exist between increased Green Line service to Lechmere and increased bus service at Lechmere.

(2) Ridership increase predicted at Lechmere and Science Park stations

(3) Increase in bus ridership at Lechmere after changing number of rail feeder trips

Based on the findings of the analysis discussed above, it is recommended that the proposals be implemented as soon as possible, preferably by next September in order to help mitigate the disruption of automobile traffic during the Longfellow Bridge reconstruction. The newly proposed CT4 requires additional work and a possible contract with a private operator, so this work should begin immediately. Discussions should also be initiated with the private operators of the M2 and EZRide shuttles to determine how best to introduce MBTA fares and fare payment methods on these services.

The rail proposal analyzed in Chapter 4 was to double service on the Green Line to Lechmere. Three different ways were presented to accomplish this: a single train could operate a loop between Lechmere and Government Center, the C branch could be extended from its current terminus at North Station, or the D branch could be extended from its current terminus at Government Center. The relative advantages and disadvantages of each of these options were addressed in Chapter 4. The extension of the D branch is preferred as it is the best mitigation proposal and that is the service pattern proposed for the GLX. Although the three options would require between five and eight additional vehicles during the peak periods, fewer vehicles would be required during other periods and more vehicles than this were to have been utilized by 2014 if the GLX were completed on time.

Based on the application of rail service elasticities, a significant increase in Green Line ridership at the Lechmere and Science Park stations can be expected if Green Line service at these stations is doubled. An increase in boardings and alightings of approximately 15-33% is estimated for Lechmere and Science Park. Since these stations will experience this increase in service once the GLX is opened, increasing service before the GLX is complete will help to develop ridership patterns at these stations based on increased service offerings. Furthermore, increased service on the Green Line will benefit bus ridership in the area through increased transfers. Based on the bus direct demand model for the MBTA system, increasing the number of rail feeder trips at Lechmere without making any other changes to the system is estimated to increase bus ridership at Lechmere by about 8% (total bus system ridership increase of 0.04%).

The other proposed changes to existing services are increases in the frequency of bus routes with terminals at Lechmere, specifically Routes 87 and 88. An increase in frequency along the entirety of Route 88 is examined while an increase in frequency along only a portion of Route 87 is proposed through the creation of a short variant of the route. Each of these proposals would require only one or two vehicles and operators to be added to the system during the peak periods while resulting in a meaningful increase in ridership. Due to their alignment close to several future GLX stations, increasing service on these two routes could help pre-generate new ridership in the GLX corridor. The ridership generated by creating a short variant of Route 87 is not estimated to be as significant as the increase due to increasing the frequency on route 88 due to the limited number of destinations served, but this route would be similar to the planned Union Square branch of the GLX and would help generate ridership patterns in the area prior to the opening of the extension. The short loop could be operated using only one vehicle during the peak periods and would likely be discontinued after the opening of the GLX when Route 87 might terminate at the new Union Square Station rather than Lechmere. Furthermore, increasing service to Union Square should aid in the city's re-development of this area, which in turn may increase ridership along Route 87.

For the service changes to Routes 87 and 88, elasticities were applied to existing ridership while the direct demand model was applied to the change in service at the stops along the routes. Since initial ridership levels were available, elasticity calculations could be used to predict a ridership increase of 14-23% or approximately 550-900 passengers after adjusting for AFC undercounting on Route 88, and 27-45% or approximately 90-160 passengers on Route 87. The Route 87 proposal has a higher percent increase in ridership due to the significant service improvement, but the absolute increase in ridership is smaller due to the small ridership base for the proposed short loop. With an additional vehicle, the short variant of Route 87 might be extended to Porter Square to strengthen ridership.

Even though these proposals are good candidates for analysis using elasticities, the direct demand model was applied to the scenarios so that the two methods could be compared and these two proposals could be compared to the next set of proposals that could not be analyzed using elasticities. According to the direct demand model, the proposed increase in service of about 30% on Route 88 would add approximately 1,100 additional riders to the system. If 52-76% of this ridership increase is assumed to be on Route 88, the Route 88 ridership increase would be about 570-830 passengers. These direct demand model results are in line with the elasticity results for the Route 88 proposal. On the other hand, the results of applying the direct demand model to the Route 87 proposal are not as comparable to the elasticity results as with the Route 88 proposal. The direct demand model estimates a 33% increase in ridership at Route 87 locations along the proposed short loop, and a ridership increase of approximately 1,170 passengers. In this situation, since the direct demand model does not incorporate destinations, the model fails to recognize the small ridership base for the proposed route and likely overestimates the nominal ridership change, but the elasticity calculation fails to capture network effects that would increase ridership and therefore likely underestimates ridership.

Based on the analysis above, the proposed increases in service on existing routes should be implemented immediately. The proposed changes to the Green Line and Routes 87 and 88 would require minimal additional vehicles and operators while having a significant ridership impact. These changes are focused in the Green Line Extension area and could help pre-generate ridership and development at future GLX stations. Implementation would be quick as the routes are already established and no new bus stops need to be created. Furthermore, these three service changes would be complementary to each other as simultaneous increases in rail and bus service at Lechmere would lead to increased transfers between the two modes.

The last set of proposals involves introducing new service into the MBTA bus system. These proposals require the application of the direct demand model because they do not have initial ridership numbers for applying elasticities. Although the direct demand model is not intended to provide highly accurate ridership estimates, it can still be used to get order of magnitude estimations to determine the value of further efforts in analyzing these proposals. Post processing can also be used to get an initial indication of the expected route ridership.

