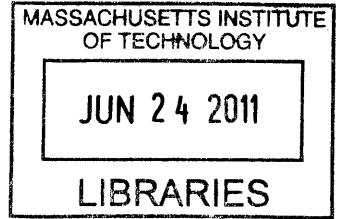


Incorporating Livability Benefits into the Federal Transit Administration New Starts Project Evaluation Process through Accessibility-Based Modeling

By

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B.S. Civil Engineering
Northeastern University, 2006



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
June 2011

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Abstract

The Department of Transportation's announcement of the "Livability Initiative" for major transit projects in January 2010 has prompted the Federal Transit Administration (FTA) to reassess the criteria used in the evaluation of New Starts projects. There is concern that the evaluation criteria for transit project benefits are too limiting and that not all project benefits are accounted for in the best way. Specifically, the FTA New Starts Program is beginning to shift away from the current measure of user benefits, a calculation of changes in mobility measured by hours of travel time saved, towards criterion based on the concept of livability. As of this writing, the FTA has yet to define livability and establish metrics that will be adopted in the next rulemaking process.

This thesis evaluates the current FTA New Starts framework and presents an improved approach for measuring some of the livability benefits of transit projects through accessibility-based modeling. It is argued in this thesis that accessibility to essential services, such as employment, education, health care, and recreation, is a key component of livability. Furthermore, the concept of accessibility is both understandable and can be measured from existing data sources, and thus is an ideal building block from which to reconsider how transit project benefits should be evaluated in the New Starts process.

Two transportation modeling software packages, TransCAD and Cube Voyager, are used to analyze the accessibility benefits of the MBTA Green Line Extension Project to illustrate the potential of accessibility measures in the project evaluation process. Findings suggest that gravity measures are more appropriate than isochrone measures when evaluating the accessibility benefits of proposed projects. The positive relationship between accessibility and mode share suggests that accessibility measures can serve as a valuable tool in the preliminary planning stages to quickly evaluate alternatives prior to the completion of a conventional four-step travel demand model and further justifies the use of accessibility measures in a livability-based project evaluation process.

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Acknowledgements

This thesis would not have been possible without the support of the following people, to whom I owe my deepest gratitude:

Fred Salvucci and Mikel Murga, thank you for your guidance and your many valuable contributions to this thesis; the opportunities you have provided me at MIT have made my graduate school experience more enriching than I ever imagined.

Professor Nigel Wilson and John Attanucci, thank you for your input and support of the Transit Research Group.

The Central Transportation Planning Staff, especially Scott Peterson, Ian Harrington, and Bruce Kaplan, thank you for providing me with an educational internship experience as well as feedback on this research project.

Fellow colleagues and labmates in the MST program, thank you for your inspiration and friendship.

My friends and family, especially my parents, thank you for your love and encouragement.

Colin, thank you for your patience and thoughtfulness during the past year and a half.

Kate Fichter, Michael Lambert, and Kathleen Ziegenfuss, thank you for your support of this research project.

Table of Contents

Acknowledgements	5
List of Figures.....	11
List of Tables.....	17
List of Equations	18
1 Introduction	19
1.1 Objectives	20
1.2 Contribution to the MBTA Green Line Extension Project	21
1.3 Thesis Organization	22
2 Livability, Accessibility, and their Connection	23
2.1 Livability	23
2.2 Accessibility	26
2.2.1 Distinction Between Accessibility and Mobility	28
2.3 The Connection Between Livability and Accessibility	28
2.4 Accessibility Measures	34
2.4.1 Isochrone Accessibility Measures	34
2.4.2 Gravity-based Accessibility Measures	35
2.4.3 Utility-based Accessibility Measures	36
2.4.4 Person-based Accessibility Measures	38
2.4.5 Use of Accessibility Measures in FTA New Starts	38
3 FTA Transit Infrastructure Project Evaluation	40
3.1 Current FTA New Starts Project Development Process	40
3.2 Current FTA New Starts Rating Criteria	43
3.2.1 Summary Rating	43
3.2.2 Project Justification Rating	43
3.2.2.1 Economic Development	44
3.2.2.2 Mobility Improvements	45
3.2.2.3 Environmental Benefits	45
3.2.2.4 Operating Efficiencies	45
3.2.2.5 Cost Effectiveness	46
3.2.2.6 Public Transportation Supportive Land Use	47

3.2.2.7	Other Factors.....	47
3.2.3	Financial Rating.....	47
3.2.3.1	Non-Section 5309 Share	48
3.2.3.2	Capital Finances	48
3.2.3.3	Operating Finances	48
3.2.4	The Critical Importance of Transportation System User Benefits	49
3.3	Assessment of New Starts Rating Criteria	50
3.4	Potential Changes to New Starts	53
3.4.1	Environmental Benefits	53
3.4.2	Economic Benefits	54
3.4.3	Social Equity Benefits	54
3.4.4	Accessibility Benefits	55
4	MBTA Green Line Extension Project	56
4.1	Context	56
4.1.1	Proposed Project	57
4.1.2	Land Use, Demographics, and Travel Behavior	58
4.2	Project Benefits	64
5	Model Development.....	67
5.1	Geographic Coverage and Structure	67
5.2	Transportation Network	68
5.2.1	Transit Routes	71
5.2.2	Park and Ride	72
5.3	Socioeconomic Data	73
5.4	Model Steps Considered	74
5.4.1	Calculation of Travel Time and Generalized Cost	75
5.4.2	Trip Generation.....	75
5.4.3	Trip Distribution	76
5.4.3.1	Friction Factor Estimation	87
5.5	Model Scenarios	88
5.6	Model Limitations	89
6	Accessibility Analysis	91
6.1	Isochrone Accessibility Estimation	91

6.2	Gravity Accessibility Estimation	93
6.3	Accessibility to Employment	100
6.3.1	Employment Opportunities	100
6.3.2	Isochrone Accessibility to Employment	104
6.3.3	Gravity Accessibility to Employment	107
6.4	Accessibility to Shopping	110
6.4.1	Shopping Opportunities	110
6.4.2	Isochrone Accessibility to Shopping	113
6.4.3	Gravity Accessibility to Shopping	115
6.5	Accessibility to Education	117
6.5.1	Education Opportunities	117
6.5.2	Isochrone Accessibility to Education	119
6.5.3	Gravity Accessibility to Education	122
6.6	Accessibility to Health Care	124
6.6.1	Health Care Opportunities	124
6.6.2	Isochrone Accessibility to Health Care	126
6.6.3	Gravity Accessibility to Health Care	128
6.7	Accessibility to Recreation	130
6.7.1	Recreation Opportunities	130
6.7.2	Isochrone Accessibility to Recreation	132
6.7.3	Gravity Accessibility to Recreation	134
6.8	Recommendations	136
6.8.1	Recommended Methodology for the Calculation of Accessibility Benefits.....	136
6.8.2	Recommended Opportunity Categories to Include in Accessibility Benefits	137
6.8.3	Example of a Potential FTA New Starts Accessibility Benefits Metric	138
7	Relationship Between Accessibility and Mode Share	140
7.1	Modeling Mode Share	140
7.2	Accessibility and Model Estimated Mode Share	143
7.3	Accessibility and Observed Mode Share	145
7.4	Summary of Findings	145
8	Conclusions	147
8.1	Summary	147

8.2	Areas of Future Research	150
8.3	Closing Remarks	152
	Bibliography	153
	Appendix A: Acronyms	157
	Appendix B: Accessibility Analysis to Transit-Accessible Employment	158
	Appendix C: Compilation of Accessibility Index Maps	165

List of Figures

Figure 2-1: Sustainability Triangle	24
Figure 2-2: Three Components of Sustainability	25
Figure 2-3: Accessibility Components and Relationships	27
Figure 2-4: Quality of Life Mind Map	29
Figure 2-5: Sustainability Mind Map	30
Figure 2-6: Livability Mind Map	31
Figure 2-7: Relationships Between Accessibility and Livability	32
Figure 2-8: Individual's Space-Time Prism	38
Figure 3-1: FTA New Starts Planning and Project Development Process	41
Figure 3-2: FTA New Starts Rating Process	43
Figure 3-3: Value of Time as a Function of Time Saved	52
Figure 4-1: MBTA Rapid Transit System	57
Figure 4-2: Proposed Green Line Extension Project	58
Figure 4-3: Population Density	59
Figure 4-4: Job Density	59
Figure 4-5: Flows of Somerville Residents to Town of Employment	60
Figure 4-6: Flows of Somerville Employees from Town of Residence	61
Figure 4-7: Existing Corridor Land Use	62
Figure 4-8: EEA Defined Environmental Justice Populations	63
Figure 4-9: Home to Work Mode Share	64
Figure 5-1: Regional TAZ Map	68
Figure 5-2: Central Business District TAZ Map	68
Figure 5-3: Transportation Network Links	70
Figure 5-4: Close-up of Model at Porter Square Station	70

Figure 5-5: Regional Transit Route Map	71
Figure 5-6: Central Business District Transit Route Map	71
Figure 5-7: Park and Ride Restrictions	73
Figure 5-8: Home Based Work Survey Trip Length Distribution	77
Figure 5-9: Model versus Survey Worker Trip Flows – All Towns	79
Figure 5-10: Model versus Survey Worker Trip Flows – All Towns Except Boston	79
Figure 5-11: Model versus Survey Home Based Shop Trip Flows – All Towns	80
Figure 5-12: Model versus Survey Home Based Shop Trip Flows – All Towns Except Boston	80
Figure 5-13: Model versus Survey Home Based School Trip Flows – All Towns	81
Figure 5-14: Model versus Survey Home Based School Trip Flows –All Towns Except Boston	81
Figure 5-15: Model versus Survey Home Based Other Trip Flows – All Towns	82
Figure 5-16: Model versus Survey Home Based Other Trip Flows – All Towns Except Boston	82
Figure 5-17: Model versus Survey Home Based Recreation Trip Flows – All Towns	83
Figure 5-18: Model versus Survey Home Based Recreation Trip Flows – All Towns Except Boston	83
Figure 5-19: Home Based Work Trip Length Distribution	84
Figure 5-20: Home Based Shop Trip Length Distribution	85
Figure 5-21: Home Based School Trip Length Distribution	85
Figure 5-22: Home Based Other Trip Length Distribution	86
Figure 5-23: Home Based Recreation Trip Length Distribution	86
Figure 5-24: Friction Factors By Trip Purpose	87
Figure 6-1: Employment Gravity Function Estimation	94
Figure 6-2: Shopping Gravity Function Estimation	95
Figure 6-3: Education Gravity Function Estimation	96
Figure 6-4: Health Care Gravity Function Estimation.....	97
Figure 6-5: Recreation Gravity Function Estimation	98

Figure 6-6: 2010 Employment (Regional View)	101
Figure 6-7: 2010 Employment (Local View)	101
Figure 6-8: 2030 Employment (Regional View)	103
Figure 6-9: 2030 Employment (Local View)	103
Figure 6-10: 2010 Existing Conditions Employment Accessibility – Isochrone Measure	106
Figure 6-11: 2030 Baseline Scenario Employment Accessibility – Isochrone Measure	106
Figure 6-12: 2030 Build Scenario Employment Accessibility – Isochrone Measure	106
Figure 6-13: 2010 Existing Conditions Employment Accessibility – Gravity Measure	109
Figure 6-14: 2030 Baseline Scenario Employment Accessibility – Gravity Measure	109
Figure 6-15: 2030 Build Scenario Employment Accessibility – Gravity Measure	109
Figure 6-16: 2010 Shopping Opportunities (Regional View)	111
Figure 6-17: 2010 Shopping Opportunities (Local View)	111
Figure 6-18: 2030 Shopping Opportunities (Regional View)	112
Figure 6-19: 2030 Shopping Opportunities (Local View)	112
Figure 6-20: 2010 Existing Conditions Shopping Accessibility – Isochrone Measure	114
Figure 6-21: 2030 Baseline Scenario Shopping Accessibility – Isochrone Measure	114
Figure 6-22: 2030 Build Scenario Shopping Accessibility – Isochrone Measure	114
Figure 6-23: 2010 Existing Conditions Shopping Accessibility – Gravity Measure	116
Figure 6-24: 2030 Baseline Scenario Shopping Accessibility – Gravity Measure	116
Figure 6-25: 2030 Build Scenario Shopping Accessibility – Gravity Measure	116
Figure 6-26: Education Opportunities (Regional View)	118
Figure 6-27: Education Opportunities (Local View)	118
Figure 6-28: 2010 Existing Conditions Education Accessibility (25 Min.) – Isochrone Measure.....	120
Figure 6-29: 2030 Baseline Scenario Education Accessibility (25 Min.) – Isochrone Measure	120
Figure 6-30: 2030 Build Scenario Education Accessibility (25 Min.) – Isochrone Measure	120
Figure 6-31: 2010 Existing Conditions Education Accessibility (35 Min.) – Isochrone Measure	121

Figure 6-32: 2030 Baseline Scenario Education Accessibility (35 Min.) – Isochrone Measure	121
Figure 6-33: 2030 Build Scenario Education Accessibility (35 Min.) – Isochrone Measure	121
Figure 6-34: 2010 Existing Conditions Education Accessibility- Gravity Measure	123
Figure 6-35: 2030 Baseline Scenario Education Accessibility – Gravity Measure	123
Figure 6-36: 2030 Build Scenario Education Accessibility – Gravity Measure	123
Figure 6-37: Health Care Opportunities (Regional View)	125
Figure 6-38: Health Care Opportunities (Local View)	125
Figure 6-39: 2010 Existing Conditions Health Care Accessibility – Isochrone Measure	127
Figure 6-40: 2030 Baseline Scenario Health Care Accessibility – Isochrone Measure	127
Figure 6-41: 2030 Build Scenario Health Care Accessibility –Isochrone Measure	127
Figure 6-42: 2010 Existing Conditions Health Care Accessibility – Gravity Measure	129
Figure 6-43: 2030 Baseline Scenario Health Care Accessibility –Gravity Measure	129
Figure 6-44: 2030 Build Scenario Health Care Accessibility – Gravity Measure	129
Figure 6-45: Recreation Opportunities (Regional View)	131
Figure 6-46: Recreation Opportunities (Local View)	131
Figure 6-47: 2010 Existing Conditions Recreation Accessibility – Isochrone Measure	133
Figure 6-48: 2030 Baseline Scenario Recreation Accessibility – Isochrone Measure	133
Figure 6-49: 2030 Build Scenario Recreation Accessibility – Isochrone Measure	133
Figure 6-50: 2010 Existing Conditions Recreation Accessibility – Gravity Measure	135
Figure 6-51: 2030 Baseline Scenario Recreation Accessibility – Gravity Measure	135
Figure 6-52: 2030 Build Scenario Recreation Accessibility – Gravity Measure	135
Figure 7-1: Ridership Forecast Accuracy of New Starts Projects	141
Figure 7-2: Model Estimated HBW Transit and Walk Mode Share for Year 2000	142
Figure 7-3: CTPP Observed HBW Transit and Walk Mode Share for Year 2000	142
Figure 7-4: Model Estimated HBW Mode Share Versus CTPP Observed HBW Mode Share	143
Figure 7-5: Model HBW Mode Share Versus Employment Accessibility	144

Figure 7-6: CTPP HBW Mode Share Versus Employment Accessibility	145
Figure B-1: 2010 Transit-Accessible Employment (Regional View)	159
Figure B-2: 2010 Transit-Accessible Employment (Local View)	159
Figure B-3: 2030 Transit-Accessible Employment (Regional View)	160
Figure B-4: 2030 Transit-Accessible Employment (Local View)	160
Figure B-5: 2010 Existing Conditions Transit-Accessible Employment Accessibility – Isochrone Measure	162
Figure B-6: 2030 Baseline Scenario Transit-Accessible Employment Accessibility – Isochrone Measure	162
Figure B-7: 2030 Build Scenario Transit-Accessible Employment Accessibility – Isochrone Measure ..	162
Figure B-8: 2010 Existing Conditions Transit-Accessible Employment Accessibility – Gravity Measure	164
Figure B-9: 2030 Baseline Scenario Transit-Accessible Employment Accessibility–Gravity Measure ...	164
Figure B-10: 2030 Build Scenario Transit-Accessible Employment Accessibility–Gravity Measure	164
Figure C-1: 2010 Existing Conditions Employment Accessibility – Isochrone Measure	165
Figure C-2: 2030 Baseline Scenario Employment Accessibility – Isochrone Measure	165
Figure C-3: 2030 Build Scenario Employment Accessibility – Isochrone Measure	165
Figure C-4: 2010 Existing Conditions Employment Accessibility – Gravity Measure	166
Figure C-5: 2030 Baseline Scenario Employment Accessibility – Gravity Measure	166
Figure C-6: 2030 Build Scenario Employment Accessibility – Gravity Measure	166
Figure C-7: 2010 Existing Conditions Shopping Accessibility – Isochrone Measure	167
Figure C-8: 2030 Baseline Scenario Shopping Accessibility – Isochrone Measure	167
Figure C-9: 2030 Build Scenario Shopping Accessibility –Isochrone Measure	167
Figure C-10: 2010 Existing Conditions Shopping Accessibility – Gravity Measure	168
Figure C-11: 2030 Baseline Scenario Shopping Accessibility – Gravity Measure	168
Figure C-12: 2030 Build Scenario Shopping Accessibility – Gravity Measure	168

Figure C-13: 2010 Existing Conditions Education Accessibility (25 Min.) – Isochrone Measure	169
Figure C-14: 2030 Baseline Scenario Education Accessibility (25 Min.) – Isochrone Measure	169
Figure C-15: 2030 Build Scenario Education Accessibility (25 Min.) – Isochrone Measure	169
Figure C-16: 2010 Existing Conditions Education Accessibility (35 Min.) – Isochrone Measure	170
Figure C-17: 2030 Baseline Scenario Education Accessibility (35 Min.) – Isochrone Measure	170
Figure C-18: 2030 Build Scenario Education Accessibility (35 Min.) – Isochrone Measure	170
Figure C-19: 2010 Existing Conditions Education Accessibility- Gravity Measure	171
Figure C-20: 2030 Baseline Scenario Education Accessibility – Gravity Measure	171
Figure C-21: 2030 Build Scenario Education Accessibility – Gravity Measure	171
Figure C-22: 2010 Existing Conditions Health Care Accessibility – Isochrone Measure	172
Figure C-23: 2030 Baseline Scenario Health Care Accessibility – Isochrone Measure	172
Figure C-24: 2030 Build Scenario Health Care Accessibility –Isochrone Measure	172
Figure C-25: 2010 Existing Conditions Health Care Accessibility – Gravity Measure	173
Figure C-26: 2030 Baseline Scenario Health Care Accessibility –Gravity Measure	173
Figure C-27: 2030 Build Scenario Health Care Accessibility – Gravity Measure	173
Figure C-28: 2010 Existing Conditions Recreation Accessibility – Isochrone Measure	174
Figure C-29: 2030 Baseline Scenario Recreation Accessibility – Isochrone Measure	174
Figure C-30: 2030 Build Scenario Recreation Accessibility – Isochrone Measure	174
Figure C-31: 2010 Existing Conditions Recreation Accessibility – Gravity Measure	175
Figure C-32: 2030 Baseline Scenario Recreation Accessibility – Gravity Measure	175
Figure C-33: 2030 Build Scenario Recreation Accessibility – Gravity Measure	175

List of Tables

Table 3-1: Cost Effectiveness Breakpoints	46
Table 3-2: Non-Section 5309 Rating Criteria	48
Table 4-1: Population and Employment Profiles	58
Table 4-2: Worker Flows To and From Somerville	61
Table 5-1: Model Link Statistics	69
Table 5-2: Transit Route Statistics	72
Table 5-3: Trip Generation Comparison	76
Table 5-4: Gamma Function Coefficients for Friction Factors	88
Table 6-1: Isochrone Accessibility Travel Time Thresholds	92

List of Equations

Equation 2-1: Isochrone Accessibility	35
Equation 2-2: Gravity-Based Accessibility	36
Equation 2-3: Utility-Based Accessibility	37
Equation 3-1: Transportation System User Benefits	49
Equation 5-1: Gamma Function	88
Equation 6-1: Employment Gravity Function	94
Equation 6-2: Shopping Gravity Function	96
Equation 6-3: Education Gravity Function	97
Equation 6-4: Health Care Gravity Function	98
Equation 6-5: Recreation Gravity Function	99
Equation 6-6: Isochrone Accessibility Index	104
Equation 6-7: Gravity Accessibility Index	107
Equation 6-8: Accessibility Benefits Metric	138
Equation 6-9: Corridor Accessibility Index	138

1 Introduction

“Through improved mobility, safety, security, economic opportunity and environmental quality, public transportation benefits every segment of American society – individuals, families, businesses, industries and communities – and supports important national goals and policies” (American Public Transportation Association, 2011). Additionally, public transportation shapes land use and increases accessibility to essential services and activities. Public transportation achieves these goals while decreasing the environmental footprint of an equivalent auto trip and at the same time generating areas with a high presence of people in the public realm. Cities across the Nation look ever more to additional investment in public transit to address these needs and provide increased quality of life to residents and visitors while decreasing the total costs of transportation.

Many of these projects are only made possible due to federal financial assistance received through the Federal Transit Administration’s discretionary New Starts program. As the demand for federal monetary assistance for local transit capital projects increases, competition for the limited funding the Federal Transit Administration (FTA) is authorized to commit is greater than ever. It is therefore essential that the evaluation criteria is able to distinguish deserving projects from the application stack and to ensure that the most worthy projects receive the federal funding often necessary for a transit project to be realized from planning through construction within each region and among regions.

The New Starts process can be applauded for incorporating a number of metrics in the evaluation of transit project costs and benefits. However, there is concern that the evaluation criteria for transit project benefits are too limiting and that not all project benefits are accounted for in the best way. As a result, the existing metrics may not discern the projects most deserving of federal or local investment. Additionally, the limited criteria discourage potential innovations that may enhance the quality of project proposals.

The United States Department of Transportation’s announcement of the “Livability Initiative” in January 2010 has prompted the FTA to reassess the criteria used in the evaluation of New Starts projects. Specifically, the FTA New Starts program is considering a shift away from the current measure of user benefits, a calculation of changes in mobility measured by hours of travel time saved, towards criteria based on a more encompassing concept of livability. In June 2010, the FTA released an Advance Notice of Proposed Rulemaking that formally announced FTA’s intention to revise their current approach and additionally asked for public input on how to measure the non-mobility benefits of transit projects. As

of this writing, the FTA has yet to establish new metrics that will be adopted in the next rulemaking process. In the meanwhile, it may be useful for applicants to document livability in their analysis to strengthen their case for funding.

Livability is a complex concept without a universally agreed upon definition. As a result, establishing evaluation metrics which capture all of the livability benefits of transit projects is a challenging undertaking. Accessibility to essential services, such as employment, shopping, education, health care, and recreation, is seen as a key component of livability. Furthermore, the concept of accessibility is both understandable and can be measured from existing data sources, and thus is an ideal building block from which to reconsider how transit project benefits should be evaluated in the New Starts process.

This thesis focuses on how to use accessibility measures in the FTA New Starts process as a way to incorporate some of the livability benefits of transit projects in the evaluation criteria. However, the concept of accessibility can also be used as a tool for the evaluation of local transportation project proposals. For example, accessibility measures can be used to evaluate and potentially improve proposed project alternatives in the early planning stages prior to a project's involvement in FTA New Starts. Accessibility can also be a constructive tool for metropolitan planning organizations (MPOs) in the evaluation of projects that are not eligible for New Starts funding, including local transit and highway proposals.

1.1 Objectives

The aim of this research is to present an improved livability-based framework for measuring transit project benefits in the FTA New Starts project evaluation process. The proposed framework is designed to improve the quality of planned projects as well as facilitate public understanding of the decision making criteria that may further enhance public support for transit capital investments. This will be approached by evaluating how project benefits are currently measured in the FTA New Starts criteria and assessing potential new metrics through the use of accessibility-based modeling. These new metrics can be adopted by the FTA in the next rulemaking process.

This thesis answers the following research questions:

- Can accessibility measures be used as a meaningful and effective metric to capture some of the livability benefits of transit projects in the FTA New Starts project evaluation criteria?

- What types of opportunities should be included in a proposed accessibility metric? For example, is measuring access to employment sufficient, or are measures to multiple opportunity types required to evaluate transit alternatives?
- How should accessibility be measured? What are the advantages and disadvantages to using different methodologies in the calculation of accessibility?
- Is there a correlation between accessibility by a mode and mode share? If so, does this correlation provide a means to close the gap of uncertainty left by traditional transportation model estimates which typically overestimate ridership? Does this correlation further justify the use of additional accessibility measures in the New Starts criteria?

1.2 Contribution to the MBTA Green Line Extension Project

The Massachusetts Bay Transportation Authority (MBTA) Green Line Extension Project consists of a northwest extension of the existing Green Line terminus at Lechmere to a proposed main line terminus at College Avenue in Medford, MA, with an additional spur branch terminating at Union Square in Somerville, MA. The Project will provide numerous air quality, mobility, and accessibility benefits along a densely populated corridor and is one of several regional transit improvement projects that the Commonwealth of Massachusetts committed to as part of the Central Artery/Tunnel project air quality conformity measures.

Successful completion of the Project relies on funding, for which the Commonwealth is pursuing federal assistance through the FTA New Starts program. With other deserving projects submitting applications for the highly competitive discretionary New Starts funds, it is essential that the MBTA Green Line Extension Project application be as strong as possible. In addition to potential New Starts funding, a strong project application could lead to flex funding opportunities.

The FTA will consider the submission of other factors that describe benefits not already included in the existing criteria as part of their project evaluation. The results of this research provide an example of accessibility measures that can be included in the Green Line Extension Project New Starts application as compelling supplementary material to strengthen the case for the Project. In addition to measuring benefits not already captured in the existing criteria, this supplementary material also presents the FTA with a potential metric that can be adopted in the next rulemaking as part of the livability focused policy change.

1.3 Thesis Organization

This thesis is organized into eight chapters including this introductory chapter. The second chapter presents a literature review of the concepts of livability and accessibility and discusses the relationship between these two concepts. The various methodologies used to quantify accessibility in literature and practice are detailed.

The third chapter is devoted to the FTA New Starts project evaluation process for transit capital investments. A summary of the current rating criteria is presented along with a discussion of potential changes to be considered in response to the FTA's announcement to incorporate livability benefits in the evaluation rating process. The discussion of potential changes will concentrate on the use of accessibility measures, which is the focus of this thesis.

Chapter four introduces the MBTA Green Line Extension Project as the context used in this thesis for the calculation and evaluation of accessibility measures for potential use in the FTA New Starts evaluation criteria.

In the fifth chapter, an academic four-step transportation model developed for the accessibility analysis is described. Particular attention is given to the trip distribution step as well as the related gamma function estimation to be directly used in the accessibility calculations.

Chapter six presents the results of two distinct accessibility calculation methodologies: using isochrone measures with unweighted time components and using gravity-based measures with weighted time components. The pros and cons of each approach are assessed to define a recommended methodology and potential metrics for inclusion in the New Starts criteria.

The seventh chapter explores the correlation between accessibility and mode share. Calculated accessibility is compared against mode shares from the model outputs as well as mode shares from United States Census data.

Conclusions are presented and areas of future research are identified in the eighth and final chapter.

2 Livability, Accessibility, and their Connection

The term “livability” has grown in popularity over the past several decades and, since the United States Department of Transportation’s announcement of the Livability Initiative, it has become a highlight of the policy discussion on how to comprehensively evaluate transit projects for federal funding decisions. The incorporation of livability principles for traditional highway project planning is also gaining momentum and is a developing practice. However, it is difficult to come up with a single and universal definition of livability from which indicators to inform livability-based policy are to be developed. Accessibility is seen as a key, measureable component of livability, and as such, provides a solid foundation on which to begin this discussion. In this chapter, the concepts of livability and accessibility, and how they are connected, will be explored. Additionally, the main methodologies that have been developed to quantify accessibility, along with the advantages and shortcomings of each, will be presented.

2.1 Livability

Livability is a “complex multifaceted concept” that can differ based on individual perceptions (National Research Council, 2002). The concept of livability can be viewed on both a micro and macro scale. On the neighborhood level, livability encompasses the notions of quality of life and quality of place. From Andrews (2001), quality of life can be defined as “a feeling of well-being, fulfillment, or satisfaction on the part of residents of or visitors to that place,” while quality of place, a related concept, can be defined as the “aggregate measure of the factors in the external environment that contribute to quality of life.”

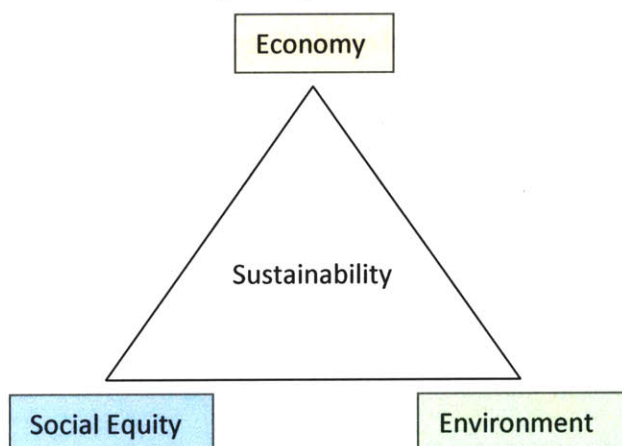
Factors influencing quality of life range from housing and transport affordability to the amount of available open space. Many of these factors can be classified using the Project for Public Spaces’ four key attributes of a high quality place (Project for Public Spaces [PPS], n.d.):

- Access and Linkages
- Uses and Activities
- Comfort and Image
- Sociability

“Access and Linkages” refer to the visual and physical connectivity of a place and include factors such as visibility (within the space and from a distance), congestion, walkability, transportation choices, and the convenience of transportation connections. In this context, convenience includes how well public transit stops are sited in relation to destinations such as parks, schools, employment, etc. The second attribute, “Uses and Activities,” accounts for land use patterns, green space, local business ownership, and cultural amenities, among other factors. A vibrant mix of uses and activities creates conditions that attract both residents and visitors, enhancing the quality of a place. Thirdly, “Comfort and Image” refer to the perceived attractiveness of a place. Examples of comfort and image factors are cleanliness, safety, availability of seating, availability of shade, and building conditions. Lastly, “Sociability” relates to sense of community and includes factors such as volunteerism, social networks, and diversity of ages and ethnic groups (PPS, n.d.).

On a macro level, livability incorporates the concept of sustainability. Sustainability, as defined by the Bruntland Commission, is the ability to “meet the needs and aspirations of the present without compromising the ability to meet those of the future” (World Commission on Environment and Development, 1987). In describing this concept, it is helpful to deconstruct sustainability into three interdependent components: the environment, social equity, and economy. The relationships between these elements are often depicted in a sustainability triangle, as shown in Figure 2-1. This figure conveys that sustainable development relies on a balance between each of these three elements.

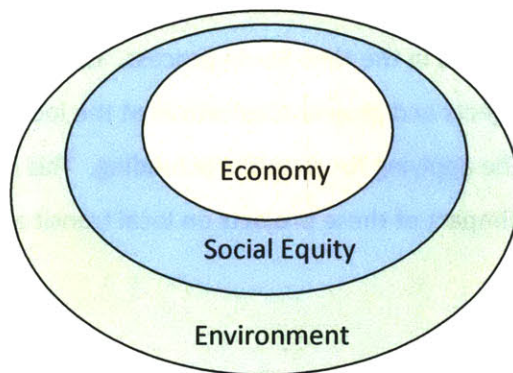
Figure 2-1: Sustainability Triangle



Hart (1999) represented the sustainability components and the limitations of each as three interdependent spheres, as illustrated in Figure 2-2. In this interpretation, the environment is the

largest sphere and represents the natural resources which are necessary for both society and the economy. The middle sphere represents social well-being and includes the equitable distribution of resources and environmental justice (National Research Council, 2002). Environmental justice is achieved when “everyone enjoys the same degree of protection from environmental and health hazards and equal access to the decision-making process to have a healthy environment in which to live, learn, and work” (United States Environmental Protection Agency [EPA], 2011a). The smallest sphere, economy, supplies the jobs and income necessary for social well-being and at the same time is restricted by the limits of both society and the environment (National Research Council, 2002).

Figure 2-2: Three Components of Sustainability (Adapted from Hart, 1999)



Since livability encompasses the notion of sustainability, each of the three elements of sustainability represented in Figure 2-1 and Figure 2-2 are also major components of livability. Livability policy must incorporate the ideals of sustainable development, considering the economy, social equity, and the environment together, without promoting one component at the expense of others. Similarly, the livability of one neighborhood should not cause detriment to the livability of another neighborhood.

It is clear that livability is a complex concept, founded on a myriad of factors relating to quality of life and sustainability, and must be considered on multiple scales. While certain components of livability may be universally agreed upon, others are more subjective and may differ across cultures and individuals. As a result, establishing a single definition for livability is an extremely challenging step towards the implementation of livability-based policy.

In the context of transportation, United States Secretary of Transportation Ray LaHood has initiated the discussion with the following definition of a livable community: “ [A community] where if people don’t

want an automobile, they don't have to have one. A community where you can walk to work, your doctor's appointment, pharmacy or grocery store. Or you could take light rail, a bus or ride a bike" (Findlay, 2009). The objectives of environmentally conscientious transport and equitable transportation options are implied in this definition. Secretary LaHood explicitly highlights the elements of transportation choice, mixed land use, and accessibility discussed above, and suggests that non-auto accessibility to the services required for daily life is a central component of livability.

Few people, if any, would dispute the idea that access to the services individuals require (and desire) is essential to livability. Public transit is capable of providing individuals equitable access to services, including individuals who cannot drive, walk, or bike. As a key, comprehensible, and measurable component of livability, the concept of accessibility can be used as one building block for the FTA as it reconsiders how transit project benefits are evaluated in the New Starts process. It can also serve as a way for MPOs to determine the most worthy projects and project alternatives at the local level, regardless of whether or not these projects will be applying for New Starts funding. This includes the evaluation of highway corridor projects and the impact of these projects on local transit accessibility.

2.2 Accessibility

Accessibility is a fundamental concept in the transportation planning field that has been studied for over fifty years. Hansen (1959) provided an early definition of accessibility as "the potential of opportunities for interaction" (p.73). Other well-known definitions of accessibility in the literature include "the benefits provided by a transportation/land-use system" (Ben-Akiva & Lerman, 1985) and the "extent to which land use and transport systems enable (groups of) individuals to reach activities or destinations" (Geurs & van Wee, 2004).

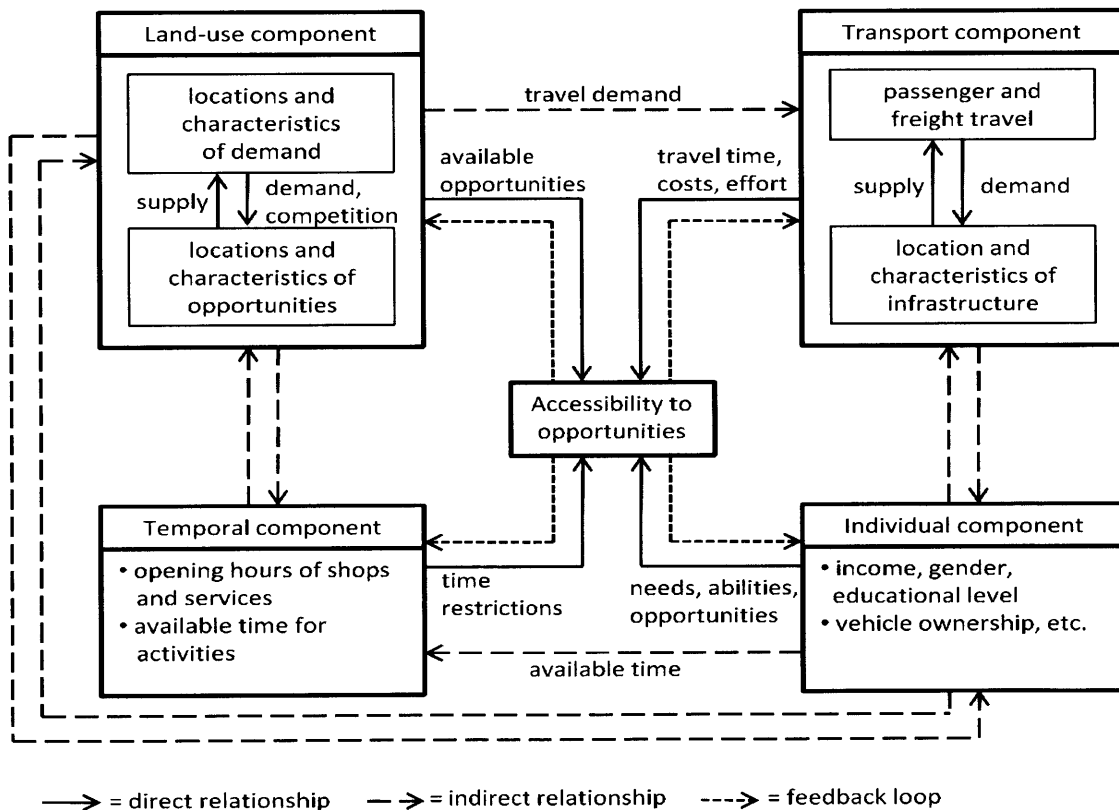
From these definitions it is clear that, from a broad perspective, accessibility is the "link between the land use and transportation systems" (Warade, 2007). The land use system reflects the amount and spatial distribution of opportunities (jobs, shops, schools, etc.) and creates the need for travel provided by the transportation system. The transportation system includes the location of transport facilities as well as the characteristics of transportation infrastructure (link speed, capacity, tolls, fares, etc.). While a single project may have a significant local impact on either the land use system, transportation system, or both, the impacts on the regional scale are often less dramatic, partly due to the legacy components of these systems that are derived from the development patterns over the past century. However, even

small incremental changes to regional accessibility may be useful in measuring directionality towards or away from livability.

Along with land use and transportation, Geurs and van Wee define temporal and individual components of accessibility (Geurs & van Wee, 2004). The temporal component captures the fact that opportunities are only available during certain times of day and that individuals have a certain time budget for which they can participate in specific activities. The individual component reflects factors that influence an individual's needs and ability to access modes of transportation and available opportunities. Examples of individual characteristics include vehicle ownership, income, age, physical condition, and level of education.

In summary, there are four major elements affecting accessibility: the spatial distribution of opportunities, the mobility provided by the transportation system, the temporal constraints of individuals and activities, and the individual characteristics of people. The relationships between each of these components and how they impact accessibility are illustrated in Figure 2-3.

Figure 2-3: Accessibility Components and Relationships (Adapted from Geurs & van Wee, 2004)



2.2.1 Distinction Between Accessibility and Mobility

In order to apply a livability-based approach to transportation policy, it is essential to understand the difference between the associated, but distinct, concepts of mobility and accessibility. Mobility can be defined as the physical ease of movement and is evaluated with throughput-focused measures such as travel distance, capacity, and speed. Mobility relates to the transportation component of accessibility. All other elements held equal, an increase in mobility will also generally increase accessibility by allowing an individual to reach more destinations within a given time. However, high levels of mobility are not a necessary condition for good accessibility. Cities, especially those with dedicated rail systems, are an example of areas that, despite relatively poor mobility due to traffic congestion, have excellent accessibility as a result of the high quantity and quality of opportunities concentrated within a small area. Conversely, a neighborhood with no traffic congestion but few desired destinations will experience poor accessibility regardless of exceptional mobility. Mobility can be viewed as a means to an end, whereas accessibility is the end provided in terms of the connection of people to desired opportunities. This highlights the importance of placing higher value on accessibility and less value on high levels of mobility alone when adopting livability-based policies that steer decision making.

2.3 The Connection Between Livability and Accessibility

The concept of accessibility is advantageous in the consideration of livability-based metrics not only because accessibility in itself is a major component of livability, but also because many elements of accessibility are either directly or indirectly linked to other components of livability. Figures 2-4 through 2-7 help illustrate the connections between the concepts of livability and accessibility. In Figure 2-4, the key components of quality of life and the elements that shape these key components are illustrated. These elements include the transportation system, the land use system, “comfort and image,” and “sociability.” The transportation system and the land use system form the concept of accessibility, making accessibility a major factor of quality of life. In Figure 2-5, the key components of sustainability and the elements that shape these key components are shown. These key components are comprised of the economy, social equity, and the environment. Figure 2-6 combines Figure 2-4 (quality of life) and Figure 2-5 (sustainability) into an overall view of livability. The numerous relationships between accessibility, livability, and their respective components are represented in Figure 2-7.

Figure 2-4: Quality of Life Mind Map

The key components of quality of life can be classified using the Project for Public Spaces' four key attributes of a high quality place (Project for Public Spaces, 2000): "Access and Linkages," "Uses and Activities," "Comfort and Image," and "Sociability." Together, "Access and Linkages" (the transportation system) and "Uses and Activities" (the land use system) form accessibility. This figure illustrates the four key components of quality of life as well as some of the factors that affect each component.

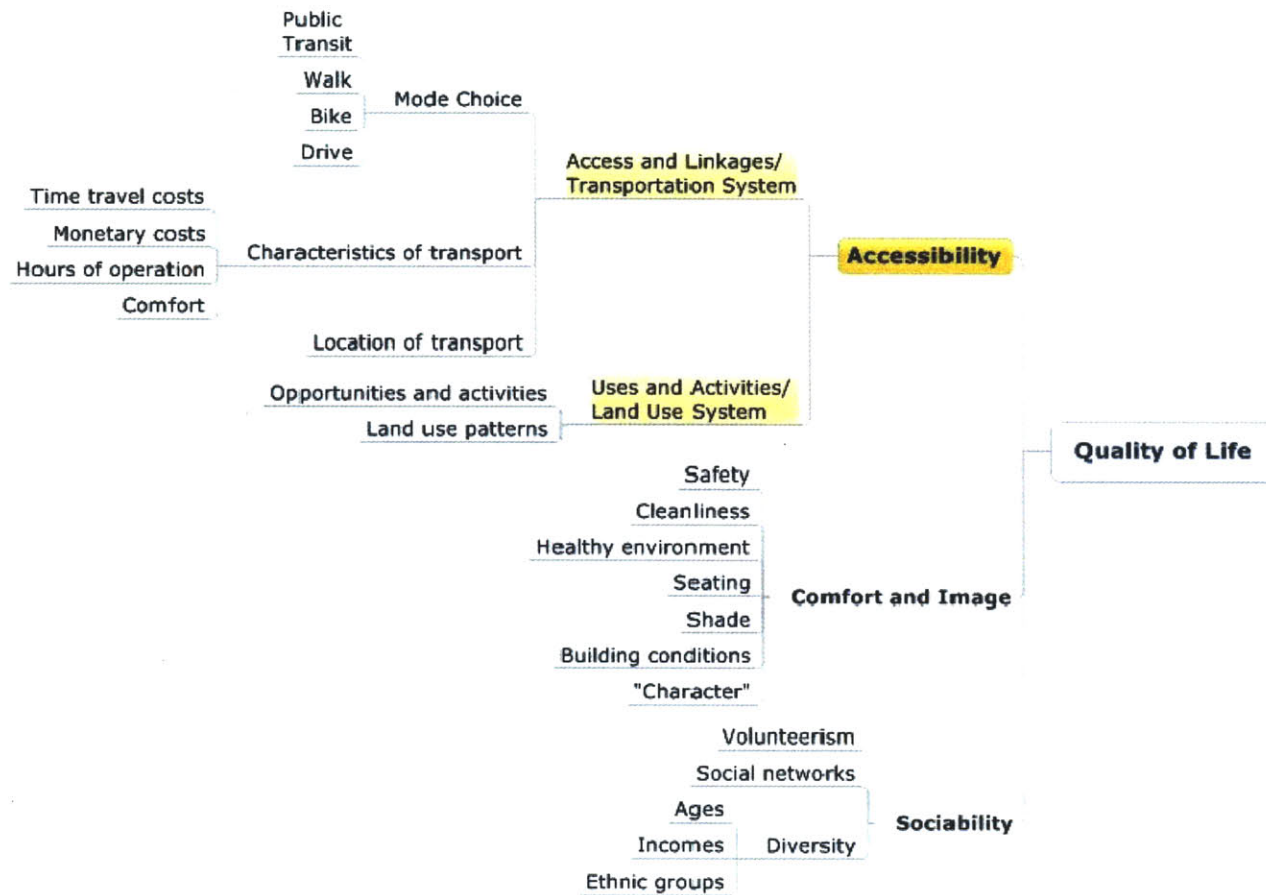


Figure 2-5: Sustainability Mind Map

Sustainability can be deconstructed into three key components: economy, equity, and environment. This figure illustrates the three key components of sustainability as well as some of the factors that affect each component.

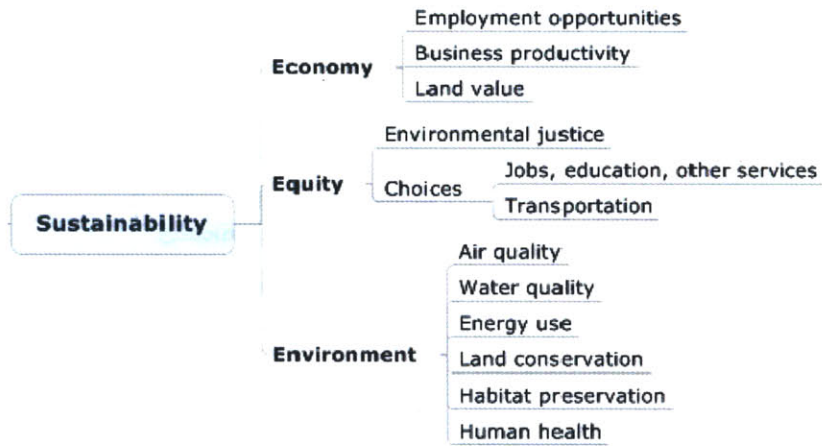


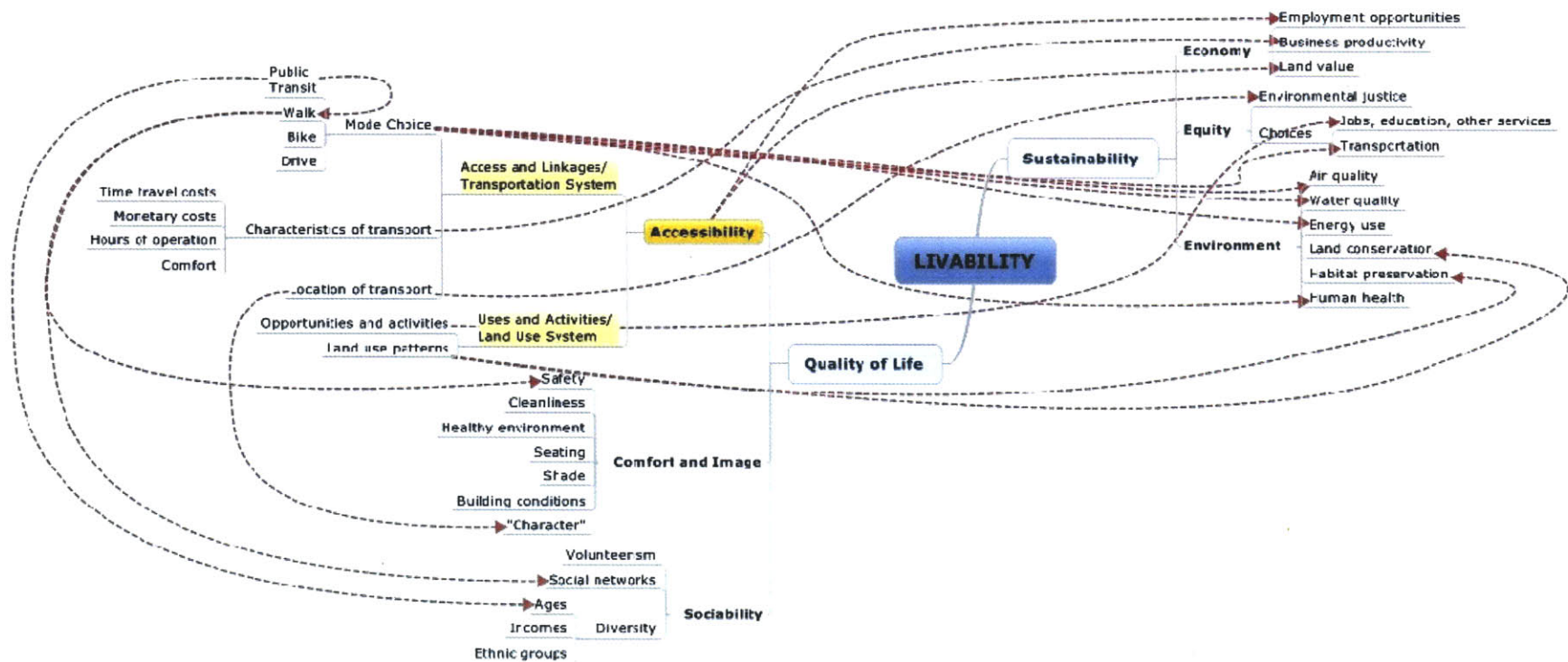
Figure 2-6: Livability Mind Map

Livability encompasses the concepts of quality of life and sustainability. This figure combines Figure 2-4 (Quality of Life Mind Map) and Figure 2-5 (Sustainability Mind Map) into an overall view of livability and its major components. Accessibility is a key component of quality of life and therefore is also a key component of livability.



