January 2016

Bicycle Transit And The Journey To Work: An Exploration Of Bicycle Accessiblity In 10 Large U.s. Cities

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BICYCLE TRANSIT AND THE JOURNEY TO WORK: AN EXPLORATION OF BICYCLE ACCESSIBILITY IN 10 LARGE U.S. CITIES

by

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Bachelor of Science, Utah State University, 2007

A Thesis

Submitted to the Graduate Faculty

of the

University of North Dakota

In partial fulfillment of the requirements

for the degree of

Master of Arts

Grand Forks, North Dakota

December

2016

This thesis, submitted by Brandon Lee Andreasen in partial fulfillment of the requirements for the Degree of Master of Arts from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

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Dean of the School of Graduate Studies

November 21, 2016

Date

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Title	Bicycle Transit and the Journey to Work: An Exploration of Bicycle Accessibility in 10 large U.S. Cities
Department	Geography and Geographic Information Science
Degree	Master of Arts

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16 November 2016

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ACKNOWLEDGMENTS

The achievement of this thesis was only possible due to the help and support of several individuals. First I wish to thank my adviser, Dr. Michael Niedzielski, and my committee members, Dr. Enru Wang and Dr. Daba S. Gedafa, from the University of North Dakota, who gave me all the support and valuable suggestions in the development of this thesis. I had many doubts but your presence and help was constant throughout. I do not have the words to express my gratitude to you. Also, I want to thank the United States Army which allowed me to pursue my graduate studies. I wish to thank my family and friends, who make my life better with their companionship. Finally, to my boon companion, my wife and the love of my life, thank you; without you none of this would be possible.

ABSTRACT

This thesis examines the access to bicycle infrastructure from home locations and the locations of employment opportunities. The accessibility of bicycle infrastructure to employment is calculated using distance thresholds of 1, 3, 5, 7, and 9 kilometers and compared using the road network, all bicycle infrastructure, and only bicycle paths for 10 United States cities. Findings indicate that on average, 71 percent of jobs in a city have access to bicycle infrastructure, which is found to be statistically significant at the 0.05 level in relation to the bicycle commute mode share, as opposed to 66 percent of residents which was not statistically significant. The results indicate a statistically significant correlation of all bicycle infrastructure accessibility and the bicycle commute mode share for travel distances of 3, 5, 7, and 9 kilometers.

CHAPTER I

INTRODUCTION

The transportation network and land use in the United States has long been designed and used for the automobile. The automobile is a critical economic and social mode of travel for most Americans, as 89 percent of trips made by Americans are made by automobile (Buehler 2011). This presents many problems such as traffic congestion, pollution, sedentary lifestyles that result in negative health effects, and increasing owner and operation costs. To offset the negative effects of unsustainable automobile practices, governmental organizations at all levels have implemented alternative transit system plans to serve as another option to the automobile. In recent years, the bicycle has also been included in the campaign to encourage people to travel by means other than the automobile (NACTO 2010, USDHHS 2008, USDOT 2010). Travel in the United States is conducted for a variety of reasons, but the largest share of trips undertaken by residents is for the purpose of traveling from one's residence to their place of employment (Ross and Svajlenka 2012).

While some growth has been experienced, many urban planners continue to explore ways to increase bicycle use for the journey to work. In the U.S., only 1 percent of the nation's share of the commute is by bicycle (Pucher, Buehler, and Seinen 2011). The variation within U.S. cities can be extreme; the city of Davis, California has a bicycle commute share of 15.5 percent (Schoner and Levinson 2014), while cities such as Dallas, Texas experience bicycle mode shares of less than 0.3 percent (Pucher, Buehler, and Seinen 2011). Some European countries experience a high level of bike share for the commute; Denmark has a national bike share of 18 percent, and the Netherlands experiences a 27 percent bike share for the commute. Within Denmark and the Netherlands, the cities also experience large shares of bicycle commuting; Copenhagen, Denmark has a mode share of 29 percent and Groningen, Netherlands has a mode share of 38 percent (Pucher and Buehler 2008).

Low levels of cycling in the U.S. have been attributed to different reasons by various research studies; the reasons can be divided into five groups of factors that affect the decision to cycle. The five groups are the built environment, the natural environment, socio-economic variables, psychological factors, and aspects related to cost and safety (Heinen, van Wee, and Maat 2010). These studies often focus on sociological and economic variables that influence an individual's decision to utilize the bicycle. The variables include such factors as cycling safety, land use, car ownership, costs of travel use, income, climate, topography, gender, time, and cultural (Pucher and Buehler 2006, Pucher, Dill, and Handy 2010, Moudon et al. 2005, Cervero and Duncan 2006, Börjesson and Eliasson 2012).

Bicycle infrastructure is a part of the built environment that provides cyclists with structures that are designed to facilitate the unique needs of a cyclist. Bicycle infrastructure consists of bikeways, bicycle parking, intersection modifications, priority signals, traffic calming designs, and service stations. For cycling to be a viable mode of commuting, residents must be able to have access to the infrastructure and be able to access a range of jobs (Tomer et al. 2011). Accessibility, or the number of potential opportunities for interaction that an individual has by utilizing bicycle infrastructure, plays an important role in determining the use of a bicycle for commuting. Many studies have been conducted that specifically examine bicycle commuting which focus on factors of the commute such as socio-economic variables (Parkin, Wardman, and Page 2008 and Zhao 2014), physical environment (Wahlgren and Schantz 2012), distance (Heinen, Maat, and Van Wee 2013), car ownership (Thigpen, Driller, and Handy 2015), and bicycle infrastructure (Dill and Carr 2003, Krizek, Barnes, and Thompson 2009, Buehler and Pucher 2011, and Schoner and Levinson 2014). These studies utilize various measures to determine the amount of bicycle infrastructure and relate the presence of infrastructure to the commute mode share. Little research has been done to study the access that residents of a city have to bicycle infrastructure and the accessibility that is provided by that infrastructure. Bicycle accessibility studies typically investigate accessibility to recreation or shopping opportunities, but do not study accessibility to jobs. Moreover, no study has analyzed access to bicycle infrastructure and the effectiveness of bicycle infrastructure compared to road accessibility (Iacono, Krizek, and El-Geneidy 2010, McNeil 2010, Dony, Delmelle, and Delmelle 2015). This thesis will examine job accessibility by bicycle and compare the effectiveness of bike infrastructure versus all road travel in providing accessibility to jobs as it relates to the bicycle commute mode share.

CHAPTER II

LITERATURE REVIEW

The bicycle commute mode share is explained through many factors and circumstances that contribute to the likelihood that an individual will utilize the bicycle for commuting purposes among the various factors. The link between the bicycle infrastructure and the mode share is important; the development of effective bicycle infrastructure plays a crucial role in the access to bicycle infrastructure and the accessibility of jobs that people have. Assessing the access that residents and places of employment have to bicycle infrastructure and determining the accessibility to jobs is a building block for determining the effectiveness of bicycle infrastructure and developing plans and strategies to increase the bicycle mode share.

2.1 Factors affecting bicycle mode share

Most studies of bicycling and the bicycle commute focus on the socio-economic factors and obtain mixed results with little consensus on the effect that most factors have on the bicycle commute (Table 1). Clearly there is a relationship between cycling and socio-economic factors; however, the strength of the relationship is not always clear cut.

Table 1. Factors of bicycling mode share findings.

Factor	Effect	Reference(s)
Gender (Male)	+	Clifton and Krizek 2004, Moudon et al. 2005, Stinson and Bhat 2005, Dill and Voros 2007, Parkin, Wardman, and Page 2008, Pucher, Buehler, and Seinen 2011
Gender	No difference	Börjesson and Eliasson 2012
Age	25-44 years	Larsen, Gilliland, and Hess 2012, Freeman et al. 2013
Income (increase)	+	Parkin, Wardman, and Page 2008,
	No difference	Dill and Carr 2003
	-	Plaut 2005
Education Level	+	Pucher and Buehler 2008, Freeman et al. 2013
	-	Rietveld and Daniel 2004
Children	-	Moudon et al. 2005
Ethnicity	-	Freeman et al. 2013
Automobile Owner	-	Stinson and Bhat 2005, Pucher and Buehler 2006, Dill and Voros 2007, Parkin, Wardman, and Page 2008,
	No difference	Moudon et al. 2005
Rainfall	-	Dill and Carr 2003
Hills (experienced cyclists)	+	Stinson and Bhat 2005
Hills (inexperienced cyclists)	-	
Safety	-	Reitvald and Daniel 2004, Pucher and Buehler 2008, Reynolds et al. 2009

An individual's bicycling behavior is directly linked to several factors such as gender, age, income, education level, children, race or ethnicity, and automobile ownership, environment, and safety.

