Build it: A Feasibility Study of GIS-Based Analyses of Cycling Infrastructure

A thesis submitted by

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Table of Contents

List of Figures

List of Tables

Abstract

Cycling for everyday transportation provides a myriad of benefits to communities. To increase their cycling levels, cities have looked to infrastructure and design strategies first used in Europe, especially physically separated bike lanes. Implementation of these designs has helped increase cycling modeshare in U.S. cities; however, limited government resources make efficient and accurate evaluation of infrastructure problematic.

This thesis explores multiple GIS-based methods for evaluating road infrastructure for cycling, and tests their feasibility for replication. Two previously published GIS-based methods are replicated for a representative sample of Somerville and Cambridge, MA. The sample is also “ground truthed” by volunteers using the methods’ criteria, and results compared to the GIS analyses. It was found that while both methods were technically feasible and compared reasonably well to real-world conditions, there were deficiencies that would increase the labor involved to verify either analysis in practice. Recommendations to improve these methods are discussed.

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Chapter 1: Introduction

Interest in urban cycling for transportation in the United States has skyrocketed in the past ten to fifteen years. Environmental, economic and public health concerns have encouraged transportation planners and local governments to take cycling seriously and examine what policies, programs and infrastructure they can implement to grow their cycling modeshares (League of American Bicyclists 2014).

Research on what encourages people to cycle shows that while some people will cycle nearly anywhere, areas with dedicated cycling infrastructure, particularly off-road paths or European-style “protected” infrastructure that separate cyclists from motor vehicle traffic tend to show an increase in cyclists (Pucher 2008). This infrastructure is generally considered the best practice in the field, and its use is gaining acceptance throughout the country, as multiple efforts show. Some examples are: the Green Lane Project, which is a program to assist cities in building protected infrastructure currently being implemented in 12 cities (Green Lane Project 2015), increased use of the NACTO (North American City Transportation Officials) design guide, which emphasizes cycling infrastructure and acceptance of the NACTO Guide by the Federal Highway Administration in city engineering, as opposed to the AASHTO guide, which contains little to no consideration of protected cycling facilities (US DOT Federal Highway Administration 2013). According to the Green Lane project, there currently are over 200 examples of protected cycletracks in the United States, compared to just 78 in 2011.

At the same time, many low-traffic, low-speed, generally residential streets are already safe and comfortable to ride on, and can be converted into

“Bike Boulevards” with simple traffic calming and signage. One example of such a conversion is Portland, Oregon (VanZerr 2010), where they have designated a network of such low-traffic streets as their bike boulevards.

Complicating this discussion is the economic reality of limited budgets and resources of many, if not most, city and local government planning departments. It is therefore important to find efficient ways to both identify suitable existing bike routes and, where prudent, install new infrastructure to improve bikeability. In larger cities especially, planning departments may not have the time to develop detailed, objective analyses of their infrastructure and its current suitability for cycling, and may not be making the best or most efficient decisions as a result.

This thesis seeks to improve the tools available to planners by evaluating the feasibility of multiple GIS-based methods to categorize and evaluate road infrastructure based on its suitability for cycling. Ideally, these methods would provide a relatively quick and reasonably accurate way to evaluate a city’s existing cycling network, identifying both existing areas where cycling should be comfortable and safe as well as areas that need improvement.

First, a literature review evaluates the benefits of cycling and rationale for promoting it, the factors that influence people’s decisions to cycle, and the existing tools to evaluate bikeability. Then, the methods are presented: existing GIS-based methods for evaluating bikeability were replicated for the study area of Somerville and Cambridge, MA. After conducting this analysis, “ground truthing” was conducted in the field to evaluate both the comparison of the methods with real conditions and gather the opinions of multiple cyclists. Finally, the results of the comparative analyses are presented, weaknesses and

strengths of the methods are compared, and recommendations are made for further work.

Chapter 2: Literature Review

This literature review will first explore the research surrounding the case for increasing cycling, and then investigate the research on factors influencing one's choice to cycle. Finally, the review will cover the various methods previously published to analyze the built environment and select definitions of "bikeability."

Benefits of Cycling

From a governmental perspective, cycling is a desirable mode of transportation for numerous reasons. Cycling does not pollute, which can help governments meet climate action goals as well as enhance local air quality (US Dept. of Energy 2013). Any strategy to replace road vehicle miles traveled with cycling trips will reduce the greenhouse gas (GHG) emissions and other air pollutants emitted from those trips. As GHG emissions from the transportation sector make up roughly 27% of the United States' overall emissions (US Environmental Protection Agency 2015), increasing cycling modeshare and other active transportation options are important GHG reduction strategies. For example, in the City of Boston's Climate Action Plan (2011), an increase in cycling modeshare to 10% of all trips in the city is expected to make up 1% of the City's greenhouse gas emission reduction goal, and 3.5% of the reduction in the transportation sector.

While GHG reduction can occur through other means such as greater fuel efficiency and shifting trips from single-occupancy vehicles to carpooling and public transit, the benefits to public health from active transportation (walking and cycling) are greater than these other GHG reduction methods. A comprehensive model comparing the overall health benefits of increasing active transportation showed that, overall, active travel was highly likely to produce greater health benefits (Woodcock 2009). The benefits from the scenario which reduced GHGs through an increase in active transportation predicted a reduction of over 500 premature deaths and over 7,000 “life-years” per 1,000,000 population, when compared to reducing the same amount of GHGs through increasing fuel efficiency in vehicles (therefore keeping VMTs constant) (Woodcock 2009). A sophisticated model which attempted to account for all of the co-benefits of cycling concluded that when governments promoted cycling, they gained back between six and 24 times their monetary cost in long-term benefits, once the public health, environmental and congestion benefits were converted to monetary value (MacMillan et al 2014).

Promoting cycling is also desirable due to its relative costs. Compared to vehicle travel and public transportation, cycling is inexpensive, both in the amount of government expenditure required and in its cost to individual citizens. The cost to build cycling-focused infrastructure is orders of magnitudes less than the cost to build car-oriented infrastructure. The median cost for a bike lane in an existing road in 2013 was roughly $90,000 per mile, and the median cost for a paved multi-use path was $261,000 per mile (UNC Highway Research Center 2013). The cost to build roads, conversely, ranges from $2 million to $4 million per mile. Even the cost to resurface an existing road is estimated at around $1 million per mile (Florida DOT 2013). A 2015 overview of 37 recent Complete Streets[1] projects showed that these projects were overwhelmingly less expensive than “conventional” road projects, with an average project cost of $2.1 million,

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[1] A “Complete Street” is defined as a road designed to be safe for users of all modes of transportation, as well as all abilities and ages of road users (LaPlante 2008).

compared to an average cost of $9 million for conventional road projects (Smart Growth America 2015).

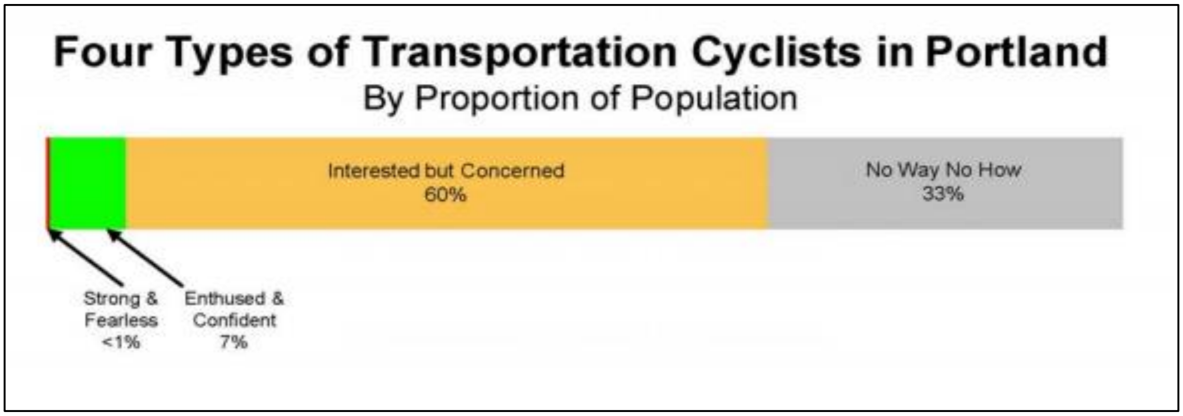
The costs to an individual of owning and maintaining a bicycle for transportation is significantly lower than traveling by car. The specific costs vary greatly depending on multiple factors, but a working paper estimated the savings to the individual due to replacing vehicle trips with bicycle trips at $1.15 per mile traveled, with an even greater savings if one can reduce car ownership (by not needing to own one or more cars) (Belter et al 2012). For many low-income citizens who cannot afford a car, cycling is an important affordable method of transportation, particularly in neighborhoods where public transportation is inadequate. Cycling has been shown to support the local economy, as citizens who cycle tend to shop locally and make more visits to businesses (Litman 2014). Bicycles also require significantly less space, both while moving and while parked, which is another important advantage in dense urban areas.

How can cities influence mode choice towards biking?

Once cities and governments decide they are interested in increasing their cycling modeshare, the obvious next question is how this can be accomplished. While the factors affecting citizens’ choice of mode are varied and different individuals value factors differently when making choices, research has shown that the most important quantifiable factors are cost and travel time (Small 2012). Cost can include all monetary costs associated with the mode; for vehicular travel, it includes the cost of the vehicle, the cost of repair, and especially important in urban areas, any costs associated with parking. While the time cost is simple to understand, it is worth noting that the reliability of the mode is an important factor influencing choice; that is, if a public transit service is unreliable, people are likely to value the extra time associated with delays more than the times when the service was on-time (Bhat 2006). There are also many non-quantifiable factors that influence mode choice, some of which are habit (Bamberg 2003), convenience, social influence and prestige, “green” choices, comfort and safety (US Dept. of Energy 2013). While cities can undertake efforts to affect all of these, comfort and safety have been found to be major barriers among potential cyclists, and are largely affected by infrastructure design.

Geller (2007) found that as much as 60% of the potential cycling public are “interested but concerned” in cycling (as opposed to those who will never [“No Way No How”], or always [“Strong and Fearless”] cycle under any circumstance [see Figure 1]). He identified these concerned citizens as a group to target via infrastructure improvements that increase safety. In order to reach these potential cyclists, researchers have looked to success stories in Europe (Pucher 2008). Pucher confirms that European case studies provide evidence that safety is critical to increasing cycling modeshare, and citing Jacobsen (2003) points out that there are “safety in numbers” – that per-mile crash numbers have declined as the number of cyclists in European cities increases. Sweden, Denmark and the Netherlands have not only the highest cycling modeshare in Pucher’s review (11%, 18% and 27%, respectively), but also have the lowest fatality rate, ranging between 1.1 and 1.5 deaths per 100 million km cycled – compared to 5.8 deaths per 100 million km in the United States.

Figure 1: The "Four Types of Cyclists" as defined by Geller (2007)



It is important to note that both the Dutch philosophy and the Four Types of Cyclists theories rely on both actual and perceived levels of safety and comfort. Studies have shown that it is not just the actual threat to safety in the built environment that influences mode choice, but also the *perceived* threat. A survey of 1,270 residents in North Carolina and Mississippi found very little correlation between the actual traffic measures and respondents' self-reported perception of traffic, and concluded that evaluating both real and perceived measures of safety was necessary when evaluating the built environment (McGinn 2007). A similar study of seniors' walking habits found a relationship between the number of intersections in one's neighborhood and how often one walks in it, but only when the respondent perceived that the neighborhood had a safe level of traffic (Li 2005). A study focusing on cyclists found that residents in low-density neighborhoods perceived lower crash risk than residents in denser, mixed-use neighborhoods, even though the latter actually had higher crash rates (Cho 2008).

It is shown in the literature that cycling can have many benefits to communities, both on an individual level and on a neighborhood and city level. This study and literature review focuses on ways to categorize and analyze the built environment, as providing more bicycle infrastructure can improve levels of safety for cyclists and convince the interested but concerned portion of the population to cycle. Improving conditions for this large portion of the population can extend the many benefits of cycling to all groups, not just those who are “strong and fearless,” who tend to be younger and male.

Evaluating Road Infrastructure for Cycling

Since the mid-1990s, researchers have developed ways to categorize roads and off-road paths by their friendliness to cyclists. It is clear that the existing methods for categorizing roads developed with vehicle traffic in mind were inadequate for cycling transportation, which requires very different considerations. The goals have generally been twofold: first, to identify what makes a road or route desirable to cyclists, and second, to develop efficient methods for categorizing these roads to aid current cyclists, attract new ones, and prioritize projects for planning and construction (Asadi-Shekari et al 2013).

Allen-Munley (2004) developed an objective model to analyze relationships between road conditions and crash likelihood. Areas with wide lanes and higher speeds were found to correlate with higher risk of crashes. Counter-intuitively, areas with heavy traffic were of lower-risk, though this could be attributed to lower operating speeds in such areas. Cyclists generally avoid grades, high activity areas and poor pavement conditions (Aultman-Hall 1997) and are willing to divert from the shortest possible path to find these routes. More recent research by Winters et al (2011) examined motivators and deterrents for cyclists. The top motivators were found to be “routes away from traffic noise and pollution; routes with beautiful scenery; and paths separated from traffic (164).” The top deterrents on particular routes were found to be related to poorly designed or maintained infrastructure as well as high levels of traffic (Winters et al 2011).

Recent research has focused on “Dutch-style” cycling infrastructure; specifically, this refers to the design standards implemented in the Netherlands and Denmark, which emphasize travel paths for cyclists that are physically separated from vehicle traffic – either by a green linear park, such as the “multi-use path” that is relatively common in North America, or, in more dense areas, by physical buffers such as grade separation (a curb), bollards, or planters (See Figures 2, 3 and 4). A focus on infrastructure and design, combined with relatively high costs of gasoline, has helped European cities move from an auto-focused transportation system to achieve some of the highest cycling modeshares among developed countries in the world (Pucher 2008).

Figure 2: Cycletrack Protected by Curb (NACTO 2014)

Figure 3: Cycletrack and Buffered Lane (NACTO 2014)

Figure 4: Grade-Separated Cycletrack (NACTO 2014)

While the European experience and approaches have shown success in increasing cycling safety and modeshare, such strategies have only been applied in the US context very recently and sparingly. The question remains whether an increase in modeshare can be achieved in this country, given differences in urban design and density, as well as the relative costs of travel modes, the availability and quality of public transportation, the political environment, and citizens' attitudes towards cycling as a transportation mode (Pucher 2008).

Canadian cities, including Montreal, Toronto and Vancouver, were the first to install cycletracks in North America. Multiple studies have focused on these cities. Harris et al (2012) focused on intersections, and found the lowest incidence of crashes involving cyclists in intersections with protected cycletracks. They also found low crash risk on local streets, especially if those streets had speed limits below 30 km/hr (roughly 20 MPH), or were specifically designed to reduce traffic volumes. Lusk et al (2011) concurred that cycletracks were safer, finding 2.5 times more cyclists and a 27% reduction in crash rate on streets with cycletracks in Montreal when compared to alternate routes without such infrastructure.

Another recent study addresses multiple questions regarding cycletracks within the context of US cities (National Institute for Transportation and Communities 2014). This study examined cycletracks installed in five US cities between 2012 and 2013, and monitored their safety, counted riders, and conducted surveys of their riders both before and after construction. They observed an increase in cyclists on every route, and found that 10-20% of the riders on each route would have made their trip by another mode if the cycletrack did not exist. Additionally, nearly 25% of the cyclists surveyed reported that they ride more overall since the installation of the new cycletrack. The specific amount of the ridership increase varied widely (between 21% and 171% within one year of the change); the researchers attributed these differences to the context in which the cycletrack existed, particularly its place in the overall bicycle network. They observed that new connections in the network saw higher growth in ridership than the projects which replaced already-existing key connections, showing that it is important to keep the entire cycling network in mind when designing and placing cycletracks. The surveys showed that the cyclists riding on these tracks overwhelmingly felt comfortable and safe on these protected routes – evidence that the tracks may reach the key "interested but concerned" demographic identified in the previous section.

An analysis of census tracts showed that a higher amount of cycling was positively correlated with both population density and amount of housing built before 1940, which suggests that older, denser cities are more conducive to cycling than newer, more sprawling cities. The same analysis found that the concentration of bicycle facilities correlated with increased cycling and found some of the highest levels of cycling at the neighborhood level on or near college campuses, which generally have low levels of traffic, low travel speeds and many off-road paths for cycling (Schneider 2015).

Analysis of Street Networks: "Build it! But Where?"

As discussed in the previous section, the early evidence shows that building Dutch-style cycling infrastructure may improve safety and increase cycling modeshare in the US, as these strategies have in Europe. Additionally, the separation from traffic provided by such infrastructure may contribute to a greater perception of safety among the “Interested but Concerned” group of cyclists.

The next question is: given limited resources, where are the most effective places to install such infrastructure? A number of ways to classify streets and identity the best places for improved infrastructure have been developed. Asadi-Shekari et al (2013) provide an overview of 11 of these “Bicycle Level of Service” methodologies. These methods attempt to classify roads under “Level of Service” for cyclists, but each have several shortcomings. Only two of the 11 consider intersections, which are where most crashes occur -- 60% in the City of Boston from 2009-12 (City of Boston 2013). Some use surveys of cyclists to develop their criteria, some use video review, and some use both. Additionally, these standards are unlinked to the current design standards and fail to take into account best practices: in some methods, shared-lane markings (“sharrows”) are considered as effective as protected infrastructure. Finally, each are complicated and time-consuming to calculate. The researchers concluded that these methodologies need improvement before they can be widely adopted by designers and planners.

GIS analysis can provide an objective and powerful tool to evaluate streets for cycling. Larsen et al (2013) have provided one methodology studying Montreal, Canada. Using cyclist surveys, cycling crash location data, and city-wide origin-destination trip data, the researchers created a raster map of “prioritized” areas to build cycling infrastructure. Areas were prioritized based on existing cycling and “short” car trips, cyclists stated preferences for routes, and locations with high numbers of crashes. Additionally, the existing cycling infrastructure was included to locate “dangling nodes,” that is, areas of high infrastructure priority where the infrastructure had ended abruptly.