Based on the results of the direct demand model, the proposed CT4 route should be implemented. At the proposed headways, the CT4 would require the most additional vehicles (7-8 vehicles during most of the day), but it would also generate the greatest ridership increase per vehicle. The results of the direct demand model suggest that introducing the CT4 service would increase total system ridership by about 2%. At locations served by the CT4, ridership would increase by over 8,000 riders, a 60% increase in ridership. Given that the direct demand model does not distinguish between routes at a location, it is difficult to predict what the actual CT4 ridership would be based on these results. Distributing the change in ridership between routes at locations along the route based on the relative number of trips on each route results in an estimated CT4 ridership of about 4,300-7,000 passengers depending on the distribution method used. Since the CT4 does not run parallel to any other routes for any significant distance, it seems reasonable that the ridership change captured by the route would be on the higher end of the range. For mitigation purposes, the allocation of the ridership impact does not affect the total air quality impact that can be expected.

Ultimately, the CT4 would provide important connections within the MBTA system that are currently missing. Implementation of this route would take longer and there would likely be a lag before reaching equilibrium ridership, but this proposal warrants immediate action due to the large ridership potential. Given the time associated with implementing this route and establishing its ridership base, as well as the short term need for mitigation, the work to implement the CT4 route should begin immediately. Monitoring the performance of the route in parallel with CTPS running their regional demand model for this proposal would also provide data that could be used to analyze the accuracy of both the direct demand model and the CTPS regional model predictions.

Finally, providing public access to the private M2 and EZRide routes would expand the MBTA's capacity with minimal costs to the MBTA. Using a private operator would eliminate concerns over vehicle constraints. Still, there may be some costs associated with partnering with the private operators. The newly introduced routes may also compete with existing MBTA routes as suggested by the fact that in both cases the net system ridership increase predicted by the direct demand model is less than the ridership increase at locations along the study route.

The direct demand model suggests that providing public access to either the M2 or EZRide shuttles would result in a net increase in system-wide ridership of about 0.4%, or about 1,850 passengers after adjusting for AFC undercounting. The two models would also have similar nominal impacts on ridership at locations along the routes, increasing ridership at those locations by about 2,400-2,700 additional passengers. Again, the direct demand model does not distinguish between routes at a location, but distributing the predicted location impacts to routes at joint locations suggests that more of the ridership increase would be concentrated on the EZRide route than on the M2 route. This distinction between the route ridership and the total increase in ridership at all locations is important for planning purposes but is not important for mitigation considerations.

Although the impact of adding these routes into the MBTA system should be analyzed further, the MBTA should begin conversations with both MASCO and the Charles River TMA to gauge how open these organizations would be to a partnership. The MBTA should also start examining the legal issues of such partnerships and begin researching the technological options and requirements for accepting MBTA fares on private operator vehicles.

Given that the actions proposed above are mitigation efforts for the delay of a capital project, funding for the proposed changes should be sourced from the capital budget rather than the operating budget. Some of the proposals, particularly the provision of additional service on the Green Line to Lechmere and the implementation of a new CT4 route could also serve as mitigation for the Longfellow Bridge reconstruction and therefore come out of the highways capital budget.

7.2. Future Research

This thesis focuses on two ridership estimation methods and a select group of proposals for mitigating the delay of the Green Line Extension. Future work could focus on other methodologies as well as improving the methodologies used here.

- Trip rates were discussed in the methodologies section. While many transportation professionals use trip rates analysis, the selection of comparable routes and segments is highly dependent on personal judgment. Although this method is similar to direct demand models, it is more route based and warrants further investigation. Future research could examine methods to make the application of trip rates more robust and the selection of trip rate proxies more quantified.
- Regional models were included in the table of estimation methodology methods (Table 1-1 and Table 3-1) and discussed in the literature review, but they were not utilized in the analysis in this thesis. Comparing the results of a regional model to those of the analyses completed here would help determine when the three methods are and are not comparable.
- The bus elasticity analysis completed for this thesis focused on applying an arc elasticity with the elasticity selected based on initial headways and with a simple fixed sensitivity range. The elasticity selection was based on only one factor (initial headways) and only a small number of headway groups were available (in this case three headway divisions

were used). Further work could be done to make the elasticity model more robust. A more complex model could be developed to provide more fine tuned elasticities and to adjust the elasticity for other characteristics such as peak vs. off peak and urban vs. suburban. Currently elasticities are only applicable to existing routes where current ridership is known, but future work could make elasticity analysis applicable to new routes by combining it with another ridership methodology to establish a base ridership, such as a trip rates model.

- Any changes made to the system as a result of the mitigation requirement should be monitored and the observed change in ridership should be compared to the results of the analysis presented here as well as any other analysis completed. A comparison of the results would help refine when each method can be used appropriately. The data collected could also be used to help refine the analysis above, including the estimation of a rail elasticity based on weekday observations.
- As part of this thesis, a direct demand model was estimated for the MBTA system. However, work on this model could be continued to improve the results. Future research could include testing additional variables, adding network considerations, and expanding the data sets utilized. A base set of variables was tested for this thesis, but one advantage of the direct demand model is the ability to include the impact of many system features. Some variables that were not tested in this iteration but could be considered for future iterations include distance to the next location, bus stop features, and road network and accessibility variables. Means to incorporate more network considerations, particularly parallel vs. perpendicular routes (also known as competing and synergistic routes), could be researched. Similarly, ways to incorporate destinations into the analysis could be considered. The direct demand model in this thesis was also only estimated using data from one day. Future work could test the model on a larger data set and also create separate models for weekends and different time periods of the day. Future iterations of the model could also be estimated correcting for the discrepancy in the time period of the different data sources.
- The final model estimated for the MBTA bus system is unable to do a good job of simultaneously estimating ridership at both low and high ridership locations. As discussed in Chapter 3, piecewise functions and terms with bus trips squared were

tested to improve the fit of the model. Regressions using only a subset of higher ridership locations were also tested but did not readily produce a better model. Further research should seek to develop a more refined model that can more accurately capture ridership at both high and low ridership locations.