Studies identify males as being more likely to use the bicycle mode of transit to work than females (Clifton and Krizek 2004, Moudon et al. 2005, Stinson and Bhat 2005, Dill and Voros 2007, Parkin, Wardman, and Page 2008, Pucher, Buehler, and Seinen 2011), while other studies have found that the gender difference is negligible (Börjesson and Eliasson 2012). However, the difference in the studies may be due to the regions of study. Parkin, Wardman, and Page's (2008) study took place in the U.K. with a mode share of 2.89 percent, Pucher, Buehler, and Seinen's (2011) study was in the U.S. with a national mode share of 1 percent, and Börjesson's and Eliasson's (2012) study was in Stockholm, Sweden with a bicycle mode share of 10 percent. Cultural differences may explain the disparity in the findings. It has been concluded by some researchers that in countries with low cycling, men tend to cycle more, but in counties with higher rates of cycling, the difference between the genders is more even (Heinen, van Wee, and Matt 2010).

Age is also used as a discriminator between cyclists. It has been noted that people aged 25 to 44 years old are more likely to engage in physical activity and specifically bicycling (Freeman et al. 2013). Research has also noted in recent years that bicycling among children has been on the decline (Larsen, Gilliland, and Hess 2012).

Income and education are closely linked in terms of cycling, and the study data shows no consensus on the subject. Individuals that have received more education are more likely to know about health and its link to exercise; these more highly educated individuals are also more likely to be employed in jobs that pay more (Parkin, Wardman, and Page 2008, Pucher and Buehler 2008, Freeman et al. 2013). These individuals will then elect to cycle because they are more concerned about their health for education reasons. This may not be the case in all circumstances where findings indicate that higher levels of education are an indicator of less cycling, but this is perhaps an indicator of affluent neighborhoods having qualities that prohibit jobs from being nearby (Rietveld and Daniel 2004). But, this is not the same reason that people of lower education levels will cycle. For some they may not make enough money that they can afford the costs that are associated with automobile ownership; for these individuals the bicycle may be an affordable alternate mode of transport (Plaut 2005). A lower educational attainment is inevitably linked to the possibility that their level of income will also be lower than a person who has achieved higher levels of education. The discrepancies in findings and the complexity have led to calls for further research (Heinen, van Wee, and Maat 2010).

Family structure in and of itself greatly influences the likelihood that a person will bicycle. Having children reduces the likelihood that a person will cycle. Children are intensive in the utility of time and cyclists value their time above any other transit mode. That most parents are more likely to choose an alternate transit mode is indicative that children are the reason behind the time budgeting (Moudon et al. 2005).

Race or ethnicity in the U.S. has been associated with active travel. It has been found that African Americans, Hispanics, and Asians are more likely to report no active travel. However, once any ethnicity reports active travel, the number of trips taken and distance do not statistically vary enough to identify a difference (Freeman et al. 2013). These findings do not reflect across all cities. In Detroit, neighborhoods that housed minorities were designed in such a manner that without access to a car, job opportunities were out of reach by residents (Grengs 2010).

Car ownership is often thought of as a more convenient mode of transportation, with the U.S. design of most cities favoring the automobile (Grengs 2010). In some instances, people need to use an automobile for employment purposes (Moritz, 1998). Car ownership is not illogical to result in less cycling; the next logical conclusion would be that an increase in the number of automobiles per working age member of the household would also result in less cycling.

The natural environment has an influence on bicycling, and while it may seem self-evident that weather and the natural terrain influence bicycling, studies have shown that what would seem intuitive is not. Many of the Nordic countries experience a level of bicycle share that is significantly higher than that experienced in places where the climate is milder. The U.S., U.K., and Australia experience a bike share that is at 2 percent or less, while the Netherlands, Germany, and Denmark experience a level of bike share that is 10 times higher (Pucher and Buehler 2008). The amount of rainfall has been negatively linked to bicycling. In a study of U.S. cities, the six cities with the lowest bicycle mode share experience over 100 days of rainfall each year; however, three of the top six cities also experience the same amount of rainfall (Dill and Carr 2003). Intuitively, slope has a negative impact on biking, but studies have found that effect varies with the experience of the cyclist. Studies that differentiate between experienced and inexperienced cyclists found that experienced cyclists may actively seek out slopes while the inexperienced will attempt to avoid them (Stinson and Bhat 2005). The natural environment affects how and when people cycle, but its influence is difficult to determine as some places with weather and terrain that are not conducive to cycling experience high bicycle mode shares.

Safety is often cited as a reason for not cycling in the U.S. While Europe does not have the perception of cycling as an unsafe mode of transit, the opposite seems to be true for the U.S. (Pucher and Buehler 2008). European cyclists often do not wear helmets because cycling is perceived as a safe form of transit due to the number of people who bicycle and the amount of bicycling infrastructure (Pucher, Dill, and Handy 2010). In

Europe as opposed to the U.S., many policies, such as right of way at traffic stops and crossings favor the cyclist over automobiles (Rietvald and Daniel 2004). These policies seem to enhance cycling safety and attract more people to cycle. While safety is often cited in cycling literature, it is often measured in fatalities because those generate police reports that can be aggregated and studied. Some researchers have pointed out that this is a poor identification for bicycle safety as it does not account for interactions between bicyclists and motorists that require either a speed or direction change from one or both parties, which usually do not result in an official report but are perceived as a level of safety (Reynolds et al. 2009).

Psychological factors also influence the decision to cycle, as people's attitudes and habits often influence their mode of transportation choice. People who have positive attitudes to cycling are more likely to cycle. This effect is not only attributed to those who already cycle; those who are also considering becoming cyclists for commuting purposes generally view cycling with a positive attitude. It is also present for the automobile, since most Americans view the automobile with a very positive attitude and are more likely to use it (Heinen, van Wee, and Maat 2010).

A person's habits often influence the use of the bicycle. If one bicycles as a child, they are more likely to continue to use the bicycle as a mode of transportation (Larsen, Gilliland, and Hess 2012). Those who are in the habit of using other modes of transit for the commute to work, other than the automobile, are also more likely not to use the bicycle for the commute to work. This can be linked to the idea that a person who is in the habit of using one type of transportation when making a decision to commute does not take into account all factors; they may not necessarily make a logical decision because of habit (Heinen, van Wee, and Maat 2010).

2.2 Bicycle infrastructure

A principal piece of the built environment is the infrastructure for both cycling and other modes of transit. With the presence of infrastructure, higher rates of cycling will take place (Pucher, Dill, and Handy 2010). It is important to note that bicycle infrastructure has two types: on-street facilities and off-street facilities (Krizek, Barnes, and Thompson 2009).

On-street bicycle infrastructure is usually identified as a bike lane and streets that may or may not include markings. When considering on-street bicycling facilities, surrounding factors are what influence the quality of the infrastructure rather than characteristics not directly related to the facility. Road conditions such as the width, number of vehicle lanes, type of automobile parking, number of intersections, and traffic conditions such as speed and volume affect how a cyclist perceives the infrastructure and is linked to their probable use of the infrastructure (Segadilha and Sanches 2014).

Off-street bicycle facilities are separated from automobile traffic and the road network, and are commonly referred to as pathways. Pathways are often associated with greenways, and studies have indicated that off-street bicycle facilities are preferred to on-street facilities due to the aesthetics that are often attributed to pathways such as large shade trees, grass, and shrubbery. Also, off-street facilities are often seen as safer as the cyclist does not have to interact with motor vehicle traffic, and the perception of increased safety on off-street facilities makes the infrastructure more appealing for use (Wahlgren and Schantz 2012).

Some research has begun to focus on infrastructure and its effects on the bicycle mode share; it has been found that route variables are not statistically significant when conducting survey and GIS-based studies of cycling (Moudon et al. 2005). Yet, other studies have found that cyclists will trade efficiency for safety and comfort (Dill 2009). This evidence is contradictory and may be due to different data collection and evaluation methods. It has been found that the addition of infrastructure will increase the bicycle mode share. It was noted that a 10 percent increase in the mileage of bicycle lanes resulted in a 3.1 percent increase in bicycle mode share in a study of 90 major U.S. cities (Buehler and Pucher 2011). This only goes to highlight the complexity and difficulty in attempting to explain cycling through evaluation of the perceived and built environment. The contradiction in evidence has been noted by several researchers and there have been calls to develop a single method for the evaluation of built environment and specifically bicycle infrastructure.

It is clear that the built environment does affect an individual's access to bicycle infrastructure specifically as it applies to density, diversity, and design (Cervero and Kockelman 1997). Specifically, population density is important in trip choice because it influences the diversity and design, which also influence how individuals choose to travel. Those areas with high population density and diversity in land use tend to decrease the number of automobile trips that are produced as opposed to the suburbs which tend to encourage automobile use through monolithic land use; street designs such as cul-de-sacs act as barriers to bicyclists for commuting purposes or increase the distance required to travel on bicycle infrastructure, rather than a street grid design (Cervero and Kockelman 1997).

