Non-residential pedestrian access to transit systems: a GIS modeling application

A Thesis Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

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December 2015

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Dedicated to my parents
Luz Marina and
Rosendo Angel

my siblings
Lody Rosario and
Wilmer Rosendo

and my nephews
Thomas James and
Samuel

ACKNOWLEDGEMENTS

I thank my parents, Rosendo and Luz Taboada, for their unconditional love, encouragement, and support. I am grateful for the guidance of my academic advisor, Dr. Chris Cherry. Thank you Dr. Shashi Nambisan and Dr. Lee Han for your involvement as committee members, for your mentorship, and for your continuous support.

I am appreciative of the Tennessee Department of Transportation (TDOT) for funding this project. Thank you Tammy Bohanan, from Knoxville Utilities Board Geographic Information Systems (KGIS); Jeff Welch and Mike Conger, from the Transportation Planning Organization (TPO); and Belinda Woodiel-Brill and Lauren Robinson, from Knoxville Area Transit (KAT) for providing the data and documents that made this research possible. Thank you Dr. Hyun Kim for your patient instruction in Geographic Information Systems (GIS). Lastly, I thank my fellow peers in the transportation group, as well as all who continue to take part in my academic and professional development.

ABSTRACT

The success of a city's urban transit system relies on the efficacy of its pedestrian infrastructure. A functional and access-oriented pedestrian network translates into safer pedestrian travel, increased demand in transit ridership, increases in commerce patronage, and reduced motorized travel (i.e., less congestion, and less vehicle emissions). Prioritization and allocation of sidewalk construction improvements are not always done in conjunction with transit service provisions. As a result, potential destinations are left inaccessible to pedestrians using the transit system. This study is motivated by concurrent research involving sidewalk improvement prioritization methods, within the scope of home-based work pedestrian transit trips. This study focuses on connecting transit to nonresidential origins and destinations. The main methodological approach developed relied on a gravity-based modeling framework. The method was applied to the City of Knoxville and the Knoxville Area Transit system. Land use, transit network configuration, and road network data for Knoxville and Knox County were used to estimate walking paths from transit stops to nonresidential destinations. These walking segments were ranked per a gravity-based potential attraction measure, and were compared to the existing sidewalk infrastructure in order to identify segments of network improvement opportunities. This study presents a methodology that can be used by transportation planners and decision makers for sidewalk improvement prioritization. Identifying key walking segments is an essential preliminary step to developing a pedestrian infrastructure that can effectively support a transit system, thus boosting transit ridership, and improving safety and access for riders.

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CHAPTER ONE:
INTRODUCTION

Pedestrian accessibility and mobility are among the central goals of planners and transport professionals when designing intermodal transportation infrastructure. Sidewalks are essential for the functionality, sustainability, and equity of transportation systems. An effective and connected sidewalk network will allow individuals to access retail, schools, parks and recreation, and health facilities. In addition, an equitable transportation system requires a connected sidewalk network in order to provide access to disabled individuals in need of accommodations. Access to trip origins and destinations is just one of the considerations weighed by planners during the process of allocating sidewalk improvements and new construction. Access of origin-based trips (e.g., home-to-work) has been addressed in previous studies. The focus of this study is access to nonresidential locations. Transit-based pedestrian trips to a nonresidential land use are the scope of the methods presented in this study.

1.1 Problem statement

Access to trip origins and destinations is just one of the considerations weighed by transportation planners and professionals during the process of allocating sidewalk improvements and new construction funds. Although transportation professionals recognize the importance of planning access-oriented pedestrian infrastructure, they may often lack feasible and replicable methods, necessary for the support and implementation of sidewalk improvement projects (Frackelton et al., 2013). Transit infrastructure investment without considering pedestrian accessibility may have limited success, due to potential destinations being left disconnected by gaps in the sidewalk network. An intermodal transportation system with inadequate sidewalk connectivity will pose safety challenges for riders who depend on transit, and also decreases demand for individuals who have alternative travel mode options (i.e., choice riders).

1.2 Objective

The objective of this study was to develop a reliable, replicable, and graphical measure that captures the potential attraction of destinations to pedestrian travelers (transit, walk access). The methods presented are intended to aid in the process of sidewalk improvements prioritization by identifying walking segments of high importance. This method is illustrated on a case study of retail land use in Knoxville. Extensions include other major land uses such as health care facilities and employment generators.

1.3 Approach

The approach presented in this study integrates classical gravity modeling methods (Wee and Pearce, 1985) with modern Geographic Information Systems (GIS) techniques. The paths linking origins and destinations were ranked per the gravity-based attraction measure. This measure can be replicated with easily accessible data, and basic spreadsheet and GIS knowledge. The results of the method can be presented in map form, and are easy to understand by both technical (e.g., transportation planners and engineers) and non-technical audiences (e.g., the public and policy-makers). This study provides a methodology for identifying accessibility gaps in a sidewalk network system. The thesis is organized into four sections. First, a review of the literature is presented. Second, the conceptual and methodological framework is discussed. Third, the developed model is applied to the City of Knoxville and the Knoxville Area Transit (KAT) system. Last, the results of the methodology are interpreted, and opportunities for further improvement and applications are discussed. Disaggregate (i.e., parcel-level) land-use, road network, and transit network data were used in a GIS software platform, ESRI ArcGIS 10.3, to estimate walking paths from non-residential locations to nearby bus stops. These walking paths were then ranked per a gravity-based potential attraction measure. This method can supplement current ad hoc methods as a preliminary iteration of sidewalk improvement prioritization and could be combined with other modeling approaches to improve walking network performance (e.g., safety models).

CHAPTER TWO:
LITERATURE REVIEW

Previous research has focused on the characteristics of pedestrian travel, the development of methods for measuring the demand and access of transit-oriented pedestrian travel, and the implications of effective pedestrian access. Past studies were reviewed and are synthesized in the following sections.

2.1 Characteristics of pedestrian travel

Most of the previous studies reviewed for this thesis focused on origin-based travel. Home-based work trips are an example of origin-based travel. Spatial and socioeconomic data have been used to make inferences on home-based work travel. An example of this is Abdelqader's (2014) disaggregation of Traffic Analysis Zone-level (TAZ) socioeconomic data to the individual residential parcels, to synthesize disaggregate populations for use in prediction of home-based walk-to-transit trips. Inferences of this type can be made because we have a good understanding of the causal relationship between the socioeconomic characteristics of individuals, and their home-based travel patterns. Destination-based travel has not been as heavily studied. Examples of this include shopping, leisure, and social activity trips. Studying destination-based access is not as prevalent because travel patterns unrelated to home-based and work-based activity are not well understood (Murray et al., 1998).

A central role of transport networks and services is to facilitate the movement of goods and people between different points in space–that is, to provide accessibility (de Stasio et al., 2011). Frackelton (2013) describes accessibility in terms of a function of opportunity and deterrence. Yigitcanlar et al. (2010) define accessibility as the ease of reaching needed or desired activities, thus reflecting characteristics of the land use system and the transportation system. Handy (1993) defines accessibility as having two parts: a transportation element (resistance factor), and an activity element (i.e., a motivation). The transportation element incorporates costs in terms of time and distance, while the second element pertains to the spatial distribution of activities, such as residences, jobs, shopping and entertainment destinations (Handy, 1993). Transportation planners and professionals use

accessibility indicators, among other metrics, to analyze the quality of transport networks.

Evans-Cowley (2006) state that comprehensive long-range planning and implementation of sidewalk policies are among the many requirements to ensure good pedestrian access. However, most communities have lacked coordinated pedestrian planning by the different parties often involved in the process (Evans-Cowley, 2006). Transportation planners, municipalities, private developers, and transit agencies are among the groups often involved in the decision-making that shapes pedestrian infrastructure networks. In recent decades, municipalities have gained awareness in the importance of providing pedestrians access to destinations of activity such as schools, parks, shopping, bus stops, and work. Nashville, TN developed a Strategic Plan for Sidewalks and Bikeways. Numerous studies have expressed the need of replicable and reliable spatial indicators related to transport in order to monitor health behaviors and outcomes, ultimately for the improvement in the practice of planning (Badland et al., 2015).

Frank and Pivo (1994) describe the location of services (e.g., business, education, employment, and recreation) and the provision of adequate transport infrastructure (e.g., sidewalks, transit, and parking accommodation) as the essence of urban planning. Disconnected sidewalk networks limit the success of transit systems. Also, declines in active travel (i.e., walking and bicycling) are observed with increases in car ownership (Dalton et al., 2015). The researchers compared GIS-generated shortest network paths (home-to-work) with actual paths traveled. They found that GIS-modeled routes are in agreement for non-motorized trips. That is, GIS-based estimates of traveled routes are accurate for walking and bicycle trips, but not as much for personal car trips.

2.2 Existing methods

Past studies evaluate the practice of determining transit service areas with the use of simple buffering operations. El-Geneidy et al. (2014) evaluate common practice in the transit industry for delineating service areas. The authors state that common practices, such as defining service areas within a 400-meter buffer of transit stops leads to redundancy and gaps in the service. Origin-destination survey

data were used to better define service areas surrounding transit services. Similarly, Biba et al. (2010) present a parcel-network method to determine the population with walking access to transit, and evaluate their results with previous buffer and network-ratio methods. Their method required readily attainable land-use data in conjunction with GIS and network analytics techniques. In addition, the parcel-network method provided precise results, without the need to perform extensive survey research.

Abdelquader (2014) addressed sidewalk investment prioritization from the perspective of home-based work (HBW) trips. Potential residence-to-employment transit trips were estimated with a logit regression model. The probabilities of residences making HBW trips via transit were mapped on the road network and compared to the existing sidewalk infrastructure.

Pulugurtha and Nambisan (1999) constructed a measure to evaluate transit market potential for transit service facility locations for a transit system. They developed a methodology to identify transit coverage and the transit market potential based on demographic characteristics in order to identify optimal locations for transit service facility locations.