- Currently, using the direct demand model developed for the MBTA bus system still involves a lot of manual work, especially when new stops are introduced so that locations and catchment area based variables must be regenerated. The current variable generation process when new stops are added takes approximately one hour to run using a mix of manual and automated steps in both ArcGIS and PostgreSQL. The final model application is then done in Excel. Further work should be done to automate more of this process so that it is easier to apply the model to new proposals.
- The analysis in this thesis focused on three sets of mitigation proposals and the analysis helped conclude that all of the proposals are worth implementation. This work used ridership as a proxy for the environmental impact of the proposals, but the legal requirement for mitigation is an issue of the environmental impact of the GLX, therefore the actual anticipated environmental impact of these proposals still needs to be studied. These proposals also may not be sufficient to meet the full mitigation commitment, therefore other proposals such as the introduction of diesel multiple unit (DMU) services to supplement the commuter rail network should be considered in parallel.
- The work in this thesis also used vehicles required during the peak as an indication of the potential cost associated with the proposals, but additional costs will be associated with all of the proposals. The specific costs of each proposal, both during the peak and at other times of the day, will need to be examined further. Although there are no vehicle costs associated with providing public access to the private M2 and EZRide routes, there are likely to be other costs associated with such partnerships.
- The results of this thesis recommend implementing the CT4 route and partnering with private operators to provide public access to the M2 and the EZRide. In addition to the legal and technological research recommended above for putting MBTA fare equipment on private vehicles, background research on partnerships and contracting elsewhere should be completed. After implementation, ridership along the newly introduced routes should be monitored with the possibility of making minor changes to either the

private routes or neighboring MBTA routes in order to maximize network efficiency. Examples of places for possible efficiencies include coordinating the Route 1 and M2 schedules at shared stations, coordinating the CT2 and the EZRide in order to potentially decrease the number of CT4 trips required, and possibly moving the EZRide Lechmere stop closer to the Green Line Station to take advantage of greater transfer potential with the increase in Green Line service.

- Further work is necessary to analyze the bus service changes required during reconstruction of the rail bridge at Washington Street, after completion of Phases 1 and 2 of the GLX construction and the opening of rail service to Washington Street and Union Square, and after the full opening of the GLX to College Avenue. The proposals presented here focus on the medium term prior to the opening of the Green Line Extension, but after opening each phase of the extension, bus routes in the area of the extension will see a change in bus demand. Some routes will see a change in ridership due to proximity to the GLX and some routes may need to be altered to better connect with the new stations. The ridership estimation methods used in this thesis can be useful in predicting the expected ridership impact of some of the anticipated changes while more robust complementary methods such as use of the CTPS regional model strengthened by parallel monitoring of each phase of implementation may be needed to get a better picture of the system after the completion of the GLX.

The focus of this research has been on using sketch planning methods to quickly develop and evaluate suitable service improvements to mitigate the slippage of the Green Line Extension (GLX) schedule prior to 2014 and within the MBTA peak vehicles constraint. This challenge is similar to the need to prepare service improvements to implement Secretary Davey's policy of achieving a tripling of mode share by transit, bicycling and walking in Massachusetts. Both the MBTA and the regional transit authorities (RTAs) throughout Massachusetts - or in other cities and states preparing climate change mitigation strategies - need new quicker evaluation methods to support action oriented agendas in the face of significant equipment constraints.

Appendix A Rail Layover Time and Trains Required Calculations

Table A-1 Lechmere-Government Center Shuttle Loop Cycle Time Calculation

Period	Run Time	Layover	Cycle Time
Early AM	12.0	2.5	14.5
AM Peak	19.0	3.0	22.0
MidDay	19.0	3.5	22.5
PM Peak	21.0	4.0	25.0
Evening	21.0	4.0	25.0
Late Night	19.0	2.5	21.5

Table A-2 Green Line Branches Layover Options

	Layover Percent of Run Time			C Branch Layover Time (min)				D Branch Layover Time (min)			
				C	E	C-east +		D	E	D-east +	
	E Branch	C Branch	D Branch	% of RT	% of RT	E-west	**Average**	% of RT	% of RT	E-west	**Average**
Early AM	17.2%	16.7%	32.5%	11.5	11.5	12.0	**11.7**	29.0	15.5	28.0	**24.2**
AM Peak	13.2%	13.9%	15.2%	12.5	12.0	11.0	**11.8**	17.0	14.5	15.0	**15.5**
MidDay	15.4%	12.8%	12.8%	11.5	14.0	8.0	**11.2**	13.5	16.0	11.0	**13.5**
PM Peak	17.6%	13.6%	14.8%	12.5	16.5	10.0	**13.0**	16.0	19.0	14.0	**16.3**
Evening	17.6%	12.3%	17.6%	11.5	16.5	14.0	**14.0**	18.5	18.5	21.0	**19.3**
Late Night	6.8%	18.3%	15.2%	15.0	5.5	10.0	**10.2**	15.0	6.5	10.0	**10.5**

Note:

A 5 minute layover is assumed currently at Cleveland Circle for the C branch in the early AM period when no trips in the schedule have layover time

Table A-3 Lechmere - Government Center Loop Shuttle Trains Required Calculation

Period	Headway	Scheduled Cycle Time	Rounded Trains
Early AM	10	14.5	2
AM Peak	5	22.0	5
MidDay	8	22.5	3
PM Peak	5	25.0	5
Evening	10	25.0	3
Late Night	14	21.5	2