The design and connectivity of the bicycle infrastructure also affects its use. Having to stop uses more energy for a bicycle rider as the effort to get the bicycle up to travel speed is more than the effort required to maintain a set speed, and red lights have been found to have a negative correlation to choosing to cycle (Wahlgren and Schantz 2012). However, intersections within the bicycle infrastructure may allow the cyclist to use a more direct route to reach their destination. The number of stops that a cyclist is required to make per kilometer has a negative association for the bicycle mode share (Rietvald and Daniel 2004), whereas connectivity and density were found to have a significant and positive effect on bicycle mode share (Schoner and Levinson 2014). A balance is needed with the implementation of bicycle infrastructure that will provide the desired connection between the point of origin and the destination in such a manner that it minimizes the number of stops that a cyclist may have to make and maximizes the choice of the cyclist for traveling.

Discontinuity within the bicycle network can often occur when a bicycle infrastructure type changes; this may occur as bicycle paths and lanes intersect and can have consequences for those who are considering using the bicycle to commute as it forces the cyclist to integrate with mixed traffic, detour, or use a different commuting method (Schoner and Levinson 2014). This is particularly important when safety is considered as some cyclists do not perceive the road as a safe method of travel and will not use the bicycle to commute if infrastructure cannot be used to access their destination (Cervero and Duncan 2003 and Pucher and Buehler 2008).

Few studies explore access to bicycle infrastructure and the accessibility that can be achieved by using bicycle infrastructure to reach a destination. Access is the opportunity for the use of a transport system based upon proximity, and accessibility is the suitability of the transportation network to reach an activity from an origin location (Murray et al. 1998). Studies that look at access to bicycle infrastructure generally do so at the individual level through the use of survey data (Moudon et al. 2005, Dill and Voros 2007, and Cevero et al. 2009). Of the studies conducted at this level, only one found that people in the Twin Cities of Minneapolis and St. Paul, living within 400 meters of bicycle infrastructure, were more likely to bicycle (Krizek and Johnson 2006). While some people may use the road network to bicycle, others for reasons of safety may only use the bicycle infrastructure. Therefore, a systematic analysis of access to bicycle infrastructure is needed to assess the level of access that cities provide to bicycle infrastructure. Such an analysis at the zonal level will allow inter-zonal and intercity comparisons. This analysis is missing from the bicycle literature. In a recent review of active accessibility, Vale, Saraiva, and Pereira (2016) called for not only the study of origins but also of destinations, as the destination is just as important as the origin.

Concerning the study of bicycle accessibility, only studies conducted at the individual or neighborhood level were found; some of the studies examined accessibility to opportunities other than work (Pearce, Witten, and Bartie 2006, Apparicio et al. 2008, Páez, Scott, and Morency 2012, and Dony, Delmelle, and Delmelle 2015). Of the studies that do examine accessibility to include work locations, they measure the accessibility at the neighborhood scale or larger (Shen 2002, Iacano, Krizek, and El-Geneidy 2010, McNeil 2010, Silva and Pinho 2010, Lundberg 2012, and Vale 2009). The methods generally fit into categories that have been well defined for years; they are based upon either gravity models, distance, or infrastructure (Vale, Saraiva, and Pereira 2016). No studies have been conducted that assess the accessibility to jobs by bicycle infrastructure at the zonal level. Because some cyclists will only choose to cycle on bicycle infrastructure, job accessibility by bicycle for these people should be measured using only the bicycle infrastructure. An analysis of the zonal level of accessibility provided by the bicycle infrastructure compared with the accessibility provided by the road network will allow for generalizations to be made on the effectiveness of bicycle infrastructure in providing accessibility to jobs.

2.3 Acceptable cycling distance and travel impedances

In exploring the built environment, urban form plays an important role in determining the amount of distance that a cyclist can cover due to the expansiveness of the roads, the bicycle infrastructure network, and how the infrastructure is laid out.

Two measures of travel impedance are used in accessibility research, time and distance. Some of the studies that focus on bicycle accessibility use a time impedance (Vale 2009, Iacano, Krizek, and El-Geneidy 2010, Silva and Pinho 2010, Páez, Scott, and Morency 2012, and Dony, Delmelle, and Delmelle 2015). The problem with using a travel time impedance is that different cyclists will travel at different speeds depending on a number of conditions that make the creation of an accurate impedance model an extremely difficult task when dealing with other than small samplings at the individual level. Studies that use the distance impedance (Shen 2002, Apparicio et al. 2008, Iacano, Krizek, and El-Geneidy 2010, McNeil 2010, and Lundberg 2012) have the advantage of being generalizable across a large number of individuals and allow for a simple method of comparison across multiple areas, as factors such as time waiting at stops and other conditions need not be accounted for. The acceptable distance that a cyclist is willing to travel for the commute has been studied, and it was found that if this distance is exceeded, then the likelihood of cycling for that trip decreases (Rahul and Verma 2014). In Beijing, China it was found that this acceptable distance ranged from 0.5 to 3.5 kilometers (Zhao 2014), while other studies have indicated acceptable bicycling distances of 6.6 kilometers for women and 11.6 kilometers for men in Phoenix, Arizona (Howard and Burns 2001). In Stockholm, Sweden, the average trip length for cyclists was 7 kilometers (Börjesson and Eliasson 2012). It is important to note that as travel distance increases, the efficiency of the use of the bicycle commute decreases. This is because cyclists value their time spent cycling three times more than the value for any other mode used for commuting (Parkin, Wardman, and Page 2007). The longer a cyclist travels, the more valuable the time spent cycling becomes. As the distance and time of cycling increases, so does the physical effort to cycle. This means that facilities such as a changing room and a shower may be required at the destination. These additional requirements add to the cost of cycling (Börjesson and Eliasson 2012).

Travel distance calculation in the study of accessibility is sensitive to the method of measure used to calculate travel impedance. Four categories of travel impedance calculation methods are generally used: Euclidean distance, Manhattan distance, network distance, and shortest network time (Vale, Saraiva, and Pereira 2016). Each of the methods have their merits and uses. For cyclists, the method used to calculate the travel distance can be very critical especially when it comes to the shortest network distance and the shortest network time; these two calculations can be influenced by slope in terms of both speed and route choice. The Euclidean distance is not generally used as it ignores the network layout; only one study used this method of all the studies of bicycle accessibility (Shen 2002). All the other studies of bicycle accessibility use the network method of travel distance calculation as this accounts for the infrastructure that is being used to access the opportunity (Shen 2002, Vale 2009, Iacano, Krizek, and El-Geneidy 2010, McNeil 2010, Silva and Pinho 2010, Lundberg 2012, Páez, Scott, and Morency 2012, and Dony, Delmelle, and Delmelle 2015).

2.4 Measures of accessibility

Accessibility is defined as "the ease with which any land-use activity can be reached from a location using a particular transport system" (Dalvi and Martin 1976). A full review of accessibility is provided by Geurs and van Wee (2004). This study is focused on a potential accessibility based measure, specifically answering the question of how many job opportunities are accessible by bicycling. Hence, what follows is a review of potential based measures.

The accessibility index is a useful tool not only for describing what the actual flows of cycle behavior are, but for understanding what the potential accessibility is with a bicycle. It is important to understand the number of jobs that are accessible by bicycle as this can act as a guide to policy makers and urban planners in deciding whether adding more infrastructure or changing land use planning would best facilitate sustainable transport in regards to active commuting.

Accessibility is measured through three interrelated factors from which a quantitative index is derived to assess accessibility, or the ease with which a destination can be reached (Shen 2000). The three factors are spatial, socioeconomic, and numeric. The spatial factors are the origin, destination, and travel network infrastructure locations. The socioeconomic factors are the characteristics that describe the traveler in terms of social or economic status. The numeric factors are the push-pull factors that affect the attractiveness of a spatial location to draw travel (Niedzielski and Boschmann 2014).

There are three general measures of potential accessibility: travel cost, gravity-based, and cumulative opportunity. Travel cost measures the cost of travel from an origin to a destination. Gravity-based measures of accessibility incorporate factors of attractiveness and an impedance function that usually is expressed as a function of inverse power (Niedzielski and Boschmann 2014). Cumulative opportunity is a measure of the number of opportunities within a given threshold of distance (Grengs 2010), and is the measure of accessibility that will be used in this study because the number of employment opportunities within a city that a cyclist can reach plays a role in an individual's choice to utilize the bicycle as a viable transportation mode option. Cumulative opportunities also have the added benefit of being easily understood and comparable among different cities.

Cumulative opportunity is a form of the gravity model put forth by Hansen (1959) and is expressed formally as:

$$A_i = \sum_j E_j f\left(C_{ij}\right) \quad (1)$$

In this equation, A_i is the accessibility score for a person living in location i. E_j is the number of employment opportunities in zone j. $f(C_{ij})$ is the distance function expressed as $f = 1$ if $Cij \leq d$ or $f = 0$ if $Cij > d$, with, d, being a distance threshold.