Evans-Cowley (2006) reviewed problems faced by small cities interested in planning for sidewalks. They created inventories of characteristics of a municipality's sidewalk system such as the percent of population that walks to work, and what entity or entities are responsible for the maintenance of sidewalks. In addition, the effectiveness of newly developed walking infrastructure improvement policies in the Columbus Ohio metropolitan region was assessed.

Yigitcanlar et al. (2010) developed a comprehensive accessibility-indexing model called the Land Use and Public Transport Accessibility Indexing Model (LUPTAI). A primary objective of this study was to develop a measure that is easily understood by the public. The LUPTAI model measures the ability of travelers to access health, education, retail banking, and employment. Results are presented in a GIS-based map with a visual representation of the ease of reaching destinations by public transit and/or walking. The results were presented in GIS-based map form with discretized levels of accessibility and density.

Frackelton et al. (2013) developed a low-cost system with large deployment to automatically assess sidewalk quality–the Quality Index. The primary goal in this study was to provide a baseline for municipal and regional sidewalk inventories. A mobile tablet (video, accelerometer, GPS, gyroscope) was mounted onto a wheelchair sent out for data collection in the streets of Atlanta, GA. The collected data included sidewalk width, pavement surface condition, presence or absence of curb ramps, and presence of obstructions in the public right-of-way.

Murray et al. (1998) examined origin-based transit travel. They discussed changes in access to public transportation in Queensland Australia as the city grew from 1991 to 1996, and presented approaches for improving accessibility to travelers.

Many pedestrian access studies rely on GIS. Frank and Pivo (1994) explored the relationship between urban form and mode choice at the census tract level. GIS provided valuable results for applications in transportation management and modeling platforms (Nyerges, 1995). Biba et al. (2010) develop a parcel-network method, which makes use of parcel-level cadastral data, demographic attributes, and network distances (as opposed to Euclidean) to determine a superior estimate for populations with transit access. Improved spatial precision, and the availability of generating statistical summaries of the trip attributes (e.g., distances) are among the benefits of the parcel-network method (Biba et al., 2010).

The process of identifying sidewalk improvement priorities has been difficult in the past due to (1) the lack of disaggregate geographic data, (2) and the lack of reliable and repeatable methods. Neutens (2015) states that the first of these complications has been addressed by more availability and sophistication of small-grain geographic (e.g., parcel-level, physical, and demographic) data, as well as by recent advancements in GIS. The authors describe the second complication as having been mitigated by an increasing interest by planners and geographers in research pertaining to transit accessibility.

Mavoa et al. (2012) developed two comprehensive accessibility indices using transit data (e.g., stops, routes, and schedules), and land use data. The first included combined public transit and walking accessibility, and the second was related to transit frequency. Mavoa et al. (2012) developed a method to explain how many destinations were accessible via the public transit system. To quantify accessibility,

they considered the number of transit stops, duration of transit journey, and access to destinations.

Access to health care services was studied in the following works. Neutens (2015) explored the geographic accessibility to health services. Badland et al (2015) developed a conceptual framework to evaluate the impacts of access to transit on health behaviors and outcomes. The developed framework was used to identify what spatial indicators could support policy and planning

2.3 Implications of pedestrian access

Frackelton et al. (2013) stated that developing access-oriented walking infrastructure promotes alternatives to automobile travel, thus decreasing roadway congestion and vehicle emissions, promoting physical activity, and improving the lives of disabled persons by providing access. In addition, the presence and quality of sidewalks were described to be good predictors for the perceived safety and satisfaction of pedestrians. Mavoa et al. (2012) also stated that accessibility to public transit modes means less car dependence, decrease in GHG emissions, a reduction in motor-vehicle congestion and traffic crashes, improvements to physical activity and obesity-related illnesses.

Frank and Pivo (1994) observed the relationship between mode choice and employment density to be nonlinear. Research observed a dramatic increase in the proportion of transit trips taking place as employment density increased to more than 75 employees per acre. Walking trips were the most sensitive to increases in employment density.

The benefits of walking go beyond physical activity, and may have wider health impacts in relation to loneliness and mental health (social contact and quality of life), particularly in individuals of older age. There should be collaboration between geographers, health professionals, and transport professionals to achieve a more strategic approach for reducing car dependency at a societal level (Davidson and Curl, 2014)

Increasing levels of car use were observed to be associated with increases in GHG emissions, more traffic congestion, traffic crashes, oil price vulnerability and physical inactivity and obesity related illnesses (Frank and Pivo, 1994). Research to

better understand public transit accessibility is necessary for encouraging mode shifts that will reduce car reliance, and essential for the wellbeing of non-car households (Mavoa et al., 2012). In addition, accessibility in urban areas can be improved by co-modality, or by a combination of transport modes (de Stasio et al., 2011).

There are several shortcomings in the existing state of the practice. They include the determination of transit service areas with simple buffer operations, focus on origin-based travel due limitations in data availability, and the development of measures that are too general to assess accessibility at a disaggregate level. This research overcomes some of those shortcomings by implementing shortest-path network distance to determine expected service areas, using spatial characteristics of locations to quantify potential non-home travel activity, and providing flexible results that can be analyzed at different scales (individual segments, or corridors). This research also combines multiple GIS procedures to develop a reliable and replicable methodology to be used by planners and transportation professionals, which informs a practical problem of pedestrian access to destinations of non-residential activity.

CHAPTER THREE:
METHOD FOR MEASURING ACCESS

3.1 Study design

The measure developed in this study makes use of transit, road network, and parcel-level (disaggregate) data in a gravity model to generate a visual representation (GIS-based map) of the potential attractiveness of paths to non-residential locations from the perspective of transit-boarding and alighting pedestrians. This method makes use of building size as a proxy for the potential opportunity, or attractiveness, of a retail destination, and of travel time (or distance) as the cost imposed on the traveler for reaching the destination. The flexibility of a GIS platform allows for results to be generated at different scales such as regional, or for individual walking segments along corridors of non-residential transit-based pedestrian activity. The following sections detail the proposed method, and are divided into the following: (3.2) model inputs, (3.3) modeling access-measure ranked paths, and (3.4) analysis and discussion of results.

3.2 Model inputs

The availability of high-quality data, especially disaggregate data, tends to be a limiting factor in developing accessibility models for pedestrians (Yigitcanlar et al., 2010). Due to recent substantial advancements in GIS, classical methods, such as Huff's Gravity Model, can be revisited and made use of with readily available socioeconomic and spatial data at various scales (e.g., aggregate, disaggregate). The method developed in this study can be replicated on any GIS platform, and makes use of easily attainable spatial and land-use data.

3.2.1 The gravity model

The gravity model was developed for applications in probabilistic econometrics. Modelling with gravity-based formulations can aid the assessment of accessibility, as the gravity-based formulation can be based on the premise that the potential attractiveness of a destination can be directly proportional to the utility

offered to the traveler, and inversely proportional to the cost imposed on the traveler in reaching the said destination (Wee and Pearce, 1985).

Travel time was chosen as the cost imposed on travelers in reaching a desired non-residential destination, given that the focus of this study is pedestrian travel. The use of travel time (walk) as a disutility to reaching a destination is consistent with common practice in transportation planning. Coefficient parameters for out-of-vehicle travel time in logit mode choice models will often negatively impact the utility of a mode, compared to travel time spent inside a vehicle. The disutility associated with travel time (or distance) from the viewpoint of a pedestrian traveler is not the same as from a car-riding traveler. The time or distance cost imposed on a pedestrian is not linearly proportional with the perceived onerousness as distance increases. The denominator in the gravity model captures the non-linear relationship between the travel time and the disutility in reaching a destination.

The Institute of Transportation Engineers Trip Generation Handbook (ITE, 2008) provides data on the number of car trips that institutional, medical, office, retail, and services land use categories produce. In the Handbook, trip generation is tabulated against several types of independent variables. Several characteristics of destinations are presented as independent variables, and present their causal effects for personal vehicle trip generation. The most common characteristic of the land use is the floor area of the building. Others include employees, number of students, etc. In most cases, the size of the building increases the trip generation (though there are many reported cases where trip generation and square footage have almost no correlation). It this sense, square footage could be considered an imperfect measure of attractiveness. In the interest of data availability and future replicability for the applications of this method, the building area size of non-residential destinations was chosen as the proxy for the potential utility for a traveler (transit-walk access). Choosing the square footage as the numerator in the gravity formulation is logical for some land use type applications, such as retail and health care facilities. The large floor area of a shopping locale can be correlated to its patronage numbers. However, causal effect of floor area for patronage levels of every land use is not perfect. For example, considerably large destinations such as industrial buildings, car dealerships, or warehouses will most likely not receive higher patronage levels than

smaller locales of land use type related to retail or food. Other possible proxies for the potential attraction of nonresidential activities include number of employees for retail land uses, and number of beds for health care facilities. Moreover, the Handbook is solely focused on car based trip generation, yet for many land uses, building area still likely results in higher attractiveness for transit passengers.

In this study, the gravity model was adapted and takes on the following form:

$$A_{ij} = \frac{S_j}{T_{ij}^{\beta}}$$

Where:

A_{ij}: The potential attraction measure of a nonresidential destination, j, by a pedestrian, i, from the nearest bus stop via the road network

S_j: The floor area of nonresidential building destination, j, per 1,000 square feet

T_{ij}: The travel time, in minutes, experienced by the pedestrian in reaching the nonresidential destination

β: An empirically estimated parameter, which reflects the effect of travel time or distance based on land use type of destination

It is important to note that this study does not extend the traditional gravity approach to compare the attraction measures between competing land uses to distribute trips on the network. It simply normalizes the attractiveness (square footage) of a building by the distance from transit to that building.

3.2.2 Disaggregate data

Aggregate data such as county-level, zip code-level, TAZ, and census tract-level data are often public and readily available from web sources (e.g., US Census Bureau). Prompted by data availability, researchers have previously used aggregate data for modeling, and in doing so have been limited to results of low resolution.

