Negotiating the Neighborhood: Modeling the Relationship Between Built Environment and Transit Choice

by

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B.Tech. Civil Engineering
Indian Institute of Technology Bombay, 2012

Submitted to the Department of Civil and Environmental Engineering
in partial fulfillment of the requirements for the degree of

Master of Science in Transportation

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

September 2014

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Abstract

This thesis examines the relationship between land use and built environment variables and peoples' mode choice for home-based work trips. Many studies recommend that factors like densification, mixed land use, optimal neighborhood design and proximity to transit can reduce auto-based trips and also decrease the average number of trips per person. From the point of view of city planning, such transit oriented development can guide development, help to contain sprawl, increase economic benefits and has the potential of making cities more sustainable. To understand if the built environment and land use have major impact on an individual's mode choice for work trips, multinomial and nested logit models have been estimated for work trips of people living in the Boston Metropolitn area. The analysis shows that mode choice primarily depends on trip attributes and household characteristics. Built environment factors are secondary for such daily trips. Among transit modes, the built environment and land use factors affect bus and rail modes almost similarly for work trips. Factors of the built environment which are more visible, like high density and a more mixed land use, may increase the likelihood of choosing bus over rail modes by a small amount.

Thesis Supervisor: P. Christopher Zegras
Title: Associate Professor of Department of Urban Studies & Planning

Acknowledgments

I cannot thank my mother enough for her love and support, especially in the past two months. From her, I have learnt how to be strong and fight my own battles. This thesis would not have been possible without her presence. I love you mum.

I would like to express my heartfelt gratitutde to my thesis supervisor, Prof. P. Christopher Zegras, for being one of the most understanding, patient and supportive persons. His encouragement and advice over the past one year has kept me motivated throughout and his calm has compensated for my occasional panic states. I have learnt a lot from him and his lectures, academically and otherwise. I could not have hoped for a better advisor. Again, thank you so much Chris!

I am grateful to the Across Latitudes and Cultures BRT Center of Excellence (ALC-BRT CoE) for selecting me for the Masters Thesis Fellowship to support my thesis research. I hope this work will be a step further in understanding how we can design places to encourage BRTOD.

I am indebted to Amir Akhavan at MAPC for providing me with the land use data and for being available to answer my questions.

I thank Prof. Murga for providing me with the technical know-how of TransCAD. His course was a great learning experience and my research would not have been as smooth without it. I also thank Prof. Sarah Williams for, without her course, my GIS skills would have been close to nonexistent.

To Michael, thank you so much for going out of your way to help. I owe you one for all the troubleshooting you helped me with.

Thank you Ankur, Himani, Parnika, Rasha, Rushabh, Sanket and, especially, Krishna. This year would not have been half as memorable had it not been for all of you. Shubham, thank you for putting up with all me and my panic calls and always being there. Kashyap, thank you for teaching me to dream.

Lastly, a big thanks to Uditi, Tejas and Mervin. You believed in me, kept me grounded and never let me forget the big picture.

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Chapter 1

Introduction

> Everything is simpler than you think and at the same time more complex than you imagine
> - Johann Wolfgang von Goethe

The concept of transit oriented development (TOD) has become very popular in recent years. TOD involves 'orienting' 'development' towards 'transit (stations)' in an attempt to create development forms and designs that increase transits attractiveness, thereby reducing automobile use and its negative externalities. However, the goals of TOD go beyond just transportation.

TOD's dense, mixed land use and pedestrian-friendly environment rejuvenates neighborhoods and may promote cultural diversity and encourage more face-to-face interactions. Getting people out of their automobiles can create a healthy and livable community. From the point of view of city planning, TODs help guide development, contain sprawl and increase economic benefits in the affected areas. Overall, TODs have the potential of making cities more sustainable. However, the basic assumption behind achieving the above mentioned benefits is that TOD influences peoples' mode choices, increases the share of non-motorized means like walking and biking and makes transit more attractive compared to automobiles. While a single definition of transit oriented development does not exist, it can generally be characterized by the three Ds of the built environment (?): high density, diverse land use and a street network design that attracts more pedestrians, while at the same time, making it unattractive for automobiles. The original three Ds framework was later expanded to include factors relating to destination accessibility, distance to transit, demand management and demographics (Ewing and Cervero, 2001, Ewing et al., 2009). The quality of transit its frequency, reliability, safety, fares, hours of operation and other factors also determine the success of TOD. Limited and/or costly parking and low speed limits also disincentivize the use of automobiles and make transit relatively more attractive. Finally, an area's demographics will certainly play a role in transit ridership. TOD may, in fact, attract people more inclined to use transit, such as childless couples, foreign immigrants, lower income people, and captive transit riders. Another factor in considering the effect of TOD on mode choice is the type of transit around which the TOD is centered. TOD has mainly been focused around different rail modes, i.e.: subway, light rail and commuter rail. More recently, however, bus-based TODs are getting attention, especially with many North American and Latin American cities developing TOD around bus stations and bus rapid transit (BRT) systems. Bus Rapid Transit (BRT) is a bus-based transit system that is expected to replicate the high capacity and high performance of urban rail transit but at a relatively lower cost. The Institute for Transportation and Development Policy defines BRT as a high quality bus-based transit system that delivers fast, confortable and cost-effective urban mobility through the provision of segregated right-of-way, rapid and frequent operations and excellence in marketing and customer service (Wright and Hook, 2007). Dedicated right-of-way is an important feature that makes BRT competitive with rail and automobiles and distinguishes it from regular bus systems. Lower or moderate quality BRT services that do not satify all criteria of a high-end BRT are often called 'BRT Lite'. BRT Lite offers some form of priority but not fully segregated busways and often has simpler bus shelters (Cervero, 2013).

Chatman (2013) found that auto trip frequencies and commuting decrease in the northern New Jersey area due to TOD-like development irrespective of the accessibility to a rail station. He observed that having a bus service with similarly dense built environment and less parking availability affected travel patterns, indicating that a bus based or rail based TOD has the same effect. Apart from this, there has been very little research on whether the type of transit in TOD affects mode choice.

1.1 Research Question

Accounting for the impact of built environment on mode choice is not easy, although it has been a focus of study for decades. According to some, the role of the built environment is captured in differences in travel time, cost and comfort and does not need to be accounted for separately. However, some researchers feel that some land use and built environment factors do not manifest themselves in observable trip attributes and have a separate influence on mode choice. With the continuing interest in and importance of TOD, and growing prevalence of BRT, understanding the behavioral impacts of TOD and possible variations across transit modes, becomes even more important.

Through my thesis, I try to examine some key issues and answer questions related to mode choice and TOD.

1. How do the various Ds of transit oriented development (density, diversity, design, distance to transit, destination characteristics) affect peoples' mode choice? Which of these factors are most relevant?

2. Does the type of transit affect the performance of transit oriented development with respect to mode choice? If yes, how should a bus based transit oriented development differ from a rail based transit oriented development?

1.2 Research Approach

Mode choice modeling is the third stage of the traditional four stage travel demand modeling. It assumes that users have a particular utility associated with each mode of transport that is based on the trip attributes, characteristics of the mode, the user's socioeconomic and demographic characteristics and on the built environment of the trip origin and destination. The assumption is that users select the mode which maximizes their utility. In the case of probabilistic utilities, the user has some non-zero probability of choosing each mode. I will specify and estimate a random utility-based nested logit model to calculate the probabilities of choosing a particular mode to assess the degree to which the built environment significantly plays a role, and whether these relationships vary by type of transit mode.

My study area for this research is a part of the Boston Metropolitan Area. The Boston region has diverse demographics and transportation infrastructure with a reasonably vast network of public transit. It has a subway system and a light rail system with a total length of 64 miles. It also has a commuter rail network. Apart from this, there is a regular bus system and a BRT Lite system. There are also ferry services and commuter boats that connect towns on the eastern edge of the region. The public transit system is mainly operated by the Massachusetts Bay Transport Authority (MBTA). Figure 1-1 shows a map of the transit system.

Many areas of the region are highly walkable and a growing bike lane network is spreading out across Boston and its neighboring cities and towns. At the same time, a large number of people use automobiles for their daily travel. The built environment is also fairly varied. There are several pockets of high density areas apart from downtown Boston with different extents of mixed land use. Some areas have less development and lower densities but are connected to transit. There is a good divide between choice riders and captive riders. All these factors make Boston a favorable study area for the purpose of my work.

1.3 Thesis Structure

My thesis is divided into six chapters. The next chapter focuses on understanding the concept of transit oriented development. It focuses on previous studies of various built environment measures, mode characteristics and their effect on mode choice, the effect of transit oriented development on trip patterns and peoples' travel behavior. It also discusses some previous relevant research done for the Boston metropolitan

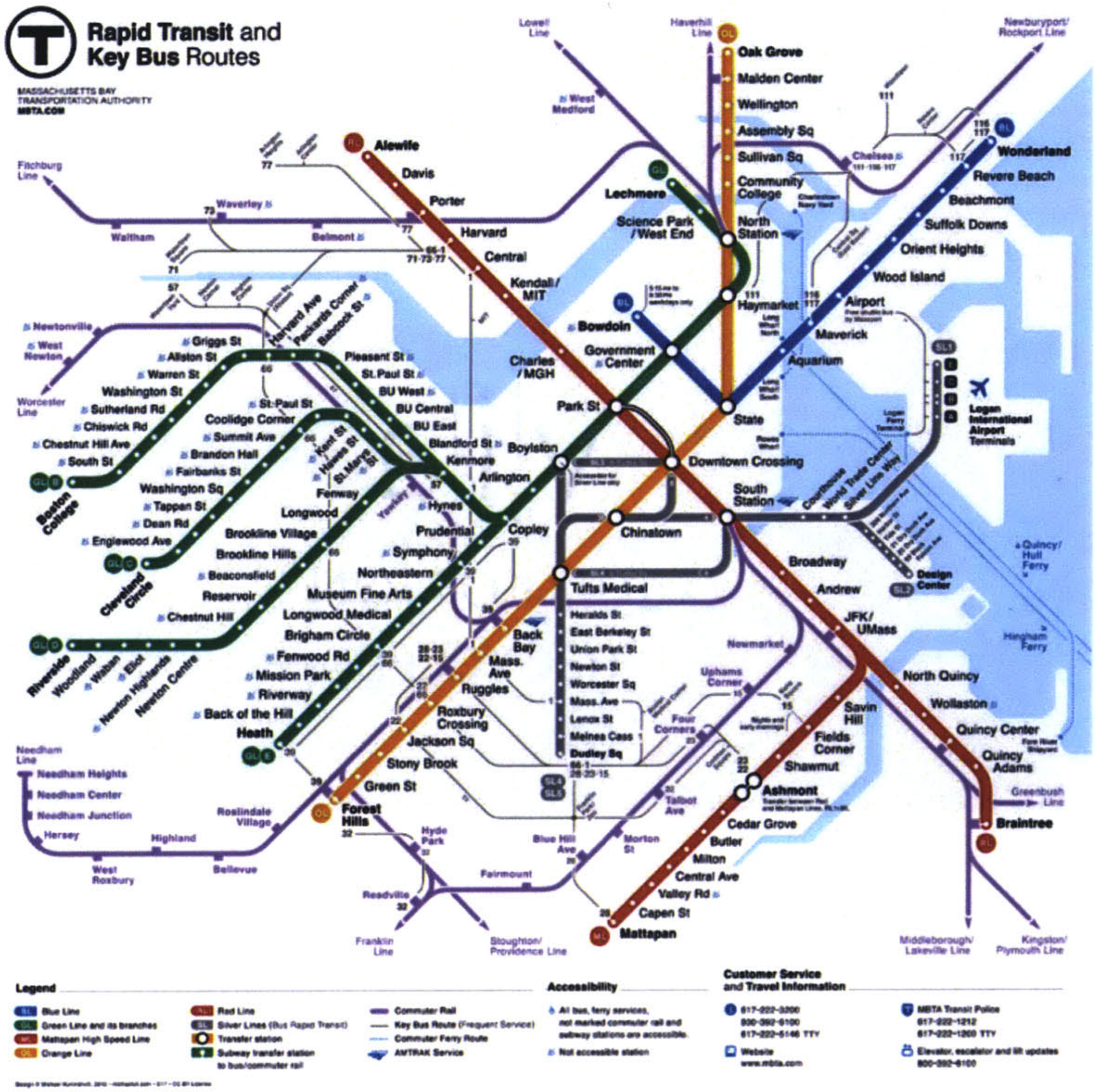

Figure 1-1: MBTA system map

area.

In chapter three, I present the context of Boston where I describe the demographics and travel patterns of the people.

Chapter four focuses on the basic theory behind discrete choice modeling and discusses the concept of multinomial logit (MNL) models and nested logit models for mode choice modeling. In this chapter, I describe the data used for the study and its sources.

Chapter five presents the MNL and nested logit models I use for my research.

Finally, I present the conclusion of my research in chapter six. I also briefly outline the limitations and future areas for research in this chapter.

Chapter 2

Literature Review

2.1 Land Use as a Function of Transportation

Theoretically, transportation influences the land use in an area, mainly by influencing accessibility. Higher accessibility from a new transportation service attracts businesses and commerce to the area. Land value also increases. The gradual change in land use attracts more people to the area, thus influencing the transportation system. Thus, there is an interaction between land use and transportation where one impacts the other and vice versa. Public transportation clearly plays an important potential role here.

Studies on these interactions have mixed conclusions. Knight and Trygg (1977) found that rapid transit cannot have substantial land use impacts unless it is supported by other factors such as policy, availability of developable land and growing regional economic development. Supporting the above conclusion, Cervero and Landis (1997) showed that even after twenty years of its service, the Bay Area Rapid Transit (BART) system only managed to create small localized effects on land use around the stations. It did not have the expected large effect on overall land use.

However, given the right conditions, transit can have a major impact on land use. Beyond accessibility and related effects on land values and economic development, public transportation may enable clustering of economic activities in an area as firms may choose to relocate near transit stations due to the better infrastructure, easier and cheaper movement of people and goods. Thus, public transportation may give rise to positive agglomeration effects that benefit firms from sharing of labor and resources, knowledge spillovers and other intangible goods. Studies on the land use effects of transit often focus on land values and property prices. Cervero and Kang (2011), for example, report that converting a regular bus route to a median-lane bus rapid transit system in Seoul led to an increase in land prices for residential and non-residential land. It also led to an increase in residential density as property owners converted single family residences to high density apartments and condominiums. Rodríguez and Mojica (2009) also showed that extension of an existing bus rapid transit line led to the same increase in property values within 500m and between 500m to 1km of the BRT. This shows how public transportation effects go beyond just the expansion areas. Several other examples of change in property values due to transit in North America exist (Knaap et al., 2001, Hess and Almeida, 2007, Duncan, 2010).

2.2 Transportation as a Function of Land Use

The influence of land-use and built environment on transportation has also been studied extensively (Boarnet and Crane, 2001b, Crane, 2000, Boarnet, 1998, Nasri and Zhang, 2013). Most researchers acknowledge the complexity of the study. Often times, changes in travel patterns are due to a combined effect of various factors including built environment, transit level of service, choice of destination and self-selection. It is difficult to single out a particular factor alone for an observed change.

Badoe and Miller (2000) found mixed results from their review of several studies aimed at analyzing land-use and transportation interactions and their policy implications. Some studies reviewed by them reported a significant impact of density, traditional neighborhood designs and mixed land use on travel behavior. Others reported only marginal effects of land use and built environment. According to Badoe and Miller, the mixed conclusions are mainly due to poor data and/or methodological weaknesses. One of the early studies identifying impacts of land use on transportation was by Pushkarev et al. (1977) who considered distance from downtown, size of non-residential floor space in downtown and residential densities to financially justify transit investments. Bus systems were found to be more effective in low density areas. Smith (1984) showed that transit usage was influenced by high residential densities and the two could be mutually supportive. A similar conclusion was drawn by Dunphy and Fisher (1996) who used the Federal Highway Administration statistics to find that high density regions had a lesser tendency for driving and were positively correlated with transit usage.