Equation (1) is useful in understanding the potential accessibility. The limitation of this approach is that it does not take into account the actual travel flows that occur nor the difference in the demand for the destination attractiveness. However, this model is useful for describing the number of jobs that are available to a person within his or her unique distance threshold (Niedzielski and Boschmann 2014).

2.5 Research gaps and questions

This literature review has identified the following gaps in the literature: (1) no studies have systematically assessed the level of access that people or jobs within a city have to bicycle infrastructure; (2) no studies have been conducted that analyze the accessibility of bicycle infrastructure to jobs; (3) no studies attempt to identify the effectiveness of bicycle infrastructure in supporting accessibility versus the accessibility of the road network; (4) no studies are conducted at the inter-zonal and intercity level that would allow the comparison of access and accessibility to bicycle infrastructure.

Given these gaps this thesis will attempt answer three fundamental questions: (1) what share of the population and jobs have access to the network of bicycle infrastructure; (2) how many jobs are accessible; and (3) how effective is bicycle infrastructure in providing accessibility to jobs compared with the road network? Then does the effectiveness vary between all bicycle infrastructure grouped together and bicycle paths alone?

CHAPTER III

DATA AND STUDY AREA

This thesis examines two aspects of bicycle infrastructure, access to infrastructure and the accessibility to jobs using bicycle infrastructure. The analysis is applied to 10 U.S. cities selected from a list constructed by Buehler and Pucher (2011) describing the amount of bicycle paths and lanes in a city per 100,000 residents. This thesis combines data on bicycle infrastructure and detailed household and employment data to determine the access to bicycle infrastructure and accessibility to jobs via different types of bicycle infrastructure within urbanized U.S. cities.

3.1 Data

Data for employment and worker characteristics comes from the U.S. Census Bureau's Longitudinal Employer-Household Dynamics (LEHD) Origin-Destination Employment Statistics (LODES) data set. This data set is organized by state, compiled for the years 2002 to 2014, and provided at the level of the 2010 census blocks. The census blocks are obtained from the U.S. Census Bureau's topologically integrated geographic encoding and referencing (TIGER) line shapefiles. These files are the most comprehensive dataset available from the Census Bureau, and are expressly designed for use in the geographic information system (GIS) environment.

The LODES data sets are organized into three groups: The Origin-Destination (OD) data, where job totals are associated with both a home census block and a work census block; Residential Area Characteristic (RAC) data, where jobs are totaled by a home census block; and Workplace Area Characteristic (WAC), where jobs are totaled by a work census block. The RAC and WAC contain the variables for race, ethnicity, education, age, and sex, while the WAC further contains data on firm age and firm size.

The WAC data will be used to obtain the total number of jobs available per census block. The LEHD covers all employment including primary and secondary jobs; however, it does not include the self-employed or the uniformed services, and coverage is estimated to be over 90 percent of the United States (Spear 2011). The resolution of the LEHD is more detailed than data sets previously available from the Census Bureau. The LEHD data is particularly useful in exploring the accessibility offered by bicycle infrastructure. The RAC has the same resolution and drawbacks as the WAC but provides the number of workers per block.

Data on the city jurisdiction, street, and bicycle network were obtained from the city government for the area within the city jurisdiction. Using the American Community Survey (ACS) from the U.S. Census Bureau, the bicycle commute mode share for each of the cities was obtained and aggregated for the years of 2008-2013.

3.2 Study Areas

Buehler and Pucher (2011) provided the data from Table 1 in the study "Cycling to work in 90 large American cities: new evidence on the role of bike paths and lanes". Standard deviations of the means for bike paths and lanes were calculated and the data divided into 4 main categories about the mean: cities with levels of paths and lanes that were larger than the mean, cities with levels of paths that were larger than the mean with bike lanes that were smaller than the mean, cities with levels of paths that were smaller than the mean with bike lanes that were larger than the mean, and cities with paths and lanes that were smaller than the mean. It is important to note that the cities were evaluated only on the length of bicycle infrastructure and not on the relative size of the populations. Within each of these four categories, the standard deviation was calculated and a city was selected from within each standard deviation based upon the availability of obtaining the bicycle infrastructure network for each city (Table 2).

Table 2. Location within the standard deviation about the mean of bike path and lane supply for cities.

	1 standard deviation	2 standard deviations	3 standard deviations
Paths > Mean **Lanes > Mean**	Washington, D.C.	Portland, OR	Aurora, CO
Paths > Mean **Lanes < Mean**	Denver, CO	Fort Worth, TX	Omaha, NE
Paths < Mean **Lanes > Mean**	Corpus Christi, TX	San Antonio, TX	-
Paths < Mean **Lanes < Mean**	Pittsburgh, PA	Detroit, MI	No data available

For two categories in Table 2 cities are not listed, both in the third standard deviations. For the category of paths less than the mean and lanes greater than the mean, no cities fell within this category. For paths and lanes less than the mean, two cities were within this category; however, no data was able to be obtained pertaining to this thesis.

Each of these cities uses different definitions of bicycle infrastructure so it is important for this analysis to develop a standard definition, to define and distinguish what defines a bicycle lane and what defines a bicycle path. Bicycle lanes and paths come in many forms and in many names; for ease of definition and standardization, the following definitions will be used in this thesis. A bicycle lane is a portion of the roadway designated for bicyclist use and bearing a marking dedicating the area to cycling and may or may not exclude all motorized traffic. A bicycle path is physically separated from motorized traffic with a barrier to enforce separation. Paths may be shared with other non-motorized modes of travel. Table 3 show the breakdown of each city's bicycle infrastructure type as they are listed and how they fit in with this thesis's definition of bicycle infrastructure.

Table 3. Bicycle infrastructure types by city and categorization.

	Lane	Path
Aurora	Bike lane	Trails
	Bike route	Sidepath
	Sharrow	
Corpus Christi	Bike lane	Hike and bike trail
	Bike route	
Denver	Bike boulevard	Regional trail
	Buffered bike lane	Heels and wheels trail
	Bike lane	Minor trail
	Climbing lane	Cycle track
	Party parking lane	Sidewalk bikes permitted
	Sharrow	
	Bike/bus lane	
Detroit	Sharrow	Greenway
	Bike lane	Inner circle greenway
Fort Worth	On-street bicycle lane	Sidepath
	On-street bicycle route	Off-street trail
	Shared bus/bicycle lane	Regional VELOWEB
Omaha	Bike Omaha system	Multi-use trails
	Bike lanes	
	Marked shared routes	
Pittsburgh	On-street bike route	Trail
	Bike route	
Portland	Bike boulevard	Multi-use path
	Buffered bike lane	
	Bike lane	
San Antonio	Bicycle lane	Multi-use path
	Signed route	Cycle track
	Bicycle Boulevard	
	Sharrow	
Washington	Bike lane	Off-street trail
	Sharrow	
	On-street signed route	

Table 4 displays the common attributes of each of the study cities. The statistics for this table were calculated for each of the cities based upon the area within the city that is classified as urban according to the 2016 U.S. Census Bureau's classification and the city jurisdiction limits.

Table 4. Study cities and bicycling data

City	Area (sq km)	Population	Total bike infrastructure (km)	Lanes (km)	Paths (km)	Bike commute share (%)
Aurora, CO	395.42	154,753	499.95	392.26	107.69	0.4
Corpus Christi, TX	302.51	128,671	636.13	620.68	15.45	0.3
Denver, CO	359.74	302,591	1,112.06	727.83	384.23	2.3
Detroit, MI	356.23	187,366	289.52	222.76	66.76	0.3
Fort Worth, TX	976.07	331,098	605.63	173.75	431.88	0.1
Omaha, NE	360.60	228,123	346.36	124.77	221.59	0.2
Pittsburgh, PA	152.45	133,275	407.09	352.36	54.73	1.3
Portland, OR	304.80	284,494	1,464.26	1,195.57	268.69	6.1
San Antonio, TX	973.06	572,564	609.15	467.50	141.65	0.2
Washington, D.C.	176.98	286,131	285.65	176.78	108.87	3.1

This table shows that many of the cities have areas and populations that are similar. From the examination of the table, four cities stand out in terms of area; the cities with the largest areas are Fort Worth, Texas and San Antonio, Texas, while the two cities with the smallest areas are Pittsburgh, Pennsylvania and Washington, D.C. Further examination of the two largest cities reveal that their populations are also the two highest among the study cities, but when looking at the amount of bicycle infrastructure that is present within each of these cities, they are not ranked in the top two cities. Looking at the two smallest cities in terms of area, their populations are not the lowest in the study, indicating the variance of population density among the study cities. When examining the bicycle infrastructure, Washington, D.C. has the lowest amount of bicycle infrastructure in terms of length than any of the other cities within the study but experiences one of the highest bicycle commute mode shares.