Figure 2-7: Relationships Between Accessibility and Livability

Not only is accessibility a major component of livability, but many elements of accessibility are either directly or indirectly linked to other key components of livability. The dashed arrows in red, illustrated in this figure, demonstrate some of the relationships between accessibility and its components with the other major factors of livability.



The cross-cutting nature of accessibility and its components (transportation and land use) is clear from the numerous relationships depicted in Figure 2-7. These associations include the following links between accessibility and its components with the “comfort and image” component of quality of life (which ultimately influences livability):

- Public transit and the right mix of land uses encourage an increase in walk trips. Increased pedestrian activity creates “eyes in the streets” which may enhance perceptions of safety.
- Transportation location can influence the “character” of a place. For example, a dense street grid with small blocks can create a sense of charm as opposed to large blocks and sparse intersections which are not designed to a human scale.

Accessibility and its components are linked to the “sociability” component of quality of life in the following ways:

- Increased pedestrian activity can augment social networks as people “bump into” neighbors, friends, business associates, and acquaintances while walking.
- Public transit can enhance the social aspect of quality of life for those otherwise unable to drive or bike while at the same time contributing to the addition of pedestrian presence in the urban environment.

The following are relationships between accessibility and the economic component of sustainability:

- Increases in accessibility may lead to development via the redistribution or growth of residences, workplaces, and activities, thereby influencing employment opportunities and land values. Regardless of the final decisions made by workers and employers, the mere presence of accessible jobs and employees is of value by providing individuals additional choices and *potential* benefits.
- Improvements to transit accessibility may reduce auto-ownership levels, thus generating savings in the family budget which eventually percolate into the local economy.
- The characteristics of the transportation system, such as travel times, costs, comfort, and ability to work while traveling impact business productivity.

Accessibility and its components are linked to the social equity component of sustainability in the following ways:

- The location of transportation may have impacts on environmental justice. Such is the case when a neighborhood suffers from negative air quality due to an adjacent highway but does not obtain the accessibility benefits afforded to those using the highway.
- Increased access to essential services by a choice of modes, including transit, enhances livability for all segments of the population.

The relationships between accessibility and the environment component of sustainability include:

- Mode choices (which may be correlated to accessibility by mode) are associated with various environmental impacts, including air quality, water quality, and energy use impacts.
- Mode choice can influence human health benefits, such as the physical activity benefits from increased walking or biking.

In summary, accessibility underlies many main components of livability, either directly or indirectly. Changes in accessibility, which can occur due to changes in either the transportation system, the land use system, or both, can influence other livability principles, including those more subjective in nature such as perceived safety and sociability. The remainder of this chapter will detail the various methodologies that can be used to quantify accessibility.

2.4 Accessibility Measures

There are a number of mathematical formulations that have been developed in the literature and used in practice to measure accessibility, each varying in their theoretical basis, ease of communication, and data requirements. A majority of these methods can be classified as one of four types: isochrone, gravity-based, utility-based, and person-based. A description of each type of measure, along with the respective advantages and shortcomings, is provided below (Geurs & van Wee, 2004; Warade, 2007).

2.4.1 Isochrone Accessibility Measures

Isochronic measures of accessibility, formulated in Equation 2-1, take into account the total number of opportunities that can be reached within a given travel time, distance, or cost threshold. An example of an isochrone measure of job accessibility is 'the number of jobs that can be reached by transit within 30

minutes' from a specified origin. The data needs for this calculation are minimal and consist of the number of opportunities in every location and the travel time (or distance or cost) between all locations.

Equation 2-1: Isochrone Accessibility (Adapted from Busby, 2004)

$$A_i = \sum_j O_j W_j$$

Where:

i = origin location

j = destination location

A_i = accessibility at location i

O_j = number of opportunities at location j

W_j = equals 1 if $C_{ij} < C^*_{ij}$, and 0 otherwise

C_{ij} = travel time (or distance or cost) from i to j

C^*_{ij} = given travel time (or distance or cost) threshold

Isochrone measures provide a quantification of accessibility that is relatively simple to compute and easy for the non-technical decision maker and public to comprehend. Shortcomings of isochronic measures include that the individual and temporal components of accessibility are not considered. Additionally, the opportunities within a given threshold are all weighted equally while opportunities outside of the threshold are not counted. In the previous example, any employment opportunity that is 31 minutes from the origin (or farther) does not contribute to job accessibility at all, which is clearly not an accurate representation of all employment opportunities that contribute to accessibility. For this reason, the definition of the threshold has the potential to greatly influence the results and should be carefully established.

2.4.2 Gravity-based Accessibility Measures

Gravity-based measures weight all opportunities by an impedance function, as shown in Equation 2-2. The impedance function describes aversion to travel and is estimated from observed travel behavior. In this way, opportunities that are farther away (or have a higher cost of travel to reach) have a lower impact on accessibility. In other words, a job 20 minutes away is weighted more than a job 40 minutes away, all else being equal. The 'number of equivalent jobs that can be reached by transit' from a

particular origin is an example of a gravity-based accessibility measure. Data required for a gravity-based accessibility calculation include the number of opportunities in every location, the travel time (or distance or cost) between all locations, and observed trip travel times (or distances or costs) to estimate the impedance function.

Equation 2-2: Gravity-based Accessibility (Adapted from Busby, 2004)

$$A_i = \sum_j O_j f(C_{ij})$$

Where:

i = origin location

j = destination location

A_i = accessibility at location i

O_j = number of opportunities at location j

C_{ij} = travel time (or distance or cost) from i to j

$f(C_{ij})$ = travel time (or distance or cost) impedance function

Gravity-based measures provide theoretical improvements over isochrone measures, since all opportunities are considered without the need for a defined threshold, while still maintaining relative ease of computation. Although based on a slightly more complex concept, the non-technical reviewer can still understand and recognize the value of gravity-based accessibility measures. Similar to isochronic measures, shortcomings of gravity-based measures include a deficiency in the consideration of the temporal and individual components of accessibility.

2.4.3 Utility-based Accessibility Measures

Utility-based measures use random utility theory and discrete choice analysis to interpret the accessibility benefit derived from a set of choices.¹ Utility-based measures are also referred to as logsum measures because, as shown in Equation 2-3, they are calculated from the natural log of the denominator of the multinomial logit model. Used in the mode choice step of traditional four-step travel demand models, the multinomial logit mode choice model estimates the proportion of travelers choosing a particular mode of transport from a choice set of available modes (auto, transit, and walk, for

¹ See Ben-Akiva and Lerman (1985) for a comprehensive review of discrete choice analysis.

example). This is based on the theory that an individual associates a utility with each alternative in the choice set and chooses the alternative that will provide him with maximum utility. The logsum is the expected value, or expected maximum utility, of all the mode choice alternatives available in the choice set. In other words, accessibility is calculated as “the utility of the choice situation to the individual” (Ben-Akiva & Lerman, 1985). To compare the logsum measure across individuals, the measure must be converted into units of time or cost using the appropriate coefficients of the utility function.

Equation 2-3: Utility-based Accessibility (Busby, 2004)

$$A_n = E (\max_{i \in C_n} U_{in}) = \{ \ln \sum_{i \in C_n} \exp(\mu V_{in}) \} / \mu$$

Where:

i = alternative

n = individual

A_n = accessibility of individual n

$E (\max_{i \in C_n} U_{in})$ = expected maximum utility

U_{in} = utility for individual n considering alternative i

V_{in} = systematic component of utility U_{in} for individual n considering alternative i

C_n = choice set

μ = scale parameter of the error associated with each alternative

In Equation 2-3, the attributes (time and cost variables) of alternatives and characteristics of individuals are considered in the utility function. Examples of time variables for transit include walk access time, wait time, transfer wait time, and in-vehicle time. Out-of-pocket cost variables for transit include fares, tolls, and parking fees for park and ride. Characteristics that describe the user may include socio-economic variables such as income and auto ownership.

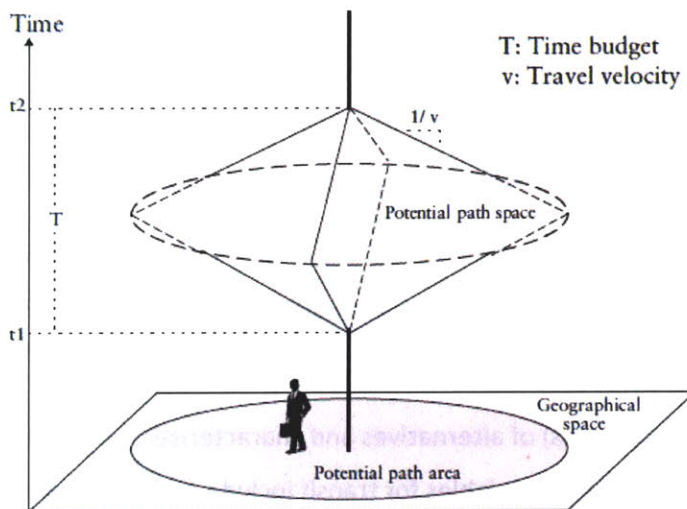
Utility-based accessibility calculations require more data than isochrone and gravity measures. Specifically, they require disaggregate travel behavior data and information on the attributes and characteristics of alternatives and individuals. However, the data needs are equivalent to those required in the traditional four-step travel demand model. Advantages to using logsum accessibility measures include their theoretical basis and ability to address the individual component of accessibility.

The difficulty in communicating the logsum results to non-technical decision makers is one of the major limitations to this methodology.

2.4.4 Person-based Accessibility Measures

Person-based measures focus on the individual and temporal components of accessibility and originate from Hagerstrand's concept of space-time geography (Geurs & van Wee, 2004). This concept considers that an individual's participation in an activity, which in itself is constrained spatially and temporally, is limited by a finite resource of time (Hagerstrand, 1970). Space-time prisms, illustrated in Figure 2-8, can be used to estimate the access to opportunities that can be reached given an individual's time constraints. An example of a person-based accessibility measure is the 'number of jobs an individual can participate in at a given time' (Warade, 2007).

Figure 2-8: Individual's Space-Time Prism (Reproduced from Miller & Wu, 2001)



Person-based measures provide a sound theoretical basis for estimating accessibility, particularly on the individual level, since they incorporate the transportation, land use, temporal, and individual components of accessibility. However, the detailed data required on individual activity travel, including individual time and cost budget information, is not available from traditional surveys and hinder the use of person-based measures in practice.

2.4.5 Use of Accessibility Measures in FTA New Starts

There are advantages and limitations to each type of accessibility methodology which relate to their theoretical validity, computation and data requirements, and ease of communication. It is also apparent

that each methodology addresses the major components of accessibility (transportation, land use, temporal, and individual) to varying degrees. When considering the inclusion of accessibility benefits in the FTA New Starts process, it is critical to recognize that no single measure will fully capture all of the aspects of accessibility. Since each type of measure is an imperfect representation of a complex concept, it is sensible and possibly more effective to use several types of measures in the effort to evaluate accessibility in its entirety.

The current FTA New Starts rating criteria is detailed in the next chapter. The discussion in Chapter 3 includes the extent to which accessibility benefits are measured in the current process and recommendations for how FTA can more fully capture accessibility benefits in the project evaluation process.

3 FTA Transit Infrastructure Project Evaluation

The FTA Section 5309 New Starts program is the main funding resource for the federal government to support local transit fixed guideway capital investments. FTA defines a “fixed guideway” as “any transit service that uses exclusive or controlled right-of-way or rails, entirely or in part” (Federal Transit Administration [FTA], 2010b). These transit investments include new systems and system extensions for heavy and light rail, commuter rail, monorail, and bus rapid transit (BRT). Among the numerous transit capital projects competing for federal grant assistance, only the most worthy projects, as determined by the New Starts rating criteria, are recommended for funding agreements. This provides an incentive for local project sponsors to choose their best projects for the application process. In order to ensure that the FTA is making sound investment decisions, it is paramount that the project evaluation framework be able to distinguish the most valuable projects from the application group.

In this chapter, the current New Starts process and rating criteria will be described along with a discussion of how well the current criteria address the costs and benefits of transit projects. Potential changes to the criteria, in response to the United States Department of Transportation’s “Livability Initiative,” will be discussed with a focus on how accessibility metrics can be used to incorporate livability in the evaluation framework.

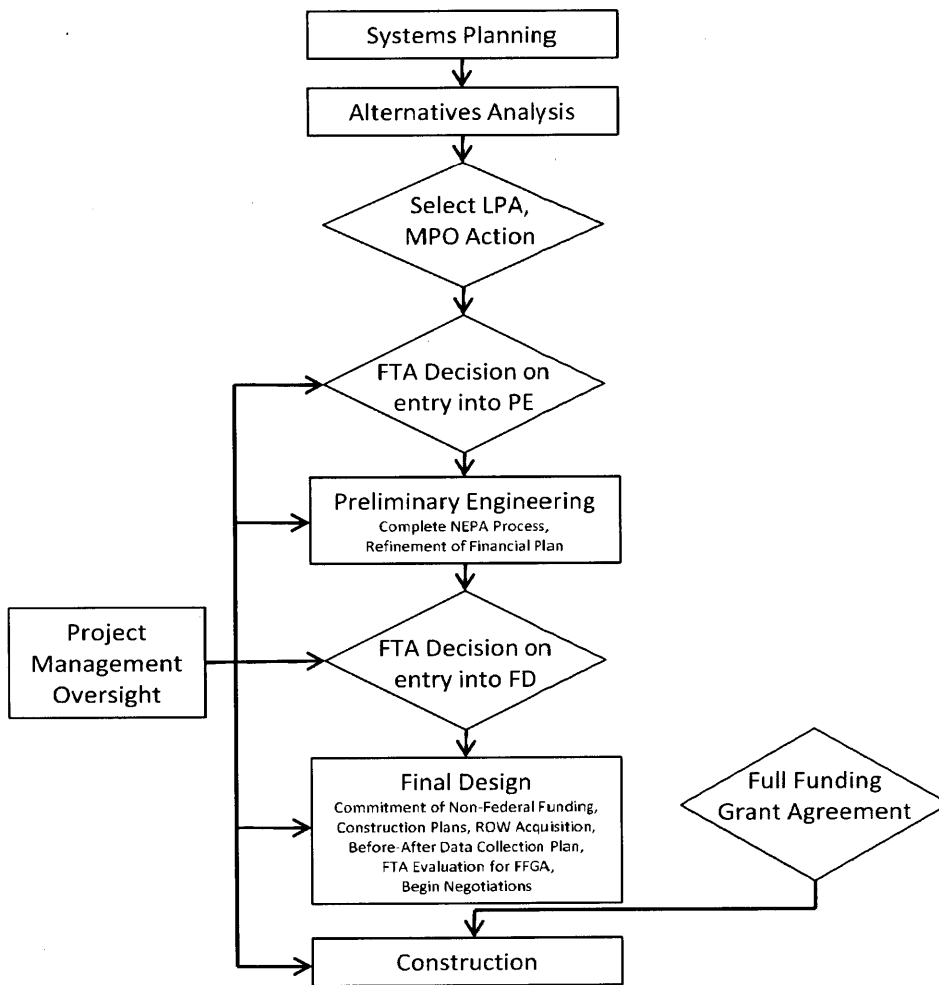
3.1 Current FTA New Starts Project Development Process

The New Starts discretionary federal funding process is authorized by the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU). Per SAFETEA-LU, FTA must evaluate and rate candidate projects at specific milestones during project development as well as for federal funding decisions. Figure 3-1 shows the SAFETEA-LU process for the planning and development of candidate New Starts projects.

The first steps of the planning process are systems planning and alternatives analysis. Although FTA approval is not required to begin alternatives analysis, FTA recommends that they become involved in alternatives analysis to improve the reliability of the data produced and expedite FTA responses regarding project advancement. In the alternatives analysis phase, the costs and benefits of transportation alternatives proposed to address a particular corridor’s needs are analyzed. The alternatives must include a non-guideway option that serves as a “baseline”, intended to be the best that can be done without major capital investment in new infrastructure. The “baseline” alternative

assists in isolating the additional value of proposed major capital investments. Actions such as low cost traffic engineering, enhanced bus services, and transit operational improvements are all examples of appropriate baseline alternatives. The selection and adoption of a locally preferred alternative into the MPO long range metropolitan transportation plan concludes the alternatives analysis phase (FTA, 2010c).

Figure 3-1: FTA New Starts Planning and Project Development Process (Adapted from FTA, 2010f)



Preliminary engineering is the next major step in the planning process. Upon FTA approval for preliminary engineering, the project sponsor can proceed to further refine the scope, schedule, cost estimate, and financial plan of the locally preferred alternative. During preliminary engineering, all environmental impacts and appropriate mitigation measures are identified and major elements of the project are designed to a sufficient level to fulfill the requirements of the National Environmental Policy Act of 1969 (NEPA). Local funding commitments to the project are set and cost estimation is completed to a point that allows the project sponsor to implement a financing strategy, including the maximum contribution required from New Starts funding. At the conclusion of the preliminary engineering phase, FTA performs a risk assessment of the project to determine the cost estimate for advancement into final design, determines the cap on the New Starts funding amount to be considered in any potential future grant agreements, and decides whether or not to approve the project to the final design phase (FTA, 2010g).

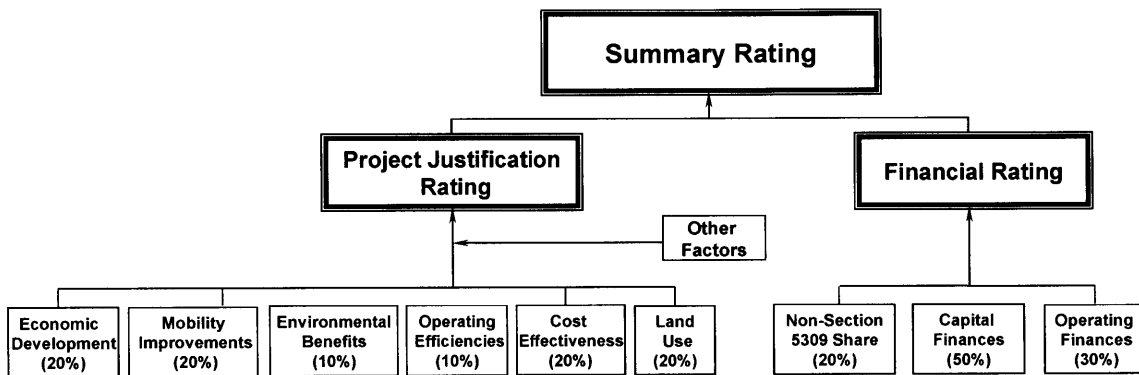
During the final design phase, the project sponsor begins activities necessary for project construction such as utility work, right-of-way acquisition, detailed specification development, preparation of final construction plans, construction cost estimation, and the development of bid documents. This stage also requires the preparation of a before and after study plan that will be used to evaluate the project's performance against model forecasts once the project is operational. After sufficient progress has been made towards the main final design tasks described above, FTA evaluates the project against the New Starts rating criteria. If the project has an overall rating of Medium or higher, the project is deemed eligible for a federal funding recommendation and the FTA may begin the negotiation of specific terms and conditions of a full funding grant agreement. Ultimately, Congress determines the final funding amounts in consideration of FTA's recommendations (FTA, 2010d).

Full funding grant agreements (FFGAs) can cover up to eighty percent of net project costs, but the average funding share is closer to fifty percent since the funding demand is greater than the funds available (Emerson & Ensor, 2010). Additionally, existing FFGA commitments are considered when determining if new funding recommendations can be made. While annual payouts for FFGAs are subject to Congressional appropriations, in the past Congress has honored the negotiated terms of FFGAs (FTA, 2010e).

3.2 Current FTA New Starts Rating Criteria

The rating procedure used by the FTA to evaluate new transit projects (per 2011 Fiscal Year documentation) is illustrated in Figure 3-2.

Figure 3-2: FTA New Starts Rating Process (Adapted from FTA, 2010a)



3.2.1 Summary Rating

FTA assigns each New Starts project a descriptive summary rating which is the basis for whether or not the project will be recommended for federal funding. Based on a five-tier scale of *High*, *Medium-High*, *Medium*, *Medium-Low*, or *Low*, the summary rating is calculated as the average of the project justification rating and the financial rating. A project must achieve a summary rating of at least *Medium* in order to advance to the next stage of project development and to be eligible for funding consideration. In order to receive a *Medium* overall rating, a project must receive a rating of at least *Medium* for both the project justification and financial commitment. FTA will round up the overall rating in cases where the average of project justification and financial commitment are unclear (ex: a project justification rating of *Medium-High* and financial rating of *Medium* results in a summary rating of *Medium-High*).

3.2.2 Project Justification Rating

The impacts of a transit project submitted to FTA for New Starts funding are evaluated in the project justification rating. Six criteria form the basis of the project justification rating: economic development, mobility improvements, environmental benefits, operating efficiencies, cost effectiveness, and public transportation supportive land use. The influence of each criterion towards the overall project justification rating is depicted in Figure 3-2. In addition, FTA will consider “other factors” that describe

significant benefits of a proposed project that are not otherwise captured in the existing criteria. A description of the specific evaluation measures for each of the criterion follows.

3.2.2.1 Economic Development

The economic development rating is based on six categories, each composed of several factors that influence the rating:²

- **Growth management:** Growth management is evaluated based on land conservation/management policies and the concentration of development around regional transit and established activity centers.
- **Transit-supportive corridor policies:** The evaluation of transit-supportive corridor policies is based on parking policies, plans to increase development along the project corridor, and plans to enhance the “transit-friendly character” of station areas and the project corridor.
- **Supportive zoning regulations near transit stations:** Supportive regulations include zoning ordinances that encourage increased densities in station areas, enhance the “transit-oriented character” of station areas, enhance pedestrian access, and allow for reduced amounts of parking.
- **Tools to implement land use policies:** This rating is based on outreach efforts to government agencies and the community in the promotion of station area planning and transit-supportive development. The adoption of regulatory and financial incentives to promote transit-oriented development is also considered.
- **Performance of land use policies:** Performance of land use policies is evaluated based on demonstrated examples of transit-supportive development in the region and the number of development proposals received for transit-supportive development along the proposed project corridor.
- **Potential impact of the transit project on regional land use:** Potential impacts on regional land use are evaluated based on the amount of land available for new development/redevelopment in the project corridor and the existing conditions of the corridor economic environment.

Each of the six categories are assessed qualitatively, assigned a numerical rating from “1” to “5” (*Low to High*), and then weighted equally and averaged to compute the overall economic development rating.

² See Federal Transit Administration (2010a) for more information on the evaluation of economic development factors.

3.2.2.2 Mobility Improvements

The following five measures are used with their respective weights to calculate a mobility improvements rating:

- Number of transit trips using the project (37.5%)
- User benefits per passenger mile on the project (37.5%)
- Number of trips by transit dependent riders using the project (12.5%)
- User benefits for transit dependent riders per passenger mile on the project (12.5%)
- Share of user benefits received by transit dependents compared to the share of transit dependents in the region (0%)

Per the 2011 fiscal year evaluation and rating process, FTA concluded that the quality of data for the fifth metric (share of user benefits received by transit dependents) did not warrant its inclusion in the mobility rating calculation. For the remaining four metrics, projects were aligned in order and categorized into five groups separated by “logical breakpoints” (as opposed to pure quintiles), with the highest grouping receiving a “5” corresponding to a *High* rating and the lowest grouping receiving a “1” corresponding to a *Low* rating.

3.2.2.3 Environmental Benefits

The environmental benefit rating is based on the Environmental Protection Agency’s current air quality designation of the metropolitan area in which the project is located for each transportation-related pollutant (ozone, carbon monoxide, and particulate matter PM-10).³ Projects in non-attainment areas for any transportation-related pollutant receive a *High* rating, while projects in attainment areas receive a *Medium* rating.

3.2.2.4 Operating Efficiencies

Operating efficiency ratings are established from a calculation of the difference in system-wide operating cost per passenger mile between the build and baseline alternatives. FTA has noted that the information submitted for operating efficiencies does not meaningfully set apart the benefits of

³ Additional information on the air quality designations of the United States Environmental Protection Agency and a list of areas designated *non-attainment* can be found in *The Green Book Nonattainment Areas for Criteria Pollutants* (EPA, 2011b).

competing projects, and therefore assigns a rating of *Medium* to all projects submitting the required information for this measure.

3.2.2.5 Cost Effectiveness

The metric used to evaluate cost effectiveness is the incremental cost per hour of transportation system user benefits in the forecast year. In this instance, cost is equal to the annualized capital and operating cost of the proposed project. Dividing this cost by the hours of transportation system user benefits results in the cost effectiveness measure, expressed in dollars per hour of transportation system user benefits. Breakpoints to be used in determining *High*, *Medium-High*, *Medium*, *Medium-Low*, and *Low* cost effectiveness ratings are determined by the FTA for each fiscal year evaluation. Table 3-1 delineates the current cost effectiveness breakpoints.

Table 3-1: Cost Effectiveness Breakpoints (FTA, 2010a)

High	\$12.49/hr and under
Medium-High	\$12.50/hr - \$15.99/hr
Medium	\$16.00/hr - \$24.99/hr
Medium-Low	\$25.00/hr - \$30.99/hr
Low	\$31.00/hr and over

Prior to the most recent policy change announced in January 2010 by United States Secretary of Transportation Ray LaHood, only projects that received a *Medium* or better cost-effectiveness rating would be considered for funding recommendation. With the current policy, cost-effectiveness alone does not determine a project’s eligibility for funding but rather is considered as one of six criteria that determine the project justification rating.

3.2.2.6 Public Transportation Supportive Land Use

Public transportation supportive land use is evaluated based on existing land use factors which include:⁴

- Existing corridor and station area development
- Existing corridor and station area development character
- Existing station area pedestrian facilities (including access for persons with disabilities)
- Existing corridor and station area parking supply

Each factor is assessed qualitatively, assigned a numerical rating from “1” to “5” (*Low to High*), and then weighted equally and averaged to determine the overall public transportation supportive land use rating.

3.2.2.7 Other Factors

The “other factors” rating is introduced after the assignment of an initial project justification rating and may increase or decrease the initial project justification rating by a maximum of one step. Any factors that describe the benefits of a proposed project and are not otherwise included in the existing criteria can be included in “other factors.” Some examples include environmental justice and equity considerations, evidence that the project is part of a congestion management strategy, and considerations of uncertainty in the data supporting the evaluation criteria.

3.2.3 Financial Rating

Transit project sponsors must demonstrate to the FTA their financial ability to build, operate, and maintain the project. This ability is reflected in the project financial rating and is based on three criteria: the share of Non-Section 5309 funding, the strength and reliability of the capital plan, and the strength and reliability of the operating plan. The weight of each criterion towards the overall financial rating is depicted in Figure 3-2. In order to obtain an overall financial rating of *Medium* or greater, a rating of at least *Medium* on both the capital plan and operating plan is required.

⁴ See Federal Transit Administration (2010a) for more information on the evaluation of existing land use factors.

3.2.3.1 Non-Section 5309 Share

The Non-Section 5309 funding share is the percent of project funds that are secured from sources other than New Starts. As can be seen in Table 3-2, the rating improves as the percent of outside funding increases.

Table 3-2: Non-Section 5309 Rating Criteria (FTA, 2010a)

High	<35 percent Section 5309 New Starts funding share
Medium-High	35-49 percent Section 5309 New Starts funding share
Medium	50-60 percent Section 5309 New Starts funding share
Low	>60 percent Section 5309 New Starts funding share

3.2.3.2 Capital Finances

The capital finances rating is based on three criteria weighted as follows:

- Current capital condition (25%)
- Commitment of capital funds (25%)
- Capital cost estimates/planning assumptions/capacity (50%)

Numerical ratings from “1” to “5” (*Low to High*) are assigned to each of these three measures based on a qualitative assessment and then combined with the weighting scheme outlined above to calculate the overall capital finances rating.

3.2.3.3 Operating Finances

The following three measures are used with their respective weights to calculate an operating finances rating:

- Current operating condition (25%)
- Commitment of operations and maintenance funds (25%)
- Operations and maintenance cost estimates/planning assumptions/capacity (50%)

Similar to the capital finances factor, numerical ratings from “1” to “5” (*Low to High*) are established from a qualitative assessment and assigned to these three measures in order to calculate an overall operating finances rating.

3.2.4 The Critical Importance of Transportation System User Benefits

The calculation of transportation system user benefits is a key input used in the New Starts criteria, influencing 30% of the overall project justification rating. Transportation system user benefits affect 50% of the mobility improvements rating and 100% of the cost effectiveness rating. User benefits are defined as “the changes in mobility for individual travelers that are caused by a project or policy change, measured in hours of travel time, and summed over all travelers” (FTA, 2009). User benefits are calculated as a utility-based accessibility measure, using a consumer surplus approach to capture the change in travel expenditures between a baseline and build alternative for all users of the transportation system. Travel expenditures refer to the time and cost of travel, expressed in equivalent units of time using a defined value of time. Equation 3-1 defines the formula for the transportation system user benefits calculation.

Equation 3-1: Transportation System User Benefits (FTA, 2009)

$$UB_{ij} = PTrips_{ij} * dP_{ij}$$

$$dP_{ij} = \{ \ln[\sum_m \exp(U_m^B)] - \ln[\sum_m \exp(U_m^b)] \} / C_{ivt}$$

Where:

i = origin zone

j = destination zone

UB_{ij} = user benefits for travelers from zone *i* to zone *j*

$PTrips_{ij}$ = person trips from *i* to *j* in the baseline alternative

dP_{ij} = change in the overall price of travel from *i* to *j* considering all modes together

$\ln[\sum_m \exp(U_m^A)]$ = inclusive price for alternative A (also referred to as the logsum variable)

C_{ivt} = coefficient of in-vehicle time

B = build alternative

b = baseline alternative

m = set of available modes

The calculation of the logsum variable, used in utility-based accessibility measures, is shown in Equation 2-3 of the previous chapter. To recap, this variable is derived from the logit mode choice model, used in the mode choice step of the four-step travel demand model. The logsum is the expected maximum utility of the available choice set of transportation modes, converted into units of time for the user benefits calculation.

In practice, a FTA mandated software called SUMMIT is used to process the outputs of a traditional four-step travel demand model and calculate user benefits. SUMMIT is capable of producing reports and maps to indicate both the magnitude and geographic distribution of benefits.

3.3 Assessment of New Starts Rating Criteria

Since inception, the New Starts criteria has changed over the years as FTA continues to improve the evaluation framework used to determine the transit investments most worthy of federal funding. An assessment of the current criteria, highlighting its success and shortcomings, is provided in this section.

An ideal evaluation framework accomplishes the following objectives:

- The most worthy investments are differentiated in consideration of all the costs and benefits of the proposed projects
- A transparent process is used with criteria that are measurable and easily communicated to decision makers and the public
- Meaningful metrics that garner public support are used in the evaluation of projects for federal funding recommendation
- The evaluation criteria provide incentives that enhance the quality of project proposals

The existing New Starts framework provides an extensive basis from which FTA evaluates the merits of proposed transit projects from across the nation. In addition to more traditional evaluation measures such as cost and mobility improvement, there is also some consideration for land use patterns, economic development, environmental benefits, and equity issues. FTAs revised policy on cost-effectiveness, which states that projects no longer require a minimum cost-effectiveness rating to be considered for funding recommendation, now encourages project sponsors to consider potential design improvements that were formerly discouraged. For example, one former project was built as an elevated line rather than an underground tunnel because the increase in user benefits did not outweigh the increase in cost; this occurred despite argument that urban development opportunities would be

enhanced with the tunnel option (Emerson & Ensor, 2010). While these examples represent areas of “success” in the current framework, the criteria used in the evaluation process still suffer several limitations and may cause perverse outcomes.

The inclusion of an environmental benefits criterion is well-intentioned, but the metric itself is based solely on the metropolitan area of the project and fails to differentiate meaningful impacts of applicant project proposals. Important and measurable indicators of transit project environmental benefits relating to energy use, air quality, water quality, and physical activity are not considered.

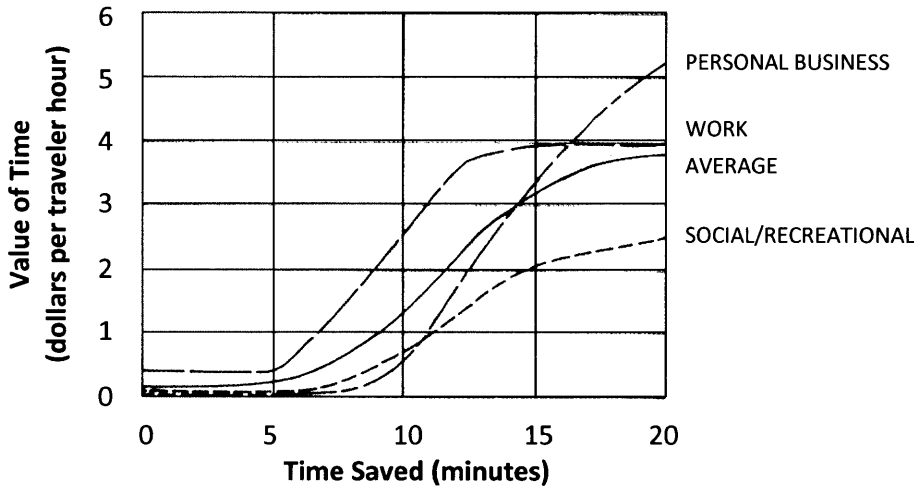
The land use and economic development benefits incorporated in the evaluation framework do not capture benefits that result from the growth or redistribution of people and opportunities made possible by the accessibility impacts of transit projects (Warade, 2007). The current categories evaluated within these ratings, such as existing land use and corridor economic environment, are meant to assess the environment in which a project would be built. There is limited, qualitative consideration for future development outcomes. Additionally, there are no metrics to capture increased productivity and agglomeration benefits from proposed transportation projects.⁵ Quantification of long term land use and economic benefits would allow the entire lifetime benefits of a project to be assessed and would additionally be more transparent than qualitative measures.

Transportation system user benefits, a key input to the mobility improvements and cost-effectiveness criteria, are not easily communicated to decision makers or the public. While this measure provides a theoretically sound assessment of the mobility benefits of a project, it lacks meaning on an individual level. A high user benefit measure may result from a large decrease in the overall price of travel, a large number of trips using the project, or both. To the individual user, a relatively small decrease in the price of travel (for example, a several minute travel time savings) may not significantly enhance quality of life; however, this could be represented as significant user benefits when summed over a large number of trips. The notion of small changes having little impact on the individual level is illustrated in Figure 3-3, taken from the American Association of State Highway and Transportation Officials (AAHSTO) “Red Book,” which shows traveler value of time as a function of travel time saved. This figure illustrates that time savings of five minutes or less has either no effect or negligible effect on traveler value of time.

⁵ Refer to Daniel Graham’s extensive work on agglomeration and the wider economic impacts of transportation projects for more information on this subject, including “Agglomeration, Productivity, and Transport Investment” (2007). See Colella, Jenkins, and Salvucci (2010) for examples of projects that have included agglomeration benefits in the project evaluation process.

The point is not made to negate the usefulness of the user benefits measure. On the contrary, user benefits provide a sound quantitative measure of travel time savings, but have drawbacks that leave a desire for supplementary measures that decision makers and the public can identify with and comprehend.

Figure 3-3: Value of Time as a Function of Time Saved (Adapted from AASHTO, 1977)



Criticism has been raised that the current approach may not sufficiently weight the impacts on access to essential opportunities. Providing additional transportation choices to key opportunities such as employment, education, health, shopping, and recreation is seen as a key component of livability. An expanded approach to accessibility may provide further encouragement for coordination between land use planners and transportation project sponsors and promote the exploration of alternative project alignments and designs that promote livable community initiatives.

In summary, the existing FTA New Starts rating process includes both successful criteria for the evaluation of transit investment projects and potential limits to fully understanding project benefits that may result in perverse impacts on decision making. Over the years, New Starts has undergone continuing review and revision to improve the process. As of this writing, the FTA is currently reassessing the project evaluation criteria with a focus on how well all benefits, including livability-based benefits, are incorporated in this important decision making process. Potential changes the FTA can consider in the next rulemaking process are discussed in the following section.

3.4 Potential Changes to New Starts

The United States Department of Transportation's announcement of the "Livability Initiative" has caused the FTA to reassess the current New Starts criteria through the concept of livability. The focus on livability, a view that encompasses the notions of quality of life and sustainability, will likely result in changes to how FTA measures and compares the environmental, economic, social equity, and accessibility benefits of transit projects and how FTA encourages project sponsors to conceptualize transit improvements.

3.4.1 Environmental Benefits

Revised environmental benefits criteria may include a series of quantitative indicators that focus on the energy use, air quality, water quality, and physical health benefits of transit. From the results of a Colloquium held at the Volpe Center in 2008, environmental indicators that FTA could incorporate in the New Starts process include, but are not limited to (John A. Volpe National Transportation Systems Center, 2009):

- Energy use per vehicle, passenger, or per revenue mile traveled
- Energy consumption for transportation per household in the project area
- Emissions of nitrogen oxide, volatile organic compound, and particulate matter emitted per mile per passenger
- Carbon dioxide emissions per mile per passenger
- Reduction of criteria pollutant area wide and locally in non-attainment areas
- Portion of the project located within an existing right-of-way
- Pedestrian/bicycle friendliness of the area as measured by sidewalk amenities and street connectivity
- Mix of shopping, residential, and work locations in proximity to transit stations
- Attributes outlined in the U.S. Green Building Council's Leadership in Environmental and Energy Design (LEED) for Neighborhood Development Rating System
- Mode shift from private vehicle to walking, bicycling, and transit
- Change in the number of bicycle and pedestrian trips

Accessibility considerations might lead to a reduced significance of measures based on revenue mile or passenger mile, instead emphasizing per trip and per capita measures.

3.4.2 Economic Benefits

One of the major shortcomings of the current evaluation criteria is the narrow measure of economic benefits which focuses on the existing economic environment. This limitation can be overcome by using metrics that also capture the long term economic development impacts of transit investments. There are several ongoing FTA research projects aimed at constructing improved metrics for economic development with the use of hedonic models and the use of integrated transportation/land-use models. Ongoing FTA sponsored studies include Transit Cooperative Research Program projects H-39 and SH-12 (FTA, 2008). Potential metrics that use the results of hedonic and integrated transportation/land-use models can include:

- Land value impacts of the build scenario versus the baseline scenario
- Increase/decrease in long-term, transit accessible job growth due to the proposed build scenario
- Increase/decrease in business productivity due to the proposed build scenario (agglomeration benefits)

According to the Bureau of Transportation Statistics (2010), the average annual cost of owning and operating a car in 2009 was \$8,487.⁶ Another possible metric could quantify the significant cost savings that result from changes in vehicle ownership, ultimately leading to shifts in consumer spending and local multiplier effects.

3.4.3 Social Equity Benefits

Social equity benefits are somewhat considered in the mobility improvements rating using the measures of number of trips by transit dependent riders and the user benefits by transit dependent riders. A more comprehensive evaluation of social equity benefits could include additional measures which describe the impacts of the proposed project on environmental justice populations. This could include, for example, the impacts of toxic air pollutants on the health of abutting environmental justice

⁶ This figure is represented in year 2010 dollars and assumes 15,000 vehicle-miles per year in stop and go conditions.

populations. Accessibility benefits, to be described in detail in the next Section, could also be measured specifically for environmental justice populations.

3.4.4 Accessibility Benefits

Accessibility is a key component of livability that can support the goals of an ideal evaluation framework. Since accessibility benefits are also connected to environmental, economic, quality of life, and equity impacts, accessibility is an excellent foundation for new livability-based metrics. Accessibility is a concept that is meaningful, can be quantified, and can be easily communicated to decision makers and the public. Additionally, because accessibility links the transportation and land use systems together, the inclusion of accessibility metrics in the evaluation process can encourage coordination between transit project sponsors and land use planners. This ultimately enhances the quality of proposed projects.

Accessibility is currently incorporated in the New Starts criteria through the calculation of transportation system user benefits (a utility-based or logsum accessibility measure). The logsum measure has many theoretical advantages, but this measure of accessibility is not easily communicated and can lack meaning on an individual scale. Since the logsum measure is based on a discrete model of mode choice, it only considers the benefits derived from mode choice and does not explicitly incorporate the benefits resulting from the amount or spatial distribution of opportunities. In order to fully evaluate accessibility, particularly from the viewpoint of livability, additional measures that capture the potential access to needed and desired opportunities should be incorporated in New Starts. Specifically, metrics which quantify the increase in an individual's accessibility to essential opportunities, such as jobs (including transit oriented jobs), health, education, shopping, and recreation can be developed for the New Starts rating process.

Isochrone and gravity-based measures, detailed in the previous chapter, provide an operational and comprehensible way to calculate these benefits. The development and assessment of these location-based accessibility metrics, using the context of the MBTA Green Line Extension Project, is the focus of the remainder of this thesis.

4 MBTA Green Line Extension Project

The MBTA Green Line Extension Project, estimated to cost \$953.7 million, represents the most significant expansion of the MBTA rapid transit system since the Red Line Extension to Alewife in 1985.⁷ The 3.4 mile service extension to College Avenue and the 0.9 mile branch to Union Square will add approximately 8.6 track miles to the MBTA transit system, resulting in a 19% increase to existing Green Line revenue track and a 7% increase to total MBTA rail transit revenue track.⁸ The Green Line Extension is expected to bring a number of long awaited benefits to the Project corridor, enhancing the quality of life for communities in Somerville and Medford, Massachusetts and providing improved connections between these communities, Cambridge, downtown Boston and the region. The following will provide an overview of the proposed Green Line Extension and the anticipated benefits of the Project.

4.1 Context

The MBTA provides public transportation services to approximately 1.24 million passengers daily through its system of bus, rail rapid transit, BRT, commuter rail, commuter ferry, and paratransit services, making it the fifth largest mass transit system (by ridership) in the country (MBTA, 2010). The MBTA urban rapid transit system, illustrated in Figure 4-1, consists of a radial network of heavy rail (the Red, Orange, and Blue Lines), light rail (the Green Line), and BRT(the Silver Line) services that interconnect in downtown Boston.

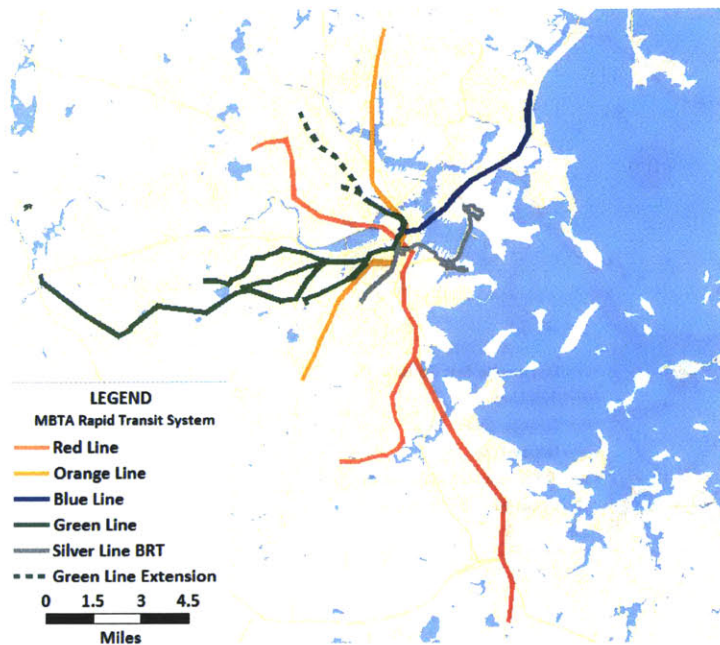
The idea of extending Green Line service north to Somerville and Medford has been the subject of a number of planning studies over the past several decades.⁹ In the early 1990s, the Project became an official commitment of the Commonwealth of Massachusetts as part of the air quality mitigation measures required for the Central Artery/Tunnel project. At the time of this writing, the status of the Green Line Extension Project includes the finalization of the federal NEPA process, the beginning of the preliminary engineering phase, and the preparation of materials for the FTA New Starts application for federal funding.

⁷ The project cost represents the total year-of-expenditure (YOE) capital costs of the project in YOE dollars (Massachusetts Department of Transportation, 2010).

⁸ See MBTA (2010) for MBTA track mile figures.

⁹ These studies include the 1962 *North Terminal Area Study*, the 1973 *Boston Transportation Planning Review Northwest Study*, the 1981 *Green Line Northwest Project Study*, and the 2005 *Green Line Major Investment Study*.

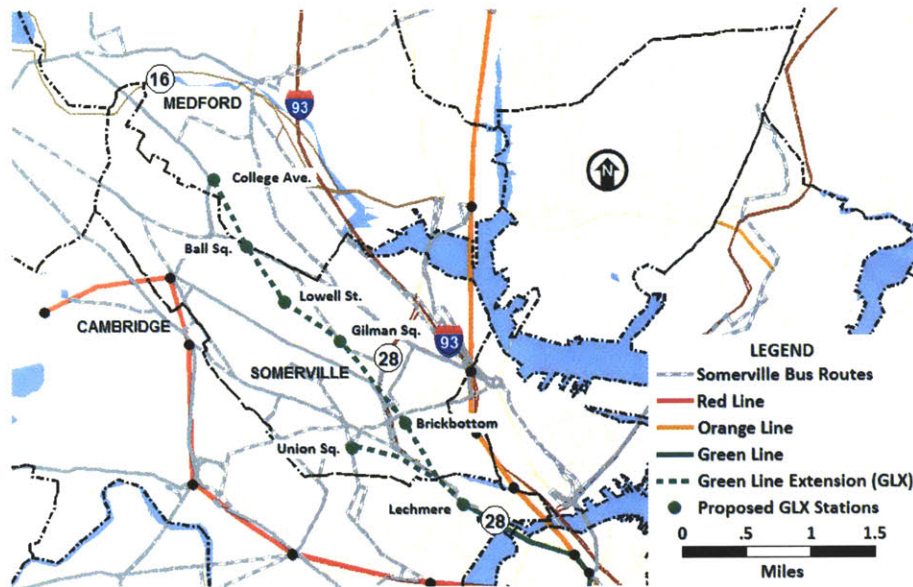
Figure 4-1: MBTA Rapid Transit System



4.1.1 Proposed Project

The proposed Project, shown in Figure 4-2, will extend the Green Line northwest from the current terminus at Lechmere Station in Cambridge to a new terminus at College Avenue in Medford. Additionally, a shorter spur branch to Union Square in Somerville is proposed. The alignments run along existing MBTA commuter rail right-of-way, using the Lowell Line right-of-way to College Avenue and using the Fitchburg Line right-of-way to Union Square. Six additional stations are proposed at Union Square, Washington Street, Gilman Square, Lowell Street, Ball Square, and College Avenue. Additionally, the extension will require the relocation and reconstruction of the current terminus station, Lechmere. An extension beyond College Avenue to a station at Route 16 and the addition of a Twin City station between Union Square and Lechmere will be considered in a future phase.

Figure 4-2: Proposed Green Line Extension Project



4.1.2 Land Use, Demographics, and Travel Behavior

The Project corridor runs through the cities of Cambridge, Somerville, and Medford, which are some of the most densely populated areas in the Boston metropolitan region. A majority of the Project catchment area lies within Somerville, a city with a population density that is over one and a half times that of Boston and the sixth densest city in the United States (Somerville Transportation Equity Partnership [STEP], 2010). The population and employment profiles of the cities along the Project corridor are tabulated in Table 4-1, with Boston data included for comparative purposes.