In another example, Winters et al (2013) provide a methodology to create a raster surface of “bikeability” in the Vancouver, BC region. They considered and weighted the following factors: density of bicycle facilities, separation from motor vehicle traffic, connectivity of bicycle-friendly roads, slope, and the density of destination locations. The output of this methodology is a map of areas that are “bike-friendly” and those where improvements should be targeted. However, as the connections between the various areas of high bikeability are not analyzed, it is possible that an area of high bikeability could be bisected by a dangerous artery, thus negating some of the value of the methodology.

While both these methods have value, it is this researcher’s opinion that the methodology provided by Mekuria et al (2013) (including Dr. Peter Furth, referred to in this thesis as the Furth method) represents a more useful method for building a bicycle network. Applying objective criteria, the methodology designates each road segment and intersection with a “Level of Traffic Stress” number from one to four based on its adherence to Dutch cycling infrastructure standards. Infrastructure that children should be comfortable riding on is given a score of LTS 1. Infrastructure that most adults can tolerate is given a score of LTS 2. This LTS level is designed to apply to the population that Geller describes as “Interested but Concerned.” LTS 3 and 4 are streets that have high amounts of traffic, high speeds, and no barriers between auto traffic and the cyclists’ path. These are the levels of stress that only the “Enthused and Confident” and the “Strong and Fearless” cyclists feel comfortable riding on.

After scoring the travel segments and intersections in the study area, the Furth method uses GIS to develop maps of the study area, and the LTS designations to identify low-stress cycling routes and to explore where segments of high traffic stress are separating destinations from each other. So far, the methodology has only been used to analyze San José, California.

The Furth method stands out in real-world applicability for multiple reasons when compared to other methods reviewed. First, the methodology focuses on connectivity within the entire network, and emphasizes that a “weak link” in the network can create barriers in access for cyclists. Another important difference in this methodology is its output of a vector network rather than a raster surface. A vector network specifies locations along lines (in this case the roads), while a raster surface divides the area analyzed into a grid (in the Winters methodology, this grid was 10m x 10m square) and applies various data to each square in the grid. Since the road network is a series of connecting lines, a vector network output would allow decision-makers to identify specific locations where the infrastructure should be improved, rather than a general area. Finally, by considering intersections and crossings, the researchers have incorporated more of the barriers to urban cycling and better addressed the process that citizens may undertake when deciding whether or not to ride.

Chapter 3: Methods

This thesis project explores multiple previously-established GIS-based methods for evaluating “bikeability” based on some objective measures, and compares their accuracy, feasibility and the intensity of labor necessary to conduct each method. Two methods were explored in-depth: the Furth method previously applied to San Jose, CA (Mekuria et al 2012), and the Winters Method (Winters et al 2013) (previously applied to Vancouver, BC, Canada). The goals of the comparative analysis are:

- To determine whether either of these methodologies provides a feasible method for city planners to analyze and evaluate their existing cycling networks and recommend new infrastructure.
- To estimate the amount of labor needed to perform both methods.
- To determine and compare both methods with the results from observing the real conditions in the field (“ground truthing”).

I conducted the comparative analyses following the methods previously established in both methodologies to analyze key cycling routes in Cambridge and Somerville, MA using ArcGIS software. Somerville and Cambridge are much smaller and denser cities than both Vancouver and San Jose. The combined areas of Cambridge and Somerville are 1.2 times denser than Vancouver and 3.2 times denser than San Jose, with 16,425 residents per square mile (US Census Bureau 2013). Additionally, the street grid and urban fabric is older, as it was nearly all built pre-World War II, while both Vancouver and San Jose expanded greatly in the latter half of the 20th century. Table 1 compares Cambridge and

Somerville (often called “Camberville” for their close proximity and overlap in culture) to Vancouver and San Jose.

Table 1: Comparison of cities evaluated

Municipality	**Population (2010)**	**Size (sq. mi.)**	**Density (population / sq. mi.)**	**Year Established**	**Population by 1940**	**Residents who Cycle to Work**[2]
Cambridge	107,289	7.1	15,047.5	1636	110,879	6.5%
Somerville	78,804	4.2	18,762.9	1842 (Settled 1630)	102,177	7.8%
Cambridge and Somerville Combined	186,093	11.3	16,424.8	n/a	213,056	7.1%
Vancouver	603,502 (2011)	44.4	13,595.4	1886	275,353	1.8%
San Jose	1,015,785	198.0	5,131.0	1850	68,457	0.9%

Somerville has recently promoted cycling among its residents, and has instituted efforts such as bike lanes, the Somerville Community Path off-road multiuse path, and traffic calming; however, many areas of the city remain stressful for cyclists. Cambridge has long been a leader in bicycle planning in the region, and has been named a Gold level bicycle-friendly community by the League of American Bicyclists – one of just two cities east of the Mississippi River to receive such a rating (City of Cambridge 2013). According to American Community Survey data, Somerville and Cambridge have the highest bicycle commute modeshare in the East, at 7.8% and 6.5%, respectively (League of American Bicyclists 2014). For these reasons, Cambridge and Somerville provide a good location to test these methods as they contrast to San Jose and Vancouver.

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[2] All commuting shares from the American Community Survey, 2009-13, except Vancouver, which is from the 2011 Metro Vancouver Regional Trip Diary Survey (TransLink).

This project attempts to answer the following research questions:

- How useful and feasible are the two methods for a city planner with limited time and resources?
- Can they be applied accurately by someone with a reasonable level of cycling-specific knowledge using generally available GIS data and tools?

The rest of this section details the steps taken to conduct this analysis.

Step 1: Selecting the comparison methodologies

To the author’s knowledge, there are only three completed studies to date, besides the Furth method, that use GIS to systematically analyze the most suitable locations to build cycling infrastructure. Two of these were published in reputable journals: studies conducted by Larsen et al (2013) and the other by Winters (2013). The Larsen methodology of conducting surveys of cyclists to determine “desired” routes is outside the scope of this study. Additionally, the cycling crash data and origin/destination data required for the Larsen study were judged to be too difficult or time-consuming to acquire and outside the scope of this thesis. Particularly, the origin/destination data used by the researchers to study the City of Montreal was noted in the literature as a particularly “large and rich” survey – surveying 5% of households in the area every five years. Nothing of the like exists in the vast majority of US cities. While substituting other data was considered, given that the purpose of this project is to determine whether a method could be employed by a city planner with limited resources, this methodology was determined at the outset to be overly resource and time-intensive. The Winters method was deemed more feasible to conduct and compare to the Furth method, as all of its data were readily available or could be gathered without extensive work.

A third method (Mefford and Griffith n.d.) used a GIS-based methodology to select potential cycling routes within a city. While this methodology appears promising, the article was found on a website and a search of multiple scholarly databases was unable to determine whether it was published elsewhere and peer-reviewed. Additionally, no reference to the “Clark index,” the formula this paper uses to determine a street’s bike-friendliness, could be found outside of the paper itself. For these reasons, this methodology was eliminated from consideration.

Step 2: Selecting the sample

As the methodologies approach the subject of cycling from the transportation viewpoint (as opposed to a recreational one) I determined that the study sample should involve “real-world” origins and destinations that would be representative of a usual home-work commuting trip. A few likely origins and destinations were selected and the routes between them analyzed. Analyzing the “bikeability” of these routes would then provide a more representative sample of a handful of realistic decisions that a cyclist may make.

In order to select the origins and destinations, I consulted the following sources:

1. The 2010 Somerville Comprehensive Plan, *SomerVision*, which details multiple nodes that the city is targeting for denser development (City of Somerville 2010). These nodes would theoretically contain concentrations of cycling origins and destinations.

2. The “Techscene @ Boston” startup map, which maps all the startups in the Boston area (using data from the CrunchBase dataset) (Techscene). This map shows areas with high concentrations of destinations, and these “creative class” jobs are often more likely to employ workers who cycle.

3. Cambridge and Somerville’s zoning maps and designated commercial districts.

Based on these sources, the following destinations were selected which contain a high concentration of businesses, particularly start-ups:

1. Kendall Square (at the MBTA Red Line stop)
2. Central Square (At the corner of Prospect St and Massachusetts Avenue)
3. Harvard Square (At the MBTA Red Line stop)

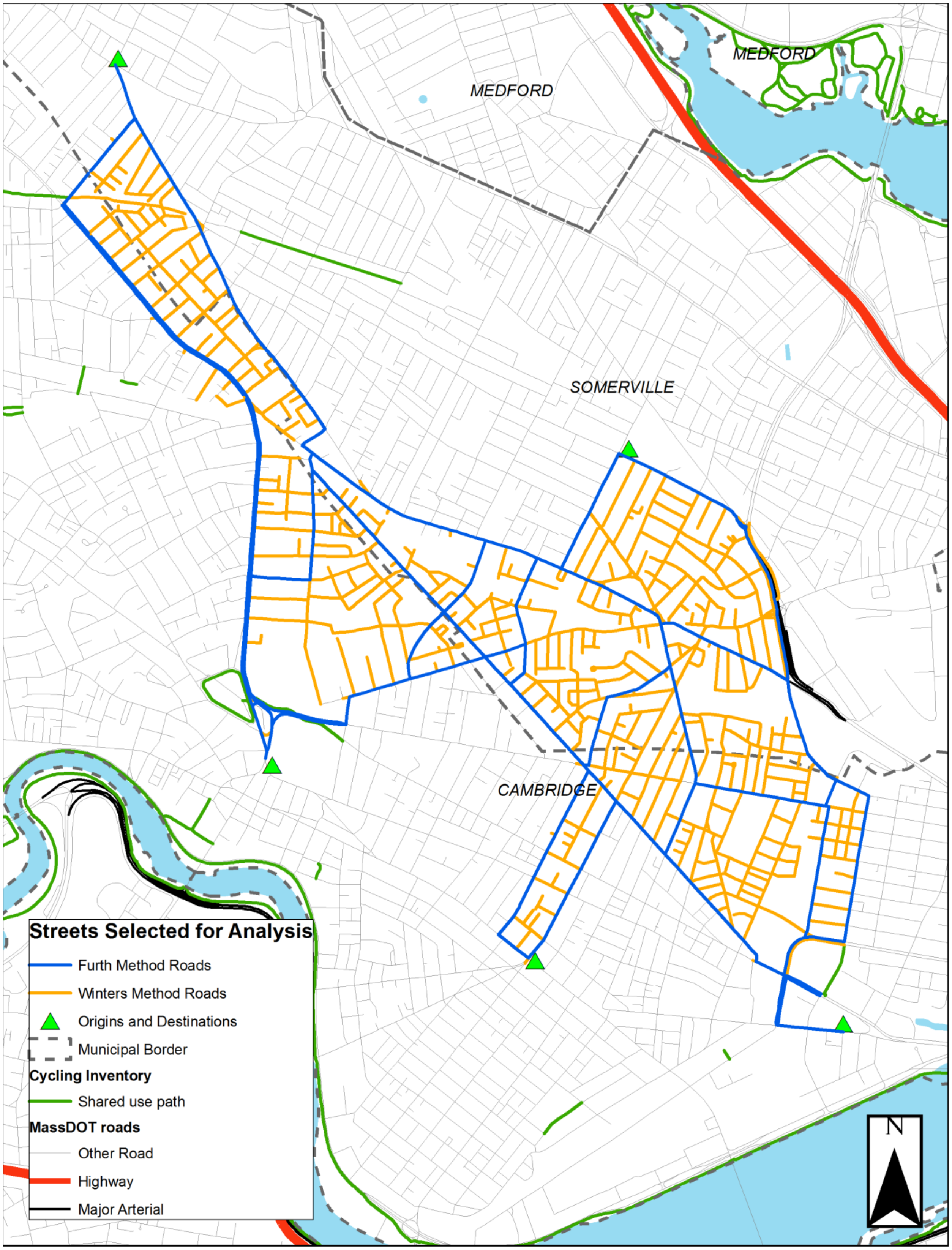
Selecting probable origins (residences) was less straightforward. While most of Somerville and Cambridge has a high population density, density is relatively uniform throughout the two cities. I selected the following two points as representative nodes in mostly-residential areas from which multiple bicycle routes could be chosen to reach the destination points.

1. Teele Square (the intersection of Broadway, Holland and Curtis St in Somerville)
2. Somerville City Hall (at the intersection of Highland Ave and School St)

To determine the choice of routes between each origin and destination point, I used the multiple routes that Google Maps’ cycling algorithm produces. Each origin-destination pair, when entered into Google Maps, gives three route choices. All the street segments contained in these routes were selected and analyzed by the Furth Method. Additionally, the shortest route according to Google’s *driving* directions was selected and analyzed. Of the multiple options for driving, I chose the driving route with the shortest travel time without traffic, and if multiple routes had the same time, the shortest in terms of distance was selected. After the streets were selected, a 500-foot buffer was drawn around the outline of the streets using GIS. The area inside this border was analyzed using the Winters method. Figure 5 shows the selected sample for both methods.

Google's bicycle algorithm prefers streets that are designated as bicycle routes, but their designation as such does not necessarily mean they will be bicycle friendly according to the two methodologies in this study. When combined with auto directions, which give preference to the quickest car route, this was intended to provide a variety of routes to analyze, with varying degrees of bicycle-friendliness. The sample includes many types of infrastructure, all the way from off-road paths to a portion of the McGrath Highway.

Figure 5: Sample Selected for Analysis



Step 3: Gathering GIS data

Steps were taken to download and analyze the datasets to ensure that the necessary data were available in usable GIS formats. Table 2 shows the datasets that were used in the project.

Table 2: Data used in GIS analysis

Data needed	Source	Components included	Availability
Road shapefiles	MassDOT	Location of roads, road type, name, jurisdiction, # of lanes, speed limit, width, curb and median information.	Available online
Somerville parcels / assessor's data	MassGIS	Type of land use, density of use, location, height and size of any structure	Available via MassGIS
Cambridge parcels / assessor's data	City of Cambridge website	Type of land use	Available via City of Cambridge website
Regional cycling routes	MassDOT Bicycle Facility Inventory	Off-road cycling trails and paths, on-road bike lanes and other infrastructure	Available via MassDOT GIS website
Digital Elevation Model	MassGIS	Raster data with 5x5m elevation data	Available online via MassGIS

Step 4: "The Furth Method" analysis

The Furth Method was employed to produce a level of traffic stress (LTS) for each road as described in Mekuria et al (2013) for San Jose. I attempted to remain as true to the description of the method as possible, but minor modifications were necessary and are explained below. This methodology is as follows:

1. I first divided all roads and off-road cycling routes into three categories: Physically separated paths and tracks, roads and streets with bike lanes, and roads with mixed traffic.

2. Using data from the cities' assessing offices, any parcel that was "residential" was selected and a new datalayer created with just these parcels. Road segments within 10 m of a residential parcel were selected and considered to be "residential" roads.

3. Many road segments in the roads data did not include a speed limit. It is Massachusetts law that all roads in a "thickly settled" area have at most a 30 MPH limit. Given that the entire study sample is thickly settled, this was assumed to be the maximum speed limit. The actual speed traveled in residential areas was likely to be lower; therefore, for any segment that didn't include speed limit information, a limit of 25 MPH was applied if it was a residential road (as defined in step 2 above) and a speed limit of 30 MPH was applied otherwise.

4. For each category, separate criteria were applied to determine the LTS. These include road speed limit, lane widths, traffic levels, the existence or lack of on-street parking, "residential" status, and the presence or lack of dedicated cycling infrastructure. There is not a complicated algorithm but rather simple cutoffs for each category. The process used to determine LTS for each route type is described in the following sub-points. Note that the full article (Mekuria et al 2013) provides detailed reasoning for each criteria as it relates to a cyclists' level of stress. The technical specifications that determine the LTS are summarized here:

4. a. Off-road paths and physically-separated lanes: Cycling paths completely separated from traffic are always considered LTS 1. This includes off-road multiuse paths as well as paths traveling alongside a street which are separated from vehicle traffic by a physical barrier (known as a “cycletrack”). Note that bike lanes separated from vehicles by paint alone do not fall into this category, even if there is a space designated between the bike lane and the vehicle lane (a “buffered” bike lane).

4. b. Roads with bike lanes: The Furth method uses multiple criteria to determine LTS of roads with bike lanes. First, these roads are subdivided into two categories: Those with a bike lane alongside a parking lane, and those with no parking lane. Then, the bike lane is evaluated for four criteria, each of which leads to a corresponding level of stress. The segment’s LTS is based on the “weakest link” among the four criteria; that is, whichever criteria has the highest LTS is applied to the entire segment regardless of the LTS of other criteria. For example, if a hypothetical road segment with parking had just one lane in each direction, and has a bike and parking lane width of greater than 15 feet, and was not in a commercial zone, but had a speed limit of 40 mph, it would be considered LTS 4 based on its speed limit, even though the other factors would suggest an LTS of 1. Tables 3 and 4 display the criteria for roads with bike lanes:

Table 3: Furth Method Criteria for Bike Lanes along a parking lane

	LTS ≥ 1	**LTS ≥ 2**	**LTS ≥ 3**	**LTS ≥ 4**
Street Width (through lanes in each direction)	1	n/a	2 or more	n/a
Sum of Parking Lane width and Bike Lane width	15 ft. or more	14 or 14.5 feet	13.5 feet or less	n/a
Speed Limit or Prevailing Speed	25 mph	30 mph	35 mph	40 mph or more
Bike Lane Blockage	rare	n/a	frequent	n/a

Table 4: Furth Method Criteria for Bike Lanes with no parking lane alongside

	LTS ≥ 1	**LTS ≥ 2**	**LTS ≥ 3**	**LTS ≥ 4**
Street Width (through lanes in each direction)	1	2, if directions are separated by a raised median	More than 2, or 2 without a median	n/a
Bike Lane width	6 feet or more	5.5 feet or less	n/a	n/a
Speed Limit or Prevailing Speed	30 MPH or less	n/a	35 MPH	40 MPH or more
Bike Lane Blockage	rare	n/a	frequent	n/a

There is no attribute in any known data set that specifies the width of the parking lanes and bike lanes. To estimate these numbers, Google Street View was used to visually estimate the width of the bike lane from curb to travel lane. This was only conducted for streets in which the width of the bike lane will be a determining factor in LTS. From the pictures in Google Street View, it was determined that none of the bike lanes (or bike lanes plus parking lanes) were wide enough to meet the standard in the Furth Method and affect the LTS level – they were all either less than 5.5 feet wide (with no parking lane) or less than 13.5 feet wide including the neighboring parking lane.

