

Access to Destinations

Application of Accessibility Measures for Non-Auto Travel Modes

Report # 9 in the series
Access to Destinations Study

Report # 2009-24

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CENTER FOR TRANSPORTATION STUDIES



Technical Report Documentation Page

1. Report No. MN/RC 2009-24		2.		3. Recipients Accession No.	
4. Title and Subtitle Access to Destinations: Application of Accessibility Measures for Non-Auto Travel Modes				5. Report Date July 2009	
				6.	
7. Author(s) Kevin J. Krizek, Michael Iacono, Ahmed El-Geneidy, Chen Fu Liao, Robert Johns				8. Performing Organization Report No.	
9. Performing Organization Name and Address College of Architecture and Planning University of Colorado Denver P.O. Box 173364 Denver, CO 80217 Department of Civil Engineering University of Minnesota 500 Pillsbury Drive SE Minneapolis, MN 55455 School of Urban Planning McGill University Suite 401, McDonald-Harrington Building 815 Sherbrooke Street West Montreal, Quebec, Canada H3A 2K6 Center for Transportation Studies 511 Washington Avenue SE Minneapolis, MN 55455				10. Project/Task/Work Unit No.	
				11. Contract (C) or Grant (G) No. (c) 89261 (wo) 75	
12. Sponsoring Organization Name and Address Minnesota Department of Transportation 395 John Ireland Boulevard Mail Stop 330 St. Paul, Minnesota 55155				13. Type of Report and Period Covered Final Report	
				14. Sponsoring Agency Code	
15. Supplementary Notes http://www.lrrb.org/PDF/200924.pdf Report # 9 in the series: Access to Destinations Study					
16. Abstract (Limit: 250 words) Conventional transportation planning is often focused on improving movement (or mobility)—most often by the automobile. To the extent that accessibility, a well-known concept in the transportation planning field since the 1950s, has been measured or used in transportation planning, such measures have also been auto-based. Broadening the scope of accessibility to include a wide array of destinations and non-auto modes such as walking, cycling, and transit has been previously proposed as a much needed aim among planning initiatives. A central issue is that to date, however, there have been few examples of measures draw from. When it comes to bicycling, walking, and transit measures of accessibility are an endeavor long on rhetoric but short on execution. This report discusses such hurdles, presents alternatives for overcoming them, and demonstrates how accessibility for walking, cycling, and transit—and for different types of destinations—can be reliably measured. We focus on explaining specific features of non-motorized transportation that complicate the development of accessibility measures, and offer solutions that conform to conventional transportation planning practice. In this research project, non-motorized measures of accessibility were developed for the entire seven counties of the Twin Cities (Minnesota, USA) metropolitan area. For purposes of this exposition in this report, we discuss the details of creating such measures using a sample application from Minneapolis, Minnesota, USA to demonstrate proof of concept for the endeavor.					
17. Document Analysis/Descriptors Pedestrian; Bicycling; Accessibility; Travel Behavior				18. Availability Statement No restrictions. Document available from: National Technical Information Services, Springfield, Virginia 22161	
19. Security Class (this report) Unclassified		20. Security Class (this page) Unclassified		21. No. of Pages 53	
				22. Price	

Access to Destinations: Application of Accessibility Measures for Non-Auto Travel Modes

Final Report

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July 2009

Published by

Minnesota Department of Transportation
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395 John Ireland Boulevard, MS 330
St. Paul, Minnesota 55155-1899

This report represents the results of research conducted by the authors and does not necessarily represent the views or policies of the Minnesota Department of Transportation and/or the Center for Transportation Studies. This report does not contain a standard or specified technique.

The authors and the Minnesota Department of Transportation and/or the authors' organizations do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to this report.

Acknowledgements

The authors thank members of the Active Communities / Transportation (ACT) Research Group including Laura Baum, Ryan Wilson, Jessica Horning, and Gavin Poindexter for their assistance in creating the networks, cleaning the parcel data, and preparing the calculations necessary for this work. In addition, the comments and suggestions of the several reviewers on earlier drafts of this report considerably helped strengthen this research.

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Executive Summary

Accessibility has been a well-known concept in the transportation planning field since the 1950s when it was defined as the ease of reaching desirable destinations. Original work on the issue developed measures that linked land use and activity systems with the transportation networks that serve them. More than one-half century later, improving accessibility has recently re-emerged as a central aim of urban planners and aligned disciplines. However, conventional transportation planning is often focused on improving movement (or mobility)—most often by the automobile. To the extent that accessibility has been measured or used in transportation planning, such measures have also been auto-based. In addition, many studies limit their focus on access to employment.

Broadening the scope of accessibility to include a wide array of destinations and non-auto modes such as walking and cycling has been previously proposed as a much needed aim among planning initiatives. Given the current policy environment of scientific uncertainty surrounding travel and urban form, accessibility offers an alternative basis for sustainability policy regarding the built environment and travel—a policy that can be bolstered provided that detailed, reliable, objective and robust metrics are available. Uncovering such measures for walking and cycling would go a long way toward assisting planning efforts with the tools they need to make sounder decisions with respect to the provision non-motorized transportation facilities.

A central issue is that to date, however, there have been few, if any, examples of measures to draw from. When it comes to bicycling, walking, and transit, measures of accessibility are an endeavor long on rhetoric but short on execution. Much has been written about the topic, even “concept” pieces offering ideas for data to account for. Where they have been uncovered, the measures are extremely location specific or cover a small geographic area. Given the requisite data, modelers in most metropolitan areas probably know what to do. However, issues including, but certainly not limited to, lack of reliable data, computational power or knowledge of non-motorized travel behavior have precluded effective progress on this front, at least when it comes to doing so for entire metropolitan areas.

This report discusses such hurdles, presents alternatives for overcoming them, and demonstrates how accessibility for walking, cycling, and transit—and for different types of destinations—can be reliably measured. We focus on explaining specific features of non-motorized transportation that complicate the development of accessibility measures, and offer solutions that conform to conventional transportation planning practice. In this research project, non-motorized measures of accessibility were developed for the entire seven counties of the Twin Cities (Minnesota, USA) metropolitan area. For purposes of this exposition in this report, we discuss the details of creating such measures using a sample application from Minneapolis, Minnesota, USA, to demonstrate proof of concept for the endeavor.

The research is the culmination of three other associated research projects. The detailed, methodology, data, and analysis procedures for several of the measures and methods of accessibility are more fully described in the previous three reports on the subject. The product of developing detailed accessibility measures for non-motorized modes across an entire metropolitan region as a credible accomplishment; more importantly, however, it is an invitation

for future work at both the academic and practitioner levels and for practitioner to employ such measures to inform their daily practices.

First, we have shown that it is in fact *possible* to construct measures of accessibility for non-motorized modes that are sensitive to spatial scale and that attempt to capture important features of non-motorized travel. The final product from this research is an extraordinary amount of data and a well proven procedure that can be relied on to calculate detailed measures of accessibility according to the following parameters:

- the seven county Twin Cities metropolitan area,
- three different years: 1995, 2000, 2005,
- three modes of non-motorized transportation: walking, cycling, transit,
- at least five different types of destinations: employment, retail, restaurant, schools, recreation,
- and for transit, under eight different time periods: 6:00, 7:30, and 8:45 am; noon, 4:15, 5:30, 8:45 pm; and for weekends/late night, assuming at least a one-half mile walk to transit stops.

The research demonstrated here is an important contribution to accessibility measures as work doing so for entire metropolitan regions is extremely limited. This effort has gone beyond previous work in this area by attempting to introduce more behavioral realism into accessibility calculations and doing so for relatively small units of analysis. Such realism is accomplished primarily through the use of impedance measures estimated for each separate combination of mode and trip purpose and highly detailed land use data. This work therefore represents an improvement over previous studies, which often borrowed values from other studies or relied on assumptions about the true value or aggregate values for a large area. Furthermore, the estimation of the impedance measures was aided by the use of a specially-constructed network that was designed to capture a fuller range of route choices for pedestrians and cyclists than most travel model networks allow. One limitation was that the assumption of shortest-path routes may not hold for certain types of non-motorized travel behavior, as in the case of walking trips for recreation or leisure purposes, where travel cost minimization may not be as important a criterion.

In developing non-motorized measures of accessibility using the methods described here, we sought to strike a balance between practical considerations and theoretical rigor. For example, we chose location-based measures of accessibility, namely gravity-based measures, as our units of analysis. These accessibility measures offer advantages in that they can easily be operationalized, and are relatively easy to interpret and communicate. On the other hand, location-based measures ignore the temporal and individual components of accessibility, and thus offer an incomplete picture of access as experienced by most individuals. More recent interpretations of the components of accessibility stress the inclusion of a *temporal* component, reflecting the availability of opportunities at different times of day and available time to allocate to accessing these opportunities, as well as an *individual* component, which reflects individual-level constraints and characteristics that might affect the measurement of accessibility.

The methods presented herein are suggestive, and there are many other possible ways to approach the methodological problems we have identified. We chose to work within the

framework of existing travel forecasting methods, which are well adapted to producing location-based measures of accessibility. While future non-motorized accessibility research may prove fruitful, we also believe that the type of non-motorized accessibility measures described herein may also have value at the practitioner level in terms of informing the design of instruments of accessibility-related policies, scenario building and sketch planning applications. For example, the maps presented indicate that there are large portions of the study area with relatively low walk accessibility to restaurants. This finding might prompt efforts to reduce zoning restrictions in certain neighborhoods to allow new restaurants to locate in underserved areas. Or perhaps it may indicate that improvements to the pedestrian infrastructure are warranted. Either approach could be employed to address the stated goal of improving access. In addition to formulating planning goals, non-motorized accessibility measures can provide one important component of an overall system for monitoring and evaluating the transportation and land use system in an urban region. With a growing level of interest in non-motorized travel in many transportation policy circles, detailed and robust accessibility measures geared to non-motorized modes provide an additional option to form and evaluate land use-transportation planning efforts.

1. Introduction

Accessibility has been a well-known concept in the transportation planning field since the 1950s when it was defined as the ease of reaching desirable destinations (Hansen 1959). The Hansen work represented one of the first efforts by planners to develop measures that linked land use and activity systems with the transportation networks that serve them. Improving accessibility has recently re-emerged as a central aim of urban planners and aligned disciplines. However, conventional transportation planning is often focused on improving movement (or mobility)—most often by the automobile. To the extent that accessibility has been measured or used in transportation planning, such measures have also been auto-based (Handy and Clifton 2001). In addition, many studies limit their focus on access to employment.

The emphasis on employment accessibility is understandable given its link to other important aspects of urban structure, such as choice of residential location, and also to outcomes hypothesized to be related to urban structure, such as social exclusion (Preston and Raje 2007). However, access to other types of destinations, such as retail, are also important because they strongly influence various dimensions of travel behavior such as trip frequency (Daly 1997), destination choice (Handy 1993), mode choice, and trip or tour complexity (Hanson and Schwab 1987). Higher access levels to activities such as shopping and recreation are also thought to improve the general quality of life.

Broadening the scope of accessibility to include a wide array of destinations and non-auto modes such as walking and cycling has been previously proposed as a much needed aim among planning initiatives (Handy 1993; Handy and Clifton 2001; Krizek 2005). Given the current policy environment of scientific uncertainty surrounding travel and urban form (Levine 2006), accessibility offers an alternative basis for sustainability policy regarding the built environment and travel—a policy that can be bolstered provided that detailed, reliable, objective and robust metrics are available. Uncovering such measures for walking and cycling would go a long way toward assisting planning efforts with the tools they need to make sounder decisions with respect to the provision non-motorized transportation facilities.

A central issue is that to date, however, there have been few, if any, examples of measures to draw from. When it comes to bicycling, walking, and transit, measures of accessibility are an endeavor long on rhetoric but short on execution. Much has been written about the topic, even “concept” pieces offering ideas for data to account for (Landis et al, 2001; Guttenplan et al, 2001; Handy and Clifton 2001, Chin et al, 2008). Where they have been uncovered, the measures are extremely location specific or cover a small geographic area (Ulmer and Hoel, 2003; Achuthan et al, 2007). Given the requisite data, modelers in most metropolitan areas probably know what to do. However, issues including, but certainly not limited to, lack of reliable data, computational power or knowledge of non-motorized travel behavior precluded effective progress on this front, at least when it comes to doing so for entire metropolitan areas.

This report discusses such hurdles, presents alternatives for overcoming them, and demonstrates how accessibility for walking, cycling, and transit—and for different types of destinations—can be reliably measured. We focus on explaining specific features of non-motorized transportation that complicate the development of accessibility measures, and offer solutions that conform to conventional transportation planning practice. In this research project, non-motorized measures of accessibility were developed for the entire seven counties of the Twin Cities (Minnesota, USA) metropolitan area. For purposes of this exposition in this report,

we discuss the details of creating such measures using a sample application from Minneapolis, Minnesota, USA, to demonstrate proof of concept for the endeavor.

The research is the culmination of three other associated research projects. The detailed, methodology, data, and analysis procedures for several of the measures and methods of accessibility are more fully described in the previous three reports, listed below.