Table 4-1: Population and Employment Profiles

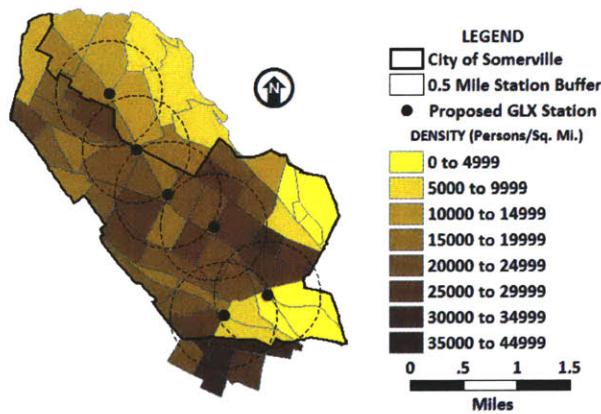
TOWN	AREA (SQ. MI.)	POPULATION	HOUSE-HOLDS	POP. DENSITY (POPULATION PER SQ. MI.)	TOTAL WORKERS	TOTAL JOBS	JOB DENSITY (JOBS PER SQ. MI.)
Somerville	4	77,480	31,560	18,850	44,110	22,950	5,600
Cambridge	7	101,360	42,620	15,760	48,520	113,480	15,920
Medford	9	55,770	22,070	6,850	27,610	17,840	2,110
Boston	50	589,140	239,530	12,170	267,500	443,920	8,890

Data Source: United States Census (United States Census Bureau [U.S. Census], 2000)

The distribution of population density and employment density along the Project corridor are mapped in Figure 4-3 and 4-4, respectively. In these figures, a half mile station buffer is shown to indicate the primary catchment areas of the proposed stations.¹⁰ This distance is selected because the stations are principally designed for walk access and a half mile is found to be the upper limit of distance that most people are willing to walk to reach a rail station within transit oriented development (Transit Cooperative Research Program, 2007). These buffers indicate that a majority of the most populated areas as well as the pocket of dense employment in southeast Somerville will be served by the Green Line Extension. It is important to note that many areas outside of the indicated buffers will also be served by the Green Line Extension via bus feeder service.

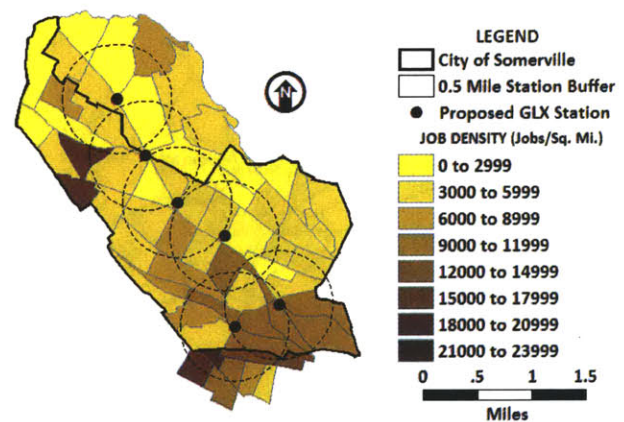
Economic revitalization is seen as one of the major benefits of the Project and is hoped to increase job densities along the corridor. Prime vacant zoning under consideration for economic revitalization include the Inner Belt, Union Square, and Twin City areas. A potential future Urban Ring connection at Lechmere and the expansion of economic growth underway at nearby Kendall Square may also lead to increased job densities in the Project area.

Figure 4-3: Population Density



Data Source: United States Census (U.S. Census, 2000)

Figure 4-4: Job Density



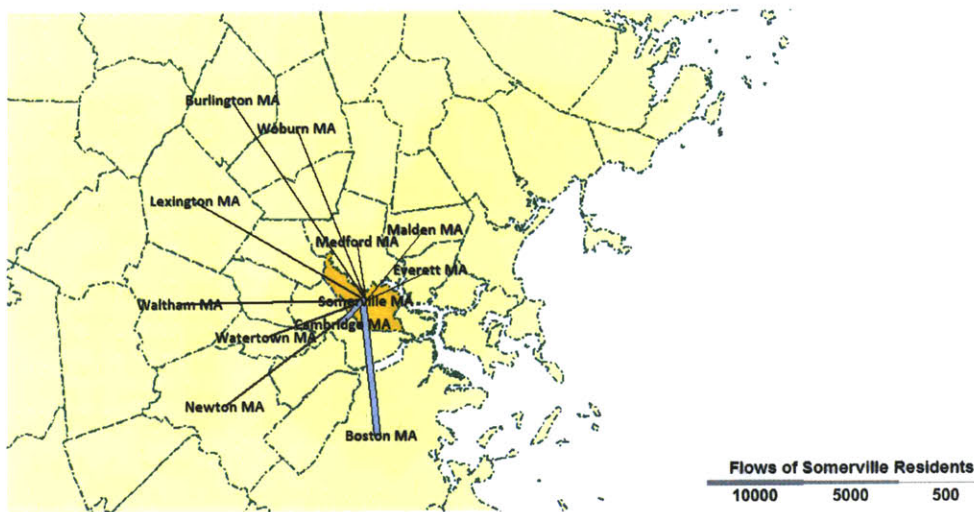
Data Source: United States Census (U.S. Census, 2000)

¹⁰ It is important to note that these buffers represent Euclidian distance on the map. In some instances, barriers to pedestrian access, such as railroad tracks or limited access highways, will result in a more distorted contour of the half mile walk shed to the proposed station locations.

The flows of workers, both residing in and attracted to Somerville, are another important consideration in regard to the role the Green Line Extension will play in serving area commuters. Figures 4-5 and 4-6 below illustrate the worker flows of Somerville residents who work in towns other than Somerville and the worker flows of Somerville employees who live in towns other than Somerville, respectively. These graphs clearly demonstrate that strong transportation connections between Somerville and Boston are crucial for both workers from Somerville commuting to Boston as well as workers from Boston commuting to Somerville.

Table 4-2 tabulates the major worker flows in the Project area. While most workers employed in Somerville also reside in Somerville (in the year 2000 there were 6,865 Somerville residents also working in Somerville), according to data from the 2000 Census, there are approximately 1,960 workers from Boston commuting into Somerville each workday. The Green Line Extension Project will provide increased transit accessibility to employment not only for Somerville residents commuting within Somerville but also for the significant number of workers living in Boston and commuting to Somerville.

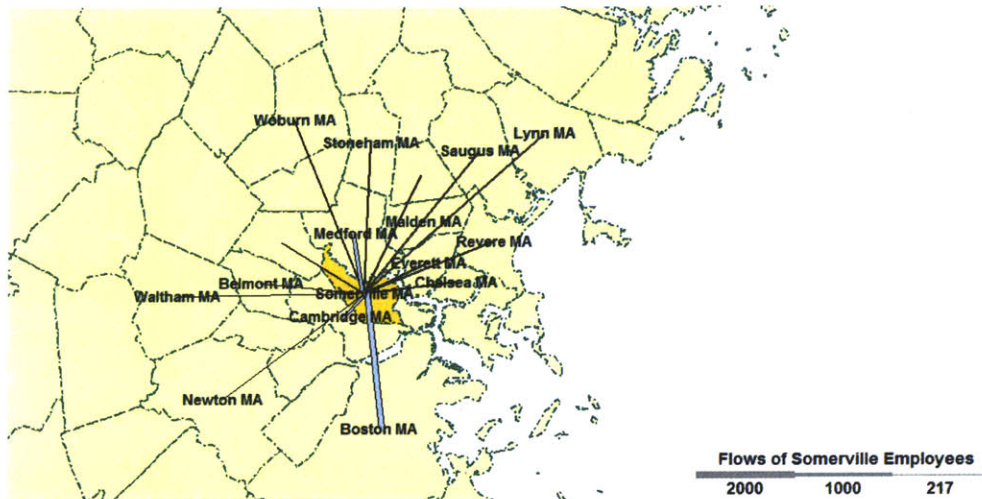
Figure 4-5: Flows of Somerville Residents to Town of Employment¹¹



Data Source: 2000 Census Transportation Planning Package (United States Department of Transportation [U.S. DOT], 2000)

¹¹ Only flows greater than or equal to one percent of total worker flows from Somerville are represented.

Figure 4-6: Flows of Somerville Employees from Town of Residence¹²



Data Source: 2000 Census Transportation Planning Package (U.S. DOT, 2000)

Table 4-2: Worker Flows To and From Somerville

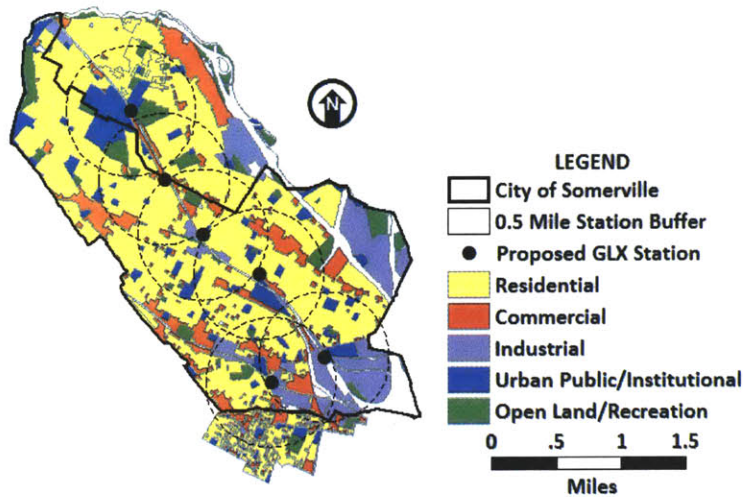
TOWN OF RESIDENCE	TOWN OF EMPLOYMENT	NUMBER OF WORKERS
Somerville	Boston	12,235
Somerville	Cambridge	8,780
Somerville	Medford	1,528
Somerville	Somerville	6,865
Boston	Somerville	1,960
Medford	Somerville	1,290
Cambridge	Somerville	1,184

Data Source: 2000 Census Transportation Planning Package (U.S. DOT, 2000)

Land use along the Project corridor is primarily residential, but there is also a mix of commercial uses as well as a significant industrial presence in the southeast. Institutional uses include the Tufts University campus, located at the College Avenue station. Aside from the recreational fields on the Tufts University campus, open and recreation space is fairly limited. In fact, Somerville has the least amount of open space in the Commonwealth (STEP, 2010). A map of these existing land uses can be found in Figure 4-7.

¹² Only flows greater than or equal to one percent of total worker flows to Somerville are represented.

Figure 4-7: Existing Corridor Land Use

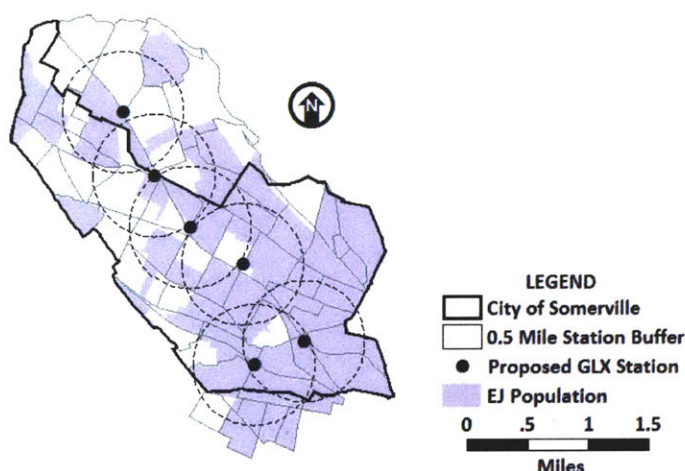


Data Source: "Land Use 2005" datalayer (Commonwealth of Massachusetts Office of Geographic Information [MassGIS], 2010)

Each of the proposed station locations has a unique character and serves a mix of land uses. Union Square station, the southern-most station on the map, is located in an area of mixed residential, commercial, and light industrial uses. The historic center of the square is a blend of ethnic stores and restaurants, with dense residential use to the north, west and south. Less desirable industrial uses, including an electric transformer, used radiator lot, junkyard, and automotive-related business can be found to the east. Washington Street station (and the proposed Twin City station) is located on the edge of a large industrial area, primarily composed of automobile related businesses and transportation uses. However, there are established residential neighborhoods to the north and the Brickbottom Artists Lofts residential building nearby. There is substantial capacity for growth and land use densification in both the Union Square and Washington Street areas. To the north lies Gilman Square, a primarily residential and institutional area that includes Somerville City Hall, the public library, and public high school. The Lowell Street station area is mainly residential, with several parks and playgrounds throughout the neighborhood. In the Ball Square station area, there is a main commercial strip at the center with residential communities beyond. The College Avenue station, which will be the end of the line until the potential extension to Route 16 is resolved, is located on the Tufts University campus. A station at College Avenue will serve the main campus area, surrounding recreation fields, and adjacent residential neighborhoods.

Many of the residents living along the Project corridor are minority, foreign-born, non-English speaking, and/or low-income. The Commonwealth's Executive Office of Energy and Environmental Affairs (EEA) defines environmental justice populations, shown in Figure 4-8, based on the aforementioned factors. Environmental justice regulations are intended to ensure these populations are not disproportionately burdened from environmental or health hazards. Nonetheless, research has shown Somerville has some of the Commonwealth's highest rates of lung and cardiovascular disease, believed in part to be a result of much of the population living in close proximity to congested regional highways such as Interstate 93, Route 28 and Route 16 (Pfeiffer, 2009).

Figure 4-8: EEA Defined Environmental Justice Populations



Data Source: "Environmental Justice Populations" datalayer (MassGIS, 2010)

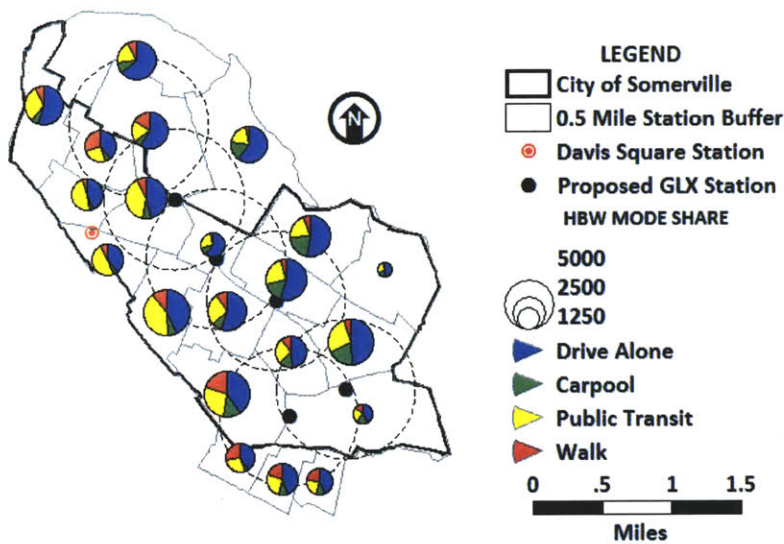
Somerville's public transit accessibility to jobs and services is limited. While Somerville is served by a number of MBTA bus lines, only Route 92 provides service to Boston. Other Somerville bus routes require multiple connections or a transfer onto the Green Line at Lechmere in order to arrive in Boston. Most local bus service is of low frequency, with peak headways typically in the range of 15 to 20 minutes. During off-peak hours, service is reduced to headways of every 30 minutes or more. Finally, bus travel times are often exacerbated by traffic congestion on Somerville's streets and deteriorate service reliability. In his thesis, Shireman (2011) provides a thorough review of bus service in the Project area, including recommendations on how to improve Somerville bus service in advance of the opening of the Green Line Extension.

Despite public transit service in Somerville being relatively poor, public transit comprises a significant amount of the home to work mode share shown in Figure 4-9. This is in part a function of auto

ownership in Somerville, as over one quarter of households do not own a vehicle (STEP, 2010). While some households choose not to own a car, others cannot afford a car; both are therefore transit captives. The presence of carpooling in many neighborhoods seems to be a reaction to the relatively low quality of bus service in the area.

Unquestionably, the largest mode share for home to work trips in Somerville is driving alone, with the exception being the area around Davis Square. The MBTA Red Line station at Davis Square is the only rail transit station in Somerville and provides frequent and reliable service in each direction. The Red Line operates in a dedicated tunnel which protects the service from traffic uncertainties. Here, public transit trips (for the journey to work) are predominant suggesting that the presence of high quality rail services may impact household decisions on car ownership and mode choice.

Figure 4-9: Home to Work Mode Share



Data Source: United States Census (U.S. Census, 2000)

4.2 Project Benefits

The Green Line Extension is anticipated to bring a number of benefits to the communities in the Project corridor, enhancing the quality of life for residents and visitors. These benefits include:

- Enhanced public transportation service through significantly improved travel times, frequency, and reliability
- Mobility improvements from the Project corridor to Boston and surrounding areas (and vice versa)
- Promotion of economic development, particularly near the Union Square and Washington Street stations (and potentially Twin City)
- Increased transit accessibility to jobs and services for residents and to labor pools for businesses
- Environmental benefits from anticipated mode share shifts
- Improved equity for transit dependent riders and environmental justice populations
- Limited growth of auto ownership (in an area that currently has relatively low auto ownership levels) by offering a reliable transit option

Significant mode share shifts from car use to transit use are anticipated which in turn lead to environmental benefits such as improved air quality. While the Green Line Extension should not be seen as a “silver bullet,” the Project will certainly help to create a more transit-oriented culture. Ridership forecasts estimate 7,900 new daily linked transit trips as a result of the Green Line Extension Project, 70% of which are expected to be shifts from auto trips to transit trips (Massachusetts Department of Transportation, 2010). Reduced auto use can also improve water quality and reduce land needs for parking thereby freeing up the land available for green space (or other desirable uses).

The mobility and reliability improvements from the Project are significant. Current transit travel time from College Avenue to Lechmere Station, estimated during the morning peak from the MBTA trip planner tool, is approximately 27 minutes on the Route 80 bus. Travel time on the Green Line for this trip is expected to be 9.5 minutes, with trains running high frequency service of 5 minute headways during peak periods and 10 minute headways during off-peak times (Massachusetts Department of Transportation, 2010). Similar high frequency service will be provided from Union Square to Lechmere Station, scheduled to run between the two locations in approximately 4.5 minutes (Massachusetts Department of Transportation, 2010). At present, the journey from the Union Square station location to Lechmere takes approximately 15 minutes via the Route 80 or Route 87 bus. These significant time savings will improve mobility both along the Project corridor and to/from surrounding areas. Service reliability will also be significantly improved since, unlike existing bus services, the Green Line will operate in a dedicated right-of-way and will not be impacted by uncertainties in congested traffic.

The Project will increase transit accessibility, linking employment opportunities and labor pools in Somerville, Medford, Cambridge, Boston, and other cities connected to the MBTA system. Workers benefit by being able to reach more potential job opportunities. Businesses benefit by being able to attract a larger pool of potential employees. This increased accessibility, combined with available land with increased density zoning permitted, should spur economic development within Somerville by encouraging developer investment and business relocation.

Accessibility benefits to residents and visitors include increased transit access to jobs, services, and activities, thereby increasing quality of life and facilitating the creation of livable neighborhoods. These accessibility benefits will be explored in detail in Chapter 6. Prior to this, the model developed to analyze the accessibility impacts of the Green Line Extension Project will be described in the next chapter.

5 Model Development

In this chapter, the transportation model developed for the analysis of accessibility impacts of the MBTA Green Line Extension Project will be described. Two types of accessibility measures, isochrone and gravity, are analyzed in this thesis, both of which require outputs from the transportation model. Specifically, the isochrone measures will use data on the travel times between origin and destination zones. The gravity-based measures require data on the generalized cost of travel between origin and destination zones as well as a function that describes the aversion to travel as generalized costs increase. The methodologies, assumptions, and limitations of the transportation model used to determine these outputs have a direct impact on the calculation of accessibility and are therefore discussed in further detail in the following sections.

Built using Cube Voyager software, the model is developed from an academic four-step travel demand model originally created by Mikel Murga at MIT.¹³ For the purposes of this thesis, the author expanded the analysis capabilities of the original model in several ways. First, the granularity of the model was increased from 986 analysis areas to 2,727 analysis areas. This finer detail allows for a more precise spatial representation of accessibility impacts, particularly in analysis areas adjacent to the proposed Green Line stations and along the Project corridor. Second, the Home Based Recreation trip purpose was added to the model in order to analyze accessibility to recreation opportunities. Third, the trip distribution step, critical for gravity-based accessibility measures, was recalibrated. Finally, changes to the model input files were made in order to model several alternative scenarios, including the baseline and build scenarios for the Green Line Extension Project. Further detail on the abovementioned changes is provided in this chapter.

5.1 Geographic Coverage and Structure

The model covers an area of approximately 2,800 square miles in the Boston metropolitan region. For analysis purposes, this area is subdivided into 2,727 areas based on the Traffic Analysis Zone (TAZ) designations of the Central Transportation Planning Staff (CTPS) to the Boston MPO. A TAZ is an area defined by local transportation officials for the purposes of analyzing transportation and travel behavior in regional models. TAZs are defined in such a way as to create areas of uniform trip making behavior so the number of trips produced and attracted to each zone can be estimated while at the same time not

¹³ See Murga (2010) for full details on the academic model.

creating unnecessary computational burden. Figures 5-1 and 5-2 show the geographic coverage of the model area and the TAZ boundaries.

Figure 5-1: Regional TAZ Map

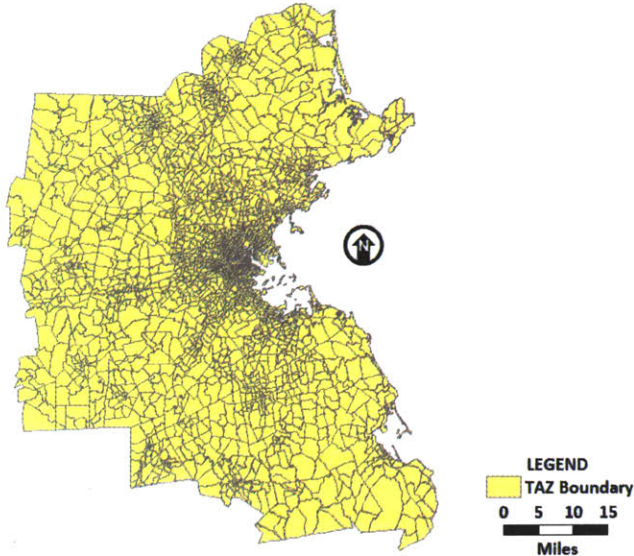
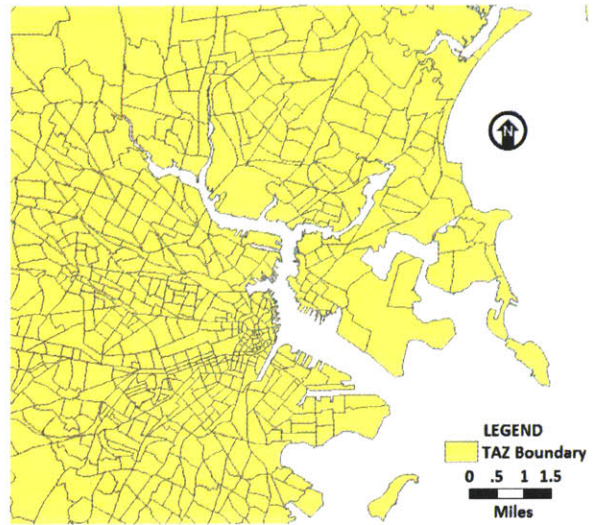


Figure 5-2: Central Business District TAZ Map



5.2 Transportation Network

The model transportation network consists of a system of nodes and links. In the base scenario, which represents existing conditions in 2010, there are a total of 105,256 nodes. 2,727 of these nodes are centroids, one for each of the 2,727 TAZs. Centroids correspond to the start and end points of a trip, from and to a particular zone, respectively. The 274,827 links in the base scenario correspond to street infrastructure (shared by autos, buses, and pedestrians), dedicated transit infrastructure (for rail and BRT), and special connections. A summary of link statistics is tabulated in Table 5-1 on the following page. An illustration of the network links can be found in Figure 5-3 which shows the extent of the street infrastructure links in the model area.

Special connections include links that describe walk access to rail platforms, pedestrian connections across platforms within a transit station, and centroid connectors. Centroid connectors are the links that connect a zone centroid to the nearby physical infrastructure links. For example, every trip will begin at the origin zone centroid, travel along a centroid connector, continue along a series of infrastructure links, and complete the trip on a centroid connector to the destination zone centroid. In Figure 5-4, a close-up of the network in the Porter Square area, it is clear to see how the centroid

connectors link each TAZ centroid to the nearest node on the physical infrastructure network. The pedestrian connections to and across the Porter Square station platforms (shown in green in the figure) are also apparent.

Each link in the network has attributes that describe its characteristics including the link distance, auto speed, transit speed, free flow auto time, congested auto time, transit time, walk time, capacity, number of lanes, and direction (one-way/two-way). All pedestrian links assume a three mile per hour walk speed. Bus speeds, for buses that travel in mixed traffic conditions, are equivalent to the congested auto speeds on each roadway link. A 25 mile per hour auto speed and 3 mile per hour walk speed is assumed for all centroid connectors.

Table 5-1: Model Link Statistics

MODEL COMPONENT	NO. LINKS
<i>Street Infrastructure</i>	
Expressways	1,983
Interchanges/Ramps	242
Main Arterials	663
Minor Arterials	10,996
Main Distributors	49,437
Minor Distributors	15,839
Local Streets	173,480
<i>Transit Infrastructure</i>	
Subway	399
Subway (GLX Build)*	411
Commuter Rail	687
Navigation Channels	58
<i>Connectors</i>	
Walk Access to Rail Stations	638
Walk Access to Rail Stations (GLX Build)*	674
Walk Connections Across Rail Platforms	167
Walk Connections Across Rail Platforms (GLX Build)*	179
Park and Ride Drive Access to Commuter Rail Stations	264
Centroid Connectors	19,974
TOTAL	274,827
TOTAL (GLX Build)*	274,887

Figure 5-3: Transportation Network Links

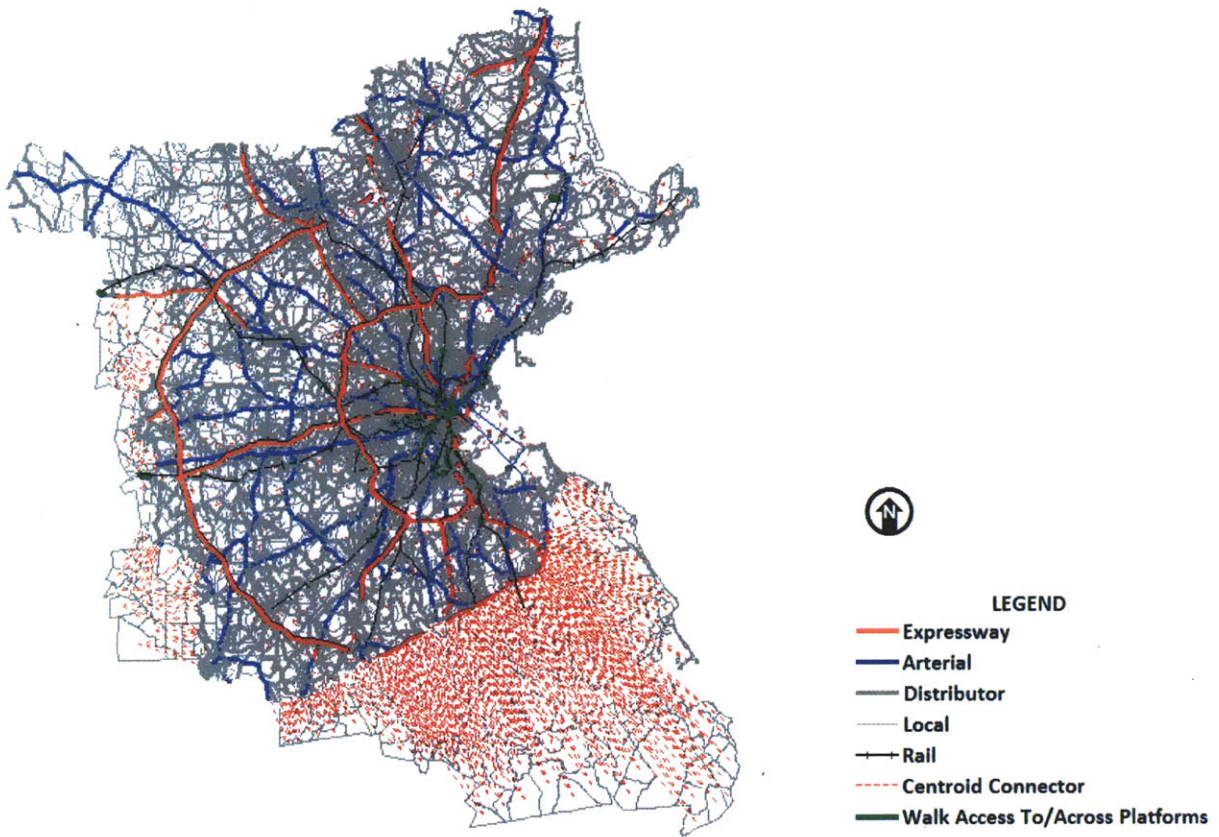
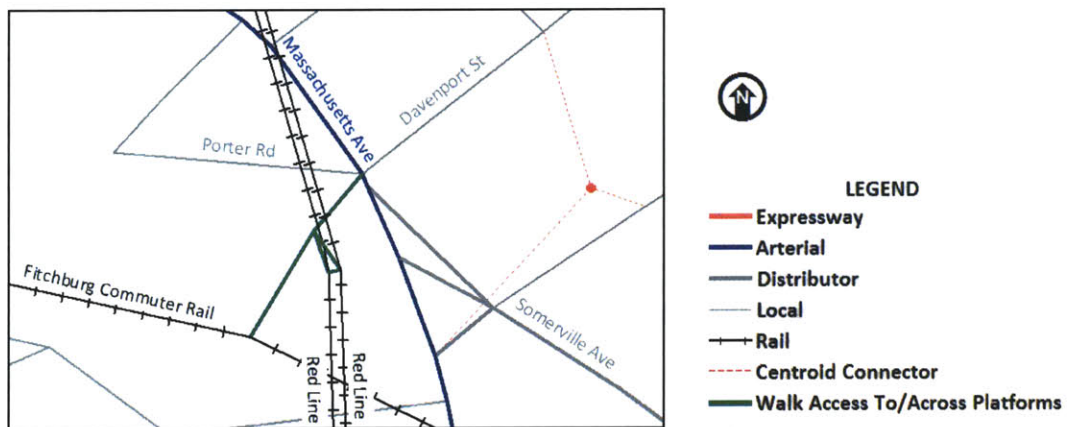


Figure 5-4: Close-up of Model at Porter Square Station



5.2.1 Transit Routes

Transit routes are defined in the model using transit line files. These files store route attributes including the route name, mode, dwell times, and headways during the AM peak, midday, PM peak, and rest of day periods. Also included are the nodes that comprise the route alignments and nodes designated as route stops.

Figures 5-5 and 5-6 illustrate the MBTA transit routes included in the model. The present state of the model incorporates all heavy rail, light rail, commuter rail, and commuter ferry routes. A total of 37 bus routes and one BRT route are also included. While the MBTA operates over 150 bus routes and a total of four BRT routes, the main routes serving the Project corridor and downtown Boston are built-in to the current model. Additional bus routes and the Silver Line BRT routes serving South Boston can be incorporated in future enhancements of the model. A summary of the transit route statistics can be found in Table 5-2.

It is important to note that the model uses existing bus routes and frequencies (approximately every 15 minutes in Somerville). Improved bus route frequencies within the Project corridor and improved coordination with the Green Line Extension would increase transit accessibility in Somerville.

Figure 5-5: Regional Transit Route Map

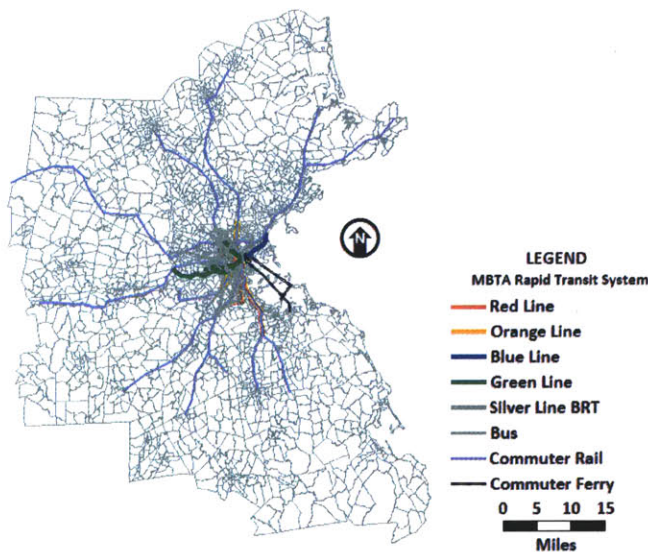


Figure 5-6: Central Business District Transit Route Map

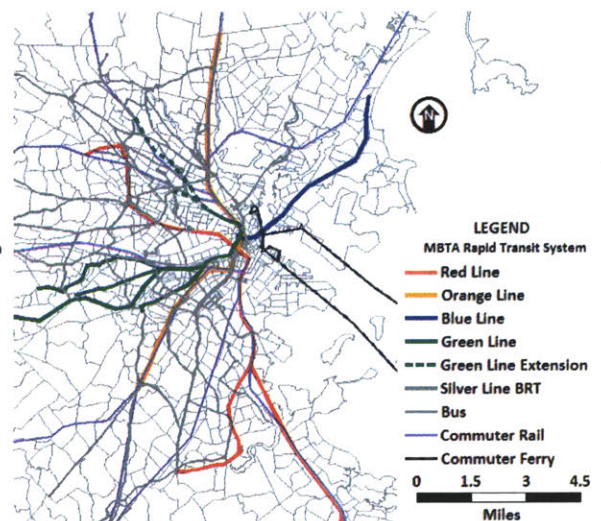


Table 5-2: Transit Route Statistics

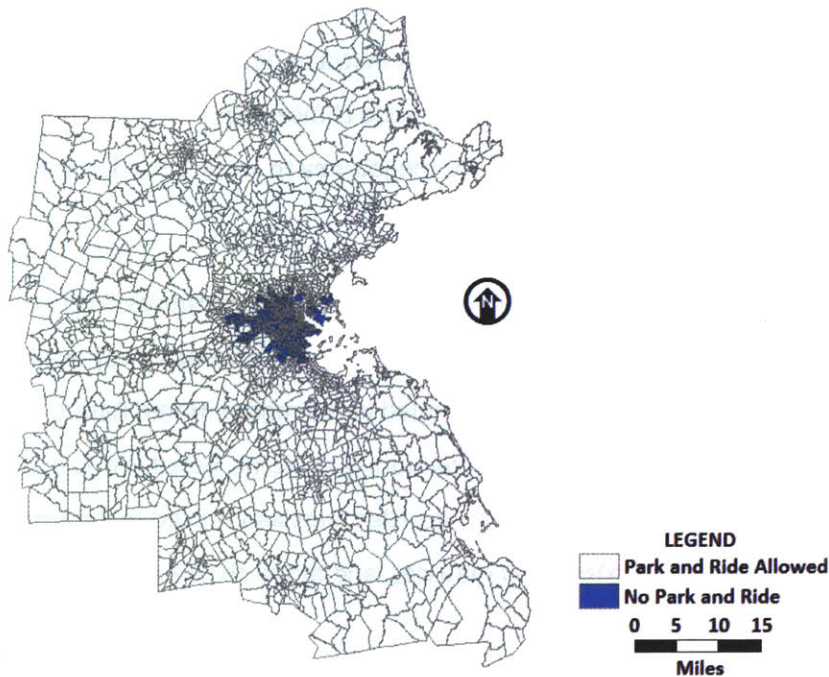
MODEL TRANSIT SERVICES	NO. ROUTES
MBTA Heavy Rail	4
MBTA Light Rail	4
MBTA Bus Rapid Transit	1
MBTA Bus	37
MBTA Commuter Rail	14
MBTA Commuter Ferry	5

5.2.2 Park and Ride

Although the proposed Green Line Extension stations are being designed for walk and bus access (as opposed to drive access), park and ride is allowed in the model in order to measure the regional accessibility impacts of the Project in areas served by park and ride commuter rail and rapid transit stations. For example, the model should capture the benefits of the Green Line Extension Project to individuals who drive to the existing Green Line park and ride terminus station at Riverside. These individuals will have increased transit access to opportunities in Somerville, attributable to the extension of the Green Line.

Challenges to modeling park and ride trips include the capacity constraints of station parking lots which, if modeled inadequately, may lead to unexpected results. For example, if the capacity constraints of parking in downtown Boston stations are not recognized in the model, transit trips originating in downtown Boston zones may be modeled as drive access transit trips rather than walk access transit trips (the more likely case). In order to prevent these counterintuitive results, a simple restriction is placed on park and ride in the model. Specifically, drive access transit trips are precluded in the model for central city zones (including Somerville), as shown by the area demarcated in dark blue in Figure 5-7.

Figure 5-7: Park and Ride Restrictions



5.3 Socioeconomic Data

Socioeconomic data is a fundamental model input and is used to inform the trip generation, trip distribution, and mode choice steps of the four-step model. The socioeconomic data sources used in the estimation and calibration of the model are:

- 2000 Census Transportation Planning Package (CTPP) (U.S. DOT, 2000)
- 1991 Boston Household Travel Survey (Boston Metropolitan Planning Organization, 1991)
- Massachusetts Executive Office of Transportation Population and Employment Forecasts (Massachusetts Executive Office of Transportation, n.d.)

The CTPP provides socioeconomic data at the block group level as well as detailed survey information on the journey to work. Based on this socioeconomic data, the model population is divided into transit captives (individuals without access to a private automobile) and transit choice riders. For the trip generation step of the model, this data is used to determine household types based on the number of people, workers, and automobiles in each household (Murga, 2010). The number and types of households in each TAZ are then stored in the TAZ centroid and, using the appropriate trip rate for each household type, the total number of work trips generated in each zone is calculated. Similarly, the

number of employment opportunities in each TAZ is stored in the TAZ centroid and used to determine the number of work trips attracted to each TAZ. Journey to work information, including trip lengths (clock time of the home to work commute) and production-attraction matrices, is used to calibrate the geographic distribution of home to work trips in the model. In the mode choice step, CTPP data on individual characteristics and the transportation mode chosen for the journey to work is used in the estimation of the logit mode choice model.

Since the CTPP only includes data on the home to work trip, the data for other trip purposes must come from other travel surveys. The 1991 Boston Household Travel Survey is the most recent survey available that provides local information on the following trip purposes included in the model: Home Based School, Home Based Shop, Home Based Other, Home Based Recreation, Non-Home Based Work, and Non-Home Based Other. This survey includes data from 39,934 recorded trips and is used to determine the trip rates, trip length distributions, production-attraction matrices, and mode choice data for each of the aforementioned trip types (Murga, 2010).

While the CTPP and Boston Household Travel Survey provide data used to describe the existing socioeconomic profile and travel behavior of the model region, information on future conditions is necessary in order to run forecast year model scenarios. Population and employment forecasts for the year 2030, provided by the CTPS, were used to inform the future baseline and build scenarios of the Green Line Extension Project. These forecasts include the population, number of households, and employment in each TAZ. The model assumes the same auto ownership rates and the same proportions of household types in each TAZ as determined from the 2000 Census and 1991 local survey data.

It is important to note that land use assumptions (population and employment) are held constant between the baseline and build scenarios in the model. This is done to ensure that any changes in accessibility between the two alternatives can be attributed to the alternatives themselves and not to uncertain land use forecasts. Since the Green Line Extension Project has the potential to influence future land use and development around the proposed station locations, this assumption underestimates the long term accessibility benefits of the build scenario.

5.4 Model Steps Considered

The following sections describe the model steps considered in the accessibility analysis. First, the calculation of travel times and costs is described. Next, the calibration and results from the trip generation and trip distribution steps are discussed in detail.

5.4.1 Calculation of Travel Time and Generalized Cost

Necessary inputs for the calculation of accessibility include the time and cost of travel. The model calculates travel times and costs through a process called skimming, resulting in 2,727 by 2,727 matrices (also called skims) that store these values from every possible origin TAZ to every possible destination TAZ. Separate matrices are created for each mode, time period, and each travel time and cost component.

Skims for the walk mode calculate the walk time from all origins to all destinations. Skims for the auto mode calculate the drive time from all origins to all destinations, and are computed for the AM peak, midday, PM peak, and rest of day time periods to reflect varying levels of congestion. Similarly, transit skims are also separated by the aforementioned time periods to reflect varying levels of service throughout the day and varying levels of congestion. Transit skims are produced for the following components of travel: access time (by foot or car), initial wait time, transfer wait time, in vehicle travel time (by rail or bus), number of boardings, and transit fares. Transit fares are converted to equivalent minutes by using a \$12 per hour value of time.

Users have different perceptions on the various components of transit travel time, such as finding walk access time and waiting time more burdensome than time spent traveling in the vehicle. For this reason, perceived times are considered by applying weight factors to the clock times calculated in the skimming process. The weights are estimated from the coefficients of the mode choice model, estimated from survey data. In simple terms, the coefficients reflect how much emphasis is placed on each time or cost component. The weights ultimately selected for use in the model are taken from the CTPS regional model, where walk time, initial wait time, and transfer wait time are all weighted by a factor of two (I. Harrington, personal communication, July 27, 2010). In addition to these weight factors, the model includes a penalty of three and a half minutes per transfer to reflect the burden of multiple boardings. While the conditions inside a transit vehicle will also influence the disutility of time spent traveling, such as having a seat versus standing in a crowded environment, these differences are not considered in this accessibility analysis.

5.4.2 Trip Generation

A few simple exercises make it apparent that it is very challenging to obtain an accurate representation of actual travel behavior from the available survey sources. One such exercise compares the number of trips generated per person as calculated from the survey data with the trip generation rates estimated

from the model. The model trip rates are determined by dividing the total population of each town by the total number of trips generated in each town to obtain the trips per person. Table 5-3 shows the survey and model results by trip purpose.

Table 5-3: Trip Generation Comparison

TRIP TYPE	MODEL TRIP RATES			SURVEY TRIP RATES		
	MIN	MAX	AVG	MIN	MAX	AVG
Home Based Work	0.2	0.7	0.5	0.2	0.5	0.4
Home Based Shop	0.2	0.5	0.4	0.1	0.7	0.4
Home Based School	0.1	0.3	0.3	0.0	0.6	0.2
Home Based Other	0.4	0.8	0.6	0.1	0.6	0.4
Home Based Recreation	0.1	0.2	0.2	0.0	0.2	0.1

The results in Table 5-3 show that the average trip rates from the model are close to, but slightly higher than, those calculated from the survey. A more interesting observation is the range between the minimum and maximum trip rates. It is hypothesized that actual trip rates are relatively constant across zones. For instance, the number of shopping trips made by an individual is not likely to differ significantly from one town to another. However, with the exception of the journey to work, the range of the survey trip rates is much wider than the range found from the model calculations. For shop trips, the model trip range is between 0.2 and 0.5 trips per person, while the survey range is between 0.1 and 0.7 trips per person. The difference in range is even greater with school trips, with the model trip range between 0.1 and 0.3 trips per person compared to the significantly more varied survey range between 0 and 0.6 trips per person. These results highlight the uncertainty of survey data and the challenges present in using survey data to estimate actual behavior.

5.4.3 Trip Distribution

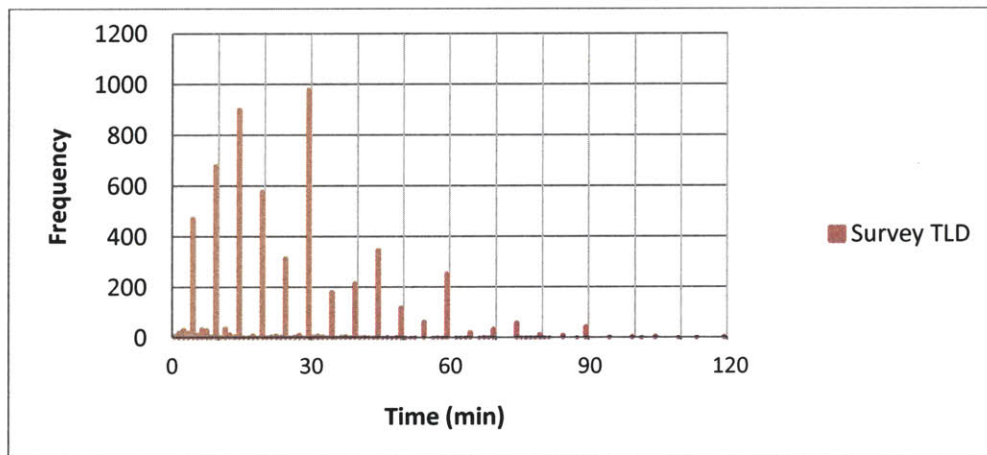
The mathematical function describing aversion to travel, necessary for gravity-based measures of accessibility, is developed from the trip distribution step of the model. Consequently, the author focused on the calibration of this very important step for the trip purposes which will be used in the accessibility measures.

The goal of the trip distribution step is to accurately represent the geographic flows of trips from origin to destination. Ideally, data such as *how many high school science teachers in East Somerville work in South Boston high schools* or *how many patients from Cambridgeport go to Somerville Hospital* would be

available. Unfortunately, existing survey data does not provide such a fine level of detail. However, we do have detailed Production-Attraction matrices and trip length data from the 2000 CTPP describing the general home to work commute. Additionally, the 1991 Boston Household Travel Survey provides Origin-Destination matrices and trip length data for other trip purposes.

Trip length distribution data is often used to calibrate the trip distribution step of models. However, solely focusing on matching journey times from surveys may not lead to an accurate geographic representation of flows. Even a preliminary look at the survey data suggests that survey responses are likely rounded. Figure 5-8 shows the Home Based Work trip length distribution from the 1991 Boston Household Travel Survey. From this figure, it is apparent that survey respondents tend to round their responses to the nearest five minutes. Many responses may be rounded even more than five minutes, as spikes at fifteen minutes, thirty minutes, forty five minutes, and sixty minutes are noticeable in the graph. Additionally, while survey journey times are intended to be clock times, it is possible that some people may have different perceived times that influence their response. Monetary costs, while influential on travel behavior, are also not reflected in the surveys. These discrepancies are large enough to influence the accurate calibration of the model trip flows.

Figure 5-8: Home Based Work Survey Trip Length Distribution



Data Source: 1991 Boston Household Travel Survey (Boston Metropolitan Planning Organization, 1991)

Because of these potential shortcomings, the calibration of the model instead focused on achieving a close geographic match of the trip flow tables. This was done by modifying the friction factors, which describe the aversion to travel, with a total of six iterations in order to determine the friction factors

that achieve the best geographic match. It is valuable to note that a single set of friction factors is used to describe aversion to travel for the entire region. Using one set of friction factors provides a meaningful description of behavior without the need for “k- factors” or the use of multiple friction factors for different geographic interchanges in order to more closely match survey results. Since some trip purposes were able to achieve a closer match than others, further iterations performed on these trip purposes may be able to further improve the match.

By plotting the model estimated trip flows by town against the survey produced trip flows, the closeness of the geographic match is determined. In Figure 5-9, the geographic match of workers is shown to be extremely good, with a rho squared coefficient of 0.99 for all data points. In Figure 5-10, the data point for intra-Boston flows, a city that experiences much higher trip flows than other areas in the model, is removed to determine the goodness of fit without this outlier. Even without Boston, the geographic match of worker flows is excellent with a rho squared of 0.89. This would improve further with the additional removal of the intra-Cambridge data point, spotted as an outlier in Figure 5-10.