Examining the total length of bicycle infrastructure shows that Denver, Colorado and Portland, Oregon have the most bicycle infrastructure of the cities within the study, and they both experience some of the highest bicycle commute mode share. This conforms with the idea that increasing bicycle infrastructure results in increased bicycle mode share (Buehler and Pucher 2011). Examining the bicycle commute mode share, the bottom city is Fort Worth, Texas, which experiences the lowest bicycle commute mode share and covers the largest area of the study.

This table shows the relationship between total bicycle infrastructure and the bicycle commute mode share is not clear. This warrants an investigation into the access that residents have to bicycle infrastructure and the accessibility to jobs provided by bicycle infrastructure.

CHAPTER IV

METHODS

To answer the three main research questions, the following metrics are used to calculate access. The equation for calculating average residential access is expressed formally as:

$$K_b = \frac{\sum_i X_i f(D_{ib})}{\sum_i X_i}$$

(3)

In equation (3), K_b is the share of people that have access to infrastructure type b for a city. X_i is the number of people living in location i. $f(D_{ib})$ is the distance function, given distance, d, of the origin, i, using infrastructure type, b, such that $f = 1$ if $D_{ib} \leq d$ or 0 otherwise. This thesis will use two types of infrastructure to calculate and compare access: all bicycle infrastructure combined, and a subset of it which is bicycle paths. A standard threshold of 400 meters is used to determine centroids that have access to bicycle infrastructure (Mulley 2014 and Vale, Saraiva, and Pereira 2016). Calculating the average access that jobs have to bicycle infrastructure is:

$$P_b = \frac{\sum_j E_j f(D_{jb})}{\sum_j E_j}$$

(4)

In equation (4), P_b, is the total access to infrastructure type b for a city. E_j is the number of job opportunities in location j. $f(D_{jb})$ is the distance function, given distance, d, of the origin, j, using infrastructure type, b, such that $f = 1$ if $D_{jb} \leq d$ or 0 otherwise.

The equation for calculating accessibility is expressed as:

$$A_{ib} = \sum_j E_j \, f\left(C_{ijb}\right) \qquad (5)$$

In this equation, A_{ib} is the accessibility score for zone i using infrastructure type b. E_j is the number of employment opportunities in zone j. $f(C_{ijb})$ is the distance function given distance, d, of the origin i, using infrastructure type, b, such that $f = 1$ if $C_{ijb} \leq d$ or $f = 0$ otherwise. This thesis will use three types of infrastructure to calculate and compare accessibility, the road network, b = 1, all bicycle infrastructure combined, b = 2, and bicycle paths, b = 3. Distance thresholds are set at 1, 3, 5, 7, and 9 kilometers for the network travel distance. Average accessibility for infrastructure type b for each city is then calculated by:

$$S_b = \frac{\sum_i A_{ib}}{W} \qquad (6)$$

In this equation, S_b is the average accessibility for infrastructure type, b, for a city. W is the number of workers in each city. The effectiveness of bicycle infrastructure is calculated by:

$$H_2 = \frac{S_2}{S_1}$$

(7)

In this equation H_2 is the effectiveness of all bicycle infrastructure for a city. S_1 is the average accessibility for the road network. S_2 is the average accessibility for all bicycle infrastructure. The effectiveness of bicycle infrastructure then produces a score that can range from 1 to 0, with 1 being bicycle infrastructure that matches the effectiveness of the road network. The effectiveness of bicycle paths is calculated by:

$$H_3 = \frac{S_3}{S_1}$$

(8)

In equation (8), H_3 is the effectiveness of bicycle paths for a city. S_3 is the average accessibility for bicycle paths.

A geodatabase was constructed using ArcGIS 10.4 to store and relate the data on the study cities. The WAC and RAC data was combined with the census blocks from which origin and destination centroids were created. From the study cities, downloadable geographic information system (GIS) shapefiles are available, detailing the bicycle infrastructure, the road network within those cities, and the areas that are directly under the jurisdiction of the city.

Using the network analyst extension, the calculation of access for residents and jobs to all bicycle infrastructure and bicycle paths alone was calculated, using equation 3 and 4. A Pearson Correlation was run for the average access of jobs and residents to all bicycle infrastructure and bicycle paths against the cities commute mode share to determine if any significant correlation exists between the access to bicycle infrastructure and the bicycle commute mode share.

The accessibility to jobs for each census block was then calculated using equation 5. Accessibility was calculated for three infrastructure types: the road network, all bicycle infrastructure, and bicycle paths alone, using a network travel distance impedance of 1, 3, 5, 7, and 9 kilometers.

A shapefile of the city urban area was then applied to the resultant census blocks and used to create the city accessibility maps located in Appendix A. Using equation 6, the average accessibility was calculated for each of the cities at each travel distance threshold and for each infrastructure type. A Pearson Correlation was calculated using the average accessibility of each infrastructure type at each of the impedance distances against the cities' commute mode share to determine if any significant correlation exists between a city's accessibility and the bicycle commute mode share. The effectiveness of each city's bicycle infrastructure was then calculated as it compares to that city's road network using equation 7.

CHAPTER V

RESULTS

The measure of a transit system's effectiveness begins with its reach (Ewing and Cervero 2010). This study examines the coverage of bicycle infrastructure, or the share of jobs and residents within a city's urban area working age population that have access to bicycle infrastructure, and the accessibility that is provided by this infrastructure to jobs.

5.1 Access to Bicycle Infrastructure

The cities of this study show differences in the coverage of bicycle infrastructure in regards to the number of jobs which have access to bicycle infrastructure (Figure 1). There is a significant positive relationship between the access jobs have to all bicycle infrastructure and the bicycle commute mode share (Table 5). There is also a significant positive relationship between the access jobs have to off-street bicycle infrastructure and the bicycle commute mode share (Table 5).

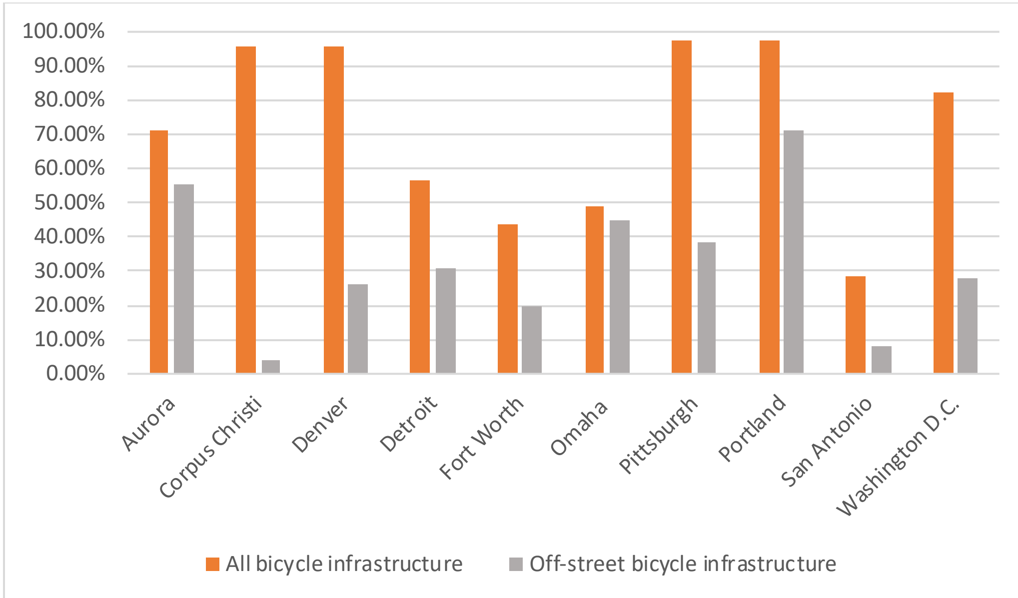

Figure 1. Share of jobs with access to bicycle infrastructure by type

Table 5. Pearson's correlation results for job access to bicycle infrastructure

	r(8)=	p=
All bicycle infrastructure	0.634	0.049
Off-street bicycle infrastructure	0.633	0.049

Similar differences show in the number of working age city urban area residents that have access to bicycle infrastructure (Figure 2). The results of the Pearson's correlation show no statistical significance with relation to the access that people have and the bicycle mode share on either type of infrastructure (Table 6).