Access to Destinations: How Close is Close Enough? Estimating Accurate Distance Decay Functions for Multiple Modes and Different Purposes
Michael Iacono, Kevin Krizek, Ahmed M. El-Geneidy
May 2008, Report no. Mn/DOT 2008-11

Access to Destinations: Refining Methods for Calculating Non-Auto Travel Times
Kevin Krizek, Ahmed M. El-Geneidy, Michael Iacono, Jessica Horning
June 2007, Report no. Mn/DOT 2007-24

Access to Destinations: Parcel Level Land Use Data Acquisition and Analysis for Measuring Non-Auto Accessibility
Jessica Horning, Ahmed M. El-Geneidy, Kevin Krizek
July 2008, Report no. Mn/DOT 2008-19

2. Measuring Accessibility for Non-Motorized Travel

In principle, it is logical to measure accessibility for non-motorized modes using similar methods as for motorized vehicle travel, thereby allowing the user to calculate any of the conventional, location-based measures of accessibility associated with zone-based travel forecasting models (e.g., cumulative opportunities, gravity-based, and utility-based measures). The measures most often used are gravity-based or other types of location-based measures, in part due to their relative ease of calculation and interpretation (Handy and Niemeier 1997; Geurs and van Wee 2004). Gravity-based measures are derived from the denominator of the gravity model (Ingram 1971) and can be described with the general form:

$$A_i = \sum_j a_j f(t_{ij})$$

...where A_i represents accessibility at zone i , a_j represents activity in zone j , and t_{ij} represents travel impedance between i and j , which can be expressed at time, distance, or cost, and $f(t_{ij})$ is a function of t_{ij} introduced to express the dampening effect of separation or cost on travel. Thus, at a minimum, accessibility reduces to a function of the size or availability of activities in each zone and the cost of accessing those activities.

One practical reason for considering gravity measures or other location-based measures of accessibility for non-motorized modes is the potential compatibility with regional travel forecasting models which can easily extract zone-to-zone travel times from coded networks. In addition, counts of potential opportunities such as employment are stored at the zone level. Extending this basic framework to measure non-motorized travel encounters serious limitations—limitations which, as will be discussed in greater detail, relate to the representation of non-motorized modes in travel demand models.

With respect to travel impedance, the networks used for modeling vehicular flows are too coarse to represent the route choices typically exercised by pedestrians and bicyclists. Also, the zones of these models are poorly matched to the spatial scale of movement by these modes, resulting in a considerable number of intrazonal trips (Eash 1999). While vehicular travel tends to be most sensitive to travel times and levels of network congestion, non-motorized route choices tend to include factors that may be more qualitative, experiential or difficult to operationalize (Page 2005), such as facility design and aesthetic treatments that may fall under the broad category of “environmental factors” (Porter et al. 1999, Tilahun et al. 2007; Hunt and Abraham 2007). That is not to suggest travel time is not an important determinant of route choice for non-motorized travelers (Stinson and Bhat 2003; Weinstein et al. 2007)—just that it is not quite as decisive. Methods for simplifying this problem and adapting zones to fit the needs of non-motorized travel are discussed in the next section.

2.1 Measurement Issues and Alternatives

Having discussed central parameters to measure access, generally, as well as access for non-motorized modes, we now turn to addressing specific sources of difficulty encountered with the inputs to accessibility calculations. These issues are fourfold as presented in Table 1 along with proposed solutions the research team employed to address them. The remainder of the report elaborates on such issues and solutions using the application of a portion of south Minneapolis, Minnesota (USA) as a case study to illustrate how these measures have been developed.

Table 1: Unique issues indicative to measuring non-motorized accessibility and proposed solutions

Issues	Proposed Solution
Lack of reliable non-motorized travel behavior data for a variety of trip purposes	Use a subset of local travel survey data set collected by the metropolitan planning agency
Lack of high-resolution land use data	Collect and prepare detailed land use data set from existing public land use data or private party business inventory data set
Inadequate zonal structure and travel networks	Use Census block-level data for zones (or other small units); employ modified GIS street layers for travel networks, complemented with detailed data (GIS layers) for non-motorized infrastructure
Completely arbitrary impedance functions used for walking and bicycling activity	Estimate impedance functions for non-motorized modes and several destination types using detailed data on trip distribution by time and distance from a variety of sources (e.g., transit on-board surveys, specialized trail use surveys)

2.2 Data

Need for Non-Motorized Travel Behavior Data

Calculating accessibility measures requires multiple data sets relating to travel behavior and land use, each of which presents unique challenges for analysts addressing non-motorized modes. For example, robust accessibility measures are built around models representing human behavior (e.g., who shops where and how far they travel for such). Unfortunately, the data necessary to reliably build such models are often in short supply for walking and cycling. User and trip characteristics at a suitable level of aggregation, along with user preferences for facility design characteristics are currently of limited quality and are considered a high priority for improvement (USDOT 2000). Characteristics about non-motorized mode users and their trips are typically aggregated to the same level as motorized trips, rather than being assigned to smaller aggregation units. Information on preferences toward different facilities is typically incomplete at best, and often entirely absent. These data items are not adequately covered in most large scale survey instruments, such as metropolitan travel surveys or the Nationwide Personal Transportation Survey (NPTS).

Such issues often result in analysts borrowing assumptions from analysis designed for other purposes. A common example is an analysis borrowing impedance values from a locally-calibrated travel model. The values extracted from these data may be sensitive to the environment in which they were collected; particularly for non-motorized behavior, issues related to weather conditions play a big role. Ideally, travel survey data would be collected year round and cover all seasons (Ortuzar and Willumsen 2001). More commonly, data are collected over a period of several months and reflect weather conditions prevailing at the time the survey data were collected. This is especially important in the case of non-motorized modes and in locations where significant seasonal climate variations exist. For example, if survey data are collected during warmer, drier months it is possible that changes in travel behavior during colder

or more precipitous months might be missed. These changes might include mode shifts, in which case the number of pedestrians and bicyclists might be overestimated during cold weather periods, and changes in destination choice for discretionary trips, which would affect the length or distance of travel, and hence the relevant impedance values.

Estimating specialized impedance functions specific to non-motorized modes requires appropriate travel survey data that can capture pedestrian and bicycling behavior. Ideally, this would involve a focused, special-purpose survey designed to oversample these types of behavior or data collected from Global Positioning Systems—a relatively costly alternative. In the absence of such data, a regional household travel survey can be used to the extent that it specifically includes trips by non-motorized modes. The current study employed household survey data collected in 2000 for the Minneapolis-St. Paul region. A limitation of this approach, however, is the variety of destinations that can feasibly be studied. Given that walking and bicycling tend to be less heavily-used and often underreported modes in many U.S. cities, any further partitioning of the data can lead to small samples and less robust inferences.

Need for High Resolution Land Use Data

The quality of land use data also affects the accuracy of accessibility measures. Improving the accuracy or robustness of accessibility calculations requires data at a spatial resolution that is not typically available in most planning organizations. There are sources of establishment-level data on attributes such as employment, sales and other variables that could potentially serve as good proxy variables for attractiveness and be easily scaled to different levels of geographic aggregation. However, these sources are typically private financial organizations or highly confidential. The data can be costly to acquire and require significant effort in terms of cleaning and preparation for spatial analytical use. Alternate, low-cost sources of data such as business directory telephone listings have been employed elsewhere (Handy and Clifton 2001) in the context of the calculation of measures of “neighborhood” accessibility, though these data sets apparently contain limited information on size or quality of establishments.

Developing measures of attractiveness at a more detailed level than the zones used in travel forecasting models requires specialized, establishment-level data that can be aggregated to relatively small units of aggregation, such as the block groups described earlier. Establishment-level data was purchased from Dun & Bradstreet, Inc. containing attribute information on location, sales, employees, and industry classification. In all, data were available for 135,928 businesses within the region. These data were merged with parcel-level land use data from the Metropolitan Council, the Twin Cities’ regional planning agency. The establishment-level data were then recoded into destination categories using the 2 to 6-digit classifications of the North American Industry Classification System (NAICS). The outcome of this process was a set of parcel-level land use data with information on employment counts and sales volumes. A small sample of this data set, with mapped parcel-level land use for an eight-block area of south Minneapolis, is shown in Figure 1.



Figure 1: Parcel-level Land Use Data

2.3 Inadequate Zonal Structure and Travel Networks

In addition, other efforts often use zones as units of analysis that do little justice to the detailed nature of pedestrian or bicycle travel. For example, they may aggregate information to census tracts, zip code areas or TAZs. These units often do little justice to the central aim; they can be quite large, almost two miles wide and contain over 1 000 households. The problem is that an ecological fallacy arises because average demographic or urban form characteristics are assumed to apply to any given individual neighborhood resident. When measures of commercial intensity are aggregated, for example, each zone could, in principle, reveal the same measure of intensity, despite each zone exhibiting considerably different development patterns. This assumption of homogeneity may also be viewed as an instance of the modifiable areal unit problem (Openshaw 1984). Using census tracts or TAZs, concentrations of development may be averaged with adjacent lower-density development thereby making it difficult to associate many neighborhood-scale aspects with travel demand. This distinction is particularly important for pedestrian travel, where travel sheds for different types of trips may encompass only a fraction of

a TAZ or similar aggregation unit. The heart of the problem—and the ability to detect such subtle geographical differences—lies with the size of the units of analysis that are employed.

Networks employed for purposes of regional travel models typically replicate roadways. Networks for walking and cycling are often different and need to be drawn at a finer scale. Specifically, the network structure is too coarse to trace the paths chosen by pedestrians and cyclists, and the zones are too large to differentiate many of the shorter trips made by bicycle and on foot. Also, few networks contain links with specialized facilities for non-motorized travel, such as sidewalks, exclusive bike paths and on-street bicycle lanes.

Incompatibility between conventional travel forecasting models and travel by non-motorized modes is characterized by travel zones that are too large and networks that are too coarse to provide detailed analysis of destination and route choice behavior by pedestrians and bicyclists. This is one area where compromise solutions must be adopted in order to make the research problem tractable.

The task of calculating travel times via a network model is one that is not easily resolved. One way around this problem is to use street network layers encoded as geographic information system (GIS) files as the basis for calculation of a minimum-cost path (with distance as a proxy measure for cost) between an origin and destination point, assuming agreement between the minimum-cost path and the actual chosen path (Witlox 2007). This method ignores the matter of congestion on networks, since it is costly and not terribly practical to code an entire street network with the appropriate capacity data. However, many studies of accessibility choose to ignore congestion effects and simply use free-flow travel times as a reasonable approximation.

GIS networks can be manually modified in order to incorporate the presence of special facilities, such as exclusive bicycle paths or joint use bike/pedestrian paths. In principle, these links are chosen because they offer travel time, quality or other advantages that lower the perceived “cost” of travel by non-motorized modes. These advantages can be operationalized by giving these links a lower cost than other unimproved links. Were the data available, one possible additional modification would be to adjust link costs to account for the density of traffic signals. If data on exclusive pedestrian and bicycle facilities are not available in a digital format, they can be checked against published maps or other available sources. This method was applied to the Twin Cities’ network of exclusive bicycle paths, which were recreated from a locally published bicycle system map.

A key assumption of constant travel speeds must be accepted for bicycle and pedestrian travel, in order for this method to be applicable. This allows for simple conversions between measurement of distance and time. As a check on this assumption, El-Geneidy et al. (2007) reviewed the literature on travel speeds for pedestrian and bicycle modes and tested the influence of different types of bicycle facilities on travel speeds. Off-street facilities were shown to have a small but statistically significant effect on speeds, lending support to their inclusion as special network links with different cost characteristics. However, this work also noted a high degree of interpersonal variability, indicating that an assumption of constant speeds may be a significant source of uncertainty in accessibility measures.

Another adaptation that allows a better characterization of travel impedance is using smaller zones to identify potential origins and destinations. This method has been used elsewhere (Eash 1999) to model non-motorized destination choice, using zones roughly aligned with Census tracts. An alternative—and smaller—zone designation used in the Twin Cities application is to use grid cells or Census block groups, which are similar in size and function.

2.4 Networks

An additional prerequisite component to calculate accessibility at the metro level is to create accurate networks for each mode of transportation: pedestrian, bicycle, and transit for three points in time (1995, 2000, and 2005). The road centerline file serves as the base for creating the other networks for the non-motorized modes. Geographic information system (GIS) shapefiles of the road centerlines, created by The Lawrence Group, were obtained from MetroGIS, the GIS division of the Metropolitan Council. Due to data availability, the 1997 road network had to substitute for the 1995 network. The first year that MetroGIS had an agreement with the Lawrence Group was 1997; this was an effort to create centerline files for the metro area. As a result, this was the oldest available shapefile.

Data Requests and Communications

The goal of creating accurate networks at each time period requires identifying when each pedestrian and bicycle facility was built. The research team contacted various agencies in the Twin Cities metropolitan region to obtain files for the pedestrian and bicycle networks. Few municipalities or agencies had record of pedestrian and bicycle facilities prior to the past five or ten years; even fewer had that information stored electronically. Even electronic information is not necessarily ready for use in a network as the next section will discuss. The team collected a number of Twin Cities bicycle maps for years 1981-2005 as primary data sources. For a complete list of maps see Appendix A. A longitudinal series of maps aided the careful creation of an accurate metro bicycle network. Beginning with the oldest map the approximate age of each facility could be determined.

Pedestrian Network

Obtaining accurate sidewalk and street intersections are a critical component in modeling pedestrian travel time. Since it is expected that travel time will vary with the quality of the sidewalk and with its presence or absence, obtaining sidewalk data was one of the first steps the research team took. After contacting several agencies the team located a final data set. However, the sidewalk data was not useful for generating a travel time matrix for several reasons. First, data are not linked to the street centerline; accordingly, measurements of sidewalk connectivity are not possible. Second the data lack alignment with the existing centerline files obtained from the Met Council. In addition, the presence of curb cuts made it even harder to generate a network from the data.

Since a usable sidewalk data was unavailable, the research team made two primary assumptions concerning the pedestrian walking network. First, pedestrians could walk on all non-freeway roads. The research team began with the road centerline network for each time period and removed the freeways, defining them as limited access roadways (primarily interstates and U.S. freeways), because they are unsafe for pedestrian travel. All of the freeways that were removed from the 1997 network were removed from the 2000 and 2005 networks. Similarly all of the freeways that were removed from the 2000 network were removed from the 2005 network. Second, pedestrians could walk on all off-street bicycle facilities verified in the next sub-section.