Figure 5-9: Model versus Survey Worker Trip Flows – All Towns

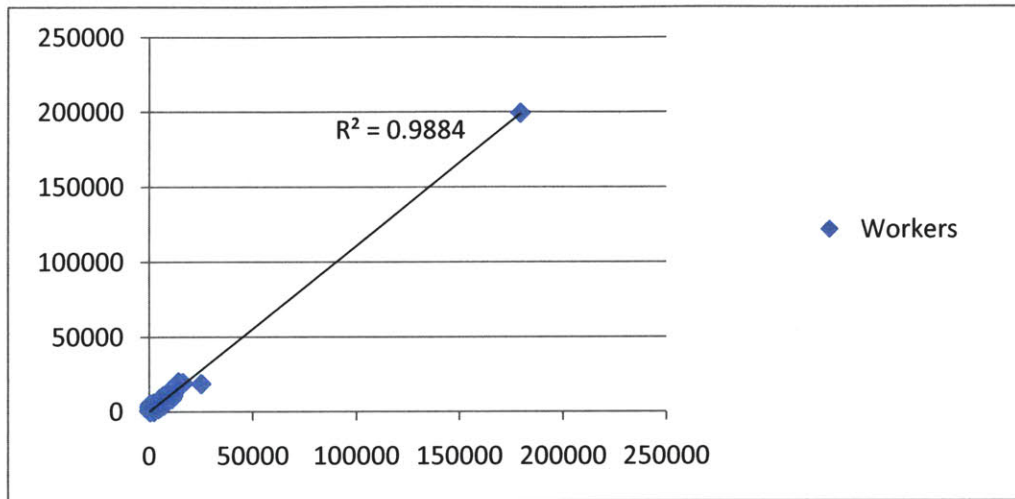
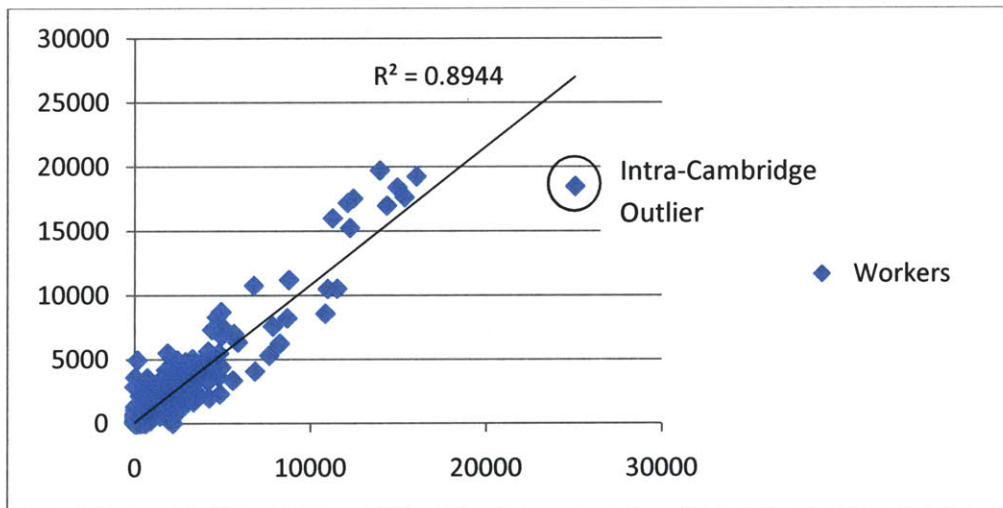


Figure 5-10: Model versus Survey Worker Trip Flows – All Towns Except Boston



In Figures 5-11 and 5-12, the correlation between the model and survey geography for Home Based Shopping trips is illustrated for all towns and with the Boston outlier removed, respectively. There is a strong correlation when considering all towns (rho squared of 0.93), but the correlation is weaker when the Boston point is removed (rho squared of 0.74). Considering that the choice of where to shop is also influenced by the uneven distribution of shopping malls, supermarkets, and specialty stores, the match achieved seems reasonable.

Figure 5-11: Model versus Survey Home Based Shop Trip Flows – All Towns

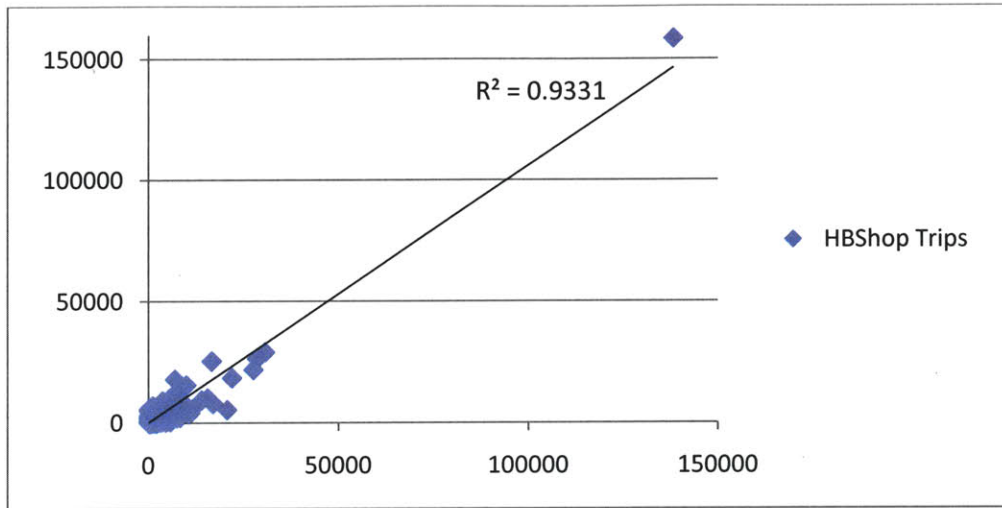
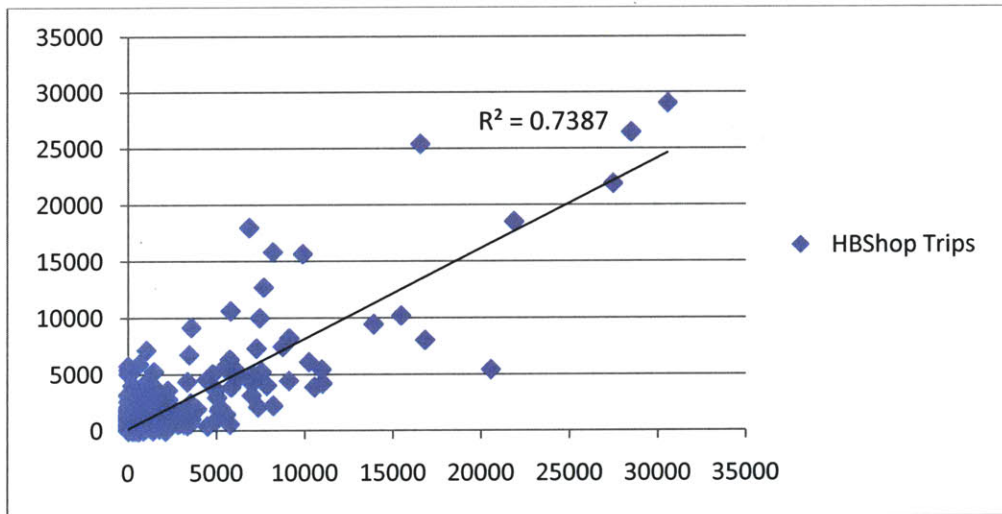


Figure 5-12: Model versus Survey Home Based Shop Trip Flows - All Towns Except Boston



Figures 5-13 and 5-14 illustrate the geographic match achieved for Home Based School trips. There is a very strong correlation when considering all towns (rho squared equal to 0.95), but the correlation is weak (0.65) when Boston is removed from the dataset. Since the decision of where to go to school is influenced by a multitude of factors not considered in the survey data, such as degrees offered, tuition, sports opportunities, etc., and the location of schools may not be uniform, achieving a very close geographic match from the model friction factors is expected to be a challenge.

Figure 5-13: Model versus Survey Home Based School Trip Flows - All Towns

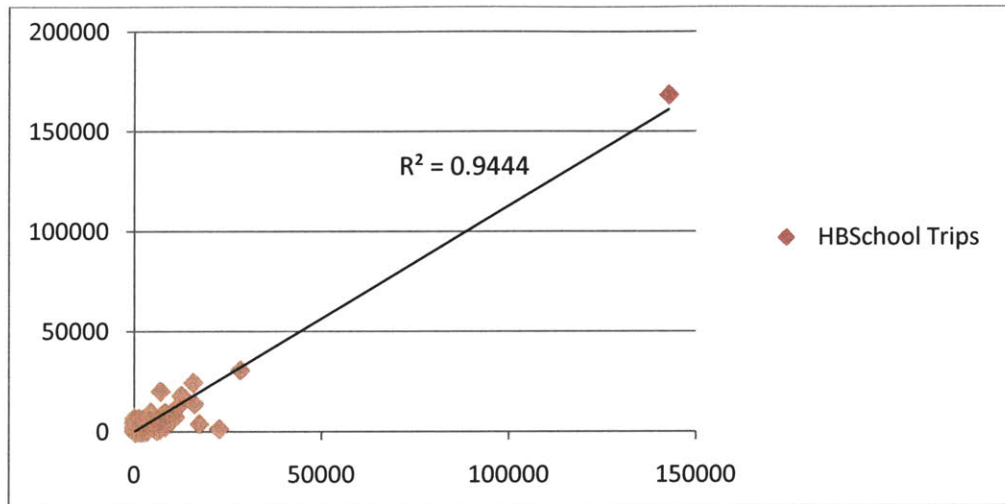
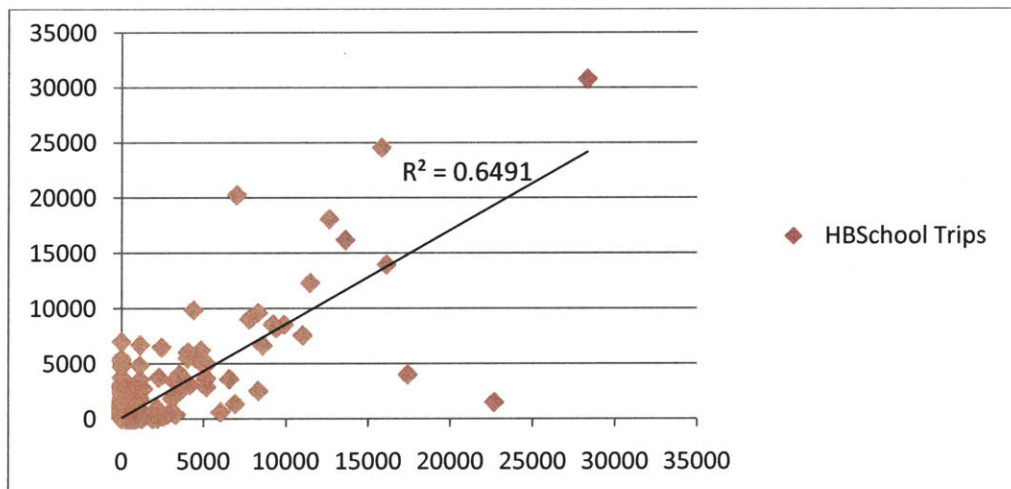


Figure 5-14: Model versus Survey Home Based School Trip Flows - All Towns Except Boston



The geographic match achieved for Home Based Other trips is shown in Figures 5-15 and 5-16. A strong match was achieved when considering all towns as well as when the Boston data point is removed, with a rho squared valued of 0.95 and 0.81, respectively.

Figure 5-15: Model versus Survey Home Based Other Trip Flows - All Towns

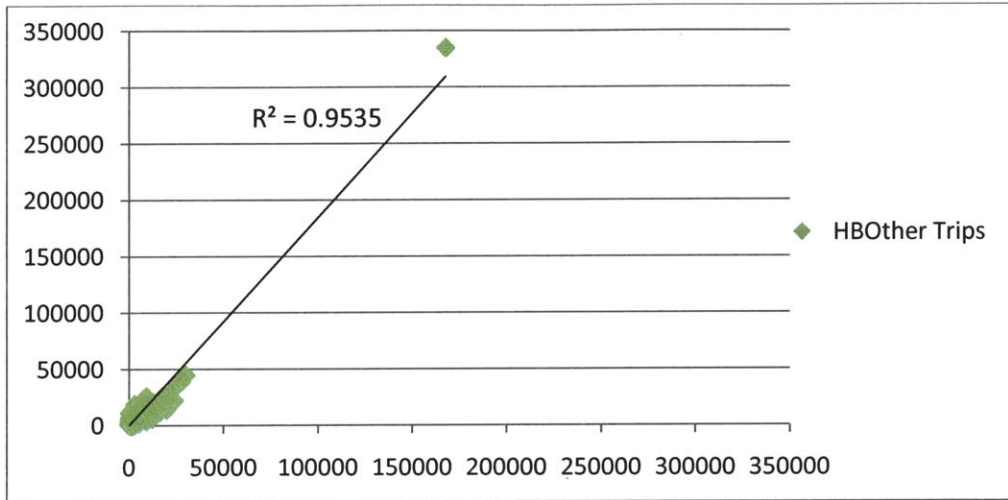
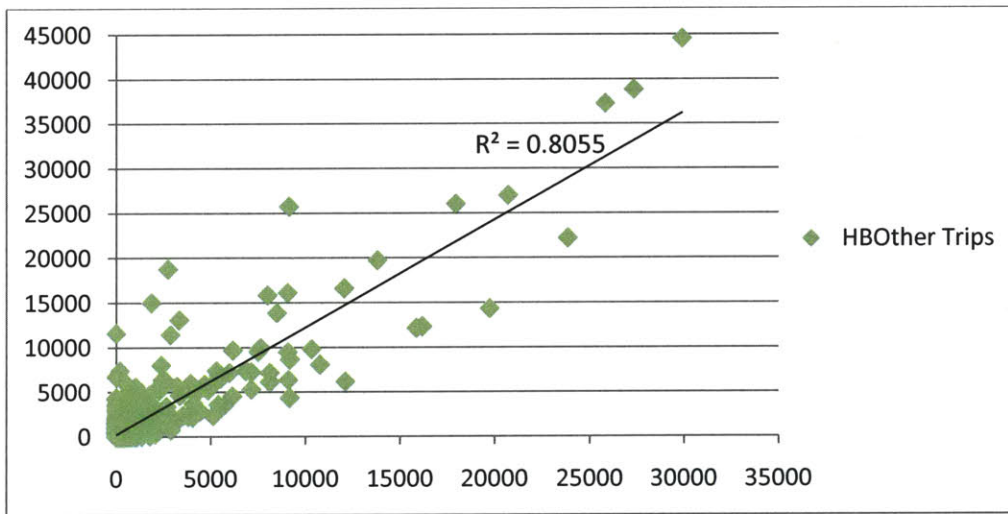


Figure 5-16: Model versus Survey Home Based Other Trip Flows - All Towns Except Boston



In Figures 5-17 and 5-18, the correlation between the model and survey geography for Home Based Recreation trips is shown. There is a strong correlation when considering all towns (rho squared of 0.92), however the correlation is weak when Boston is removed (rho squared equal to 0.64). Achieving a close match for recreation may be difficult given the existing data sources because recreational destinations are likely determined by a variety of factors including the specific recreational activity the individual wishes to partake in. If an individual desires to go hiking, for example, there are a discrete number of parks with hiking trails that the individual could choose to travel to. More detailed input data is necessary in order to further improve the spatial matching of recreation trips.

Figure 5-17: Model versus Survey Home Based Recreation Trip Flows - All Towns

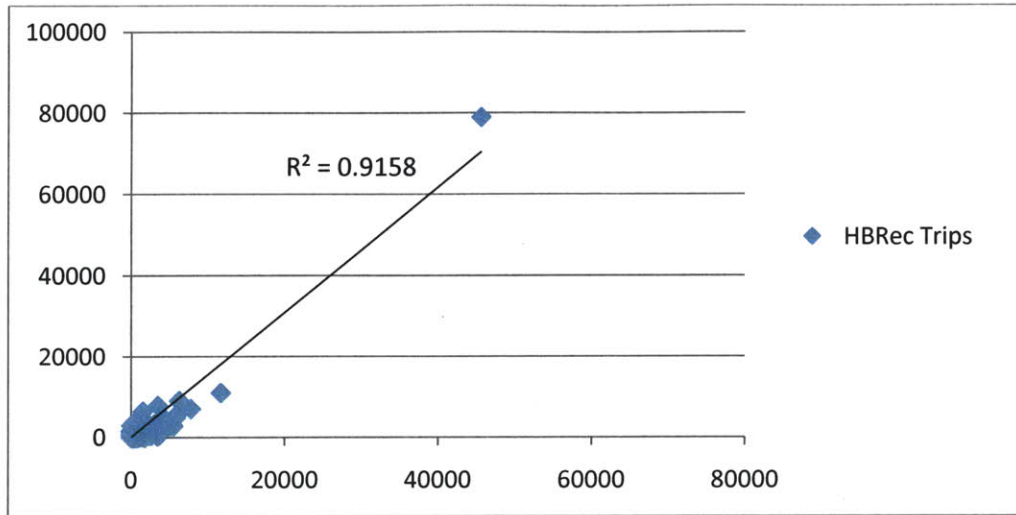
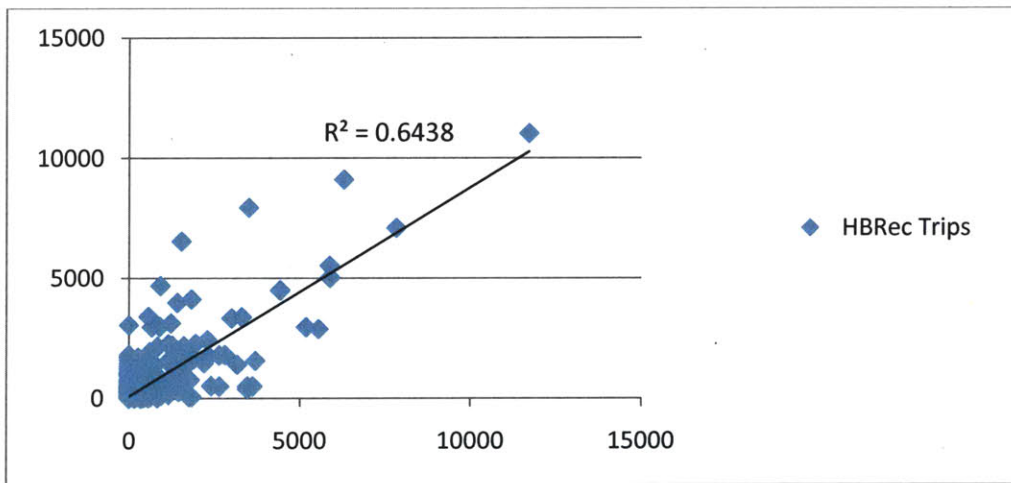


Figure 5-18: Model versus Survey Home Based Recreation Trip Flows - All Towns Except Boston



The above graphs indicate that over all towns, strong geographic matches of trip flows were obtained for each of the trip purposes. While the matches were not as strong when the Boston data point was removed, Home Based Work and Home Based Other still showed excellent geographic correlation. The weaker relationship for Home Based Shop, School, and Recreation trips may be explained by the variety of factors that go into deciding where to pursue these particular activities. In summary, the trip distribution calibration performed provides a reasonable geographic match for all trip purposes using a meaningful methodology, which was the goal of this exercise.

Given this geographic matching, the trip length distributions between the model outputs and the survey data are compared for each trip purpose in Figures 5-19 through 5-23 on the following pages. In these graphs, survey data points were aggregated to five minute intervals for easier comparison of the trip length clock times. The results indicate that the model trip length distributions follow the survey distributions closely for the Home Based Work and Home Based School trip purposes. The patterns are not closely aligned for the Home Based Shop and Home Based Recreation purposes, with the survey data showing more short trips (particularly trips under ten minutes) than the calibrated model outputs. The survey data for the Home Based Other trip purpose does not appear to have a strong pattern, making it difficult to compare the survey and model results. Despite the trip length distribution differences shown for some of the trip purposes, the only way to truly know that the model flows are accurate is to compare the geographic flows. This comparison, discussed previously, shows that the model achieves a satisfactory trip distribution match.

Figure 5-19: Home Based Work Trip Length Distribution

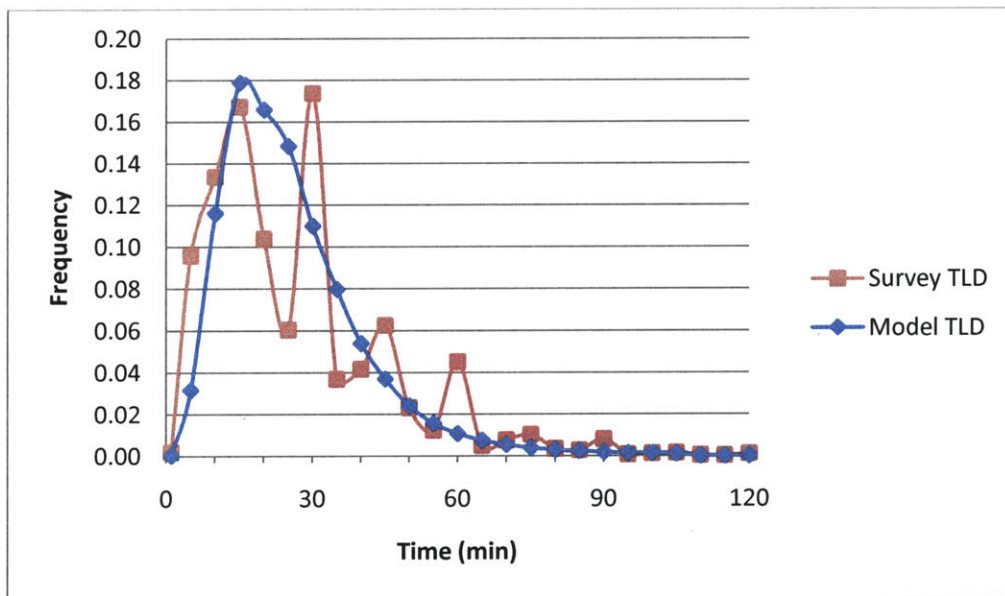


Figure 5-20: Home Based Shop Trip Length Distribution

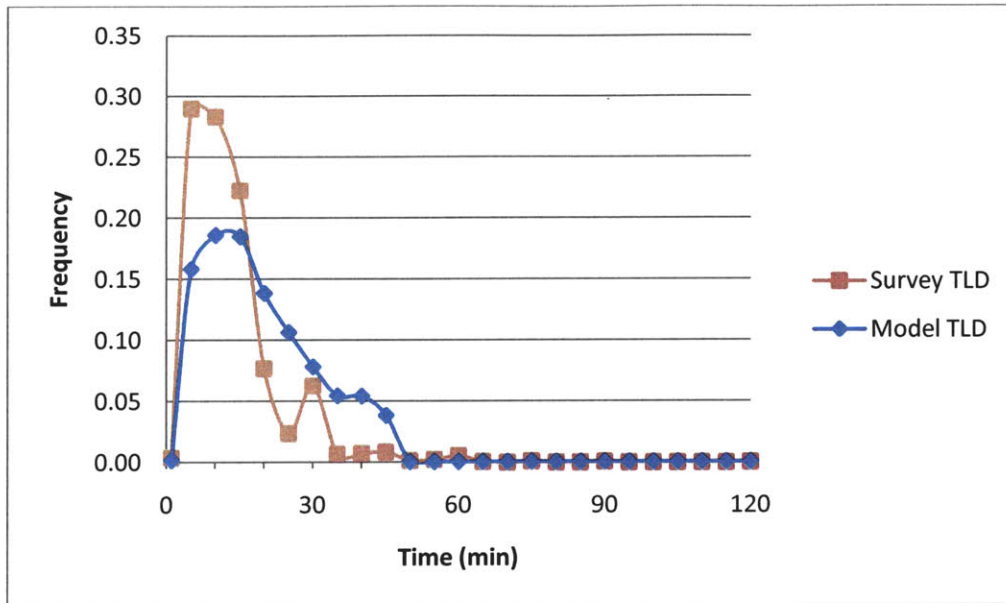


Figure 5-21: Home Based School Trip Length Distribution

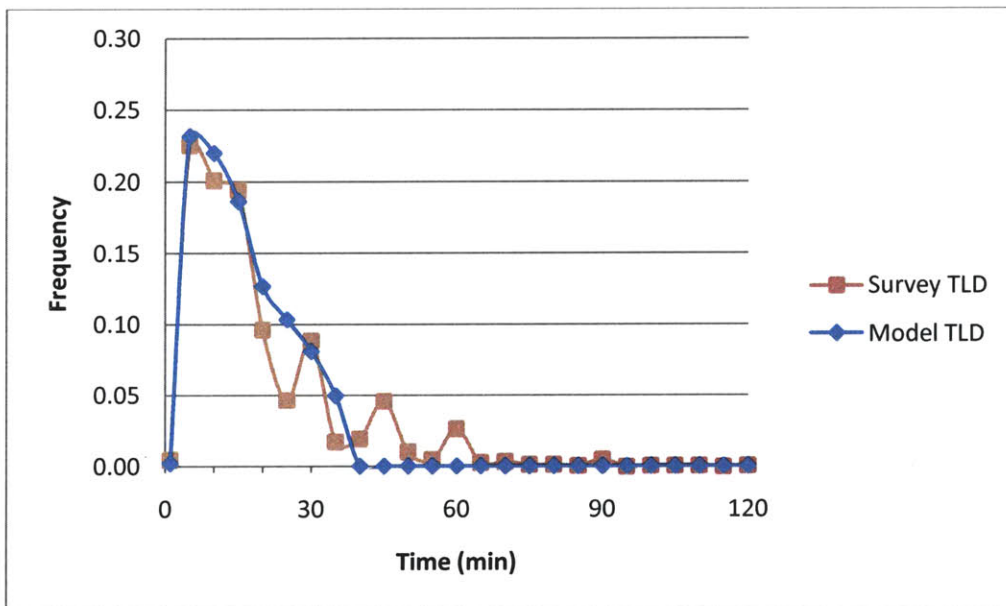


Figure 5-22: Home Based Other Trip Length Distribution

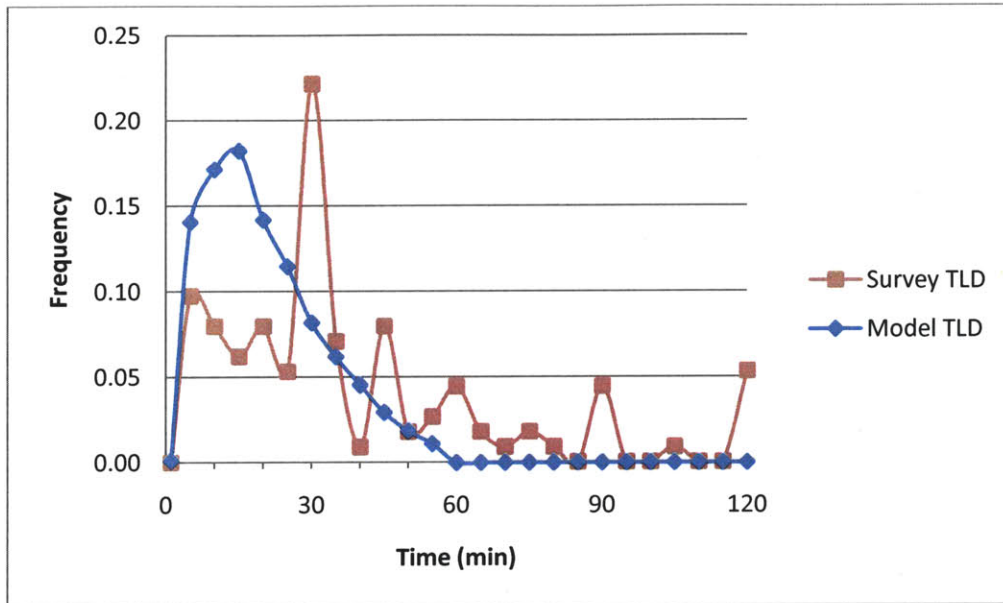
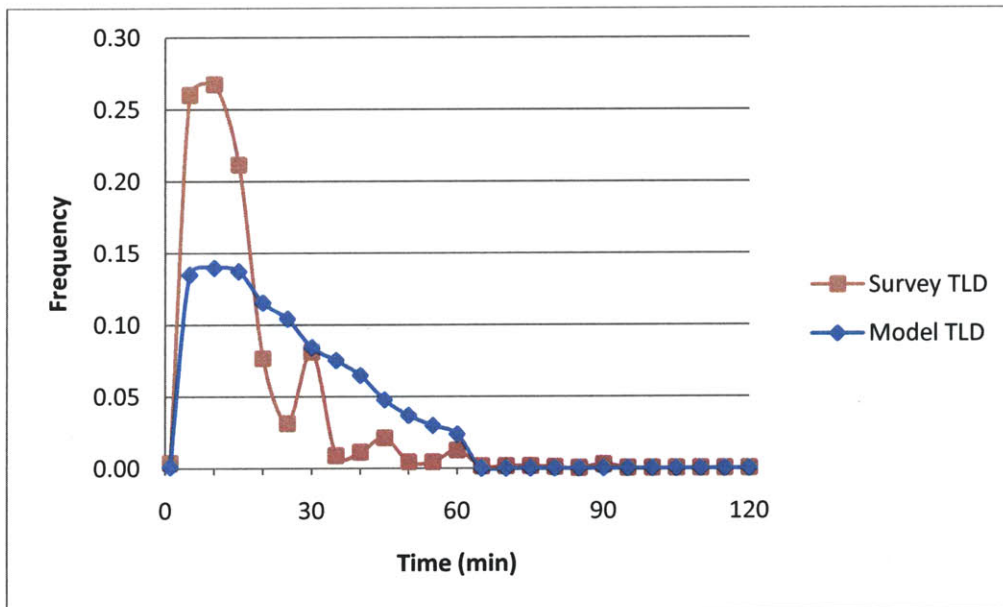


Figure 5-23: Home Based Recreation Trip Length Distribution

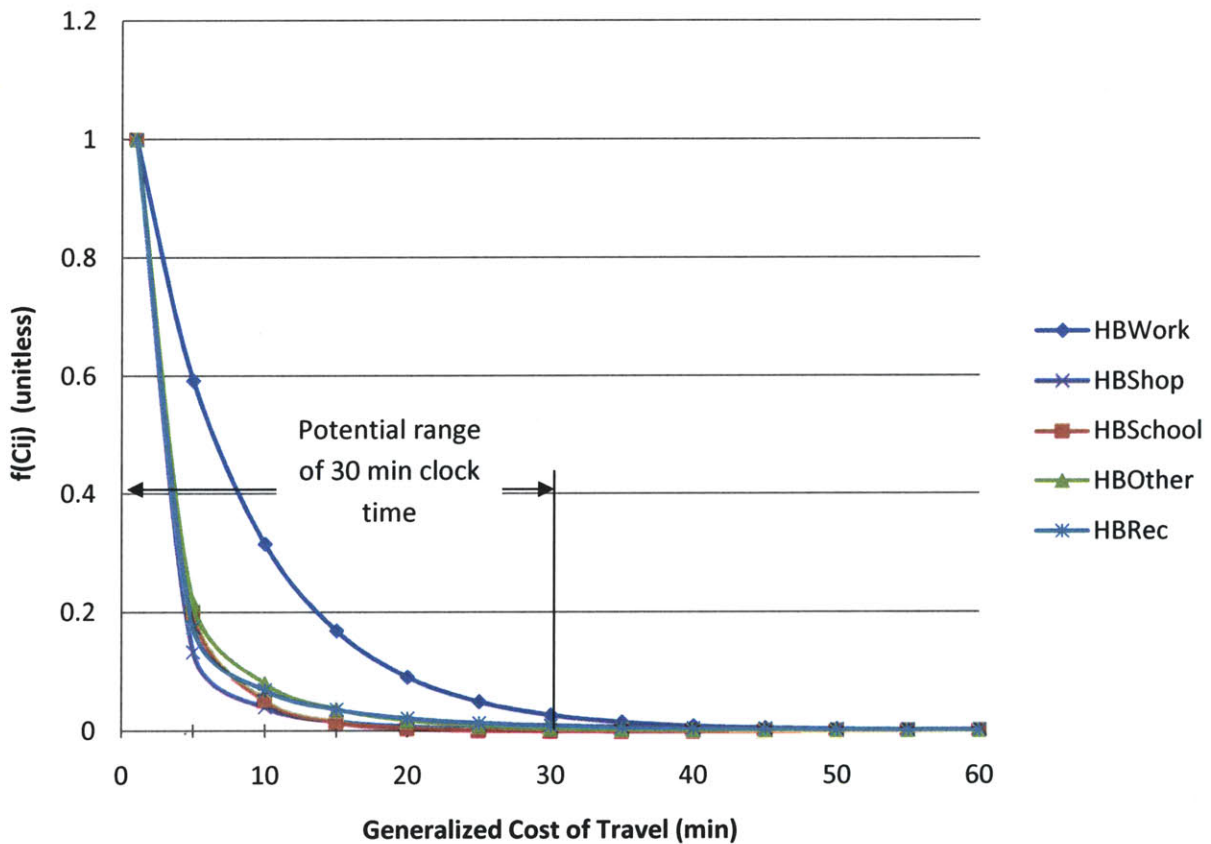


5.4.3.1 Friction Factor Estimation

A critical input for gravity-based accessibility calculations is a function that describes the aversion to travel. Theoretically, this function should be continuously decreasing to indicate that as the cost of reaching an opportunity increases, the relative attractiveness of that opportunity decreases.

The equation used to determine the friction factors in the trip distribution step fulfills the requirement of a continuously decreasing function and additionally is based on the geographic matching of trip flows. The functions estimated for each purpose are shown in Figure 5-24, scaled within a range of zero to one. The cost of travel used in the estimation of these functions represents the total generalized cost, and comprises weighted travel times as well as transit fares converted to minutes using a \$12 per hour value of time. Since the generalized cost includes perceived times and fares, the corresponding clock time will be less than the displayed cost of travel.

Figure 5-24: Friction Factors By Trip Purpose



The functional form used to estimate the friction factors is a gamma function, shown in Equation 5-1. The estimated coefficients of Equation 5-1 for each trip purpose, corresponding to the best geographic match, are shown in Table 5-4.

EQUATION 5-1: Gamma Function (Murga, 2010)

$$f(C_{ij})=a * C_{ij}^{-b} * \exp(-c * C_{ij})$$

Where :

i = origin location

j = destination location

C_{ij} = travel cost from i to j

a, b, c = estimated coefficients

Table 5-4: Gamma Function Coefficients for Friction Factors

TRIP TYPE	A COEFFICIENT	B COEFFICIENT	C COEFFICIENT
Home Based Work	28507	0.020	0.123
Home Based Shop	1200	1.000	0.100
Home Based School	2000	0.500	0.200
Home Based Other	2000	0.700	0.100
Home Based Recreation	500	0.950	0.053

5.5 Model Scenarios

Several scenarios were modeled in order to calculate accessibility benefits of the Green Line Extension Project. These include:

- 2010 base scenario
- 2030 FTA baseline scenario
- 2030 build scenario
- 2000 retrospective scenario

First, a base scenario was established to reflect current conditions. This base scenario uses the most recent socioeconomic data from the 2000 Census and 1991 Boston Home Travel Survey. The transportation network and transit route system reflect 2010 conditions to the extent they are incorporated in the model.

Next, FTA baseline and build scenarios for the year 2030 were created using CTPS population and employment forecasts. The FTA baseline reflects the best that can be done in the project corridor without the proposed major capital investment. In the case of the Green Line Extension Project, the baseline scenario includes enhanced Route 80 bus service that will run at the same frequencies as the Green Line Extension (approximately every five minutes during peak hours and every ten minutes during non-peak hours) and serve the same station locations. Additionally, the baseline scenario includes a shuttle service between Lechmere and Union Square that will run at the same frequencies as the proposed Union Square spur of the Green Line Extension Project. The 2030 build scenario incorporates the proposed Green Line Extension capital investment from Lechmere to College Avenue with a spur to Union Square.

Finally, a 2000 retrospective scenario was developed in order to analyze the possible correlation between accessibility and mode share. The year 2000 was selected because Census data regarding actual mode shares is readily available and the network changes to the base model were minimal. These network changes primarily reflect modifications to I-93 due to the Central Artery/Tunnel project. Specifically, creation of the 2000 model includes a modification of lanes on I-93 from the current eight or more lanes through downtown Boston and across the Charles River to the six lanes that previously existed before the Central Artery/Tunnel.

5.6 Model Limitations

The biggest limitations of the model's ability to represent actual conditions are a lack of detailed socioeconomic data and more relevant travel surveys. Simple Census and travel survey data were used in the initial development of the model to get the model "up and running". More detailed data on specific attractions, such as parks, hospitals, and shopping centers, as well as better socioeconomic and travel behavior data to describe how individuals chose where they pursue these activities, would greatly enhance the model's ability to represent trip flows and travel behavior. The addition of major special generators, such as Mass General Hospital and Logan Airport, will also improve the model.

External trips are currently not incorporated in the model. It is likely that, particularly on interstate routes such as I-93, through traffic originating outside of the model area and destined for zones outside of the model area represents a significant portion of the traffic flow. Similarly, trips destined for areas within the model region but produced outside the model limits and trips originating in the model region but destined outside the limits of the model are not included.

In order to apply the model to applications other than the accessibility analysis of the Green Line Extension Project, additions and refinements to the transportation network and transit routes incorporated may be needed. For example, the roadway network does not cover the southern area of the region and there are also a number of local bus routes that are not currently included in the model.

Lastly, another limitation of the model is the scale on which it can be used, particularly from the perspective of accessibility and livability. There are many micro-scale aspects to both of these concepts that the model may not adequately address. These aspects include the perceived pleasantness or unpleasantness of the travel environment. Also, the presence of physical barriers, particularly for pedestrian connections, may be better addressed using a microscopic model.

6 Accessibility Analysis

The Green Line Extension Project is expected to increase the livability of communities in the Project corridor by increasing transit accessibility to essential opportunities. In this chapter, transit accessibility for three Project scenarios is quantified and analyzed for opportunity categories vital to a high quality of life. Accessibility will be calculated using isochrone and gravity methodologies and the results later compared in order to recommend the most appropriate method for project evaluation purposes.

To begin with, the assumptions and tools used in the isochrone and gravity accessibility calculations are described. The isochrone measures are a simplistic method for calculating accessibility benefits; gravity measures, on the other hand, are more complex and rigorous. Comparing the results from these two different methods will provide insight as to whether simplistic measures of accessibility are adequate for project evaluation or if more thorough methods are required.

Next, the results of the isochrone and gravity accessibility analyses are presented for five opportunity categories essential to livability: employment, shopping, education, health care, and recreation. The analyses are performed for three of the model scenarios described in detail in Section 5.5. These scenarios consist of an existing conditions scenario in year 2010, a baseline scenario in year 2030, and a Green Line Extension build scenario in year 2030.

A discussion of the results is provided regarding the suitability of including isochrone and gravity measures in the FTA New Starts process. The opportunity categories which should be included when calculating the accessibility benefits of New Starts applicant projects are also discussed.

Lastly, an example of a potential accessibility metric that can be incorporated in the New Starts rating criteria to more fully capture livability benefits of transit projects is presented. This metric can also be used by MPOs to support flex funding decisions.

6.1 Isochrone Accessibility Estimation

Isochrone accessibility measures consider the total number of opportunities that an individual can reach within a given travel time or cost threshold.¹⁴ The isochrone accessibility results presented in this chapter assume unweighted travel time. Unweighted travel time is equivalent to clock time, and refers

¹⁴ Refer back to Section 2.4.1 for a detailed formulation and explanation of isochrone accessibility.

to the equal consideration of access walk time, wait time, transfer wait time, in-vehicle travel time (by rail or bus), and egress walk time. Additional penalties for particular time components (such as considering walk time more burdensome than in-vehicle travel time), transfer penalties, and fares are not included in the isochrone accessibility calculations. Consideration of these time penalties will be explored in the more complex gravity measures presented later in this chapter.

The isochrone time threshold is defined using the 90th percentile travel time from the model trip lengths. Using the 90th percentile travel time ensures that the threshold is both meaningful and at the same time insensitive to outliers. Thresholds are defined for each opportunity category using the appropriate trip type and the appropriate time period, determined by the time of day in which a majority of trips are made. For example, the threshold used for accessibility to employment uses the 90th percentile travel time from all Home Based Work trips in the AM period since most of these trips are made in the morning peak. A majority of shopping trips, on the other hand, are taken in the PM period. Therefore, the threshold used for shopping accessibility is determined by the trip lengths of Home Based Shop trips in the PM period.

The calculated thresholds for each opportunity type are delineated in Table 6-1. As shown in the table, work and recreation trips tend to be longer than the other trip types, with thresholds of 40 and 45 minutes, respectively. Shopping and “other” trips (“other” includes trips to health care) both have a 35 minute travel time threshold. School trips represent the shortest trips, with a travel time threshold of 25 minutes.

Table 6-1: Isochrone Accessibility Travel Time Thresholds

OPPORTUNITY CATEGORY	TRIP TYPE	TIME PERIOD	90TH PERCENTILE TRAVEL TIME
Employment	Home Based Work	AM	40 minutes
Shopping	Home Based Shop	PM	35 minutes
Education	Home Based School	AM	25 minutes
Health Care	Home Based Other	AM	35 minutes
Recreation	Home Based Recreation	PM	45 minutes

Travel times used in the isochrone accessibility calculations are derived from the Cube Voyager model skims, described in detail in Section 5.4.1. TransCAD software is used to calculate the isochrone accessibility for each model TAZ as well as create maps illustrating the results of the isochrone calculations.¹⁵

6.2 Gravity Accessibility Estimation

Gravity accessibility measures take all opportunities into account while considering that the attractiveness of an opportunity decreases as the cost of travel to reach the opportunity increases.¹⁶ The generalized cost of travel used in the gravity accessibility analysis includes transit fares, a transfer penalty of three and a half minutes per transfer, and weighted travel times. Specifically, walk time, wait time, and transfer wait time are weighted twice as heavily as in-vehicle travel time.

In order to account for the relative attractiveness of opportunities, gravity measures apply a weight to all opportunities using a function that describes the aversion to travel. In order to estimate this function for each opportunity category, the model trip length distributions for the appropriate trip type are used.¹⁷ An inspection of the trip length distributions, illustrated in Figures 6-1 to 6-5, shows each distribution curve initially rising to a maximum point and then decreasing exponentially with increasing travel cost. This initial rise in the curve reflects the low probability of the proximity between locations of residence and desired destinations such as work and school due to many factors, including zoning regulations. However, if used as a measure of opportunity attractiveness, this curve implies that an opportunity ten minutes away is more attractive than an opportunity only five minutes away. This is counterintuitive, and suggests that the trip length distribution curve in itself is not an appropriate functional estimation for use in the accessibility calculation. In order to resolve this issue, an indifference time period is assumed up to the maximum point of the trip length distribution curve. Beyond this determined indifference shelf, a best-fit equation is estimated from the decreasing portion of the trip length distribution.

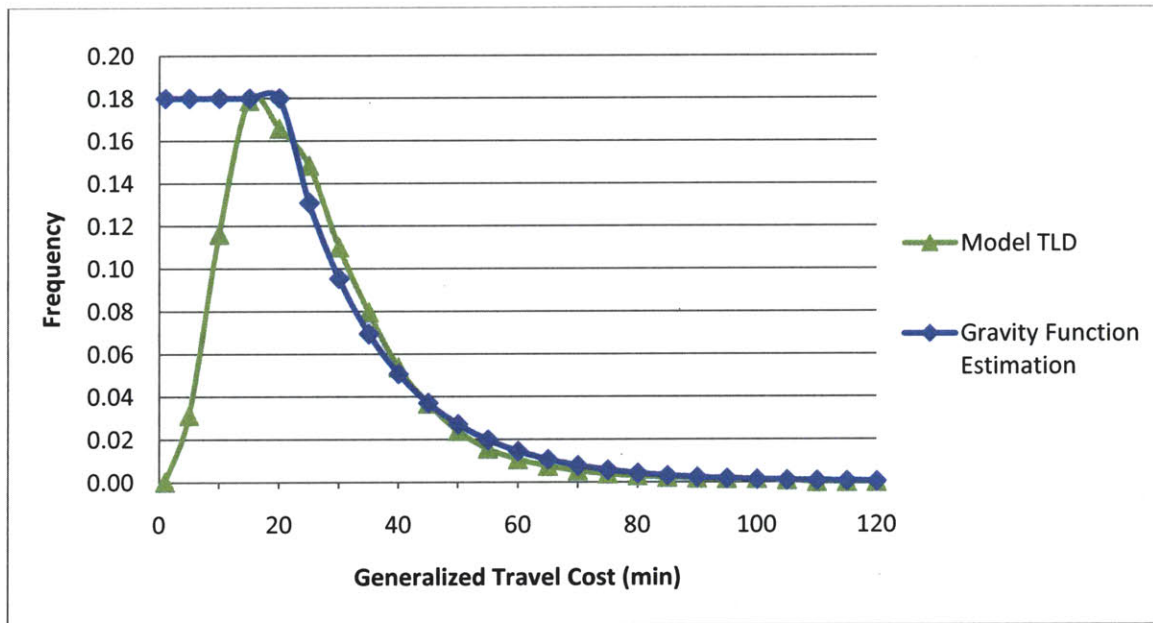
¹⁵ Cube Voyager software is used to create skims for this research due to the prior development of an academic Cube Voyager travel demand model of the study area by Mikel Murga at MIT as part of the 1.254 Transport Modeling class. TransCAD can also be used to create model skims and run a full four-step travel demand model. A full four-step model of the study area is currently being developed in TransCAD for future offerings of 1.254.

¹⁶ Refer back to Section 2.4.2 for a detailed formulation and explanation of gravity-based accessibility.

¹⁷ The trip length distribution is derived from the generated and attracted trips and is weighted by the friction factors estimated during the calibration of the trip distribution step of the model as detailed in Section 5.4.3.

For example, as shown by the blue gravity function estimated in Figure 6-1, there is an indifference time period of 20 minutes for employment opportunities. In other words, any employment opportunities within 20 minutes of a particular origin are of equal attractiveness to an individual, while the attractiveness of employment opportunities beyond 20 minutes decreases exponentially with increasing travel time and/or cost. The formulation for this piecewise equation is given in Equation 6-1.

Figure 6-1: Employment Gravity Function Estimation



EQUATION 6-1: Employment Gravity Function

$$f(C_{ij}) = \{0.18, \text{ if } C_{ij} \leq 20$$

$$0.69 * C_{ij}^{-0.35} * \exp(-0.062 * C_{ij}), \text{ if } C_{ij} > 20\}$$

Where :

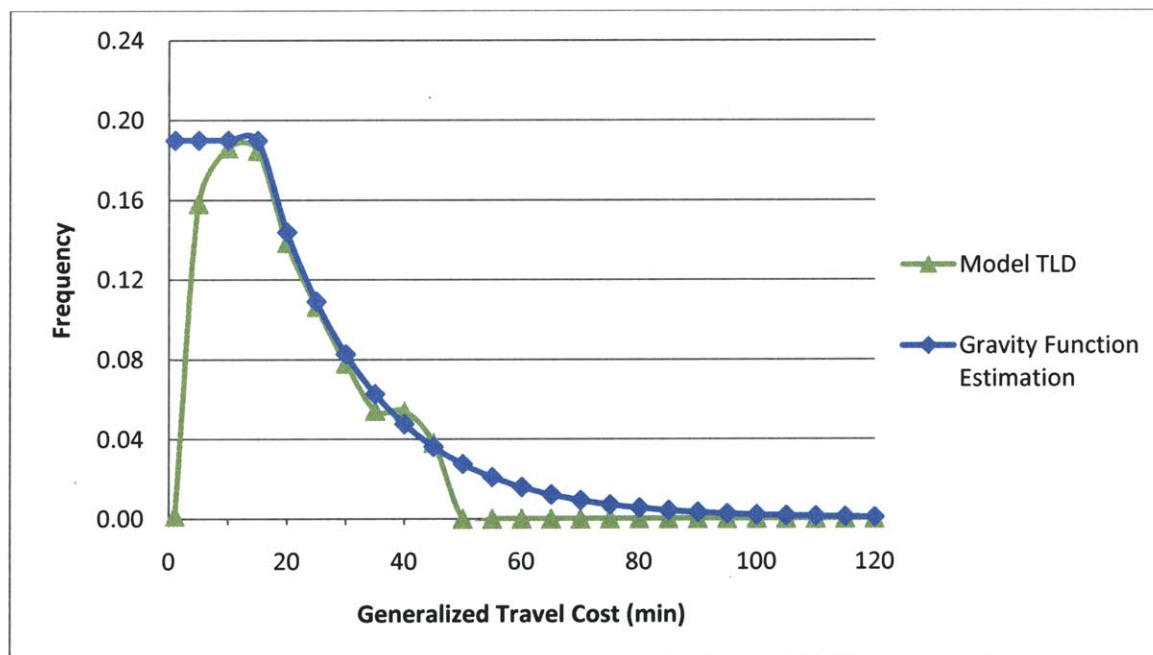
i = origin location

j = destination location

C_{ij} = travel cost from i to j

Figure 6-2 illustrates the gravity function estimation for shopping opportunities, with the formulation indicated in Equation 6-2. From the figure, it is apparent that the indifference time period is shorter for shopping opportunities than for employment opportunities (15 minutes as opposed to 20 minutes). This is expected, as many people will tolerate a relatively long commute to work for a specific job, whereas few will travel farther than necessary for most shopping needs. For example, one might as well go to the nearest Cumberland Farms for a gallon of milk because the product will be similar whether you purchase the milk at the nearest corner store or a grocery store further away. The exception to this rule is specialty shopping trips, such as the purchase of furniture, where quality will vary significantly between retailers. Since most weekday shopping trips are not specialty trips and therefore fall under the previous category, the gravity estimation shown in 6-2 is appropriate.