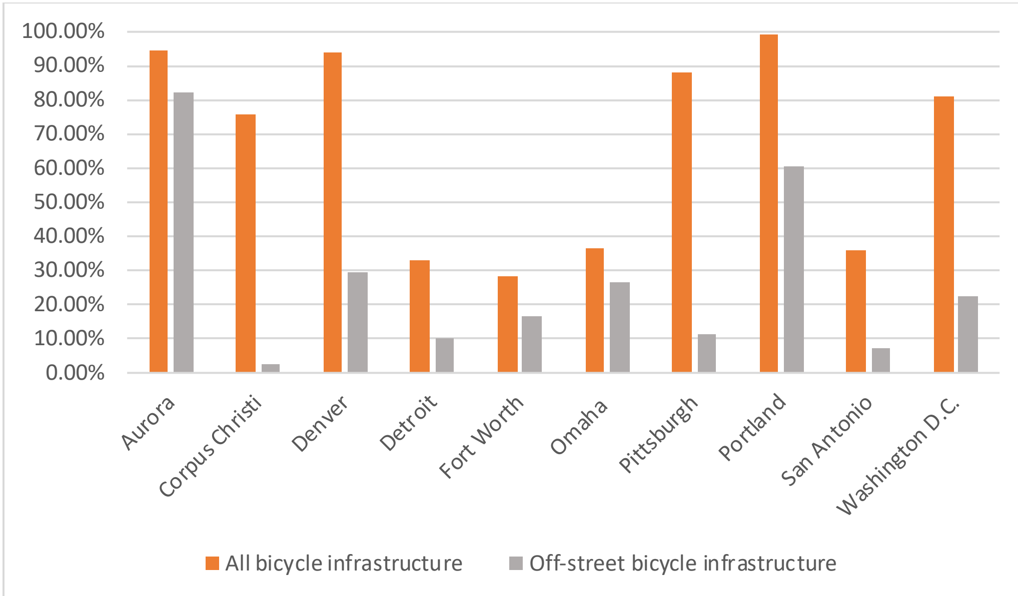

Figure 2. Share of residents with access to bicycle infrastructure by type

Table 6. Pearson's correlation results for resident access to bicycle infrastructure

	r(8)=	p=
All bicycle infrastructure	0.628	0.052
Off-street bicycle infrastructure	0.408	0.242

5.2 Accessibility Results

Accessibility results were mapped at the census block for each distance threshold for three networks. This resulted in a series of 147 total maps and are included as appendices to this thesis. The average accessibility score was calculated for each of the cities under each of the threshold distances and within each of the available travel networks. From the accessibility scores of each city under each threshold, an average accessibility score was calculated for each city and displayed in Figures 5 through 9. A Pearson's correlation was run on each infrastructure type with the bicycle commute mode share, which are graphed by the travel threshold distance and display the three types of infrastructure network utilized for bicycle travel in Tables 7 thru 11. There is a significant positive relationship between all bicycle infrastructure and the bicycle commute mode share at travel impedance thresholds of 3, 5, 7, and 9 kilometers (Tables 8-11).

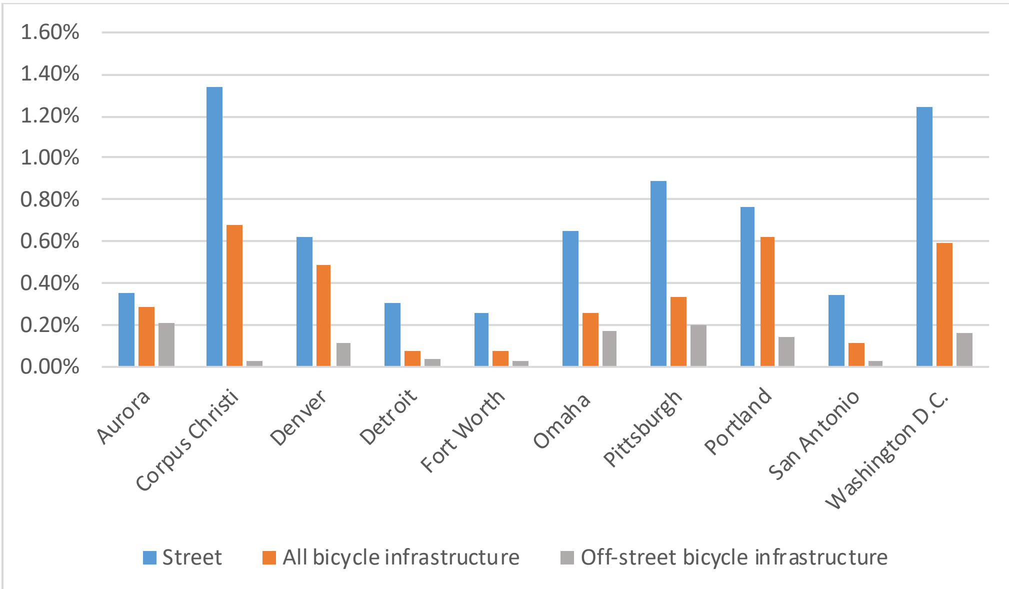

Figure 3. 1-kilometer travel distance average accessibility

Table 7. Pearson's correlation results for 1-kilometer travel distance threshold for all infrastructure types against the bicycle commute mode share

	r(8)=	p=
Street	0.334	0.345
All bicycle infrastructure	0.629	0.051
Off-street bicycle infrastructure	0.321	0.365

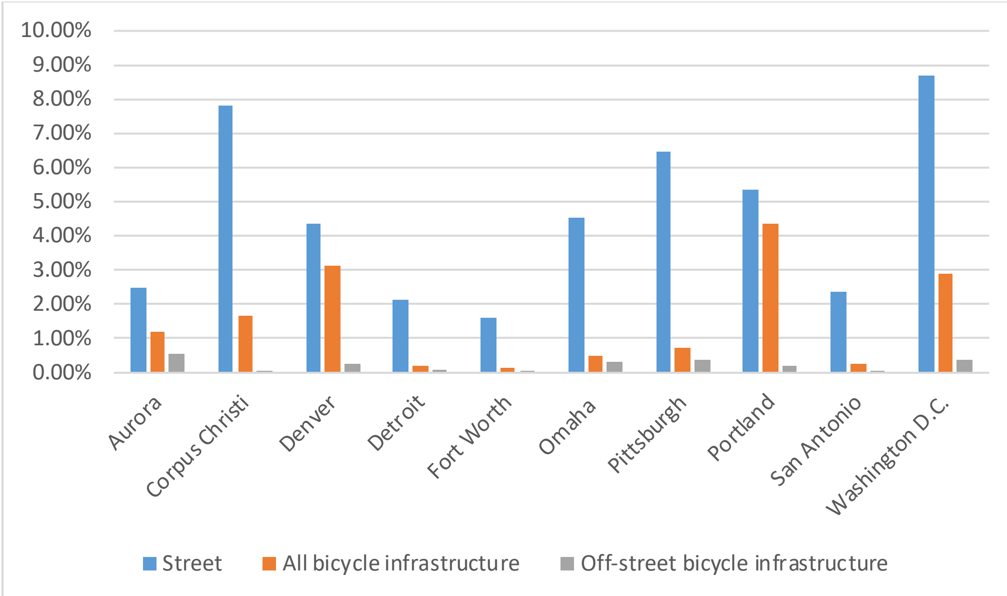

Figure 4. 3-kilometer travel distance average accessibility

Table 8. Pearson's correlation results for 3-kilometer travel distance threshold for all infrastructure types against the bicycle commute mode share

	r(8)=	p=
Street	0.418	0.229
All bicycle infrastructure	0.907	0.000
Off-street bicycle infrastructure	0.173	0.632

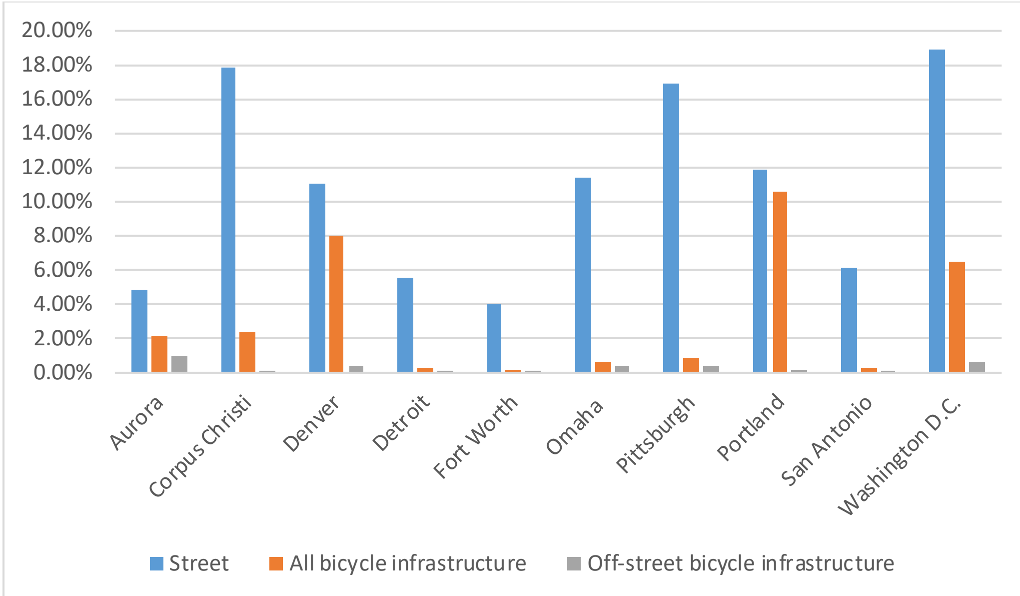

Figure 5. 5-kilometer travel distance average accessibility

Table 9. Pearson's correlation results for 5-kilometer travel distance threshold for all infrastructure types against the bicycle commute mode share

	r(8)=	p=
Street	0.369	0.249
All bicycle infrastructure	0.92	0.000
Off-street bicycle infrastructure	0.113	0.755