Identifying and marking the location of pedestrian bridges was another key task in creating the pedestrian, and later the bicycle, network. The addition of freeway overpasses is

particularly significant as these facilities are often located between automobile overpasses and may provide noticeable travel time savings. Only one of the collected maps, The 2001 Bicycle Commuter Map, identified the location of these facilities. The research team marked their location, used aerial photos to determine the type of access to each facility, either pedestrian access only (stairs) or pedestrian and bicycle access (ramp), and added each to the pedestrian network. The potential problem with this approach was each facility had to be marked as existing before 1995 since a single map identified their location. This problem is likely small, however, as few such facilities were built between 1995 and 2001.

Bicycle Network

The bicycle network has a greater number of facility types, requiring a few basic assumptions. Bicycles could travel on the same non-freeway road and off-street bicycle network as the pedestrians. In terms of pedestrian bridges, bicycles could only travel on those with ramp access. In addition, bicycles utilize on-street bicycle facilities.

The research team used three sources of information to create the bicycle network: the aforementioned paper bicycle maps, conversations with government officials, and GIS shapefiles of off-street bicycle facilities from the Minnesota Department of Transportation (Mn/DOT). Mn/DOT created these shapefiles by asking each of the 170 cities in the Twin Cities to identify the location of off-street bicycle facilities. However, not all cities participated and the definition of off-street bicycle facility varied (some cities considered concrete sidewalks others only asphalt trails). Subsequently, the paper maps served as primary sources for the bicycle network. Clusters of facilities that did not appear on the maps were verified using aerial photographs. When a facility was identified, it was assumed to have been built at the same time as the roads in the area as several Twin Cities suburbs require bicycle facilities be included in subdivisions. When the facilities could not be verified they were removed from the network (See Figure 2).

For the on-street bicycle facilities, the research team identified and selected each road segment that had an on-street bicycle facility. Only two maps included on-street facilities which made it difficult to determine the year each was built. Areas outside Minneapolis had little or no information concerning the location of on-street facilities. Although, we are unsure how many of the on-street facilities existed prior to 2000, we are assuming that those that we can verify existed prior to 1995 were added after 1995. This is based on the research team's general knowledge of the growth of on street bicycle facilities in the metro area. Figure 3 shows the on-street bicycle network for each time period.

The 1995 off-street bicycle network includes facilities identified in maps printed in 1995 or earlier. The 2000 off-street network includes the entire 1995 network and those facilities that appeared on a May 2001 map. Since a year 2000 map was not available, the 2001 map (printed in May) is the best approximate of the year 2000 off-street network. In several instances, through conversations with various government officials, the year of facility construction was available and labeled. Similarly, the 2005 network includes all facilities from the 2000 network, those that appeared on a year 2005 map, and those verified through conversations with various government officials. One such example is the second phase of the Midtown Greenway in the central Minneapolis. This trail first appeared on the 2001 map, but a local official confirmed completion in 2000. Figure 4 shows the off-street bicycle network.

Identifying and Correcting Network Errors

A complete network free of errors is nearly as critical as accurate one. Even the most carefully crafted network, created manually trail-by-trail, is bound to have some errors. Failing to extend a new feature to the existing network (undershoot) and extending a new feature beyond the existing network (overshoot) are the two most common types. Other researchers or practitioners following this approach may also wish to use an existing GIS bicycle network. The research team found the obtained bicycle map did not receive the same care during creation as the road centerline file; a large number of small (20 meters or less) undershoot and overshoot errors existed. Multiply these errors for each time period and considering the difficulty of fixing each error manually in ArcGIS, a fast global fix was highly desirable.

After many discussions with staff at ESRI (ArcGIS technical support) and perusing existing ArcGIS scripts from their website, it was clear a quick-fix solution was not available. After myriad hours of troubleshooting, the research team crafted a solution using the Topology Editor feature in ArcMap. Topology works well to eliminate overshoots and nearly as well to fix undershoots. While this solution is not flawless, the resulting errors are small and do not have a significant impact on bicycle travel time. The most common error is the bicycle facility might extend or snap to an adjacent road instead of the correct one. This problem is rather insignificant in an area with a dense grid-street pattern because the distance ‘error’ is small. In a location with fewer and more curvilinear streets the chance for error is slightly greater, although trails often loop back to the same road or connect subdivisions; a small error in this regard will not have a large impact on accessibility or travel time. For those who encounter a similar problem or wish to build upon the research team’s efforts please refer to an abbreviated step-by-step guide in Appendix A.

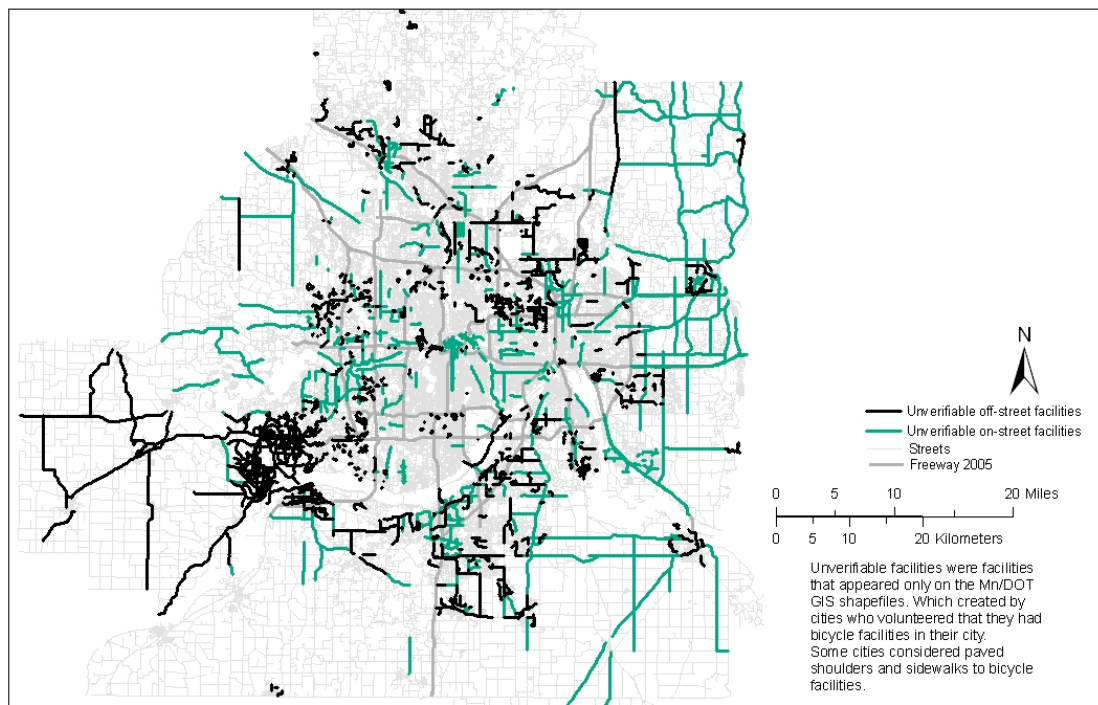


Figure 2: Unverifiable Mn/DOT Bicycle Facilities



Figure 3: On-street Bicycle Networks

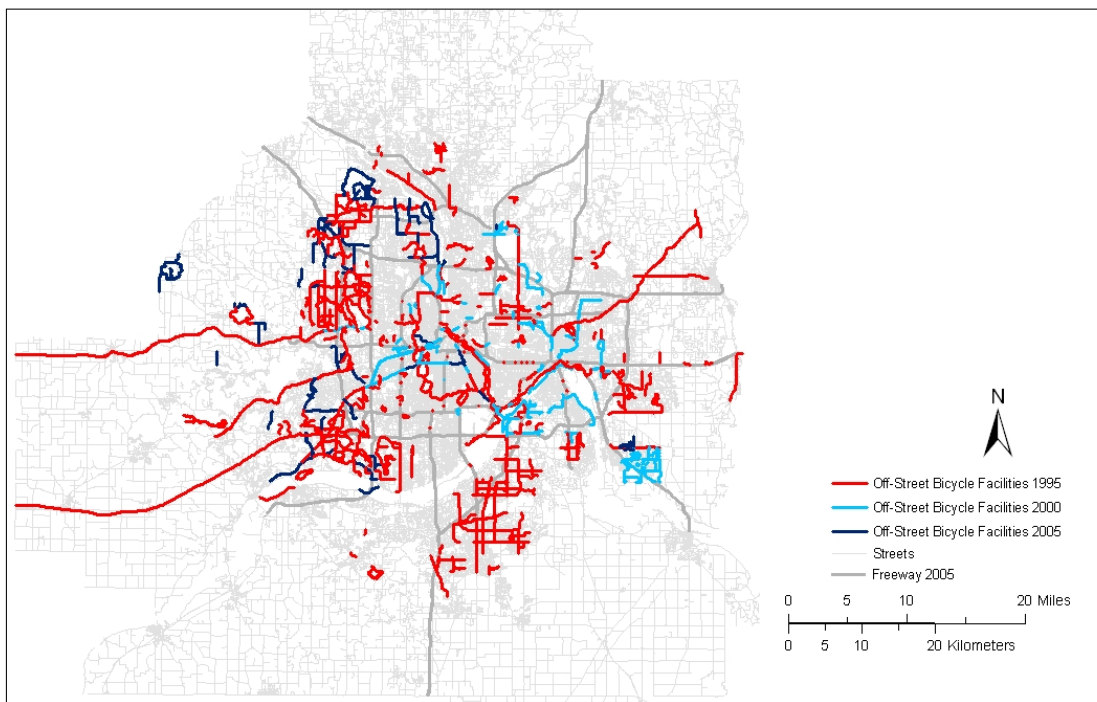


Figure 4: Off-street Bicycle Networks

2.5 Estimating Travel Impedance

Related to the issue of inadequate networks and data is the applicability of model components of four-step transportation planning models to non-motorized modes. Most relevant to accessibility calculations is the impedance function, representing the influence of travel time, money and other costs on the willingness of individuals to travel longer distances. In transportation planning practice, it has been common to use gravity or other synthetic models to forecast the spatial distribution of trips, from which an impedance value can be estimated. While this approach works reasonably well for motorized modes, which tend to have a more regional distribution, there are often a large number origin-destination pairs with zero observations. This problem, known as the sparse matrix problem (Ortuzar and Willumsen 2001), is exacerbated by the application of such models to origin-destination data for non-motorized modes, which tend to have a more concentrated spatial distribution.

Since the full specification of the gravity model is not applicable for forecasting the distribution of trips by non-motorized modes over a large area, some modifications must be made. One option is to estimate impedance directly from the frequency distribution of trip lengths. While this approach is feasible, it has some serious limitations. Estimating an impedance parameter in the absence of information about the spatial distribution of activities (as is provided in the gravity model) is equivalent to assuming that activities are evenly distributed in space (Sheppard 1995). Clearly this assumption is not reasonable for most metropolitan regions and can lead to biased results.

A second caveat relates to the functional form of the impedance function. While many different specifications of the impedance function have been used, there is little available evidence to suggest *a priori* which one might be superior. Most of the specifications differ in their treatment of the effects of distance, which would in turn affect accessibility measurement. Here, we choose the negative exponential form ($e^{-\beta x}$). This function has the advantage that it declines more gradually than the power function, and thus better estimates shorter trips, such as those made by non-motorized modes (Kanafani 1983). This advantage, along with a record of numerous empirical applications made it an appropriate functional form to be estimated for the set of impedance functions applied in the current study.

In addition to choosing a form for the impedance function, the analyst must specify which variable is being used to measure separation or impedance (time, cost or both). In practice, both measures have been used, along with some examples of the use of the *generalized cost* concept (Handy and Niemeier 1997). In the case of non-motorized travel, however, the options appear to be limited to the use of distance, due to the problems associated with extracting accurate travel times from existing network models for bicycling and walking. Past research has suggested that using either time or distance as an impedance variable is acceptable (Handy and Niemeier 1997), though very detailed and data-rich applications might use the logsum of the mode choice calculation for a given origin-destination pair.

To resolve the matter of which impedance variable to use in our example, both were tested in the calculation of accessibility measures and compared. Gravity-based accessibility measures were calculated for work, shopping and restaurant trips by walking and bicycling modes using time and distance variables. Simple correlation coefficients between the time and distance-based measures ranged from approximately 0.92 to just under one, indicating little sensitivity to the specification of impedance variable. Thus, we concluded that either variable would be acceptable.

To calculate impedance values for each mode and trip purpose, household travel survey data was used to fit a negative exponential curve that provided a continuous approximation to the shape of the trip length distribution, using both trip duration and distance data. The same functional form was used for all impedances to ensure consistency of application across modes and trip purposes. A set of impedance functions for walk trips using distance as an impedance measure was used from the previous report from the project. Destinations for which these functions were estimated include work, shopping, restaurant and entertainment trips.

One drawback of this method is that it imposes the same functional form on each impedance function regardless of the underlying distribution, thus producing a poor fit in some situations. Nonetheless, this procedure provides a disaggregate alternative to assuming identical travel behavior for all trip purposes.

3. An Example of Non-Motorized Accessibility Measures

To illustrate the procedures used to produce estimates of non-motorized accessibility, as a proof of concept demonstration, we calculated accessibility measures for a small study area in South Minneapolis. The study area is bounded on the west by Lyndale Avenue, on the north by Franklin Avenue, on the east by the Mississippi River, and on the south by 50th Street. This area contains approximately 1 600 block groups, which represent the unit of analysis. The accessibility values calculated for each block group are *integral* accessibility measures (Ingram 1971; Song 1996), where the activities in each destination zone, discounted by their associated impedance value, are summed across destinations and normalized by dividing by the total activities in the study area. This method provides a measure that can be easily interpreted and compared across zones on the same zero to one scale. Analytically, this measure is represented as

$$A_i = \frac{\sum_j E_j e^{-\beta x_{ij}}}{E}$$

where:

A_i denotes accessibility evaluated at origin zone i

x_{ij} denotes the distance (or travel time) between zones i and j

E_j denotes the amount of activity in destination zone j

E denotes total activity in the study area, summed across all zones, and

β is a parameter of the impedance function, to be empirically estimated

Thus, for each accessibility measure, representing a combination of mode and destination type, accessibility is expressed as a decimal indicating proximity to destinations in each location. In the case of each accessibility calculation, an attractiveness measure is constructed for each block group by summing the level of retail sales at each establishment within the block group. Impedance measures are introduced by calculating the shortest path through the network between each block group pair, then using this value to discount activities at the destination using the functional form described previously.