Figure 6-2: Shopping Gravity Function Estimation



Equation 6-2: Shopping Gravity Function

$$f(C_{ij}) = \begin{cases} 0.19, & \text{if } C_{ij} \leq 15 \\ 0.445 * C_{ij}^{-0.01} * \exp(-0.055 * C_{ij}), & \text{if } C_{ij} > 15 \end{cases}$$

Where :

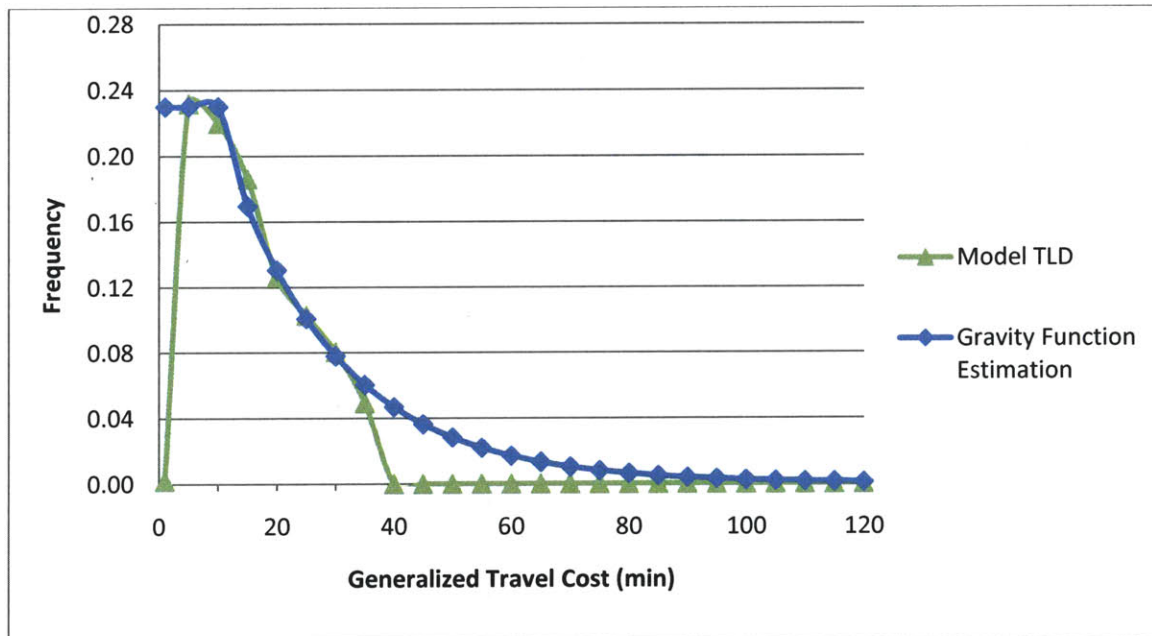
i = origin location

j = destination location

C_{ij} = travel cost from i to j

The gravity function estimation for education opportunities is illustrated and formulated in Figure 6-3 and Equation 6-3, respectively. The indifference time period for education opportunities is only 10 minutes, the shortest of all the opportunities considered. Since the analysis only considers colleges and universities in the education accessibility measure, this short indifference time segment appears reasonable as many college students either live on campus or find off-campus housing close to their place of study.

Figure 6-3: Education Gravity Function Estimation



Equation 6-3: Education Gravity Function

$$f(C_{ij}) = \begin{cases} 0.23, & \text{if } C_{ij} \leq 10 \\ 0.395 * C_{ij}^{-0.035} * \exp(-0.05 * C_{ij}), & \text{if } C_{ij} > 10 \end{cases}$$

Where :

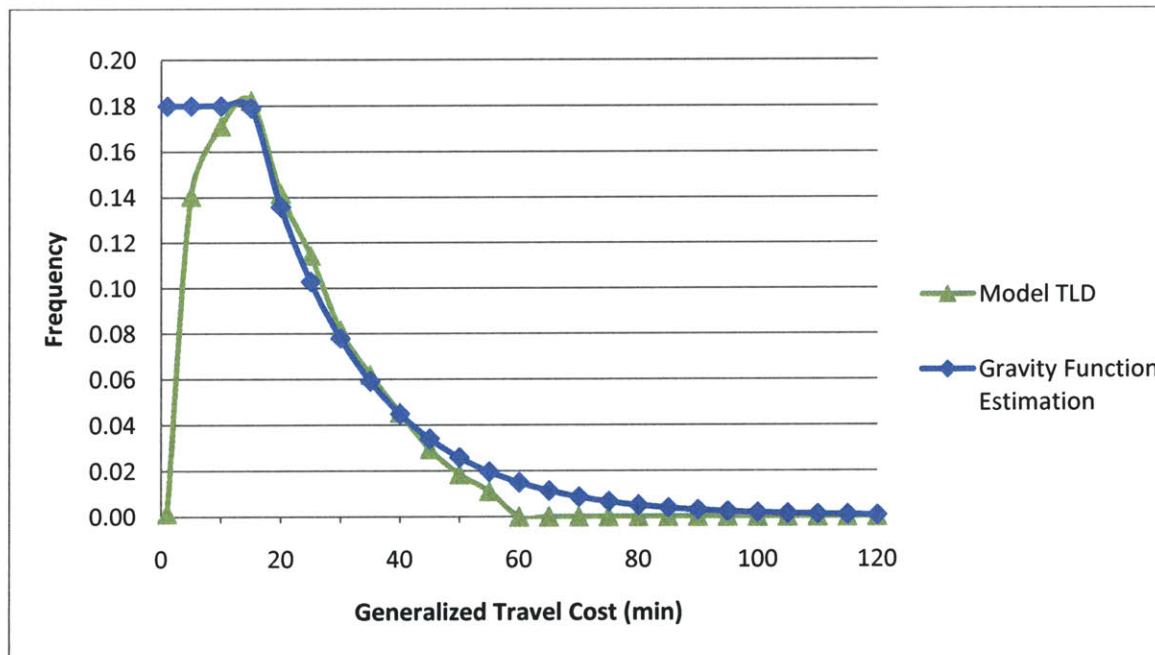
i = origin location

j = destination location

C_{ij} = travel cost from i to j

Figure 6-4 shows the gravity function estimation for health care opportunities, found to have an indifference time period of 15 minutes. The piecewise function for the health care gravity function estimation is shown in Equation 6-4.

Figure 6-4: Health Care Gravity Function Estimation



Equation 6-4: Health Care Gravity Function

$$f(C_{ij}) = \begin{cases} 0.18, & \text{if } C_{ij} \leq 15 \\ 0.42 * C_{ij}^{-0.01} * \exp(-0.055 * C_{ij}), & \text{if } C_{ij} > 15 \end{cases}$$

Where :

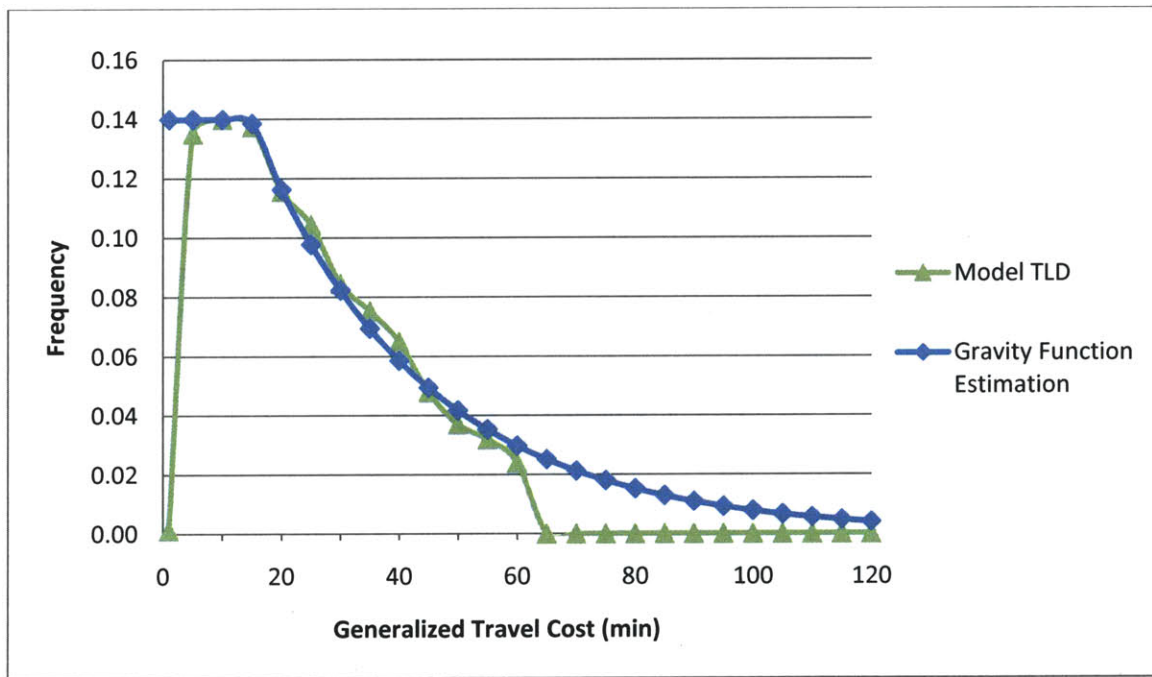
i = origin location

j = destination location

C_{ij} = travel cost from i to j

The gravity function estimation for recreational opportunities is presented in Figure 6-5, indicating a 15 minute indifference time period. The decreasing portion of the curve is less steep than the other opportunity types, indicating that the attractiveness of recreation does not decrease as quickly as other opportunity types with increasing travel time and/or cost. Equation 6-5 shows the formulation of the gravity function estimation for recreation.

Figure 6-5: Recreation Gravity Function Estimation



Equation 6-5: Recreation Gravity Function

$$f(C_{ij}) = \begin{cases} 0.14, & \text{if } C_{ij} \leq 15 \\ 0.25 * C_{ij}^{-0.035} * \exp(-0.033 * C_{ij}), & \text{if } C_{ij} > 15 \end{cases}$$

Where :

i = origin location

j = destination location

C_{ij} = travel cost from i to j

It is important to note that the trip length distributions used in the gravity function estimations above consider all transportation modes and are not solely restricted to transit trips. Since auto trips represent a majority of total trips in the regional model, auto trips may disproportionately impact the overall trip length distribution used. For this reason, the overall trip length distributions versus the transit only distributions were compared. It was found that the discrepancies between the two distributions were mainly limited to the range of indifference, beyond which the distributions have a similar decreasing exponential form. This finding indicates that the use of overall trip length distribution data is acceptable for the transit accessibility calculations. In this way, the accessibility model developed can also be used to calculate the accessibility impacts of other modes, such as auto and bike. Furthermore, it makes intuitive sense that the attractiveness of an opportunity is a function of the travel cost to reach that opportunity, regardless of the transportation mode chosen for the trip.

The generalized cost data used in the gravity accessibility calculations are derived from the Cube Voyager model skims, described in detail in Section 5.4.1. TransCAD software is used to calculate the gravity accessibility for each model TAZ as well as create maps illustrating the results of the gravity calculations.¹⁸

¹⁸ Cube Voyager software is used to create skims for this research due to the prior development of an academic Cube Voyager travel demand model of the study area by Mikel Murga at MIT as part of the 1.254 Transport Modeling class. TransCAD can also be used to create model skims and run a full four-step travel demand model. A full four-step model of the study area is currently being developed in TransCAD for future offerings of 1.254.

6.3 Accessibility to Employment

According to the 2000 Census, workers represent roughly half of the population in the model area. The ability to access employment opportunities is, undoubtedly, critical to a high quality of life for these workers and the families they support. An analysis of transit accessibility to employment for the existing conditions, baseline, and build scenarios of the Green Line Extension Project is presented in the following sections and will aid in the development of livability-based metrics that can be used in the FTA New Starts process. The transit accessibility results presented in the following sections provide a measure of how many of the regional employment opportunities an individual can reach by transit from each TAZ.¹⁹

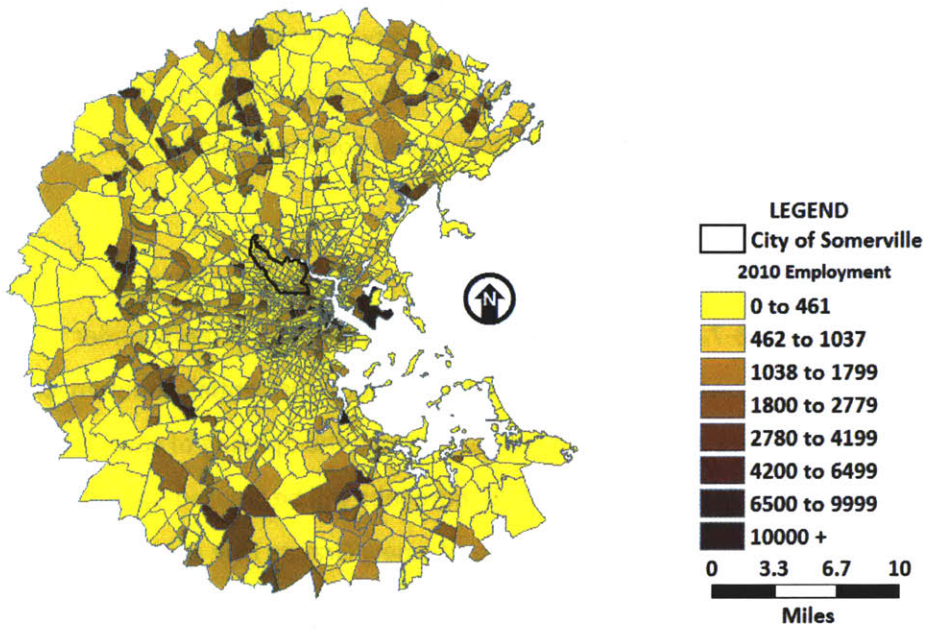
6.3.1 Employment Opportunities

The number of employment opportunities available in the existing conditions scenario, 2030 baseline scenario, and 2030 build scenario are determined from the Massachusetts Executive Office of Transportation employment estimates for 2010 and 2030. The distribution of total employment for 2010 is shown in Figure 6-6, which illustrates the concentration of jobs in the central business district (CBD) as well as in suburban locations along the Interstate 95/ Route 128 belt.

A close-up of the CBD is shown in Figure 6-7. Areas of especially high employment include the Financial District, the Prudential Center, Logan Airport, Mass General Hospital, Alewife, and the college and university campuses located along the MBTA Red and Green Lines.

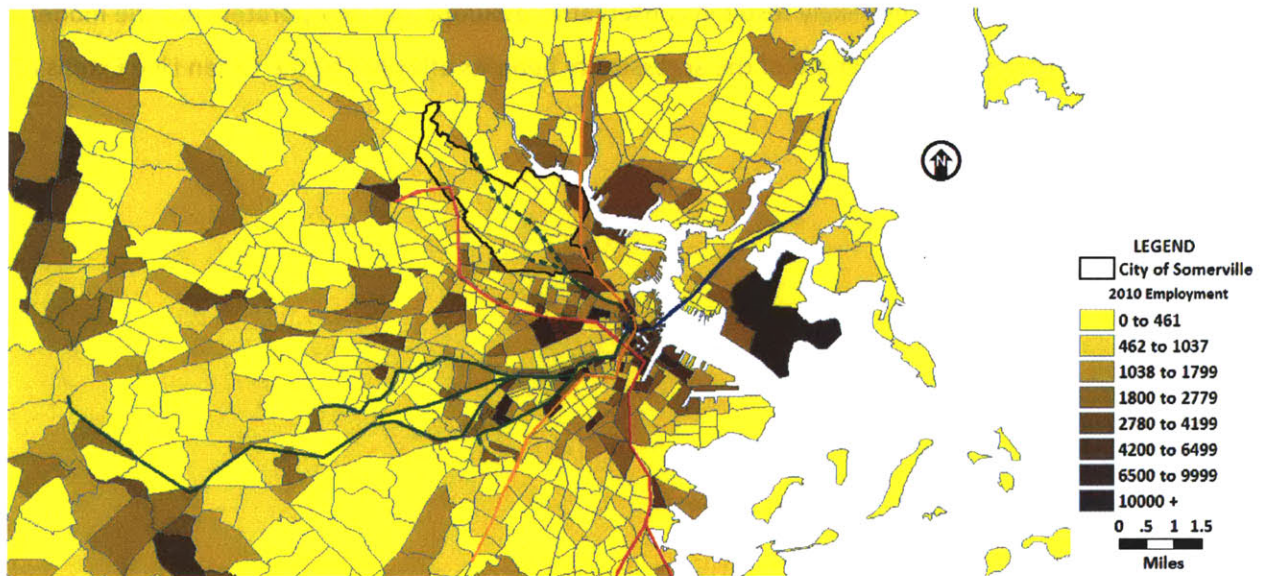
¹⁹ Due to a lack of detailed transportation network data in certain portions of the model (as illustrated in Figure 5-3), the Region considered for all accessibility analyses in this thesis will consist of the TAZs contained within 15 miles of downtown Boston. All TAZs within this 15 mile circle contain detailed local transportation data and are therefore appropriate for the accessibility analyses.

Figure 6-6: 2010 Employment (Regional View)



Data Source: Employment estimates (Massachusetts Executive Office of Transportation, n.d.)

Figure 6-7: 2010 Employment (Local View)



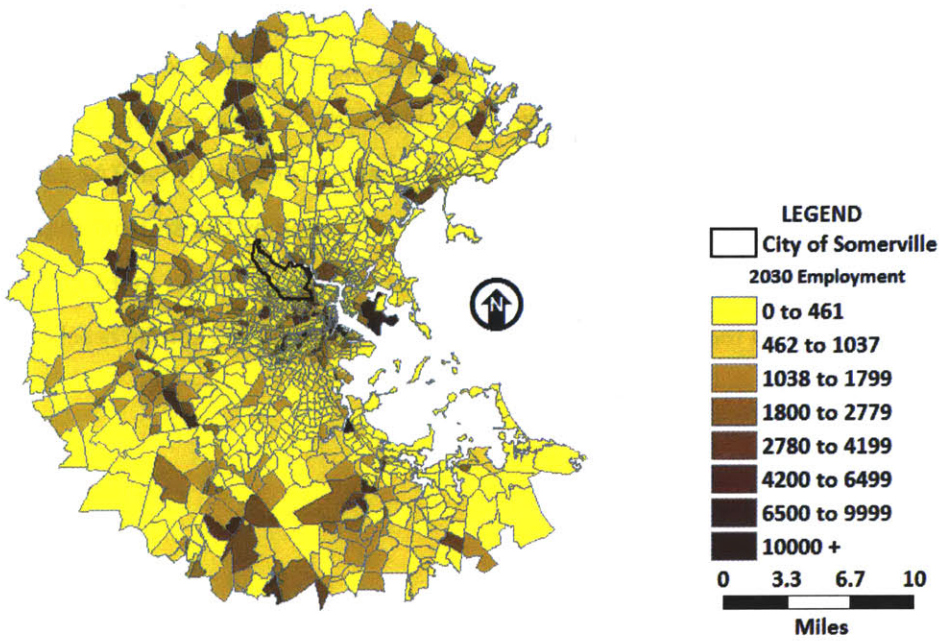
Data Source: Employment estimates (Massachusetts Executive Office of Transportation, n.d.)

Employment forecasts for the year 2030 are shown in Figures 6-8 and 6-9 for the Region and the CBD area, respectively. Comparing these figures to the existing 2010 numbers, it appears that the spatial distribution of employment will remain relatively stable over the next two decades. The 2030 scenario does represent overall job growth, with the total number of jobs in the region increasing from approximately 2,543,530 in 2010 to 2,767,720 in 2030. Employment in Somerville alone is projected to increase by 7,550 jobs.

Most of this increase is concentrated in the Assembly Square area of Somerville along the Orange Line, apparent from a comparison of Figures 6-7 and 6-9. Assembly Square is an area currently under redevelopment with a planned smart-growth urban village that will include residential, commercial, and R&D space. More than 500 new jobs have already been created through the opening of several retail stores (Federal Realty Investment Trust, 2011). Around 4,000 more jobs will be created upon the completion of the development, made viable with the opening of a new Orange Line station.

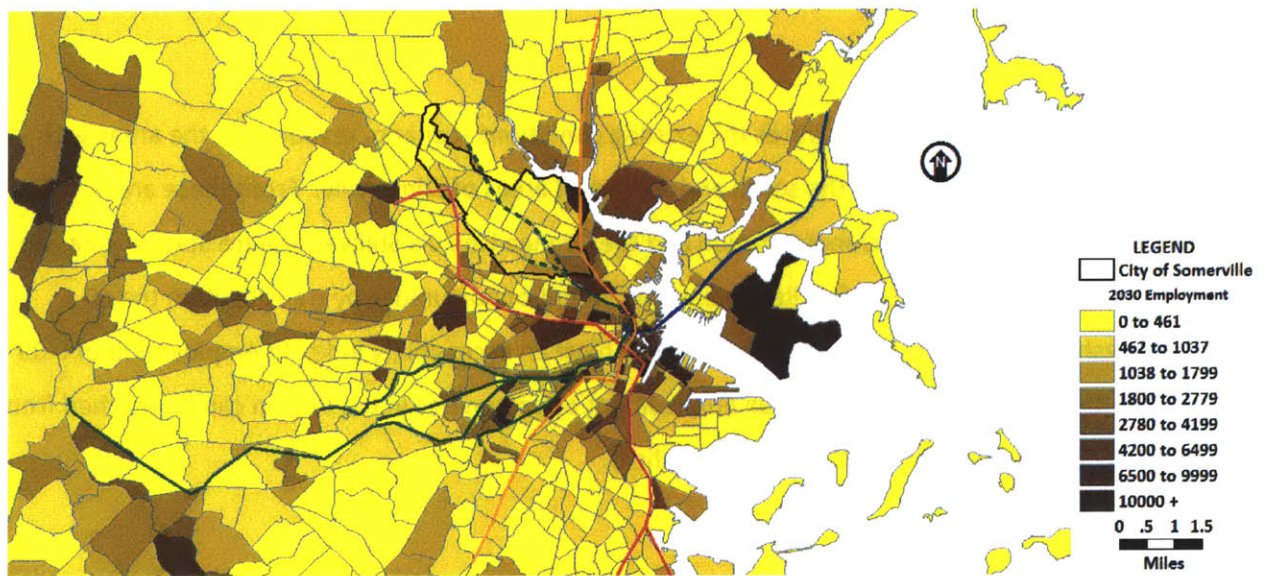
With proper land use planning, similar redevelopment and employment growth may also be possible along the Green Line Extension. Although significant land use changes along the Green Line Extension are not represented in the 2030 employment forecasts, Somerville has already begun land use planning efforts for major redevelopment in station areas such as Union Square and Washington Street. These efforts may appreciably increase employment accessibility around the Green Line Extension station areas. Uncertainties in land use likely result in conservative assumptions incorporated into the model and therefore a conservative estimate of the accessibility benefits afforded by the Green Line Extension Project.

Figure 6-8: 2030 Employment (Regional View)



Data Source: Employment estimates (Massachusetts Executive Office of Transportation, n.d.)

Figure 6-9: 2030 Employment (Local View)



Data Source: Employment estimates (Massachusetts Executive Office of Transportation, n.d.)

6.3.2 Isochrone Accessibility to Employment

Figures 6-10 to 6-12 map the transit accessibility index to employment for each TAZ in the Project corridor using isochrone estimation for the existing conditions scenario, 2030 baseline scenario, and 2030 build scenario, respectively.²⁰ The accessibility measures are indexed by a range of zero to one using the formula in Equation 6-6. In this way, the isochrone index measure for a particular TAZ can be interpreted as the percentage of all Regional opportunities that can be reached by transit from that origin within the determined isochrone threshold. For example, a TAZ with an isochrone index of 0.05 for employment indicates that 5% of all the employment opportunities in the Region can be reached by transit within a 40 minute threshold.²¹

Equation 6-6: Isochrone Accessibility Index

$$AI_i = A_i / O_R$$

Where:

i = origin location

AI_i = (isochrone) accessibility index at location i

A_i = (isochrone) accessibility at location i

O_R = total number of opportunities in the Region

Inspection of Figure 6-9, which illustrates the existing conditions scenario, reveals that the areas with the highest indices are located in the south and southeast areas of Somerville. From these areas, with access to the Green Line via Lechmere Station and the Orange Line via Sullivan Square Station, one can reach up to approximately 20% of all Regional employment opportunities by transit within the 40 minute threshold. In contrast, the TAZs to the north have an accessibility index to employment of 0.05 or less. In other words, less than 5% of all employment opportunities in the Region can be reached from these areas by transit within the 40 minute threshold.

²⁰ See Appendix B for a complementary analysis that only considers employment opportunities that can be reached via public transportation, as opposed to all Regional opportunities.

²¹ See Table 6-1 for the isochrone thresholds of each opportunity type, including employment, shopping, education, health care, and recreation.

Accessibility to employment does not significantly improve with the baseline scenario of improved bus service along the Project corridor. A comparison of the existing conditions and baseline scenarios, in Figures 6-10 and 6-11 respectively, shows little to no increase in accessibility to employment. The index measure actually appears to slightly decrease in the baseline scenario in several TAZs. However, this unexpected phenomenon can be explained by the definition of the map intervals in conjunction with minor variations in the travel time skims between scenarios.

An examination of the build scenario results in Figure 6-12 show a striking increase in accessibility to employment along the Project corridor. A majority of TAZs within a half mile of the proposed station locations now have index measures of more than 0.05. The areas surrounding Union Square and Washington Street in the south become hyper-accessible locations with transit access to 15-20% of all Regional jobs.

Figure 6-10: 2010 Existing Conditions Employment Accessibility – Isochrone Measure

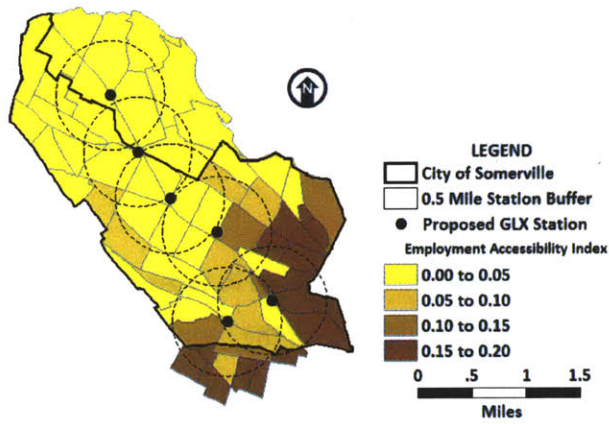


Figure 6-11: 2030 Baseline Scenario Employment Accessibility – Isochrone Measure

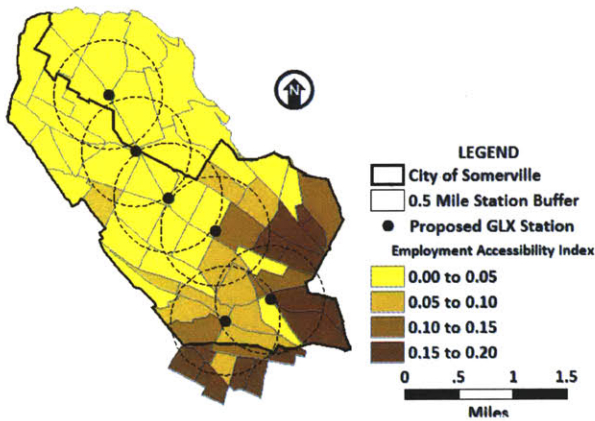
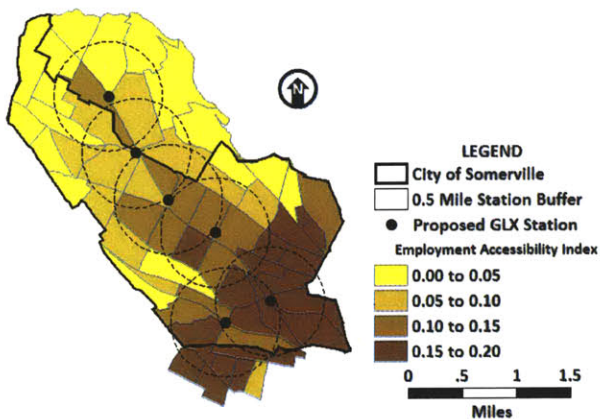


Figure 6-12: 2030 Build Scenario Employment Accessibility – Isochrone Measure



6.3.3 Gravity Accessibility to Employment

Figures 6-13 to 6-15 map the accessibility index for employment for each TAZ in the Project corridor using gravity estimation for the existing conditions scenario, 2030 baseline scenario, and 2030 build scenario, respectively.²² As described previously, gravity functions are estimated for each specific opportunity type.²³ These gravity functions are used to calculate a gravity accessibility measure for each TAZ which is then indexed using Equation 6-7. In this case, the gravity index measure for a particular TAZ can be interpreted as the percentage of all equivalent Regional opportunities that can be reached by transit from that origin.²⁴ For example, a TAZ with a gravity index of 0.05 for employment indicates that 5% of all equivalent employment opportunities in the Region can be reached by transit from that location.

Equation 6-7: Gravity Accessibility Index

$$AI_i = A_i / (F_{ITP} * O_R)$$

Where:

i = origin location

AI_i = (gravity) accessibility index at location i

A_i = (gravity) accessibility at location i

F_{ITP} = frequency of the indifferent time period as determined by the gravity function estimation for the opportunity type in consideration

O_R = total number of opportunities in the Region

$(F_{ITP} * O_R)$ = total number of equivalent opportunities in the Region

²² See Appendix B for a complementary analysis that only considers employment opportunities that can be reached via public transportation, as opposed to all Regional opportunities.

²³ See Equations 6-1 to 6-5 for the gravity function estimations of each opportunity type, including employment, shopping, education, health care, and recreation.

²⁴ The concept of "equivalent" opportunities reflects the consideration that the attractiveness of an opportunity decreases as the travel time and/or cost to reach that opportunity increases. For example, using the estimated gravity function for employment opportunities graphed in Figure 6-1, let us consider the case of two job opportunities. In order to reach Job A, an individual needs to spend 10 minutes of generalized travel cost. In order to reach Job B, an individual needs to spend 30 minutes of generalized travel cost. According to the estimated gravity function in Figure 6-1, Job A can be weighted as 0.18 equivalent jobs whereas Job B can be weighted as approximately 0.09 equivalent jobs. In other words, Job A is roughly two times more attractive to an individual than Job B.

Figure 6-13, which illustrates the existing conditions scenario, shows that the areas with the highest indices for employment are located in the south and southeast areas of Somerville. These zones have transit access to up to 4% of all equivalent opportunities in the Region. Most other zones have an employment accessibility index between 0.010 and 0.015. Note that, due to the nature of equivalent opportunities, the value of the gravity indices will always be less than the value of the isochrone indices. However, the spatial patterns of accessibility can still be compared between the two.

Similar to the isochrone results, accessibility to employment does not significantly improve in the baseline scenario but shows a marked increase in the build scenario. Illustrated in Figure 6-15, the Green Line Extension Project creates hyper-accessible locations to employment in the Union Square and Brickbottom areas. Increases to equivalent employment opportunities are also apparent around the other proposed station locations and are indicated by the darker shading of these TAZs in Figure 6-15 compared to Figures 6-13 and 6-14.

Figure 6-13: 2010 Existing Conditions Employment Accessibility – Gravity Measure

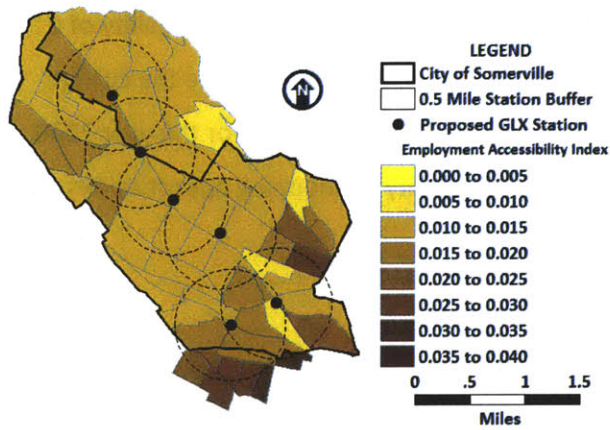


Figure 6-14: 2030 Baseline Scenario Employment Accessibility – Gravity Measure

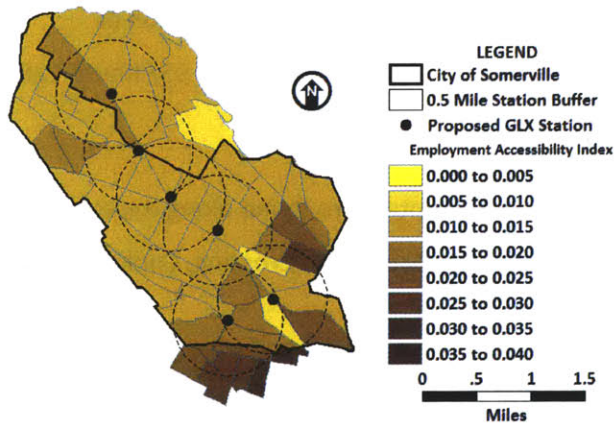
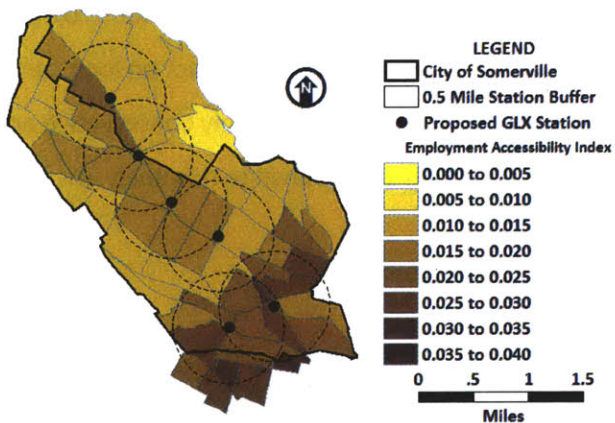


Figure 6-15: 2030 Build Scenario Employment Accessibility – Gravity Measure



6.4 Accessibility to Shopping

Accessibility to shopping opportunities is an important contributing factor towards the livability of a neighborhood and the quality of life of its residents. The following sections will describe the current distribution of shopping opportunities in the Boston Region as well as the forecasts for the year 2030. The results of the isochrone and gravity analyses for transit accessibility to shopping opportunities will also be presented and discussed.

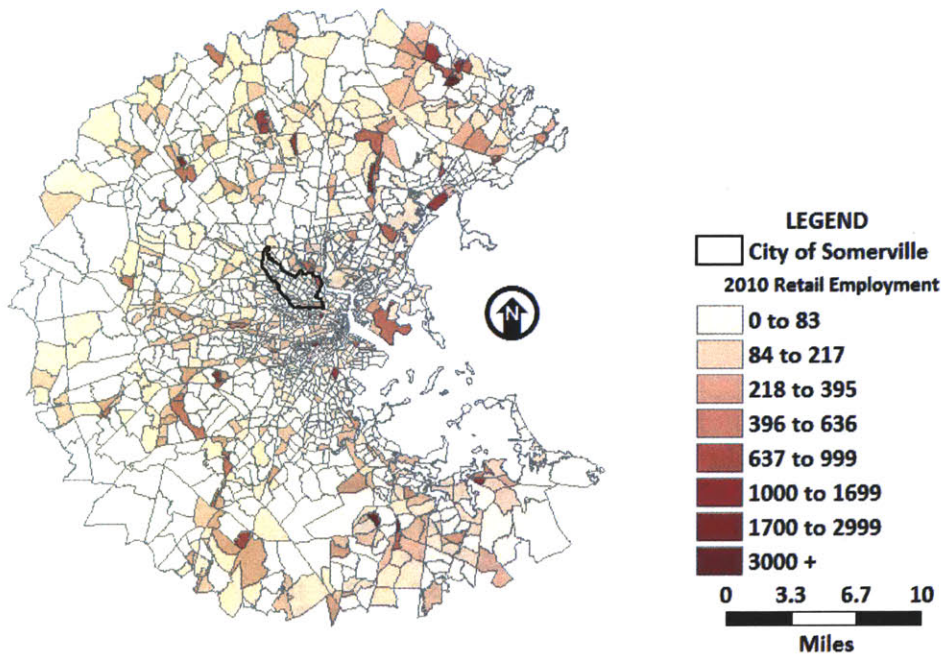
6.4.1 Shopping Opportunities

The number of shopping opportunities available in the existing conditions scenario, 2030 baseline scenario, and 2030 build scenario are determined from the Massachusetts Executive Office of Transportation employment estimates for 2010 and 2030. In lieu of the availability of a detailed shopping database for the Region, retail employment is used as a proxy for shopping opportunities. The distribution of shopping for 2010 is shown in Figure 6-16, which illustrates the concentration of shopping opportunities in the CBD as well as in suburban locations along the Interstate 95/ Route 128 belt.

A close-up of the CBD is shown in Figure 6-17. Many major retail centers are found along the existing Green Line, including the CambridgeSide Galleria mall, Park Street/Downtown Crossing, Copley Square, the Prudential, and the Chestnut Hill mall.

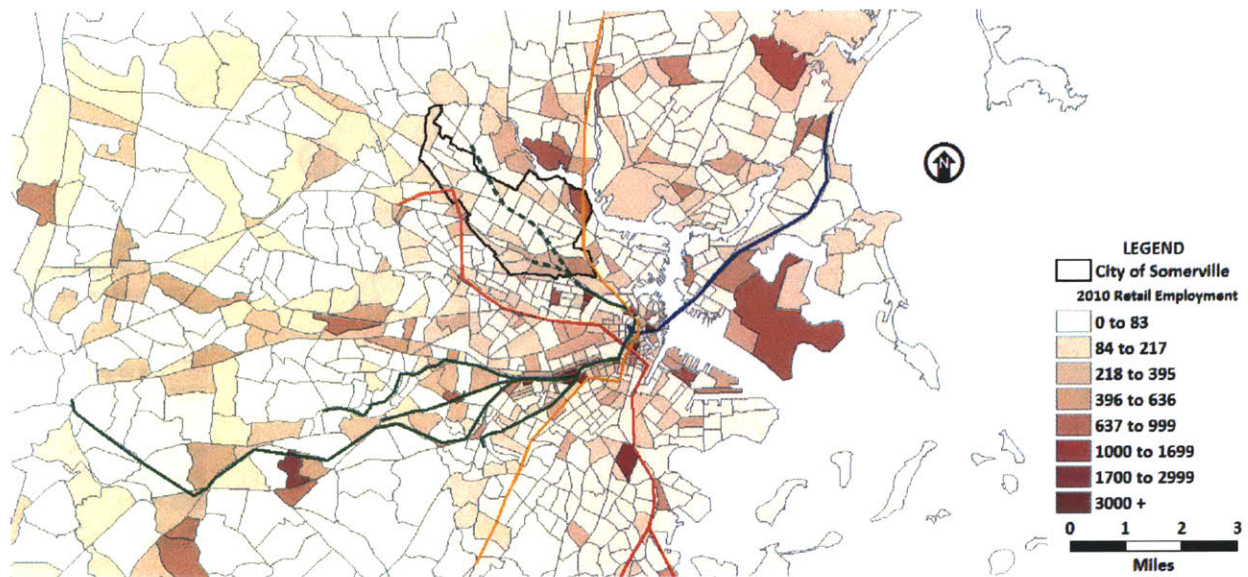
Retail forecasts for the year 2030 are shown in Figures 6-18 and 6-19 for the Region and the CBD, respectively. The spatial distribution of retail in 2030 remains more or less consistent with the existing conditions, but there is a predicted growth from approximately 416,190 retail jobs in 2010 to 460,215 retail jobs in 2030. Almost all of the retail growth in Somerville, roughly 1,340 retail jobs, is anticipated for the Assembly Square area. It is important to note, however, that the Green Line Extension Project as well as land use planning around the proposed station areas can have a significant impact on long-term development. Therefore, the retail assumptions incorporated in this analysis are likely conservative and the actual shopping accessibility gains from the Project may be higher than shown in this analysis.

Figure 6-16: 2010 Shopping Opportunities (Regional View)



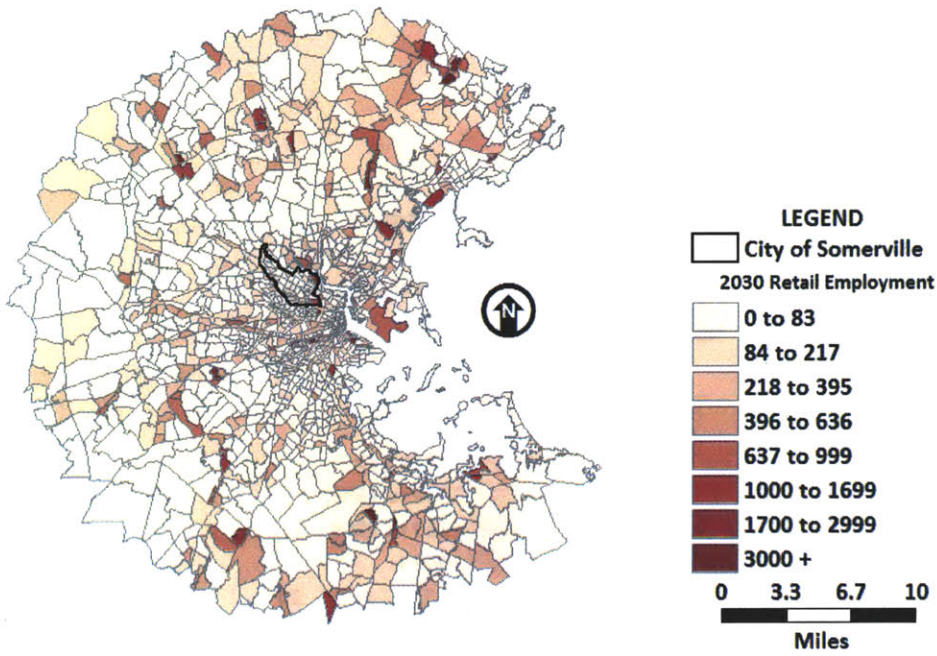
Data Source: Employment estimates (Massachusetts Executive Office of Transportation, n.d.)

Figure 6-17: 2010 Shopping Opportunities (Local View)



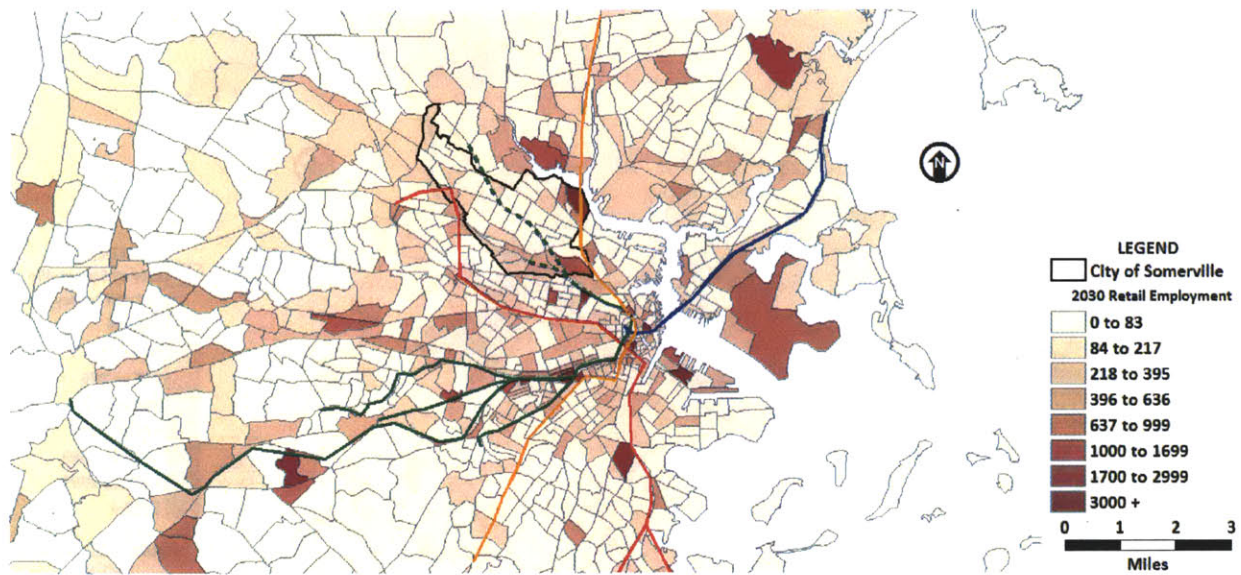
Data Source: Employment estimates (Massachusetts Executive Office of Transportation, n.d.)

Figure 6-18: 2030 Shopping Opportunities (Regional View)



Data Source: Employment estimates (Massachusetts Executive Office of Transportation, n.d.)

Figure 6-19: 2030 Shopping Opportunities (Local View)



Data Source: Employment estimates (Massachusetts Executive Office of Transportation, n.d.)

6.4.2 Isochrone Accessibility to Shopping

Figures 6-20 to 6-22 map the transit accessibility index for shopping in the Project corridor using isochrone estimation for each analysis scenario. The accessibility measures are indexed by a range of zero to one using the formula in Equation 6-6. For example, a TAZ with an isochrone index of 0.05 for shopping indicates that 5% of all the shopping opportunities in the Region can be reached by transit within a 35 minute threshold.²⁵

In the existing conditions scenario shown in Figure 6-20, accessibility to shopping is relatively low in much of Somerville with an index of less than 0.03. The exceptions are the areas in the south near the CambridgeSide Galleria mall and the areas in the southeast with access to the Orange Line providing direct access to Downtown Crossing. In these areas, the accessibility index climbs to almost 0.12.

Accessibility to shopping is not greatly impacted in the baseline scenario illustrated in Figure 6-21, however substantial increases to shopping accessibility are apparent in the build scenario shown in Figure 6-22. Shopping opportunities at Copley and the Prudential, greater than 35 minutes away from much of Somerville in the baseline scenario, are less than 35 minutes away with the travel time savings provided by the Green Line Extension Project. In the build scenario, most zones along the Project corridor have access to 6-15% of all regional shopping opportunities.

²⁵ See Table 6-1 for the isochrone thresholds of each opportunity type, including employment, shopping, education, health care, and recreation.

Figure 6-20: 2010 Existing Conditions Shopping Accessibility – Isochrone Measure

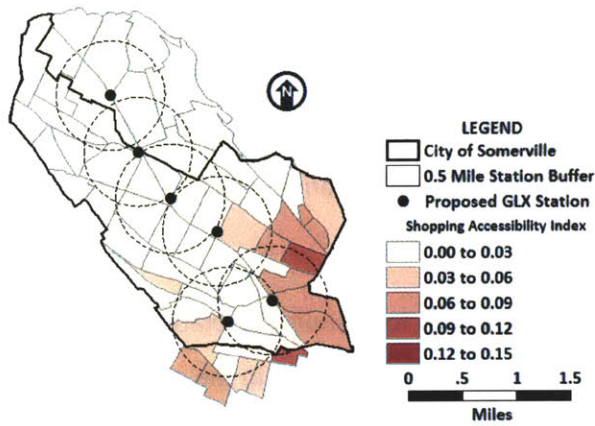


Figure 6-21: 2030 Baseline Scenario Shopping Accessibility – Isochrone Measure

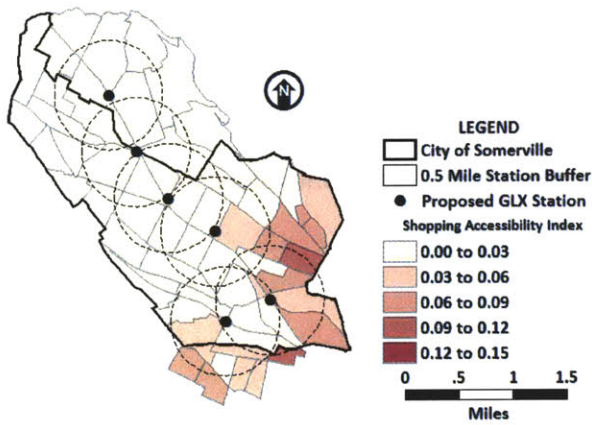
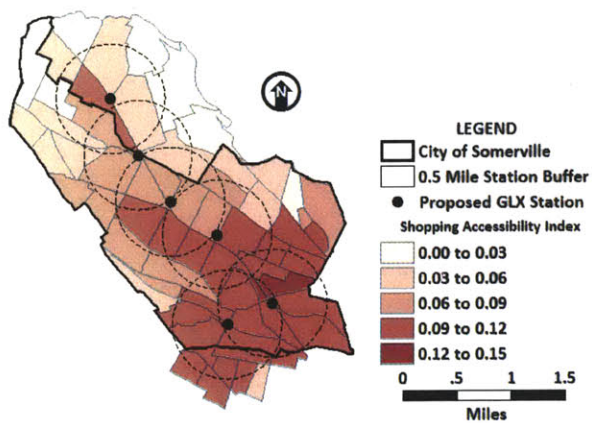


Figure 6-22: 2030 Build Scenario Shopping Accessibility – Isochrone Measure



6.4.3 Gravity Accessibility to Shopping

Figures 6-23 to 6-25 map the accessibility index for shopping in each TAZ in the Project corridor using gravity estimation for the existing conditions scenario, 2030 baseline scenario, and 2030 build scenario, respectively. Equation 6-7 is used to calculate the gravity accessibility index on a scale of zero to one. A TAZ with a gravity index of 0.05, for example, indicates that 5% of all equivalent shopping opportunities in the Region can be reached by transit from that location.