Recent advancements in computation and GIS have facilitated the use of fine-scale data in modeling. Parcel-level property ownership data were gathered for the method proposed in this study. This data were obtained from the metropolitan planning organization (MPO) serving Knox County, and is of high resolution (parcel level).

The property ownership data is of vector type and is represented by closed polygons with tabulated spatial and non-spatial attributes. The flexibility of GIS allows for the computation of geometric centroids for each polygon, and for the relating of the generated points with the tabulated data from the buildings. Similarly, the tabulated spatial and non-spatial data can then be related to the access paths (i.e., bus stop to destination) generated with Network Analyst, thus facilitating the graphical representation of any desired calculations in relation to the original buildings. The road and sidewalk network datasets are also of vector type and are represented by individual line segments. The transit system dataset is comprised of points representing bus stop locations.

3.3 Model development

The following steps outline the process of estimating the gravity-based potential attraction measure for transit-based pedestrian access to locations of non-residential activity.

3.3.1 Data requirements and preparation

Transit bus stops, road network, and property ownership data shapefiles are required in the next steps of the procedure. These data are represented as point, line, and closed polygon coverage respectively in a GIS environment. The parcels of interest can be selected from the property ownership layer based on land use type. The parcels dataset can be further reduced by only selecting locations in proximity to bus stop locations. Determining an adequate buffer distance surrounding bus stops is subject to judgment and to the characteristics inherent to the area of study. A non-spatial attribute must be selected as the numerator of the gravitational formulation– that is, a proxy for the potential attraction of a destination. This attribute (e.g., square footage of building) must then be related and joined to the spatial parcels dataset. Determining access paths from bus stops to non-residential parcels requires origins and destinations of point coverage type. The bus stops are already coded as point coverage in the GIS environment. Point coverage can be generated from the non-residential parcels' polygon coverage data by computing the geometric centroid of each polygon.

3.3.2 Network Analyst

The Network Analyst extension in the GIS platform is used to generate shortest network distance access paths between bus stops and parcels. The use of a Boolean restriction parameter (e.g., 0 for walk and 1 for no walk) prevents access paths from forming along high-speed motorized roads, where it would be unreasonable to consider sidewalk construction (e.g., interstate highways). As observed in Figure 1, it is not necessary to create direct connections between the point coverage and the road network. The Closest Facility tool in the Network Analyst extension will still find adequate shortest network path solutions, which will terminate at a location orthogonal to each respective point. Previous iterations of the proposed methodology considered the use of access link-type connections, and resulted in topological errors by the Network Analyst in the road network. The closest path algorithm generates as many access paths, as there are non-residential parcel centroid points.

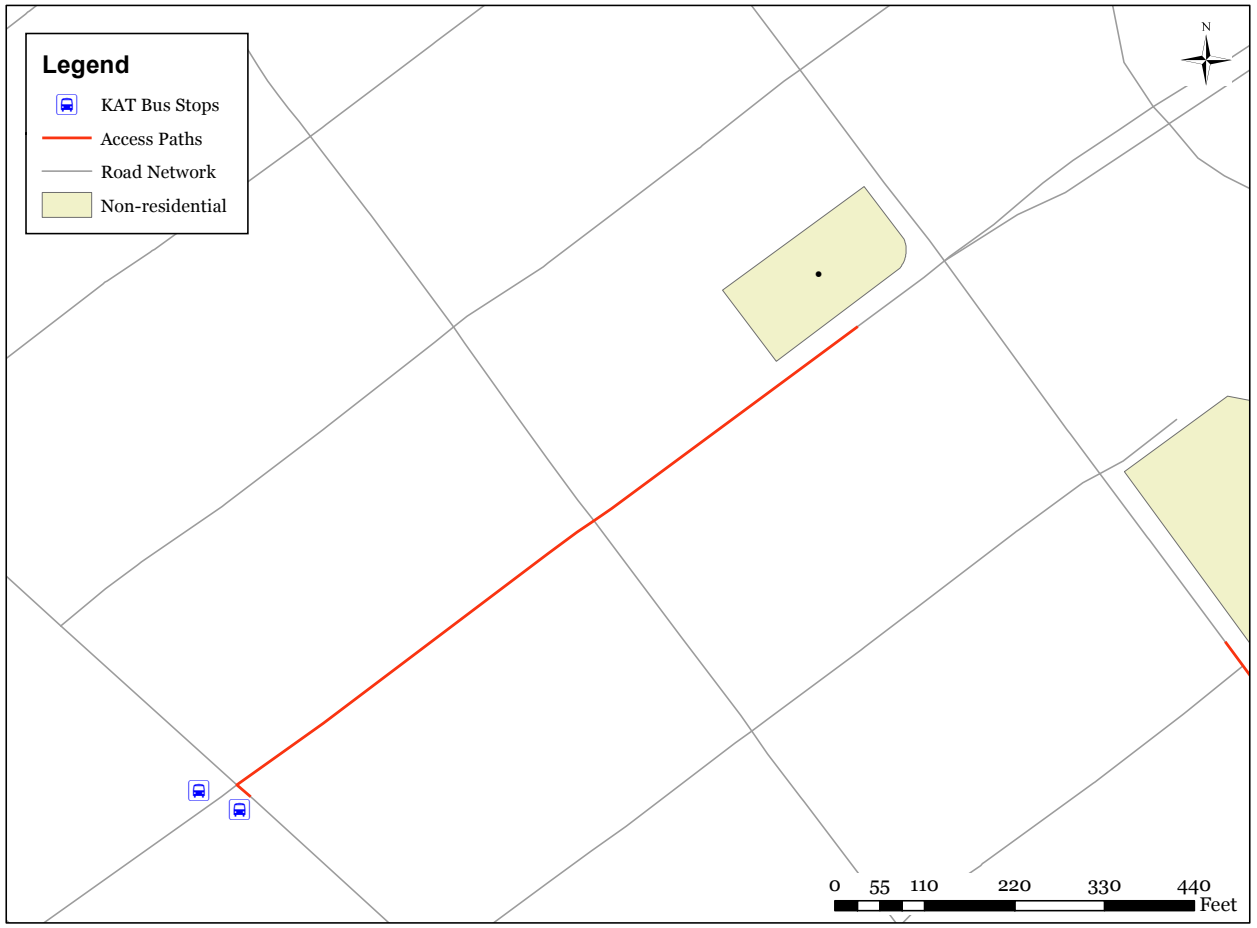


Figure 1. Shortest-network distance access paths generated with Network Analyst

3.3.3 The gravity-based measure

The values necessary for computing the gravity-based measure are related to the access paths shapefile, and loaded as attributes (i.e., columns) in GIS. The spreadsheet capabilities of the GIS platform allow for computations to be programmed into newly added attributes. The relationship considers building floor area per 1000 square feet, and access path distances converted to travel time. The characteristics of the study area should dictate the value selected for the walking speed of pedestrians. A value of 3.5 feet per second was selected for this study. Values of 1.0, 1.5, and 2.0 are chosen for the exponential value in the denominator of the formula. This exponential term can be selected per empirical calibration for each land use class. Assigning records (rows) a specific exponential term per land use class could improve the explanatory power of the independent variables (proxy, and travel time), but would require extensive collection of empirical data. Moreover, varying activity intensity per unit of building area is different between different land use classifications, and could be appropriately weighted in future studies.

3.4 Analysis of results

The proposed methodology makes use of the building floor area (per 1,000 square feet) of non-residential locations as a proxy for the potential opportunity available to a pedestrian traveler. Implicit to this generalization is the assumption that a large destination means an attractive destination for travelers depending on transit and walking modes. This assumption is not perfect, but has been explored in previous practice–square footage of retail buildings has been applied as a proxy for utility to patrons (Wee and Pearce, 1985), and population growth has been used as a proxy for economic growth in rail transport (Koopmans et al., 2012).

The methods result in access paths with a measure of potential attraction. The resulting access paths can be ranked and discretized from a continuous measure to categories of priority. A threshold of access can then be selected (e.g., top 25 percentile) and presented in map form. The results can be compared to the existing sidewalk infrastructure in order to identify gaps in the network.

CHAPTER FOUR:
ACCESS TO DESTINATIONS IN KNOXVILLE, TN

The following sections outline the application of the method formulated in this study using spatial and cadastral data for Knox County, specifically for the city of Knoxville, Tennessee. The Knoxville Utilities Board Geographic Information System (KGIS), the Tennessee Department of Transportation (TDOT), Knoxville Area Transit (KAT), and the Transportation Planning Organization (TPO) were the source of the high-resolution data necessary for the parcel-level GIS operations highlighted in the following sections.

4.1 Study area

Knox County is in the eastern region of the U.S. state of Tennessee. It is comprised of five hundred eight (508) TAZs, and has a population of 432,226 as of the US 2010 census. A map of TAZ population density, in persons per square mile for each TAZ, is presented in Figure 2.

KAT service terminates at the city limits. Therefore, the model was only applied to the City of Knoxville, despite the availability of data for Knox County. Non-residential activity in Knoxville is organized into corridors along roads of high-motorized vehicle travel, as shown in Figure 2. There were 191,583 property parcels in the KGIS dataset. 3,305 locales of nonresidential activity were queried out of the property ownership dataset. Figure 3 shows these categorized by land use class.

4.2 Knoxville Area Transit

KAT operates the public bus system for the city of Knoxville. Knoxville's public transit service originated in 1876, and it officially became KAT in 1995. KAT serves over three million passengers per year (KAT, 2015). The KAT network is comprised of 28 bus routes, 1,126 bus stops, and a terminal located in the central business district (CBD), as shown in Figure 4. The shapefile for bus stops used in this study only contains spatial location; route information associated with each route can be related from external sources if needed.