Table A-4 C Branch Trains Required Calculations

	Current Headway, Current Route			E Branch Headway, Current Route			
	Headway	Scheduled Cycle Time	Rounded Trains	Headway	Scheduled Cycle Time	Rounded Trains	Change in Trains
Early AM	10.0	70.0	7	10.0	70.0	7	0
AM Peak	6.0	90.0	15	5.0	90.0	18	3
MidDay	10.0	88.0	9	8.0	88.0	11	2
PM Peak	6.5	92.0	15	5.0	92.0	19	4
Evening	6.5	91.0	14	9.5	91.0	10	(4)
Late Night	13.5	84.0	7	13.5	84.0	7	0

	E Branch Headway, Extended Route to Lechmere Layover = Average of Three Methods			
	Headway	Scheduled Cycle Time	Rounded Trains	Change in Trains
Early AM	10.0	79.7	8	1
AM Peak	5.0	102.8	21	6
MidDay	8.0	101.2	13	4
PM Peak	5.0	106.0	22	7
Evening	9.5	107.0	12	(2)
Late Night	13.5	93.2	7	0

	E Branch Headway, Extended Route to Lechmere											
	Layover = C Branch Percent of Run Time				Layover = E Branch Percent of Run Time				Layover = C-East + E-West Layover			
	Head-way	Cycle Time	Rounded Trains	Total Change in Trains	Head-way	Cycle Time	Rounded Trains	Total Change in Trains	Head-way	Cycle Time	Rounded Trains	Total Change in Trains
Early AM	10.0	79.5	8	1	10.0	79.5	8	1	10.0	80.0	8	1
AM Peak	5.0	103.5	21	6	5.0	103.0	21	6	5.0	102.0	21	6
MidDay	8.0	101.5	13	4	8.0	104.0	13	4	8.0	98.0	13	4
PM Peak	5.0	105.5	22	7	5.0	109.5	22	7	5.0	103.0	21	6
Evening	9.5	104.5	11	(3)	9.5	109.5	12	(2)	9.5	107.0	12	(2)
Late Night	13.5	98.0	8	1	13.5	88.5	7	0	13.5	93.0	7	0

Table A-5 D Branch Trains Required Calculations

	Current Headway, Current Route			E Branch Headway, Current Route			
	Headway	Scheduled Cycle Time	Rounded Trains	Headway	Scheduled Cycle Time	Rounded Trains	Change in Trains
Early AM	11.0	102.0	10	10.0	102.0	11	1
AM Peak	6.0	106.0	18	5.0	106.0	22	4
MidDay	10.5	97.0	10	8.0	97.0	13	3
PM Peak	5.5	101.0	19	5.0	101.0	21	2
Evening	10.0	100.0	10	9.5	100.0	11	1
Late Night	13.0	91.0	7	13.5	91.0	7	0

	E Branch Headway, Extended Route to Lechmere Layover = Average of Three Methods			
	Headway	Scheduled Cycle Time	Rounded Trains	Change in Trains
Early AM	10.0	113.2	12	2
AM Peak	5.0	126.5	26	8
MidDay	8.0	118.5	15	5
PM Peak	5.0	125.3	26	7
Evening	9.5	125.3	14	4
Late Night	13.5	108.5	9	2

	E Branch Headway, Extended Route to Lechmere											
	Layover = D Branch Percent of Run Time				Layover = E Branch Percent of Run Time				Layover = C-East + E-West Layover			
	Head-way	Cycle Time	Rounded Trains	Total Change in Trains	Head-way	Cycle Time	Rounded Trains	Total Change in Trains	Head-way	Cycle Time	Rounded Trains	Total Change in Trains
Early AM	10.0	118.0	12	2	10.0	104.5	11	1	10.0	117.0	12	2
AM Peak	5.0	128.0	26	8	5.0	125.5	26	8	5.0	126.0	26	8
MidDay	8.0	118.5	15	5	8.0	121.0	16	6	8.0	116.0	15	5
PM Peak	5.0	125.0	25	6	5.0	128.0	26	7	5.0	123.0	25	6
Evening	9.5	124.5	14	4	9.5	124.5	14	4	9.5	127.0	14	4
Late Night	13.5	113.0	9	2	13.5	104.5	8	1	13.5	108.0	8	1

Appendix B Transfer Penalty

Guo (2008; Guo and Wilson, 2004) used a path-choice approach based on revealed preferences to calculate the penalty that passengers attribute to a transfer. Guo's work focused on passengers with final destinations in downtown Boston. This area includes four stations offering rail to rail transfers: Downtown Crossing, Government Center, Park Street and State Street. The trips analyzed could have been taken using two alternative paths: one including a transfer, and one excluding a transfer and thereby requiring additional walking. A series of models were estimated to determine the transfer penalty in terms of walk time.

Guo ultimately presented five main model specifications. The results of these models can be found in Table B-1. Models A and B are most relevant given the situation being analyzed here. The base model (Model A) includes a transfer constant, walking time savings, and extra in-vehicle time. The resulting transfer penalty is 7.3 minutes walking time (or 10.6 minutes in-vehicle travel time). The second model of interest (Model B) adds station dummy variables to the base model. Park Street was used as the base case because it is considered the best transfer station, and dummy variables were included for the other three stations (Downtown Crossing, Government Center and State Street). The transfer penalties predicted by this model were 4.8 minutes for Park, 8.6 minutes for Downtown Crossing, 9.0 minutes for Government Center, and 9.7 minutes for State Street. If State Street is excluded because it has different characteristics than the remaining three stations and is not on the Green Line, the remaining three stations have an average transfer penalty of 7.5 minutes of walking time.

Subsequent models (Models C and D) account for differences between stations by including station factors. These models were able to account for most of the station variation. However the Government Center dummy variable remains significant, implying that it is inherently a worse transfer station. For the purposes of this analysis, the pure dummy variable model is considered sufficient. The final models estimated by Guo but not used here look at the pedestrian environment (Model E) and trip and demographic characteristics (Model F).