The results from the gravity analysis are similar to those found in the isochrone analysis in the previous section. Specifically, the existing conditions and baseline scenario display similar spatial patterns of high and low accessibility. The gravity accessibility index for shopping in the Project corridor ranges from less than 0.005 to almost 0.030, with the highest accessibility found in the southern and southeastern TAZs.

Also similar to the isochrone results, the build scenario shows increases in shopping accessibility along the Project corridor. The Green Line Extension Project increases the shopping accessibility index to at least 0.015 for almost all neighborhoods of Somerville. Since many of the regional shopping centers are located along the Green Line, it is not surprising that the build scenario generates such large shopping accessibility improvements.

Figure 6-23: 2010 Existing Conditions Shopping Accessibility – Gravity Measure

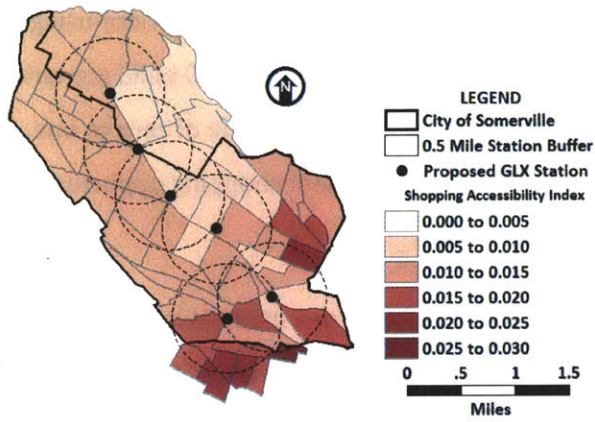


Figure 6-24: 2030 Baseline Scenario Shopping Accessibility – Gravity Measure

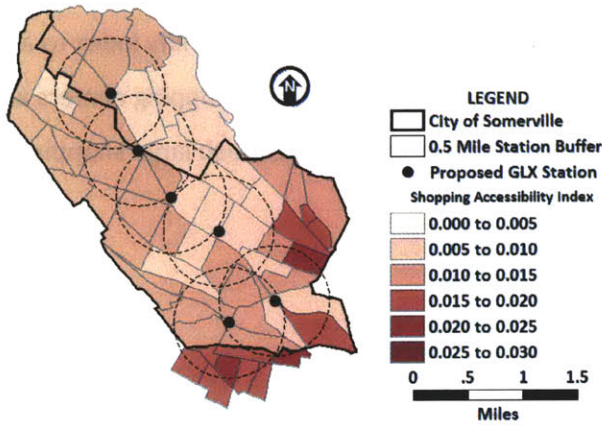
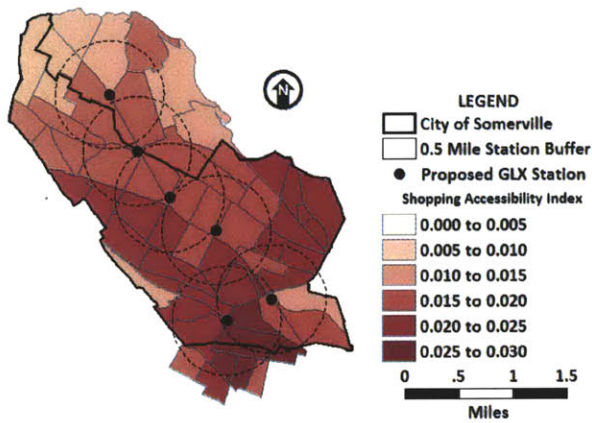


Figure 6-25: 2030 Build Scenario Shopping Accessibility – Gravity Measure



6.5 Accessibility to Education

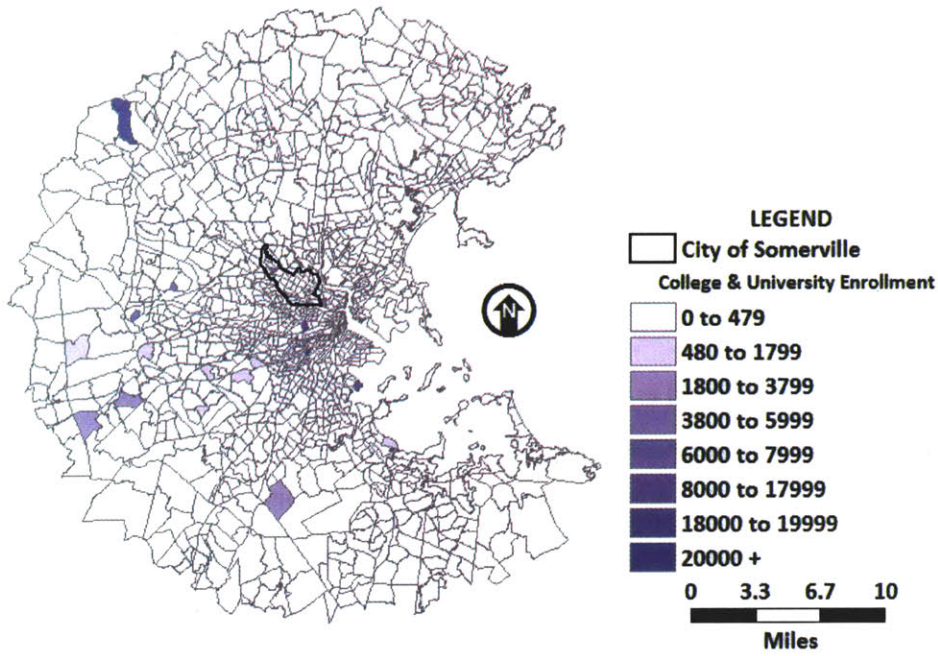
The ability to access educational opportunities is a key factor in the quality of life for the student population. Even non-students benefit from being connected to the numerous academic and social activities held at educational institutions that are often open to the public. In the following sections, the distribution of educational opportunities in the Boston Region, results of the isochrone transit accessibility analysis, and results of the gravity transit accessibility analysis will be discussed.

6.5.1 Education Opportunities

Educational institutions that could be included in an accessibility study include primary schools, secondary schools, as well as higher education colleges and universities. Due to the limited data available, only colleges and universities are considered in this analysis. The datasource used for this analysis is the MassGIS “Colleges and Universities” datalayer which contains information on the locations of higher education in the Commonwealth as well as the enrollment for each institution. Enrollment data is used as a weighting criterion in order to reflect the difference in size and impact of a particular opportunity. For example, the size (enrollment) of a school will determine its impact towards the education opportunity category within each TAZ. Enrollments are assumed to remain constant among the 2010 existing conditions, 2030 baseline, and 2030 build scenarios.

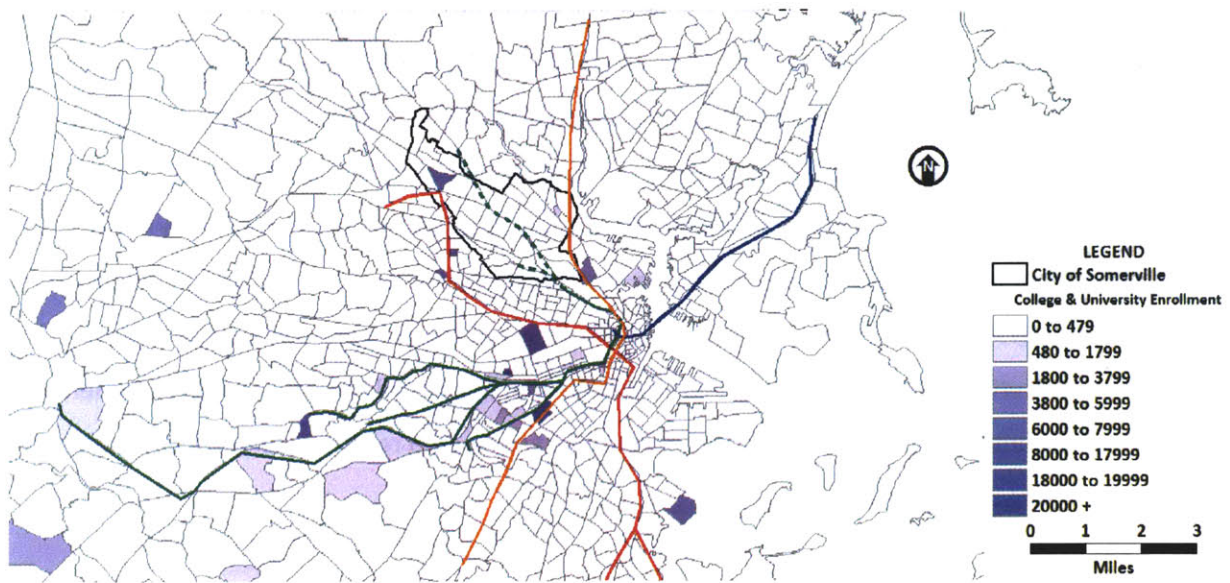
The distribution of education opportunities, weighted by enrollment, is shown in Figures 6-26 and 6-27. From these figures it is evident that, unlike the more continual distribution of employment and retail explored in the previous sections, the distribution of education is very “lumpy” by nature. In other words, educational opportunities are only present in a few distinct TAZs with the vast majority of TAZs having no education opportunities located within them at all. It is interesting to note from Figure 6-27 that the majority of higher education institutions in the central Boston area are located along the Green Line. Boston University, Northeastern University, the Colleges of the Fenway, and Boston College are all among these institutions. The proposed Green Line Extension Project will not only connect Somerville residents to these institutions but also connect Somerville and Boston residents to Tufts University via the proposed College Avenue Station.

Figure 6-26: Education Opportunities (Regional View)



Data Source: "Colleges and Universities" datalayer (MassGIS, 2010)

Figure 6-27: Education Opportunities (Local View)



Data Source: "Colleges and Universities" datalayer (MassGIS, 2010)

6.5.2 Isochrone Accessibility to Education

Figures 6-28 to 6-30 map the transit accessibility index for education opportunities in the Project corridor using isochrone estimation for each analysis scenario. The accessibility measures are indexed by a range of zero to one using the formula in Equation 6-6. For example, a TAZ with an isochrone index of 0.05 for education opportunities indicates that 5% of all the education opportunities in the Region can be reached by transit within a 25 minute threshold.²⁶

Since many of the main institutions of higher education are located along the Green Line, it is expected that the Green Line Extension Project will result in noticeable accessibility benefits to Somerville residents by providing a direct connection to these universities. Under existing conditions, illustrated in Figure 6-28, the education accessibility index in the Project corridor is in the range of 0 to 0.08 with the areas surrounding Tufts University containing the highest index values. The results of the baseline and build scenarios, shown in Figures 6-29 and 6-30, respectively, surprisingly don't show any major increases to education accessibility.

In order to determine the influence of the isochrone threshold on the sensitivity of the results, the isochrone threshold was increased from the relatively short 25 minutes to 35 minutes. The analysis results for the revised threshold are shown in Figures 6-31 to 6-33 for the existing conditions, 2030 baseline, and 2030 build scenarios, respectively. These results indicate that the build scenario does indeed result in significant improvements to education accessibility along the Project corridor. Up to 30% of all regional education opportunities are accessibility by transit from the TAZs in the build scenario within the 35 minute threshold. This example demonstrates that the selected threshold is critical to the results of isochrone measures. The necessary definition of a threshold for isochrone measures is one of the weaknesses of this methodology.

²⁶ See Table 6-1 for the isochrone thresholds of each opportunity type, including employment, shopping, education, health care, and recreation.

Figure 6-28: 2010 Existing Conditions Education Accessibility (25 Min. Threshold)– Isochrone Measure

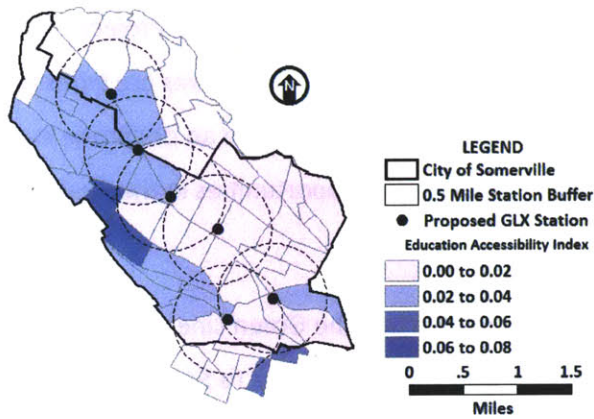


Figure 6-29: 2030 Baseline Scenario Education Accessibility (25 Min. Threshold)– Isochrone Measure

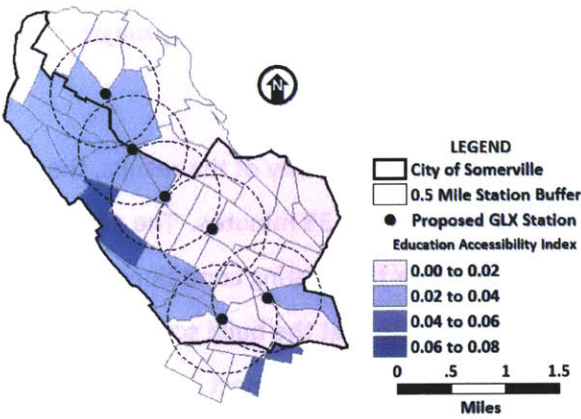


Figure 6-30: 2030 Build Scenario Education Accessibility (25 Min. Threshold)– Isochrone Measure

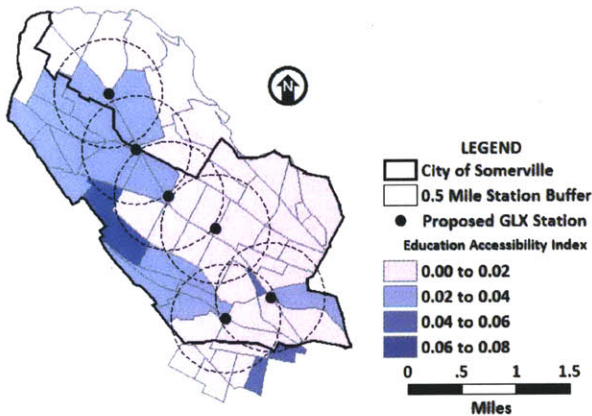


Figure 6-31: 2010 Existing Conditions Education Accessibility (35 Min. Threshold) – Isochrone Measure

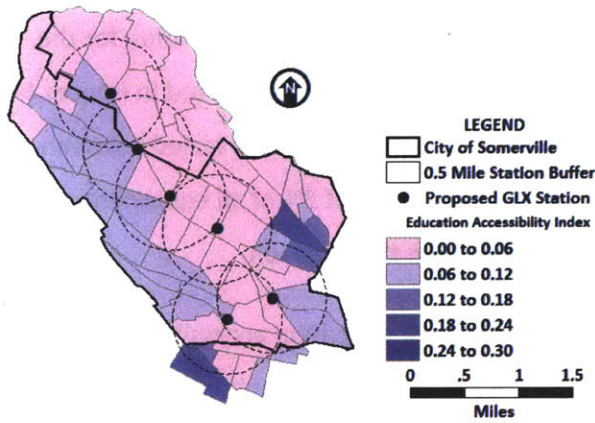


Figure 6-32: 2030 Baseline Scenario Education Accessibility (35 Min. Threshold) – Isochrone Measure

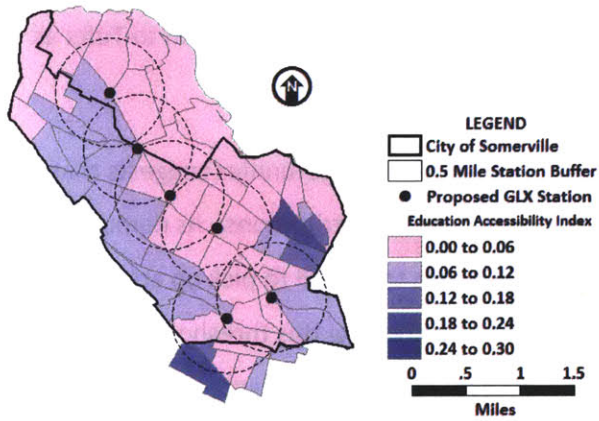
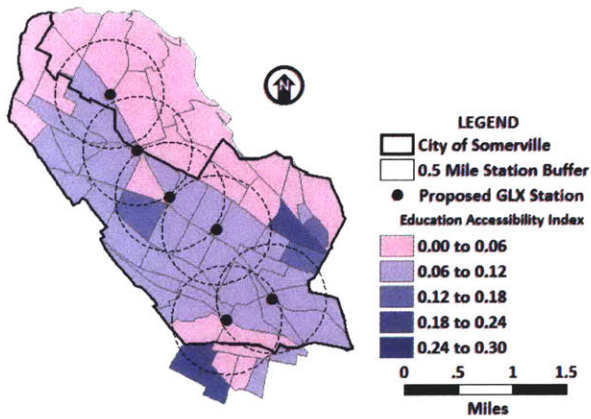


Figure 6-33: 2030 Build Scenario Education Accessibility (35 Min. Threshold) – Isochrone Measure



6.5.3 Gravity Accessibility to Education

The education accessibility index for each TAZ in the Project corridor using gravity estimation for the existing conditions scenario, 2030 baseline scenario, and 2030 build scenario is illustrated in Figures 6-34 to 6-36, respectively. Calculated from Equation 6-7, the gravity accessibility index is scaled between zero and one. A TAZ with a gravity index of 0.05, for example, indicates that 5% of all equivalent education opportunities in the Region can be reached by transit from that location.

In all scenarios, the TAZs adjacent to Tufts University have the highest education accessibility index, as can be expected. In these locations, roughly 6% of all regional education opportunities can be reached by transit in comparison to only 1-2% in many other neighborhoods in Somerville . The gravity analysis also shows a noticeable increase in accessibility along the Project corridor in the build scenario. Education accessibility around Union Square, Brickbottom, Gillman Square, and Lowell Street particularly show increased accessibility to higher education via the Green Line connection to Tufts as well as to universities in Boston.

A comparison of the gravity and isochrone analysis results for education opportunities suggests that gravity measures are better suited to opportunities with “lumpy” spatial distributions. As demonstrated in Section 6.5.2, the initial threshold used for the isochrone analysis is too small to pick up any education accessibility benefits from the Green Line Extension Project. After increasing this threshold by just ten minutes, the results of the revised isochrone analysis show accessibility improvements in the build scenario similar to the gravity results. This example demonstrates that gravity measures can provide a valuable uncertainty check for the threshold used in isochrone analyses. This is particularly critical when considering opportunities that display “lumpy” distribution patterns.

Figure 6-34: 2010 Existing Conditions Education Accessibility – Gravity Measure

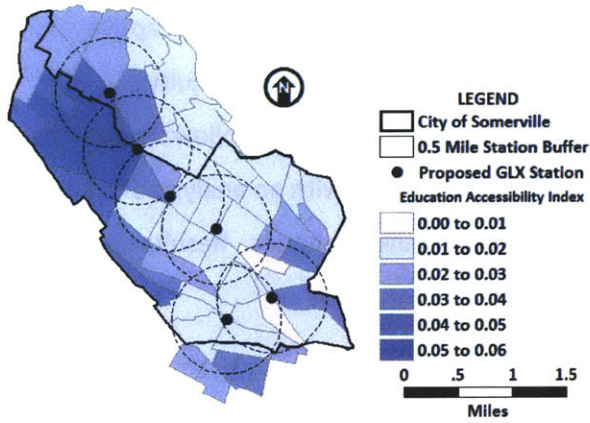


Figure 6-35: 2030 Baseline Scenario Education Accessibility – Gravity Measure

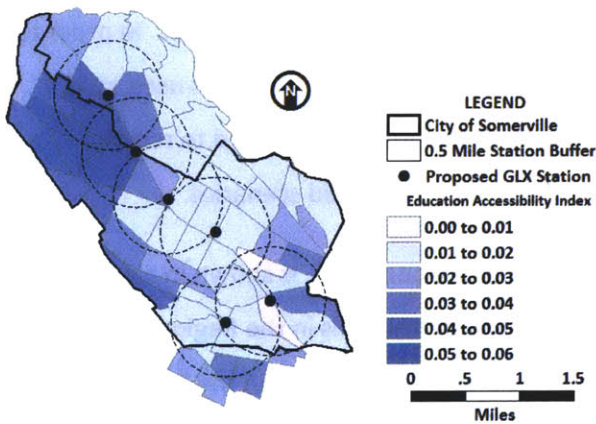
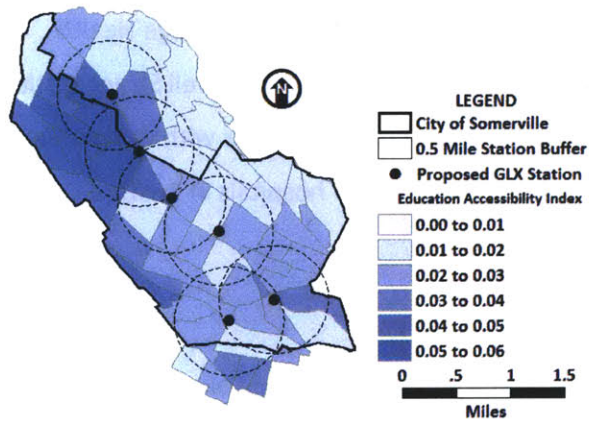


Figure 6-36: 2030 Build Scenario Education Accessibility – Gravity Measure



6.6 Accessibility to Health Care

Accessibility to health care is a critical component of quality of life. The ability for transit-captive populations to reach medical services via public transportation is an important social equity consideration that should be taken into account with livability-based policy. In the following sections, the distribution of health care in the Boston Region will be discussed along with an analysis of transit accessibility to health care for the existing conditions, baseline, and build scenarios. Results for both isochrone and gravity accessibility measures will be presented and compared.

6.6.1 Health Care Opportunities

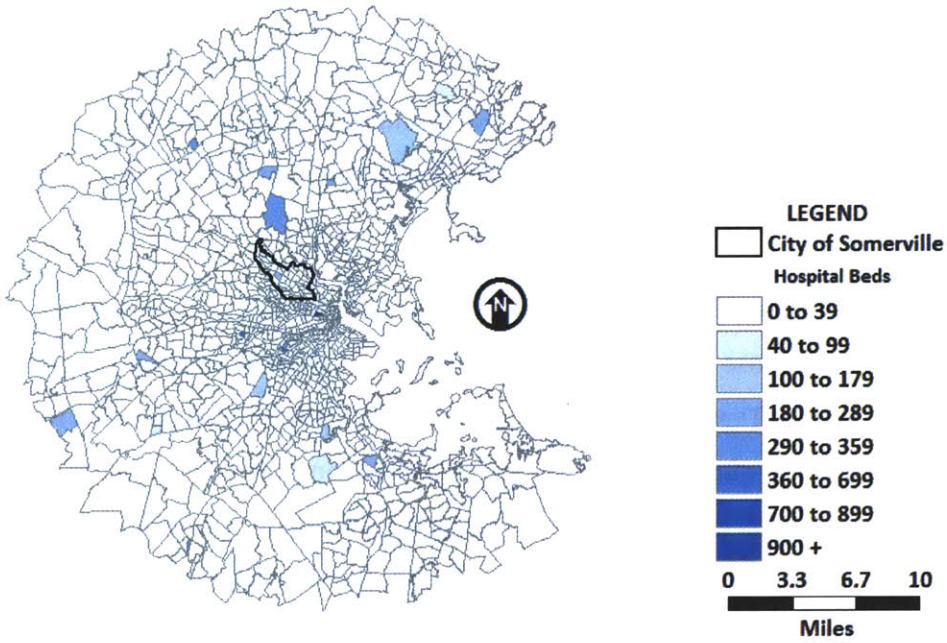
A number of measures of health care opportunities were considered for this analysis, including primary care facilities, community health centers, and hospitals. In order to take advantage of data that is readily available, only hospitals are considered in this analysis. The MassGIS “Acute Care Hospitals” datalayer is used to determine the locations of acute care hospitals in the Commonwealth. In order to reflect the difference in size and impact of each hospital, the number of hospital beds is used as a weighting criterion.²⁷ The locations and number of beds in each hospital are assumed to remain constant between the 2010 existing conditions, 2030 baseline, and 2030 build scenarios.

The distribution of acute care hospitals, weighted by number of hospital beds, is shown in Figures 6-37 and 6-38. From this illustration one can see that the distribution of hospitals in the Region is quite “lumpy” by nature. Hospitals are only located in a small percentage of the zones in the Region with most TAZs having no hospitals located within them.

In Figure 6-38, the locations of major hospitals are indicated by dark blue, with Massachusetts General Hospital and the hospitals in the Longwood Medical Area standing out as major health care facilities located within a half mile walk of the Green Line. Somerville’s only hospital, the Cambridge Health Alliance Somerville Campus, is located a five minute walk away from the proposed Lowell Street Station. The Green Line Extension will provide Somerville residents along the Project corridor with convenient, one-seat transit access to Cambridge Health Alliance as well as to the major hospitals in Boston.

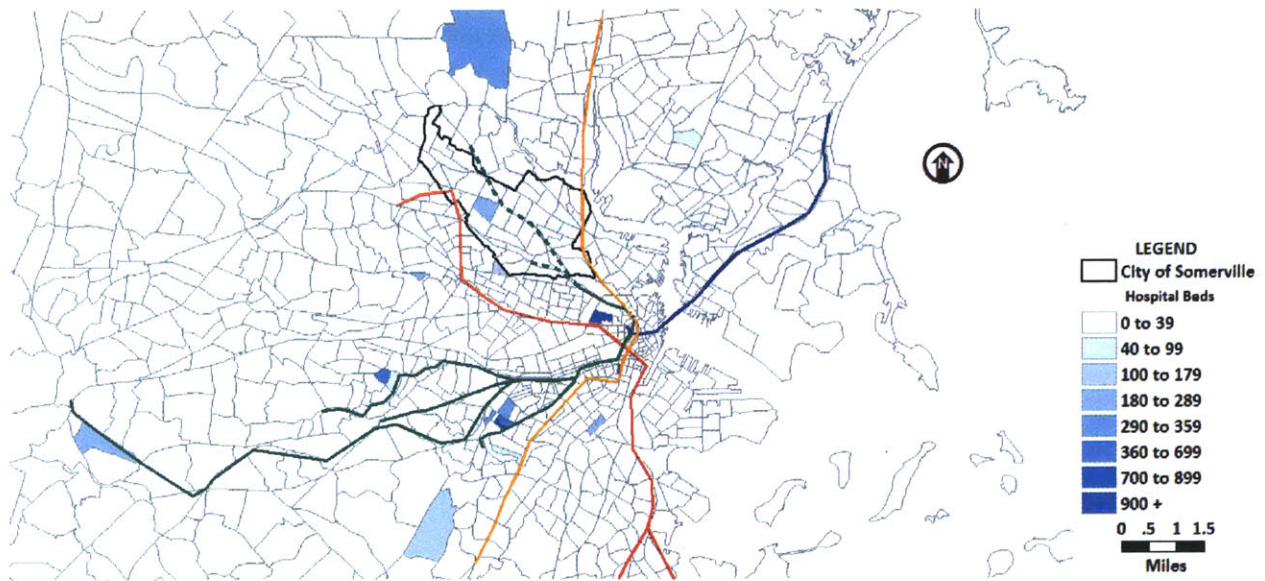
²⁷ Hospital bed data was collected from the American Hospital Directory (American Hospital Directory, 2010). There were several instances where a hospital was not included in the American Hospital Directory database. In these cases, the number of hospital beds was obtained directly by a call to the hospital in consideration.

Figure 6-37: Health Care Opportunities (Regional View)



Data Source: "Acute Care Hospitals" datalayer (MassGIS, 2010)

Figure 6-38: Health Care Opportunities (Local View)



Data Source: "Acute Care Hospitals" datalayer (MassGIS, 2010)

6.6.2 Isochrone Accessibility to Health Care

The transit accessibility index for health care opportunities in the Project corridor using isochrone estimation is mapped in Figures 6-39 to 6-41 for each analysis scenario. Equation 6-6 is used to index the isochrone accessibility measures on a zero to one scale. For example, a TAZ with an isochrone index of 0.05 for health care opportunities indicates that 5% of all the health care opportunities in the Region can be reached by transit within a 35 minute threshold.²⁸

Existing conditions, illustrated in Figure 6-39, show that accessibility to health care is highest in the southeast area of Somerville. From these locations, one can reach up to 15% of all Regional hospital beds within the 35 minute threshold. These accessible hospitals include Massachusetts General Hospital (the largest hospital in the Commonwealth) as well as the Tufts Medical Center in Boston. Much of the Project corridor north of Gilman Square, however, has relatively low accessibility. Many of these TAZs, including the TAZ containing the Cambridge Health Alliance Somerville Campus, only have access to less than 3% of all Regional hospital beds. Several neighborhoods on the Somerville/Cambridge border have slightly higher accessibility because Mount Auburn Hospital in Cambridge can also be reached within the time threshold.

The enhanced bus service of the baseline scenario, shown in Figure 6-40, noticeably increases health care accessibility to several TAZs in the Gilman Square area. Aside from this location, significant changes to accessibility are not experienced in other areas of the Project corridor in the baseline scenario.

Figure 6-41 shows the build scenario and the clear increase in accessibility along the Project corridor. In the build scenario, most TAZs adjacent to the proposed station locations have accessibility indices between 0.09 and 0.12. These increases are due to the significant time savings that the Green Line Extension Project will provide for the trip to Massachusetts General Hospital.

²⁸ See Table 6-1 for the isochrone thresholds of each opportunity type, including employment, shopping, education, health care, and recreation.

Figure 6-39: 2010 Existing Conditions Health Care Accessibility – Isochrone Measure

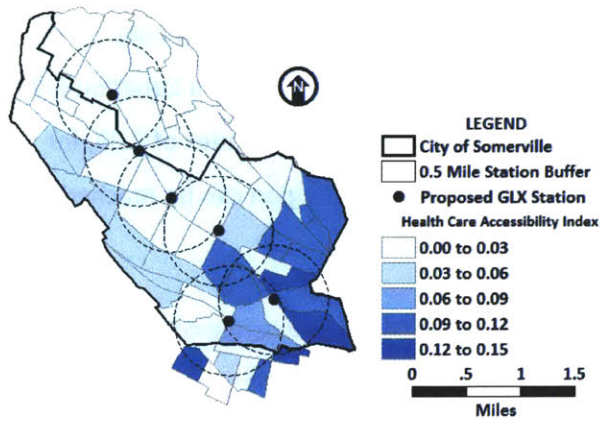


Figure 6-40: 2030 Baseline Scenario Health Care Accessibility – Isochrone Measure

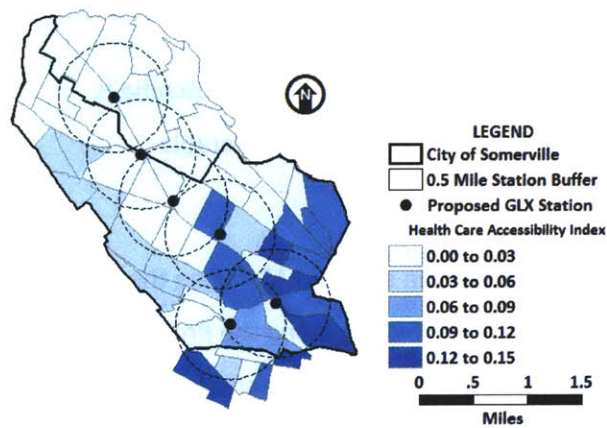
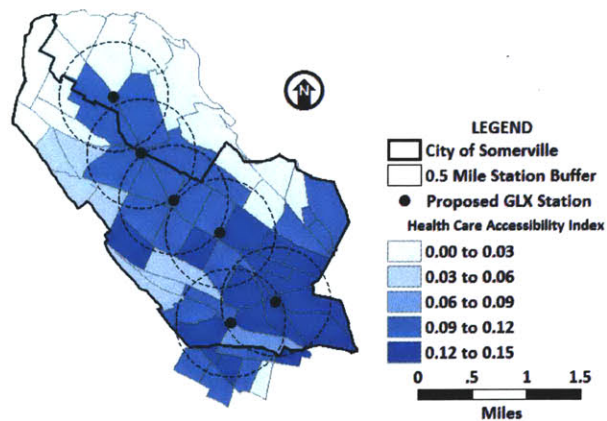


Figure 6-41: 2030 Build Scenario Health Care Accessibility – Isochrone Measure



6.6.3 Gravity Accessibility to Health Care

The transit accessibility index for health care opportunities in the Project corridor using gravity estimation is mapped in Figures 6-42 to 6-44 for each analysis scenario. Calculated from Equation 6-7, the gravity accessibility index is scaled between zero and one. A TAZ with a gravity index of 0.05, for example, indicates that 5% of all equivalent health care opportunities in the Region can be reached by transit from that location.

The health care accessibility index ranges from close to 0 to around 0.04 in the existing conditions scenario, illustrated in Figure 6-42. The TAZs surrounding the Cambridge Health Alliance Somerville Campus hospital have the highest health care accessibility index. This result, which differs from the outcome of the isochrone analysis, is due to the fact that gravity measures take travel impedance into account when measuring the attraction of each opportunity. In other words, a nearby health care opportunity in Somerville is more attractive than more distant opportunities in Cambridge or Boston.

Results from the baseline scenario can be seen in Figure 6-43. The baseline scenario outcome is analogous to the existing conditions scenario and does not show any areas of considerable improvement to accessibility.

The build scenario, on the other hand, shows increased accessibility in several TAZs along the proposed Green Line Extension alignment. Figure 6-44 shows the accessibility indices along the Project corridor which primarily fall within a range of 0.01 to 0.05. These increases in accessibility are due to the decreased travel times from Somerville to many of the major hospitals in Boston.

Figure 6-42: 2010 Existing Conditions Health Care Accessibility –Gravity Measure

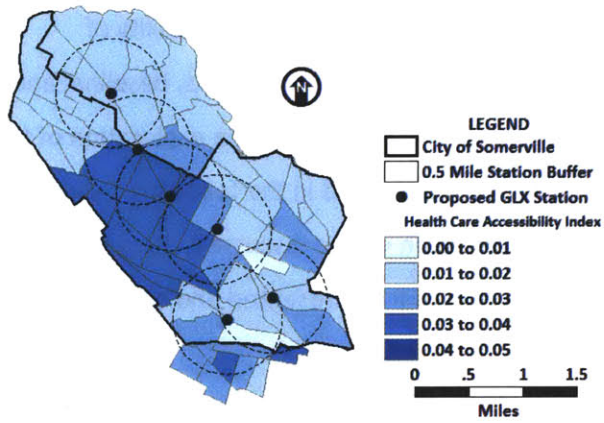


Figure 6-43: 2030 Baseline Scenario Health Care Accessibility –Gravity Measure

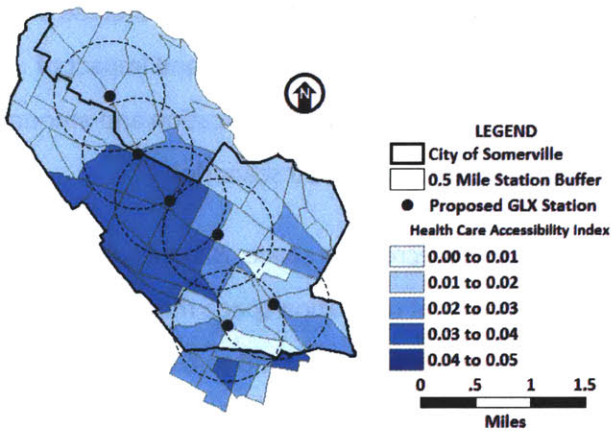
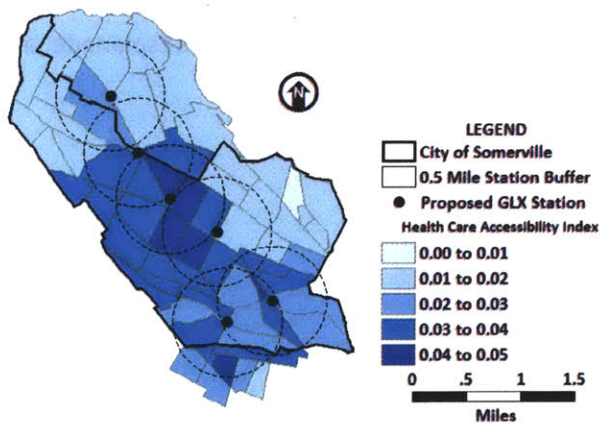


Figure 6-44: 2030 Build Scenario Health Care Accessibility –Gravity Measure



6.7 Accessibility to Recreation

Providing residents and visitors with access to recreation opportunities enhances the livability of communities. An analysis of transit accessibility to recreation for the existing conditions, baseline, and build scenarios of the Green Line Extension Project have been performed to aid in the exploration of the livability-based metrics for the FTA New Starts process and will be presented in the following sections. First, the distribution of recreation opportunities in the Boston Region will be discussed. Next, the outcomes from both an isochrone and gravity accessibility analysis will be presented and compared.

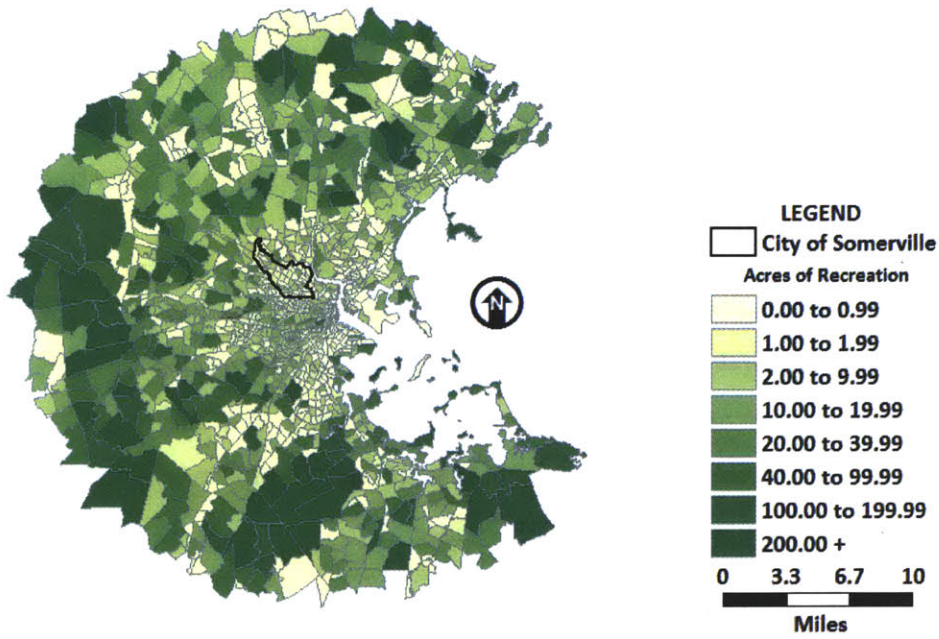
6.7.1 Recreation Opportunities

Recreation opportunities, as defined for this analysis, are comprised of parks, playing fields, golf courses, bike paths, fish and game clubs, and conservation areas with walking or hiking trails (MassGIS, 2010). For the purposes of this analysis, a recreation opportunity database was built using the “Protected and Recreational Open Space” MassGIS datalayer. In order to reflect the difference in size and impact of each opportunity, acres of recreation space are used as a weighting criterion. The location and amount of recreation space is assumed to remain constant between the 2010 and 2030 scenarios.

The distribution of recreation opportunities, weighted by acres of recreation space, is shown in Figures 6-45 and 6-46. TAZs within the CBD area tend to have fewer acres of recreation space than the TAZs outside the city. This is partially explained because the size of TAZ boundaries tend to be smaller in heavily populated urban areas. Regardless of the size of the TAZ, recreation spaces are typically smaller in the city than in the suburbs.

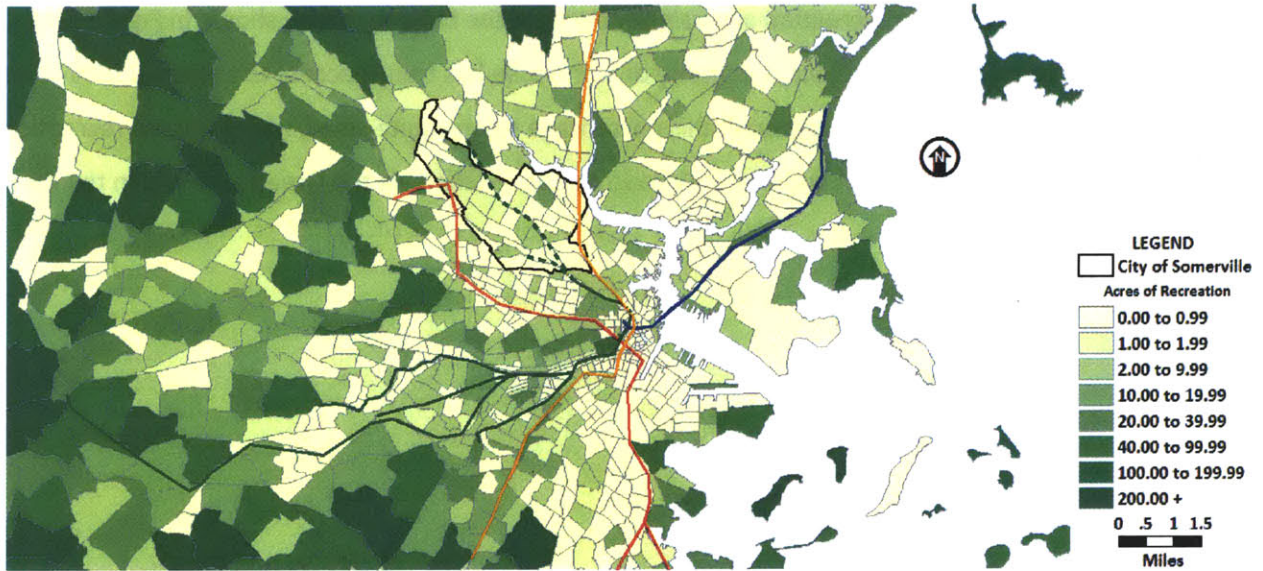
In general, Somerville has few recreation opportunities in comparison to many neighborhoods in nearby Cambridge and Boston. With the Green Line Extension Project, Somerville residents will have rapid transit access to recreation areas in downtown Boston that include Boston Common, the Esplanade, and the parks of the Emerald Necklace.

Figure 6-45: Recreation Opportunities (Regional View)



Data Source: "Protected and Recreational Open Space" datalayer (MassGIS, 2010)

Figure 6-46: Recreation Opportunities (Local View)



Data Source: "Protected and Recreational Open Space" datalayer (MassGIS, 2010)

6.7.2 Isochrone Accessibility to Recreation

Figures 6-47 to 6-49 map the transit accessibility index for recreation in the Project corridor using isochrone estimation for each analysis scenario. The accessibility measures are indexed by a range of zero to one using the formula in Equation 6-6. For example, a TAZ with an isochrone index of 0.05 for recreation indicates that 5% of all the recreation opportunities in the Region can be reached by transit within a 45 minute threshold.²⁹

Overall, the existing accessibility to recreation in Somerville is low. As seen in Figure 6-47, the highest accessibility index is equal to approximately 0.012, or only 1.2% of the Regional recreation opportunities. The index values for most of the Project corridor are even lower, at around 0.002 to 0.004. However, since most of the recreational acres are located in the suburbs, these low index values are to be expected.

In the baseline scenario, illustrated in Figure 6-48, increases to recreation accessibility can be seen by Gilman Square and Lowell Street. Since the scale interval in these figures is so small, these increases are also inevitably quite minor. The enhanced bus service of the baseline scenario does not provide enough travel time savings to bring major recreation areas in Boston within 45 minutes of most Somerville neighborhoods.

More substantial increases to recreation accessibility occur in the build scenario, shown in Figure 6-49. With the Green Line Extension Project, a majority of Somerville has transit access to at least 0.06% of all regional recreation opportunities. Although this percentage seems quite small, major Boston recreation areas such as the Boston Common and the Esplanade can be reached via the Green Line within the 45 minute threshold.

²⁹ See Table 6-1 for the isochrone thresholds of each opportunity type, including employment, shopping, education, health care, and recreation.

Figure 6-47: 2010 Existing Conditions Recreation Accessibility –Isochrone Measure

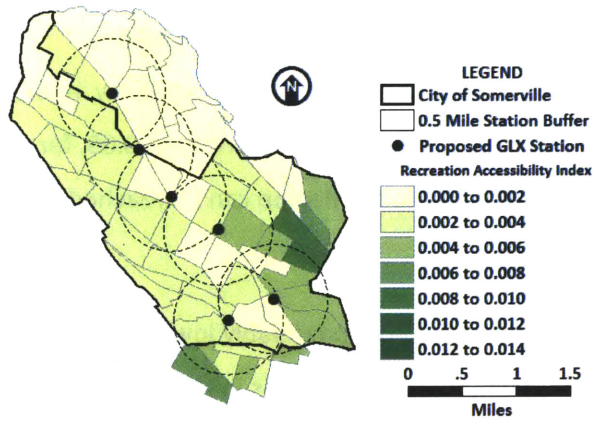


Figure 6-48: 2030 Baseline Scenario Recreation Accessibility –Isochrone Measure

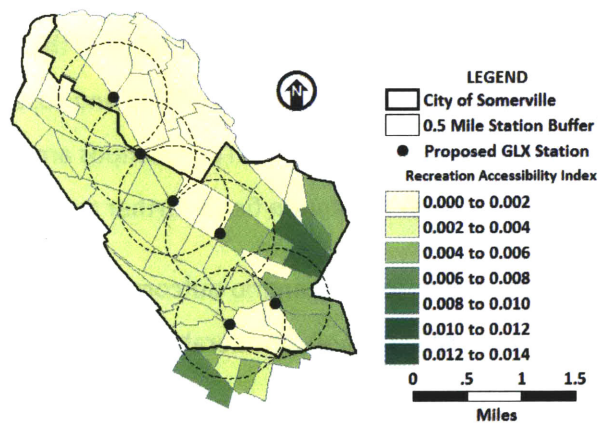
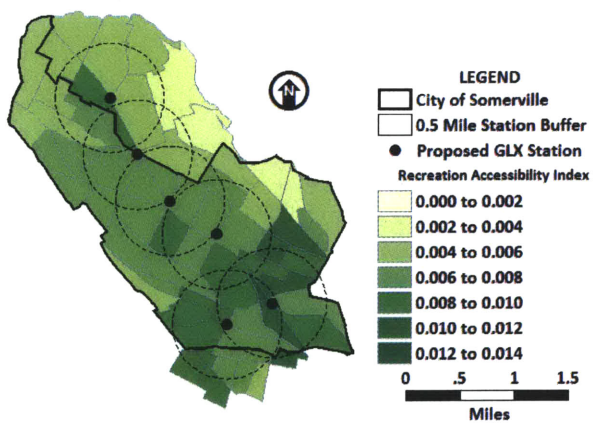


Figure 6-49: 2030 Build Scenario Recreation Accessibility –Isochrone Measure



6.7.3 Gravity Accessibility to Recreation

The transit accessibility index for recreation opportunities in the Project corridor using gravity estimation is mapped in Figures 6-50 to 6-52 for each analysis scenario. The gravity accessibility index, calculated from Equation 6-7, is scaled between zero and one. A TAZ with a gravity index of 0.05, for example, indicates that 5% of all equivalent recreation opportunities in the Region can be reached by transit from that location.

Similar to the isochrone results, the index values in each scenario are understandably low since most of the recreational acres are located in the suburbs. Despite the marginal differences in the index values between each scenario, the general spatial distribution of areas with relatively high and low accessibility can be observed.

In the existing conditions scenario, illustrated in Figure 6-50, the TAZs surrounding the Tufts University campus have some of the highest accessibility index scores. This concentration is not reflected in the isochrone results because all opportunities are weighted equally regardless of the travel time and cost to reach them. Using gravity measures, the many sport and recreation fields of the Tufts campus are considered more attractive to neighborhoods in Somerville than other recreation fields further away.

Results from the baseline scenario can be seen in Figure 6-51. The baseline scenario outcome is analogous to the existing conditions scenario and does not show any areas of considerable improvement to accessibility.

Figure 6-52 illustrates the outcome of the build scenario and highlights the spread of increased recreation accessibility along the entire Green Line Extension alignment. These accessibility increases are produced from the time savings to various parks and recreation areas in Boston made possible by a one-seat ride on the Green Line.