Figure 5 presents maps displaying measures of accessibility to restaurant destinations for the walking mode. Again, the maps show the same measures calculated using time and distance as alternate measures of travel impedance. Consistent with the findings described earlier, they show a high degree of similarity. Areas near clusters of restaurant destinations are shown to have high levels of accessibility, with a gradual decline as one moves away from these clusters.

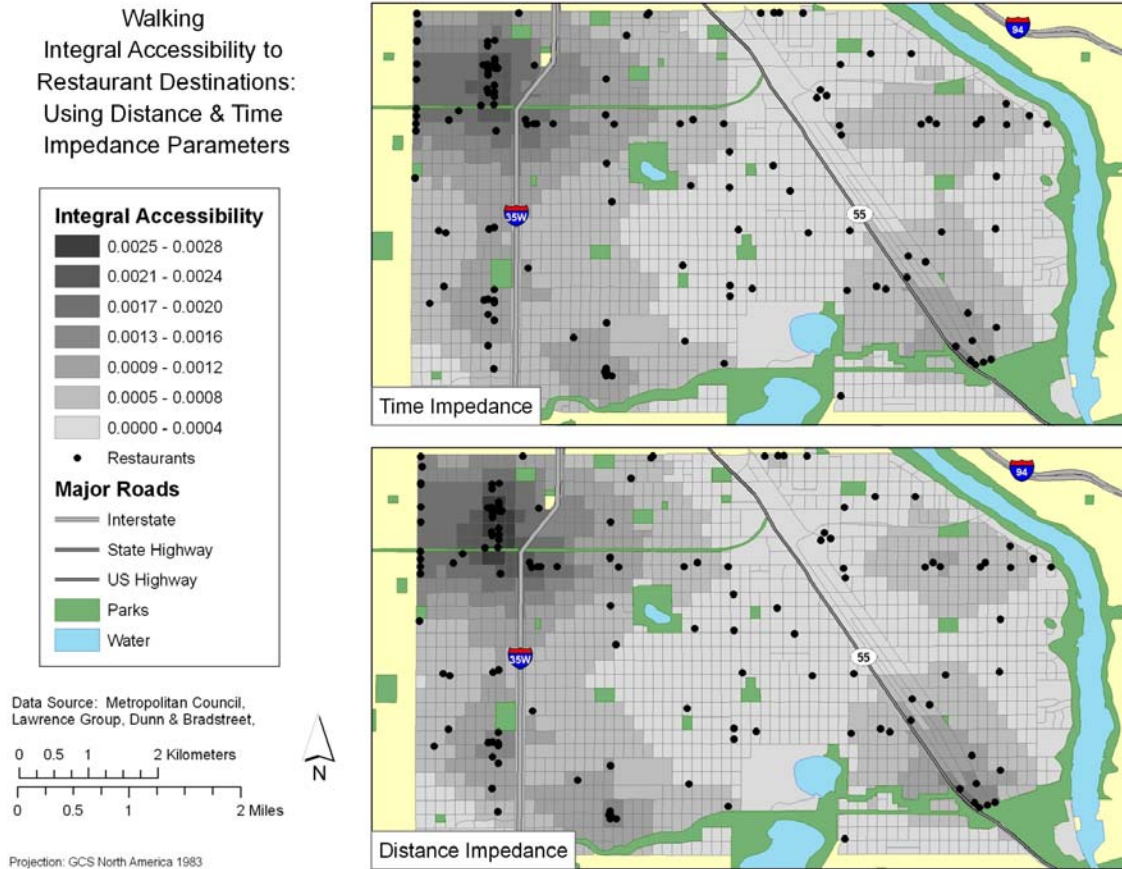


Figure 5: Walk Accessibility to Restaurants

Figure 6 presents a pair of maps showing accessibility to shopping destinations by bicycle with distance and time impedance measures. In this case, destinations are spread more evenly throughout the study area, leading to higher overall accessibility values in each zone. Retail establishments appear to align themselves along linear corridors, reflecting the historical network of streetcar routes in South Minneapolis. One particularly such corridor is found along Lake Street, a major east-west route that lies at the center of the swath of high accessibility shown in both maps. This high-accessibility location results from a combination of clustering of activities and proximity to the Midtown Greenway, a grade separated off-street bicycle facility highlighted in green on the map.

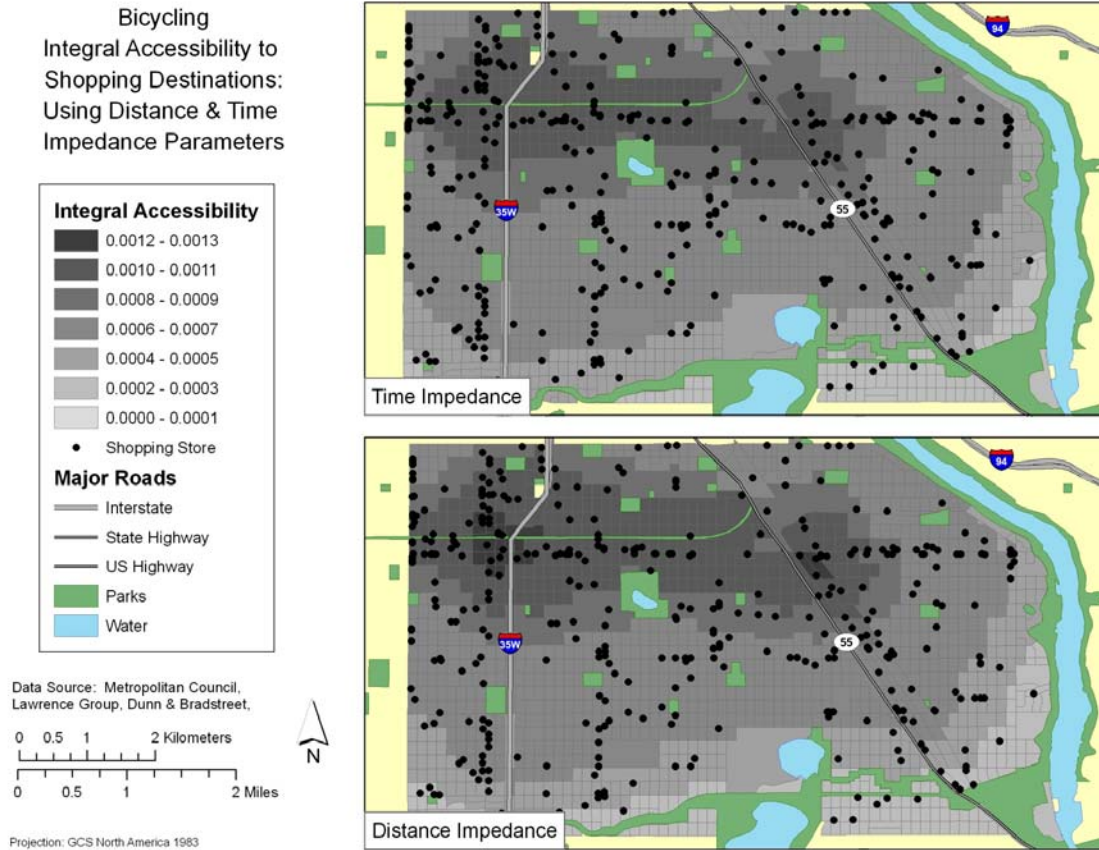


Figure 6: Bicycle Accessibility to Shopping

Together, these two examples illustrate the roles that location and space play in determining non-motorized accessibility, robustly measured, for an urban area, and graphically displays the outcomes associated with the interaction of these forces.

In addition to the above, similar exercises at a similar level of detail was completed for transit services. The following decisions and protocol were used in arriving at such measures:

- Schedules and headways available from Metro Transit were used for 1995, 2000 and 2005. Schedules for 2005 were available in digital form. Paper schedules from the other two years were scan them and then recoded using Optical Character Recognition.
- Walk to and from each stop was modeled using centroids for each block. Thus, the research team estimated walk times along the pedestrian network to the closest transit stop that would serve given destinations.
- To account for headways, the research team assigned the waiting time as half of the headway unless the headways were large. In this case, eight minutes was used.
- Transfer times were accounted for through a combination of consulting the transit timetables for different times of day.
- It was assumed that two transit transfers were the maximum number for purposes of these measures.

4. Conclusions and Prospects

We view the product of developing detailed accessibility measures for non-motorized modes across an entire metropolitan region as a credible accomplishment; more importantly, however, it is an invitation for future work at both the academic and practitioner levels and for practitioner to employ such measures to inform their daily practices. Some of these ideas are discussed further in this concluding section.

First, we have shown that it is in fact *possible* to construct measures of accessibility for non-motorized modes that are sensitive to spatial scale and that attempt to capture important features of non-motorized travel. The final product from this research is an extraordinary amount of data and a well proven procedure that can be relied on to calculate detailed measures of accessibility according to the following parameters:

- the seven county Twin Cities metropolitan area,
- three different years: 1995, 2000, 2005,
- three modes of non-motorized transportation: walking, cycling, transit,
- at least five different types of destinations: employment, retail, restaurant, schools, recreation,
- and for transit, under eight different time periods: 6:00, 7:30, and 8:45 am; noon, 4:15, 5:30, 8:45 pm; and for weekends/late night, assuming at least a one-half mile walk to transit stops.

Example products of the calculations and maps (for different timeframes, modes, and geographies) are shown in Appendix B.

The research demonstrated here is an important contribution to accessibility measures, as none of the researchers are aware of other efforts that have done so for entire metropolitan regions, been documented in peer-reviewed publications, and that have used original data to provide an empirical basis for the measures. This effort has gone beyond previous work in this area by attempting to introduce more behavioral realism into accessibility calculations and doing so for relatively small units of analysis. Such realism is accomplished primarily through the use of impedance measures estimated for each separate combination of mode and trip purpose and highly detailed land use data. This work therefore represents an improvement over previous studies, which often borrowed values from other studies or relied on assumptions about the true value or aggregate values for a large area. Furthermore, the estimation of the impedance measures was aided by the use of a specially-constructed network that was designed to capture a fuller range of route choices for pedestrians and cyclists than most travel model networks allow. One limitation was that the assumption of shortest-path routes may not hold for certain types of non-motorized travel behavior, as in the case of walking trips for recreation or leisure purposes, where travel cost minimization may not be as important a criterion.

In developing non-motorized measures of accessibility using the methods described here, we sought to strike a balance between practical considerations and theoretical rigor. For example, we chose location-based measures of accessibility, namely gravity-based measures, as our units of analysis. These accessibility measures offer advantages in that they can easily be operationalized, and are relatively easy to interpret and communicate (Geurs and van Wee 2004). On the other hand, location-based measures ignore the temporal and individual components of accessibility, and thus offer an incomplete picture of access as experienced by most individuals.

More recent interpretations of the components of accessibility stress the inclusion of a *temporal* component, reflecting the availability of opportunities at different times of day and available time to allocate to accessing these opportunities, as well as an *individual* component, which reflects individual-level constraints and characteristics that might affect the measurement of accessibility (Geurs and van Wee 2004).

The methods presented here are suggestive, and there are many other possible ways to approach the methodological problems we have identified. We chose to work within the framework of existing travel forecasting methods, which are well adapted to producing location-based measures of accessibility. A promising direction for future research would be to frame the problem of non-motorized accessibility calculation within a larger reconceptualization of travel behavior modeling. Much effort in the geographical and planning research fields during the past 10 to 15 years has been devoted to adapting accessibility measures to concepts of space and time geography, thus resulting in the development of person-based accessibility measures (Kwan 1998; Miller 1999). This is a critically important concept in both travel behavior and accessibility research, since temporal and individual or household-level constraints can often have a great influence on the level of accessibility a person actually experiences at a given location (Weber 2006), something that cannot be demonstrated using location-based measures. Being able to account for individual-level characteristics or constraints, such as car ownership (or perhaps bicycle ownership), gender, household structure and other variables would allow for a more nuanced understanding of the relationship between accessibility and travel behavior by non-motorized modes. One could even extend the analysis to situations of group travel and “joint” accessibility, as is described by Neutens et al. (2007). The possibilities for this type of research seem boundless, given that much of the basic methodology has already been established and could, with some effort, be focused on the issue of non-motorized accessibility.

While future non-motorized accessibility research may prove fruitful, we also believe that the type of non-motorized accessibility measures described in this report may also have value at the practitioner level in terms of informing the design of instruments of accessibility-related policies (Farrington 2007), scenario building and sketch planning applications. For example, the maps in Figures 5 and 6 indicate that there are large portions of the study area with relatively low walk accessibility to restaurants. This finding might prompt efforts to reduce zoning restrictions in certain neighborhoods to allow new restaurants to locate in underserved areas. Or perhaps it may indicate that improvements to the pedestrian infrastructure are warranted. Either approach could be employed to address the stated goal of improving access. In addition to formulating planning goals, non-motorized accessibility measures can provide one important component of an overall system for monitoring and evaluating the transportation and land use system in an urban region. With a growing level of interest in non-motorized travel in many transportation policy circles, detailed and robust accessibility measures geared to non-motorized modes provide an additional option to form and evaluate land use-transportation planning efforts.

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Appendix A

A Procedure to Fix Global Network Errors

The procedure discussed herein provides one method to fix a network with a multitude of small errors. The two most common types of network errors (called dangles in ArcGIS) occur during network creation and include failing to extend a new feature to the existing network (undershoot) and extending a new feature beyond the existing network (overshoot). Many discussions with staff at ESRI (ArcGIS technical support) and perusing existing ArcGIS scripts from their website revealed a quick-fix global solution does not exist. The following steps are an abbreviated step-by-step guide for a proficient ArcGIS user to create a network topology and generate and fix the network. The possibility of generating an inaccurate connection while fixing the network errors increases with the size of the dangles. Large dangles (greater than 30 meters) are better fixed manually to ensure an accurate fix.