Averaging the transfer penalties estimated by the base model and the station dummy variables model (excluding the State Street results), a transfer penalty of 7.4 minutes walking time is obtained. These two models do not differentiate between peak and off-peak, but the other model results show that the transfer penalty is greater in the off-peak. Assuming walk time and wait time are weighted equally and that the wait time is, on average, half of the headway, adding or removing a transfer is equivalent to increasing or decreasing the headway by 14.9 minutes.

One shortcoming of using Guo's analysis here is that it does not differentiate between the different branches of the Green Line. There are two features of Green Line transfers that are incorrectly captured by Guo's analysis. The first feature is that Green Line frequency is taken as the joint headway of all of the branches rather than the individual branch headways. This does not impact Guo's analysis since he only looks at trips with a potential transfer and a final destination in Downtown Boston, so all of the branches serve the relevant stations. However, Guo also therefore does not analyze transfers between the Green Line branches since they are not necessary in the trips being studied. It is likely that intra-line transfers would be subject to a smaller penalty than inter-line transfers since they will generally require less walking (often these transfers are on the same platform and no walk is required along with no level change). Since the focus of the analysis in this thesis is on transfers between the Green Line branches, a lower transfer penalty is assumed and a sensitivity range is applied. For the purpose of the intra-line transfers in this thesis, analysis is conducted using a transfer penalty range of four to six minutes and the equivalent headway reduction of eight to twelve minutes is used for the potential one-seat ride trips.

Table B-1 Model Estimation Results (Guo, 2008, p. 108)

Variables	Model A	Model B	Model C	Model D		Model E	
				Peak Hour	Non-Peak Hour	Peak Hour	Non-Peak Hour
Transfer Constant	-2.29***	-1.39***	-0.99***	-1.08***		-1.39***	
Transfer Path Variables							
Walking Time Savings (minute)	0.316***	0.289***	0.285***	0.315***	0.220***	0.286***	0.194***
Extra In-vehicle Time (minute)	-0.216***	-0.21***	-0.20***	-0.24***	-0.17***	-0.24***	-0.16***
Transfer Attributes							
Transfer walking time (minute)			-1.13***	-1.39***	-1.22***	-1.28***	-0.99***
Transfer waiting time (minute)			-0.16**		-0.29***		-0.27***
Assisted level change			0.27**	0.39**	0.48***	0.39***	0.45*
Government Center (GOVT)		-1.21***		-1.28***	-1.26*	-1.20***	-1.28**
State Street (STAT)		-1.41***					
Downtown Crossing (DTXG)		-1.09***					
Pedestrian Environment Variables							
Extra PFP density							-0.20**
Extra sidewalk width						-0.03***	-0.03***
Boston Common						0.73***	0.79***
Beacon Hill						-0.73**	-1.07***
# of Observations	3140	3140	3140	2173	967	2173	967
Adjusted ρ^2	0.339	0.369	0.385	0.414	0.357	0.425	0.376

Note 1. ***: $P < 0.001$, **: $P < 0.05$, *: $P < 0.1$

2. In model A, if the walking time saving is replaced by total travel time saving, the adjusted ρ^2 is 0.355

3. Coefficients that are statistically insignificant ($P > 0.1$) are not shown in the table.

4. Adjusted ρ^2 is the goodness-of-fit of the model. A higher value indicates an improved explanatory power of the model to the dataset