4. c. Mixed Traffic: Any road without a marked bike lane was designated as “mixed traffic” by the Furth Method. This includes roads marked as bicycle routes or marked with “sharrows” painted on the road. The Furth method proposes that the prevailing travel speed, road width by number of lanes and whether the road is in a residential area are the determinants of the LTS for mixed traffic streets. Criteria for mixed traffic is illustrated in Table 5.

Table 5: Level of Traffic Stress for roads designated as Mixed Traffic by the Furth Method

	Road Width (in Both Directions)		
Speed Limit	2-3 lanes	4-5 lanes	6 or more lanes
25 MPH or less	LTS 1 (residential) or 2 (non-residential)	LTS 3	LTS 4
30 MPH	LTS 2 (R) or 3 (non-R)	LTS 4	LTS 4
35 MPH or more	LTS 4	LTS 4	LTS 4

5. Streets were coded by LTS in GIS software. The resulting data layer includes a new attribute field for LTS level for all the cycling routes in the sample area and the shortest travel route via automobile, including off-road paths.

Table 6: The Furth Method Summary: Types of cycling routes and criteria used to evaluate them

Type of cycling route	**Factors influencing LTS**	**LTS rating**	**Factors for which ground truthing will be useful**	**Notes**
Physically Separated Path (Off-road trail or path completely separated from traffic)	None	1	Unnecessary	Off-road paths are always considered LTS 1 for the segments between any intersections.
Roads with bike lanes	Existence of on-street parking, prevailing speed limit, number of travel lanes, width of lanes, frequent bike lane blockage	1-4	Ground truthing will be important to verify and in some cases determine bike lane width as well as to determine the “prevailing” speed limit (which can be different from the posted speed limit), and bike lane blockage (determined through GIS by the existence of a commercial district).	This is the most complicated category of street, but is the most important for the analysis as it is the easiest to design quickly and cheaply.
Mixed Traffic	Speed Limit and number of travel lanes, residential zone or not	1-4	High level analysis is expected to generate good accuracy for this road type. Ground truthing will be important to more generally confirm the determined LTS.	

Intersections and Crossings

The Furth Method includes treatment of both intersections and crossings. Intersections can have an effect on LTS if they include a right turn lane which interferes with the cyclists' path (whether a bike lane is present or not). If a bike lane was present, the criteria in Table 7 were used to determine the right turn lane's effect on LTS. If no bike lane was present, the criteria in Table 8 were used. Intersections were examined via orthographic satellite photos as well as Google Street View to determine if an LTS adjustment was needed.

Table 7: Level of Traffic Stress Criteria for Pocket Bike Lanes (Furth Method)

Configuration	Level of Traffic Stress
Single right-turn lane up to 150 ft. long, starting abruptly while the bike lane continues straight, and having an intersection angle and curb radius such that turning speed is < 15 mph.	LTS ≥ 2
Single right-turn lane longer than 150 ft. starting abruptly while the bike lane continues straight, and having an intersection angle and curb radius such that turning speed is < 20 mph.	LTS ≥ 3
Single right-turn lane in which the bike lane shifts to the left but the intersection angle and curb radius are such that turning speed is < 15 mph.	LTS ≥ 3
Single right-turn lane with any other configuration; dual right-turn lanes; or right-turn lane along with an option (through-right) lane.	LTS = 4

Table 8: LTS Criteria for Mixed Traffic with a Right-Turn Lane Present (Furth)

Configuration	Level of Traffic Stress
Single right-turn lane with length < 75 ft. and intersection angle and curb radius limit turning speed to 15 mph.	No effect
Single right-turn lane with length between 75 and 150 ft., and intersection angle and curb radius limit turning speed to 15 mph.	LTS ≥ 3
Other type of right turn lane with no bike lane present.	LTS = 4

Crossings occur when a road intersects a larger arterial. If no signal is present, these crossings can be highly stressful for cyclists as they must wait for a break in traffic to cross the road. In Cambridge and Somerville, however, few of these crossings occur. Additionally, by using Google's bicycle (or driving) directions, the algorithm has already selected a path with few of these crossings.

Therefore, unsignaled crossings will be few and do not need to be accounted for in GIS. A visual review of the Furth sample showed no such crossings.

Step 5: The Winters Method

In this section, I describe the Winters method of evaluating the road infrastructure’s “bikeability.” I used this methodology to perform an analysis on the same representative portion of Cambridge and Somerville as the Furth method, but included all the streets in between the Furth roads. As with the Furth Method, the availability of necessary data and the labor required to conduct the alternate methodology was also recorded and compared to the Furth method.

The Winters methodology combines five factors into a bikeability index for the city (in Winters’ study’s case, Vancouver, BC), which creates a score from one to 10 for each factor. The factors are: bicycle route density, bicycle route separation, the connectivity of cycle-friendly streets, the difficulty of the topography (specifically the slope), and the density of cycling destinations in the area. These factors combine to create a bikeability score for a raster surface. As in the Winters method, the raster surface used cells of 10m x 10m. For each cell, a score of one to 10 was possible for each criterion, and all the criterions weighed equally. The total possible score for each cell was five to 50, which was then divided by five to end at a score of one to 10.

Once completed and the “bikeability” scored, this raster surface was transferred onto the vector surface for the study area under evaluation. While the Winters method does not include this step, using a vector surface for both methods was the best way to compare the two approaches. The specific criteria were created as follows:

Route density: All designated bicycle routes (according to the MassDOT Bicycle Facility Inventory GIS layer) within the borders of the sample were identified and then converted into a density surface using the Line Density tool in

ArcMap. This was then given a score of one to 10 as shown in Table 8 below. While the Winters method's criteria were based on the relative density of routes in the Vancouver, BC, area, Cambridge and Somerville are considered comparable in terms of cycling friendliness to Vancouver. Therefore, the same scale that was used in Vancouver was considered applicable. Note that these "designated bicycle routes" include "sharrows," which the Furth Method considers as no different from a "mixed traffic" street.

Route separation: Any separated paths (designated as "Shared Use Path" or "Cycletrack" in the MassDOT bike inventory) were given a score of 10, with a buffer of 500 feet from the track applied to the raster surface. Areas further than this were given a score of one for this category. While the Winters method applied a buffer of one-quarter mile, with the reasoning being that this was the maximum a cyclist would be willing to detour to find an off-road path, their analysis applied to the entirety of the Vancouver region rather than a small portion. It was estimated that roughly two block's distance was the maximum a cyclist would detour when the routes were as close together as the selected sample.

Connectivity of cycle-friendly streets: Local roads, off-street paths, and designated cycling routes in Cambridge and Somerville were selected; then, any intersection of a cycling route and another road within the Winters sample was converted to a point in ArcGIS. The density of these points (number of intersections in a 400m radius) was calculated using ArcMap's Point Density tool, and compared to the scale used by Winters to determine the connectivity score, on a scale of one to 10.

Topography: The "slope" Spatial Analyst tool was used to create a raster surface of slope for the sample, using the USGS Digital Elevation Model data at the one-third arc-second level (roughly 8.9 m, re-sampled to 10 m). The percentage rise for each cell was scored according to the scale used in the Winters method.

Destination Density: Using assessor's data from the two cities, the density of the following land use types was calculated by converting the parcel shapefiles into points (choosing their centroids) and calculating the density of these points: Commercial, education, and offices. Mixed use parcels with one of the above uses were included as a potential destination as well. A kernel density raster layer was created in GIS using a 400m search radius, and this raster layer was added to the bikeability raster.

Table 9 summarizes the scoring for each criterion according to the Winters method:

Table 9: Five scoring factors for the Winters methodology

Score	Bicycle Route Density (m of bicycle routes within buffer)	Bicycle Route Separation (is cell within 500 feet of an off-road or protected path?)	Connectivity of bicycle-friendly streets (# of intersections within buffer)	Topography (% slope)	Destination Density (# of destinations within buffer)
1 (unfriendly)	0	No	0	>20	0
2	0-250	-	1	10-20	0
3	250-450	-	2-3	7-10	1-2
4	450-600	-	4-6	5-7	3
5	600-750	-	7-10	3-5	4-5
6	750-850	-	11-15	2-3	6-8
7	850-1100	-	16-20	1-2	9-10
8	1100-1400	-	21-25	0.5-1	11-20
9	1400-1800	-	26-30	0-0.5	21-40
10 (friendly)	1800-6000	Yes	31-60	0	40-300

Each factor was given the same weight, and their score for each category was added together to determine one "bikeability score" for each raster cell (a number theoretically between five and 50). This number was the reclassified to determine an overall score from one to 10 as noted in Table 10:

Table 10: Reclassifying the overall Winters score on a scale of 1-10

Original Score	Reclassified from 1-10
5	1
6-10	2
11-15	3
16-20	4
21-25	5
26-30	6
31-35	7
36-40	8
41-45	9
46-50	10

Additional analysis - Classifying the Winters methods according to their relative levels: The classifications in the Winters method were designed to apply to the broad Vancouver area, some of which is urban and dense in form and some of which is very suburban and spread-out. For that reason, applying the same classifications to the Somerville and Cambridge sample, which is mostly dense and contains less variety in urban form than the Vancouver sample, produced some results which could be improved upon. For example, nearly the entire sample area scored an eight or above in the “Bike route density” category, and nearly the entire sample scored a 10 in the “Connectivity of bike-friendly streets” category. While it may be true that relative to the average space, these areas would rank highly in these categories, it is also useful to learn which areas rank highly relative to the average space in the local region.

To conduct this additional analysis, the raster layers for the Bike Route Density, Bike Route Connectivity Density and the Destination Density categories were re-classified into 10 categories, with an equal amount of cells in each category, using the quantiles function in GIS. The new scores for the reclassification are listed below. Bike Route Separation and Slope were left the same as these were considered to be useful scales regardless of the region.

Table 11: Reclassifying three criteria relative to the sample area

Score	Bicycle Route Density (m of routes within buffer)	Connectivity of bicycle-friendly streets (# of intersections within buffer)	Destination Density (# of destinations within buffer)
1 (unfriendly)	0	0	0
2	0-301	0-2	0-7
3	301-533	2-5	7-17
4	533-696	5-9	17-29
5	696-812	9-15	29-45
6	812-1091	15-21	45-59
7	1091-1439	21-27	59-78
8	1439-1833	27-35	78-105
9	1833-2414	35-47	105-152
10 (friendly)	2414-5919	47-123	152-400

Step 6: Ground Truthing

“Ground truthing” is the process of recording the real-world conditions analyzed in the GIS analysis, and comparing them to the results of the GIS analysis. To conduct this, the researcher and volunteers cycled the streets analyzed in steps one and two, and recorded any discrepancies between the GIS analysis and the actual conditions on the roadways. The aspects of the roads that will be of particular importance to confirm via ground truthing are noted in the Table 6 description of the Furth methodology.

Ground truthing volunteers used both sets of criteria to evaluate the real-world conditions of the roads, and scored the roads either LTS 1-4, or 1-10, based on these criteria. They did not have the results from the GIS analysis when out in the field. The goal of this is not to compare the input criteria to the real-world road details, but rather the final score to the overall conditions of the road or intersection. For example, the surveyor did not evaluate whether bike lanes end in places not specified in the GIS layers, but rather evaluate the end level of stress or bikeability, based on the criteria outlined in the methodologies.

Volunteers were given a map of streets to evaluate and a summary of the criteria they should use. They then assigned each street segment[3] a LTS score (from one to 4) and a Winters score (from one to 10). They were given full instructions, and I discussed the procedure with each of them before they conducted the ground truthing. Additionally, they were given “cheat sheets” with shorthand versions of the scoring rubric that they could refer to quickly while out in the field. These are included in Appendix A.

The Winters method does not give clear criteria upon which to evaluate road conditions (as the Furth method does) but rather a general score from one to 10, with one being “least bikeable” and 10 being “most bikeable.” Based on the literature, the researcher developed a set of criteria on which to evaluate road conditions according to the inputs that Winters’ research determined had an impact on one’s likelihood of cycling in a particular area.

Appendix A gives the instructions that volunteers were given before going out into the field, along with the criteria taken from the Furth method and the criteria developed from the Winters literature to score the streets for that method.

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[3] A segment is considered to be a portion of public roadway between two intersecting streets, or between one intersection and the end of the road. If no intersections occur along a road for 500 feet, it is considered one segment.

Chapter 4: Results

The Furth Method GIS analysis was conducted on just the roads as defined by the Google Maps directions between the selected origin and destination points, however, the entire sample was ground truthed using this method as it needed to be for the Winters method. Table 15 shows the results from the GIS analysis as well as the ground truthing results. For ground truthing, results from the four volunteers were coded and averaged, and then rounded to the nearest whole number to determine a score. Table 12 shows a comparison of the GIS results and the ground truthing on an overall basis. The GIS analysis was reasonably similar to the ground truthing. The GIS showed 27% of the Furth roads as LTS 1, but much of these roads are the yet-to-be built cycletrack on Beacon Street in Somerville, which is shown as already completed in the GIS data due to an error. The other large difference was that ground truthers designated more roads as LTS 4 than the GIS analysis did. The ground truthing of the entire sample shows a large portion as LTS 2, which is likely due to these roads being mostly 2-lane residential streets in between the Furth Roads which were more arterial streets.

Table 12: Overall Furth Method Results Comparison

	GIS Analysis			**Ground Truthing (Furth Roads)**			**Ground Truthing (Entire Sample, Furth Method)**		
	km	Miles	Percent	km	Miles	Percent	Km	Miles	Percent
LTS 1	8.3	5.2	27.1%	0	0	0%	0.4	0.3	0.5%
LTS 2	4.2	2.6	13.6%	6.1	3.8	21.3%	53.4	33.2	60.8%
LTS 3	17.1	10.7	55.8%	14.0	8.7	48.9%	21.3	13.2	24.2%
LTS 4	1.1	0.7	3.5%	8.6	5.3	29.9%	10.1	6.3	11.5%
No Data	n/a	n/a	n/a	n/a	n/a	n/a	2.6	1.6	3.0%

For the Winters Method, results were coded and analyzed in much the same way as the Furth Method. Table 13 shows these results on a percentage basis. The ground truthers tended to rate the streets as 2-4 points less bikeable than the GIS analysis did. Possible reasons for this are discussed in Chapter 5.

Table 13: Overall Winters Method Results Comparison

Winters Bikeability Score	Percent of Area (GIS)	Percent of Road Length (Ground Truthing)
1	0%	1.2%
2	0%	2.8%
3	0%	11.4%
4	0.04%	41.7%
5	2.13%	24.7%
6	6.31%	8.4%
7	20.95%	6.3%
8	54.33%	0.1%
9	4.32%	0.5%
10	11.91%	0.0%
No Data	0%	3.0%

The following charts and maps show the difference in results between the GIS-based analysis and the ground truthing. These were calculated by subtracting the GIS score for each road segment from the ground truthing score for each segment. This is different from Tables 12 and 13, which added up the totals for each score rather than comparing each segment individually. Figure 6 shows the comparison between the GIS results and ground truthing for the Furth Roads only, and Figure 7 shows this difference on a map.