However, the above studies did not consider other factors such as mixed land uses or neighborhood designs which might influence travel patterns. Kockelman (1997) investigated the influence of measures of urban form on household vehicle kilometers traveled, auto ownership and mode choice in the San Francisco Bay Area. She found that after controlling for demographic characteristics, measures of land-use mix, land-use balance and accessibility had a significant impact on travel behavior. However, density had a negligible impact after controlling for accessibility. ? defined the term the 'three Ds' density, diversity and design for characterizing the built environment. They developed models relating trip rates, mode choice and VMT in San Francisco to these three Ds. It was found that high residential density, a diverse mix of land use and good neighborhood street design reduce trip rates and encourage non-auto travel. Though the effects were marginal, these factors were statistically significant in the model. Neighborhoods with grid street structures and restricted parking were found to have the lowest vehicle miles traveled (VMT). In another study for United States metropolitan areas using the American Housing Survey data, Cervero (1996) found that presence of retail activities within 300 feet of residence encouraged transit use, walking and biking. The presence of commercial land uses was also correlated with low vehicle ownership rate and shorter commuting distances among residents of a mixed use neighborhood. Destination accessibility and distance to transit are dimensions that were later included to further characterize the built environment for travel behavior research (Ewing and Cervero, 2010, Ewing et al., 2009). Many studies now explicitly include demand management measures in their models, including parking supply and cost.

Drawing from decades of research, Ewing and Cervero (2010) carried out a meta-analysis of studies modeling the relationship between the built environment and travel behavior, including car use (VMT), walking, and transit usage. The meta-analysis derives weighted averages of elasticities for individual studies of auto use, walking and transit with respect to density, diversity, design and distance to transit. All the values were inelastic. Many variables had a negligibly small weighted average elasticity (the largest magnitude of the weighted average elasticity was 0.39 for destination accessibility). Job accessibility by auto and distance to downtown were found to have the most influence on automobile VMT. The other strongly associated metrics with VMT were intersection density and street connectivity. Walk trips were most influenced by land use diversity and street design of the neighborhood. Several variables were used to characterize design and diversity number of intersections had the highest elasticity followed by job-housing balance and distance to stores. Population density was more strongly related to walking than job density. In the case of transit, accessibility to transit was the most important factor for determining transit usage followed by road network variables (intersection density and street connectivity) and land-use mix. Ewing and Cervero (2010) justify the calculated elasticity values by explaining that high intersection density and good street connectivity shorten access distances and provide more routing options for transit users and a good land-use mix links up transit trips with daily errands and helps to decrease the number of trips. Across all modes (automobiles, transit and walking), the calculated weighted average values of elasticity for destination accessibility were higher than other 'D's and those for density were low.

2.3 Self-Selection

Many studies conclude that a dense, compact and walkable built environment with mixed use near a transit station is associated with the choice of non-motorized modes and transit. However, association does not imply causality. Often, residents choose to live in a neighborhood that is conducive to their travel preferences. For example, a person who prefers walking would choose to live in a more walkable neighborhood while a person who prefers taking transit would choose to live close to a transit station, irrespective of how walkable the neighborhood is. According to Cervero and Arrington (2008), residential self-selection is one of the main reasons for lower levels of automobile travel in transit-oriented neighborhoods. Cao et al. (2009) illustrate the difference between association-causation very well (Figure 2-1). Along with built environment, attitudinal and residential preferences also have a statistically significant effect on travel behavior. Several different approaches have been used to take such self-selection into account while developing mode choice models. Cao et al. (2009) classified self-selection approaches into 9 methodological categories - direct questioning, statistical control, instrumental variables, sample selection, propensity score, joint discrete choice models, structural equations models, mutually dependent discrete choice models and longitudinal designs. They reviewed 38 empirical studies that addressed residential self-selection and found that even after controlling for self-selection, the built environment had a statistically significant influence on mode choice. Other studies that quantify the effect of self-selection on travel behavior include Bhat and Eluru (2009) who used data from the Bay Area Household Travel Survey (BATS 2000), Cao et al. (2010) who used a 2006 data from a travel diary in Raleigh NC and more recently, Lee et al. (2014) who estimated the role of built environment and self-selection on travel behavior of baby-boomers in the Boston metropolitan area.

2.4 Bus Rapid Transit

Bus Rapid Transit (BRT) is a high-quality bus-based transit system that delivers fast, comfortable, and cost-effective urban mobility through the provision of segregated right-of-way infrastructure, rapid and frequent operations and excellence in marketing and customer service (Wright and Hook, 2007). It is often seen as an alternative to high-investment rail transit. Its flexibility and ability to serve low-density

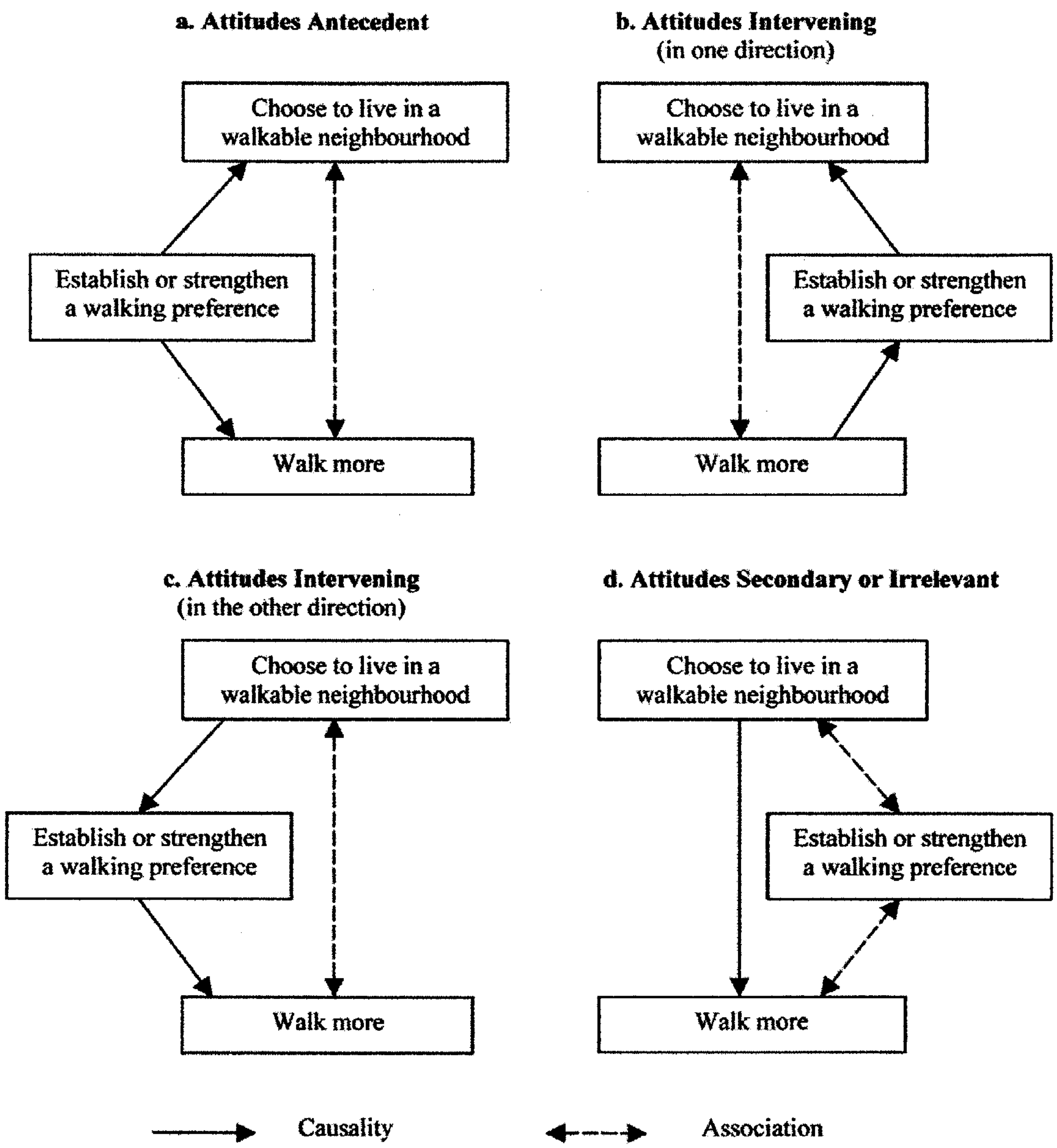

Figure 2-1: Some potential relationships among travel attitudes, built environment and travel (Adapted from Cao, Mokhtarian and Handy, 2009)

settlements while at the same time providing the comfort and speed of a rapid rail system make it attractive. In terms of key design and operating systems, a high-end BRT system is expected to have a separate right-of-way or fully segregated busway, pre-boarding fare collection, an integrated network of routes, high-quality bus stations and frequent service. BRTs that do not have a fully segregated right-of-way and are lacking in on or more of the other features are often termed 'BRT Lite' (Cervero, 2013). High-end BRTs also have advanced technologies such as automatic vehicle location systems for real-time vehicle tracking and dispatching, preferential signals for buses at intersections and real time passenger information systems. Differences between a full BRT service and BRT Lite are compared in Table 2.1 adapted from (Cervero, 2013).

Table 2.1: Comparison between Full/high-end BRT service and BRT Lite

	High-end BRT	BRT Lite
Running ways	Exclusive transit-ways; dedicated bus lanes; some grade separation; intersection treatments	Mixed traffic; modest intersection treatments
Stations	Enhance shelters to large, temperature-controlled transit centres	Stops, sometimes with shelter, seating, lighting, and passenger information
Service design	Frequent services; integrated local and express services; timed transfers	More traditional service designs
Fare collection	Off-vehicle collection; smart cards; multi-door loading	More traditional fare media
Technology	Automated Vehicle Location (AVL); passenger information systems; traffic signal preferences; vehicle docking/guidance systems	More limited technological applications

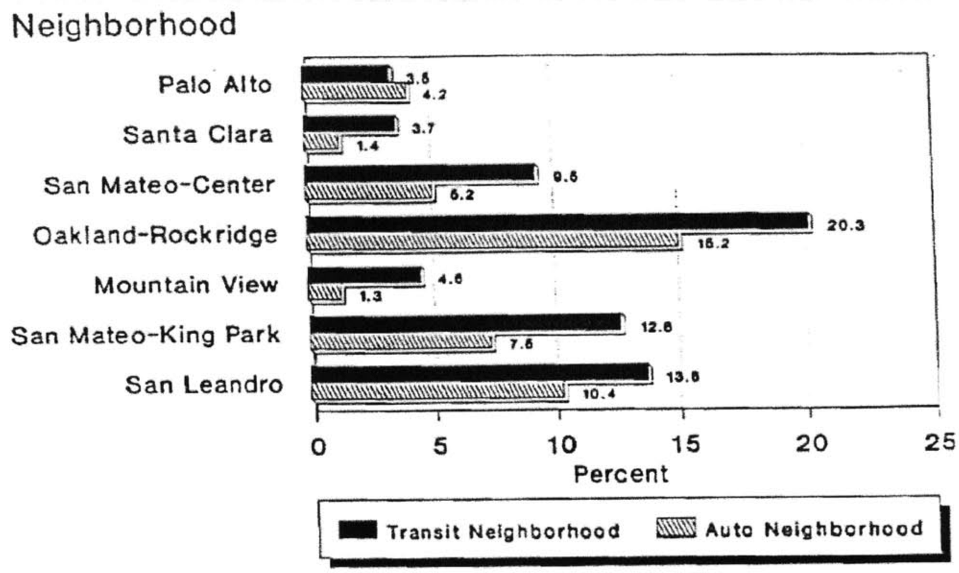

Figure 2-2: Neighborhoods comparisons of transit modal splits of work trips (1990) in the Bay Area (Adapted from Cervero, 1993)

2.5 Transit Oriented Development

The aim of transit oriented development is mainly to decrease the dependence on automobiles, reduce trip lengths, encourage walking, biking and transit usage. Such development presumably leads to a healthier society with better air quality in most cases. Bringing people out of their cars and creating better public spaces can also revitalize neighborhoods and improve the economy. Despite being studied and implemented widely, there is no clear definition of TOD. Calthorpe (1993) first formally used the term. He suggested designing neighborhoods around a central feature, mostly transit, replacing cul-de-sacs with through streets and encouraging mixed land use in an attempt to contain sprawl and create more walkable neighborhoods. A study by Cervero (1993) on transit supportive development in the San Francisco bay area showed that transit neighborhoods (neighborhoods having higher density and more gridded street patterns than their automobile counterparts) had higher pedestrian modal shares and transit trip generation rates (Figure 2-2).

Other descriptions of TOD include developing or intensifying land use near rail stations (Boarnet and Crane, 2001a), developing areas around transit stations with a variety of land uses and a multiplicity of landowners (SALVESEN, 1996), mixed-use community that encourages people to live near transit stations and decrease their dependence on driving (Still, 2002). Bernick and Cervero (1994, p. 1) described transit oriented development as "a residential development within a one-quarter-mile radius of a rail transit station built to tie into the station through easy walking or shuttle access" with an aim to increase transit ridership, reduce vehicle trips to the station and increase station attractiveness and safety.

Governments have long been interested in leveraging the relationship between land-use and transportation. In the USA, ideas of 'livable communities', 'smart growth' and 'transit oriented development' are often espoused. The United States Department of Transportation has made livability one of its key policy objectives. There are several grants and programs within the DOT that support projects that aim to revitalize communities and promote transit oriented development. Under the New Starts program, for example, funding is provided for new fixed guideway transit projects which have a total cost greater than $250 million. The projects are evaluated based on the integration between land use and transportation, environmental and economic benefits, increase in mobility and congestion relief. A similar program for smaller projects is the Small Starts program (Federal Transit Administration, 2012). The bicycle and pedestrian program by the Federal Highway Authority promotes bicycle and pedestrian transport, safety and accessibility by helping the states in implementing federal policies and legislations for cyclists and pedestrians. Other such programs that promote the goals of TOD include Design and Art in Transit program, Transportation, Community, and System Preservation program, Congestion Mitigation and Air Quality Improvement.

2.6 Effect of the 'T' in TOD

There is little research that compares rail-based transit oriented development and bus-based transit oriented development. At the outset of the concept, it was taken for granted that TOD is centered on rail stations. Most TODs were planned around rail stations and all research was also focused around rail based TOD (Calthorpe, 1993, Bernick and Cervero, 1994, Boarnet and Crane, 2001b). Examples of TOD around bus stations in North America and more predominantly in Latin America show that bus based transit oriented development can exist (Messenger and Ewing, 1996, Judy, 2007, Estupiñán and Rodríguez, 2008). From a user's perspective, any modal differences around TOD potential would relate to the relative attractiveness of one transit mode versus another. In this respect, Ben-Akiva and Morikawa (2002) found that people are indifferent to rail or bus transit where quantifiable characteristics such as travel cost and time are concerned but prefer rail based modes when considering quality. Chatman (2013) studied travel patterns in neighborhoods of New Jersey with respect to their proximity to rail transit station and observed that having a bus service with a densely built environment and less parking availability influenced travel patterns, irrespective of the proximity of the neighborhood to a railway station. This suggests that both bus-based and rail-based TOD can have some effect on travel behavior. However, Chatman does not give a numerical comparison of the impact of rail-based vs bus-based TOD. From the development perspective and implications for transit supply and levels of service, Pushkarev et al. (1977)'s seminal work showed how differences in transit ridership in urban areas can be explained by densities, the size of downtown in terms of nonresidential land use and presence of rail transit. Zhang (2009) identified that there is no one answer to which is better - bus rapid transit or light rail transit. He did a meta-analysis where he compared BRT and LRT systems with respect to costs, capacities and land use impacts and found that each has its benefits when placed in the right market. From a review of several studies of transit impact on land use, he observed that rail based transit systems resulted in greater property value increase than bus based systems in most cases. He also did a meta-analysis of densities required for specific modes. In general, while no specific densities for BRT were identified, it was seen that BRTs perform better than LRTs in low density areas.