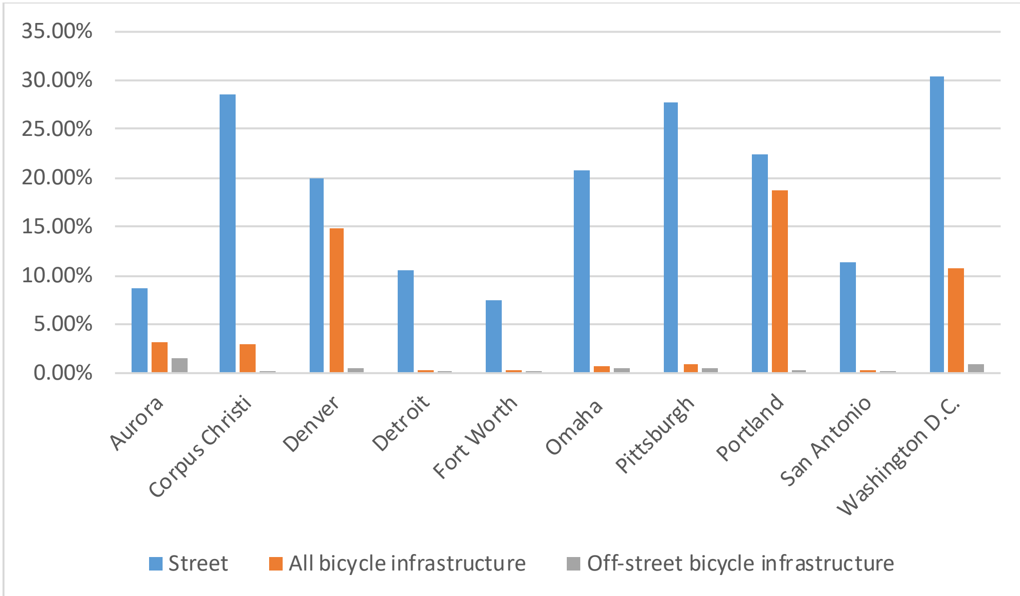

Figure 6. 7-kilometer travel distance average accessibility

Table 10. Pearson's correlation results for 7-kilometer travel distance threshold for all infrastructure types against the bicycle commute mode share

	r(8)=	p=
Street	0.438	0.206
All bicycle infrastructure	0.915	0.000
Off-street bicycle infrastructure	0.062	0.865

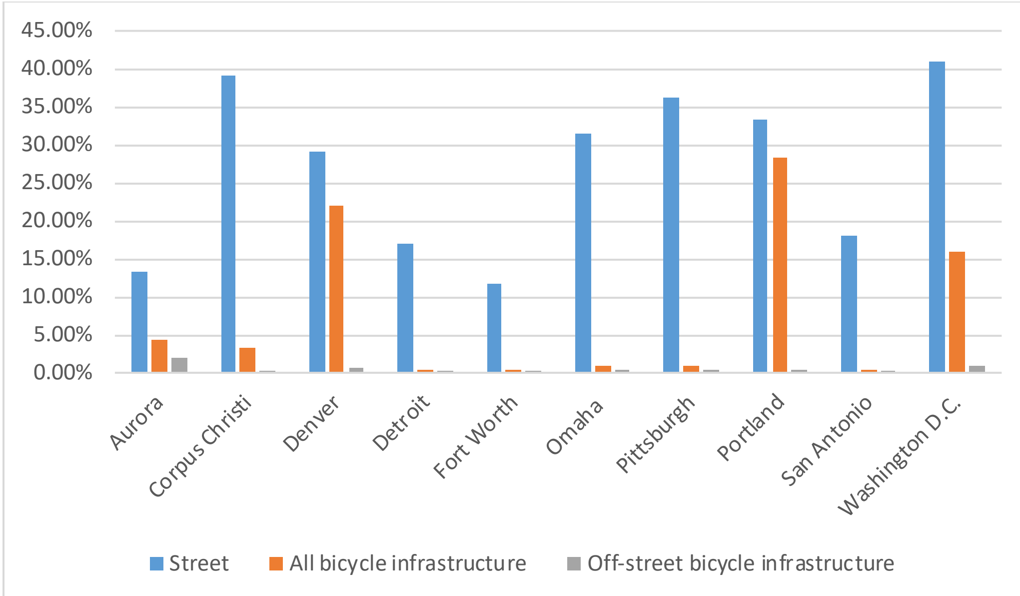

Figure 7. 9-kilometer travel distance average accessibility

Table 11. Pearson's correlation results for 9-kilometer travel distance threshold for all infrastructure types against the bicycle commute mode share

	r(8)=	p=
Street	0.474	0.167
All bicycle infrastructure	0.919	0.000
Off-street bicycle infrastructure	0.036	0.92

Table 12 shows the effectiveness of all bicycle infrastructure and bicycle paths for each city as it is compared with the accessibility offered by the road network. A score of 1 would indicate that the infrastructure would offer the same accessibility to jobs as that of the road network.

Table 12. Bicycle infrastructure effectiveness

City	Infrastructure type	1 km	3 km	5 km	7 km	9 km
Aurora	All bike infrastructure	0.83	0.49	0.46	0.37	0.32
	Bicycle paths	0.61	0.23	0.20	0.17	0.14
Corpus Christi	All bike infrastructure	0.51	0.21	0.13	0.10	0.09
	Bicycle paths	0.02	0.00	0.00	0.00	0.00
Denver	All bike infrastructure	0.78	0.72	0.72	0.74	0.76
	Bicycle paths	0.18	0.06	0.04	0.03	0.02
Detroit	All bike infrastructure	0.25	0.08	0.05	0.03	0.02
	Bicycle paths	0.11	0.03	0.01	0.01	0.01
Fort Worth	All bike infrastructure	0.29	0.10	0.05	0.04	0.03
	Bicycle paths	0.10	0.03	0.02	0.01	0.01
Omaha	All bike infrastructure	0.39	0.11	0.06	0.04	0.03
	Bicycle paths	0.26	0.07	0.03	0.02	0.02
Pittsburgh	All bike infrastructure	0.38	0.11	0.05	0.03	0.03
	Bicycle paths	0.22	0.06	0.02	0.02	0.01
Portland	All bike infrastructure	0.82	0.81	0.89	0.84	0.85
	Bicycle paths	0.19	0.04	0.02	0.01	0.01
San Antonio	All bike infrastructure	0.33	0.10	0.05	0.03	0.02
	Bicycle paths	0.09	0.02	0.01	0.01	0.00
Washington D.C.	All bike infrastructure	0.47	0.34	0.35	0.36	0.39
	Bicycle paths	0.13	0.05	0.03	0.03	0.02

CHAPTER VI

DISCUSSION AND CONCLUSIONS

Across the study cities, on average 71 percent of jobs have access to some type of bicycle infrastructure, and on average 66 percent of working-age people live in neighborhoods that have access to bicycle infrastructure. This implies that a majority of people and jobs have access to bicycle infrastructure, but 30 percent of the population within urbanized cities across the U.S. do not have access to bicycle infrastructure in their communities. The cities experience vast differences in the percent of jobs and residents with access to bicycle infrastructure with some cities having coverage of well over 90 percent to cities that have coverage as low as 32 percent.

The amount of access that both jobs and residents have to all bicycle infrastructure is generally less than a 15 percent difference for all but three cities, Aurora, Corpus Christi, and Detroit, which experience differences in access of greater than 20 percent. Detroit and Corpus Christi's bicycle infrastructure favored access to places of employment over residents, where Aurora's bicycle infrastructure favored residents over places of employment. In Detroit and Aurora, it makes sense when the location and primary activity of each city is taken into account; Detroit is an economic center around which many suburban cities have formed and Aurora is a residential suburb of Denver, Colorado. Corpus Christi, however, does not fit neatly into either category and may be a situation where the urban form of much of the residential areas is not in a regular grid pattern but follows a pattern of irregular roads and cul-de-sac's, making the development of bicycle infrastructure difficult to service residential areas. Most surprising is that the access jobs have to bicycle infrastructure is statistically significant in its correlation with the bicycle mode share. With this in mind city planners could use this metrics correlation when planning to build new elements of bicycle infrastructure to help in deciding where to place the bicycle infrastructure and to evaluate the potential impacts it could have.