Appendix C MBTA System Ridership Growth

Figure C-1 Average Daily Orange Line Ridership by Month

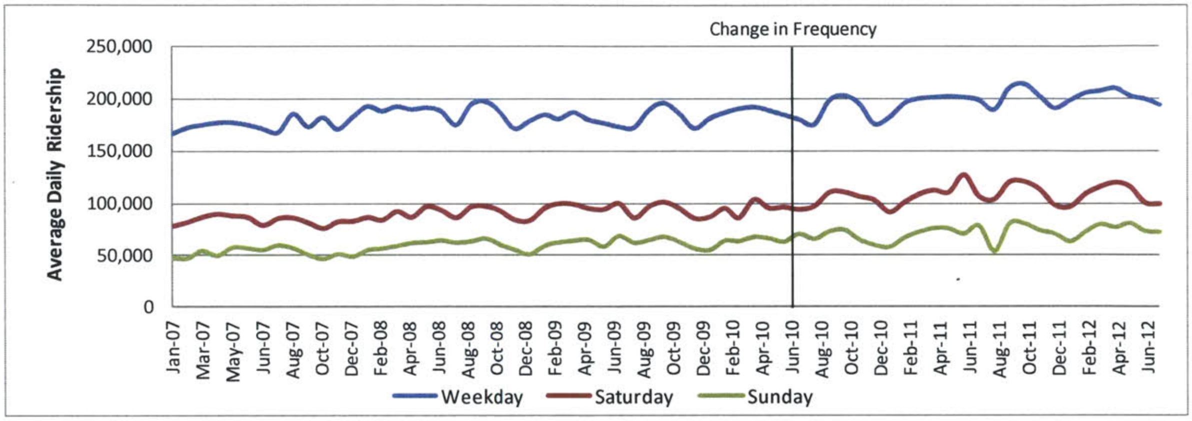


Figure C-2 Month-Over-Month Change in Orange Line Ridership

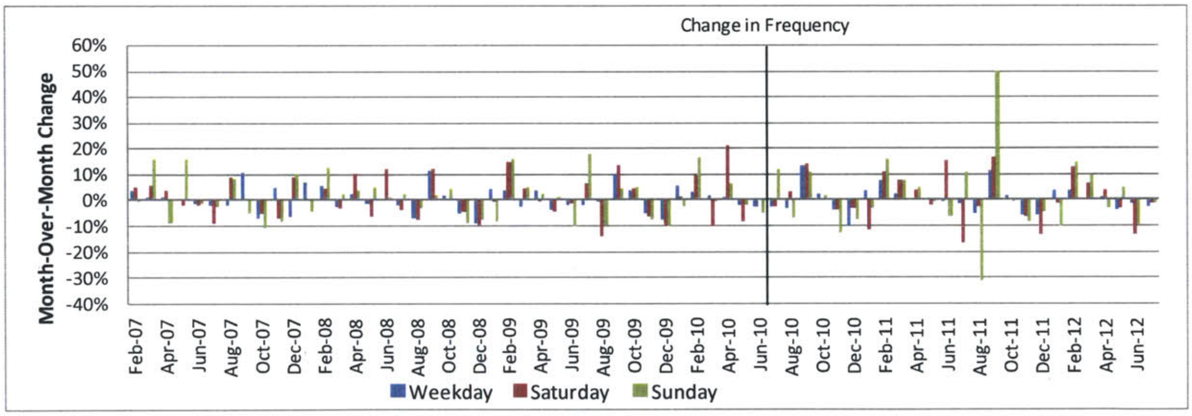


Figure C-3 Year-Over-Year Change in Orange Line Ridership by Month (same as Figure 4-2)

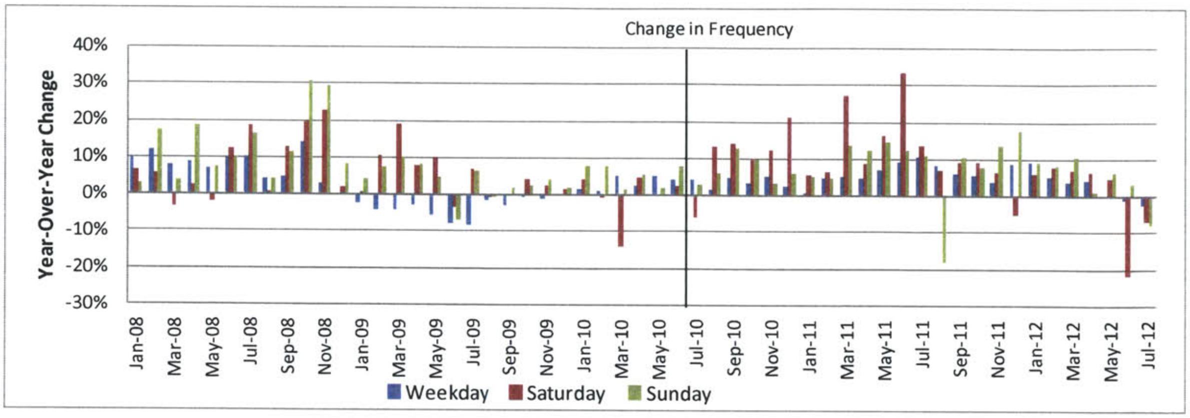
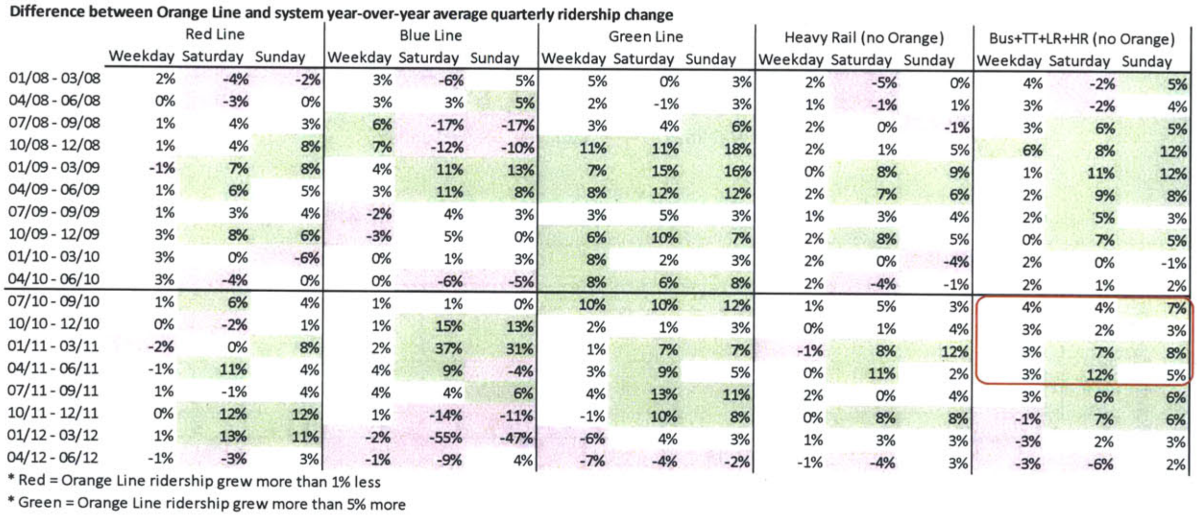


Table C-1 Quarterly Year-Over-Year Orange Line Ridership Growth Compared to System Ridership Growth



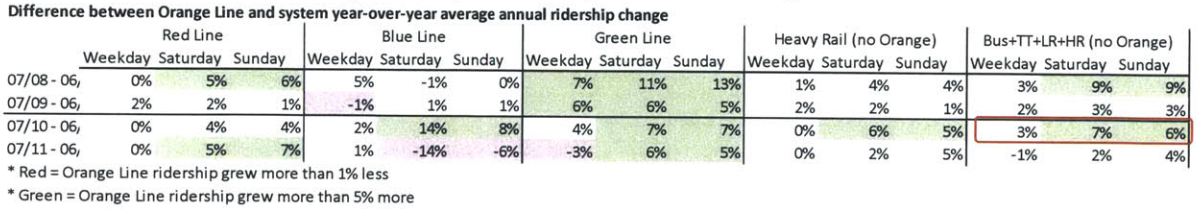
Difference between Orange Line and system year-over-year average quarterly ridership change