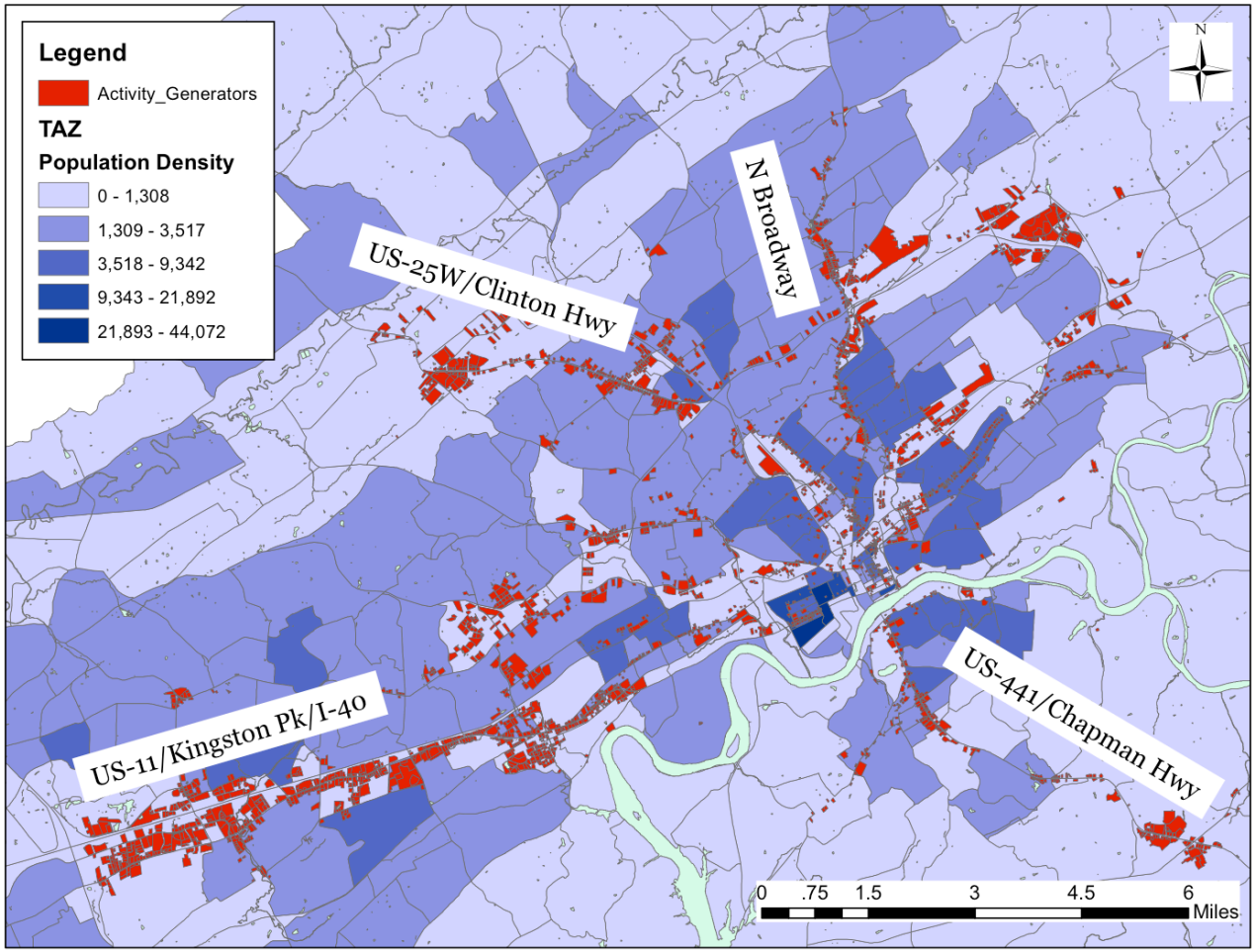


Figure 2. Population density by Traffic Analysis Zones (TAZ) in Knox County.
Source: Luis Taboada (2015)