For ease of explanation, this guide assumes 1) the desired output is a bicycle network free of errors and 2) the existence of a complete and accurate (without errors) road centerline file. In this case, bicycle network errors exist when facilities do not intersect other facilities or the road centerline file.

- 1) Create a single shapefile
 - a) This file needs to include both the bicycle facilities and road centerlines. Be sure to have a unique field which assists in linking the single shapefile back to the original bicycle and road shapefiles at the end of the process.
 - b) Add a field that identifies each type of facility. For instance, road centerlines might have a value of 1 and bicycle trails a value of 3. It is helpful, although not necessary, to group like shapes together. For example, road centerlines should be ordered FID 1 thru 10,000 while bicycle trails occupy 10,001 thru 11,000, etc.
- 2) Create Geodatabase in ArcCatalog
 - a) File > New > File Geodatabase
 - b) Right click on the Geodatabase, New > Feature Dataset
 - c) Right click on the new Feature Dataset, Import > Feature Class (single, if you only have one shapefile as discussed in Step 1a)
- 3) Create Topology in ArcCatalog
 - a) ArcToolbox > Data Management Tools > Topology > Create Topology
 - b) Input Feature Database when asked. Topology will export to Feature Dataset
- 4) Define Topology Rules and Validate Topology in ArcCatalog
 - a) Right click on Topology, click 'Properties'
 - i) Select the 'Feature Classes' tab and add the Feature Class from Step 2c
 - ii) Select the 'Rules' tab, then 'Add Rule', select the Feature Class, select 'Rule' "Must Not Have Dangles" (other options exist for other errors)
 - iii) Click 'Apply' and then 'Ok'.
 - b) Right click on Topology again and select 'Validate'
- 5) Editing Topology in ArcMap
 - a) Add topology to the map
 - b) Add Editor Tools
 - c) Start editing; be sure to select appropriate topology

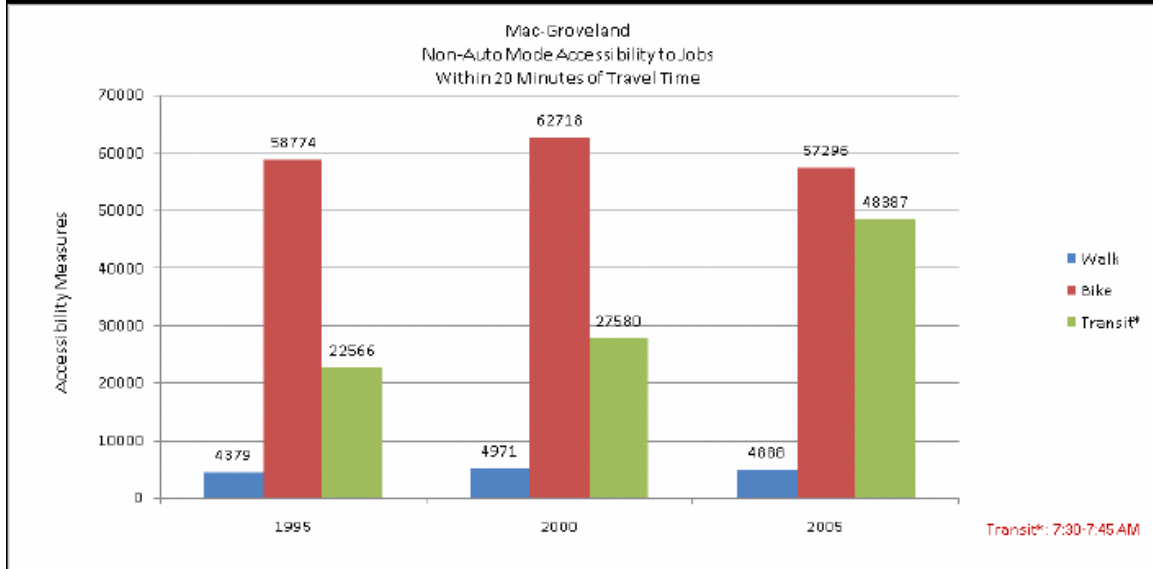
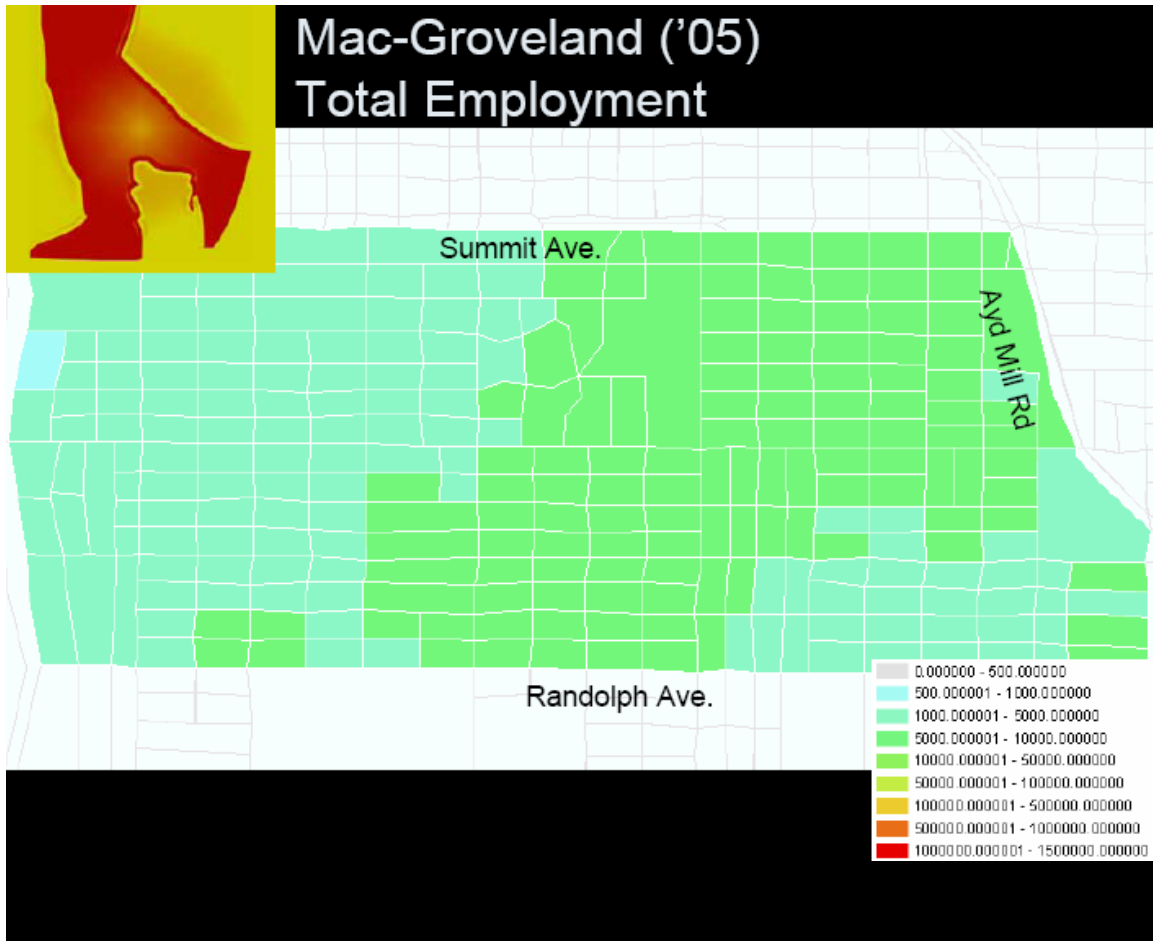
There are two key remaining steps, each utilizing one of the Topology Editor functions. The first task uses 'Error Inspector' to mark all the road centerline dangles (e.g. culs-de-sac, end of

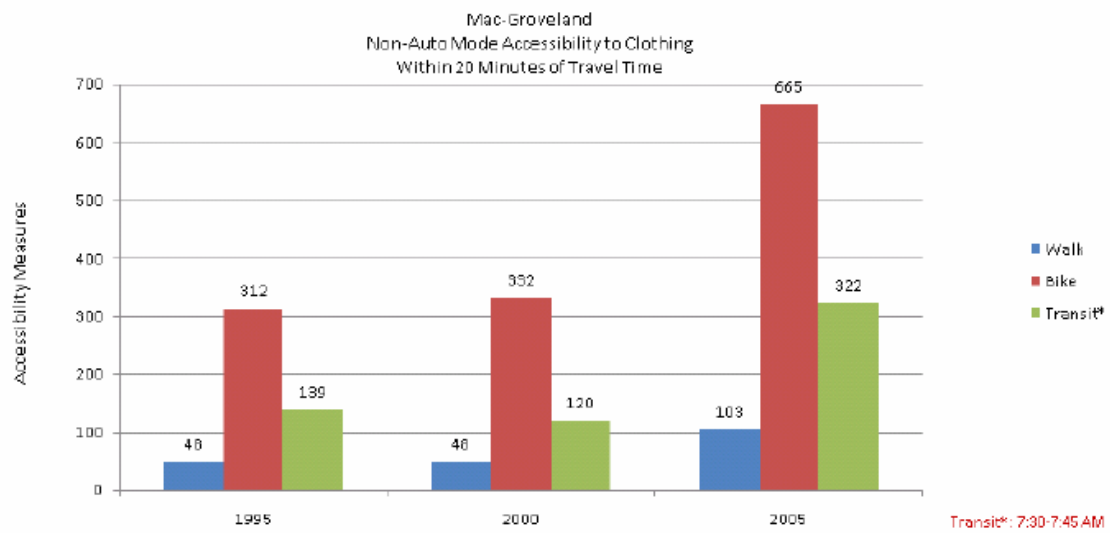
network) as exceptions. The second uses the 'Fix Topology Error Tool' to iteratively fix the network errors.

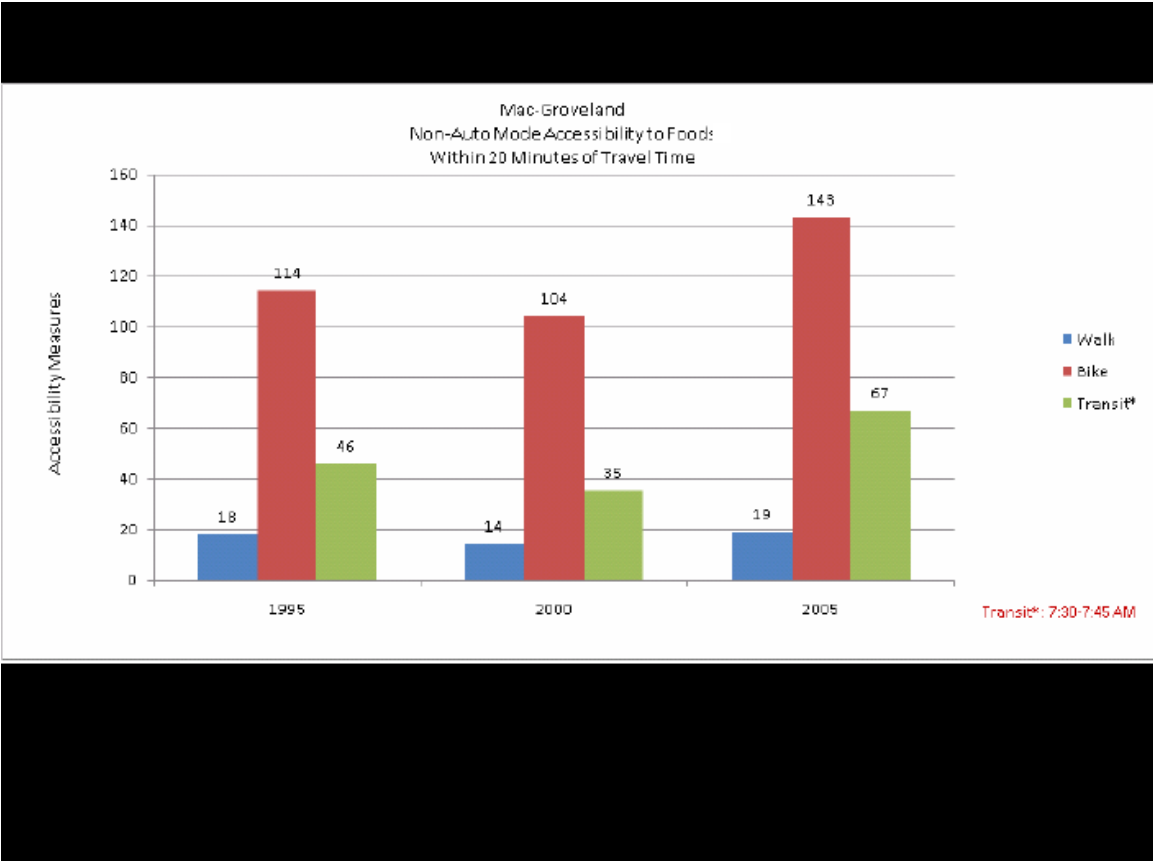
- d) Click 'Error Inspector' in the Topology Editing toolbar. Note, these steps could take 20-30 minutes for a large network, even on a fast computer.
 - i) Show '<Errors from all rules>', uncheck 'Visible Extent only' and click 'Search Now'.
 - ii) Select all road centerline errors (i.e. all non-bicycle facility error). This is why it is helpful to group FID's by type as mentioned in 1.b. and to sort by that field in Error Inspector.
 - iii) Go back to the map space. Right click and select 'Mark as Exception'. All these errors should go away as they are exceptions to the "Must Not Have Dangles" rule.
 - e) Select all the remaining errors on the map. We will work iteratively to fix as many bicycle network errors as possible.
 - i) Right click on the map. There will be three options: snap, extend, and trim. We will employ them in this order: trim, extend, and snap.
 - ii) Select Trim first, which will correct for overshoots. We found 5 meters to be an appropriate length. Some of the dangles should go away.
 - iii) Select the remaining errors on the map space and right click again. Choose Extend to correct for undershoots. We found 20 meters to be an appropriate length for our network. Many errors should go away
 - iv) Select the remaining errors and right click again. Choose Snap, to correct for remaining errors. Twenty meters seems to be an appropriate length.
 - f) Save your edits
- 6) Export the Topology back to a shapefile
 - a) Right click on the Feature Class, Export > To Shapefile (single).
 - b) You can then link the shapefile back to individual road and centerline files.
 - 7) Convert shapefile to network in ArcCatalog
 - a) Right click on the shapefile in ArcCatalog
 - b) Click on New Network Data base
- Click through the prompts, though build network