Figure 6: Comparison of GIS and Ground Truthing - Furth Method

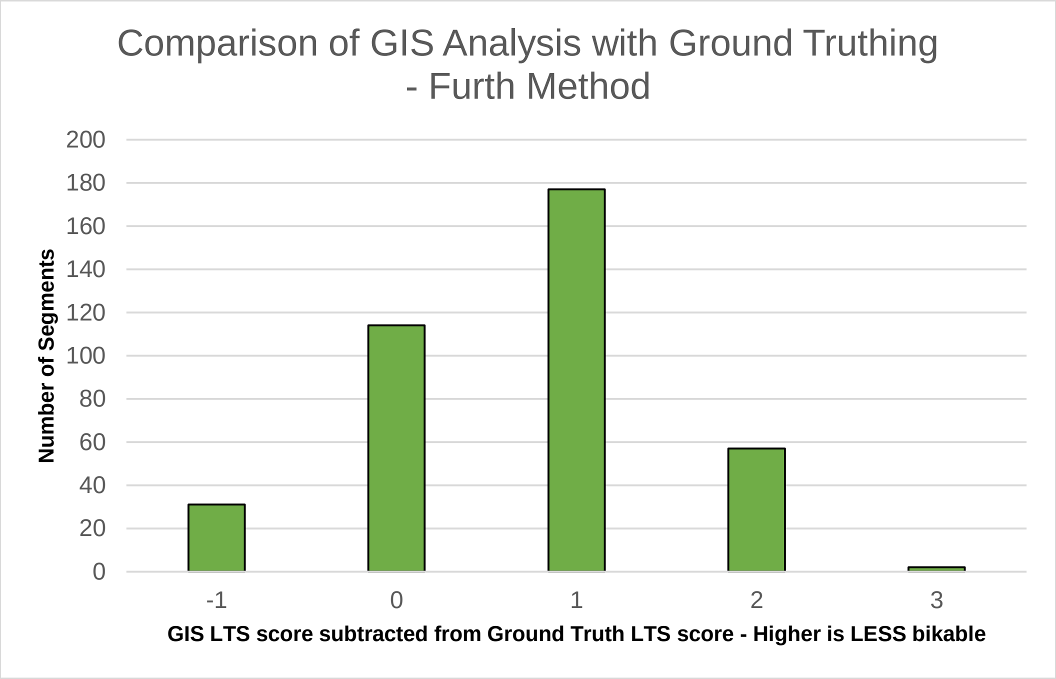
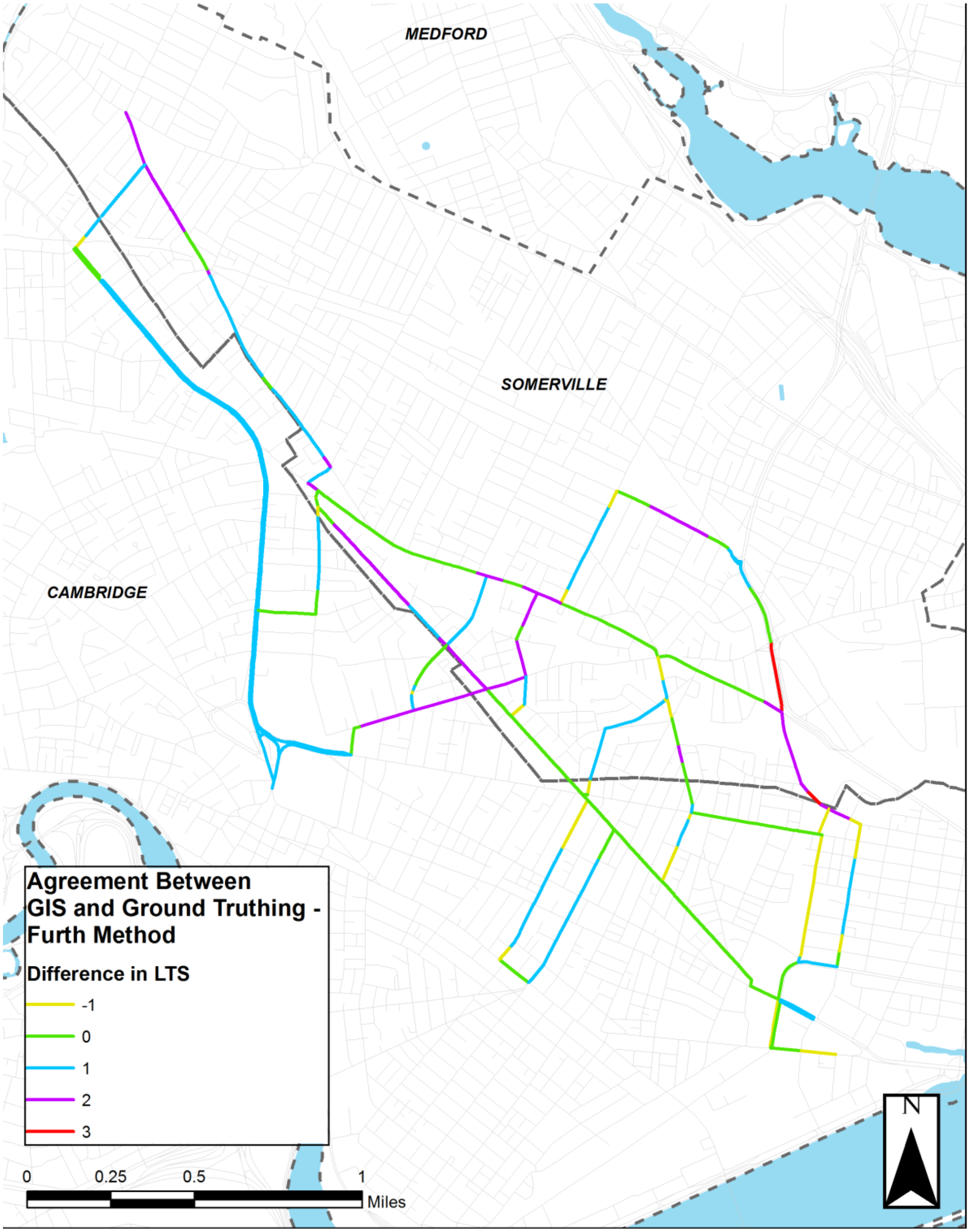


Figure 7:Agreement of GIS and Ground Truthing - Furth Method Map



For the Furth Method (Figures 6 and 7), GIS results were in relatively good agreement with the ground truthing results. To construct this chart, the GIS analysis-based LTS number was subtracted from the average ground truthing score for each road segment and the differences were totaled. Of the 381 Furth road segments which were ground truthed, 114 (29.9%) had the same score in both the GIS-based analysis and the ground truthing verification. For 177 (46.4%) segments, ground truthers found the segment to be one LTS level higher than the GIS analysis, and for 31 (8.1%) segments, ground truthers found the segment to be one LTS level lower. In total, nearly 85% of segments on the ground truthed Furth Roads were within one LTS of the GIS score. There are also some relatively simple explanations that likely explain much of the discrepancies:

- Much of the road area that is designated as “LTS 1” by the GIS analysis is the future cycletrack on Beacon St in Somerville. This cycletrack is not yet built, so when ground truthed, the road was obviously not designated as a low LTS. This accounts for much of the area that was 2 LTS apart (purple in figure 7).
- The criteria for designating LTS 4 in GIS requires the road be 40 mph or greater or contain six or more lanes, neither of which apply to many roads in the sample. The criteria for ground truthing, however, is more subjective, simply suggesting that a level of stress “beyond level 3” qualifies as LTS 4. This difference probably leads to much of the discrepancy between levels 3 and 4, especially Massachusetts Ave. (the westernmost road on Figure 7). That said, there is little practical

difference between LTS 3 and 4 as both are considered to be beyond the tolerance of most cyclists.

- The ground truthing showed more roads as LTS 2 than the GIS analysis, but this is likely due to some roads the GIS analysis considered LTS 1 being designated as LTS 2 by the ground truthers. Both LTS 1 and 2 are considered to be within the tolerance of most adults, so the difference is less pronounced than the difference between 2 and 3.
- It should be emphasized that ground truthers evaluated many neighborhood residential streets which were in between the main routes in the sample area, while these streets were not evaluated in the GIS analysis. If they had been, it is likely that the agreement between the GIS analysis and the ground truthing would increase greatly, as these streets make up the majority of the road segments in the sample and would likely nearly all be considered LTS 2 by both the GIS analysis and the ground truthers.
- Finally, there were multiple ground truthers and their scores were averaged and then rounded to the nearest whole number. This process likely muddied some of the results. The majority of road segments showed some level of disagreement between the ground truthers (see Table 14), likely due to differing interpretations of the criteria.

Figure 8: Comparison of GIS with Ground Truthing - Winters Method

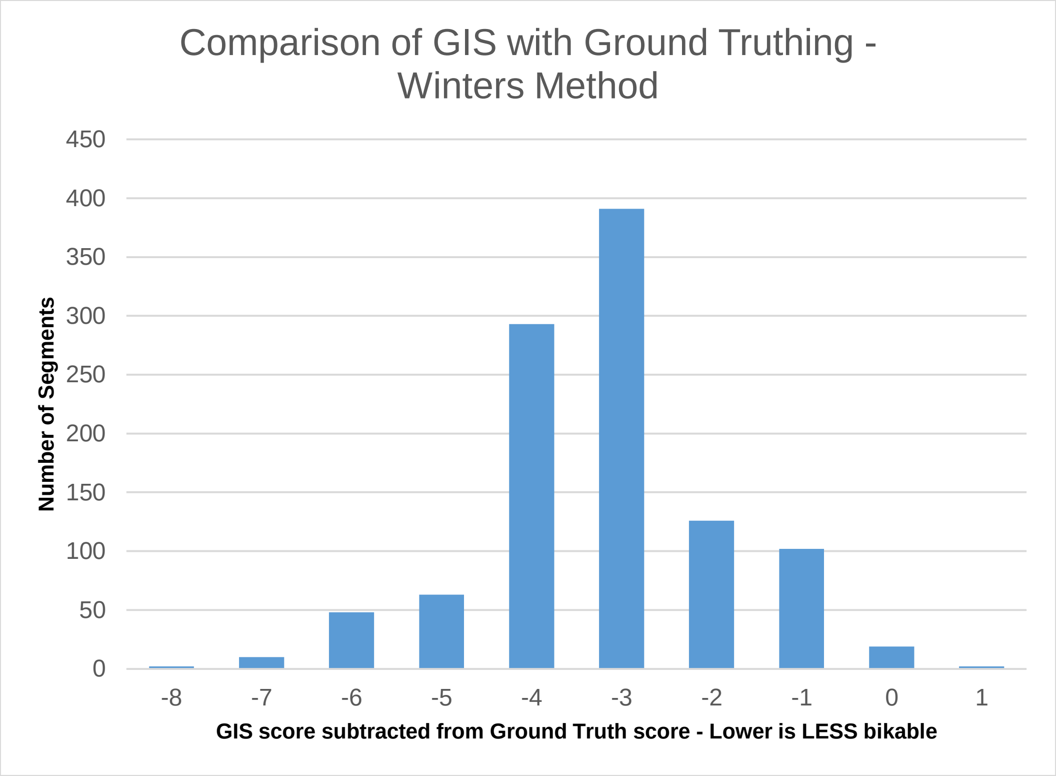
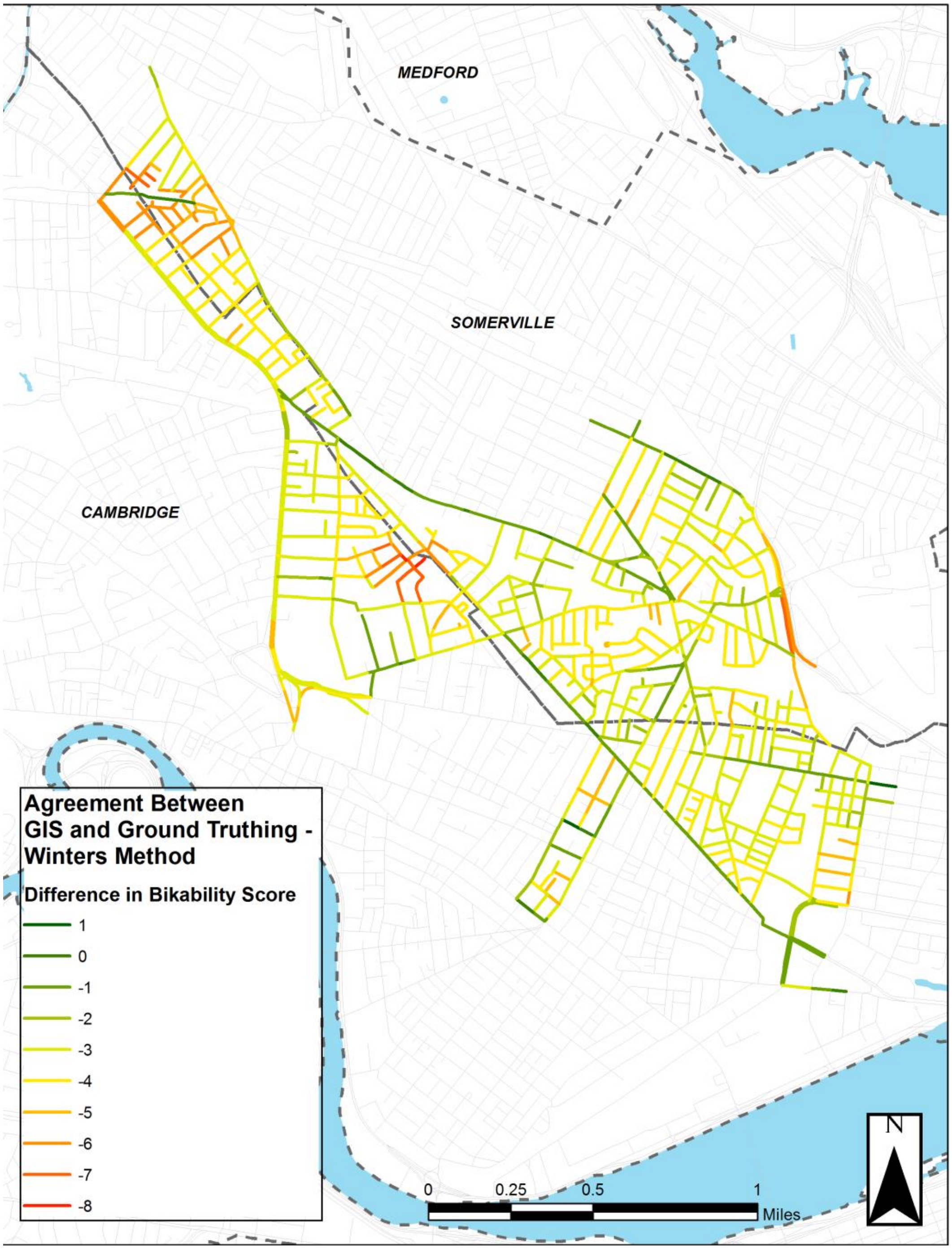


Figure 9: Agreement of GIS - Winters Method Map



For the Winters Method (Figures 8 and 9), the ground truthing systematically rated streets as less bikeable as the GIS-based method did, to a significant degree. Of the 1,056 road segments which received a Winters method ground truthing score, 391 (37.0%) of them were rated 3 points lower by ground truthers as they were by the GIS analysis. An additional 293 (27.7%) segments were rated 4 points below the GIS-based score, and ground truthers only agreed with the GIS analysis on 1.9% of segments. These ratings appeared to follow a normal distribution, but skewed towards less bikable – with most segments scored by the ground truthers between 1 and 5 points lower than the GIS analysis. It should be noted that this was on a scale of 1-10, as compared to the Furth score of 1-4, so a broader difference in scores should be expected.

Ground truthers were not asked to give their scores for the individual categories that make up the Winters scoring, so a detailed analysis of the difference is not possible; however, possible reasons for the discrepancies are as follows:

- The GIS analysis uses multiple density "heat-maps" to develop its final score. For four of the method's five criteria (all but slope), a score is developed not at a single point but rather taking into account various criteria within a distance of the point. For example, the "bike route separation" criterion gives two points to any point within 500 feet of a separated bike route, even if the road itself is not bike-friendly. While ground truthers were instructed to take the buffer distance into account when assigning scores, it is difficult to do this when out in the field. This can be seen in Figure 9 as the streets near the Somerville Community Path in the northern section of the study area are very different from the GIS analysis.

- It is sometimes much more clear what is considered a designated "bike route" when viewing the GIS layer than it is when out on a street, especially if that route is not well-marked or if the paint has faded.
- Similarly, what is considered a concentration of "bike-friendly" destinations is easier to discern from a GIS layer than it is when out in the field.
- Notably, the ground truthers seemed to show more agreement with the GIS analysis on the main roads than they did on side streets, as shown in Figure 9. This is good in this situation, as most of the travel is likely to occur on the main roads, but in other cities with a different urban form, there may be useful bike routes on roads with less traffic that the GIS analysis would mis-classify.

Labor

The process for conducting the GIS analysis was relatively complicated and required a high level of aptitude and experience with GIS. Multiple data layers were used and each needed multiple steps to transform or otherwise modify the data to establish a bikeability scale. Additionally, multiple advanced GIS tools from various ArcMap extensions were used, which not all municipalities may have access to, even if they have an ArcGIS license.

Once the workflow was developed, it took this researcher approximately 20 hours to conduct the GIS analysis for the Winters method, which included gathering the data and creating a usable datalayer, and another 15 hours to conduct the Furth method. Approximately 10 hours were required to refine these data and generate the maps. The ground truthing took each of the three volunteers between 10 and 15 hours to conduct. It seems likely that the entire project could be completed by one person within 2-3 weeks for a mid-sized city, or perhaps in less time if undertaken by a previously-trained team.

Maps

The following pages show the maps that were developed in both GIS and using the ground truthing results. Using the Furth “weakest link” philosophy, it is notable that it is essentially impossible to plot a route between any of the chosen origins and destinations that does not involve some travel on a LTS 3 street – by definition, beyond the tolerance level of most of the population. This may be possible using lower-stress streets and avoiding the “Furth Roads” recommended by Google Maps, but likely not without going far out of the cyclist’s way. For the detailed maps of the five components that went into the final Winters scoring, see Appendix B.

In order to display each map on its own page in the largest size possible, descriptions of the maps are given here.

Figure 10: Furth Method LTS GIS Results

This map shows the results for the Furth method from the GIS analysis. Of particular note is Beacon Street, where a cycletrack is planned but not yet built. As discussed above, an error in the data showed this track as already-built, which made its LTS score lower than it really is. Also of note is that there are long stretches that Google suggests as bike routes (especially Massachusetts Ave and Hampshire Street) which are LTS 3 – considered above the tolerance of most adults.

Figure 11: Ground Truthing Results - Furth Sample Roads

This map shows the averaged results for the Furth roads between the ground truthers. Notable on this map is Massachusetts Ave, which the ground truthers designated LTS 4.

Figure 12: Furth Method LTS Ground Truthing Results

This map shows the ground truthing results for the entire sample. Most roads in between the main arterials were designated LTS 2. These roads could be possibilities for alternate bike routes. It is notable that Google's directions algorithm ignored these roads.

Figure 13: Winters Method GIS Results: Final Score

This raster map shows the results from the Winters Method GIS analysis. It is notable that most of the area scored a 7 or higher. Also, note the areas around the separated paths, which register as a 9 or 10.

Figure 14: Winters Method Final Score – Scored by Quantiles Relative to the Study Area

This is the Winters Method when scored as quantiles (relative to the sample area) rather than using the original criteria from its application to Vancouver, BC. For a detailed description of this method, see pages 33-34 of this document. While interesting, there does not appear to be a great difference between this and the original method (Figure 13).

Figure 15: Winters Method Ground Truthing Results

This map shows the averaged ground truthing results using the Winters criteria. This is a vector map, as ground truthers were instructed to evaluate the roads themselves. Particularly notable here is the area near Somerville City Hall, which includes steep hills.