Overall, factors like mixed-use, compact growth, intensifying land use near transit stations (in many cases, rail transit) are repeatedly used in most descriptions of TOD.

We can delineate each term of transit oriented development to understand how the concept of TOD can help us achieve the goals mentioned previously:

- Transit: TOD must be around a transit station. Transit may be bus based or rail based. The service quality of transit matters. This includes its frequency, hours of operation, increase in accessibility that transit brings, reliability, safety and many other factors. It is expected that a good quality transit system will attract more customers.
- Orientation: One of the major issues in successful implementation of TOD is that most people who can afford to live close to transit do not use it and people who would use transit cannot afford living closer to transit stations due to the higher property values in those areas. Orientation implies that such developments must be focused towards people who form the core of transit riders, people who are captive riders, low-income households, women, childless couples since these sections of the society tend to use transit more than others.
- Development: Proximity to transit stations alone is not sufficient to induce a change in travel behavior. Neighborhood street network design that improves walkability, a mixed land-use that has commercial and retail businesses along with residential buildings and a high density of population as well as jobs can help to reduce travel times and the number of motorized trips and often encourage transit use.

Different institutions have tried to create their own rating systems to identify the 'amount' or 'quality' of TOD in an area. One such rating system for identifying the amount of TOD is the eTOD station area rating system developed by the Dukakis Center for Urban and Regional Policy at Northeastern University and the Center for Transit Oriented Developement, focusing on equitable TOD for transit station areas (Pollack et al., 2014). Piloted in Massachusetts, the aim of the study was to develop a rating system that can predict which station areas in a region are likely to achieve the best TOD performance. The system identifies easily quantifiable, and comparable,

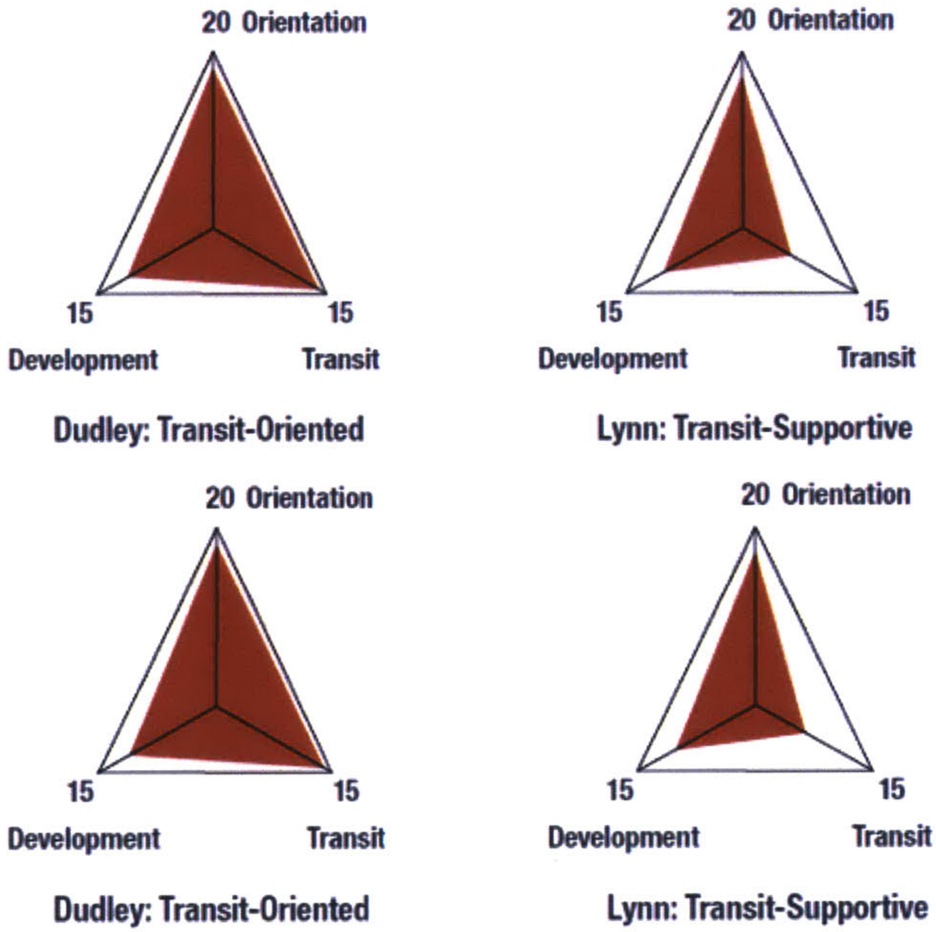

Figure 2-3: Performance of some MBTA stations based on the eTOD rating criteria (image taken from eTOD station area rating system by Dukakis Center for Urban and Regional Policy)

built, social and transit attributes that reduce driving, encourage higher transit ridership and promote transit equity and accessibility. Each attribute has a maximum of five points and each transit area is given a score out of 50 for ten attributes based on transit characteristics, neighborhood orientation and development. Points are given based on the quintile distribution of the attributes across all the transit stations in the MBTA system. Transit station areas are classified as transit-oriented, transit-supportive, transit-related or transit-adjacent based on their eTOD score. Figure 2-3 shows examples of performance of four transit areas across the Boston Metropolitan area for each category of the eTOD rating system.

Transit accessibility, transit connectivity and transit use were considered as metrics for the transit factor. The orientation of the transit station area was determined by metrics such as no car households or captive users, low income families, rental housing and affordability which was measured from the percentage of income spent on transportation. For development, walkability from Walkscore®, residential density and employment accessibility were considered. Employment accessibility was a gravity measure assessing the number of jobs in a region and the distance to employment destinations relative to any location in the region. Based on these metrics, a score was calculated for each of the station out of a total of 50. It is worth noting that this eTOD system does not distinguish between bus stations and rail stations while rating them. All transit stations are rated against the same metrics. In their sample that consisted of 345 station areas of which 69 were bus stations along high frequency 'key MBTA bus routes' and 276 were rapid transit stations, Pollack et al. (2014) found that there was a statistically significant difference between the TOD performance of the rail stations and bus stations based on the transit sub-scale. The selected high frequency bus areas performed better than all the rail areas.

The Institute for Transportation and Development Policy (ITDP) in its report 'TOD Standard' (2014) has created a score system to benchmark the performance of projects based on various TOD factors and thus to identify the 'TOD-ness' for urban projects. The system gives a maximum of 100 points across 21 metrics based on the impact they have in creating transit oriented development. The metrics are based on eight principles that ITDP considers essential for TOD: better walkability, good cycling infrastructure, shorter and more direct connections, availability of transit, diverse land use mix, high density, compact development and policies and street designs that encourage a shift of modes from motorized to non-motorized.Table 2.3 summarizes the score system prescribed by the standard. The ITDP TOD Standard does not distinguish between rail or bus transit station area. It evaluates all high capacity transit station areas based on similar criteria including heavy rail, commuter rail, subways, light rail, bus rapid transit and even regular bus and para-transit services whose frequencies are less than 20 minutes and systems whose operating hours are at least from 7am to 10pm.

Table 2.3: Principles and metrics of the ITDP TOD Standard

Principle	Metric	Measurement
Walk (15points)	Walkways	Percentage of block frontage with safe, wheel-chair accessible walkways
	Crosswalks	Percentage of crosswalks with safe, wheelchair accessible crosswalks in all directions
	Visually active frontage	Percentage of walkway segments with visual connection to interior building activity
	Physically permeable frontage	Average number of shops and pedestrian building entrances per 100 meters of block frontage
	Shade and shelter	Percentage of walkway segments that incorporate adequate shade or shelter element
Cycle (5points)	Cycle network	Percentage of total segments with safe cycling conditions
	Cycle parking at transit stations	Secure multi-space cycle parking facilities are provided at all high-capacity transit stations
	Cycle access in buildings	Buildings allow interior access for cycles and cycle storage within tenant-controlled spaces
Connect (15points)	Small blocks	Length of the longest block (long side)
	Prioritized connectivity	Ratio of pedestrian and cycle intersections to motor vehicle intersections
Transit (TOD requirement)	Walk distance to transit	Walking distance in meters to nearest transit station
Densify (15 points)	Land use density	Average density in comparison to local conditions

Principle	Metric	Measurement
Mix (15points)	Complementary uses	Residential and non-residential uses combined within same or adjacent block
	Accessibility to food	Percentage of buildings that are within 500 meters radius of an existing or planned source of fresh food
	Affordable housing	Percentage of residential units provided as affordable housing
Compact (15points)	Urban site	Number of sides of the development adjoining existing built-up sites
	Transit options	Number of transit stations on different transit lines that are accessible within walking distance
Shift (20points)	Off street parking	Total off-street area dedicated to parking as a percentage of total land area
	Driveway density	Average number of driveways per 100 meters of block frontage
	Roadway area	Total road area used for motor vehicle travel and on-street parking as percentage of total land area

Many North American cities are looking toward TOD with the hope to decrease auto use and increase transit ridership. Increasing empirical evidence on ridership and land values exists. A technical assistance report, 'Encouraging Transit Oriented Development: case studies that work', produced by Reconnecting America for the United States Environmental Protection Agency, states that implementation of TOD in the Rosslyn Ballston Corridor in Arlington, Virginia has led to an increase in land values by 81% in 10 years, with 50% of the residents taking transit to work and 73% walking to stations. Another example is the light rail system in Portland, Oregon, that has been able to achieve most of the TOD objectives with support from private investors. The streetcar service started by the city and the neighborhood improvements along with up-zoning the private property along the corridor led to densification. This has been responsible for development of 10,000 housing units of which one quarter are affordable. 4.6 million square feet of commercial space has been developed within 2 blocks of the streetcar, providing up to 21,000 jobs (America, 20009). Before and after studies of the light rail transit operation by Dallas Area Rapid Transit showed higher economic growth in areas served by the rail (Ibewuike and Weinstein, 2000). A more recent study of 17 TOD areas in San Francisco, New Jersey, Philadelphia, Portland and Washington DC showed that the TOD projects had fewer average vehicle trips by 44% than the trips estimated by Institute of Transportation Engineer's Trip Generation manual estimates (Cervero and Arrington, 2008). It was observed that trip rates fell as neighborhood densities increased.

2.7 Relevant Precedents for the Boston Region

Numerous research precedents of transportation and planning has been done in the Boston region. Srinivasan (2000) examined the effect of land use, network and accessibility related characteristics of the neighborhood on individual travel behavior and attempted to understand trip chaining and mode choice of individuals living in the Boston metropolitan area. She concluded that land use and accessibility measures do not directly affect travel behavior but influence latent characteristics that describe the location, which in turn possibly influences travel behavior. Expanding on this study, Srinivasan and Ferreira (2002) analyzed built environment characteristics such as commercial-residential mix and balance, cul-de-sac oriented design, non-work accessibility by auto, pedestrian convenience, transit access and suburban character of the household to understand trip chaining behavior at a household level. They found that pedestrian convenience of home location increased the likelihood of using non-auto modes and improving land use mix combined with better pedestrian facilities and transit access could increase work-based non-auto tours. Zhang (2004) analyzed the influence of land use factors such as distance to transit, population density, employent density, percentage of non-cul-de-sac intersections and entropy of land use at the origin and the destination on travel mode choice in Boston and Hong Kong and concluded that higher population density at trip origin and destinations and higher employment densities at trip destination were significantly associated with higher probability of commuting by non-auto modes; decreased connectivity at trip destinations resulted in greater likelihood of driving alone; distance to nearest transit station and entropy measures of land use diversity were not a significant factor for work trips. Block-Schachter (2012) studied the hysteretic effect of the rail system in the Boston region on population and employment density, connectivity, auto ownership and travel behavior. The study found that built environment attributes of home location do not affect the choice of modes but proximity to bus network has significant influence on mode choice. Chen (2013) analyzed the relationship between Boston's rail transit station ridership and factors of the transportation system, built environment and socio-demographics. His research found that higher transit ridership was associated with the stations that have a more walkable environment and higher levels of employment and population.

2.8 Hypotheses

All studies indicate that land use and the built environment in Boston do have some effect on travel behavior. The question that follows is what are the characteristics of TOD for a transit type that would improve the TOD performance? The performance may be measured in terms of higher transit ridership, more non-motorized trips, fewer vehicle miles traveled or fewer trips. Based on the literature reviewed above, I hypothesize the effect of some built environment attributes on mode choice for home based work (HBW) trips.

Table 2.5: Hypothesizing the role of built environment and land use for HBW trips

Variable	Hypothesis
Density	Areas with high population density or high employment density are expected to have a higher walk, bike and transit mode share. In part, the high transit share may be due to a better transit service provided in such areas since they have the necessary critical mass required for operating the route. In the case of transit mode share, trains or BRTs having their own right-of-way may be the more preferred alternatives than regular bus services since the latter tend to slow down considerably due to congestion in such high density areas.
Distance from CBD	People living closer to the CBD might walk, bike and use transit more often, since areas closer to the CBD have a dense fabric, fewer car parking spaces and narrow streets that make driving inconvenient. The distance from CBD should not affect choice between rail based and bus based transit.
Street design	Areas with dense, grid-like street network, small block lengths, wide and continuous sidewalks might have higher walk share. Frequent intersections and orthogonal geometry of streets assist pedestrian movement and make wayfinding easy. For bicycles, frequent intersections disrupt their normal speeds and increase the chances of a traffic collision, thus, decreasing the bike share.

Variable	Hypothesis
Diversity	Mixed land uses put commercial, residential and recreational uses in proximity, thus decreasing trip distances. This makes walking and biking more viable. Transit shares will also be high as diverse land uses give people the opportunity to finish other chores while walking to or from the transit station. I hypothesize that the amount of land use mix affects the choice between rail based and bus based transit. Lesser diversity may increase the likelihood of choosing rail based transit over a bus based transit.

This research strengthens previously established relationships that indicate a significant influence of the built environment on mode choice in particular and transit oriented development in general. It expands on previous studies by considering many more variables as indicators for level of TOD. It differs from prior reserach in that it explores how different characteristics of TOD might influence different transit modes in distinct ways.

The next chapter discusses the context of Boston and describes the demographics, land use and public transportation system of the region.

Chapter 3

The Context of Boston

The Boston region is one of the most populated metropolitan areas of the United States. Located in the New England region, the Boston metropolitan area comprises of 101 cities and towns encompassing 3,639 square kilometers according to the Boston Region Metropolitan Planning Organization (Figure 3-1). The region has grown around the city of Boston. Boston is one of the oldest cities in United States and also the capital of the Commonwealth of Massachusetts.

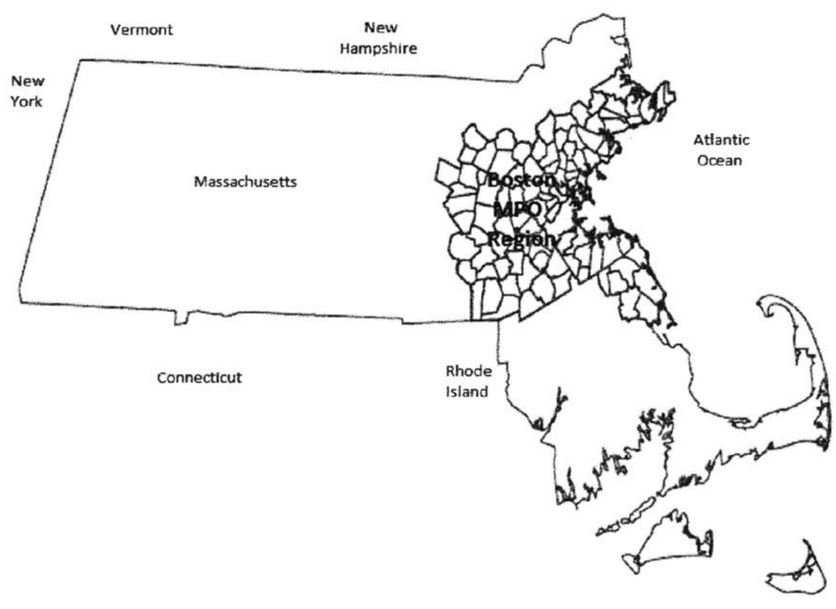

Figure 3-1: Boston Metropolitan Region

3.1 Demographic Profile

The population of the Boston metropolitan region is about 3.16 million. The region has about 1.2 million households with an average household size of 2.44 persons (Table 3.1). Single person households comprise of 30.1% of all households in the region. About 9% of the population is of Hispanic origin. The median age of the population is about 38 years; 20.7% of the population is below 18 years of age and 13.4% of the people are older than 65 years, slightly lower than the 13.8% proportion for the state (Figure 3-2). These characteristics play an important role in determining a person's travel behavior.