Figure 6-50: 2010 Existing Conditions Recreation Accessibility –Gravity Measure

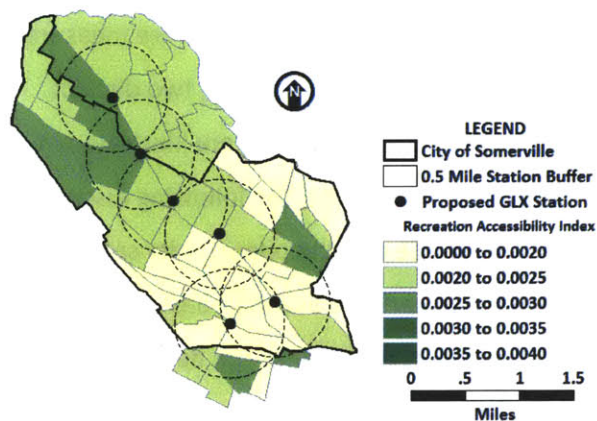


Figure 6-51: 2030 Baseline Scenario Recreation Accessibility –Gravity Measure

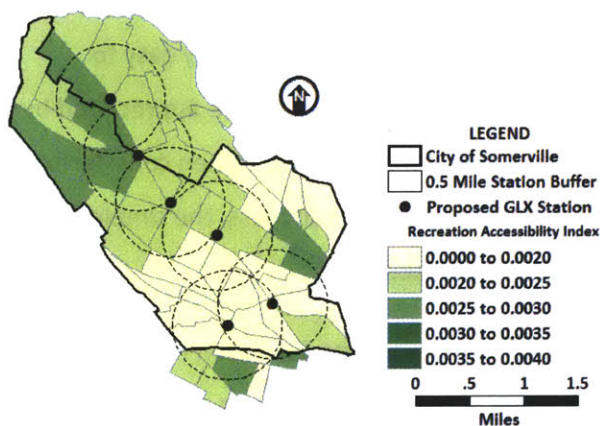
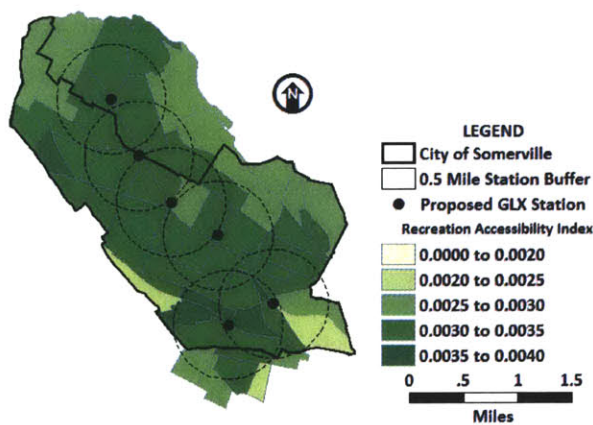


Figure 6-52: 2030 Build Scenario Recreation Accessibility –Gravity Measure



6.8 Recommendations

The accessibility benefits of the Green Line Extension Project to essential opportunities were measured and presented in the preceding sections. The accessibility benefits are calculated using two distinct methodologies. Isochrone accessibility measures and gravity accessibility measures are illustrated in accessibility index maps and the results are compared. Based on these results, the following discussion will provide recommendations on the most appropriate method to use and the opportunity categories that should be considered when calculating accessibility benefits as part of a livability-based project evaluation process. An example of a potential New Starts accessibility metric that can be used to compare projects from across the country will also be presented.

6.8.1 Recommended Methodology for the Calculation of Accessibility Benefits

Isochrone and gravity-based measures of accessibility provide an operational and comprehensible way to calculate the accessibility benefits of proposed projects. Both measures are relatively easy to compute from existing travel demand models. Isochrone and gravity measures can be appreciated by non-technical stakeholders, however gravity measures are slightly more complex. When considering the implementation of an accessibility benefit measure in the project evaluation process, the simplest measure that produces meaningful and accurate results should be used.

In general, the isochrone and gravity accessibility analyses for the Green Line Extension Project both produce results that lead to similar conclusions. Each measure shows little change to accessibility between the existing conditions and baseline scenarios. The results of both methodologies also generally illustrate noteworthy increases to accessibility along the Project corridor in the build scenario. However, the need to define a threshold when calculating isochrone accessibility is one of the major weaknesses of this method and can lead to unexpected and potentially inaccurate conclusions in certain instances. The example of accessibility to education opportunities detailed in Section 6.5 highlights this shortcoming and suggests that isochrone measures may not be appropriate when considering opportunities that have a “lumpy” spatial distribution.³⁰ For this reason, it is recommended that gravity measures be used to calculate the accessibility benefits of proposed projects.

³⁰ A lumpy spatial distribution refers to a distribution that is concentrated in multiple discrete locations.

6.8.2 Recommended Opportunity Categories to Include in Accessibility Benefits

The accessibility benefits presented in this chapter consider five opportunities essential to livability: employment, shopping, education, health care, and recreation. In terms of implementing a required metric in the FTA New Starts process, it is important that the calculation of the metric not be unnecessarily burdensome but at the same time be thorough enough to allow for a meaningful evaluation of project alternatives. The following discussion will highlight several important points to consider when determining which opportunities should be considered for livability-based project evaluation metrics, including varying needs between different population segments and data limitations.

It is safe to say that accessibility to employment is critical to the quality of life for much of the population. However, accessibility to employment has very little, if any, importance to certain segments of the population. With an aging demographic in the United States, an increasing percentage of the population will be retired and/or elderly and will have different quality of life needs than workers. Transportation is among the top five supports sought by the elderly from their family and friends (Coughlin, 2010). Although one can plan ahead and rely on a ride to the store, for example, quality of life is greatly enhanced when one can spontaneously decide to go to the store independently using public transportation (Coughlin, 2010). The ability to travel to shopping, health appointments, post-retirement educational classes, and recreation by transit is an important livability factor for these growing segments of the population and should therefore be considered as part of a comprehensive analysis when evaluating transit project benefits.

Existing data availability and limited resources for additional data collection present a challenge to requiring an exhaustive accessibility analysis to all opportunities that have an impact on quality of life. The opportunity types selected for the accessibility analysis presented in this thesis were selected in part because the necessary data is readily available. There are other specific opportunities and services, such as grocery stores and pharmacies, which are important to livability but are not included due to limited data. The continuing development of local and national geographic information system (GIS) data will aid in new database development for the purposes of measuring accessibility to a variety of key opportunities and services. In the meantime, local MPOs can support their planning and project evaluation efforts by measuring the accessibility benefits to opportunities for which data is readily available in their area.

6.8.3 Example of a Potential FTA New Starts Accessibility Benefits Metric

As a key component of livability, accessibility benefits to desired opportunities can be incorporated into the FTA New Starts project evaluation criteria as a way to address some of the livability benefits of transit project proposals. An example of a potential New Starts accessibility metric is formulated in Equation 6-8 below. This metric can also be used by MPOs to evaluate local project alternatives.

Equation 6-8: Accessibility Benefits Metric

$$AB_{\text{corridor}} = (AI_{\text{corridor_build}} - AI_{\text{corridor_baseline}}) * P_{\text{corridor}} / C_{\text{FederalFunding}}$$

Where:

AB_{corridor} = project corridor accessibility benefits

$AI_{\text{corridor_build}}$ = corridor gravity accessibility index in the build scenario

$AI_{\text{corridor_baseline}}$ = corridor gravity accessibility index in the baseline scenario

P_{corridor} = population residing in the project corridor

$C_{\text{FederalFunding}}$ = dollar amount of Section 5309 Federal funding for project

A corridor accessibility index measure for the baseline and build scenarios is used in the calculation of the accessibility benefits metric. Recall from Section 6.3 to Section 6.7 that an accessibility index measure can be calculated for each TAZ. Corridor accessibility is simply calculated as the sum of the accessibility index ratings of each TAZ in the corridor, weighted by the TAZ population. See Equation 6-9 for the mathematical formulation of the corridor accessibility index.

Equation 6-9: Corridor Accessibility Index

$$AI_{\text{corridor}} = \sum(AI_i * P_i) / P_{\text{corridor}}$$

Where:

i = origin location (origin TAZ)

AI_{corridor} = gravity accessibility index of the corridor

AI_i = gravity accessibility index at location i per Equation 6-7

P_i = population residing in location i

P_{corridor} = population residing in corridor

In order to compare various projects from across the country, the proposed accessibility benefits metric in Equation 6-8 is normalized by corridor population and amount of Section 5309 funding. Using corridor population, as opposed to a measure such as projected ridership, allows for the consideration that all individuals along the corridor will receive accessibility benefits from a project. This is true regardless of whether or not an individual shows up as a system rider in a travel demand model. The fact that an individual has additional transit options to reach desired activities increases his quality of life. An individual will directly experience these accessibility benefits by being a daily rider of the system, by being an occasional rider of the system, or by profiting from the potential increased resale value of their residence. Additionally, since there is more certainty in existing population data than in ridership forecasts, using corridor population may be a more appropriate unit for normalization. The proposed accessibility benefits metric could be further normalized by the amount of Section 5309 funding. By only considering the federal funding amount, project sponsors could add locally-funded design elements that enhance the quality of a project without being penalized for increasing the total project cost.

FTA can establish a set of core opportunity categories for which project sponsors must calculate the accessibility benefits measure. The importance of each opportunity category towards the overall accessibility score can be weighted by the percentage of trips to that particular opportunity category. For example, the percentage of Home Based Work trips can be used as a weight for accessibility to employment while the percentage of Home Based School trips can be used as a weight for accessibility to education.

The proposed accessibility metric can be rated by FTA on a relative scale. In other words, the accessibility benefit measure of all project applications can be ranked in order from least to greatest and divided into logical breaks, similar to the current rating of the New Starts mobility criteria. From these natural breaks, scores from 1 to 5 (*Low to High*) can be assigned for each project.

Until FTA formally adopts an accessibility metric into the New Starts rating criteria, project sponsors can submit accessibility measures as “supplemental material” on a voluntary basis if they feel the criteria helps to state the case of overall project benefits.

7 Relationship Between Accessibility and Mode Share

Increasing transit mode share provides a number of livability benefits. These livability benefits can include improved air quality through decreases in greenhouse gas emissions, improved water quality, decreased oil dependency, and human health benefits. Human health benefits are comprised of those linked to improved air quality as well as the physical activity benefits received by the increased amount of walking encouraged by transit. Accessibility may be correlated with the aforementioned benefits, thereby further justifying the use of accessibility metrics in the livability-based FTA New Starts criteria.

In addition, studies have found that traditional methods of forecasting transit ridership (based in part on the mode share step of the traditional four-step model) typically overestimate transit ridership of New Starts applicant projects (Emerson & Ensor, 2010). These studies include Pickrell's seminal 1990 report that found "consistent over-estimation of future ridership on recent rail transit projects" (Pickrell, 1990). Accessibility measures serve as a powerful tool that can improve our understanding of the phenomena being modeled. If there is a correlation between accessibility and mode share, accessibility measures may be able to provide a means to close the gap of uncertainty left by traditional transportation model estimates.

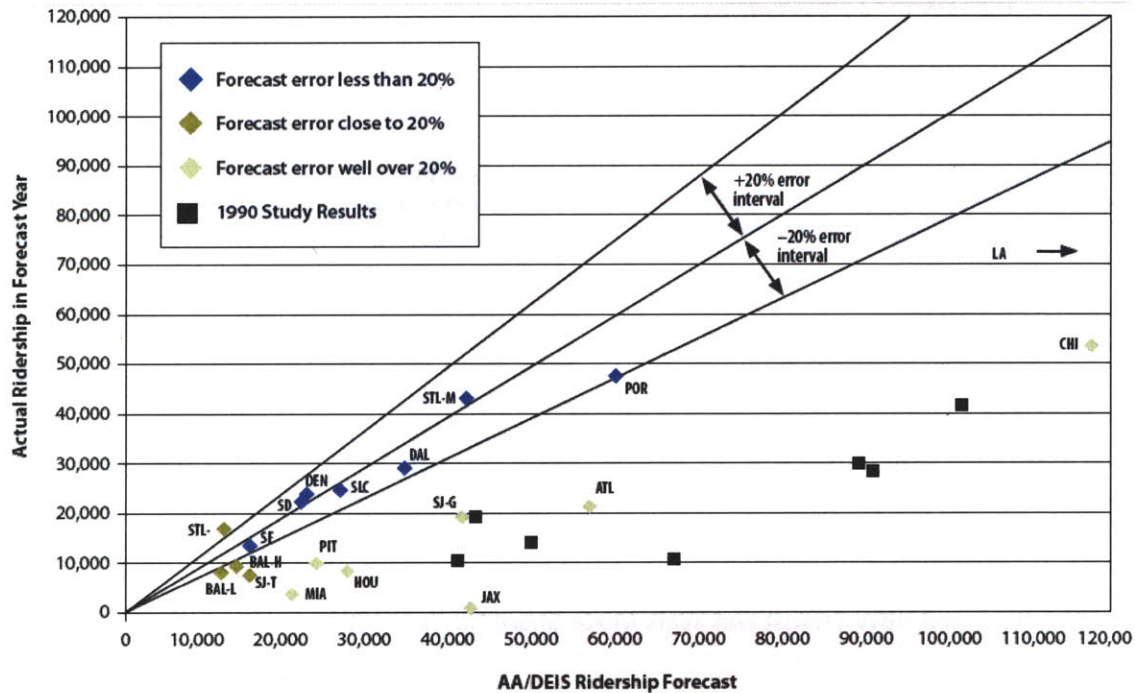
In the following sections, the relationship between mode share and accessibility (both the isochrone accessibility and the gravity accessibility index measures calculated in the previous chapter) will be explored. The author hypothesizes that areas with high transit accessibility will also experience high transit mode share. Regression analyses are performed using the academic model estimated mode share from the year 2000 model scenario and the observed mode share from 2000 CTPP data. Since the Census only provides data on the journey to work, the analysis is limited to the correlation between Home Based Work mode share and accessibility to employment.

7.1 Modeling Mode Share

It is challenging to accurately model the expected ridership and mode shift impacts of a transit project from traditional travel models. The results of a 2003 FTA study on ridership forecast accuracy, presented in Figure 7-1, show that a majority of New Starts project forecasts overestimate ridership. In this figure, projects prior to 1990 are illustrated with black squares, while more recent projects are illustrated with blue, gold, and silver diamonds. It can be seen that while the accuracy of ridership

forecasts has improved since pre-1990, most forecasts still overestimate ridership with forecast error greater than 20%.

Figure 7-1: Ridership Forecast Accuracy of New Starts Projects (Reproduced from Emerson & Ensor, 2010)



The use of accessibility measures may be able to further close the gap in ridership forecast estimates. Resolving the issues in ridership error is not the focus of this thesis, however the first step in determining whether accessibility may be valuable a tool to aid in mode share and ridership forecasting is to detect whether or not a relationship between accessibility and mode share exists.

Before the results of the accessibility index and mode share regressions are presented, a comparison of the mode share estimated from the academic model and the observed mode share obtained from the U.S. Census is warranted. The accessibility index measures assume the best case between walking and transit for trips with a walk time of 20 minutes or less. This assumption is used in the accessibility index calculation to capture the accessibility to opportunities in nearby zones where the travel cost of walking is less than that of transit. Since these accessibility scores are “transit and walk” accessibility, they will therefore be compared to “transit and walk” mode share in this chapter. Figures 7-2 and 7-3 illustrate the Boston region Home Based Work “transit and walk” mode splits from the model estimates and from the observed Census data, respectively.

Figure 7-2: Model Estimated HBW Transit and Walk Mode Share for Year 2000

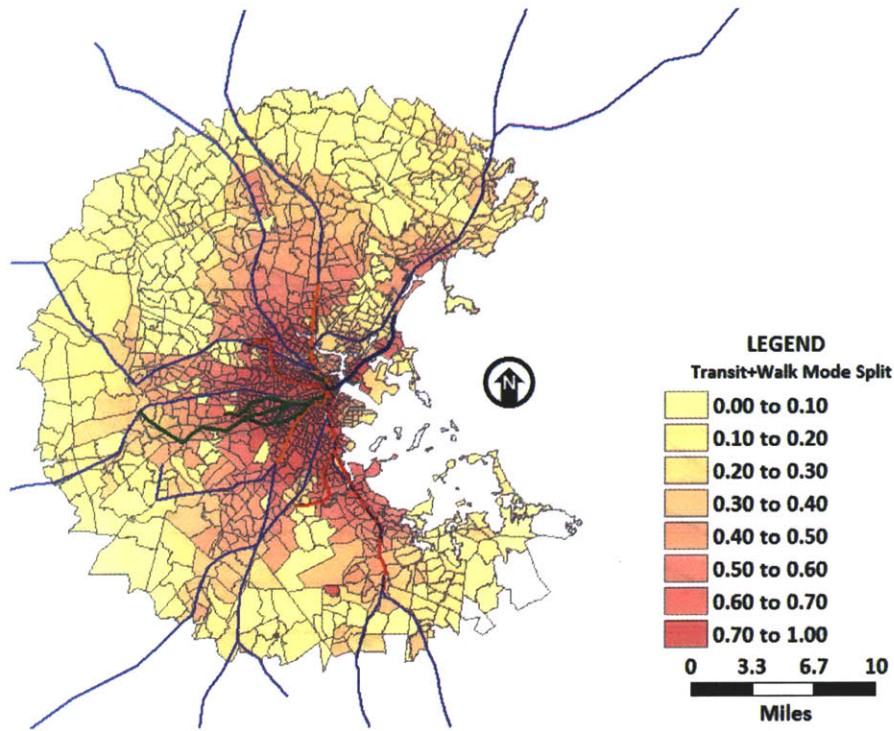
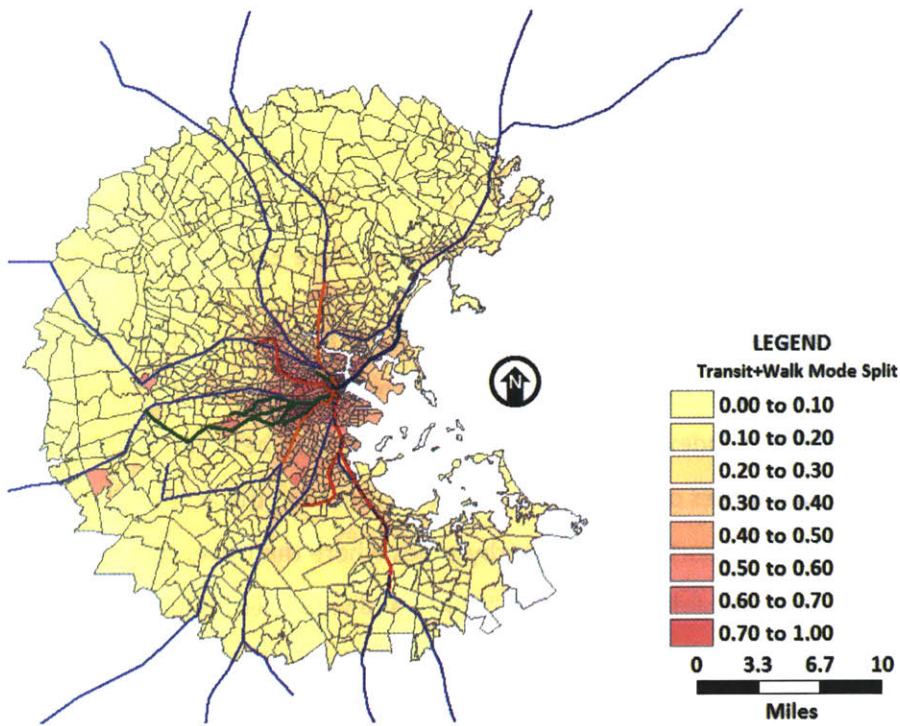


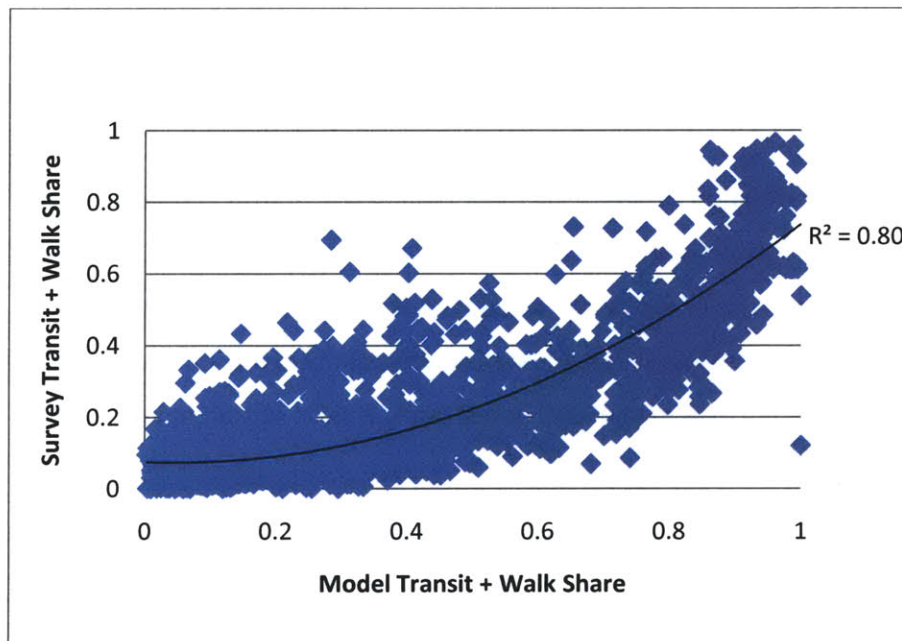
Figure 7-3: CTPP Observed HBW Transit and Walk Mode Share for Year 2000



Both the model estimates and the Census data show the highest “transit and walk” mode share in the central City, with higher “transit and walk” mode share in the suburbs appearing to lie along and adjacent to the MBTA subway and commuter rail lines, as expected. Although the general geographic trends are consistent between the model estimates and the Census data, the model appears to overestimate transit use in the suburbs, particularly in zones along the MBTA commuter rail lines. This is likely due to the challenges in accurately modeling park and ride in the academic model.

Figure 7-4 graphs the model estimated “transit and walk” mode share versus the survey observed “transit and walk” mode share for the journey to work. This graph also shows that the model tends to overestimate “transit and walk” mode share. Since the mode share step of the model is not used in the calculation of accessibility, the model development performed as part of this research did not focus on the mode split step. Further development and refinement of the model, specifically regarding park and ride trips, should improve the model mode share results.

Figure 7-4: Model Estimated HBW Mode Share Versus CTPP Observed HBW Mode Share

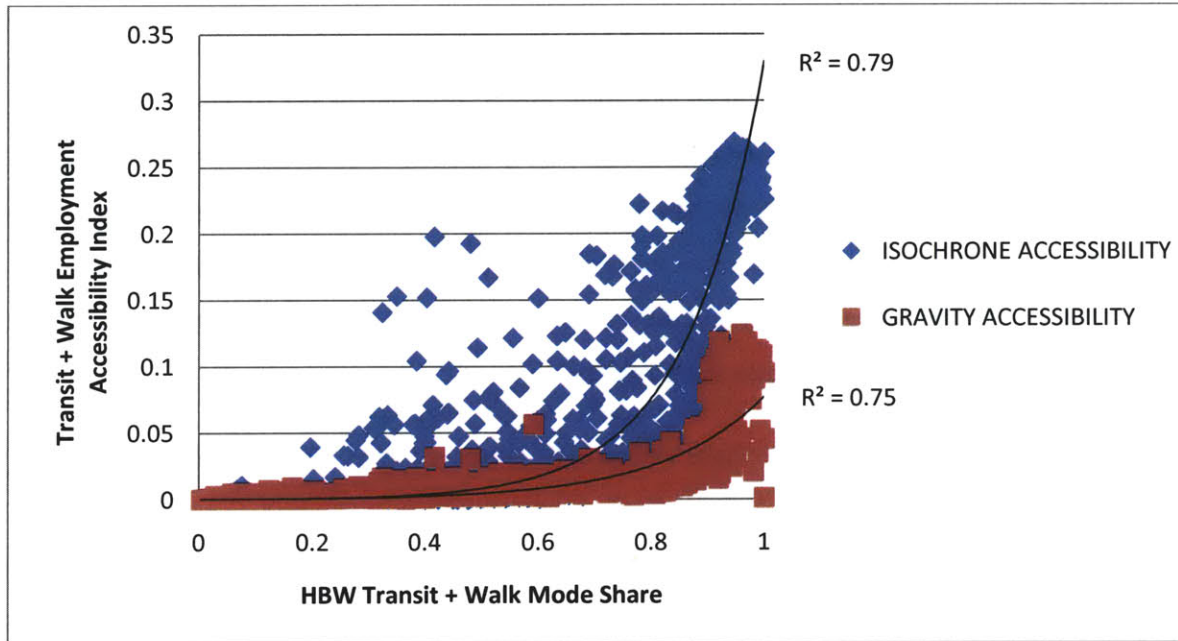


7.2 Accessibility and Model Estimated Mode Share

As discussed above, the mode share step of the model requires additional refinement to more accurately represent “transit and walk” mode share. Despite the discrepancies between the model and

survey mode share, a regression analysis was performed using the model estimates to determine the relationship between the model estimated mode share and accessibility scores for each TAZ. The results of this analysis are shown in Figure 7-5.

Figure 7-5: Model HBW Mode Share Versus Employment Accessibility



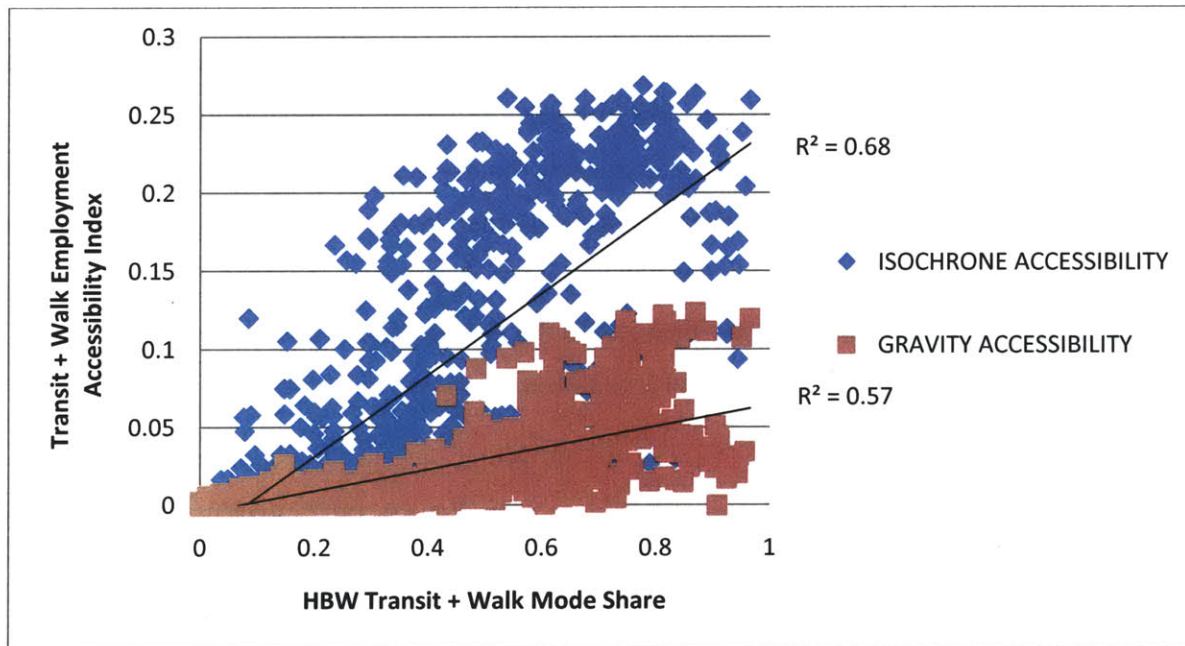
As hypothesized, there is a positive correlation between the model estimated “transit and walk” mode share for the journey to work and the “transit and walk” accessibility index to employment. There is a strong exponential relationship between model mode share and both the isochrone and gravity-based accessibility measures, with the analysis resulting in rho-squared values of 0.79 and 0.75, respectively. A rho-squared value of one indicates perfect exponential correlation while a value of zero indicates no relationship.

The results of the model mode share exercise support the hypothesis that there is a positive correlation between accessibility and mode share. However, there is uncertainty in the models ability (in its current state) to accurately predict mode share. The true test of the correlation between accessibility and mode share uses the observed mode share data obtained from the 2000 CTPP and is described in the subsequent section.

7.3 Accessibility and Observed Mode Share

The relationship between the observed journey to work mode share from the 2000 CTPP and the accessibility to employment in each TAZ are shown in Figure 7-6. The results of this regression exercise indicate that there is a linear correlation between the survey “transit and walk” mode share for home to work trips and the “transit and walk” accessibility to employment, and further support the hypothesis of a positive correlation between accessibility and mode share. The mode share correlation with the isochrone accessibility measure appears to be slightly stronger than with the gravity accessibility measure, as indicated by their respective rho-squared values of 0.68 and 0.57. In this case, a rho-squared value of one indicates perfect linear correlation while a value of zero indicates no relationship.

Figure 7-6: CTPP HBW Mode Share Versus Employment Accessibility



7.4 Summary of Findings

The regression exercises with both the model estimated mode share and the observed mode share from the U.S. Census indicate there is a positive relationship between accessibility to employment (measured by either isochrone or gravity methodologies) and mode share for the home to work commute. These examples cannot prove causality as there are many other factors that may play a role in the decision of

mode choice. Such factors include parking supply and cost policies which may become more restrictive with enhanced transit accessibility. Nonetheless, it is clear that areas with high “transit and walk” accessibility to employment tend to have a higher percentage of “transit and walk” trips for the home to work journey than areas with low “transit and walk” accessibility.

While the correlation between accessibility and mode share explored in this chapter does not appear to be strong enough to improve the ridership estimates produced from traditional methods, the results do show a clear positive relationship between accessibility and mode share. This weak correlation is partly due to the fact that there are other important factors that play a major role in mode share, such as parking availability, which are not included in accessibility. However, the positive relationship suggests that accessibility measures can serve as a valuable tool in the preliminary planning stages to quickly evaluate, and potentially improve or filter, alternatives prior to the completion of a conventional four-step travel demand model. Additional research is needed to look into the relationship between accessibility and mode share shifts, particularly shifts that occur over time due to the virtuous cycle that may be created in terms of business and residential relocation as well as the creation of a “transit culture.” This research has the potential to further develop the use of accessibility measures as a way to more accurately predict ridership and mode shift impacts of proposed transit projects. In the meantime, the positive relationship found between accessibility and mode share in this chapter further supports the use of isochrone and gravity accessibility measures in the FTA New Starts criteria in order to incorporate the numerous livability benefits that result from increasing transit mode share.

8 Conclusions

This chapter provides a summary of the research work presented in this thesis. A synopsis of the findings and recommendations that are produced from this research are discussed. Several areas of future research, in the local context of the Green Line Extension Project as well as in the broader context of livability measures, are outlined.

8.1 Summary

Many public transportation projects across the Nation are only made possible due to federal funding received through the FTA's discretionary New Starts program. While the New Starts process can be applauded for incorporating a number of metrics in the evaluation of transit project costs and benefits, there is concern that the evaluation criteria are too limiting and that not all project benefits are accounted for in the best way. As a result, the existing criteria may not distinguish the projects most worthy of federal or local investment. Moreover, the evaluation doesn't extend to highway projects or even to flex funding decisions of MPOs.

The United States Department of Transportation's announcement of the "Livability Initiative" has driven the FTA to reassess the current New Starts criteria through the concept of livability. Livability is a complex notion founded on the concepts of quality of life and sustainability. Some components of livability are universally agreed upon, while others can differ across cultures and individuals. When considering the adoption of livability-based metrics for the project evaluation process, it is essential that the definition of livability consist of factors that are universally agreed upon and non-negotiable.

Accessibility is a fundamental concept in the transportation planning field and refers to the ability of an individual to reach desired opportunities or destinations given the land use and transportation systems. Few people, if any, would dispute the idea that accessibility to essential opportunities is a key component of livability. As a non-negotiable, comprehensible, and quantifiable factor of livability, the concept of accessibility can be used as one building block for the FTA as it reconsiders how transit project benefits are evaluated in the New Starts process. The inclusion of accessibility metrics in the evaluation process can additionally encourage coordination between project sponsors and land use planners, ultimately enhancing the quality of proposed projects.

Regardless of whether or not certain projects are appropriate or eligible for New Starts funding, accessibility measures can serve as a way for MPOs to evaluate multi-modal project alternatives at the

local level. For example, accessibility measures may also be constructive in the evaluation of highway corridor project alternatives and on the impact of highway project alternatives to local transit accessibility. There may also be potential to evaluate the accessibility benefits of highway proposals against transit project proposals. Although auto accessibility may far surpass transit accessibility in many cases, there are several important advantages to valuing high levels of transit accessibility over high levels of auto accessibility. While auto time savings are typically fragile and easily eroded with increasing congestion, the accessibility benefits of rapid transit are more permanent. Additionally, transit accessibility can act as a catalyst in favor of more sustainable land use development, ultimately leading to a lower number of vehicle-miles traveled.

A number of methods are used to quantify accessibility, each varying in their theoretical basis, ease of communication, and data requirements. Most of the methods can be classified as one of four types: person-based, utility, isochrone, and gravity (Geurs and van Wee, 2004). Detailed data requirements hinder the use of person-based accessibility measures in practice. Utility measures, currently incorporated in the FTA New Starts criteria, are difficult to communicate to non-technical decision makers and can lack meaning on an individual scale. The remaining two methods, isochrone and gravity measures, provide an operational and meaningful way to calculate accessibility benefits within the context of livability.

Both isochrone and gravity measures can be understood by non-technical stakeholders. However, gravity measures are slightly more complex but also more rigorous. When considering the implementation of an accessibility benefit measure in the project evaluation process, the simplest measure that produces meaningful and accurate results should be used. The appropriateness of isochrone and gravity accessibility measures for project evaluation purposes is explored in this thesis within the context of the Green Line Extension Project in Somerville, MA.

An academic four-step travel demand model was developed in order to obtain the input data necessary to calculate isochrone and gravity accessibility for three Green Line Extension Project model scenarios. These scenarios consist of existing conditions in year 2010, an enhanced bus baseline scenario in year 2030, and a Green Line Extension build scenario in year 2030. Transit accessibility measures to five opportunity types essential to livability are calculated for each scenario and illustrated in accessibility index maps of the Project area. The opportunity types considered are employment, shopping, education, health care, and recreation. The results of the accessibility analysis are ultimately used to

recommend a preferred method for quantifying accessibility benefits as well as opportunity types that should be considered in a livability-based project evaluation process.

In general, both isochrone and gravity accessibility measures show little to no change in transit accessibility between the existing conditions scenario and baseline scenario. Significant increases to transit accessibility are, however, generally produced along the Project corridor in the build scenario. The exception is isochrone accessibility to education, which did not increase in the build scenario with the original isochrone threshold definition. This example highlights one of the shortcomings of the isochrone method (the sensitivity of isochrone accessibility benefits to the definition of a time threshold) and suggests that isochrone measures may not be appropriate when considering opportunities with a spatial distribution that is concentrated in multiple “lumpy” discrete locations. This outcome, together with the fact that a gravity approach is more congruent with actual travel behavior, prompted the recommendation that gravity measures, instead of isochrone measures, be used to calculate the accessibility benefits of proposed projects. Gravity measures are also better able to incorporate the benefits resulting from bus feeder services, which may be outside the range of the defined isochrone threshold.

Accessibility to a variety of opportunities and services should be considered as part of a comprehensive analysis when evaluating project benefits because livability can mean different things to different people. The aging demographic trend will make transit accessibility increasingly important to a larger percentage of the population. An aging population also means that transit accessibility to services such as shopping, health care, and recreation will be more important than accessibility to employment for the quality of life of many people. Although available data will limit the accessibility indicators that can be analyzed, it is recommended that a complete view of all essential opportunities be considered in the analysis of accessibility benefits.

Based on the above recommendations from the Green Line Extension Project accessibility analysis, an example accessibility metric that can be incorporated in the FTA New Starts process was developed. This metric quantifies the accessibility benefits in a project corridor between the build and baseline scenario. In order to evaluate various projects from around the country, this proposed metric is normalized by corridor population and amount of Section 5309 New Starts funding. Limiting the cost variable to federally funded dollars is suggested in order to allow project sponsors to add locally-funded design elements that may enhance the quality of a project without being penalized for increasing the total project cost.

Lastly, the correlation between accessibility by mode and mode share is tested. The calculated accessibility to employment measures are compared to both the model estimated Home Based Work mode share and the observed Home Based Work mode share from the U.S. Census. In both cases, a positive relationship between accessibility by mode and mode share is found. The correlation results are not strong enough to suggest that accessibility could be a substitute for a conventional demand model. This is partly due to the fact that there are other important factors that play a major role in mode share, such as parking availability and cost, which are not included in the transit accessibility calculation. However, the positive correlation between transit accessibility and transit mode share suggests that accessibility measures can serve as a valuable tool in the preliminary planning stages to quickly evaluate alternatives prior to the completion of a conventional four-step travel demand model. This positive correlation also further justifies the use of accessibility measures in a livability-based project evaluation process.

8.2 Areas of Future Research

Several areas of future research that can provide enhancements or extensions to the research presented in this thesis include:

- ***Analyze the impact of enhanced bus frequency in Somerville and better bus coordination with the Green Line Extension on accessibility benefits.*** Coordinating bus and rail transit schedules will improve travel times for trips requiring a transfer either from rail to bus or vice versa. It is hypothesized that the improvement of bus frequencies in Somerville and the additional coordination (both physical coordination and schedule coordination) of bus routes with the Green Line Extension will increase the accessibility benefits of the Project.
- ***Analyze the accessibility impact of land use densification in the Green Line Extension corridor.*** There are several large sites along the proposed Green Line Extension that are suitable for transit-oriented development and land use densification, including Union Square, Boynton Yards, Twin City, and the Washington Street area. Using accessibility measures to analyze the impacts of various land use scenarios can provide a tool to create better land use and transportation planning coordination and ultimately improve the quality of the Project.

- ***Test the ability of accessibility measures to calculate the incremental benefits of additional Green Line Extension Project phases, including the extension to Route 16 and the addition of a station at Twin City.*** Measuring the accessibility benefits of a future scenario with a Route 16 extension and Twin City station, individually and combined, may provide insights on the incremental accessibility benefits in the areas immediately surrounding these stations as well as to other areas in the Project corridor.
- ***Further explore the correlation between mode share and accessibility using a time-series case study approach.*** The correlation between accessibility and mode share is vulnerable to the fact that transit accessibility measures do not incorporate several parameters that are important to transit mode share, such as parking availability and cost. Nonetheless, performing a retrospective study on accessibility and mode share through time may provide insights into the long term changes, including systemic ones, and the actual correlation between the two variables as well as provide indications of what to expect in the future. In order to better predict transit needs and potential ridership along the Green Line Extension corridor in the future, one could study the accessibility and mode share correlations at Davis Square (the only Red Line Extension station stop in Somerville) before and after the Red Line Extension was put into operation in 1985. A similar case study that analyzes the changes along the existing D branch of the Green Line in Brookline and Newton could also prove to be interesting and useful in planning for the future extension to Somerville.
- ***Test the robustness and evaluation ability of the proposed FTA New Starts metric by performing a similar accessibility analysis with the models and data from other transit projects.*** This thesis uses the context of the Green Line Extension Project to calculate accessibility changes between various project scenarios and to propose a potential accessibility benefits metric. By performing this same exercise with other projects from across the country, the ability of the proposed metric to meaningfully distinguish the benefits between various projects and sets of circumstances can be further tested.
- ***Test the ability of the accessibility benefit metric to better incorporate livability in the evaluation of highway project proposals.*** While there is no equivalent New Starts process for highway project evaluation, the incorporation of livability considerations in traditional highway

projects is a necessary part of livability-based transportation planning. The mobility benefits of highway projects are often fragile and disintegrate with increased congestion. Highway accessibility also decreases with increasing congestion, unless land use densities increase enough to offset the growth in congestion. The accessibility benefit metric can be tested in the context of highway project proposals on the local level as a tool to aid MPOs in the decision making process and to encourage coordinated land use and transportation planning.

- ***Develop measures of additional livability benefits for FTA New Starts and local project evaluation purposes.*** The scope of this thesis focused on accessibility, one key component of livability, and how to quantify the accessibility benefits of transit projects. Other important livability components that could be better incorporated into the New Starts rating process include environmental benefits, economic development benefits, agglomeration benefits, and social equity benefits.

8.3 Closing Remarks

The concept of accessibility provides a meaningful and operational way to incorporate some of the livability benefits of transit projects into the project evaluation process. At the same time, valuing accessibility provides incentives to better transportation and land use planning coordination which ultimately leads to the enhanced quality of project proposals. However, formal project evaluation procedures are currently non-existent for highway projects or flex funding decisions. The accessibility measures presented in this thesis provide an example of potential metrics that can be adopted by FTA in the next New Starts rulemaking as part of the livability focused policy change. In the meantime, these measures can be used by project sponsors as compelling supplementary material to strengthen the case of the project in the New Starts application or as a planning tool to assist MPOs in evaluating multi-modal project alternatives on the local level.

Bibliography

- American Association of State Highway and Transportation Officials. (1977). *A Manual on user benefit analysis of highway and bus transit improvements*. Washington, DC: American Association of State Highway and Transportation Officials.
- American Hospital Directory. (2010). *Free Hospital Profiles* [Data]. Available from <http://www.ahd.com>
- American Public Transportation Association. (2011). Transit benefits. Retrieved from <http://www.publictransportation.org/benefits/>
- Andrews, C.J. (2001). Analyzing quality-of-place. *Environment and Planning B: Planning and Design*, 28, 201-217.
- Ben-Akiva, M.E., & Lerman, S.R. (1985). *Discrete choice analysis: Theory and application to travel demand*. Cambridge, MA: MIT Press.
- Boston Metropolitan Planning Organization. (1991). *1991 Boston household travel survey* [Data files].
- Bureau of Transportation Statistics. (2010). Table 3-14: Average cost of owning and operating an automobile. Retrieved from http://www.bts.gov/publications/national_transportation_statistics/2010/html/table_03_14.html
- Busby, J. (2004). *Accessibility-based transit planning*. Cambridge, MA: Massachusetts Institute of Technology.
- Colella, M., Jenkins, J., Salvucci, F. (2010). *Agglomeration benefits and transportation: Theory, measurement, and application to Crossrail*. (Transportation Research Board paper submission).
- Commonwealth of Massachusetts Office of Geographic Information. (2010). *Datalayers/GIS Database* [Data files]. Available from <http://www.mass.gov/mgis/>
- Coughlin, J.F. (2010, November 2). *The future is gray, small, and female: Disruptive demographics and transportation tomorrow*. [Video file]. Retrieved from MIT World: <http://mitworld/mit/edu/video/863>
- Emerson, D.J., & Ensor, J.D. (2010). *New Starts: Lessons learned for discretionary federal transportation funding programs*. Washington, DC: Bipartisan Policy Center.
- Federal Transit Administration. (2008). Discussion paper on the evaluation of economic development. Retrieved from http://www.fta.dot.gov/documents/Econ_Dev_Discussion_Paper_1-16-09_Final.pdf
- Federal Transit Administration. (2009). *Travel forecasting for New Starts: A workshop sponsored by the Federal Transit Administration* [PowerPoint slides].

- Federal Transit Administration. (2010a). *Annual report on funding recommendations: Fiscal year 2011*. Washington, DC: Federal Transit Administration.
- Federal Transit Administration. (2010b). Fixed guideway modernization. Retrieved from http://www.fta.dot.gov/funding/grants/grants_financing_3558.html
- Federal Transit Administration. (2010c). FTA major capital transit investment fact sheet: Alternatives analysis. Retrieved from http://www.fta.dot.gov/planning/newstarts/planning_environment_2608.html
- Federal Transit Administration. (2010d). FTA major capital transit investment fact sheet: Final design. Retrieved from http://www.fta.dot.gov/planning/newstarts/planning_environment_2608.html
- Federal Transit Administration. (2010e). FTA major capital transit investment fact sheet: Full funding grant agreement. Retrieved from http://www.fta.dot.gov/planning/newstarts/planning_environment_2608.html
- Federal Transit Administration. (2010f). FTA major capital transit investment fact sheet: New Starts project development. Retrieved from http://www.fta.dot.gov/planning/newstarts/planning_environment_2608.html
- Federal Transit Administration. (2010g). FTA major capital transit investment fact sheet: Preliminary engineering. Retrieved from http://www.fta.dot.gov/planning/newstarts/planning_environment_2608.html
- Federal Realty Investment Trust. (2011). Assembly Square redevelopment. Retrieved from <http://www.assemblysquare.com/redevelopment.html>
- Findlay, C. (2009, October 1). Living in a post-car world. *AARP Bulletin*.
- Geurs, K.T., & van Wee, B. (2004). Accessibility evaluation of land-use and transport strategies: Review and research directions. *Journal of Transport Geography*, 12, 127-140.
- Graham, D. (2007). Agglomeration, productivity, and transport investment. *Journal of Transport Economics and Policy*, 41, 317-343.
- Hagerstrand, T. (1970). What about people in regional science? *People of the Regional Science Association*, 24, 7-21.
- Hansen, W. G. (1959). How accessibility shapes land use. *Journal of the American Planning Association*, 25, 73-76.
- Hart, M. (1999). *Guide to sustainable community indicators*. North Andover, MA: Hart Environmental Data.
- John A. Volpe National Transportation Systems Center. (2009). Proceedings from a Colloquium held October 28 & 29, 2008: *Comparing the Environmental Benefits of Transit Projects*. Cambridge, MA.

- Massachusetts Bay Transportation Authority. (2010). *Capital investment program:FY2011-FY2015*. Retrieved from http://www.mbta.com/uploadedfiles/About_the_T/Financials/MBTA%20FY11-FY15.pdf
- Massachusetts Department of Transportation. (2010). *Final environmental impact report: Green Line Extension project EEA #13886*.
- Massachusetts Executive Office of Transportation. (n.d.). *Population and employment estimates for year 2000,2010 and 2030* [Data files].
- Miller, H.J., & Wu, Y. (2001). Computational tools for measuring space-time accessibility within dynamic flow transportation networks. *Journal of Transportation and Statistics*, 4 (2&3), 1-14.
- Murga, M. (2010). *1.254 Transport Modeling* [PowerPoint slides]. Retrieved from <http://stellar/S/course/1/sp11/1.254/>
- National Research Council. (2002). *Community and quality of life: Data needs for informed decision making*. Washington, DC: National Academy Press.
- Pickrell, D.H. (1990). *Urban rail transit projects: Forecast versus actual ridership and costs*. Washington, DC: United States Department of Transportation.
- Pfeiffer, S. (2009, October 19). On the streets of Somerville, an RV on a mission. *WBUR*. Retrieved from <http://www.wbur.org/2009/10/19/air-pollution/>
- Project for Public Spaces. (n.d.). What makes a successful place? Retrieved from <http://www.pps.org/articles/grplacefeat/>
- Shireman, M. (2011). *Using automatically collected data for bus service and operations planning*. Cambridge, MA: Massachusetts Institute of Technology.
- Somerville Transportation Equity Partnership.(2010). Background. Retrieved from <http://www.somervillestep.org/background/>
- Transit Cooperative Research Program. (2007). Traveler response to transportation system changes. In *TCRP Report 95* (Chapter 17). Washington, DC: Transportation Research Board.
- United States Census Bureau. (2000). *Census 2000* [Data files]. Available from <http://www.census.gov/main/www/cen2000.html>
- United States Department of Transportation. (2000). *Census Transportation Planning Package 2000* [Data files]. Available from <http://www.fhwa.dot.gov/ctpp/>
- United States Environmental Protection Agency. (2011a). Environmental Justice. Retrieved from <http://www.epa.gov/environmentaljustice/>
- United States Environmental Protection Agency. (2011b). The green book nonattainment areas for criteria pollutants. Retrieved from <http://www.epa.gov/airquality/greenbook/>

Warade, R. (2007). *The accessibility and development impacts of new transit infrastructure: The circle line in Chicago*. Cambridge, MA: Massachusetts Institute of Technology.

World Commission on Environment and Development. (1987). *Our common future*. New York, NY: Oxford University Press.