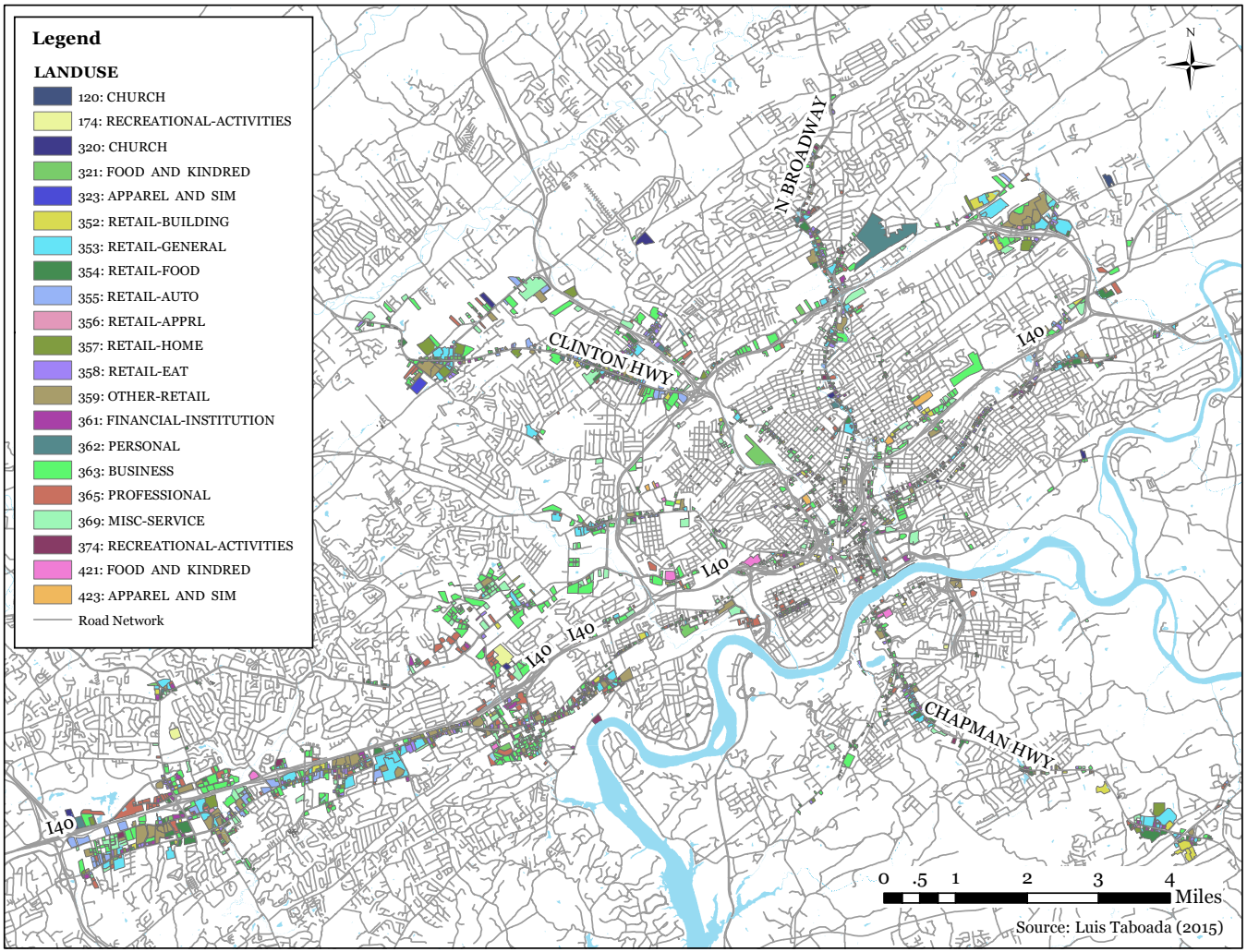


Figure 3. Classified nonresidential locales in Knoxville, TN

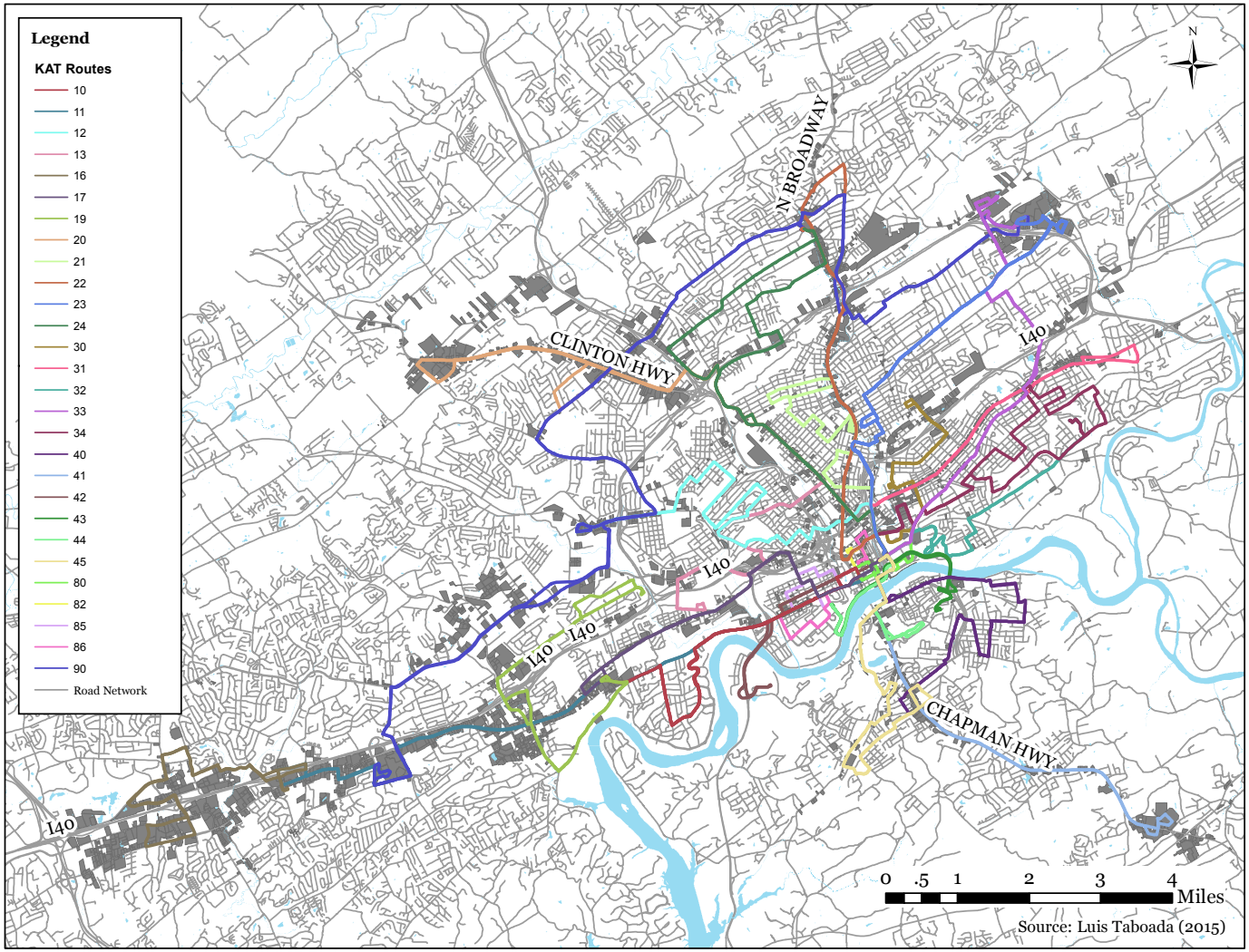


Figure 4. Knoxville Area Transit Routes

4.3 Knox County data preparation and analysis

The flexibility of the gravity-based attraction model allowed for the use of readily available parcel and network data. The following sections detail the methods applied to the Knoxville dataset using ESRI ArcGIS 10.3.

4.3.1 Building areas

The property ownership shapefile was loaded into the GIS platform. The values for building area were joined from a tabulated land use dataset, and normalized by 1,000 square feet. 3,305 nonresidential parcels were selected per the desired land use types, as shown in Figure 3, and exported as a separate shapefile. Figure A.1 (in appendix) provides a classification of the non-residential building areas, in square feet. The minimum value of building area size in square feet was 105 ft^2, the maximum was 393,893 ft^2, the average was 7,842 ft^2, the median 3,416 ft^2, and the standard deviation 17,972 ft^2. The normalized values for building area were used as the numerator of the gravity-based potential attraction formulation.

4.3.2 Network Analyst

Access paths were generated from bus stops to parcel centroids along the road network. The closest facility tool in ArcGIS Network Analyst was used to calculate the shortest network distance from the geometric centroid of each parcel (count 3,305), to a respective bus stop (count 1,126). Network Catalog was used to convert the road network shapefile to a Network Dataset file (nodes and edges), as a preliminary step to solving the closest facility problem by the Network Analyst. Within the settings for the Network Analyst, no restriction was placed wrong-way travel via one-way streets–a restriction common when performing calculations for motor vehicle travel. However, a restriction was implemented to prevent paths from being generated on Interstate highways (e.g., I-40, I-275, and US-129), since Interstate highways generally prohibit non-motorized travel. As mentioned in the previous chapter, an attempt to generate access links from the point coverage (i.e., bus stops and centroids) to the road network coverage repeatedly led to errors in the Network Analyst procedure. Topological errors in the joints between the access links and the

road network would have to be manually identified and corrected. We later determined that the Closest Facility tool in Network Analyst is able generate adequate solutions from “facility” to “incident,” by terminating the path of access along the road network at a location orthogonal to each point. The two distances that are left as remainder for each path can be neglected, as they are minimal in comparison to the total length of each access path. An exception to this is in the case of very large buildings, the geometric centroid will be at a significant distance from the termination of the access path along the road network, as seen in Figure 5. The remaining distance between parcel centroid (black point) and where the access path terminates (red line) is significant, but one can neglect this since the destination of the respective locale is not necessarily its geometric centroid.

Network Analyst found 3,273 solutions to the closest facility problem. The paths are shown in Figure A.2, classified by total distance in feet. The length (feet) values were converted to travel time, in minutes, using a walking speed of 3.5 feet per second; a value assumed reasonable and used in practice (FHWA, 2009). The 3,273 walking segments are represented in GIS as line coverage (i.e., vector data). The building size area data were joined with the paths shapefile using spatial proximity and tabular association. The GIS platform was used to allocate all necessary values for the gravity-based computation to the access paths shapefile as new attributes.

4.4 Model results

The gravity-based calculation performed for each access path resulted in 3,273 values of potential attraction measure (AM). The flexibility of using a GIS platform allows for these results to be presented in a manner accordingly to the scale of interest. The range of the results is vast. That is, the maximum value is greater than the minimum by five or more orders of magnitude. There is more explanatory worth in the model through parameterization the results from continuous to discrete values.

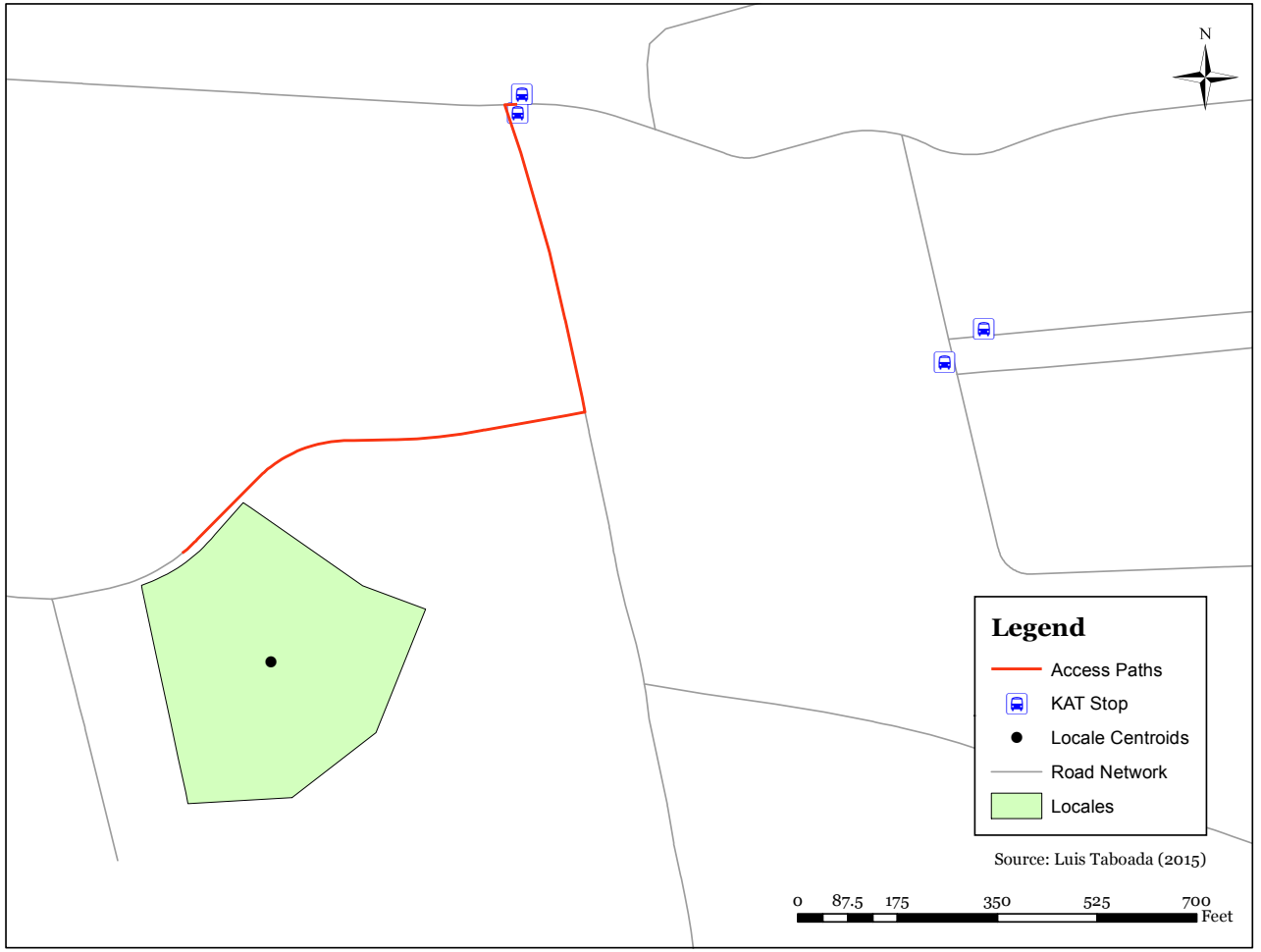


Figure 5. Model limitations in reaching geometric centroid of parcel

4.4.1 Sensitivity analysis of beta

Empirical calibration of the exponential term, beta, was not in the scope of this study and was not feasible due to extensive data requirement needs. A sensitivity analysis was performed to assess the effects on the results of using distinct exponential parameters. The AM values were calculated using three different exponential terms. The three sets of results are denoted by AM1.0, AM1.5, and AM2.0. Each set of results was sorted by increasing magnitude of the gravity-based potential attraction measure. High-priority paths were defined as the highest-ranking 30 miles of results from each attribute. Choosing a 30-mile length as the top-ranked paths of access paths was arbitrary, and done to reflect a common situation in which financial constraints dictate a maximum length of possible sidewalk improvements.

Statistical and graphical results suggest that the model used in this study is somewhat sensitive to changes in the exponential parameter. Table 1 presents a summary of descriptive statistics for the building areas (in feet^2), the access path lengths (in feet), and the gravity-based potential attraction measures associated with the highest-ranking 30 miles for the three sets of results. Graphical results of the three sets of values are shown in a GIS-based map in Figure A.3.