Table 3.1: Demographic Statistics for the Boston Region

Variable	Value
Area (sq. km)	3,639
Population	3,161,712
Number of households	1,243,189
Number of workers	1,542,548

Source: CTPS, Massachusetts Demographic Profile 2010

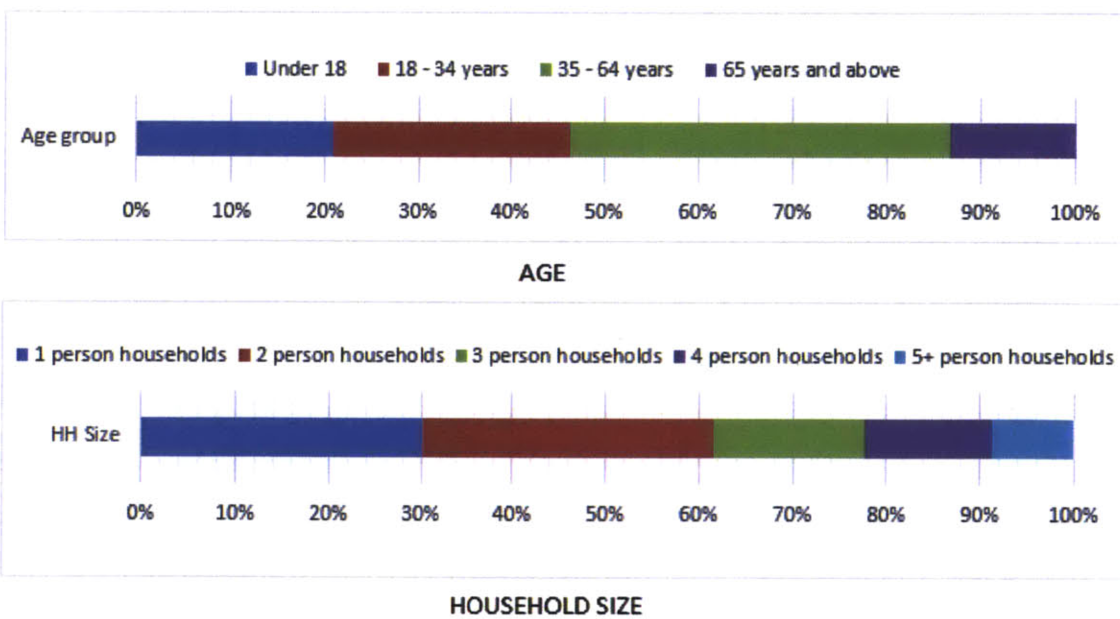

Figure 3-2: Demographic profile - age and household size

The median annual household income for the Boston region MPO is $70,829, higher

Table 3.2: Mode of Transport to work

Means of Transportation	Percent
Car - drove alone	63.97%
Car - carpooled	7.46%
Bus	5.04%
Subway	7.38%
Street car	0.78%
Commuter rail	2.07%
Ferry	0.16%
Taxi, motorcycle and other means	0.84%
Bicycle	1.03%
Walked	6.75%
Worked at home	4.50%

Source: CTPS, Massachusetts Demographic Profile 2010

than the state median of $64,509. The average vehicle ownership in the region is 1.49 vehicles per household, lower than the state average of 1.6 vehicles per household. Compared to the national proportion of 9.1%, about 15.75% of the households do not own a vehicle in the region (U.S. Census Bureau, 2012). The mode of transportation to work in the region is summarized in Table 3.2. A large proportion of workers drive to work. Public transport constitutes 15.27% of the journey to work mode share.

The average travel time to work is 28.7 minutes and the median time is 26.7 minutes. According to the Texas Transportation Institute's Urban Mobility Report (2012) that uses a measure called Travel Time Index (TTI) to measure congestion, the Boston metropolitan area is the fifth most congested metropolitan area in the United States. It has a 53 hour yearly delay per commuter. TTI is the ratio of average peak hour travel times to average free flow travel times. However, this measure of congestion does not consider the effects of different land use patterns of cities and varying trip distances in different metropolitan areas and has attracted criticism (Cortright, 2010). Unlike congestion measures, accessibility measures can examine land use and the transportation system together. The Access Across America study by David Levinson (Levinson, 2013) compares trends in accessibility to jobs during the morning peak hours in 51 metropolitan areas across America. Levinson created a weighted average of accessibility, giving a higher weight to closer jobs. Jobs reachable within ten minutes are weighted most heavily, and jobs are given decreasing weight as travel time increases up to 60 minutes. According to this study, the Boston Metropolitan Region is the 9th most accessible metro area in the country.

Figure 3-3 shows ten U.S. cities with the highest and lowest alternative (non-automobile) mode share based on the 2007 U.S. Census. Boston has the third highest transit mode share in the country.

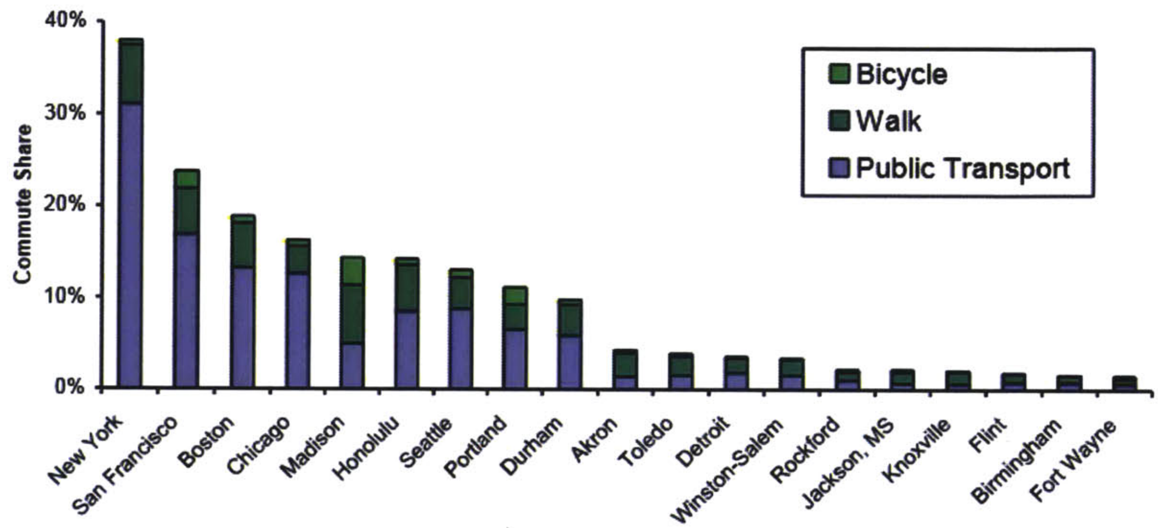

Figure 3-3: Ten U.S. cities with the highest and lowest non-automobile commuteshare (Source: Litman, 2014)

3.2 Regional Transportation System

The Boston region has a well-developed road network. The Boston downtown area does not have a strong grid-like network of streets (Figure 3-4).

Highways connect the suburbs to the downtown. Figure 3-5 shows the interstate highways, US highways and state routes in the region. The Massachusetts Bay Transportation Authority (MBTA) is the public agency that operates most public transportation services in the Boston Area. Commuter rail, heavy rail or subways, light rail, BRT Lite, regular bus services and ferries services are available for daily commute in the region. The variety of public transport systems and a pervasive public transport network make Boston an interesting case for studying the possible variation

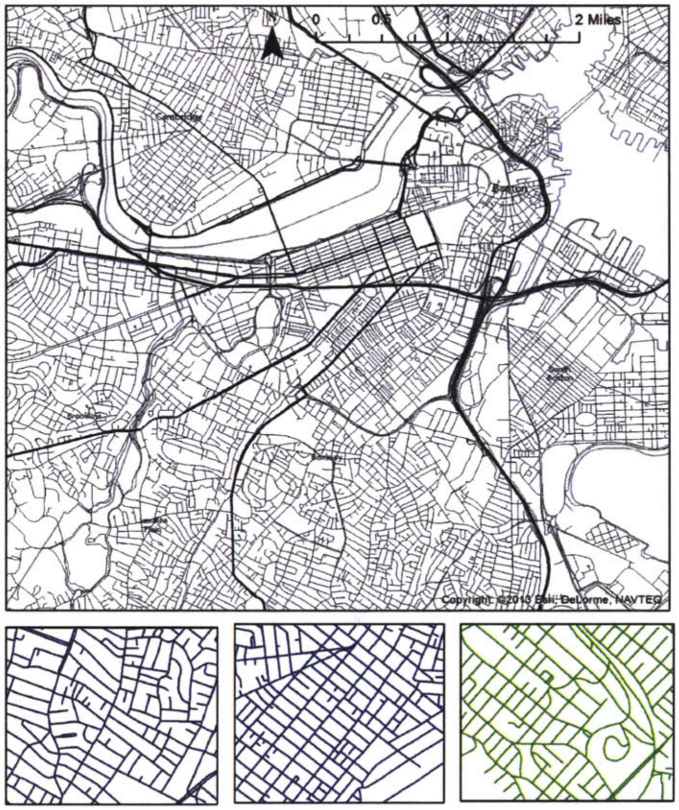

Figure 3-4: Irregular street network near the Boston downtown

of peoples' mode choice.

The MBTA was one of the first combined regional transportation planning and operating agencies to be established in the United States. It is the country's 5th largest mass transit system, serving a population beyond the MPO's: over 4.6 million people across 175 towns and cities across an area of 8,402 square miles (MBTA, 2010). The MBTA's system consists of 183 bus routes, 4 of which are BRT Lite lines (the 'Silver Line'), 3 rapid transit lines (subways), 5 light rail (Central Subway/Green Line) routes, 4 trolleybus lines, 14 commuter rail routes and 3 ferry routes. The average weekday ridership for the entire system is approximately 1.24 million passenger trips. In 2010 about 370 million unlinked trips were recorded by the MBTA (MBTA, 2010).

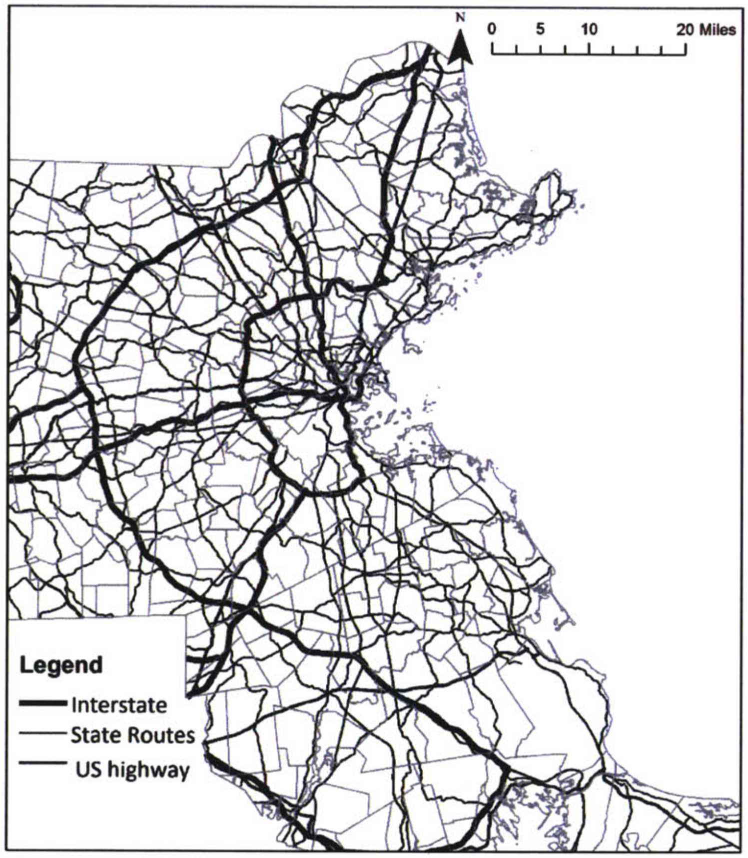

Figure 3-5: Major roads in the Boston Metropolitan Region

3.2.1 Subway

The subway or rapid rail transit service consists of heavy rail —red, blue and orange lines —and light rail —the green line and the Mattapan-Ashmont trolley system (Figure 3-6). The subway service has 121 stations and a length of 63.5 miles without accounting for overlapping routes. The unlinked trips for each subway line for FY2010 are summarized in Table 3.3. The red line has the highest ridership followed by the green line.

The weekday operating hours of the subway are from 5.00AM up to 12.15AM. Recently late night services, operating until 2.30AM, for subway and key bus routes have also been started by the MBTA on Friday and Saturday nights. The scheduled rush hour headways for each line are summarized in Table 3.4. The non-rush hour headways vary from 7 min to 15 min.

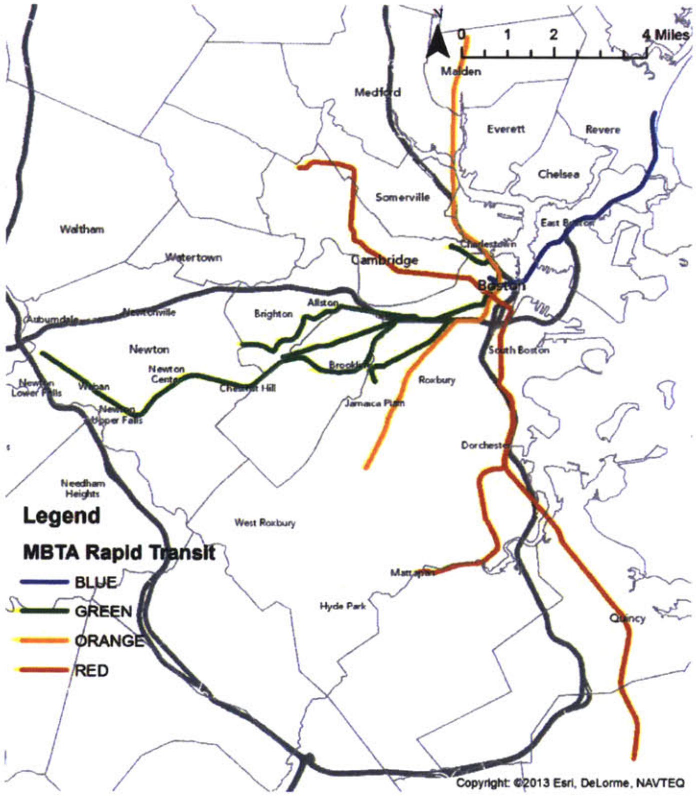

Figure 3-6: MBTA heavy and light rail routes

3.2.2 Bus Rapid Transit

The MBTA's Silver Line was introduced in 2002 as the city's first BRT service. The line has four routes with a total route length of 13 miles (Figure 3-7). The routes are numbered SL1, SL2, SL4 and SL5. SL1 and SL2 have 9 stops along the route including the South Station. 15 stations lie on the SL4 and SL5 routes. In some stretches, the routes have mixed traffic lanes. The fleet consists of low-floor, dual

Table 3.3: MBTA subway ridership

Line	Unlinked annual trips	Unliked weekday ridership
Red line	74,445,042	241,603
Orange line	54,596,634	184,961
Blue line	17,876,009	57,273
Green line and Mattapan-Ashmont trolley	75,916,005	236,096*

Source: MBTA, 2010 (* green line only)

Table 3.4: MBTA subway rush hour headways

Subway	Rush hour frequency
Red line	9 min
Blue line	5 min
Orange line	6 min
Green line	6-7 min
Mattapan-Ashmont trolley	5 min

Source: mbta.com

Table 3.5: Silver Line average weekday ridership

Silver Line service	Average unlinked weekday ridership
SL1 and SL2	14,940
SL4 and SL5	15,086

Sources: MBTA, 2010 Authority (2010)

mode articulated buses. The service operates on weekdays from 5.30 AM to 2.30 AM. The weekday peak hour service headway varies between 5 to 10 minutes along the four routes —providing 6 to 12 buses per hour. The service operates on weekends at headways between 10 and 15 minutes. Fare collection is done onboard except at South station. Most stations have some form of bus shelters except at Chinatown and Boylston where there are no permanent facilities. Thus, the Silver Line is more accurately characterized as BRT Lite (Section 2.4). Table 3.5 summarizes the average weekday ridership on the Silver Line routes.