	Red Line			Blue Line			Green Line			Heavy Rail (no Orange)			Bus+TT+LR+HR (no Orange)		
	Weekday	Saturday	Sunday	Weekday	Saturday	Sunday	Weekday	Saturday	Sunday	Weekday	Saturday	Sunday	Weekday	Saturday	Sunday
01/08 - 03/08	2%	-4%	-2%	3%	-6%	5%	5%	0%	3%	2%	-5%	0%	4%	-2%	5%
04/08 - 06/08	0%	-3%	0%	3%	3%	5%	2%	-1%	3%	1%	-1%	1%	3%	-2%	4%
07/08 - 09/08	1%	4%	3%	6%	-17%	-17%	3%	4%	6%	2%	0%	-1%	3%	6%	5%
10/08 - 12/08	1%	4%	8%	7%	-12%	-10%	11%	11%	18%	2%	1%	5%	6%	8%	12%
01/09 - 03/09	-1%	7%	8%	4%	11%	13%	7%	15%	16%	0%	8%	9%	1%	11%	12%
04/09 - 06/09	1%	6%	5%	3%	11%	8%	8%	12%	12%	2%	7%	6%	2%	9%	8%
07/09 - 09/09	1%	3%	4%	-2%	4%	3%	3%	5%	3%	1%	3%	4%	2%	5%	3%
10/09 - 12/09	3%	8%	6%	-3%	5%	0%	6%	10%	7%	2%	8%	5%	0%	7%	5%
01/10 - 03/10	3%	0%	-6%	0%	1%	3%	8%	2%	3%	2%	0%	-4%	2%	0%	-1%
04/10 - 06/10	3%	-4%	0%	0%	-6%	-5%	8%	6%	8%	2%	-4%	-1%	2%	1%	2%
07/10 - 09/10	1%	6%	4%	1%	1%	0%	10%	10%	12%	1%	5%	3%	4%	4%	7%
10/10 - 12/10	0%	-2%	1%	1%	15%	13%	2%	1%	3%	0%	1%	4%	3%	2%	3%
01/11 - 03/11	-2%	0%	8%	2%	37%	31%	1%	7%	7%	-1%	8%	12%	3%	7%	8%
04/11 - 06/11	-1%	11%	4%	4%	9%	-4%	3%	9%	5%	0%	11%	2%	3%	12%	5%
07/11 - 09/11	1%	-1%	4%	4%	4%	6%	4%	13%	11%	2%	0%	4%	3%	6%	6%
10/11 - 12/11	0%	12%	12%	1%	-14%	-11%	-1%	10%	8%	0%	8%	8%	-1%	7%	6%
01/12 - 03/12	1%	13%	11%	-2%	-55%	-47%	-6%	4%	3%	1%	3%	3%	-3%	2%	3%
04/12 - 06/12	-1%	-3%	3%	-1%	-9%	4%	-7%	-4%	-2%	-1%	-4%	3%	-3%	-6%	2%

* Red = Orange Line ridership grew more than 1% less

* Green = Orange Line ridership grew more than 5% more

Table C-2 Year-Over-Year Orange Line Average Annual Ridership Growth Compared to System Average Annual Ridership Growth



Difference between Orange Line and system year-over-year average annual ridership change

	Red Line			Blue Line			Green Line			Heavy Rail (no Orange)			Bus+TT+LR+HR (no Orange)		
	Weekday	Saturday	Sunday	Weekday	Saturday	Sunday	Weekday	Saturday	Sunday	Weekday	Saturday	Sunday	Weekday	Saturday	Sunday
07/08 - 06,	0%	5%	6%	5%	-1%	0%	7%	11%	13%	1%	4%	4%	3%	9%	9%
07/09 - 06,	2%	2%	1%	-1%	1%	1%	6%	6%	5%	2%	2%	1%	2%	3%	3%
07/10 - 06,	0%	4%	4%	2%	14%	8%	4%	7%	7%	0%	6%	5%	3%	7%	6%
07/11 - 06,	0%	5%	7%	1%	-14%	-6%	-3%	6%	5%	0%	2%	5%	-1%	2%	4%

* Red = Orange Line ridership grew more than 1% less

* Green = Orange Line ridership grew more than 5% more

Appendix D Green Line Elasticity Results

AM Peak

Table D-1 Green Line Ridership Elasticity - AM Peak (Transfer Penalty = 8min)

	Origin			Destination		
	Extend D Branch	Extend C Branch	Loop Shuttle	Extend D Branch	Extend C Branch	Loop Shuttle
Initial Ridership	1,134	1,134	1,134	985	985	985
Initial Headway	5.0	5.0	5.0	5.0	5.0	5.0
New Weighted Average Headway	2.4	2.5	2.7	2.4	2.4	2.7
Projected Ridership						
Low Elasticity (e = -0.23)	1,334	1,324	1,299	1,155	1,157	1,129
% Change	*17.6%*	*16.7%*	*14.6%*	*17.2%*	*17.4%*	*14.6%*
Midium Elasticity (e = -0.33)	1,432	1,416	1,379	1,238	1,242	1,198
% Change	*26.3%*	*24.9%*	*21.6%*	*25.6%*	*26.0%*	*21.6%*
High Elasticity (e = -0.43)	1,538	1,516	1,464	1,328	1,333	1,272
% Change	*35.6%*	*33.7%*	*29.1%*	*34.8%*	*35.3%*	*29.1%*

Table D-2 Green Line Ridership Elasticity - AM Peak (Transfer Penalty = 10min)