Appendix A

A.1 List of Acronyms

AASHTO	American Association of State Highway and Transportation Officials
BRT	Bus Rapid Transit
CBD	Central Business District
CTPP	Census Transportation Planning Package
CTPS	Central Transportation Planning Staff
EEA	Executive Office of Energy and Environmental Affairs
FFGA	Full funding grant agreement
FTA	Federal Transit Administration
GIS	Geographic Information System
HBW	Home Based Work
LEED	Leadership in Environmental and Energy Design
LPA	Locally Preferred Alternative
MBTA	Massachusetts Bay Transportation Authority
MPO	Metropolitan Planning Organization
NEPA	National Environmental Policy Act of 1969
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users
TAZ	Traffic Analysis Zone

Appendix B

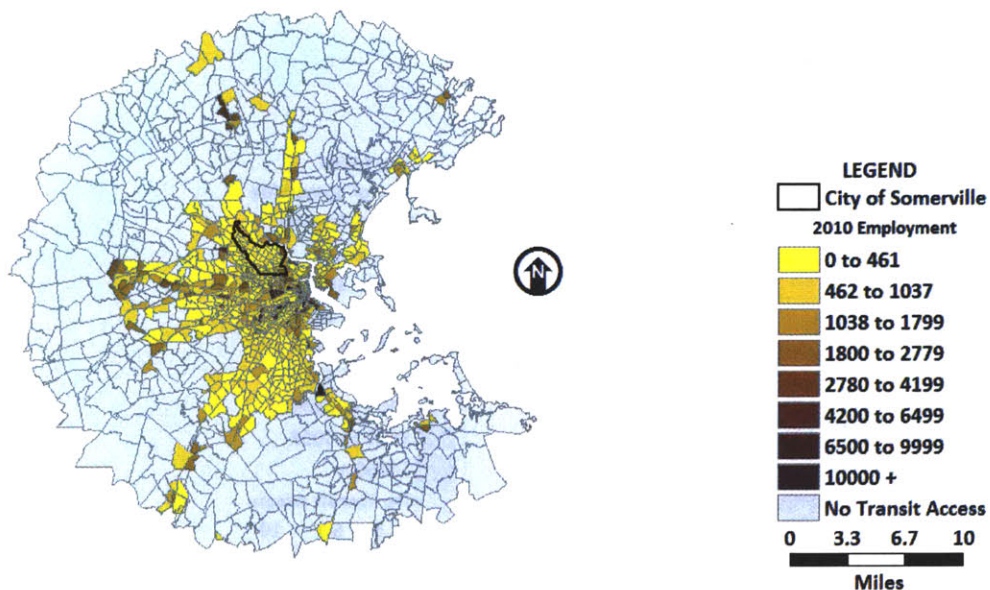
B.1 Accessibility Analysis to Transit-Accessible Employment

The following contains the results of an analysis of accessibility to employment and complements the results included in Section 6.3. While the analysis in Section 6.3 considers transit accessibility to all employment opportunities in the Region, this analysis only considers employment opportunities that can be reached via public transportation. These opportunities are hereafter referred to as “transit-accessible” employment opportunities. Transit-accessible employment opportunities are defined as jobs located within a half mile of a public transportation station/stop. Since opportunity attributes in the model are stored in the TAZ centroid, all jobs in a TAZ whose centroid is within a half mile of transit are counted as transit-accessible jobs.

B.1.1 Transit-Accessible Employment Opportunities

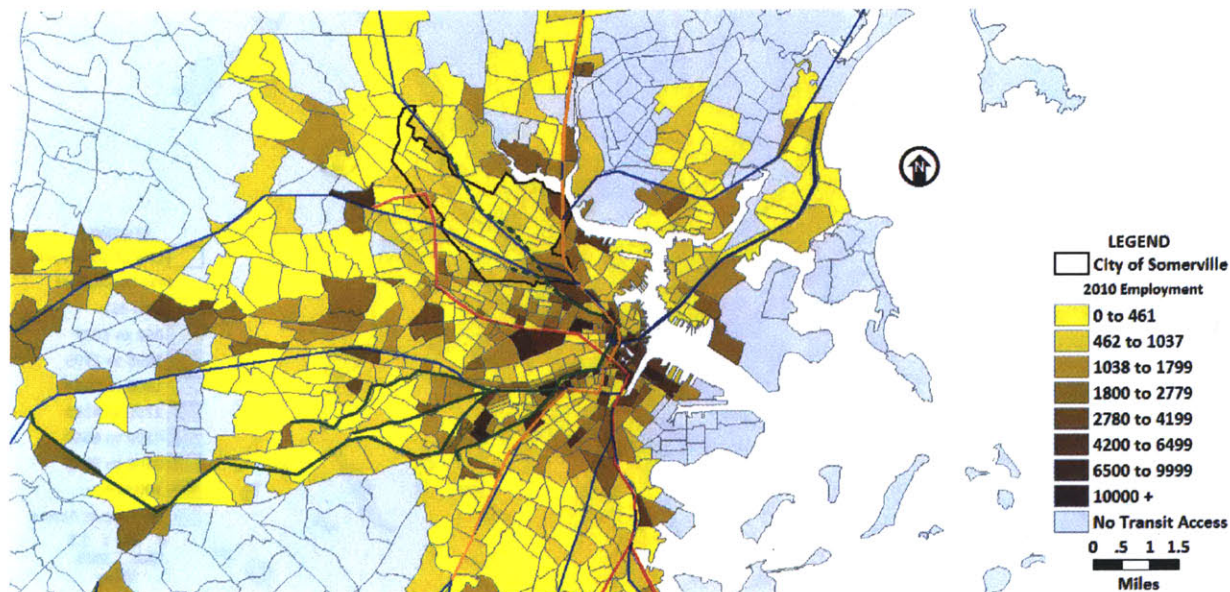
The number of employment opportunities available in the existing conditions scenario, 2030 baseline scenario, and 2030 build scenario are determined from the Massachusetts Executive Office of Transportation employment estimates for 2010 and 2030. The distribution of transit-accessible employment for 2010 is shown in Figures B-1 and B-2. In Figures B-3 and B-4, the 2030 projections of transit-accessible employment are illustrated. Note that all zones in Somerville have transit access either via rapid rail transit or via the local bus system. The “islands” of employment opportunities located in suburbs represent zones that have walk access to a commuter rail station.

Figure B-1: 2010 Transit-Accessible Employment (Regional View)



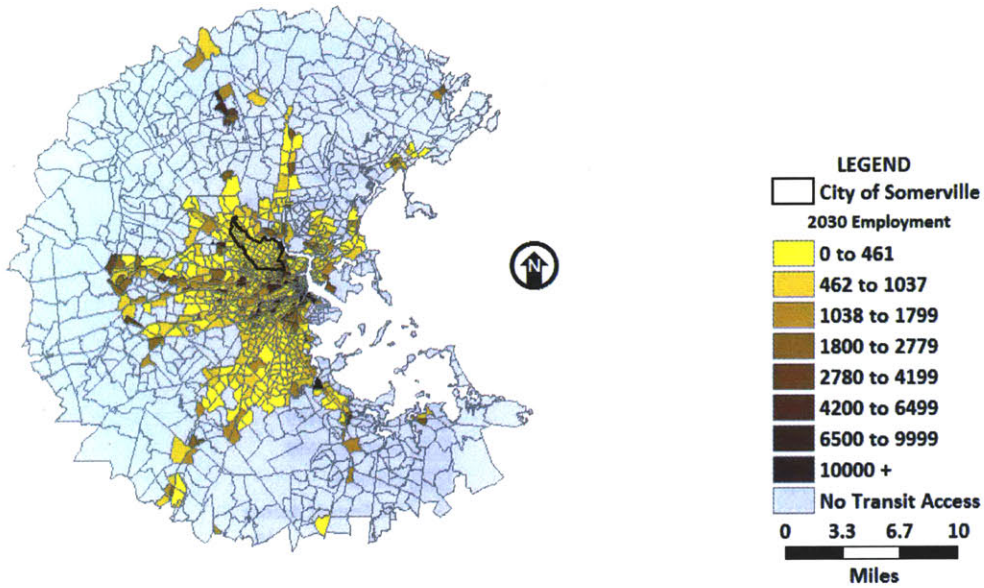
Data Source: Employment estimates (Massachusetts Executive Office of Transportation, n.d.)

Figure B-2: 2010 Transit-Accessible Employment (Local View)



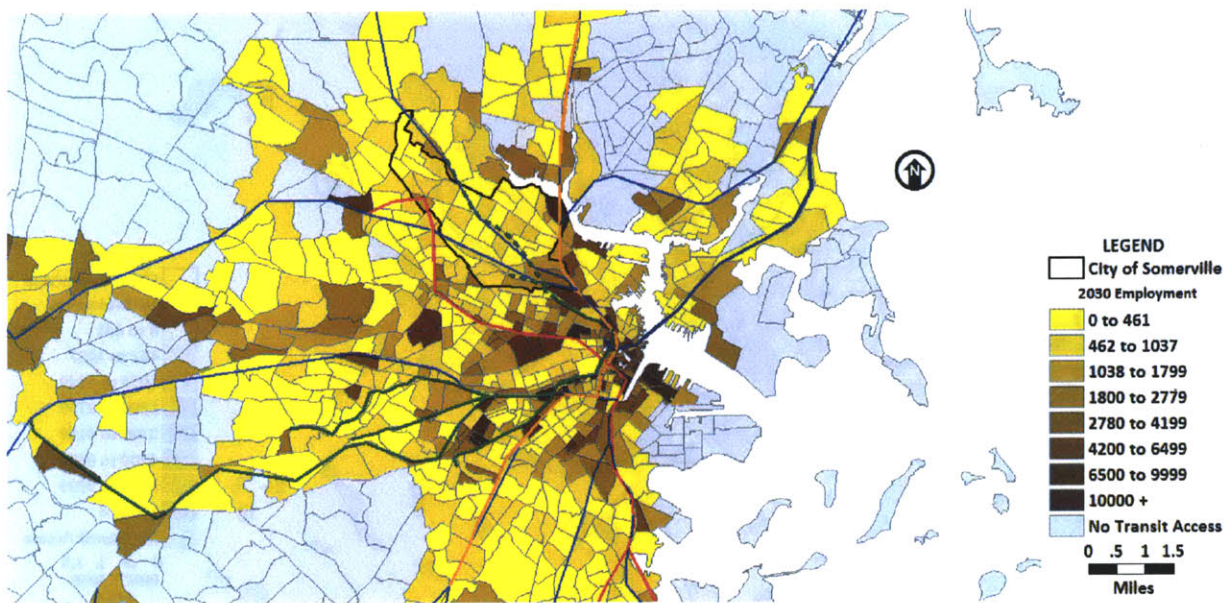
Data Source: Employment estimates (Massachusetts Executive Office of Transportation, n.d.)

Figure B-3: 2030 Transit-Accessible Employment (Regional View)



Data Source: Employment estimates (Massachusetts Executive Office of Transportation, n.d.)

Figure B-4: 2030 Transit-Accessible Employment (Local View)



Data Source: Employment estimates (Massachusetts Executive Office of Transportation, n.d.)

B.1.2 Isochrone Accessibility to Transit-Accessible Employment

Figures B-5 to B-7 map the transit accessibility index to employment for each TAZ in the Project corridor using isochrone estimation for the existing conditions scenario, 2030 baseline scenario, and 2030 build scenario, respectively. The isochrone index measure for a particular TAZ can be interpreted as the percentage of all transit-accessible opportunities that can be reached by transit from that origin within the determined isochrone threshold. For example, a TAZ with an isochrone index of 0.1 for employment indicates that 10% of all the transit-accessible employment opportunities in the Region can be reached by transit within a 40 minute threshold.

The results in these figures show accessibility indices that are generally greater than the indices calculated in the Section 6.3 analysis. For example, the areas with the highest accessibility in Figures B-5 to B-7 have index values reaching 0.6 compared to a maximum index of 0.2 in the Section 6.3 analysis. This makes intuitive sense because the indices in the Section 6.3 analysis are normalized by the total number of Regional jobs whereas the indices in Figures B-5 to B-7 are normalized by only a fraction of total jobs (only the transit-accessible jobs).

Despite differences in index values, the general conclusions remain the same. Accessibility to employment remains relatively unchanged between the existing conditions and the 2030 baseline scenario. Noteworthy increases in accessibility along the Green Line Extension corridor are seen in the build scenario.

Figure B-5: 2010 Existing Conditions Transit-Accessible Employment Accessibility – Isochrone Measure

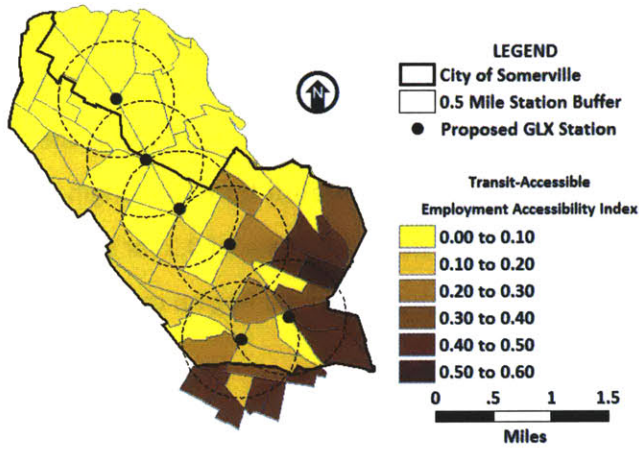


Figure B-6: 2030 Baseline Scenario Transit-Accessible Employment Accessibility – Isochrone Measure

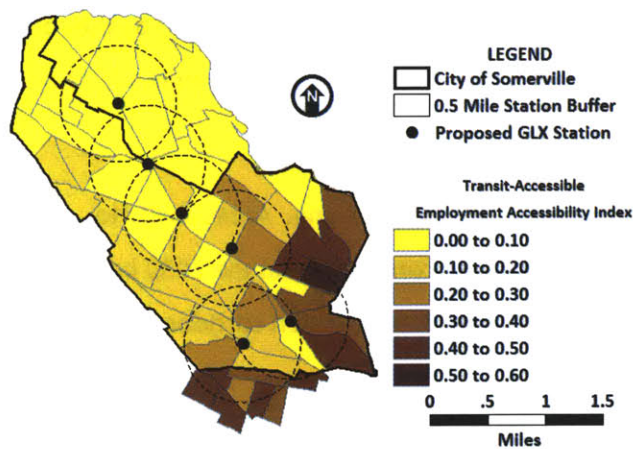
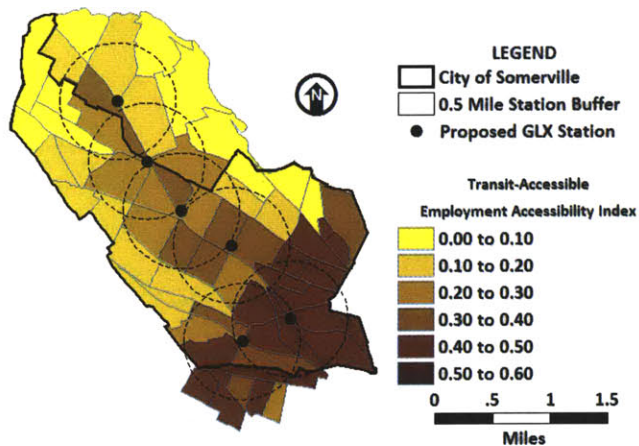


Figure B-7: 2030 Build Scenario Transit-Accessible Employment Accessibility – Isochrone Measure



B.1.3 Gravity Accessibility to Transit-Accessible Employment

Figures B-8 to B-10 map the transit accessibility index to employment for each TAZ in the Project corridor using gravity estimation for the existing conditions scenario, 2030 baseline scenario, and 2030 build scenario, respectively. The gravity index measure for a particular TAZ can be interpreted as the percentage of all equivalent transit-accessible opportunities that can be reached by transit from that origin. For example, a TAZ with a gravity index of 0.1 for employment indicates that 10% of all equivalent transit-accessible employment opportunities in the Region can be reached by transit from that location.

As expected, the gravity results in these figures show accessibility indices that are generally greater than the indices calculated in the Section 6.3 analysis. Again, despite the distinction in the range of index values, the conclusions are uniform. Accessibility to employment does not significantly increase in the 2030 baseline scenario. Noticeable increases are seen along the Project corridor in the build scenario due to the travel time savings and one-seat ride into Boston provided by the Green Line Extension.

Figure B-8: 2010 Existing Conditions Transit-Accessible Employment Accessibility – Gravity Measure

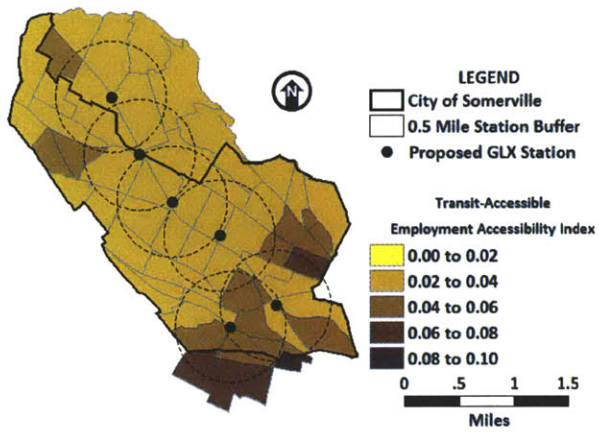


Figure B-9: 2030 Baseline Scenario Transit-Accessible Employment Accessibility – Gravity Measure

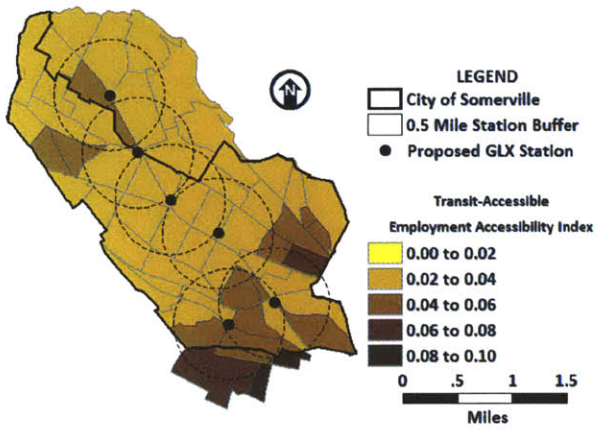
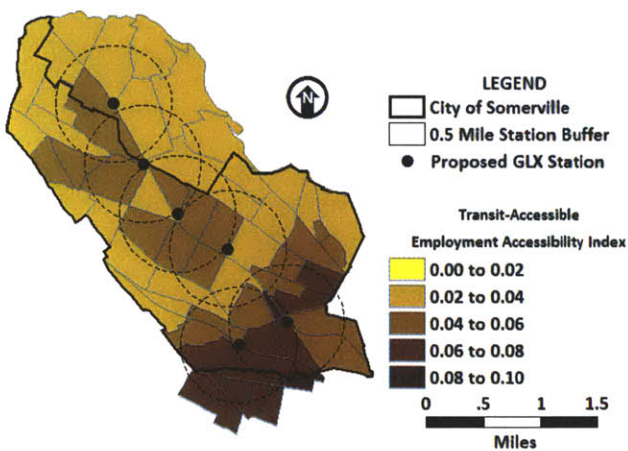


Figure B-10: 2030 Build Scenario Transit-Accessible Employment Accessibility – Gravity Measure



Appendix C

C.1 Compilation of Accessibility Index Maps

Figure C-1: 2010 Existing Conditions Employment Accessibility – Isochrone Measure

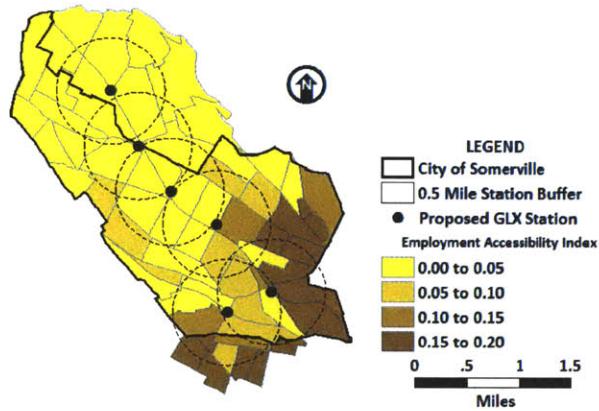


Figure C-2: 2030 Baseline Scenario Employment Accessibility – Isochrone Measure

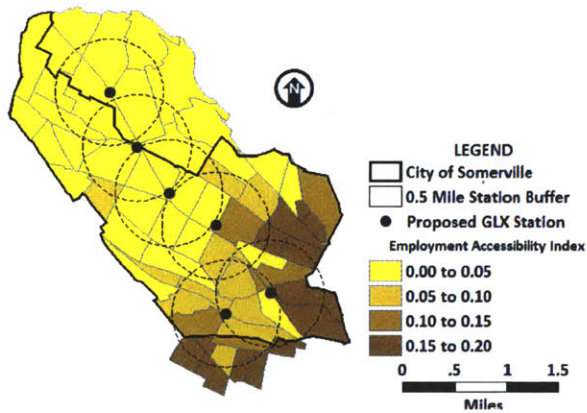


Figure C-3: 2030 Build Scenario Employment Accessibility – Isochrone Measure

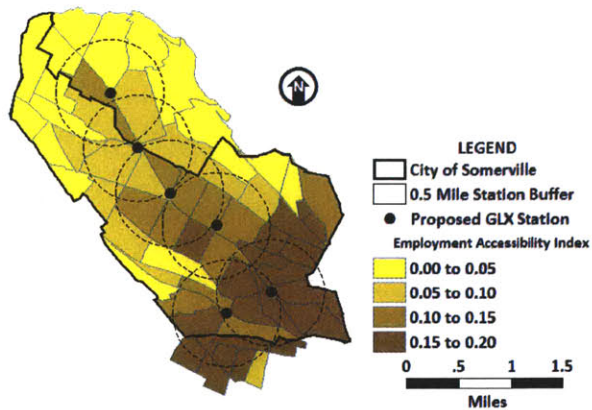


Figure C-4: 2010 Existing Conditions Employment Accessibility – Gravity Measure

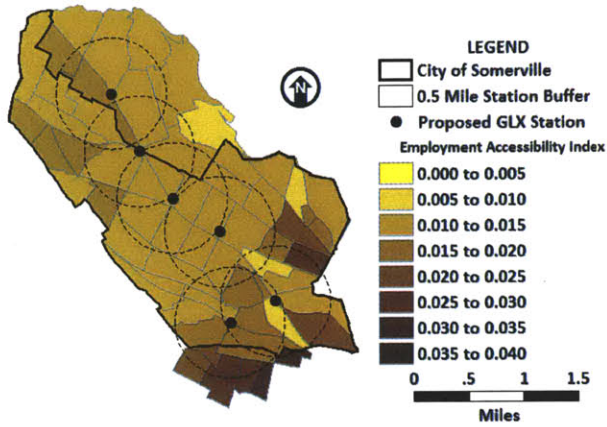


Figure C-5: 2030 Baseline Scenario Employment Accessibility – Gravity Measure

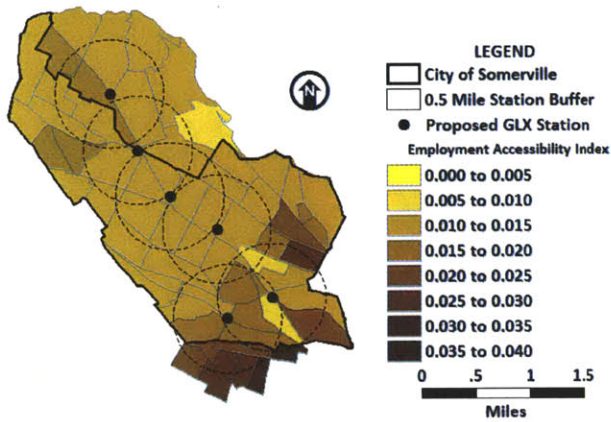


Figure C-6: 2030 Build Scenario Employment Accessibility – Gravity Measure

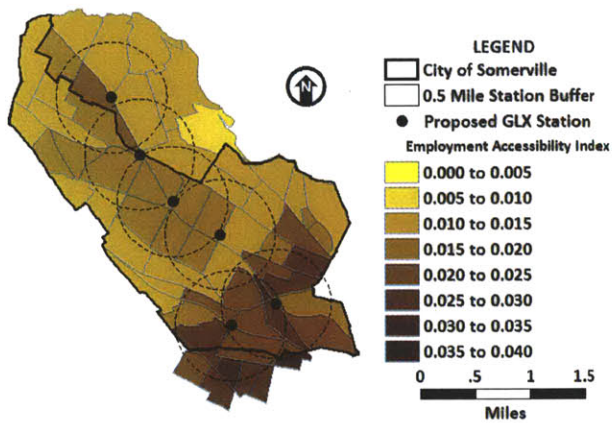


Figure C-7: 2010 Existing Conditions Shopping Accessibility – Isochrone Measure

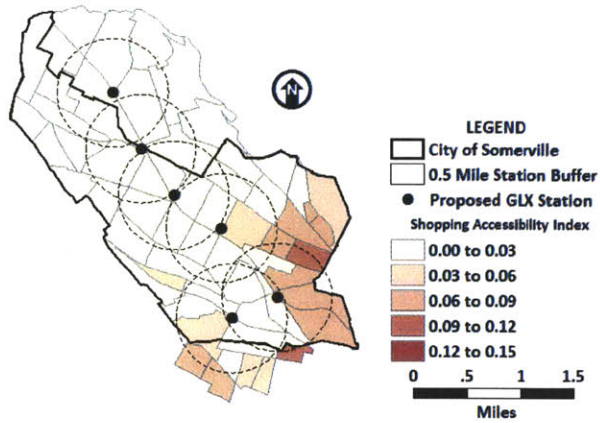


Figure C-8: 2030 Baseline Scenario Shopping Accessibility – Isochrone Measure

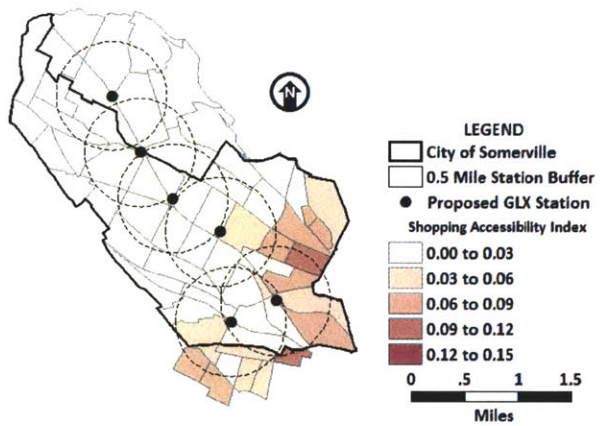


Figure C-9: 2030 Build Scenario Shopping Accessibility – Isochrone Measure

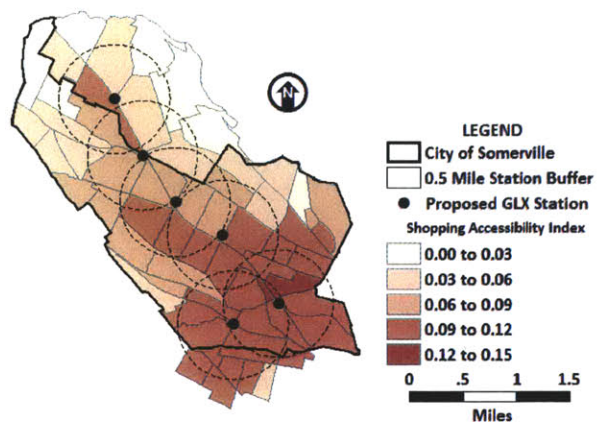


Figure C-10: 2010 Existing Conditions Shopping Accessibility – Gravity Measure

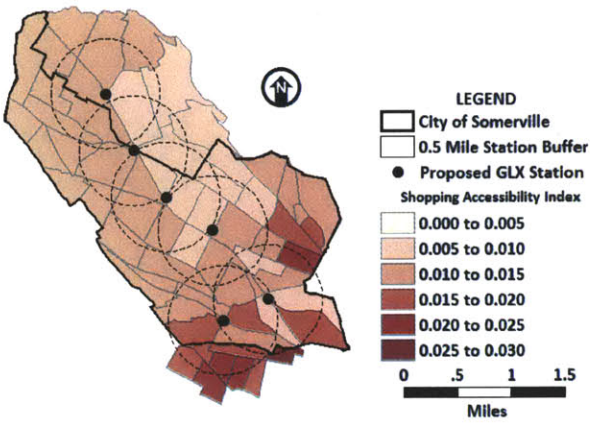


Figure C-11: 2030 Baseline Scenario Shopping Accessibility – Gravity Measure

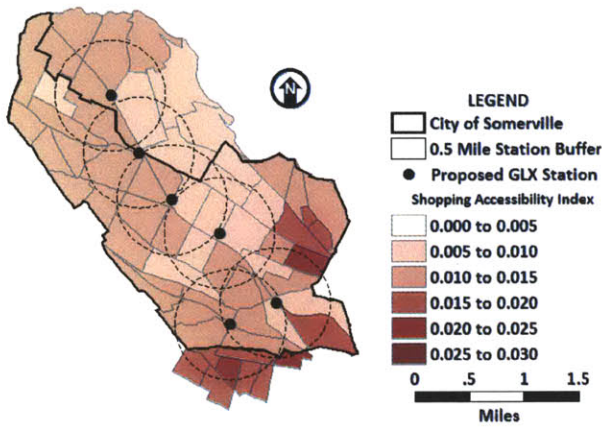


Figure C-12: 2030 Build Scenario Shopping Accessibility – Gravity Measure

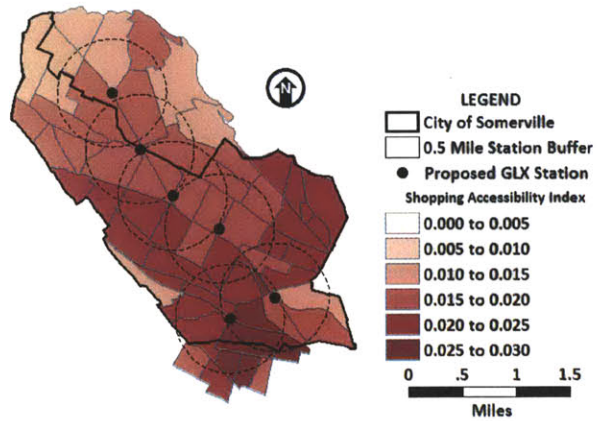


Figure C-13: 2010 Existing Conditions Education Accessibility (25 Min. Threshold)– Isochrone Measure

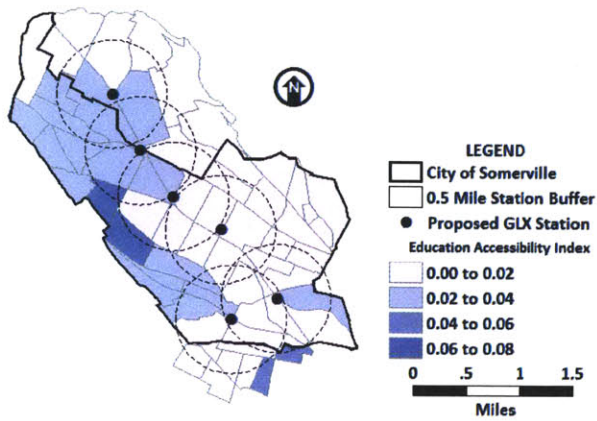


Figure C-14: 2030 Baseline Scenario Education Accessibility (25 Min. Threshold)– Isochrone Measure

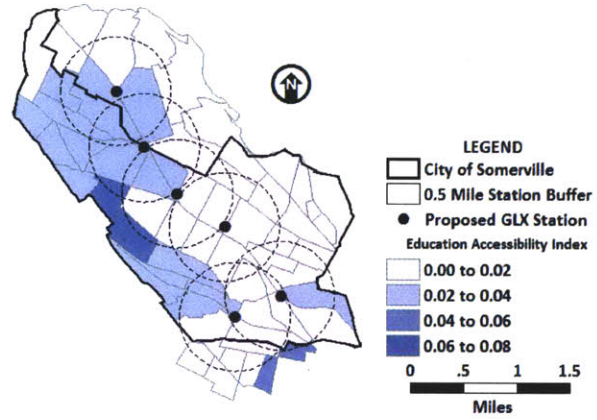


Figure C-15: 2030 Build Scenario Education Accessibility (25 Min. Threshold)– Isochrone Measure

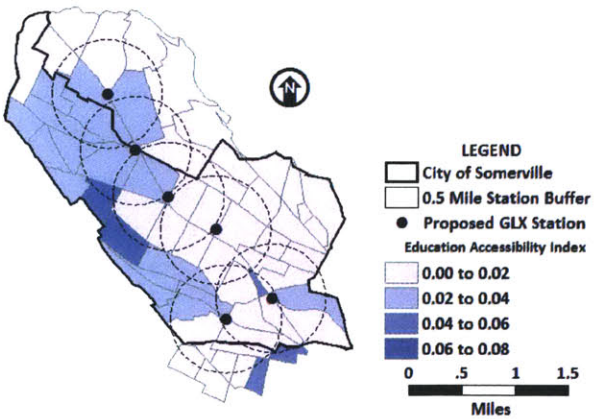


Figure C-16: 2010 Existing Conditions Education Accessibility (35 Min. Threshold) – Isochrone Measure

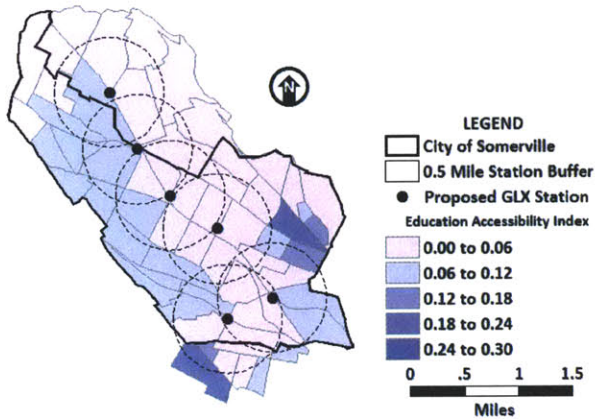


Figure C-17: 2030 Baseline Scenario Education Accessibility (35 Min. Threshold) – Isochrone Measure

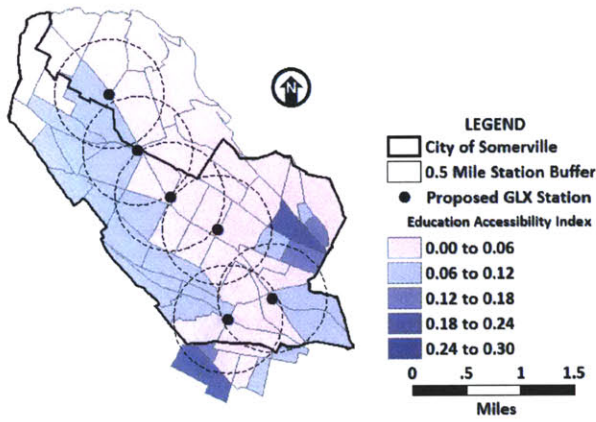


Figure C-18: 2030 Build Scenario Education Accessibility (35 Min. Threshold) – Isochrone Measure

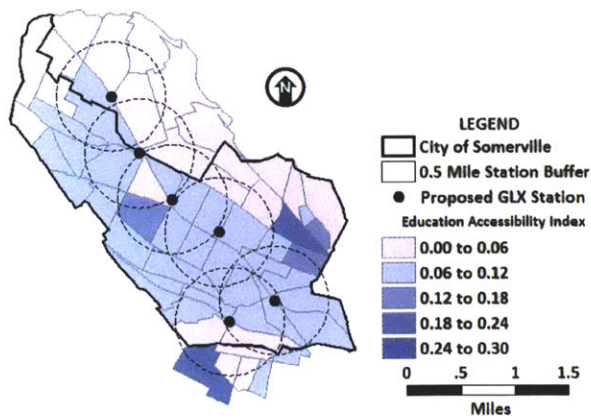


Figure C-19: 2010 Existing Conditions Education Accessibility – Gravity Measure

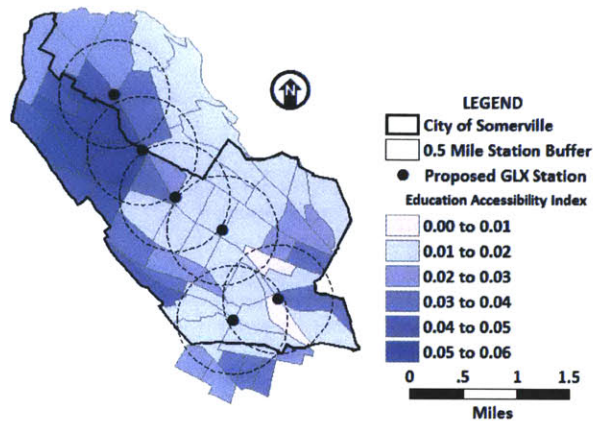


Figure C-20: 2030 Baseline Scenario Education Accessibility – Gravity Measure

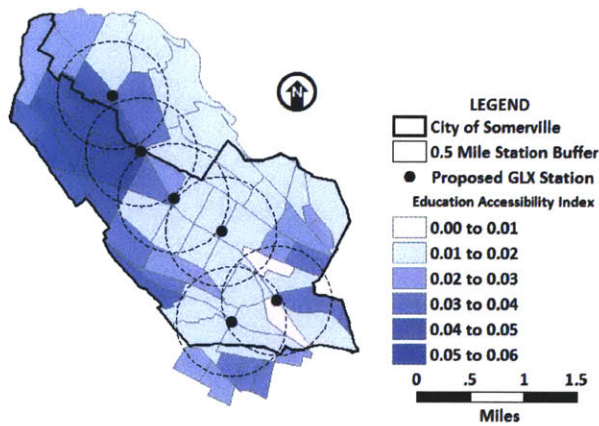


Figure C-21: 2030 Build Scenario Education Accessibility – Gravity Measure

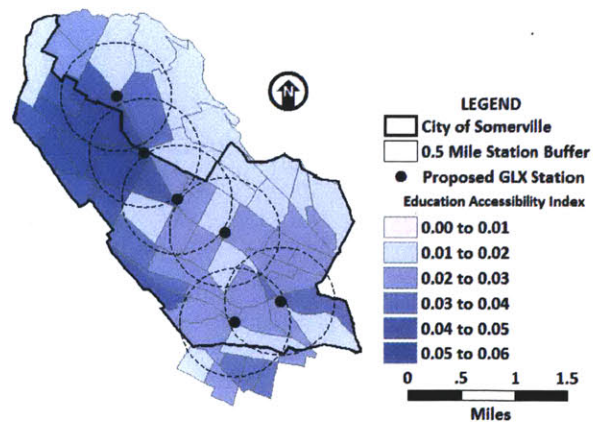


Figure C-22: 2010 Existing Conditions Health Care Accessibility – Isochrone Measure

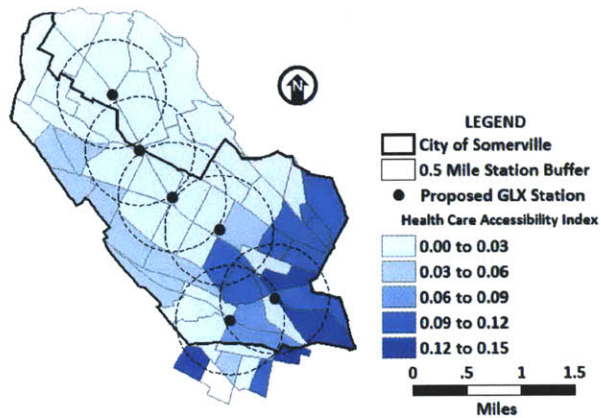


Figure C-23: 2030 Baseline Scenario Health Care Accessibility – Isochrone Measure

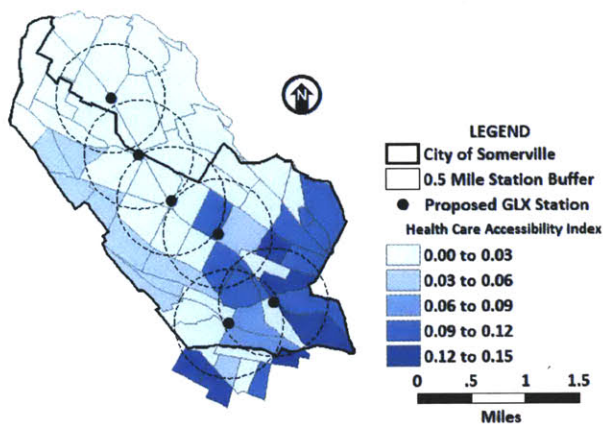


Figure C-24: 2030 Build Scenario Health Care Accessibility – Isochrone Measure

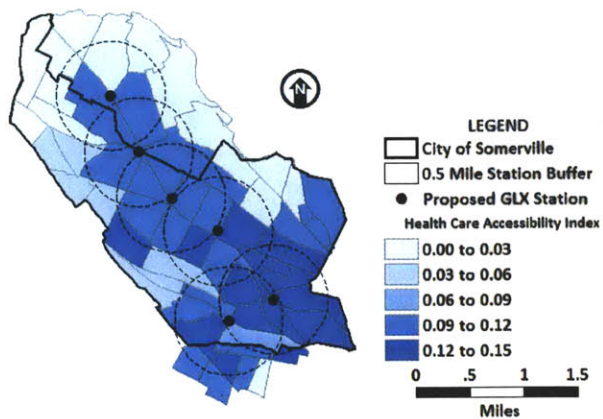


Figure C-25: 2010 Existing Conditions Health Care Accessibility –Gravity Measure

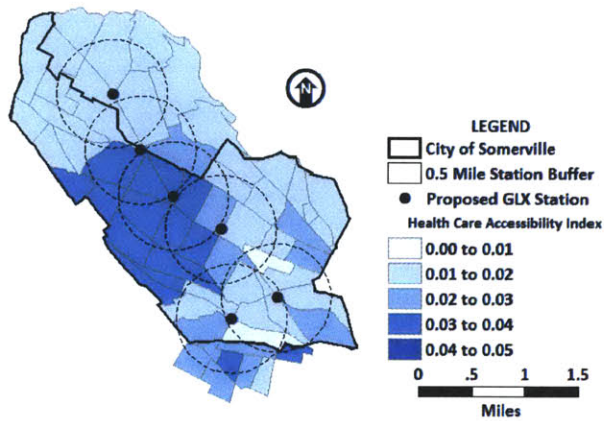


Figure C-26: 2030 Baseline Scenario Health Care Accessibility –Gravity Measure

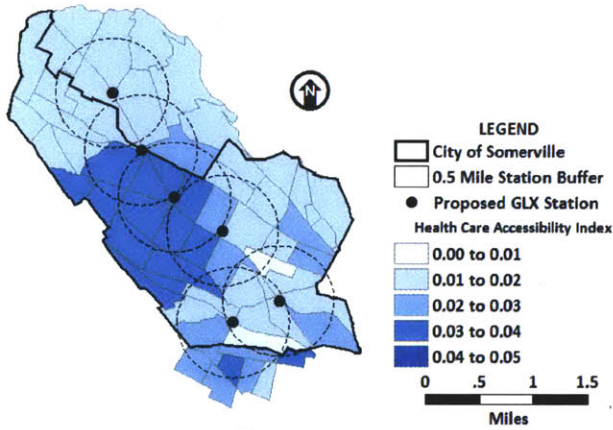


Figure C-27: 2030 Build Scenario Health Care Accessibility –Gravity Measure

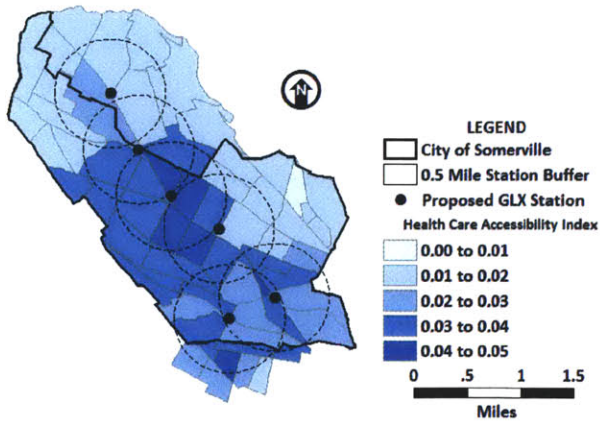


Figure C-28: 2010 Existing Conditions Recreation Accessibility –Isochrone Measure

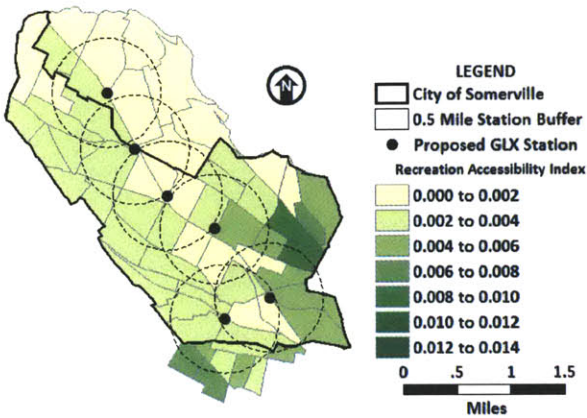


Figure C-29: 2030 Baseline Scenario Recreation Accessibility –Isochrone Measure

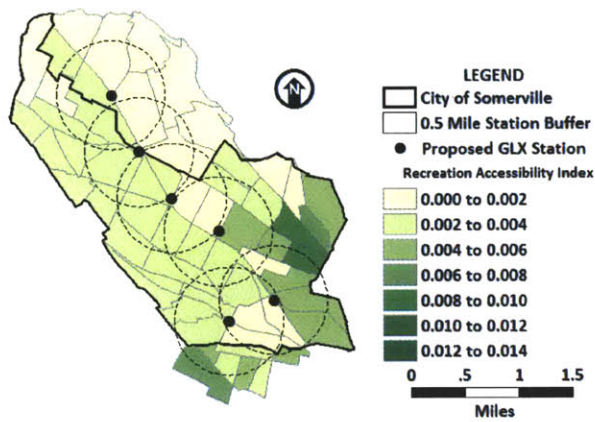


Figure C-30: 2030 Build Scenario Recreation Accessibility –Isochrone Measure

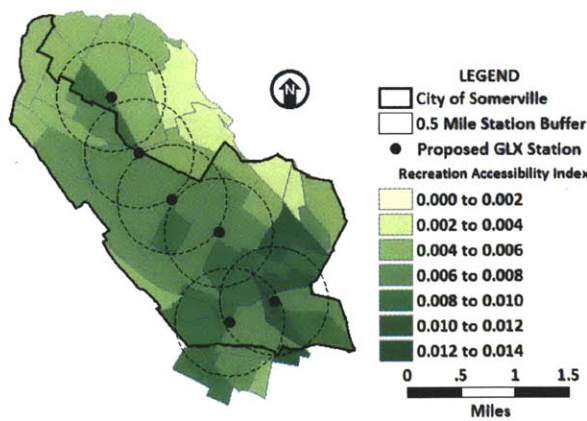


Figure C-31: 2010 Existing Conditions Recreation Accessibility –Gravity Measure

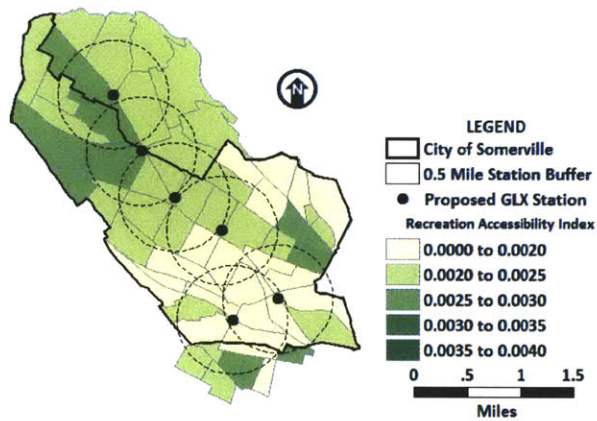


Figure C-32: 2030 Baseline Scenario Recreation Accessibility –Gravity Measure

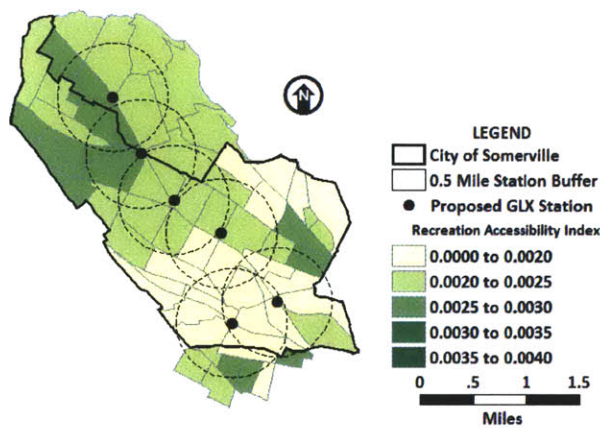


Figure C-33: 2030 Build Scenario Recreation Accessibility –Gravity Measure