3.2.3 Bus

MBTA operates regular bus services and trolleybus services in the greater Boston region. Its network included approximately 180 routes. The network is well spread out across the region, covering 740 non-duplicative route miles one way (Figure 3-8). According to MBTA, 'talking bus' announcement systems are in use on all buses. Headways vary from 5 minutes to up to 60 minutes for different routes during the peak period. Fare payment is onboard and integrated with the subway and BRT system. The typical weekday regular bus ridership is 331,650. There are 8500 bus stops of which 675 have shelters. Bus fares during the time of the travel survey used

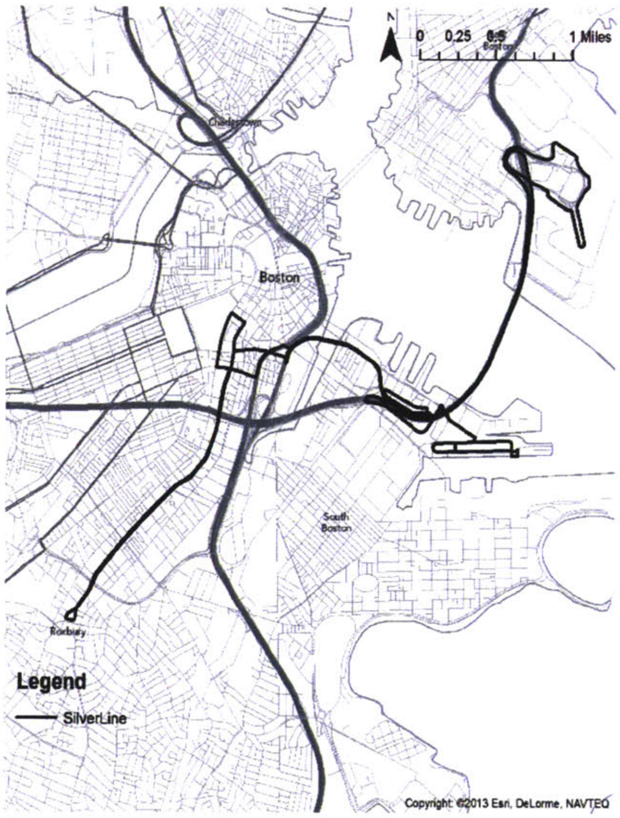

Figure 3-7: Silver Line route

in my analysis (2010) were $1.50 ($1.25 for Charlie card users) with free bus to bus and rail to bus transfers and an incrmental fare for bus to rail and bus to Silver Line transfers.

3.2.4 Commuter Rail

The commuter rail network in Boston connects distant suburbs to downtown Boston. The commuter rail system is 394 miles long and includes 5 north side routes and 9 south side routes with 135 stations. Average weekday commuter rail boarding as per FY2010 was 132,730. Commuter rail stations have 26,936 park-n-ride spaces in total to encourage people to leave their autos in the suburbs. The commuter rail network is shown in Figure 3-9.

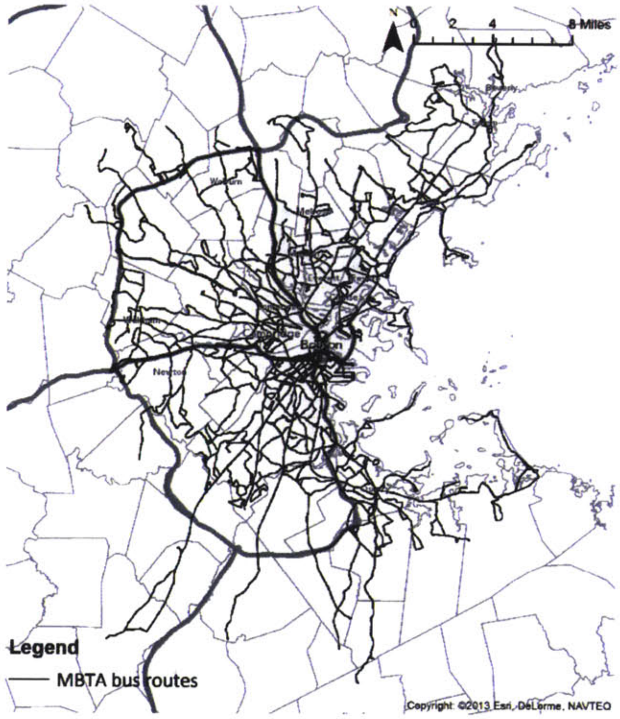

Figure 3-8: MBTA bus routes

Figure 3-9: Boston region commuter rail network

3.3 Regional Land Use

The Metropolitan Area Planning Council (MAPC) is the regional land use planning agency for 101 cities and towns in the Boston Metropolitan region. It serves to promote smart growth by integrating transportation and land use in the region. MAPC provides a number of programs for municipalities to help them implement MetroFuture, the 30 year plan for the Boston region that promotes efficient transportation systems and conservation of land and natural resources among other objectives. To support planning, analysis and policy development, MAPC has classified municipalities across Massachusetts into five basic types —inner core, regional urban centers, maturing suburbs, developing suburbs and rural towns (MAPC, 2008). The criteria used for classification of municipalities include land use, housing patterns, growth trends and projected development patterns. MAPC identifies transit oriented development in the Boston region as a way to reduce greenhouse gas emissions, boost transit ridership and make it affordable, mitigate congestion and reduce sprawl (Reardon and Dutta, 2012). It has estimated that transit station areas in the region can accommodate 76,000 new housing units and more than 130,000 jobs in the next 25 years. MAPC has compiled a land parcel data which was previously available only on a town-by-town basis in each Massachusetts' municipality. This Massachusetts land parcel database (version 1.0, 2013) has been used for analysis in this research.

The Boston Region Metropolitan Planning Organization (MPO) conducts a metropolitan transportation-planning process to develop a vision for the region and decides how to allocate federal and state transportation funds to programs and projects that support that vision. The Central Transportation Planning Staff (CTPS) of the MPO provides it the expertise in comprehensive, multimodal transportation planning and analysis, to promote interagency cooperation, to ensure consistency among planning efforts required to accomplish its goals. MAPC provides planning support to the MPO. Its work includes developing regional bicycle and pedestrian plans, and providing alternative land-use analyses for upcoming projects.

The above sections attempt to strengthen the case of the Boston region as a good study area for mode choice and transit oriented development. In the following chapter, I delineate the study area, present the data that I use and describe my methods.

Chapter 4

Data and Methodology

4.1 Study Area

The aim of this study is to verify whether land use and built environment play a possible role in peoples decision of choosing between different modes of transportation including at least one mode of public transit.The study area for this research was constructed based on a 'skeleton' of 1.5 mile buffer area around the MBTA rapid transit routes (Figure 4-1). The 1.5 mile buffer accounts for possible bike access to the transit stations. The entire study area is serviced by the MBTA bus network.

The main source of travel behavior-related data was the Massachusetts Travel Survey (MTS) 2012 conducted on behalf of Massachusetts Department of Transportation (MassDOT) and the 13 Metropolitan Planning Organizations of Massachusetts. The MTS 2012 provides detailed information on households, sampled across the Commonwealth of Massachusetts, and their trip characteristics. Income is an important factor that often explains a persons mode choice and travel behavior. I estimated the income range of households that did not disclose their income using regression analysis (Appendix A). The estimated income distribution of the households is shown in Figure 4-2. I found that these households are not from one particular income category. Since I did not have accurate knowledge about their incomes, I excluded these households from the analysis. Excluding these households may bias the model results.

The survey provided the location of households geolocated at the census block

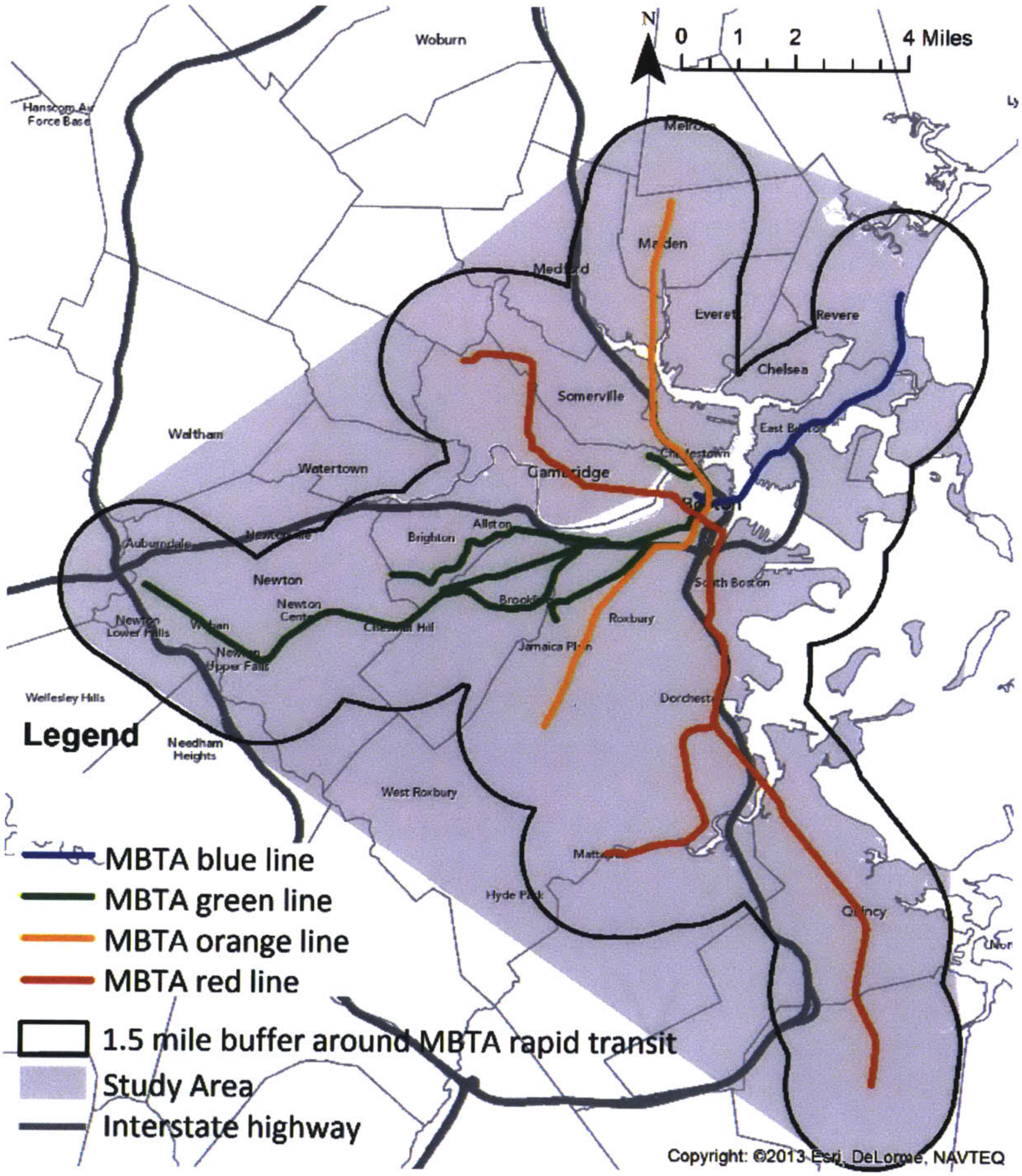

Figure 4-1: Study Area

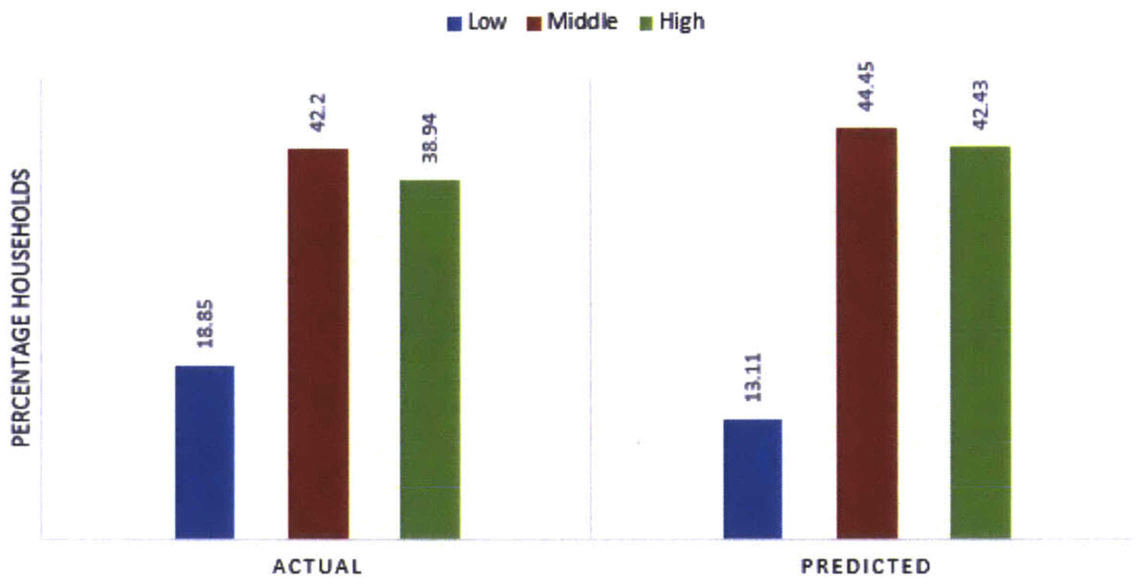

Figure 4-2: Model Validation for Income

level; a sample of 1300 households blocks in the study area were mapped and a 0.5 mile network buffer was drawn from the centroid of each block to determine the characteristics of the household blocks' surrounding land use and built environment. The 0.5 mile block is justified from common assumption that an average person may walk up to 10 minutes (equivalent to a distance of 0.5 miles) to get to a transit station.

4.2 Data

In this section, I discuss the variables I considered for model specification. The variables can be classified in three types trip attributes, personal and household characteristics and land use and built environment factors.