	Origin			Destination		
	Extend D Branch	Extend C Branch	Loop Shuttle	Extend D Branch	Extend C Branch	Loop Shuttle
Initial Ridership	1,134	1,134	1,134	985	985	985
Initial Headway	5.0	5.0	5.0	5.0	5.0	5.0
New Weighted Average Headway	2.3	2.4	2.7	2.3	2.3	2.7
Projected Ridership						
Low Elasticity (e = -0.23)	1,347	1,333	1,299	1,165	1,168	1,129
% Change	*18.8%*	*17.5%*	*14.6%*	*18.2%*	*18.6%*	*14.6%*
Midium Elasticity (e = -0.33)	1,453	1,431	1,379	1,253	1,259	1,198
% Change	*28.1%*	*26.2%*	*21.6%*	*27.2%*	*27.8%*	*21.6%*
High Elasticity (e = -0.43)	1,568	1,537	1,464	1,350	1,357	1,272
% Change	*38.2%*	*35.5%*	*29.1%*	*37.0%*	*37.8%*	*29.1%*

Table D-3 Green Line Ridership Elasticity – AM Peak (Transfer Penalty = 12min)

	Origin			Destination		
	Extend D Branch	Extend C Branch	Loop Shuttle	Extend D Branch	Extend C Branch	Loop Shuttle
Initial Ridership	1,134	1,134	1,134	985	985	985
Initial Headway	5.0	5.0	5.0	5.0	5.0	5.0
New Weighted Average Headway	2.2	2.3	2.7	2.2	2.2	2.7
Projected Ridership						
Low Elasticity (e = -0.23)	1,361	1,343	1,299	1,175	1,180	1,129
% Change	*20.0%*	*18.4%*	*14.6%*	*19.3%*	*19.7%*	*14.6%*
Midium Elasticity (e = -0.33)	1,475	1,446	1,379	1,270	1,277	1,198
% Change	*30.0%*	*27.5%*	*21.6%*	*28.9%*	*29.6%*	*21.6%*
High Elasticity (e = -0.43)	1,599	1,558	1,464	1,373	1,383	1,272
% Change	*41.0%*	*37.4%*	*29.1%*	*39.3%*	*40.4%*	*29.1%*

All Day

Table D-4 Green Line Ridership Elasticity - All Day (Transfer Penalty = 8min)

	Origin			Destination		
	Extend D Branch	Extend C Branch	Loop Shuttle	Extend D Branch	Extend C Branch	Loop Shuttle
Initial Ridership	5,070	5,070	5,070	5,123	5,123	5,123
Initial Headway	7.8	7.8	7.8	7.8	7.8	7.8
New Weighted Average Headway	3.9	4.0	4.2	3.9	4.0	4.2
Projected Ridership						
Low Elasticity (e = -0.23)	5,904	5,860	5,828	5,955	5,946	5,881
% Change	*16.5%*	*15.6%*	*15.0%*	*16.2%*	*16.1%*	*14.8%*
Midium Elasticity (e = -0.33)	6,311	6,244	6,194	6,360	6,347	6,247
% Change	*24.5%*	*23.2%*	*22.2%*	*24.2%*	*23.9%*	*22.0%*
High Elasticity (e = -0.43)	6,749	6,655	6,586	6,797	6,777	6,638
% Change	*33.1%*	*31.3%*	*29.9%*	*32.7%*	*32.3%*	*29.6%*

Table D-5 Green Line Ridership Elasticity – All Day (Transfer Penalty = 10min)

	Origin			Destination		
	Extend D Branch	Extend C Branch	Loop Shuttle	Extend D Branch	Extend C Branch	Loop Shuttle
Initial Ridership	5,070	5,070	5,070	5,123	5,123	5,123
Initial Headway	7.8	7.8	7.8	7.8	7.8	7.8
New Weighted Average Headway	3.8	4.0	4.2	3.8	3.9	4.2
Projected Ridership						
Low Elasticity (e = -0.23)	5,942	5,886	5,828	5,992	5,978	5,881
% Change	*17.2%*	*16.1%*	*15.0%*	*17.0%*	*16.7%*	*14.8%*
Midium Elasticity (e = -0.33)	6,370	6,283	6,194	6,418	6,397	6,247
% Change	*25.7%*	*23.9%*	*22.2%*	*25.3%*	*24.9%*	*22.0%*
High Elasticity (e = -0.43)	6,833	6,711	6,586	6,878	6,848	6,638
% Change	*34.8%*	*32.4%*	*29.9%*	*34.3%*	*33.7%*	*29.6%*

Table D-6 Green Line Ridership Elasticity - All Day (Transfer Penalty = 12min)

	Origin			Destination		
	Extend D Branch	Extend C Branch	Loop Shuttle	Extend D Branch	Extend C Branch	Loop Shuttle
Initial Ridership	5,070	5,070	5,070	5,123	5,123	5,123
Initial Headway	7.8	7.8	7.8	7.8	7.8	7.8
New Weighted Average Headway	3.7	3.9	4.2	3.7	3.8	4.2
Projected Ridership						
Low Elasticity (e = -0.23)	5,982	5,912	5,828	6,030	6,012	5,881
% Change	*18.0%*	*16.6%*	*15.0%*	*17.7%*	*17.4%*	*14.8%*
Midium Elasticity (e = -0.33)	6,431	6,323	6,194	6,477	6,448	6,247
% Change	*26.9%*	*24.7%*	*22.2%*	*26.4%*	*25.9%*	*22.0%*
High Elasticity (e = -0.43)	6,919	6,767	6,586	6,961	6,920	6,638
% Change	*36.5%*	*33.5%*	*29.9%*	*35.9%*	*35.1%*	*29.6%*

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