Figure 10: Furth Method LTS GIS Results

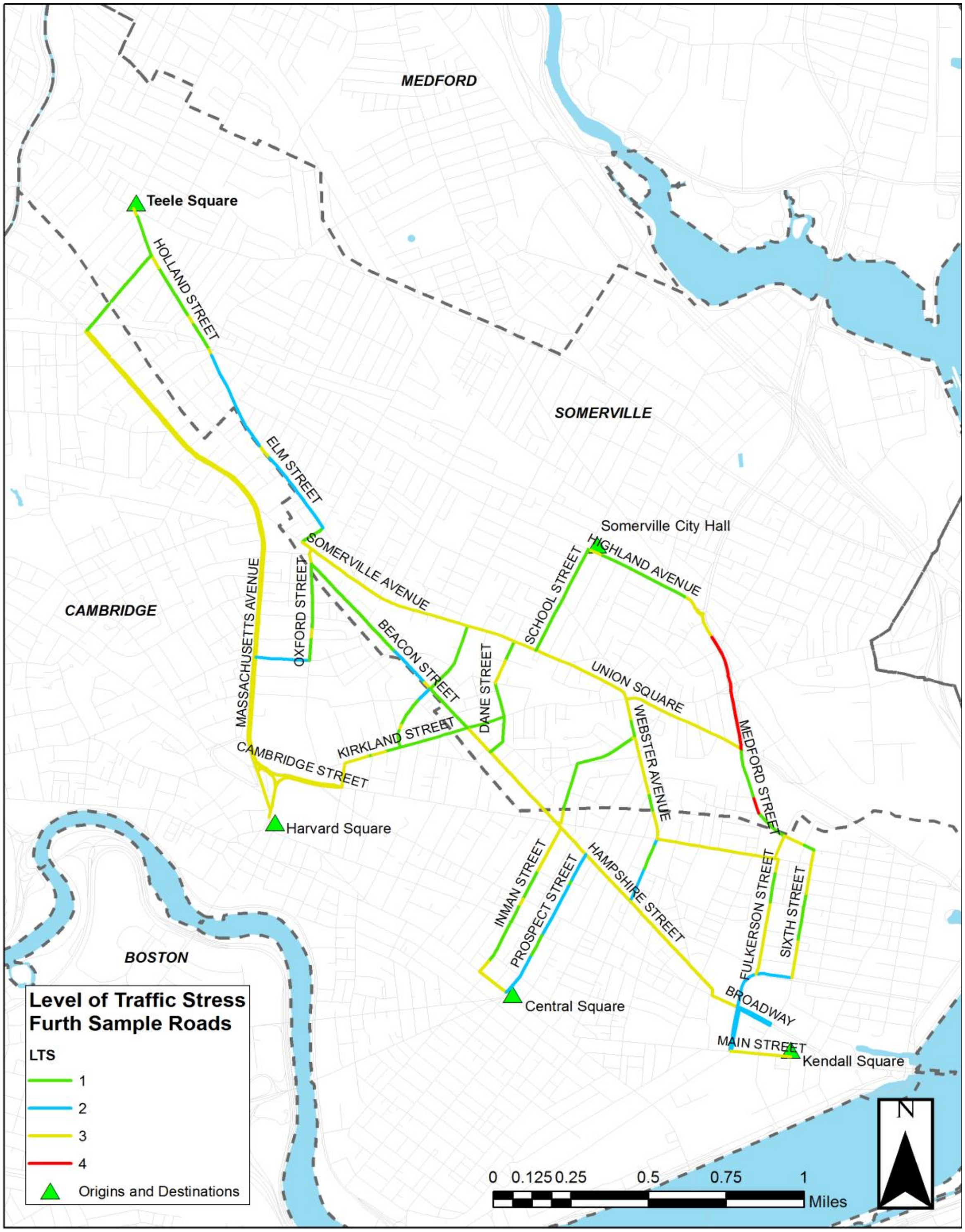


Figure 11: Ground Truthing Results - Furth Sample Roads

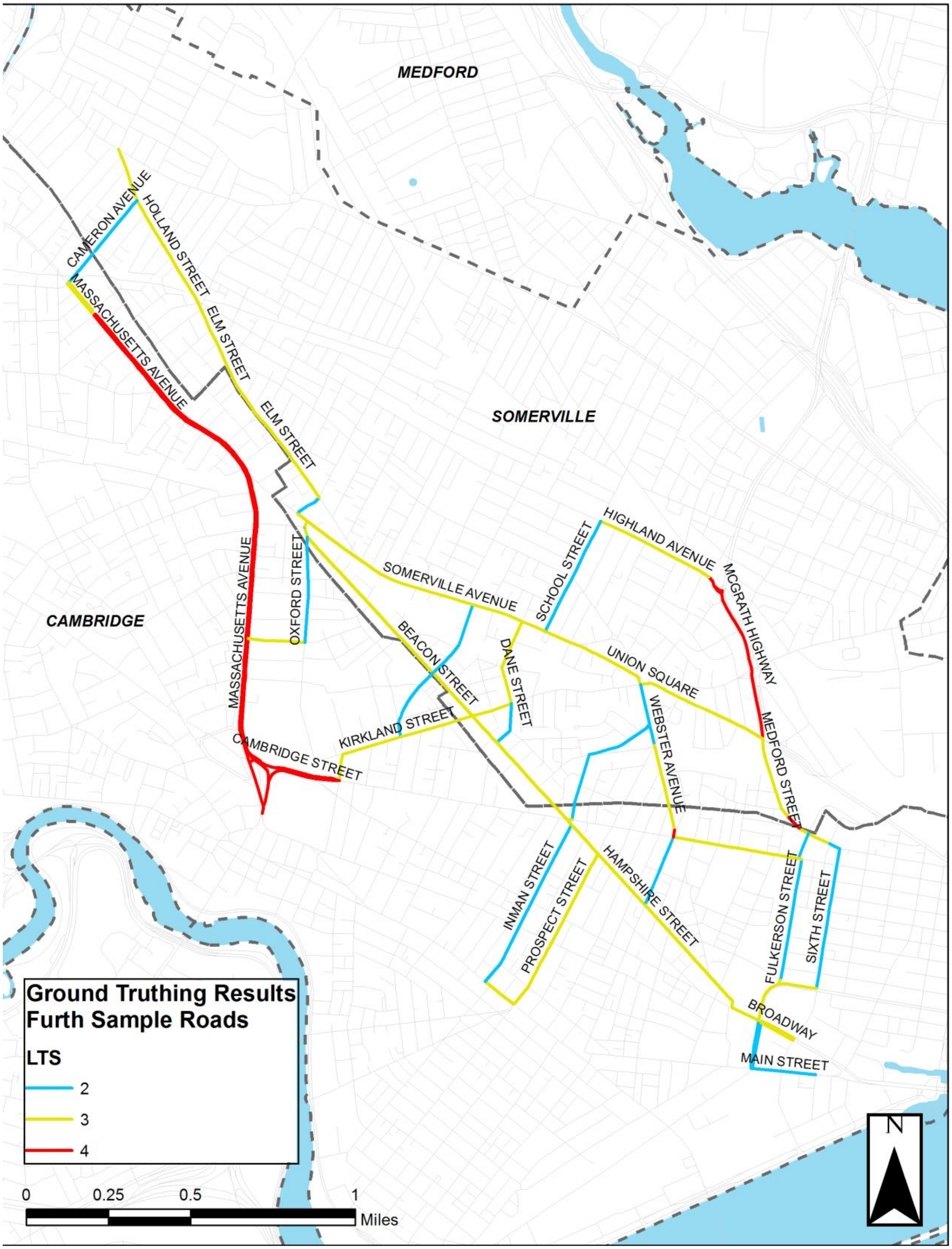
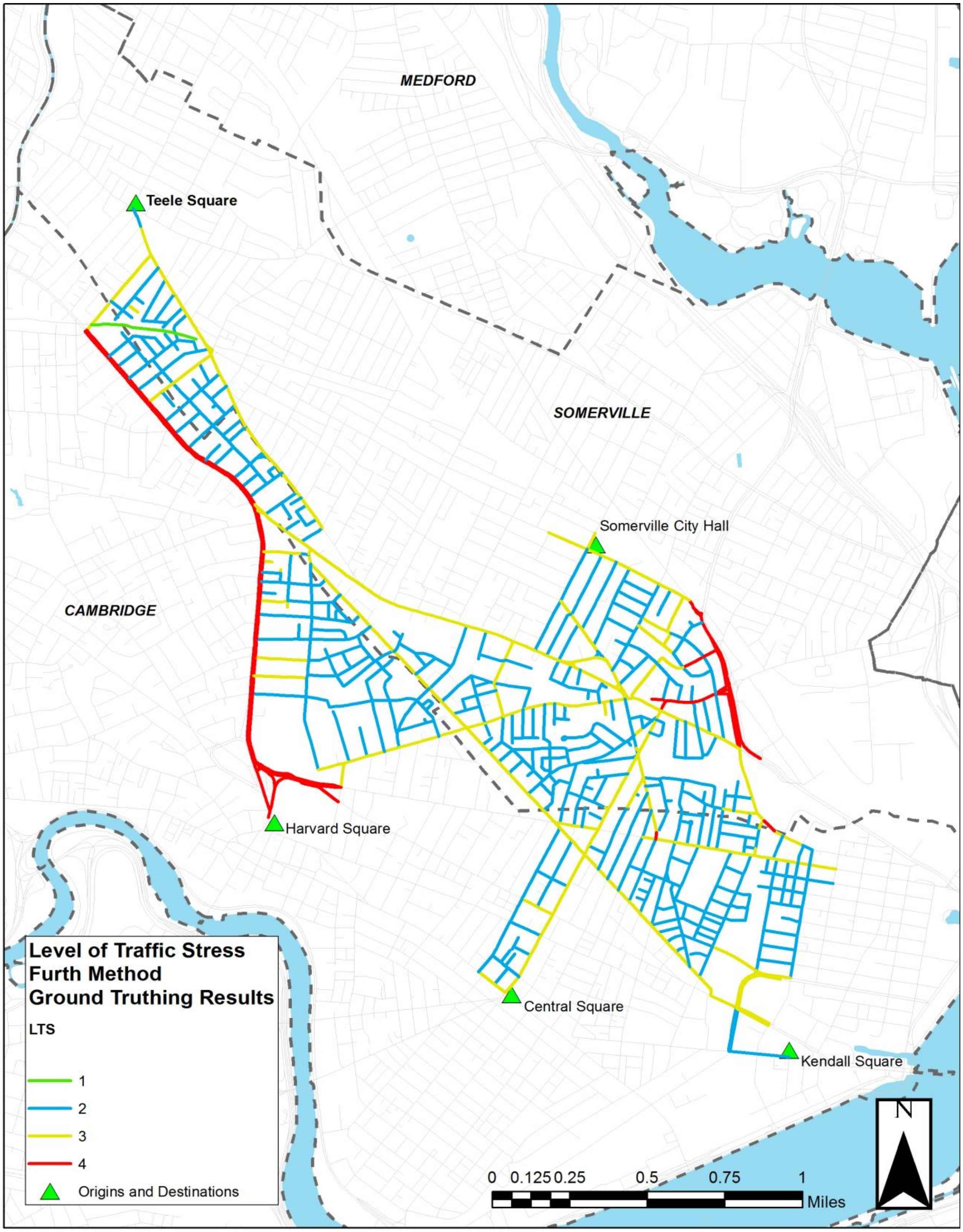


Figure 12: Furth Method LTS Ground Truthing Results



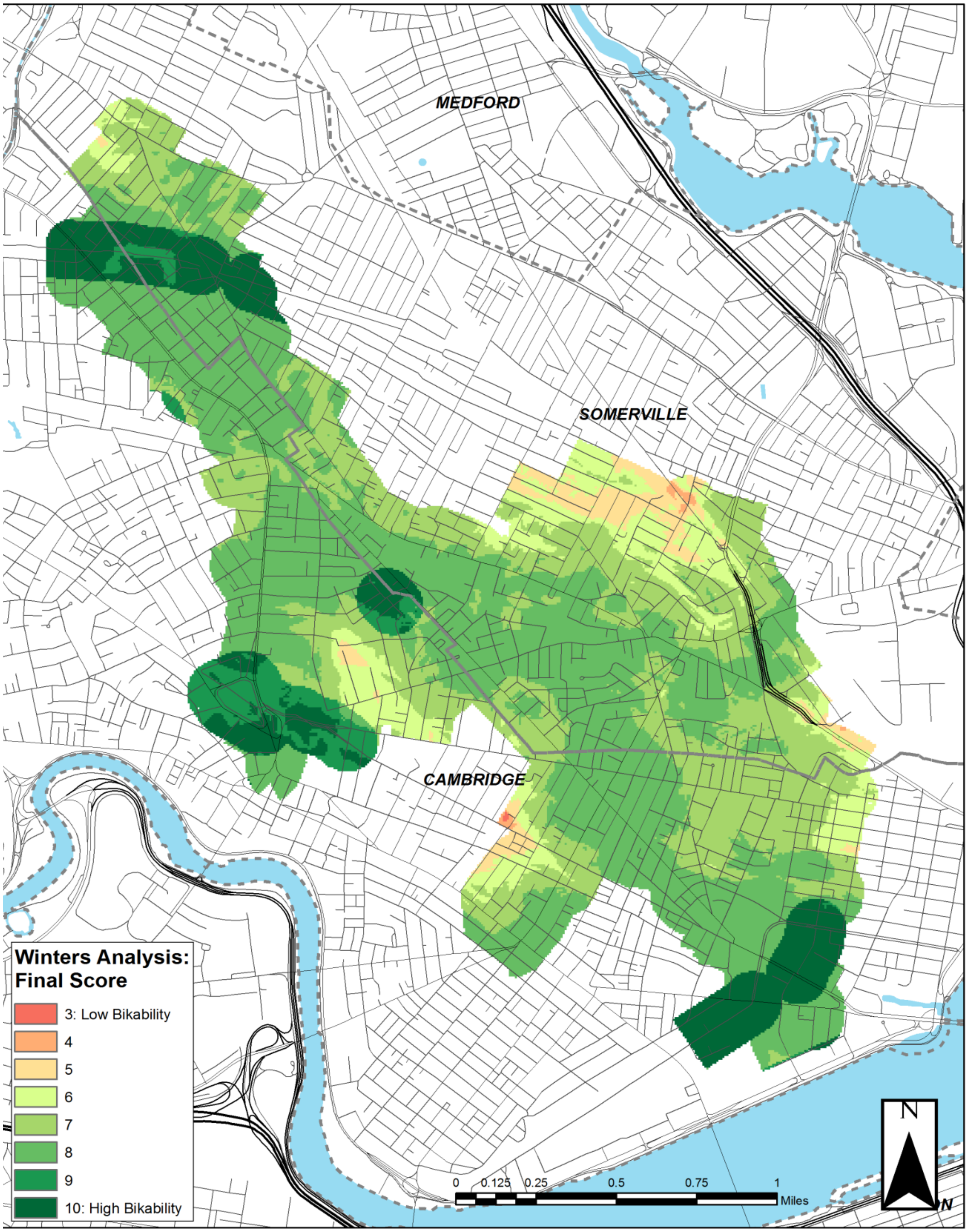


Figure 13: Winters Method GIS Results: Final Score

Figure 14: Winters Method Final Score – Scored by Quantiles Relative to the Study Area