Selecting an exponential parameter of 1.0 resulted in less, but longer high-priority paths, as reflected in the maximum and standard deviation values for the path lengths of AM1.0 shown in Table 1. In addition, the top 30 miles of high-priority paths for AM1.0 were more representative of larger buildings, as reflected in the minimum, median, and standard deviation values for building sizes. Graphical representation of the differences in quantities and lengths of high-priority paths are shown in Figure 6 and Figure 7. Using a beta of 1.5 or 2.0 in the gravity-based model results in high-priority paths that are concentrated along the activity corridor, whereas using a beta of 1.0 gives priority to some long and isolated paths that provide access to relatively large buildings.

The explanatory worth of the exponential term can be further explored with comprehensive empirical calibration. Such an exercise would involve correlation between the characteristics of patronage and land use characteristics of locales.

Table 1. Descriptive statistics for high-priority results with three betas

		AM1.0	AM1.5	AM2.0
BETA		1	1.5	2
Count		515	726	821
Building floor areas in ft^2	Min	625	595	493
	Max	393,893	393,893	393,893
	Median	8,211	5,099	4,222
	SD	38,735	32,263	27,956
Path lengths in ft	Min	0.141	0.141	0.141
	Max	5,401	2,471	2,471
	Median	151	146	151
	SD	510	271	181
Gravity-based Potential Attraction Measure	Min	5	3	2
	Max	50,940	1,966,913	75,946,385
	Median	10	8	7
	SD	2,270	73,086	2,651,116

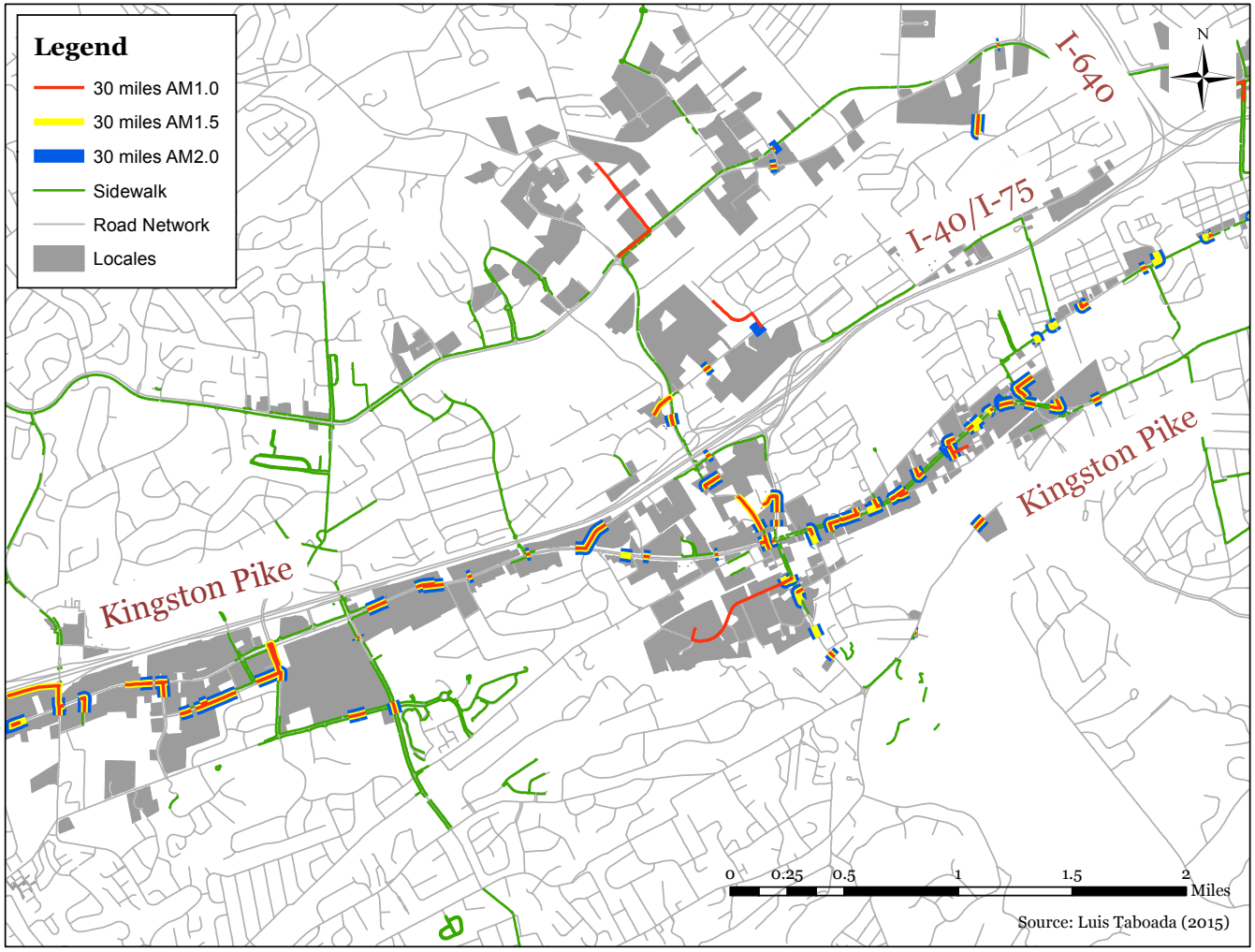


Figure 6. Detail of sensitivity analysis results. West Knoxville

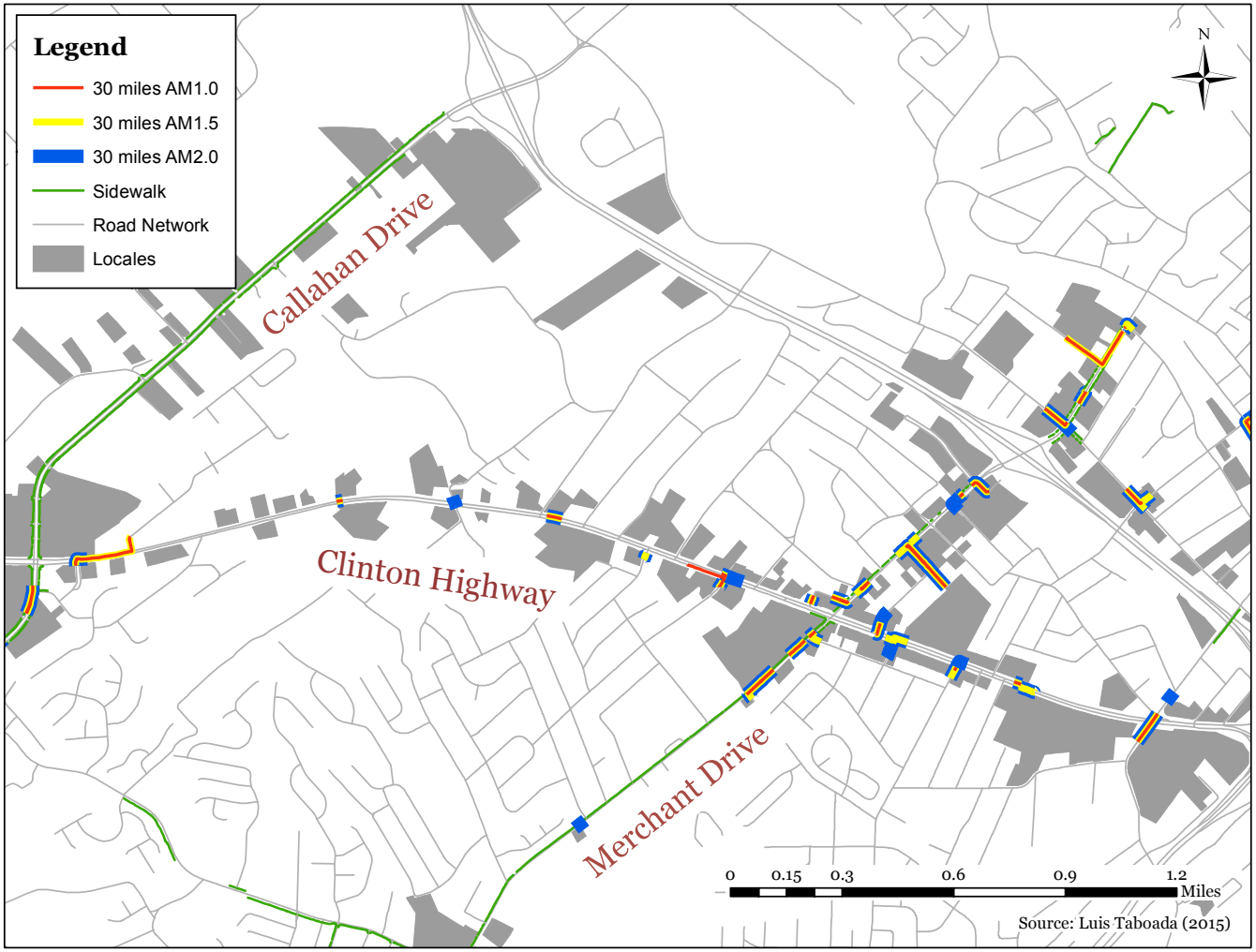


Figure 7. Detail of sensitivity analysis results. Northwest Knoxville

4.4.2 Clinton Highway case study

A section of Route 20 of the KAT bus system was considered for the case study. Route 20 provides service to Central Pike and Clinton Highway in northwest Knoxville. There is existing-sidewalk coverage along Merchant Drive. However, there are no sidewalk segments on Clinton Highway, despite the presence of several non-residential locations and numerous bus stops servicing Clinton Highway. A traveler egressing transit in the vicinity and wishing to access non-residential activity along Clinton Highway would need to walk on road shoulders and grass, and face high-speed vehicle traffic (45 mph). A land-use classification of the destinations along the corridor of interest is shown in Figure 8. The Clinton Highway road segment considered for this case study spans approximately 0.5 miles in each direction from the intersection of Merchant Drive and Clinton Highway, as shown in Figure 9. There are more than twenty (20) bus stops within a 0.5-mile radius of the intersection. Gravity-based potential attraction measures for the access paths were calculated with an exponential value of 2.0. The results were discretized into five categories per Quantile classification. That is, each class contains the same number of paths. The results are presented in Table 2.