Appendix B

Example Maps and Accessibility Measures, by Geography, Time, and Mode

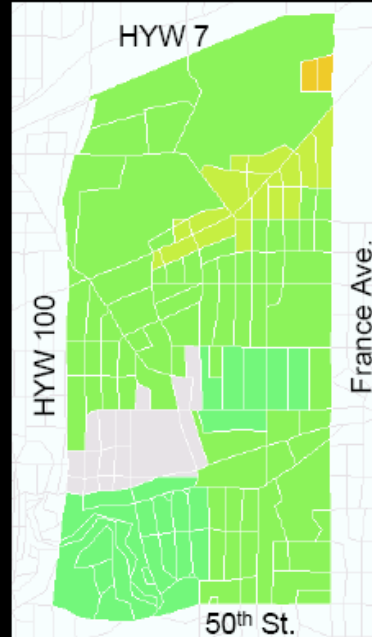
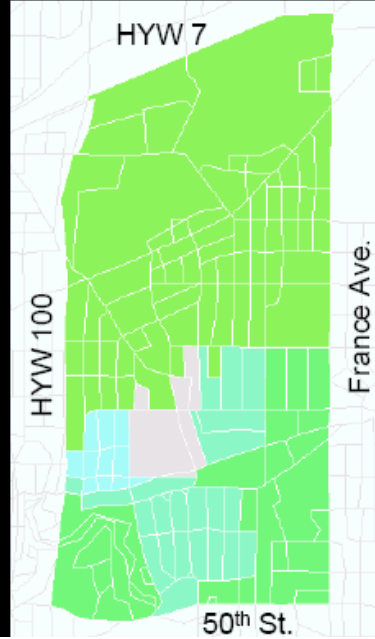
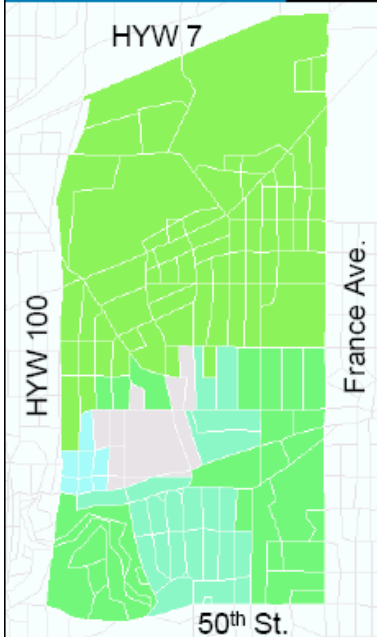
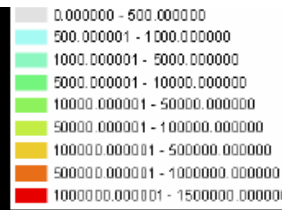






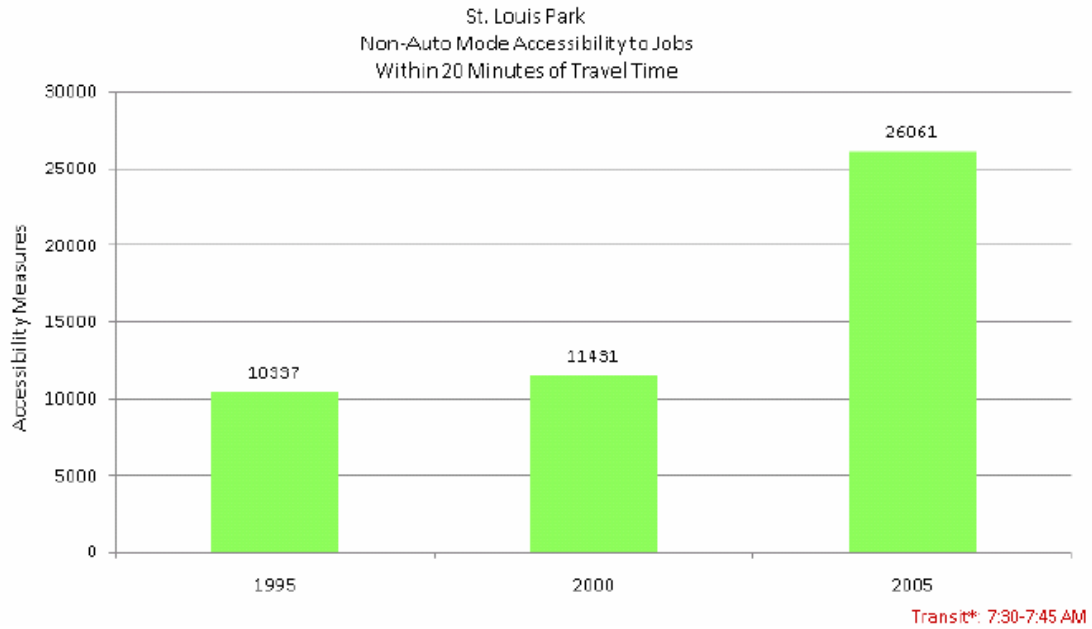
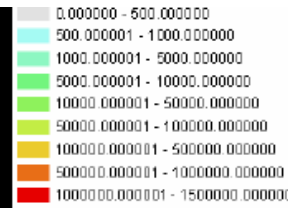


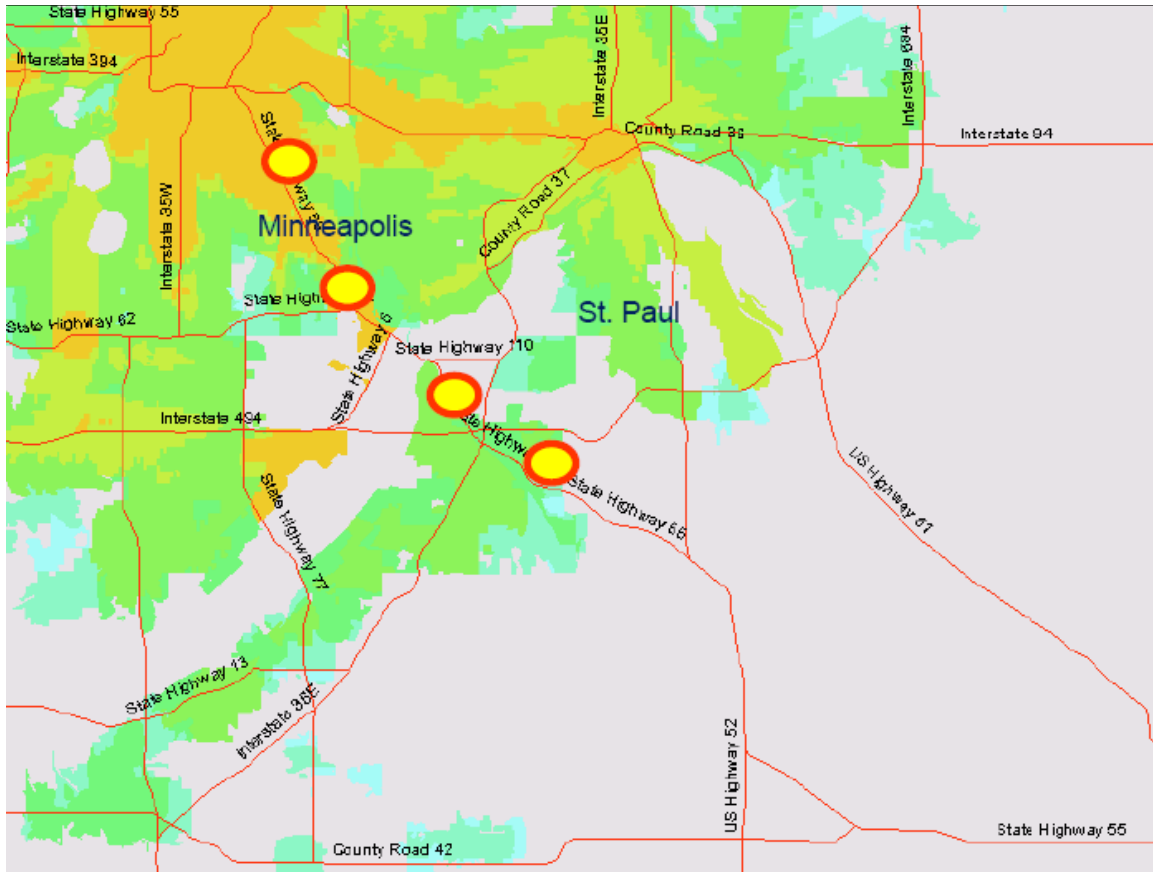
St. Louis Park ('95, 00, 05) Total Employment

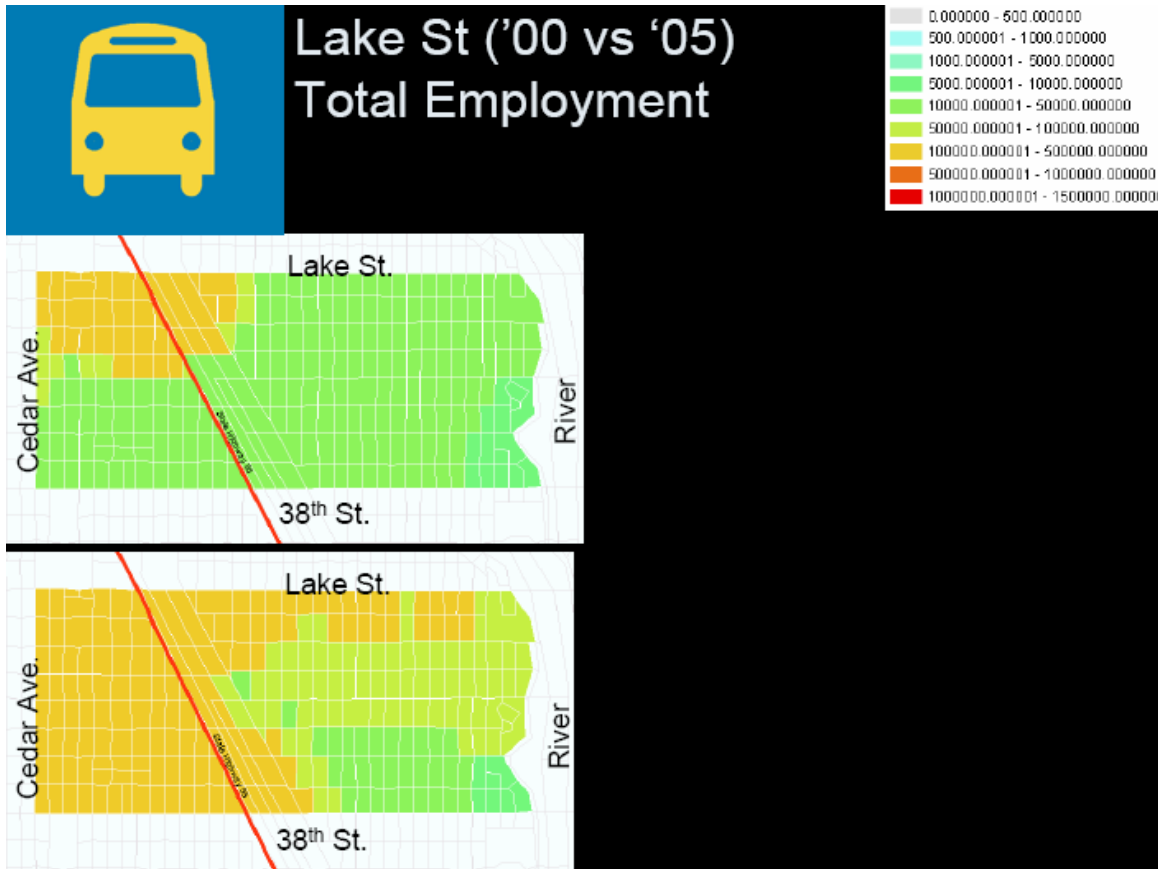




St. Louis Park ('95, 00, 05) Total Employment

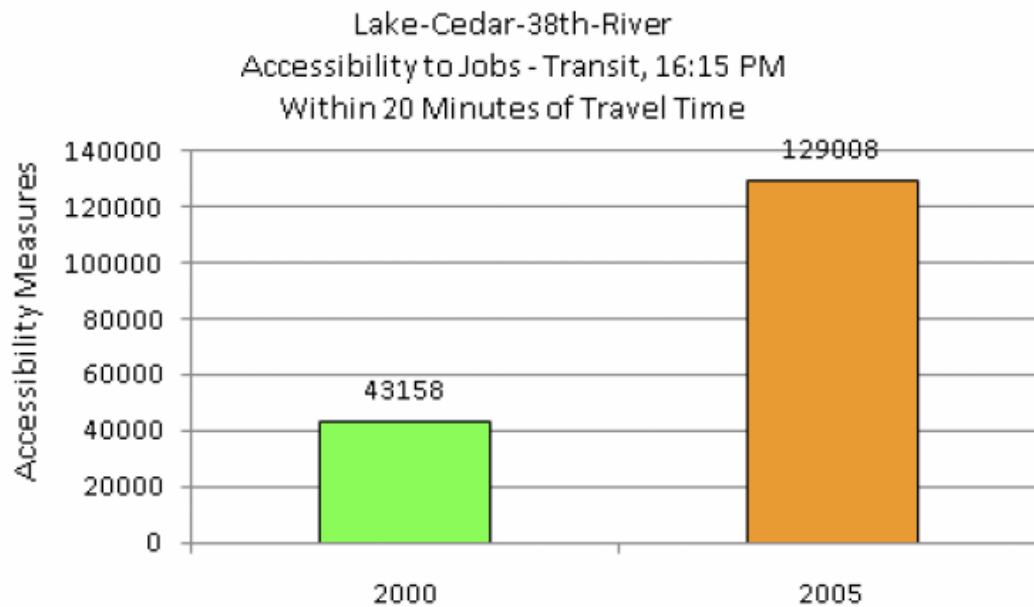
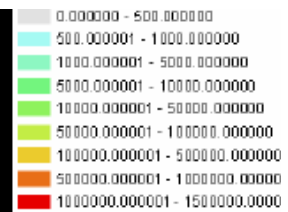