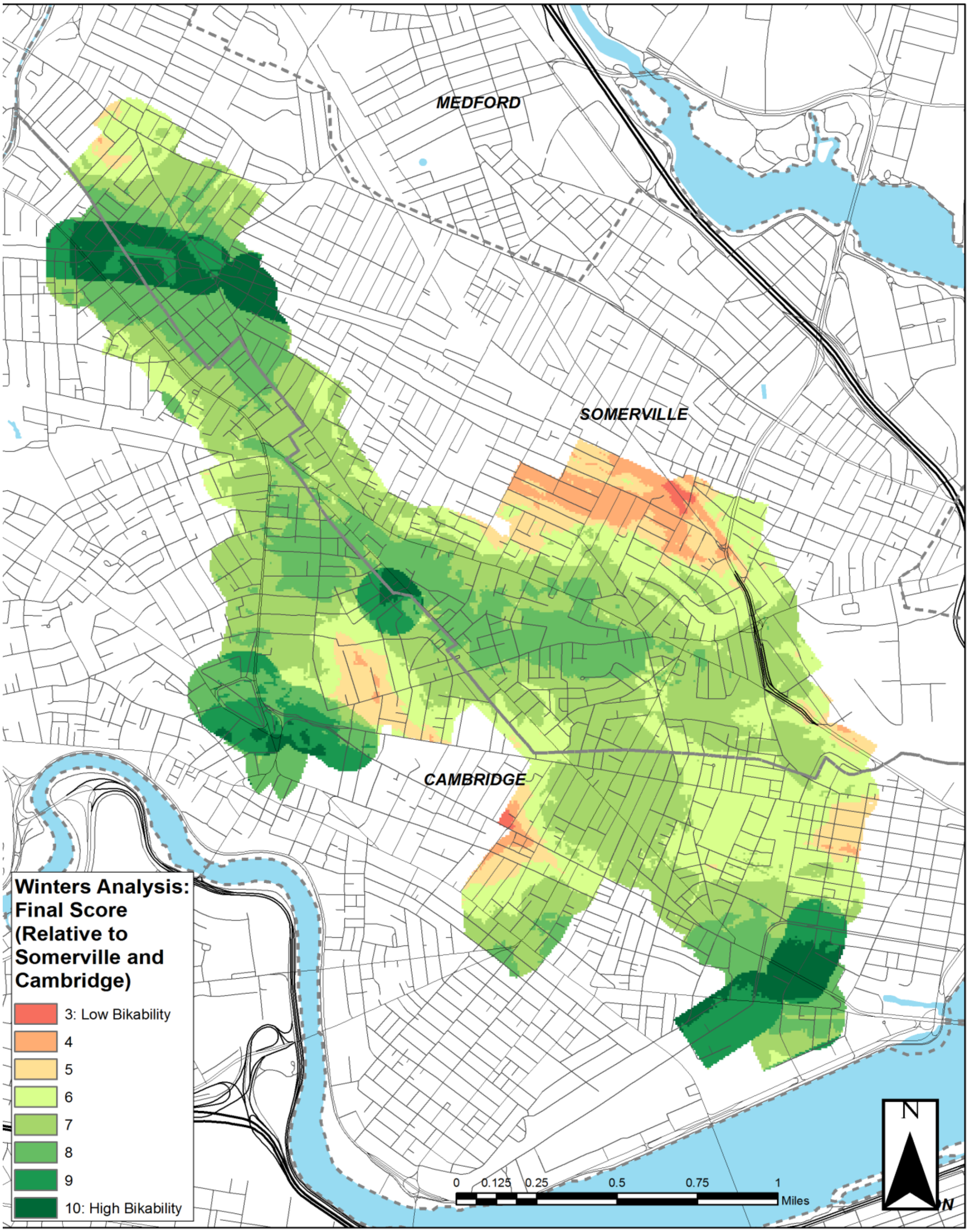
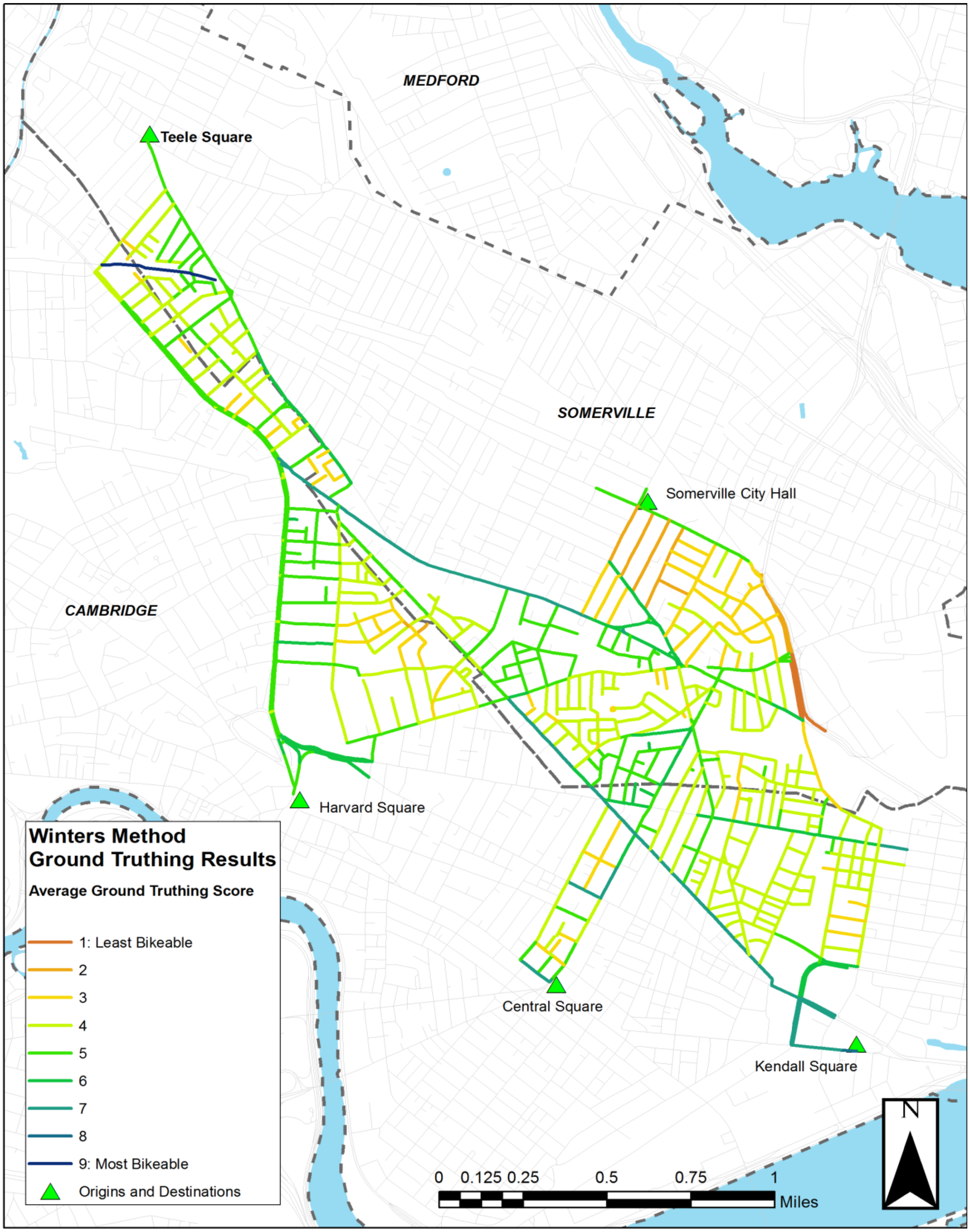


Figure 15: Winters Method Ground Truthing Results



Chapter 5: Discussion

The goals of this thesis project were essentially twofold: to evaluate the feasibility of conducting the GIS analyses for a resource-strapped local government, and to compare these methods with the real-world conditions as surveyed by multiple volunteers. In accomplishing these goals, the thesis is also intended to provide a guide to future research and recommendations for any local governments who attempt to use GIS methods to evaluate their existing cycling infrastructure for the purposes of transportation.

Feasibility

The labor involved in conducting the analysis is feasible for a small planning office. In all, each method took between 30 and 35 hours to conduct the GIS analysis (assuming all data were readily available) and another 15 hours for each of the volunteers to conduct ground truthing. While it might seem from these estimates that conducting only the field work would be more efficient, it is worth noting three points about this analysis: First, the analysis was conducted on two cities with differing assessing datasets, which made the work involved in the GIS analyses more complicated than if just one city (or county) were involved. Second, the GIS analysis is more scalable than the ground truthing: while the sample selected took over 30 hours to analyze, it wouldn’t have taken much longer to analyze the entirety of the cities, while ground truthing a larger area would take proportionally longer (approximately 55-80 hours to survey the entirety of Cambridge and Somerville if the surveying was conducted at the same rate). Finally, if one workflow was chosen and perfected, it would likely take less time to conduct the GIS analysis than it did in this example.

The Study Sample

In previous analyses using the two selected methodologies (Furth and Winters), studies were conducted over the entirety of cities. Conducting analyses over the whole of Somerville was considered, but determined to be both overly time-consuming and unnecessary given that the purpose of this study was to test out these methodologies rather than to perform a full-scale analysis for the benefit of Somerville or another municipality. For these reasons, I decided to choose a smaller sample of the Somerville / Cambridge area to perform and compare the two methodologies. As noted above, an analysis of the entirety of both cities would have not taken much more time in GIS (in fact, in the Winters method, it was just as easy to analyze the entire city as the sample); however, the ground truthing would have taken a proportionately longer time to conduct with any increase in the size of the sample.

Data Availability, Detail and Comparison

Both GIS methods rely on the necessary data layers being available, detailed and accurate. While Massachusetts state agencies maintain both transportation (including cycling routes) and assessor's parcel datalayers for the whole state, this is not necessarily the case in all states. The cycling route data in particular may be difficult to find (and even in Massachusetts' case, was found to be inaccurate as described below). If these datasets are unavailable, they would need to be compiled manually, which would likely take longer than simply surveying the bikeability of the municipality and defeat much of the purpose of the GIS analysis.

Even if these datalayers are available, care needs to be taken to ensure they are current and accurate before conclusions are drawn from them.

Additionally, they need to have a certain levels of detail which may or may not be present. Specific examples are provided below.

Speed Limits

Data on speed limits were incomplete in the state roads layer file. This is not uncommon, as the speed limits for roads under municipal jurisdiction (the vast majority) are not maintained by the state DOT. A cursory review of neighboring states showed similar results. At the municipal level, available datasets for Somerville and Cambridge gave no additional speed limit information.

Even if speed limit attributes were available for the entire sample (and indeed, it is a state law that the speed limit is no higher than 30 MPH in any densely settled area, which includes the entire study area), there could be and often is a difference between the posted speed limit and the usual speed in the area. For segments with no posted speed limit, this study assumed a 25 MPH speed in residential areas and a 30 MPH in non-residential areas, but there are other factors which influence actual speeds, among them traffic, road design, pedestrian activity and enforcement of posted speed limits.

Given the Furth methodology is so reliant on the difference between 25 and 30 mph for determining LTS, this is an important limitation to applying the methodology to the study area. Since the actual speed can range widely even in areas with the same speed limit, it is recommended for maximum accuracy that further methods be developed to estimate the actual travel speed on streets on a wider scale.

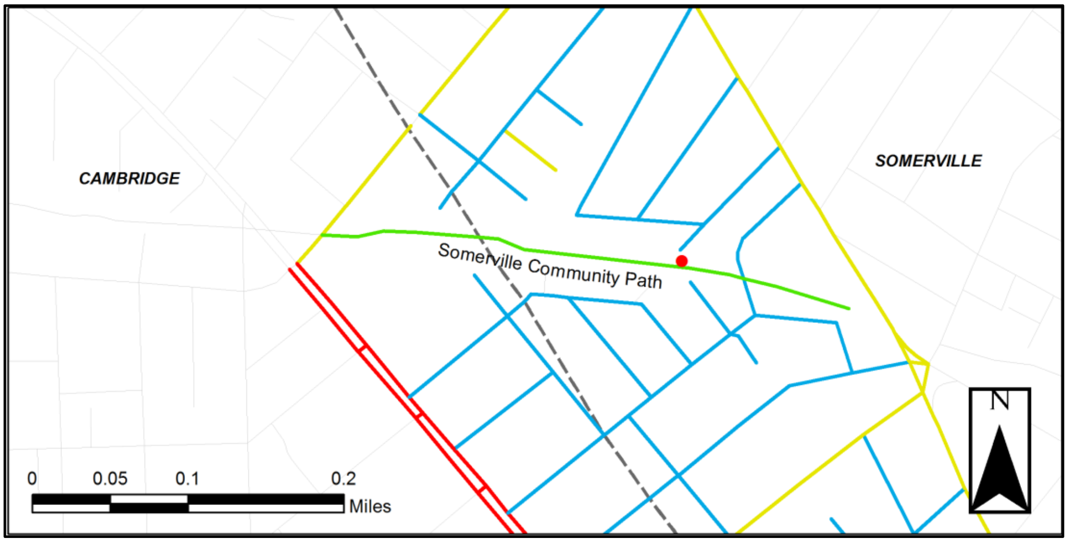
Cycling Routes

MassDOT maintains a “cycling inventory,” a GIS layer which contains information on all the current and planned cycling routes in the state, including off-road paths, bike lanes, cycletracks and even sharrows. That said, a fairly significant amount of error was found in this dataset as the currently *planned* cycletrack on Beacon St. in Somerville was listed as built. This is shown in the map in Figure 10: The GIS analysis showed a LTS 1 or 2 for Beacon St between Somerville Ave and Washington St (where the cycletrack is to be built) but the ground truthers average score for that segment was LTS 3. That said, for major projects like this one, an error like that should stand out and be caught relatively quickly.

Connections

The roads datalayer is accurate for any intersections between regular streets, but it does not always take into account pedestrian and bike-only connections which cars can’t travel on. For example, the Somerville Community Path appears from the data to not be connected to any of its neighboring roads, but there are actually multiple streets that are accessible via bicycle or on foot. See Figure 16 for illustration – the red dot denotes streets that connect the area by bike and foot, but not by car. Given that both methods take the connectivity of streets into account, this could influence the results if not accounted for.

Figure 16: Connections and the Somerville Community Path



Ground Truthing Accuracy

While the purpose of the ground truthing was to verify the GIS analysis, there is a possibility of error or misinterpretation in the field study itself. Each of the three volunteers was an experienced cyclist who knew the area, and while each was given clear instructions, the possibility of bias exists: surveyors could be more comfortable riding than an average person, and score roads as easier than they are, or, alternately, they could over-compensate and score a road as less bikeable than an average adult would find it. That said, looking at the scores in aggregate should provide a decent evaluation of the results.

Table 14 shows some statistics about the ground truthers. Volunteer 2 gave the highest average score based on the Winters method, but also the highest (and thus least bikeable) score based on the Furth scoring. Volunteers 1 and 2 have a higher variability in their scores in both methods. Overall, the average scoring was reasonably consistent, especially in the Winters method.

Table 14: Statistics about Ground Truthers

	Winters Score		Furth Score	
	Average	Std. Deviation	Average	Std. Dev.
Volunteer 1	4.29	1.27	2.55	0.81
Volunteer 2	4.57	1.74	2.71	0.83
Volunteer 3	4.39	1.03	2.37	0.52
Volunteer 4	4.42	1.06	2.40	0.53

Furth Method vs. Winters Method

Both methodologies have strengths and weaknesses, which were revealed by this study. The Furth Method is simpler to conduct and to understand than the Winters method, for the following reasons:

1. There are fewer criteria, from less varied datasets, that go into the analysis.
2. The method of scoring is just 1-4, instead of 1-10, and the LTS tracks reasonably closely to the "Four Types of Cyclists".
3. Scoring only vectors (streets) rather than a raster area is more realistic, as cyclists only ride on streets. This also allows a more streamlined approach as dead-ends or cul-de-sacs that do not connect major origins and destinations could be ignored in the analysis.

As the ground truthing showed, the Furth Method is also probably closer to the real "experience" of cycling, being a vector-based method, than the Winters method which overrates locations that are near infrastructure but are not particularly bike-friendly themselves. For the purposes of route choice, using land use-related criteria such as the Winters method to establish bike-friendliness accounts for the destination density while ignoring important safety aspects of the route choice. The two methods also disagree on the usefulness of designated bike routes that do not have dedicated Dutch-style infrastructure or low speeds. The Winters Method considers sharrows and narrow lanes bike routes and only makes a distinction between them and completely separated paths, while the Furth Method doesn't consider sharrows or sub-par bike lanes any different from no infrastructure at all.

Where the Winters Method clearly improves upon the Furth Method, however, is in its consideration of slope. The Furth Method doesn't consider slope at all, which may be sufficient in some cities, but hinders the analysis in many others. A good illustration is School St in Somerville, which is considered LTS 2, but is quite steep. While it may be a safe street to ride on, most cyclists would probably avoid it, especially less experienced ones, as it would be difficult for them to climb heading uphill, and might cause them to gain too much speed to stay in control going downhill.

An additional problem with the feasibility of the Furth Method is its very specific criteria for the width of bike lanes and parking lanes. The methodology makes a distinction between 5.5 foot-wide bike lanes and 6 foot or wider lanes. In this analysis, every bike lane was far too narrow for this to come into play, but in a city with wider lanes, this could cause difficulty as few GIS layers record the width of bike lanes and it is very tough to discern between 5-ft and 6-ft lanes without going out into the field.

Recommendations

For cities that wish to evaluate their existing infrastructure to develop bike routes or prioritize areas to improve, the two methodologies studied provide useful tools and lessons. The Winters Method is likely to be useful on a regional level (as used in Vancouver) to predict generally where improving bike infrastructure and promoting bike use may be good strategies, while the Furth Method is useful on a more granular level to develop specific routes and identify roads to improve. The Furth method was determined to be the better choice if developing cycling routes for the purpose of everyday transportation is the primary objective, as the LTS scale is simpler to understand and the method is precise (it can be used to identify the level of stress on specific streets) and can be applied to a large area reasonably quickly. In terms of the labor and data needs involved

Taking the lessons learned from this analysis and developing a new method may be a useful path to follow. To simplify the process, it would be helpful to identifies ways to make the Furth method more applicable across a wider geographic scale and to increase its accuracy, for example:

1. Incorporate slope: While in most streets the slope isn't enough to change a perceived level of stress, a steep-enough hill can change an otherwise comfortable ride to an uncomfortable one, especially if there is traffic alongside. I recommend increasing a road's LTS to LTS 3 if its slope is over 5%, unless it has a cycletrack or an off-road path.
2. Refine bike lane width: For bike lanes next to a parking lane, the Furth Method requires that the total width of the bike lane and parking lane must be 14.5 feet or more to qualify as LTS 1. The reasoning behind this is so that the cyclist would be out of the "door zone" (the area where a person leaving their parked car could open their door into the lane without looking). But, unless a cyclist rides on the far left of the bike lane, they could be in the door zone

regardless of the width of the lane. It is more feasible to look for areas where parked cars may frequently open their doors – commercial areas and perhaps schools as well. I suggest that rather than trying to decide the width of the parking lane and bike lane, or the bike lane by itself, that bordering land uses be the determinant of LTS, adding one level of stress to the segment if there are retail, office, or educational uses next to the lane.

3. Develop expert teams: Either consultants or academic teams could become familiar with the processes and data and labor needed to perform these analyses. This would eliminate the learning curve needed for some of the complicated processes and over time the groups could become familiar with potential problems in the analysis that required special attention.
4. Combine the Furth Method with Ground Truthing: Given the difficulty of certain aspects of the methodology, it is perhaps best to perform it for the majority of the city, and then spend a day or so “ground truthing” any areas that were unclear from the GIS analysis. Specifically, this could be areas where bike lane blockage or door opening frequency is unknown, slope is a concern, or complicated intersections or crossings. In cities with active cyclists, preliminary maps could be released to a group of volunteers and crowdsourcing methods could be used to zero in on the areas of disagreement.

Incorporating the methodologies and philosophies into a new, codified workflow, it should be possible to develop a best practice for cities and towns to perform a reasonably accurate, comprehensive analysis of their infrastructure from the perspective of cyclists with minimal labor and resource needs.

Chapter 6: Conclusion

Political and cultural impetus exists in many cities and towns to increase the amount of travel done by bicycle. The reasons for this are many, among them: to improve public health, to reduce reliance on the automobile, to increase equity for citizens, and lower cities' carbon footprint. While factors such as land use and transportation demand management strategies influence the viability of cycling, it is also shown that having infrastructure which supports a low-stress cycling experience can encourage people to cycle.

This project's goals were to explore multiple GIS-based methodologies for evaluating existing cycling infrastructure and determine both their feasibility for governments with limited resources, and compare them to real-life conditions. Overall, the two methodologies studied in-depth proved to be feasible to perform for a mid-sized city and plausibly scalable to larger cities. Assuming all data were available, the GIS process for either method should be doable within a workweek.