4.2.1 Trip Attributes

Each mode has specific attributes presumably influencing its attractiveness to users and that therefore need to be accounted for while estimating the mode choice model. For my analysis, the trips used to estimate the model are those with an origin and destination in the 2727 transportation analysis zones defined by the Central Trans-

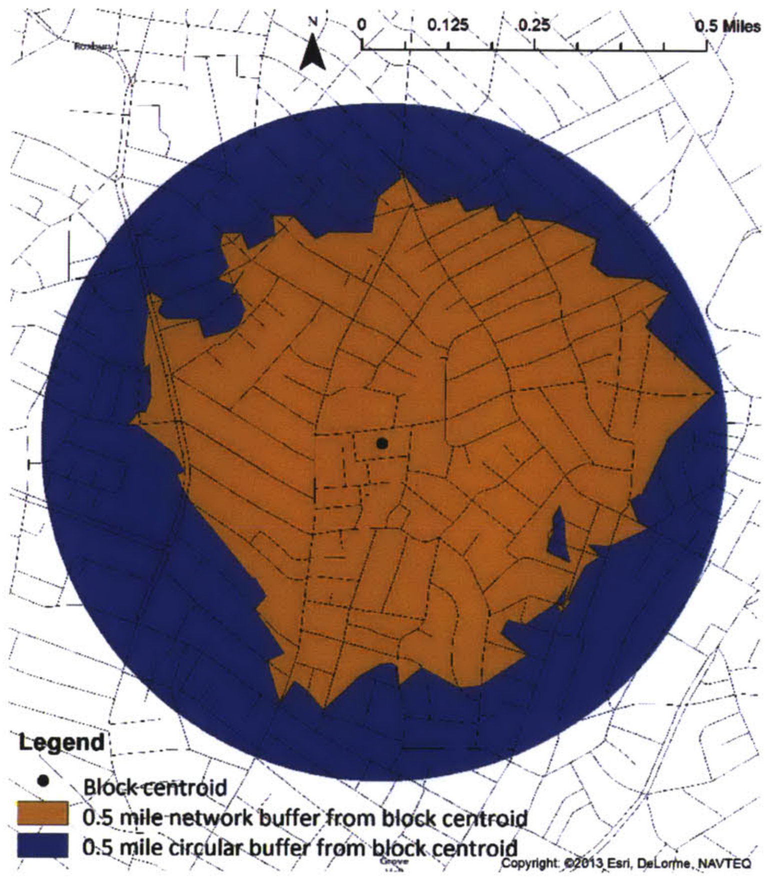

Figure 4-3: Euclidean buffer vs network buffer

portation Planning Staff. The basic TransCAD road and transit network used for estimating trip characteristics was provided by MIT Professor Mikel Murga. I edited the transit network to add the missing Silver Line bus routes.

Auto travel time and distance for a trip was calculated using AM peak travel time values between the respective pair of OD zones. I used the shortest time path to estimate the auto times and distances associated with each OD pair. Auto trip cost was calculated based on the average miles per gallon (mpg) of the car type used by the trip maker and the fuel cost per gallon as summarized in Table 1. The price of gas and diesel were assumed to be \$ 3.132 per gallon and \$ 3.315 per gallon respectively (U.S. Energy Information Administration, Dec 2010). For carpools, the trip cost is divided among the number of people travelling together. When a trip is made using modes other than the automobile, the cost attribute for the automobile choice in modeling is calculated by assuming that the trip maker would have used the vehicle indicated by them as their primary vehicle.

Table 4.1: Fuel economy

Car type	Fuel economy
Cars and wagons	34.8
Vans	26.7
SUVs	30.9
Pickup trucks	27.0
Other trucks	27.7
Recreational vehicles	26.7

Source: Transportation energy data book Edition 32 (2013), Oak Ridge National Laboratory

For transit trips, the total travel time for bus and rail mode was calculated. The constituent access time to the station, egress time, transfer wait time, transfer walk time, number of transfers and in-vehicle travel time were also calculated for each trip. Other trip attributes such as bike facilities at the workplace and number of people traveling together were taken from the Massachusetts Travel Survey 2012.

4.2.2 Personal and Household Characteristics

Age, gender, income, vehicles per household, number of driving license holders in the household, number of bikes, transit pass ownership, household ownership, household size and race were considered for modeling.

4.2.3 Built Environment and Land Use Characteristics

The following built environment and land use characteristics were calculated and considered for estimating the model.

- Density: population density and housing unit density in the home buffer and work buffer were considered. Employment in the home TAZ and work TAZ was also taken into account.

- Relative location: distance of home and workplace from CBD was calculated. I used a dummy variable to identify if a location was within 5 miles of the CBD. Distance from nearest bus and train stations was also calculated.

- Street design: Number of four way intersections, number of cul-de-sacs, number of cul-de-sacs per intersection, proportion of sidewalk length over road length, sidewalk area and average sidewalk width is calculated for each buffer.

- Diversity: Land uses given in the MAPC parcel land use data are classified based on 9 categories - residential, commercial, retail, office, industrial, administrative, public service, entertainment or recreational and other land uses.

  For land use diversity within the buffer areas around the trip origin and destination blocks, I developed several indices as described below. I used each of these indices to in different model specifications and picked the one that gave the best results.

- The Herfindahl Hirschmann Index (HHI) is the sum of squares of percentages of various land uses. A higher value of this variable indicates less diversity. The maximum possible value of 10,000 is attained if the area has a single land use.

$$HHI = R^2 + C^2 + I^2 + A^2 + E^2 + O^2$$

Where

R = percentage land under residential use

C = percentage land under commercial, office and retail use

I = percentage land under industrial use

A = percentage land used for administrative and public service

E = percentage land used for entertainment and recreation

O = other land uses

This index gives a higher weight to large areas of a land use. Minimum values are attained only when each land use type covers an equal area. This index has been used to quantify diversity in prior research (Coombes et al., 2010, Zahabi et al., 2011)

- The Balance Index is adapted from Cervero and Duncan (2003) who used the formula:

$$Balance\, index = \frac{|Employed\, residents - Jobs|}{|Employed\, residents + Jobs|}$$

This index shows the balance between the number of potential jobs and potential employees within an area, a version of a jobs-housing balance measure. Purely residential areas will have a balance index value 1. Similarly, job-intensive areas (e.g., near the CBD) will have a balance index close to 1.

- The Diversity Index is adapted from Rajamani et al. (2003). The value of this index varies between 0 and 1. A high value indicates more diversity of land use.

$$Diversity index = 1 - \frac{|\frac{R}{T} - \frac{1}{6}| + |\frac{C}{T} - \frac{1}{6}| + |\frac{I}{T} - \frac{1}{6}| + |\frac{A}{T} - \frac{1}{6}| + |\frac{E}{T} - \frac{1}{6}| + |\frac{O}{T} - \frac{1}{6}|}{\frac{5}{3}}$$

Where

R = Total floor area for residential use

C = Total floor area for commercial, office and retail use

I = Total floor area for industrial use

A = Total floor area for administrative and public service

E = Total floor area for entertainment and recreation

O = other land uses

4.2.4 Descriptive Statistics

Table 4.2 summarizes the final variables used in the models, their descriptive statistics and their source.

Table 4.2: Descriptive Statistics

Variables	Mean	Median	Std Dev	Min	Max	Source
Auto time	12.43	9.81	16.44	0.04	118.45	Calculated from TransCAD models
Walk time	89.84	80.20	64.08	0.34	454.03	
Bike time	29.97	26.73	21.36	0.11	151.34	
Bus time	57.91	53.44	33.19	7.66	144.43	
Rail time	41.70	38.65	16.95	100.73	11.06	
Proportion of workplaces with bike facilities	0.51					Calculated from Massachusetts Travel Survey 2012
Total number of people traveling together	1.10	1.00	0.37	1.00	5.00	
Proportion of women in sample	0.52					
Household bikes	1.48	1.00	1.59	0.00	8.00	
Household vehicles per license	0.75	0.39	1.00	0.00	2.00	
Proportion of population having a transit pass	0.66					
Proportion of workplaces within 5 miles from CBD	0.77					Calculated using ArcGIS network analysis

Proportion of homes within 5 miles from CBD	0.52					
Employment in workplace TAZ	2.79	1.64	3.11	0.01	14.32	MetroFuture and current trends, CTPS 2008
Population density in workplace buffer	17.81	13.69	12.96	0.00	72.38	Tiger files census block data 2010
Population density in home buffer	21.22	19.18	12.88	1.68	68.73	
Diversity in home buffer (HHI)	8145.11	9383.15	2319.24	2216.30	10000.00	MAPC parcel land use data, 2013
Proportion of sidewalk/road in home buffer	1.40	1.47	0.38	0.17	1.97	Tiger files census block data 2010

4.3 Methodology

Individual choices are typically based on the following four elements the decision maker, the alternatives available, the attributes of the alternatives, and the decision rule (Ben-Akiva and Lerman, 1985). The decision maker may be a person, a group of people or a household that faces different choices and has different tastes and priorities which affect the choice made from among a set of alternatives. Decision makers choose between alternatives based on the alternatives qualities. Some alternatives may have qualities that the decision maker values more over others. Often, there is a tradeoff between attributes of different alternatives. In the case of transportation, a mode may be fast and hence more attractive but more expensive than a slower mode. The decision rule is the basis upon which a decision maker makes a choice from a set of alternatives with the given attributes. It describes the internal mechanisms presumably used by the decision maker to process information and arrive at a unique choice. Utility maximization is one such decision rule by which the attractiveness of an alternative is based on its utility index which in turn is calculated as a function of its attributes. An individual chooses the alternative with the highest utility.

Sometimes, decision makers may not follow any of the above rules and instead follow intuition or imitate another person. Choice theory assumes that decision makers show rational behavior by making a consistent and calculated choice based on their beliefs.

Calculating the utility for each alternative requires perfect knowledge of the alternatives for each individual. If U_{in} is the utility for alternative j for individual n, we can divide the utility U_{in} into a systematic component (V_{in}) that is deterministic and can be measured accurately and a random component (ϵ_{in}).

$$U_{in} = V_{in} + \epsilon_{in}$$

The systematic part of the utility can be specified as a function of the characteristics of the decision maker and the attributes of the alternative.

$$V_{in} = f(Z_{in}, S_n)$$

where Z_{in} is a vector of the attributes of the alternative and S_n is a vector of characteristics of the decision maker.

In case of a choice set of C_n for decision maker n, the probability that an individual chooses alternative i is given by

$$P_n(i) = Pr(U_{in} \geq U_{jn}, \forall j \in C_n)$$

$$P_n(i) = Pr(\epsilon_{jn} \leq V_{in} - V_{jn} + \epsilon_{in}, \forall j \in C_n, j \neq i)$$

4.3.1 Multinomial Logit and Nested Logit Models

Assuming that the random error term is identical and independently distributed (IID) with a Gumbel distribution and a scale parameter μ, the multinomial logit (MNL) model can be expressed as

$$P_n(i) = \frac{e^{\mu V_{in}}}{\sum_{j \in C_n} e^{\mu V_{jn}}}$$

The most common functional form for V is linear in the unknown parameters (β). In this case, the scale parameter,μ, cannot be distinguished from the scale of theβs, which requires an arbitrary assumption about the value of μ. For convenience, the typical practice in the logit approach is to normalize this value to 1.

The IID assumption means that all error terms must be equal. Another important assumption of MNL models is the independence from irrelevant alternatives (IIA) property. According to this assumption, the probability of choosing between two alternatives depends on their utility alone and is not affected by the systematic utility of any other alternative. This assumption is violated if the error terms are correlated.

The nested logit model relaxes the IIA assumption of MNL models by allowing correlation in the error terms of alternatives in the same nest.

The nested logit generalization of the MNL model structures the choice process in a joint fashion, whereby decision-makers choose alternatives from within groups of possible outcomes. The decision process does not represent a sequential process, but shows the pattern of similarities within a decision process that is simultaneous. In other words, in the depiction in Figure 4-4, the traveler views all of the a2 modes as more similar to each other than all of the a1 modes.

The probability of choosing to a mode can be represented as

$$P_n(ab) = P_n(b|a)P_n(a)$$

$$P_n(b|a) = \frac{e^{(V_b+V_{ab})\mu^b}}{\sum_{b \in B_{na}} e^{(V_b+V_{ab})\mu^b}}$$

$$P(a) = \frac{e^{(V_a+V_a')\mu^a}}{\sum_{a \in A_n} e^{(V_a+V_a')\mu^a}}$$

$$V_a' = \frac{1}{\mu_b} ln(\sum_{b \in B_{na}} e^{(V_b+V_{ab})\mu^b})$$

For a nested logit model normalized from the top, the value of the scale parameter μ is fixed to 1. The default value of each nested parameter is 1. For each nest, the nest parameter μ^a must be greater than or equal to to be consistent with discrete choice theory. In the next chapter, I present the MNL and nested mode choice models.

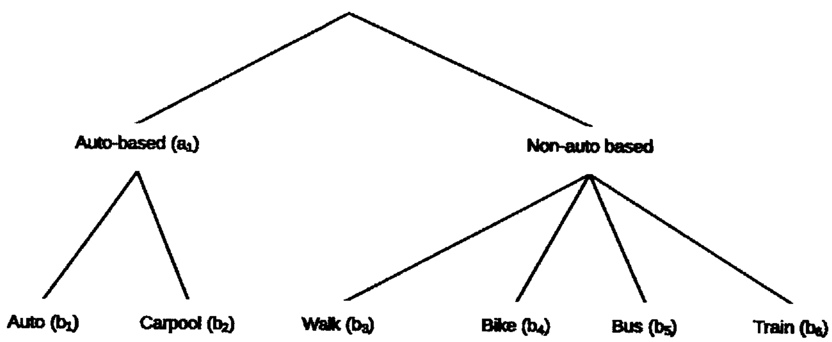

Figure 4-4: Example of a nested model

Chapter 5

Mode Choice Models

To examine the relationship between the built environment and travel mode choice in Boston, I estimated multinomial logit and nested logit models for home-based work trips.

The available modes from the survey data were classified into 6 main modes walk, bike, auto (drive alone), carpool, bus and train. Since my main interest is to find the effect of land use and built environment on mode choice between bus and rail, all the rail alternatives light rail, commuter rail and subway are grouped into rail and the bus alternatives (bus rapid transit lite and regular bus service) are grouped under the bus category.

The utility function associated with a mode only contains the variables that affect an individuals decision in choosing that mode. Like personal and household characteristics, land use and built environment attributes are the same across different alternatives. They are included in the model with alternative specific variables across different nests and across modes.

Table 5.1 shows the variables used in the model.

Table 5.1: Variable Definitions

Dependent variable	
CHOICE	1: WALK, 2: BIKE, 3: AUTO (drive alone), 4: CARPOOL, 5: BUS, 6: RAIL

Price variables	
wktim	Travel time by walk (minutes)
bktim	Travel time by bike (minutes)
crtim	In-vehicle travel time by car (drive alone and carpool) (minutes)
bstim	Total travel time by bus (minutes)
rltim	Total travel time by subway or commuter rail (minutes)
crcost/inc	Travel costs by car divided by household income (dollar/dollar)
crplcost/inc	Travel costs by car per traveler divided by household income (dollar/dollar)
Other trip attributes	
bikfac	Dummy variable for bike facilities at workplace; 1 if facilities provided
tottr	Total number of people traveling together
Personal and household characteristics	
hhbic	Number of bikes in the household
vehperlic	Number of household vehicles per license holder in the house
tpass	Dummy variable for availability of transit pass; 1 if available
female	Dummy variable for gender; 1 if female, 0 otherwise
Location and land use variables	
opopden	Population density in the household buffer
dpopden	Population density in the workplace buffer
demp	Employment density in the workplace TAZ

ocbd5	Dummy variable for location near CBD; 1 if household is within 5 miles of CBD
dcb5	Dummy variable for location near CBD; 1 if workplace is within 5 miles of CBD
ohhil	Herfindahl-Hirshman index for landuse mix in the household buffer/1000
hswlen	Total sidewalk length on both sides of the road/total road length

5.1 MNL Model

Table 5.2 describes the MNL model structure for individuals mode choices for home-based work trips followed by Table 5.3 which shows the estimated values of coefficients. The basic model does not contain land use and built environment attributes.