Pedestrian access improvements have already taken effect along Merchant Drive. In the case that limitations in funds do not allow for the construction of the entire corridor, the methodology presented in this study can be used to identify high-priority segments for accessing non-residential destinations along Clinton Highway. The GIS-based results can be tailored to specific scales (e.g., regional, neighborhood, or intersection), and to specific land use classes (e.g., retail, eateries, or health care facilities).

Table 2. Summary of results along Clinton Hwy

Priority	Count	Total length (feet)
Low	18	15,667
Low-mid	17	11,494
Mid	17	9,680
Mid-high	17	6,024
High	17	2,203



Figure 8 . Land use classes along Clinton Highway at Merchant Drive.

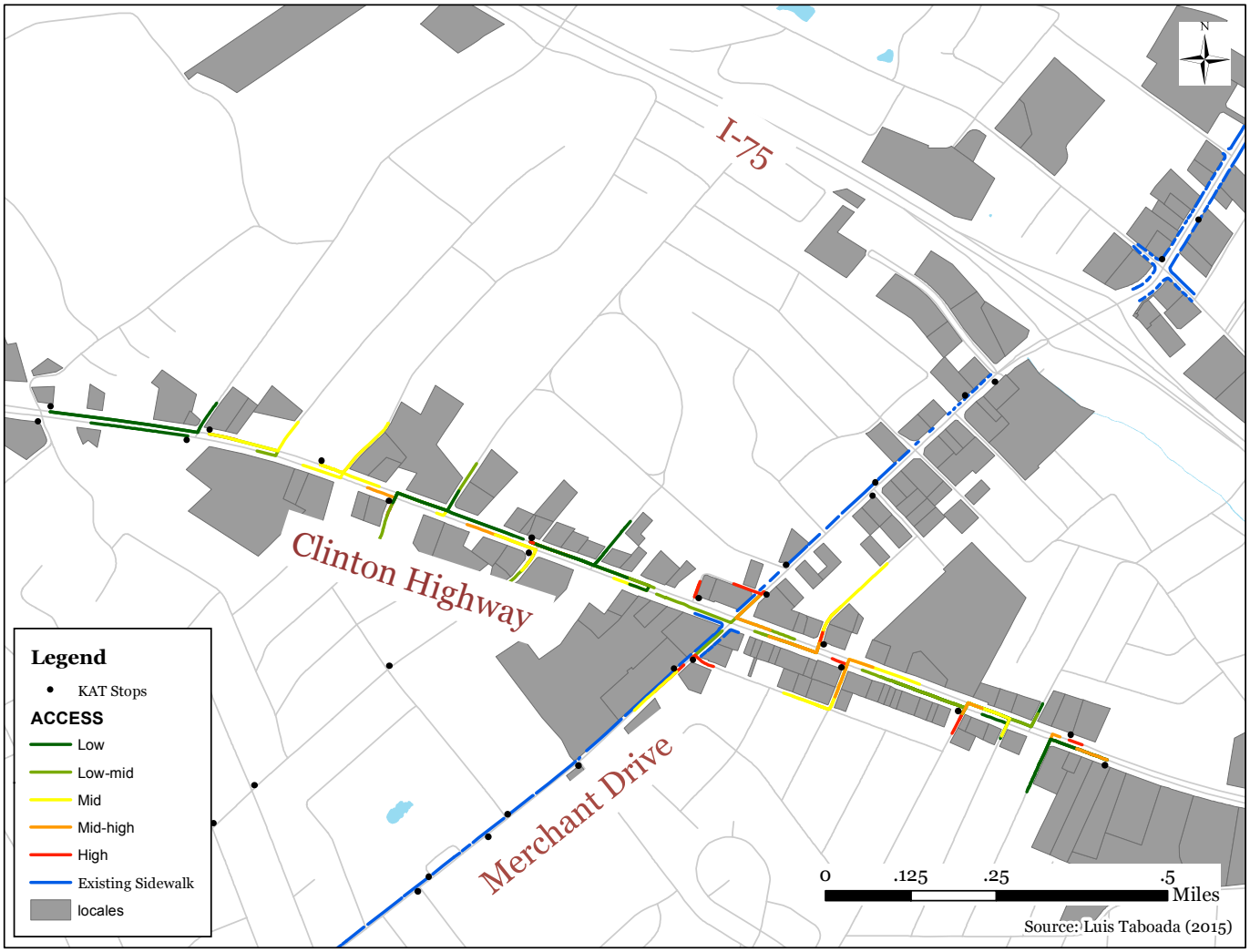


Figure 9. Model results along Clinton Highway corridor

CHAPTER FIVE:
CONCLUSION AND FUTURE RESEARCH

A method was developed to evaluate access of transit-based pedestrian travel to non-residential activity. This method can be implemented using easily attainable data and a GIS platform. The computed gravity-based measures capture the potential attraction of non-residential activity, at a disaggregate scale. This provides a method that can be used to assess the efficacy of both the coverage of the existing sidewalk network, and the configuration of the transit network system (e.g., bus stop locations). The gravity-based potential attraction measure can be presented at the disaggregate level, for assessing individual walking paths and sidewalk segments; or at the aggregate level, for studies at a scale of lower resolution (e.g., regions or neighborhoods). City engineers, planners, transportation professionals, and decision makers are among those who can benefit from the methodology. Ad hoc measures involving the allocation of limited improvements funds could be enhanced with methods such as this.

There are several assumptions implicit to gravity-based modeling. The first of these is that the attractiveness of a locale is proportional to its size. The use of this proxy is common in transportation planning (e.g., trip generation), and has been validated in previous studies (Wee and Pearce, 1985). Secondly, it is not absolute that a pedestrian will in fact choose the shortest network distance as a path of access to a locale. A traveler may consider many other factors such as grade changes in the route, safety, lighting, and trip touring (i.e., sequencing destinations in some preferential order).

Opportunities for further research and improvements of the methodology detailed in this study include: (1) integrating the characteristics of the roadways on which the sidewalk allocation is to be considered. That is, the potential attraction index assigned to walking paths could take roadway characteristics such as speed limits, presence of existing bike lane, and configuration of road shoulder into consideration. New sidewalk allocations along high-speed roadways would receive more priority than allocations along low-speed residential roadways. (2) In addition, the characteristics of the bus route (e.g., headways, wheelchair ramps, or ridership

volumes) used by the traveler could also be considered in the index assigned to walking paths. (3) Empirical calibration of the exponential term based on land use classes would further improve the explanatory power of the gravity-based measure. This would require economic data or patronage records for different classes of land use. (4) Implementing methods common to urban planning that capture the intensity and extent of land use in the built environment would add sophistication to the model and explanatory power to the measures–this could be achieved by using floor-to-area ratios instead of building areas. (5) Finally, there are opportunities to explore the development of an iterative method in which the methodology presented in this study is implemented, and then reassessed based on new bus stop locations (i.e., new facilities for Network Analyst). The new results would be compared to previous iterations until reaching an optimal configuration of bus stops. The implications of an iterative process are that it may be more economical for a municipality to relocate bus stops than it would be to build new sidewalk segments.

The implications of the proposed methodology go beyond providing travelers with access to retail and entertainment. Individuals from no-car households depend on urban transit to access destinations of employment, social, health care, and financial services. A transit system will only be as capable in providing access, as its surrounding pedestrian infrastructure is effective. Coordination between transit agencies, planners, and private developers in the design and allocation of pedestrian improvements will ensure that urban transit systems can provide access and equity to all.