Both methods showed a reasonable level of agreement with the real-world conditions according to the ground truthing volunteers. For the Furth method, nearly 85% of the road segments were rated by the truthers within one level of traffic stress of the GIS analysis, and some of the disagreement can be attributed to data errors and ambiguity in the application of speed limits to the sample. For the Winters method, the majority (nearly 55%) of ground truthers rated the roads as either three or four points less bikable than the GIS analysis. Although the difference between the two scores appeared approximately normally distributed, the average ground truther scores skewed towards rating the sample as less bikable. This suggests that the analysis is relatively sound and the GIS data generally agrees with the real-world conditions, but perhaps the various criteria could be adjusted to better define the scale of less to more bikable.

Notably, ground truthers tended to rate the real world conditions as *less* bikable than the GIS analysis did in both methods. This suggests that perhaps the GIS analyses are being too “easy” and could be adjusted. One possible area to examine more closely is the methods’ treatment of speeds – while the speed limit for nearly the entire sample is 30 MPH or less, there are likely many areas where the actual speeds traveled on the roads are higher.

Certain strategies may be useful for cities in developing a map using either methodology. The GIS analysis could be used as a starting point and further refined based on ground truthing. In areas with an active cycling community, crowdsourcing the areas of disagreement could be a way to refine the map without having to ground truth the entire area. Alternately, given the complexities involved, perhaps an efficient way to perform either analysis would be for consultants or academic teams to become adept at the methods and be hired by various cities, rather than a planning staff who may not be familiar with the methods and would likely have difficulty performing the analyses.

It is clear from this project that GIS analyses can be a fairly efficient way to classify roads for cycling, just as it is used to classify roads for driving. With further work, methods can be developed to categorize these roads for the purpose of cycling that can be as useful. This project shows that the methods analyzed can be duplicated with reasonable accuracy and points to ways they can be improved and refined.

Appendix A: Ground Truthing Field Sheets

The following instructions and cheat sheets were given to volunteers to bring with them as they conducted the ground truthing.

Ground Truthing Instructions

Attached is a map of the area to be ground truthed with the streets to be scored marked in blue. Your scores will be compared to the GIS analysis from two methods; the Furth Level of Traffic Stress Method (Furth Method) and the Winters method. Please survey the area and write your score for each segment on the map using the above criteria. Use the attached note sheet to record your start and stop time and any key observations that influenced your scoring – you do not need to record your reasoning for every single segment.

Notes: A segment is defined as the distance along a street or path between two intersections, or roughly 500 feet if there are no intersections along the segment.

For the Furth method, record your scores as "F1-F4" based on the above criteria.

For the Winters method, please score each road segment from 1-10 based on the likelihood that you would choose to cycle there. Please only consider the criteria from the above table in your score, weighing each equally (from 0-2 points for each). In the case that a segment scores a zero in all categories, the final score should be one for the segment (not zero).

Table 15: Ground Truthing: Levels of Traffic Stress from the Furth Method

Level of Traffic Stress	**Description**
LTS 1	Presenting little traffic stress and demanding little attention from cyclists, and attractive enough for a relaxing bike ride. Suitable for almost all cyclists, including children trained to safely cross intersections. On links, cyclists are either physically separated from traffic, or are in an exclusive bicycling zone next to a slow traffic stream with no more than one lane per direction, or are on a shared road where they interact with only occasional motor vehicles (as opposed to a stream of traffic) with a low speed differential. Where cyclists ride alongside a parking lane, they have ample operating space outside the zone into which car doors are opened. Intersections are easy to approach and cross.
LTS 2	Presenting little traffic stress and therefore suitable to most adult cyclists but demanding more attention than might be expected from children. On links, cyclists are either physically separated from traffic, or are in an exclusive bicycling zone next to a well-confined traffic stream with adequate clearance from a parking lane, or are on a shared road where they interact with only occasional motor vehicles (as opposed to a stream of traffic) with a low speed differential. Where a bike lane lies between a through lane and a right-turn lane, it is configured to give cyclists unambiguous priority where cars cross the bike lane and to keep car speed in the right-turn lane comparable to bicycling speeds. Crossings are not difficult for most adults.
LTS 3	More traffic stress than LTS 2, yet markedly less than the stress of integrating with multilane traffic, and therefore welcome to many people currently riding bikes in American cities. Offering cyclists either an exclusive riding zone (lane) next to moderate-speed traffic or shared lanes on streets that are not multilane and have moderately low speed. Crossings may be longer or across higher-speed roads than allowed by LTS 2, but are still considered acceptably safe to most adult pedestrians.
LTS 4	A level of stress beyond LTS3.

Table 16: Ground Truthing: Scoring criteria based on the Winters Method

Criterion	**Description and Scoring**
Bicycle Routes	Score the road segment higher if the road is a designated bicycle route, either a low-traffic road with sharrows or a road with a bike lane painted on it. Add **one** point for sharrows or a signed (but not painted) bicycle route, or add **two** points for well-marked bicycle lanes.
Route Separation	Score the road segment higher if the road contains a physically separated bicycle path (or is an off-road path itself). Add **two** points if the road contains a physically separated route (a cycletrack) or is an off-road path itself.
Connectivity of Bike-Friendly Streets	Score the road segment higher if there are other bike routes or likely routes that branch off from it. If there seem to be no bike-friendly routes connecting to the segment, add **zero** points. If there are one or two, add **one** point. If there are two or more within 500 feet, add **two** points.
Topography	Score the road segment higher if the topography is flat. If it is hilly enough to deter you from cycling here, score the segment lower. If the road segment is flat (or so low a grade that it would not affect your decision) add **two** points. If it is hilly enough that you would prefer to cycle elsewhere, add **one** point, and if it is so steep that you would only cycle there if you needed to, add **zero** points.
Destination Density	Score the road segment higher if there is a high concentration of potential cycling destinations (shops, offices, restaurants or schools). If there are one or two potential destinations within sight or 500 feet, add **one** point. If there are three or more, add **two** points.

Volunteers were also given the following information to use as a “cheat sheet” while conducting the field work:

Field Work Cheat Sheet

“Furth Method”

1 is *lowest-stress*, 4 is highest

Table 17: Levels of Traffic Stress Cheat Sheet

Level of Traffic Stress	**Short Description**
1	Suitable for children - protected cycletrack or off-road path
2	Suitable for nearly all adults - low-speed, low-volume street; or buffered bike lane; or a wide bike lane with clearance from parked cars (not frequently blocked)
3	More stressful than level two, but suitable for the "Enthused and Confident" category. Either a bike lane next to relatively high, moderate speed traffic or sharrows on a single-lane road.
4	Most stressful - only for "Strong and Fearless." Either no attempts at infrastructure or sharrows and moderate to high speeds and / or multilane roads.

“Winters Method”

Score from 1-10, with 0-2 points in each category: 1 is *least bikeable*, 10 is most bikeable (best). If all categories score a 0, award 1 point.

Table 18: Winters Bikeability Method Cheat Sheet

Category	**0 points**	**1 point**	**2 points**
Bicycle Routes	Not a bike route	Road has sharrows or a signed "bike route"	Road has a well-marked bike lane or cycletrack.
Route Separation	No physically separated path	n/a	Road has a physically separated path
Connectivity of Bike-Friendly Streets	No bike routes connected to road	One or two bike routes connected to road	Two or more connections within 500 feet
Topography	Steep enough that you would avoid route unless absolutely necessary	Enough slope that you would prefer another route	Flat terrain
Destination Density (*Retail, Restaurants, Office bldg., schools / college facilities*)	No destinations within sight	One or two destinations within 500 feet	Three or more destinations within 500 feet

Appendix B: Winters Analysis Parts

The following pages show the scores for each individual criterion that make up the Winters Analysis. These raster layers were combined and reclassified to make up the one to 10 Winters “bikeability” scale.