Table 5.2: Model structure for mode choice model for HBW trips

Coefficient	Variable list in mode specific utility function					
	Walk	Bike	Car	Carpool	Bus	Rail
ASC_WALK	constant	-	-	-	-	-
ASC_BIKE	-	constant	-	-	-	-
ASC_CAR	-	-	constant		-	-
ASC_CARPOOL	-	-	-	constant	-	-
ASC_BUS	-	-	-	-	constant	-
ASC_RAIL	-	-	-	-	-	constant
a_time	wktim	bktim	crtim	crtim	bstim	rltim
a_costpercapinc	-	-	crcost/inc	crplcost/inc		-
a_bikefacility	-	bikfac	-	-	-	-

a_tottravel_carpool	-	-	-	tottr	-	-
a_tottravel_bus	-	-	-	-	tottr	-
a_tottravel_rail	-	-	-	-	-	tottr
b_hhbic	-	hhbic	-	-	-	-
b_hhveh_car	-	-	vehperlic	-	-	-
b_tpass	-	-	-	-	tpass	tpass
b_female_walk	female	-	-	-	-	-
b_female_bike	-	female	-	-	-	-
b_female_carpool	-	-	-	female	-	-
b_female_transit	-	-	-	-	female	female
c_opopden_nmt	opopden	opopden	-	-	-	-
c_opopden_bus	-	-	-	-	opopden	-
c_opopden_rail	-	-	-	-	-	opopden
c_dpopden_nmt	dpopden	dpopden	-	-	-	-
c_dpopden_bus	-	-	-	-	dpopden	-
c_dpopden_rail	-	-	-	-	-	dpopden
c_demp_nmt						
c_demp_bus	-	-	-	-	demp	-
c_demp_rail	-	-	-	-	-	demp
c_odisttocbd_walk	ocbd5	-	-	-	-	-
c_odisttocbd_bike	-	ocbd5	-	-	-	-
c_odisttocbd_bus	-	-	-	-	ocbd5	-
c_odisttocbd_sub	-	-	-	-	-	ocbd5
c_ddisttocbd_bus	-	-	-	-	dcbd5	-
c_ddisttocbd_rail	-	-	-	-	-	dcbd5
c_oswlength_walk	hswlen	-	-	-	-	-
c_oswlength_transit	-	-	-	-	hswlen	hswlen
c_ohhi_walk	ohhi1	-	-	-	-	-

c_ohhi_bike	-	ohhil	-	-	-	-
c_ohhi_bus	-	-	-	-	ohhil	-

Table 5.3: MNL Mode choice model for HBW trips: Estimation Results

Coefficient for corresponding variable	Basic Model			Extended Model		
	Estimated value	Std. error	t-statistic	Estimated value	Std. error	t-statistic
ASC_WALK	2.14	0.43	4.92**	0.67	1.04 5	0.64
ASC_BIKE	-0.67	0.63	-1.06	-2.65	1.10	-2.40**
ASC_CARPOOL	-6.36	0.99	-6.45**	-6.51	1.02	-6.38**
ASC_BUS	0.62	1.06	0.56	1.79	1.56	1.15
ASC_RAIL	0.96	0.87	1.10	-0.68	1.22	-0.55
a_time	-0.04	0.00	-8.95**	-0.05	0.01	-8.61**
a_costperinc	-0.04	0.01	-2.79**	-0.04	0.01	-2.99**
a_bikefacility	1.13	0.43	2.64**	1.09	0.44	2.49**
a_tottravel_bus	-0.74	0.83	-0.90	-0.89	0.90	-0.98
a_tottravel_carpool	3.74	0.514	7.28**	3.82	0.52	7.30**
a_tottravel_rail	-0.773	0.611	-1.26**	-0.91	0.63	-1.43
b_hhbic	0.33	0.11	3.03**	0.29	0.11	2.59**
b_hhveh_car	1.97	0.40	4.97**	1.98	0.42	4.70**
b_tpass	2.54	0.45	5.66**	2.48	0.47	5.28**
b_female_walk	-0.04	0.32	-0.13	0.06	0.34	0.17
b_female_bike	-0.61	0.40	-1.50	-0.60	0.42	-1.43
b_female_carpool	0.94	0.53	1.77*	0.98	0.54	1.82*
b_female_transit	0.36	0.27	1.34	0.43	0.29	1.49

c_opopden_nmt				0.00	0.01	-0.05
c_opopden_bus				0.00	0.02	-0.22
c_opopden_rail				0.00	0.01	0.09
c_dpopden_nmt				0.01	0.01	1.23
c_dpopden_bus				-0.03	0.02	-1.38
c_dpopden_rail				-0.02	0.01	-1.29
c_demp_nmt				0.07	0.05	1.42
c_demp_bus				0.21	0.07	3.00**
c_demp_rail				0.12	0.05	2.55**
c_odisttocbd_walk				1.63	0.47	3.48**
c_odisttocbd_bike				1.13	0.48	2.37**
c_odisttocbd_bus				-1.27	0.57	-2.424*
c_odisttocbd_rail				-0.44	0.41	-1.07
c_ddisttocbd_bus				1.44	0.69	2.09**
c_ddisttocbd_rail				1.86	0.59	3.16**
c_oswlength_walk				-0.04	0.44	-0.08
c_oswlength_transit				0.38	0.38	1.00
c_ohhi_walk				0.01	0.07	0.03
c_ohhi_bike				0.13	0.10	1.30
c_ohhi_bus				-0.21	0.07	-2.78**
Initial log likelihood			-868.17		-868.17	
Final log likelihood			-500.96		-454.679	
Number of observations			573		573	
Rho-square			0.42		0.476	
Adjusted rho-square			0.40		0.433	

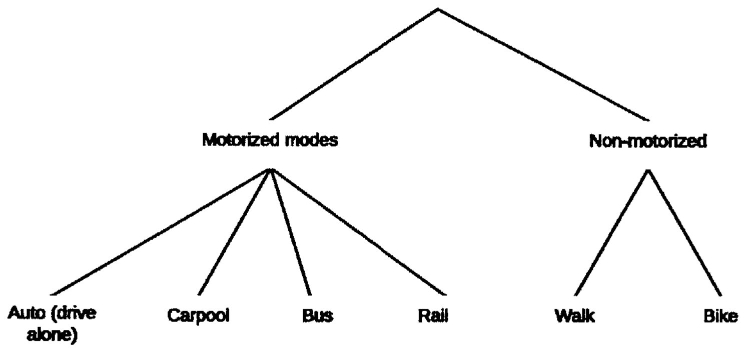

Figure 5-1: Nest structure of the estimated nested model

5.2 Nested Logit Model

Various nesting structures were considered. The best result came from nesting non-motorized modes and motorized modes in separate groups. The nest structure is shown in Figure 5-1. Table 5.2 shows the results of the nested logit model estimation.

Table 5.4: Nested logit model for mode choice of HBW trip

Coefficient for corresponding variable	Basic Model			Extended Model		
	Estimated value	Std. error	t-statistic	Estimated value	Std. error	t-statistic
ASC_WALK	2.20	0.41	5.36**	0.72	0.85	0.85
ASC_BIKE	0.63	0.54	1.17	-1.64	0.83	-1.97**
ASC_CARPOOL	-6.30	0.98	-6.41**	-6.48	1.02	-6.35**
ASC_BUS	0.55	1.05	0.53	1.67	1.54	1.09
ASC_RAIL	0.94	0.87	1.08	-0.77	1.19	-0.64
a_time	-0.03	0.00	-8.21**	-0.04	0.00	-7.93**

a_costperinc	-0.03	0.01	-2.38**	-0.04	0.01	-2.64**
a_bikefacility	0.55	0.28	2.00**	0.32	0.24	1.31
a_tottravel_bus	-0.76	0.82	-0.92	-0.89	0.90	-0.98
a_tottrave_carpool	3.73	0.51	7.26**	3.84	0.53	7.31**
a_tottravel_rail	-0.79	0.61	-1.30	-0.91	0.63	-1.45
b_hhbic	0.15	0.08	1.81*	0.10	0.06	1.79*
b_hhveh_car	1.99	0.39	5.08**	2.02	0.42	4.84**
b_tpass	2.56	0.45	5.73**	2.49	0.47	5.35**
b_female_walk	-0.09	0.29	-0.32	-0.09	0.30	-0.31
b_female_bike	-0.42	0.30	-1.41	-0.34	0.30	-1.14
b_female_carpool	0.92	0.53	1.74*	0.97	0.54	1.79*
b_female_transit	0.38	0.27	1.41	0.43	0.28	1.50
c_opopden_nmt				0.00	0.01	-0.17
c_opopden_bus				0.00	0.02	-0.25
c_opopden_rail				0.00	0.01	0.00
c_dpopden_nmt				0.02	0.01	1.60
c_dpopden_bus				-0.03	0.02	-1.33
c_dpopden_rail				-0.01	0.01	-1.26
c_demp_nmt				0.06	0.05	1.26
c_demp_bus				0.20	0.07	2.86**
c_demp_rail				0.12	0.05	2.51**
c_odisttocbd_walk				1.41	0.39	3.67**
c_odisttocbd_bike				1.46	0.38	3.81**
c_odisttocbd_bus				-1.22	0.56	-2.18**
c_odisttocbd_rail				-0.42	0.40	-1.05
c_ddisttocbd_bus				1.34	0.68	1.98**
c_ddisttocbd_rail				1.87	0.59	3.20**
c_oswlength_walk				0.10	0.28	0.48

c_oswlength_transit				0.42	0.36	1.16
c_ohhi_walk				0.01	0.06	0.16
c_ohhi_bike				0.15	0.07	2.18**
c_ohhi_bus				-0.20	0.07	-2.77**
Non-motorized nest	3.26	1.48	2.21**	5.50	2.19	2.51**
Motorized nest	1 (fixed)			1 (fixed)		
Initial log likelihood			-868.17		-868.17	
Final log likelihood			-498.27		-447.04	
Number of observations			573		573	
Rho-square			0.43		0.49	
Adjusted rho-square			0.40		0.44	

There are tests to identify which among the nested or non-nested model is better (Small and Hsiao, 1985, Hausman and McFadden, 1984). The other approach is to specify various nested and non-nested models based on common knowledge and estimate them using the same data set. The best model is chosen based on the estimates of the variable coefficients and structure coefficients (Zhang et al., 2002).

I conducted the McFadden IIA test on the extended MNL model (Appendix B). The t-statistic for the estimated IIA parameter for the non-motorized and motorized modes were both significantly different from 0 at a 95% level of confidence. This indicates that the IIA property does not hold among the motorized modes and among the non-motorized modes. Auto (drive alone), carpool, bus and rail modes might share some unobserved attributes. Similarly, walk and bike modes may also share some unobserved attributes. From the test results, we can say that the IIA property does not hold and the nested logit model is better than the MNL model for mode choice. The null hypothesis in nested models is that the structure coefficient is equal to one. In that case, the model collapses into a MNL model if the null hypothesis is accepted. The structure coefficient in our model is significantly greater than one since the model is normalized from the top.

The constant coefficients for bike, carpool and rail in the extended nested model are negative and significant meaning that individuals prefer to drive alone to work than choose any of these modes. Trip time has significant negative impact on travel demand. Travel costs per capita income have significant negative impact on auto-based modes. Costs are not considered for bus and rail modes because when people choose to take transit for work, they usually buy a pass to minimize their daily out of pocket costs and buy transit passes instead. The coefficient of the transit pass variable is positive and significant supporting this argument. Having bike facilities at workplace like secure parking spaces encourages more people to bike to work. Similarly, people from households with higher number of bikes or are more likely to bike to work. Individuals from households with more cars per license holder are more likely to drive alone to work. Similarly, if more people are traveling in the trip, they are more likely to carpool than use other modes. The coefficient for the gender dummy variable is insignificant for all modes except carpool, meaning women are more likely to carpool to work than men.

The coefficients for population density are insignificant for all modes indicating that population density is not an important factor that affects mode choice. However, the coefficient for employment density in the workplace TAZ is positive and significant for transit modes. People who work in places with higher employment density are more likely to take the bus or train to work. One possible reason for this is high employment TAZs, like areas around CBD, are more likely to be better connected by transit than places with lower employment density. The employment density coefficient for buses is higher than for rail suggesting that if we control for other factors, people are more likely to choose a bus over rail. The distance of the household from CBD is statistically significant for all modes except rail. If a household is within

5 miles of CBD, an individual is more likely to walk or bike to work than take transit. This makes sense since if the home and work trips are both close to CBD, people would prefer to walk or bike and if the workplace is in the suburbs, people may find driving more convenient than bus or rail modes.

On the contrary, if the workplace is within 5 miles from CBD, people choose transit over other modes. This may be because parking is a hassle closer to the CBD and the CBD is well connected to other parts of the metropolitan region by transit. People prefer trains over buses to get to the CBD, probably since trains are, often, more direct and have their own right of way unlike buses.

The HHI coefficient is negative and significant for bus indicating that higher land use diversity encourages more bus travel to work, as expected. Individuals can finish smaller chores on their way to the bus stop. Besides, walking to the bus stop and waiting may be perceived less cumbersome with a higher diversity in land use in the area. The coefficient for mixed use around the household for rail was removed as it was insignificant and did not improve the model. For the same reason, the mixed land use coefficient in the workplace buffer was also removed. The coefficient for diversity in land use for bikes is positive and significant implying that people tend to bike less in mixed use areas. Mixed use areas often have more foot and vehicular traffic which may make it more inconvenient to bike in such areas. The diversity coefficient for walking is insignificant.

The coefficient for sidewalk length is positive indicating that people are more likely to walk or take transit if there is a continuous network of sidewalks on both sides of a road. However, the coefficient is insignificant. Other design variables were used to estimate the model including number of four way intersections in the household and workplace buffer, number of cul-de-sacs and cul-de-sacs per intersection. However, none of the variables improved the model.

The result of the models indicate that very few land use and built environment variables were significant for home based work trips. The neighborhood design characteristics and population density were all insignificant. There was a strong relationship between location of home and workplace with respect to the central business district or downtown Boston.

The next chapter summarizes the conclusion of the models and possible policy implications.

Chapter 6

Conclusion

In the previous chapter, I presented results from the nested logit model for home-based work trips examining the role of land use and the built environment in shaping an individual's mode choice for work trips. In this chapter, I draw conclusions from the results of the model. Finally, I highlight the shortcomings of this study and outline ways to extend it for future research.

6.1 Conclusion and Discussion

The model outcomes show that trip attributes affect mode choice for the home-based journey to work significantly. Household and personal characteristics and built environment variables do affect mode choice, but not always significantly.

As expected, the travel time variable affects all modes negatively in a statistically significant manner. The coefficient for monetary cost variable (included as cost/income) affects auto-based modes negatively and is significant. Individuals who use public transit modes to work usually purchase a transit pass for daily travel. For such individuals, the monetary cost per day is apparently perceived as minimal. Personal and household characteristics such as age, ethnicity, home ownership and residence type do not affect mode choice significantly. All of them were removed from the final model except gender. However, coefficients of household characteristics directly related to travel such as number of vehicles per license holder and transit pass ownership are significant. Among the built environment and land use variables, only the relative location-based variables and land use mix affect the mode choice significantly.

While considering these results, we must take into account that we have only considered home-based work trips. For working individuals, travel time, cost and comfort is more important than secondary factors such as neighborhood street design or density. Traveling to work is a part of daily routine unlike home-based other trips which are less frequent and which may have more flexible destinations. Since individuals often know the neighborhood around their home and workplace well, factors such as street design and density would not matter as much as they would in a lesser known neighborhoods. The distance from CBD captures the agglomeration effects of the downtown which is well connected with the rest of the metro area. Hence, people working in high employment density areas such as the CBD are more likely to use transit.

Zhang (2002) did a similar mode choice analysis for work and non-work trips in Boston and Hong Kong and noted that land use variables that are statistically significant work in the expected direction and encourage non-auto modes. However, he observed that the land use variables displayed a varying level of significance for mode choice based on the trip origin and destination and the trip purpose. For home-based work trips, people primarily considered trip attributes, mainly time and cost, to choose their mode to work.

Most built environment factors affect bus and rail modes in the same direction. There are only small differences in the magnitude of the bus coefficients from the rail coefficients. While comparing between bus and rail, built environment variables that are more 'visible', such as employment density and mixed land use, increase the likelihood of choosing the bus. The nested model results show that for a given employment density at work place, controlling for other factors, people are more likely to choose bus over rail. Similarly, a more diverse land use around a household's neighborhood makes it more likely for people to choose bus. For rail, the land use diversity coefficient is insignificant. However, the results do not show any big difference on how land use and built environment affects bus and rail modes differently.