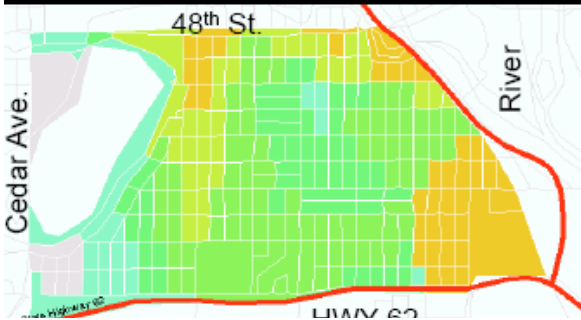
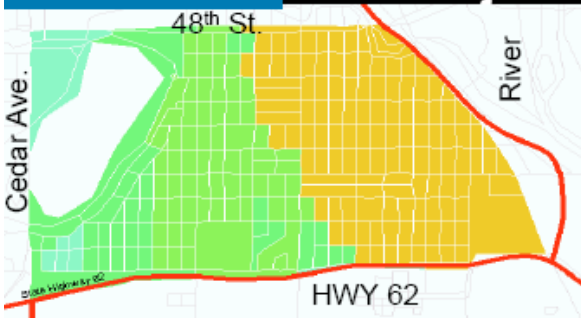
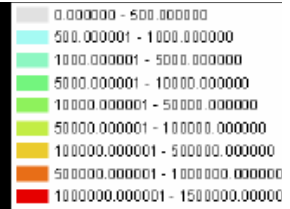


Lake St ('00 vs '05) Total Employment



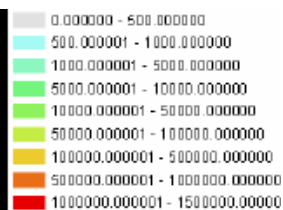


Fort Snelling ('00 vs '05) Total Employment

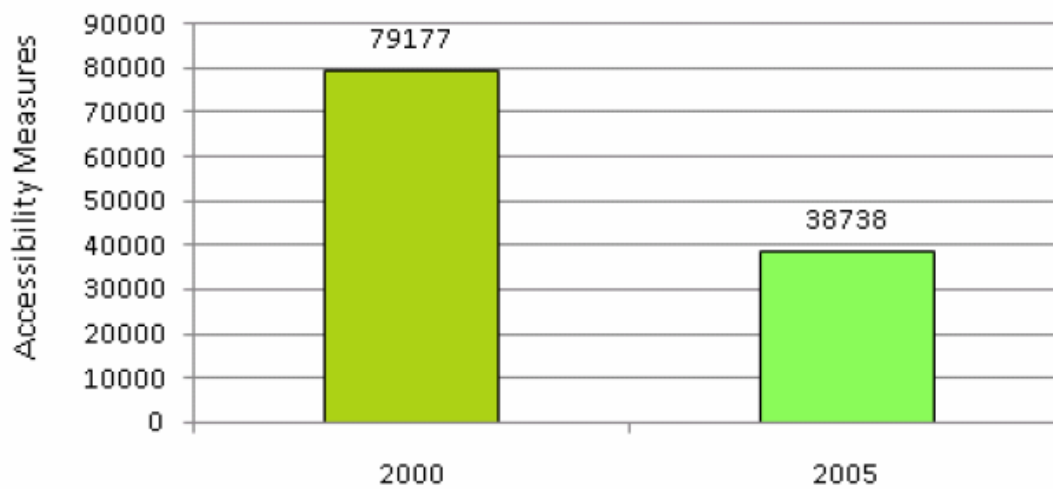


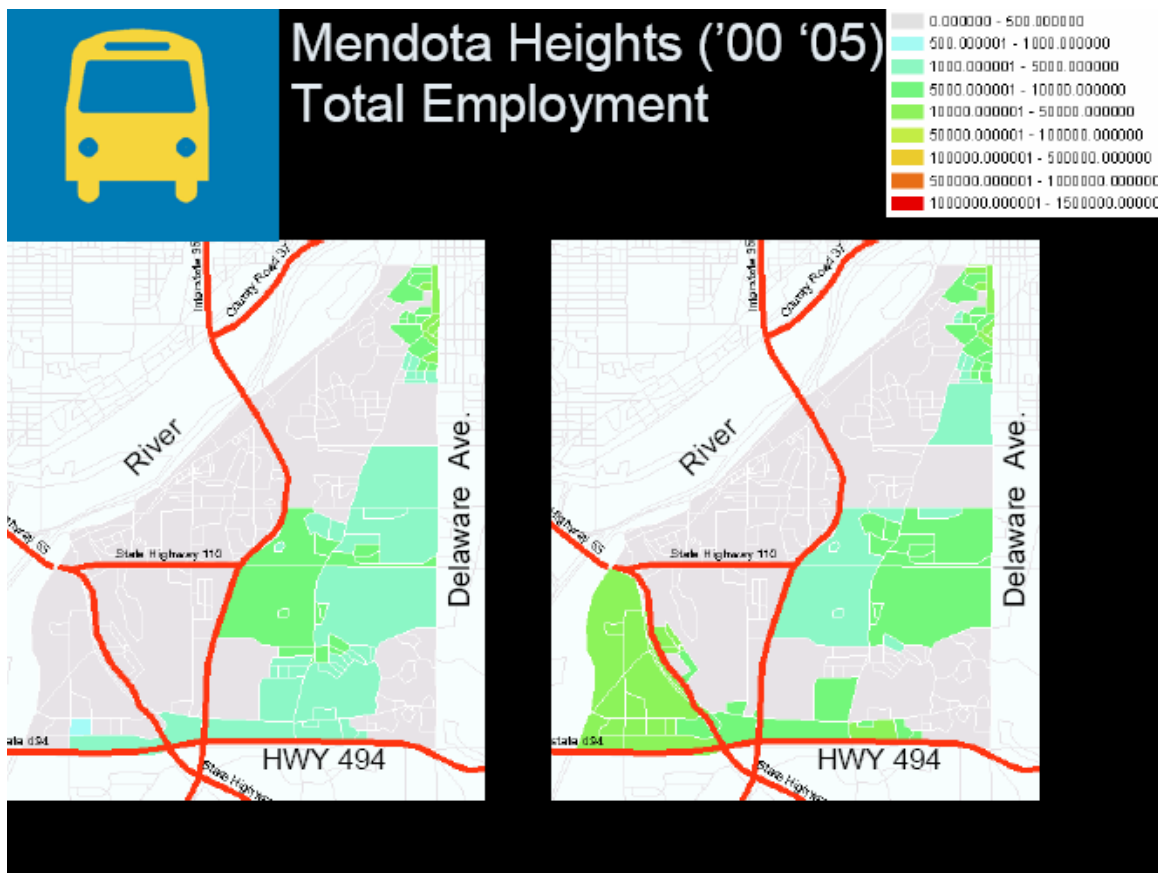


Fort Snelling ('00 vs '05) Total Employment



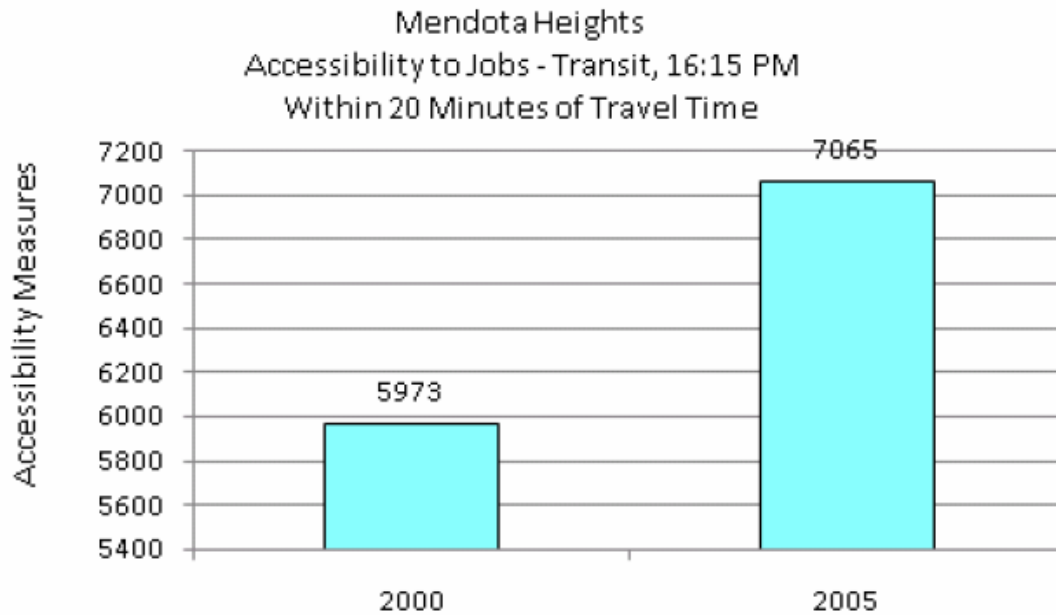
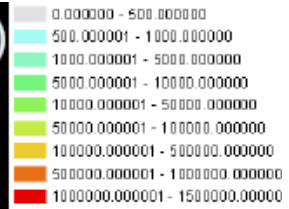
48th-Cedar-Hwy 62-River
Accessibility to Jobs - Transit, 16:15 PM
Within 20 Minutes of Travel Time

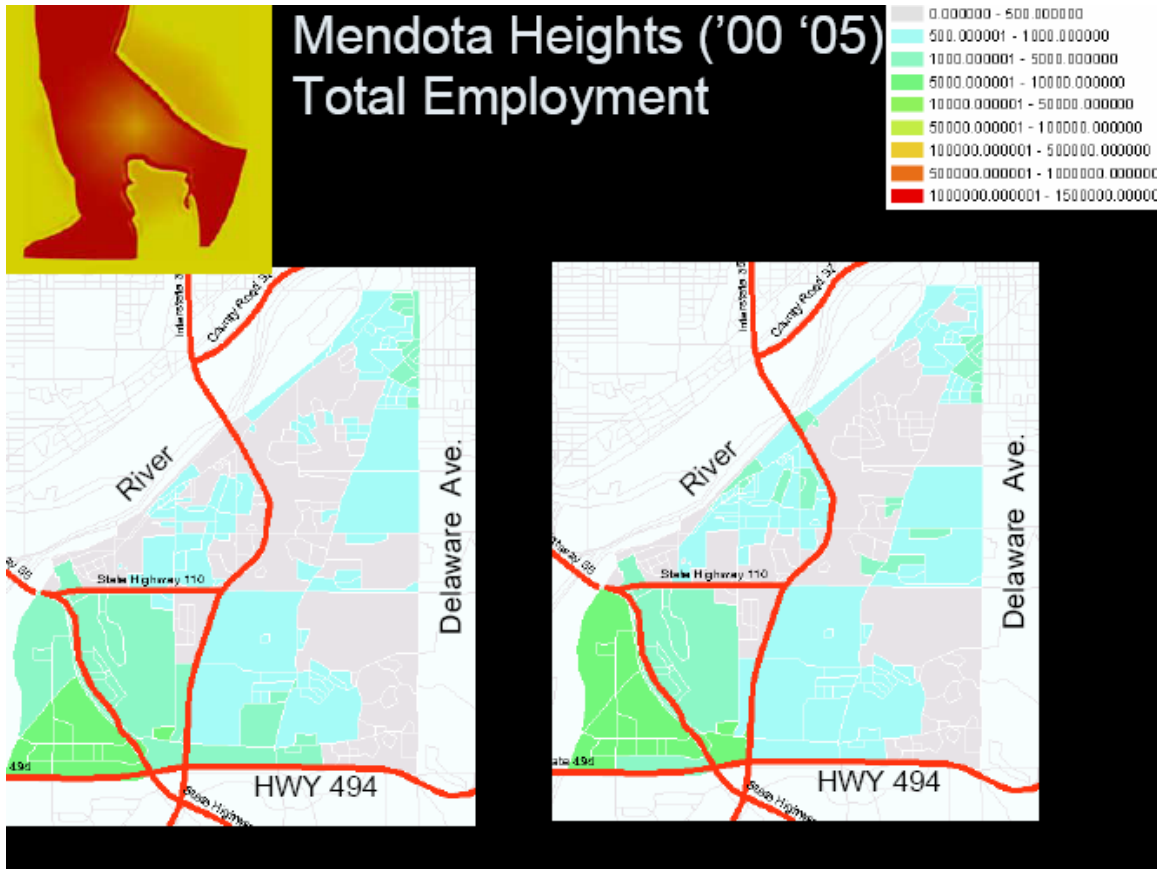






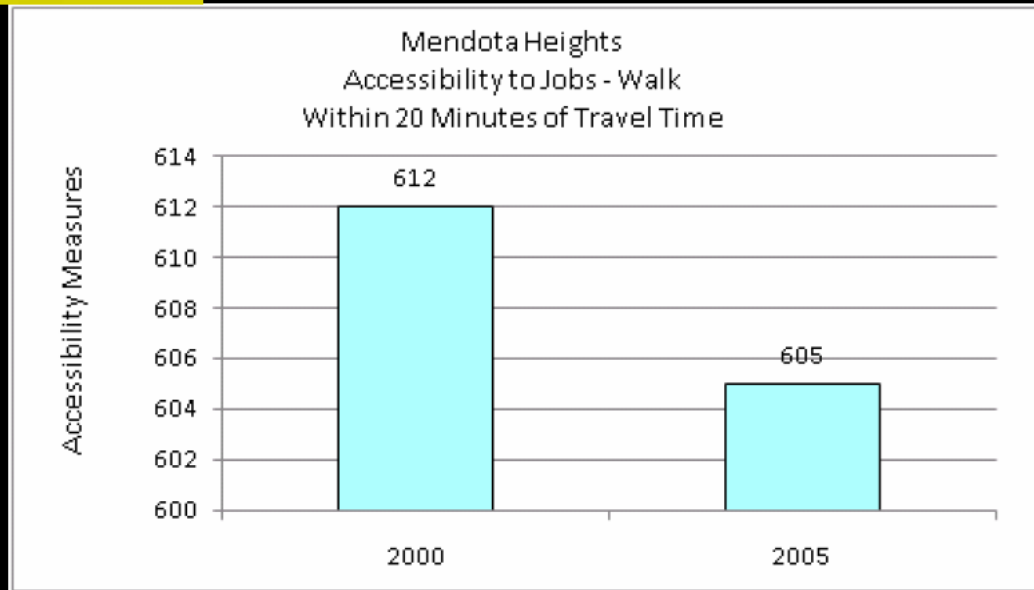
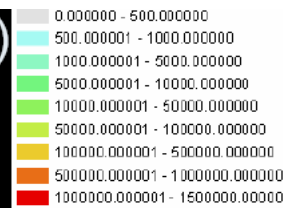
Mendota Heights ('00 '05) Total Employment