Figure 17: Winters Method Results: Bike Route Density Component

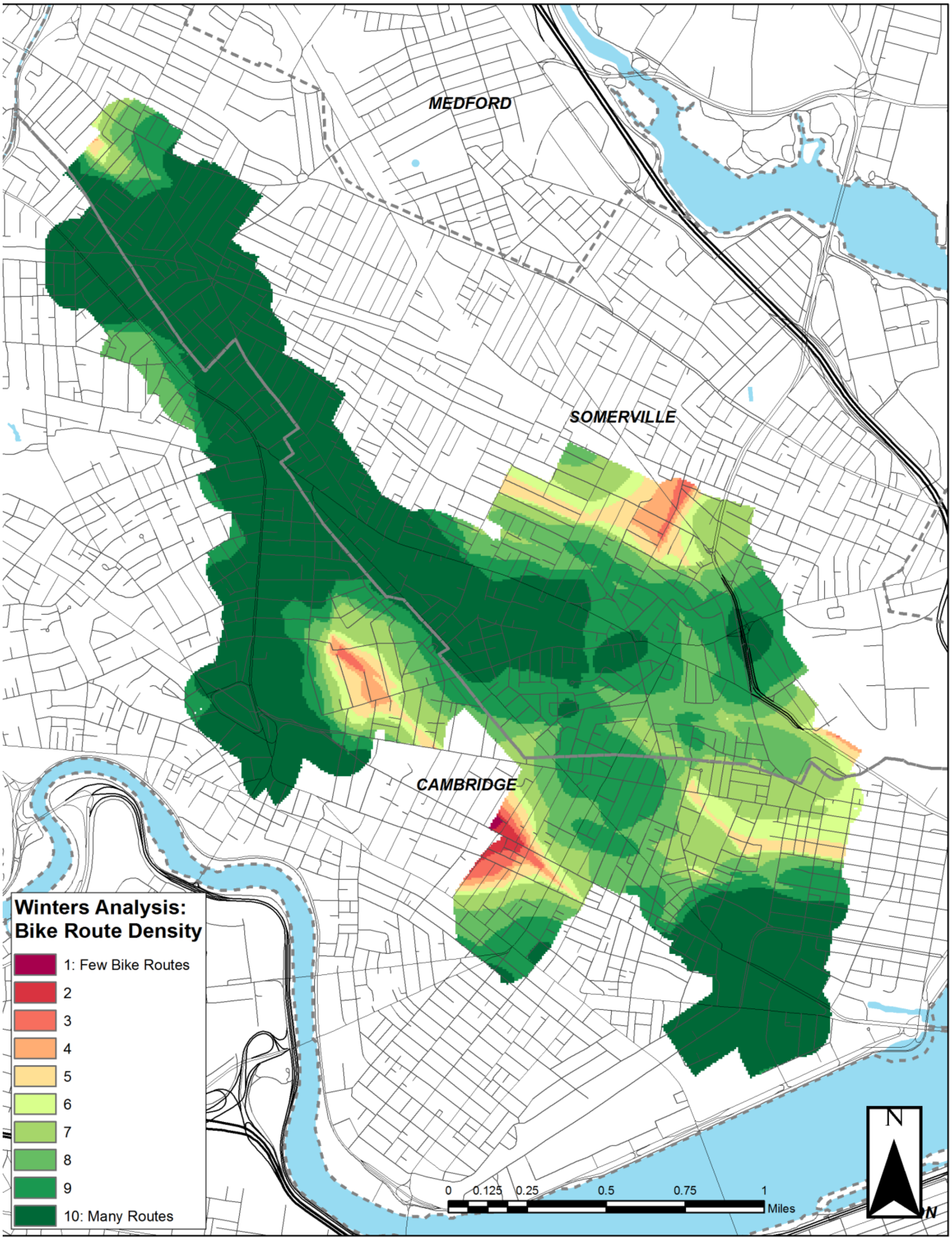


Figure 18: Winters Method Results: Bike-Friendly Destinations Component

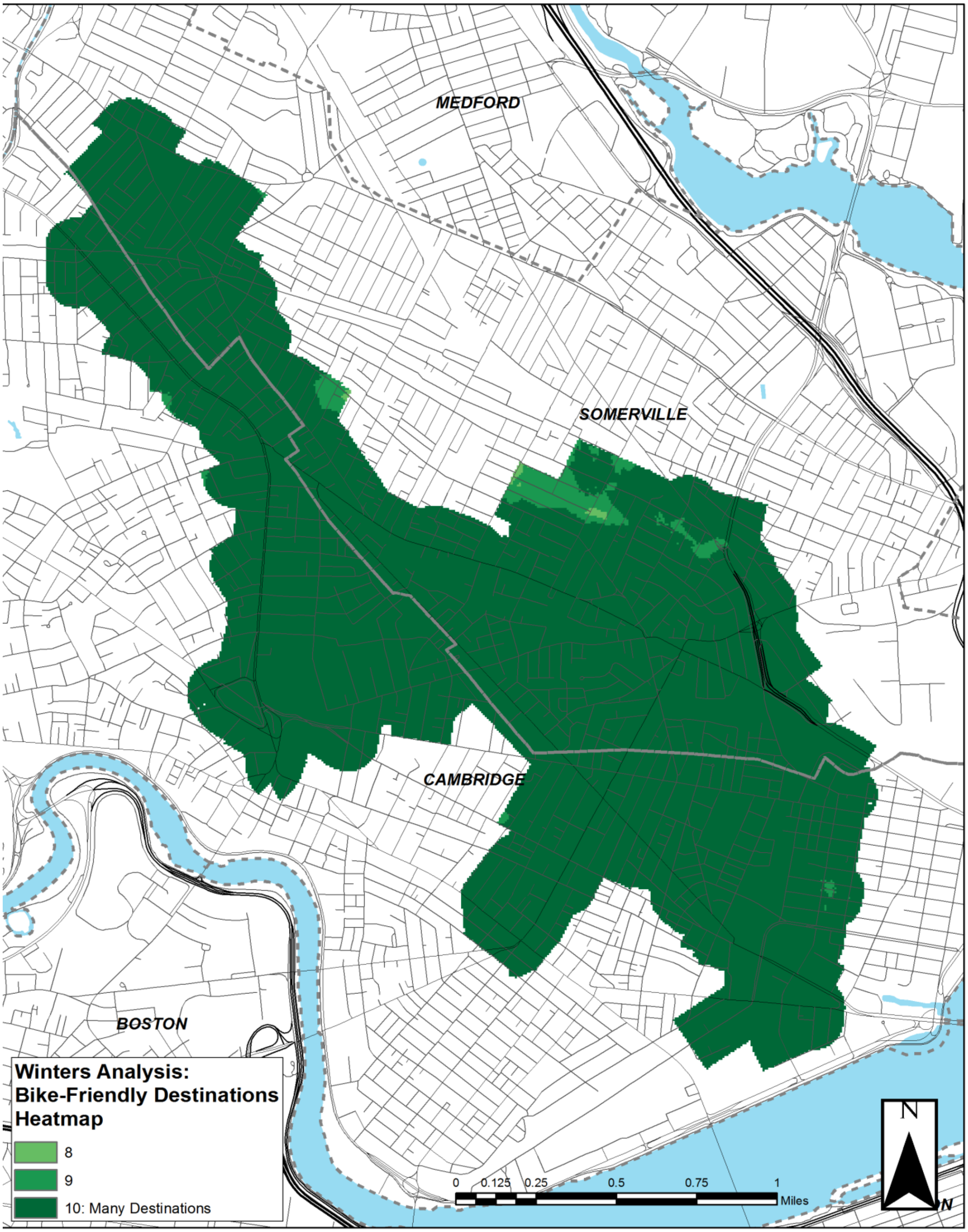


Figure 19: Winters Method Results: Separated Paths Component

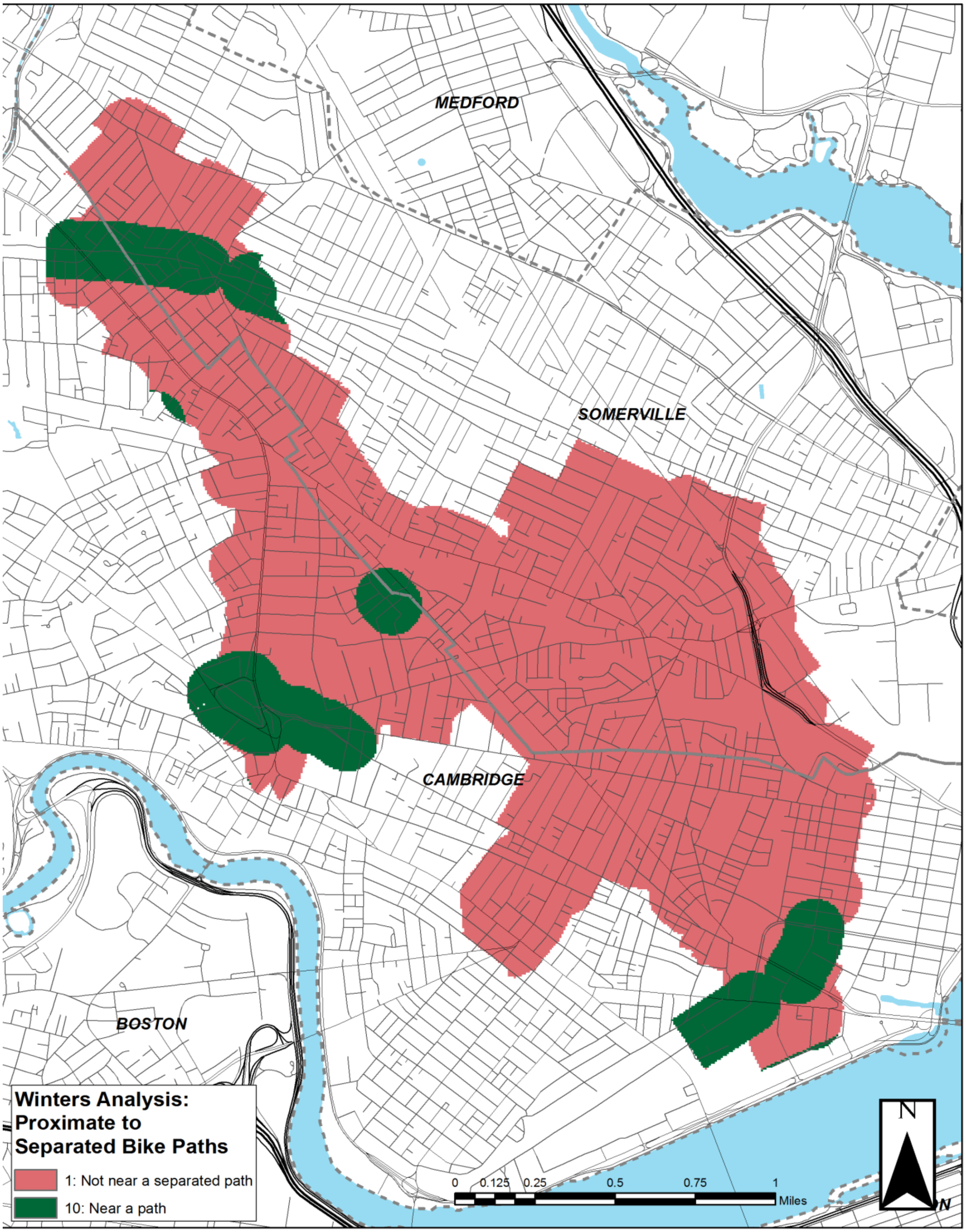


Figure 20: Winters Method Results: Slope Component

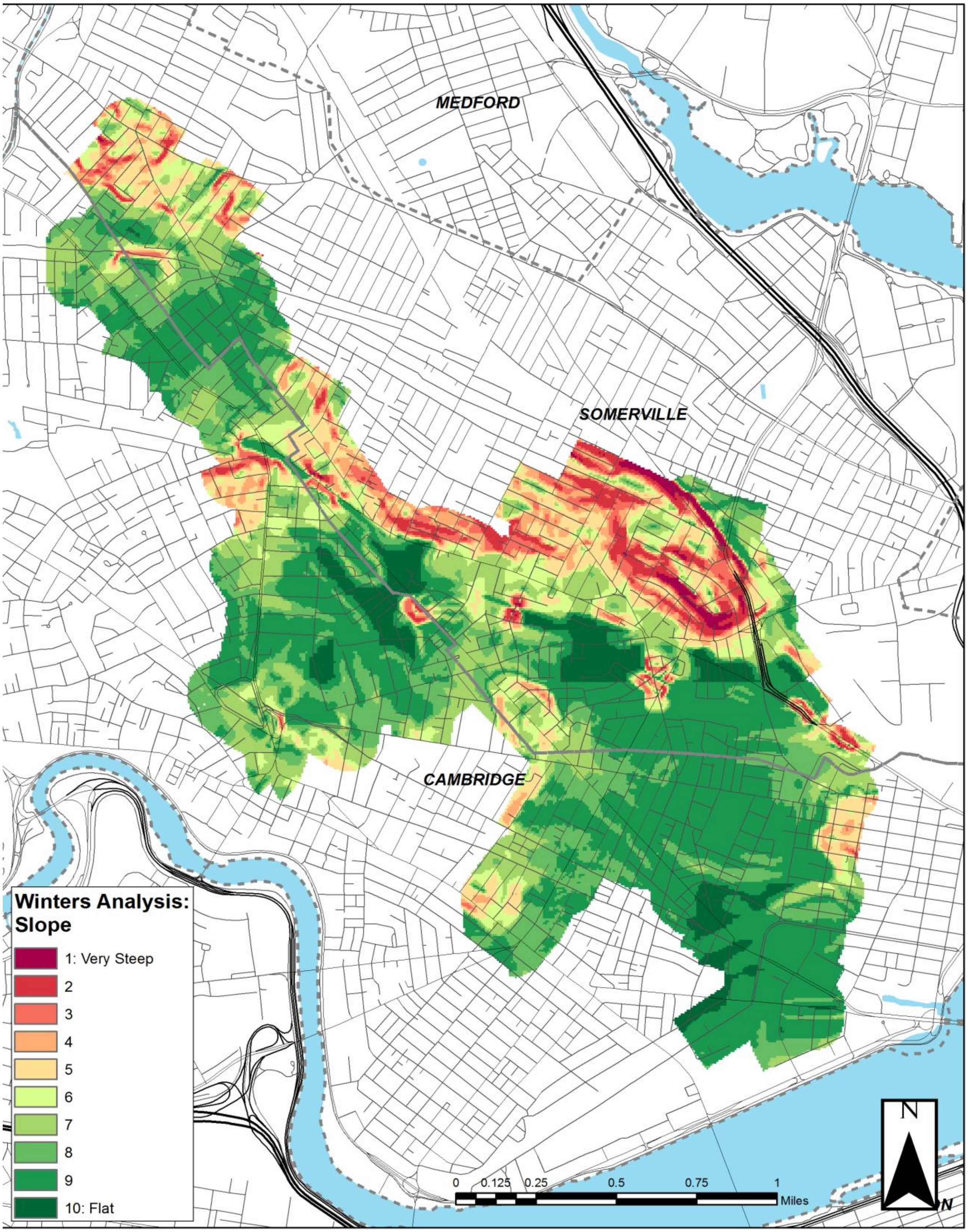
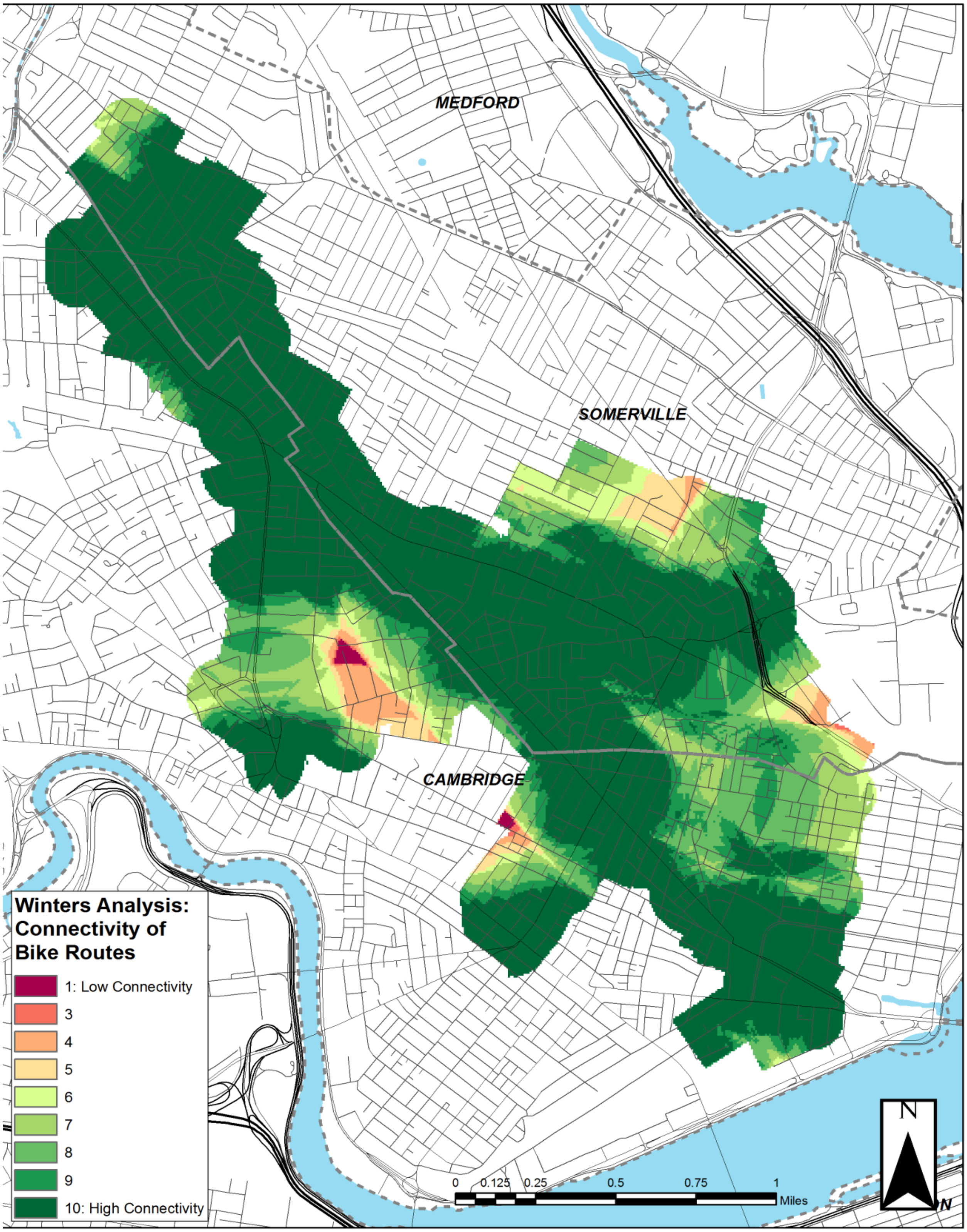


Figure 21: Winters Method Results: Bike Route Connectivity Component



Works Cited

Allen-Munley, C., Daniel, C. J. and Dhar, S. (2004). Logistic model for rating urban bicycle route safety. *Transportation Research Record,* 1878: 107–115

Alliance for Biking and Walking (2012). *Bicycling and Walking in the United States: 2012 Benchmarking Report*. Retrieved from http://bikewalkalliance.org/resources/benchmarking

Asadi-Shekari, Z., Moeinaddini, M. & Shah, M. Z. (2013). Non-motorised Level of Service: Addressing Challenges in Pedestrian and Bicycle Level of Service. *Transport Reviews: A Transnational Transdisciplinary Journal*, 33:2, 166-194, DOI: 10.1080/01441647.2013.775613

Aultman-Hall, L., Hall, F. & Baetz, B. (1997). Analysis of bicycle commuter routes using geographic information systems: Implications for bicycle planning. *Transportation Research Record,* 1578:102–110.

Bamberg, S., Ajzen, I., & Schmidt, P. (2003). Choice of Travel Mode in the Theory of Planned Behavior: The Roles of Past Behavior, Habit, and Reasoned Action. *Basic and Applied Social Psychology*, 25:3, 175-187, DOI: 10.1207/S15324834BASP2503_01

Belter, T., von Harten, M. & Sorof, S. (2012). Costs and benefits of cycling. SUSTRAMM: Sustainable transports for managing mobility. Retrieved from: http://enercitee.eu/files/dokumente/Subprojects/SUSTRAMM/SustraMM_Costs_and_benefits_of_cycling.pdf

Bhat, C., & Sardesai, R. (2006). The impact of stop-making and travel time reliability on commute mode choice. *Transportation Research Part B: Methodological,* 40:9, 709-730.

Cho, G., Rodriguez, D. & Khattak, A. (2009). The role of the built environment in explaining relationships between perceived and actual pedestrian and bicyclist safety. *Accident Analysis and Prevention*, 41 (2009), 692-702.

City of Boston (2013). *Boston Cyclist Safety Report 2013*. Retrieved from: http://www.cityofboston.gov/news/uploads/16776_49_15_27.pdf

City of Boston (2014). *State of the Hub: Boston Bikes Update 2013*. Retrieved from: https://www.cityofboston.gov/images_documents/2013%20ReportFinal_tcm3-44028.pdf

City of Cambridge, MA Community Development Department (2013). *The League of American Bicyclists Designates Cambridge as a Gold Level Bicycle Friendly Community*. Retrieved from: http://www.cambridgema.gov/CDD/News/2013/05/bicyclefriendlycommunities.aspx

City of Copenhagen, Denmark (2013). *Copenhagen Bicycle Account 2012*. Retrieved from: http://subsite.kk.dk/sitecore/content/Subsites/CityOfCopenhagen/SubsiteFrontpage/LivingInCopenhagen/CityAndTraffic/~/media/4ADB52810C484064B5085F2A900CB8FB.ashx

City of Somerville, MA (2010). *Somervision: City of Somerville, Massachusetts Comprehensive Plan.* Retrieved from: http://www.somervillema.gov/spotlights/comp-plan

De Hartog, J. J., Boogaard, H., Nijland, H., & Hoek, G. (2010) Do the Health Benefits of Cycling Outweigh the Risks? *Environ Health Perspectives 2010*: 118: 1109–1116.

Florida Department of Transportation (2014). Generic Cost per Mile Models. Retrieved from: ftp://ftp.dot.state.fl.us/LTS/CO/Estimates/CPM/summary.pdf

Geller, R. (ca. 2007). Four Types of Cyclists. *City of Portland Office of Transportation*. Retrieved from http://www.portlandoregon.gov/transportation/article/158497

Geller, R. (2011). Build It and They Will Come: Portland Oregon's Experience with Modest Investments in Bicycle Transportation. *City of Portland Office of Transportation*. Retrieved from https://www.portlandoregon.gov/transportation/article/370893

Green Lane Project (2015). About the Project. Retrieved from http://www.peopleforbikes.org/green-lane-project/pages/about-the-project

Harris, M. A., Reynolds, C. C., Winters, M., Cripton, P. A., Shen, H., Chipman, M. L.,… & Teschke, K. (2012). Comparing the Effects of Infrastructure on Bicycling Injury at Intersections and Non-Intersections Using a Case-Crossover Design. *Injury Prevention*. DOI:10.1136/injuryprev- 2012-040561

Krizek, K., & Roland, R. (2005). What is at the end of the road? Understanding discontinuities of on-street bicycle lanes in urban settings. *Transportation Research D,* 10:1, 55–68.

Landis, B., Vattikuti, V. & Brannick, M. (1997). Real-time human perceptions: towards a bicycle level of service. *Transportation Research Record,* 1578, 119–126

Larsen, J., Patterson, Z. & El-Geneidy, A. (2013). Build It. But Where? The Use of Geographic Information Systems in Identifying Locations for New Cycling Infrastructure. *International Journal of Sustainable Transportation*, 7:4, 299-317, DOI: 10.1080/15568318.2011.631098

League of American Bicyclists, the (2014). *Where we Ride: Analysis of Bicycle Commuting in American Cities.* Retrieved from http://bikeleague.org/content/revised-bike-data-breakdown

Li, F., Fisher, K. J., Brownson, R. & Bosworth, M. (2005). Multilevel modelling of built environment characteristics related to neighbourhood walking activity in older adults. *J Epidemiol Community Health* 2005, 59: 558-564 DOI: 10.1136/jech.2004.028399

Litman, T. (2014) Evaluating Active Transport Benefits and Costs. *Victoria Transportation Policy Institute.* Retrieved from http://www.vtpi.org/nmt-tdm.pdf

Lusk, A. C., Furth, P. G., Morency, P., Miranda-Moreno, L. F., Willett, W.C., & Dennerlein, J. T. (2011). Risk of Injury for Bicycling on Cycle Tracks Versus in the Street. *Injury Prevention.* DOI: 10.1136/ip.2010.028698

McGinn, A., Evenson, K., Herring, A., Huston, S. $ Rodriguez, D. (2007). Exploring Associations between Physical Activity and Perceived and Objective

Measures of the Built Environment. *Journal of Urban Health: Bulletin of the New York Academy of Medicine*. 84:2, 162-184

Mefford, C. and Griffith, T. (n.d). Using Geographic Information Systems to Design On-Street Bicycle Routes. Retrieved from http://www.bikewalktwincities.org/sites/default/files/Using_GIS_to_Design_On-street_Bicycle_Routes.pdf

Mekuria, M. C., Furth P. G., & Nixon, H. (2012). Low-Stress Bicycling and Network Connectivity. *Mineta Transportation Institute Report* 11-17. Retrieved from http://transweb.sjsu.edu/project/1005.html

National Association of City Transportation Officials (NACTO) (2011). *Urban Bikeway Design Guide*. Retreived from: http://nacto.org/cities-for-cycling/design-guide/

National Institute for Transportation and Communities (2014). Lessons from the Green Lanes: Evaluating Protected Bike Lanes in the U.S. Retrieved from: http://ppms.otrec.us/media/project_files/NITC-RR-583_ProtectedLanes_FinalReport.pdf

Pucher, J. & Buehler, R. (2008). Cycling for Everyone: Lessons from Europe. *Transportation Research Record,* 2074, 58–65

Schneider, R.J. & Stefanich, J. (2015). Neighborhood Characteristics that Support Bicycle Commuting: Analysis of the Top 100 United States Census Tracts. *Transportation Research Record: Journal of the Transportation Research Board,* 2015.

Techscene @ Boston. [Online map]. Retrieved from http://techscene.at/boston

TransLink (2011). *2011 Metro Vancouver Regional Trip Diary Survey*

Briefing Paper #1. Retrieved from: http://www.translink.ca/~/media/Documents/about_translink/media/2012/2011%20Metro%20Van%20Trip%20Diary%20Survey%20Briefing%201.ashx

United States Dept. of Energy (2013). Effects of Travel Reduction and Efficient Driving on Transportation: Energy Use and Greenhouse Gas Emissions.

Prepared by Cambridge Systematics. Retrieved from http://www.nrel.gov/docs/fy13osti/55635.pdf

United States Dept. of Transportation, Federal Highway Administration (2013). Guidance: Bicycle and Pedestrian Facility Design Flexibility. Retrieved from: http://nacto.org/wp-content/uploads/2013/09/design_flexibility_memorandum_092013.pdf

United States Environmental Protection Agency (2015). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2013. Retrieved from http://www.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2015-Main-Text.pdf

VanZerr, Mariah (2010). Resident Perceptions of Bike Boulevards: A Portland, Oregon Case Study. Retrieved from: https://www.pdx.edu/ibpi/sites/www.pdx.edu.ibpi/files/VanZerr_TRB2010_Paper10-4105.pdf

Winters, M., Davidson, G., Kao, D., & Teschke, K. (2011). Motivators and Deterrents of Bicycling: Comparing Influences on Decisions to Ride. *Transportation,* 38, 153-168.

Winters, M., Brauer, M., Setton, E., & Teschke, K. (2013). Mapping Bikeability: a Spatial Tool to Support Sustainable Travel. *Environment and Planning B: Planning and Design,* 40, 865–883 DOI: 10.1068/b38185

Woodcock, J., Edwards, P., Tonne, C., Armstrong, B., Ashiru, O, Banister, D…Roberts, I. (2009). Public Health Benefits of Strategies to Reduce Greenhouse-Gas Emissions: Urban Land Transport. *Lancet 2009*, 374: 1930-43