6.2 Shortcomings

The estimated model has several limitations in its variable specification and data.

Specifying monetary cost for home-based work trips is difficult for transit trips. Often, individuals who take public transit modes to work buy a pass that requires them to pay a monthly or weekly amount which is much cheaper than individual trip costs. For such individuals, the daily out-of-pocket cost for travel is almost negligible and hence, quantifying monetary cost of travel for such individuals is difficult. Apart from this, the MBTA has flat fares for buses and subways which means that people traveling longer distances pay a smaller charge per mile than people traveling short distances in transit modes. Thus, finding the best way to specify transit costs is difficult. We may expect a similar effect influences auto trips, since vehicle purchase is a sunk cost and parking costs may be the most immediately perceived cost to the traveler; nonetheless, auto costs do have a significant coefficient in my models.

Another major shortcoming was the lack of a reliable road and transit network required to calculate travel time for auto and transit accurately. The TransCAD network does not have centroids for every block and hence, each block origin and destination block had to be related to the nearest TAZ centroid to calculate trip attributes. This creates inaccuracies of unknown effect in model estimation. The MTS data does not mention the specific bus mode or rail mode used by every transit rider. As a result, it was difficult to tell the exact transit type (e.g., BRT, light rail) that an individual used to travel between an OD pair that is serviced by multiple transit modes.

6.3 Future Research

There are several ways of extending on this research. A similar mode choice model can be specified for home-based non-work trips to examine if the built environment affects peoples' choices differently for such trips. Another interesting topic of study could be to analyze how people perceive monetary travel costs and what is the best way to specify them for different trip types and different transit fare payment media. With more detailed data of mode choice, a better model can be estimated by incorporating different bus and rail modes separately. Yet another contribution would be to create a walkability metric for the neighborhood based on the built environment variables. By studying the effect of trip chaining on mode choice and one can recommend a transit network structure that minimizes the disutility of a tour. Finally, the potential problem of residential self-selection on desired mode choice warrants further research in the Boston case.

To conclude, people may perceive bus and rail trips differently for most trips based on various tangible and intangible factors. However, for home-based work trips, my model shows that there is no major difference in the way people choose between the two modes. Trip attributes such as travel time and travel cost are still more important for such trips.

Appendix A

Dealing with Unknown Income

Income in the household survey data is given in categories from 1 to 8. The income for 2597 households is known in my study area. 235 households refused to provide their income. Ultimately, these households were removed from my analysis. I predicted the category in which the income of these unknown-income-households would fall based on other socio-demographic factors: high (household income greater than $100,000), middle (household income between $50,000 and $100,000) and low income (household income less than $50,000). Figure A-1 shows a spatial distribution of the households that refused to disclose their income.

These households are scattered across the study area. Their geographical location cannot be used to predict their income category. Household income was predicted based on the number of household workers, household size, number of students, vehicle ownership, bike ownership, mobile phone ownership, household density in a half mile buffer around the block, Hispanic ethnicity and house ownership. Other factors such as distance from CBD, residence type, income per capita and interactions between different factors were also considered but the resulting income estimation was not as good. The following regression model (using R) was used to predict income:

$$\begin{aligned} income = & 7887.6 + 6116.4 \times HHVEH + 4779.6 \times HHBIC + 3795.5 \times HHSIZ \\ & + 22117.4 \times HHWRK + 23139.8 \times OWN - 16405.8 \times HISP + 6585.8 \times CELL \\ & - 41013 \times HHSIZ \times HHSTU + 621.1 \times RESDEN \end{aligned}$$

(A.1)

Where

- HHVEH = household vehicle ownership
- HHBIC = household bicycle ownership
- HHSIZ = household size
- HHWRK = number of working people in the household
- OWN = dummy variable for home ownership
- HISP = dummy variable for Hispanic households
- CELL = mobile phone ownership
- RESDEN = density of housing units in the neighborhood

Multiple R-squared: 0.3702

Adjusted R-squared: 0.3658

F-statistic: 83.8 on 9 and 1283 DF

P-value: $< 2.2e\text{-}16$

The comparison of the predicted and actual values from validation are shown in Figure A-2. The model overestimates household income.

Figure A-3 shows the distribution of the known and the predicted income level of the households. A large proportion of households that did not provide their income were predicted to be middle income households. Fewer low and high income houses refused to provide their income. Excluding the households which did not provide their income in the survey will have some effect on the results, especially in case of predicting mode choice for middle income category households. Since the model overestimates incomes, the proportion of low income households will be slightly larger than that estimated. At the same time, the proportion high income households will be lesser than estimated. I believe the effect of excluding these households will not be extreme since they are spread across various income levels.

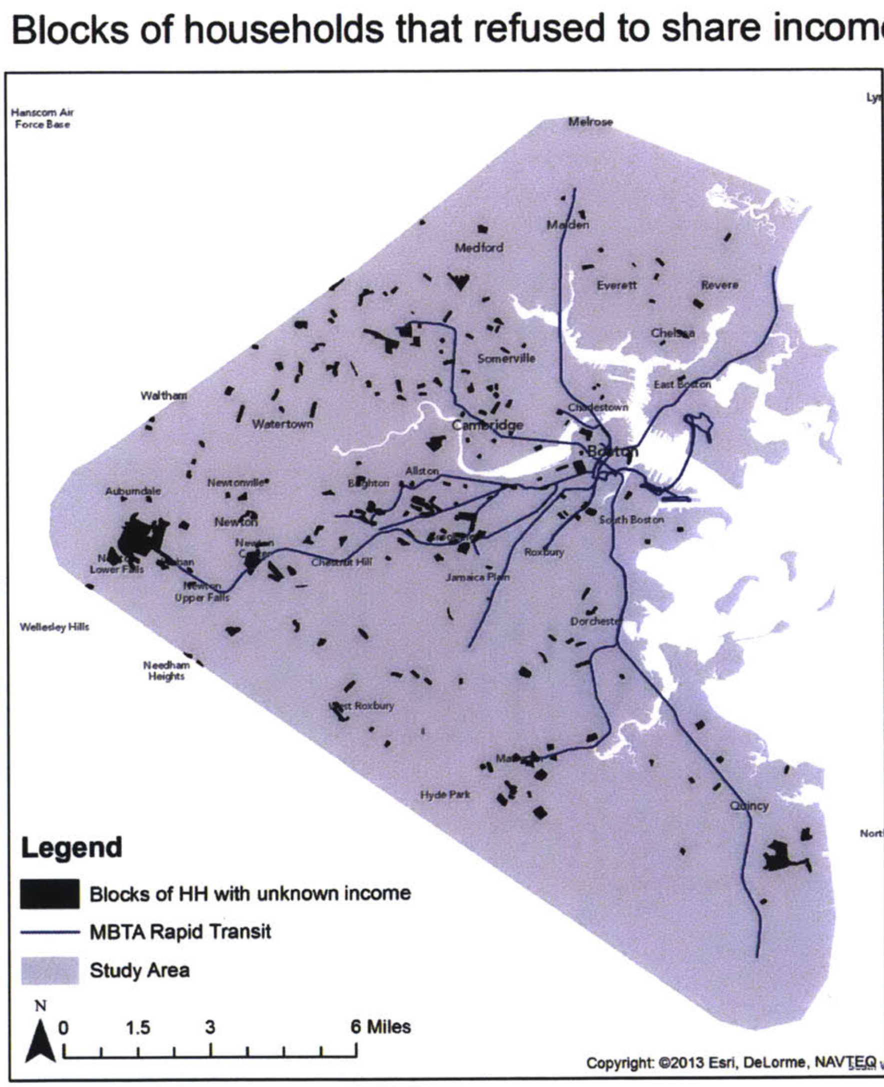

Figure A-1: Spatial distribution of households blocks that did not disclose their income

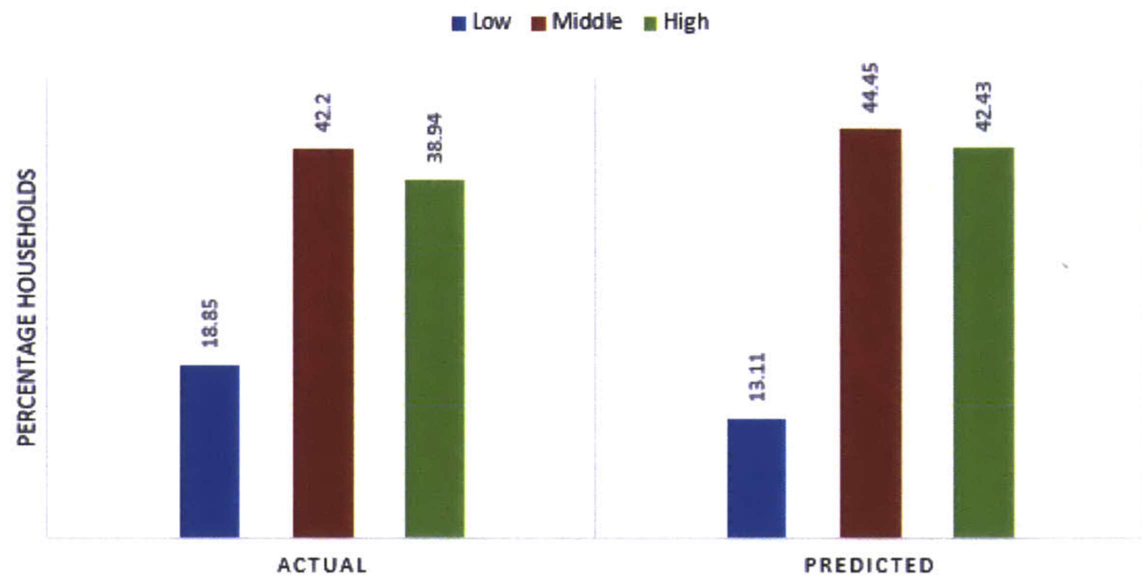

Figure A-2: Model Validation for Income

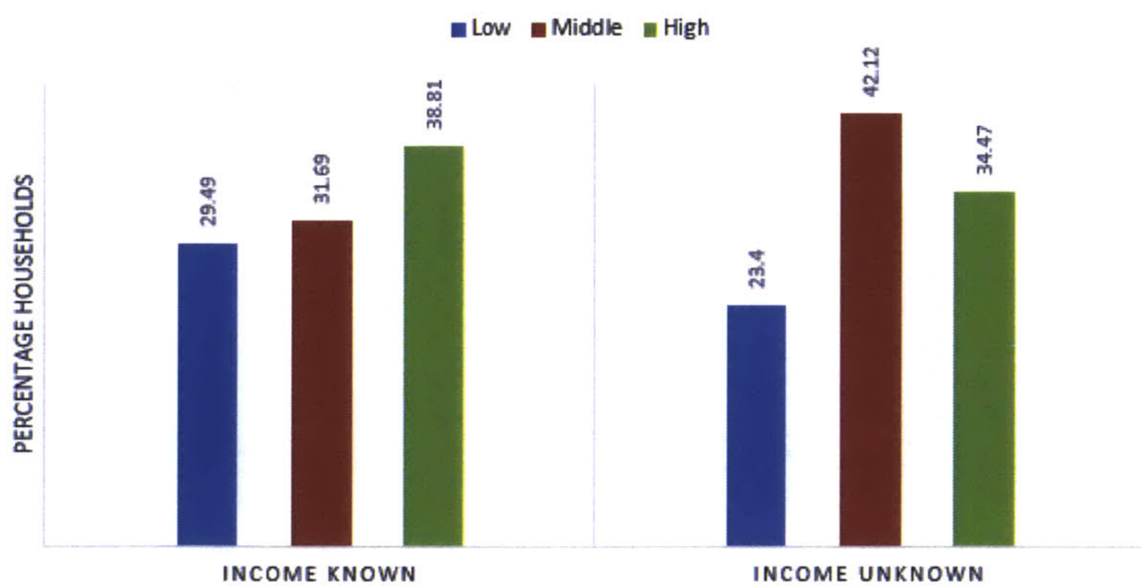

Figure A-3: Distribution of known income households and the estimated income households

Appendix B

Testing the IIA Assumption - McFadden IIA Test

It is possible that there are common unobserved attributes between two or more modes. In such a case, the coefficients of the modes may be correlated. To identify such possible correlation, I have performed the McFadden IIA test (Hausman and McFadden, 1984) on the extended multinomial logit (MNL) model specified in Chapter 5. I test this model for correlation among the motorized modes (drve alone auto, carpool, bus and rail) and among non-motorized modes (walk and bike). A new model with IIA auxiliarly variables is specified and estimated.

Table B.1 shows the results of the estimated model.

Table B.1: McFadden IIA test results

Coefficient	Value	Std err	t-test
ASC_BIKE	-1.76	1.14	-1.55
ASC_BUS	2.76	1.71	1.61
ASC_CARPOOL	-10.8	1.60	-6.78**
ASC_RAIL	-1.62	1.22	-1.32
ASC_WALK	1.70	1.14	1.49
a_time	-0.0570	0.00754	-7.55**
a_costpercapinc	-0.0569	0.0150	-3.80**

Coefficient	Value	Std err	t-test
a_tottravel_bus	-2.06	1.15	-1.79*
a_tottravel_carpool	6.18	0.857	7.21**
a_tottravel_rail	-1.43	0.645	-2.21**
a_bikefacility	0.811	0.470	1.72*
b_hhbic	0.217	0.120	1.81*
b_hhveh_car	2.82	0.493	5.72**
b_tpass	3.83	0.622	6.16**
b_female_bike	-0.351	0.444	-0.79
b_female_carpool	1.60	0.562	2.84**
b_female_transit	0.595	0.288	2.07**
b_female_walk	-0.00830	0.364	-0.02
c_ddisttocbd_bus	1.77	0.670	2.64
c_ddisttocbd_sub	2.83	0.652	4.34**
c_demp_bus	0.294	0.0775	3.80**
c_demp_nmt	0.123	0.0551	2.24**
c_demp_sub	0.179	0.0510	3.51**
c_dpopden_bus	-0.0329	0.0191	-1.72*
c_dpopden_nmt	0.0123	0.0118	1.05
c_dpopden_sub	-0.0231	0.0117	-1.96**
c_odisttocbd_bike	1.38	0.501	2.76**
c_odisttocbd_bus	-1.60	0.589	-2.71**
c_odisttocbd_sub	-0.549	0.406	-1.35
c_odisttocbd_walk	1.71	0.501	3.41**
c_ohhi_bike	0.119	0.103	1.16
c_ohhi_bus	-0.334	0.0795	-4.19**
c_ohhi_walk	-0.0269	0.0761	-0.35
c_opopden_bus	-0.00418	0.0203	-0.21
c_opopden_nmt	-0.000757	0.0140	-0.05
c_opopden_sub	0.00254	0.0142	0.18

Coefficient	Value	Std err	t-test
c_oswlength_transit	0.641	0.383	1.67*
c_oswlength_walk	-0.0293	0.469	-0.06
d_iia_12	1.12	0.513	2.19**
d_iia_3456	-0.646	0.184	-3.52**

Number of observations: 566

Null log-likelihood: -857.208

Final log-likelihood: -435.329

Likelihood ratio test: 843.757

Rho-square: 0.492

Adjusted rho-square: 0.445

The t-statistic for the estimated IIA parameter for the non-motorized modes (d_iia_12) and motorized modes (d_iia_3456) were both significantly different from 0 at a 95% level of confidence. This indicates that the IIA property does not hold among the motorized modes and among the non-motorized modes. Auto (drive alone), carpool, bus and rail modes might share some unobserved attributes. Similarly, walk and bike modes may also share some unobserved attributes. From the test results, we can say that the IIA property does not hold and the nested logit model is better than the MNL model for mode choice.

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