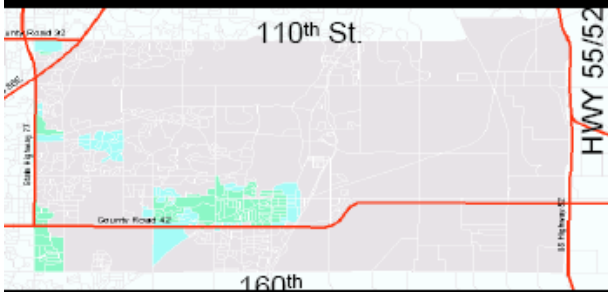
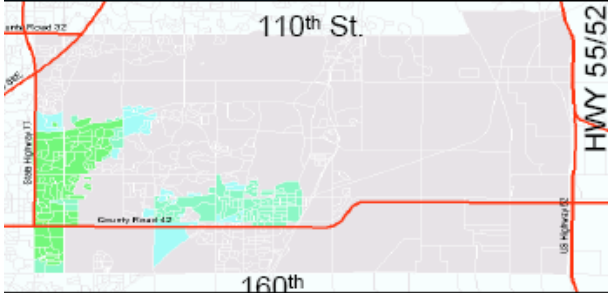
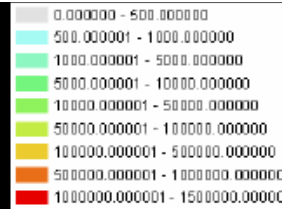


Mendota Heights ('00 '05) Total Employment



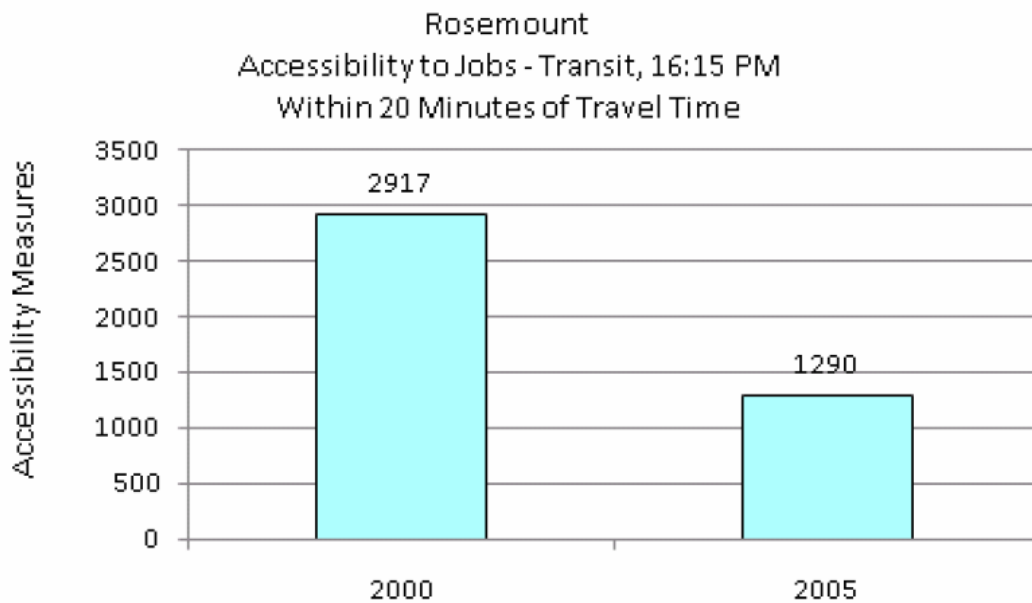
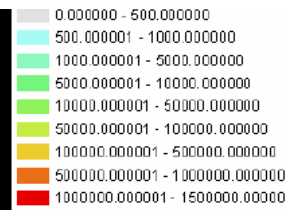


Rosemount ('00 vs '05) Total Employment



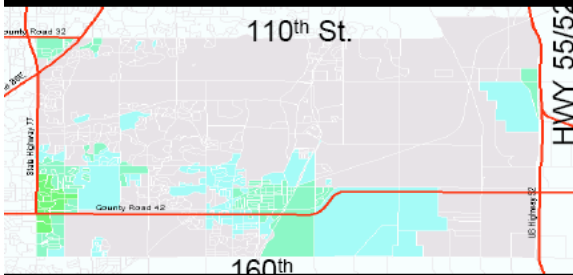
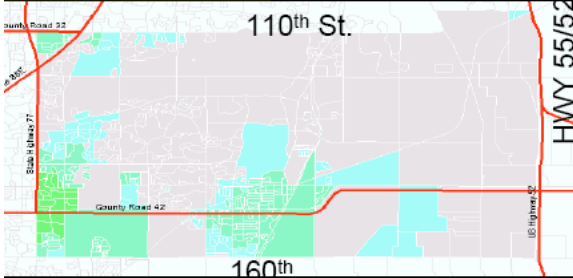
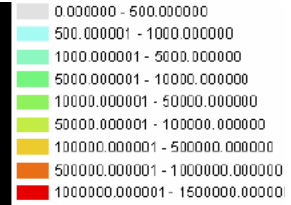


Rosemount ('00 vs '05) Total Employment



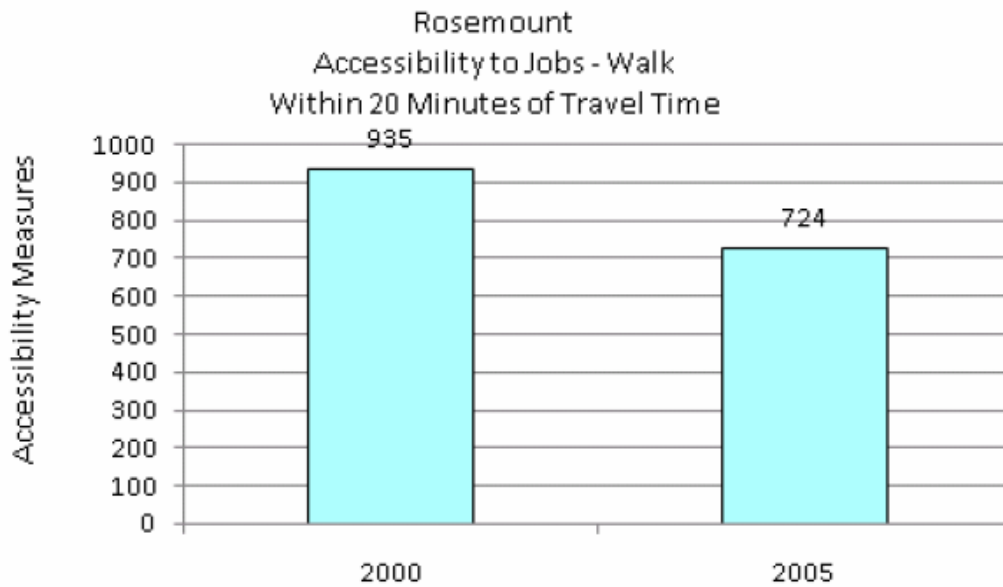
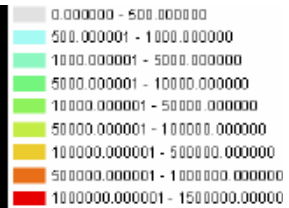


Rosemount ('00 vs '05) Total Employment

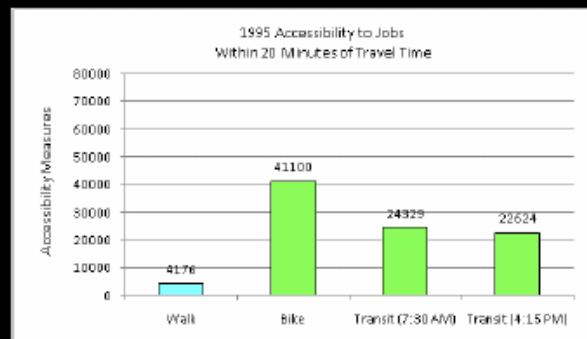
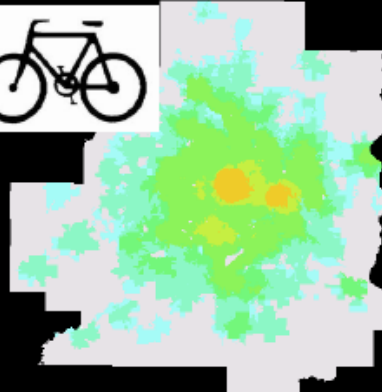
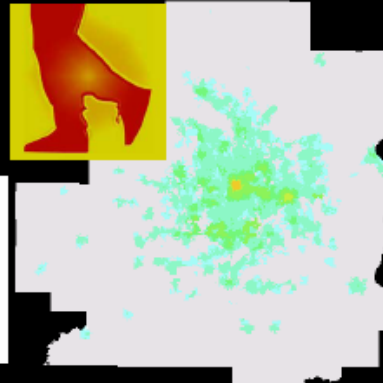
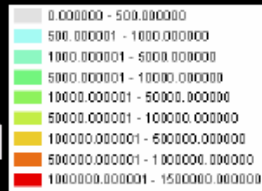
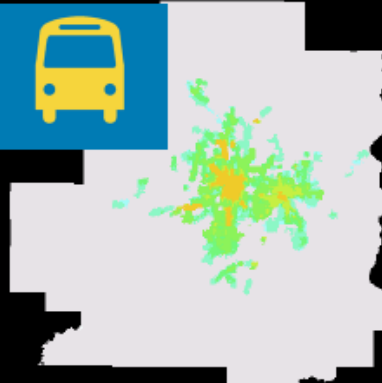




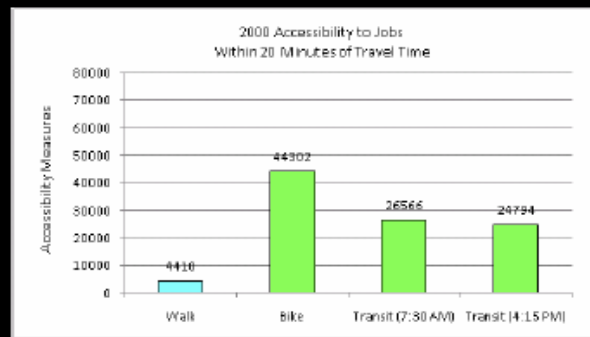
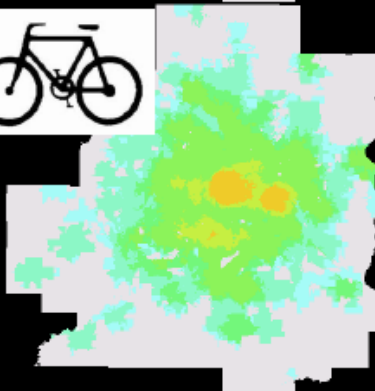
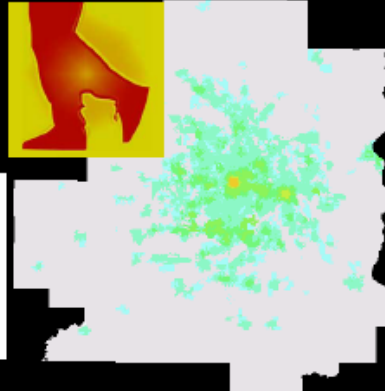
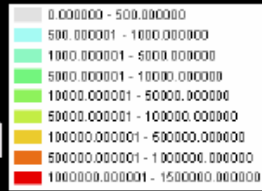
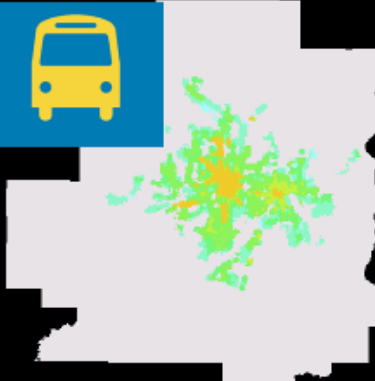
Rosemount ('00 vs '05) Total Employment



'95 Total Employment



'00 Total Employment



'05 Total Employment