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APPENDIX

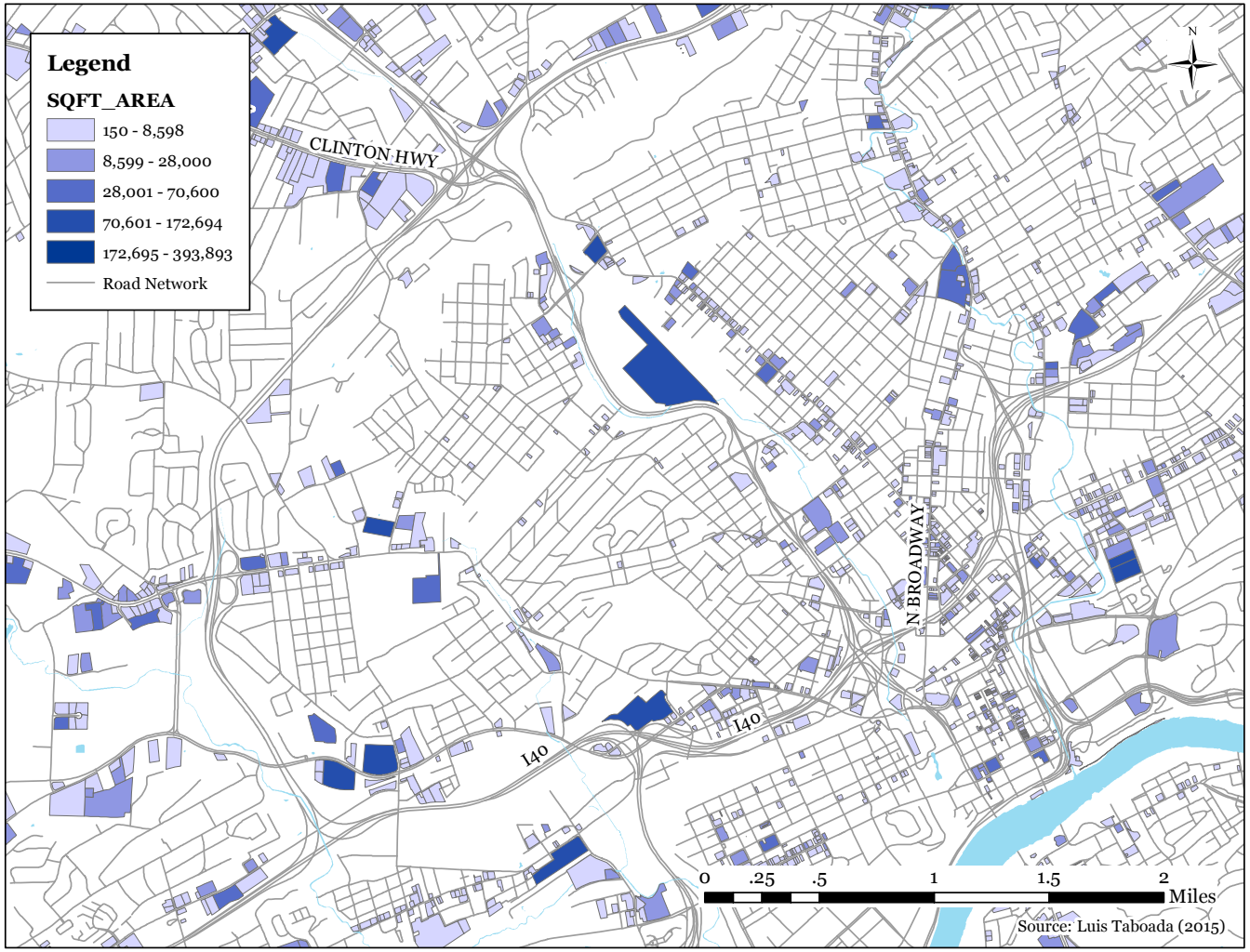


Figure A.1. Classification of building areas in square feet

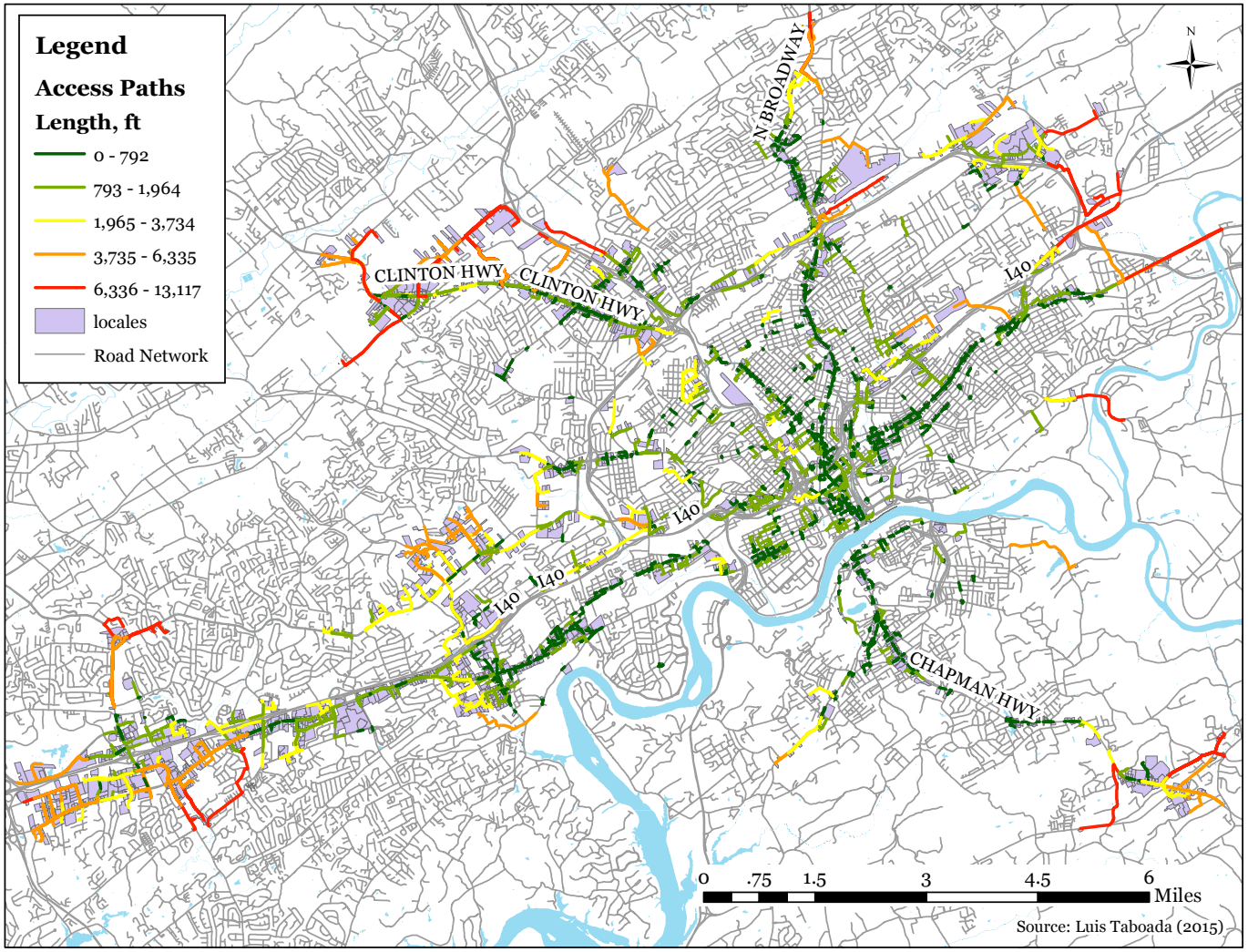


Figure A.2. KAT stop-to-parcel access paths, classified by distance in feet

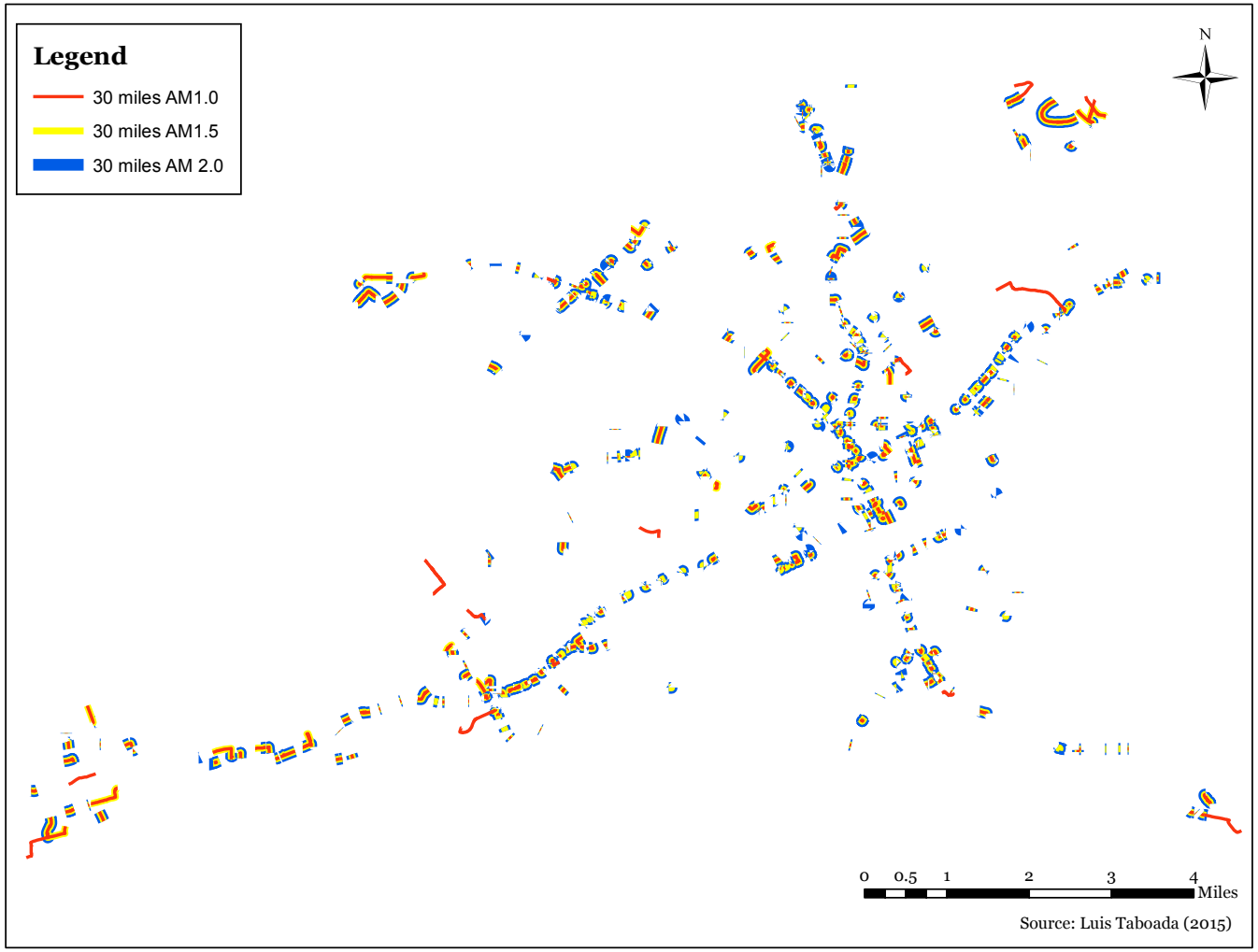


Figure A.3. Results of sensitivity analysis for the exponential term

VITA

Luis Taboada was born in Bogota, Colombia, and immigrated with his family to the United States when he was eight years old. He graduated with a Bachelor of Science in Civil and Environmental Engineering from Tennessee Technological University, Cookeville, Tennessee. Luis developed an interest in transport planning and traffic operations during his undergraduate studies. After leaving Tennessee Tech, he enrolled as a graduate student at University of Tennessee, under the tutelage of Dr. Chris Cherry. While at UT, Luis worked as a graduate teaching assistant in computer programming applications to engineering; and as a graduate research assistant in the areas of transportation planning, transit, eBike technologies, and sustainability. After graduation, Luis is joining industry as a civil engineering consultant in southeast Florida.