The amount of access that jobs and residents have to off-street bicycle infrastructure is much the same as for all bicycle infrastructure, with only two cities that have over a 20 percentage point difference, those being Aurora and Pittsburgh. Aurora favors residents for access. Pittsburgh favors places of employment with access to its off-street bicycle infrastructure, and this has potential implications for the bicycle mode share that Pittsburgh experiences over other cities.

Differences in urban form and public policies among cities account for some of the discrepancies in bicycle infrastructure coverage. Urban cities are heavily influenced by geographic barriers, such as rivers and mountains, that greatly restrict the ability to travel throughout an urban area, and also by the historical development of the city, which influences whether economic and residential concentration is developed or a mixed land use.

The percent of jobs and residents that have access to bicycle infrastructure could be used as a measure of the density and coverage. With the exception of two cities in the study, all cities that had 50 percent of both jobs and residents having access to bicycle infrastructure had indicated bicycle shares of greater than 1 percent. Aurora and Corpus Christi are the exceptions in the study. Both cities' data would seem to indicate that higher levels of bicycle commuting mode share would be experienced, however, they both experience bicycle shares of less than 0.4 percent.

The difference in the average accessibility score and the effectiveness of Aurora, Colorado and Denver, Colorado is intriguing. Aurora experiences a very low bicycle travel mode share and its effectiveness is much lower than that of Denver which is located just fifteen kilometers away. It may be the proximity to Denver which skews the results. However, this identifies a potential problem with the planning that is being executed in metropolitan statistical areas (MSA) that are composed of multiple cities. The potential exists that the MSA does not have an overall transportation plan that is agreed to among all the cities, causing cities to plan the development of their infrastructure without the consideration of the rest of the MSA.

Pittsburgh, Pennsylvania is interesting because the effectiveness of the bicycle infrastructure is quite low, though the city does experience a mode share of 1.3 percent. The average accessibility score for Pittsburgh on bicycle infrastructure is low compared to the other cities in this thesis that experience a mode share greater than 1 percent. Pittsburgh's bicycle mode share situation is further complicated by the presence of the Allegheny, Monongahela, and Ohio rivers and a topography that is characterized by steep sloped hills. These physical forms may act to contain sprawl and result in a more mixed land use environment increasing short commuting possibilities (Charron 2007). In investigating the average accessibility score of Pittsburgh, it is apparent that the road network offers one of the highest accessibility scores within the study cities, exceeded only by Washington D.C. and Corpus Christi, Texas. This may account for cyclists that are choosing to commute by bicycle and using bicycle infrastructure when available but may be forced into a mixed traffic situation to reach their destination.

With an examination of the effectiveness of the bicycle infrastructure network types, there are certainly some trends that become apparent in the data at the different travel distance thresholds. Particularly in that most of the cities in this thesis have bicycle infrastructure that reaches its peak effectiveness at the 3 to 5-kilometer travel distance range. This finding is similar to that of other studies that have found that trip distances in this range experience the most use (Howard and Burns 2001 and Zhao 2014).

At the 1-kilometer travel distance threshold, the results are somewhat confusing if you take into account each city's bicycle commute mode share. Though this is confirmed by the Pearson's correlation finding no significance at this travel distance threshold. The street network and the built environment influence the accessibility that each city has and places some of the largest cities in terms of area at a disadvantage in obtaining high accessibility scores in regards to a commute that would facilitate a non-motorized mode of transportation. This is evident in the accessibility scores of Fort Worth and San Antonio, Texas, which are the two largest cities in the study in terms of area and have the lowest average accessibility. It is impressive that Fort Worth and San Antonio are able to reach close to the same levels of all bicycle infrastructure accessibility as Detroit despite the disadvantages that they must overcome in terms of having to cover nearly three times the area. In terms of effectiveness, the cities in this thesis with the lowest bicycle mode share experience the most effective infrastructure at the 1-kilometer travel distance. All off-street bicycle infrastructure reaches peak effectiveness at this threshold; this is not unexpected. It may be due to that many paths being located in parks and other places that have the primary purpose of recreation and are not purposely designed for commuting as opposed to on-street bicycle infrastructure. At the 3-kilometer threshold, the effectiveness of bicycle infrastructure begins to peak and all bicycle infrastructure becomes significantly correlated with the bicycle mode share.

Although the accessibility provided by bicycle infrastructure is a factor of the bicycle commute mode share, the decisions made by local transportation, urban, and policy planners greatly influence the mode share as much as the local culture and attitudes of the residents. There are commuters that are choosing to cycle to work in areas that have low accessibility via bicycle infrastructure and other commuters that have higher levels of accessibility via bicycle infrastructure that are choosing not to commute by bicycle; this is the case when looking at Corpus Christi and Pittsburgh.

There are cities that, such as in the case of Portland, have an average accessibility to all jobs of 28.29 percent. This is only 5 percent less accessibility than that offered by the road network. While this adds to the understanding of the bicycle commute and the potential for people to use this form of transportation as a sustainable method for reaching a place of employment, there are clearly other factors at work which this thesis does not account for.

Perhaps the greatest contribution of this research is to the urban planners and policy makers. The methods used can be applied to other cities, and the results will highlight areas where adding bicycling paths or lanes have the potential to increase the accessibility that is provided and the effectiveness of the bicycle network coverage. This research is also important for bicycle commuters and those individuals that may be considering the bicycle commute as they may be unaware of the potential opportunities that are afforded to them by using the bicycle to commute.

Policies within many U.S. cities have been developed to encourage bicycling and improve the bicycle commuter's experience by expanding bicycle path and lane coverage and opening new opportunities to reduce the amount of automobile traffic within an urban city in an effort to ease congestion and to encourage sustainable transportation practices among the citizens. In some cases, a bicycle commuter can travel faster than an automobile by traveling in areas that are both on and off the road network; by doing so the cyclist is able to see parts of the community that they would normally not see when confined to an automobile on the road and experience the world as a bigger place, as well as receiving the health and cost reducing benefits of cycling. The community benefits as more people choose the bicycle to commute and will experience reduction in congestion and gas emissions.

Within the architecture of the study of transportation geography, the study of bicycle transportation is relatively new but is an area of study that has been steadily increasing as the benefits of cycling have become better understood. This research seeks to increase the understanding of the bicycle commute through the systematic evaluation of the effectiveness of bicycle infrastructure in serving the commuter.

CHAPTER VII

Limitations and Future Research

7.1 Limitations

This thesis has several limitations. The nature of the census data leads to the modifiable areal unit problem (MAUP) in that the census measures of jobs and housing are aggregated into census blocks; the selected boundaries of the census blocks can influence the resulting summary of the values. For this study the census block was used as it is the smallest unit available which contained the necessary values. While other studies have proposed studying bicycle accessibility at the parcel level, the data necessary to conduct such a study is not openly available (Iacono, Krizek, and El-Geneidy 2010).

The Pearson's correlation is limited in a small sample size and it simply describes the relationship between the average accessibility and the bicycle mode share that a city experiences and cannot be interpreted as proof of a cause and effect relationship. The value of the correlation may be affected greatly by the range of scores in the data and due to the small number of cities used. Therefore, the Pearson's correlation is only useful in describing the relationship for these study cities and should not be used to make generalizations about cities not included within the scope of this study.

Additionally, the entire metropolitan statistical area (MSA) was not included in the study, only the city urban area. The focus on the urban area was determined to avoid difficulties that are encountered with rural census blocks that are often in excess of a mile wide. Because city municipalities are an urban administrative division that have powers of self-government and jurisdiction, the city urban area was used in the study.

This thesis does not explore the reasons or the choice behind the bicycle mode share that is experienced by each of these cities. While the differences can be identified through the comparison of the results, this study is not able to determine the why behind the varying levels of accessibility that each city experiences.

A further limit to this thesis is that the possible destinations of bicycle commuters was only the job and did not account for the potential for trip chaining such as stopping at a market on the way home from work, or other destinations that may influence an individual to commute by bicycle.

7.2 Future Research

Future research should include an accessibility study using the methods of this study but looking at accessibility from the perspective of job locations and the number of residents that jobs have accessibility to. Jobs could be segregated by types of jobs and different worker characteristics. Additionally, an accessibility study of bicycle infrastructure that includes the entire MSA should be conducted. Interactions occur across the municipalities of cities that are dependent upon each other for workers and jobs. People do travel solely within cities, but there are definitely other factors that may act to pull an individual to travel to another city within a metropolitan area. This thesis does not capture those interactions or how cities that are located next to each other plan and implement a bicycle infrastructure network to facilitate a cyclist's movement across a larger urban network.

Additionally, future research should be conducted to examine the mixed land use and how bicycle infrastructure is integrated with that land use. This leads to integrating that research with the purpose city planners and policy makers want their cities' bicycle infrastructure to be used for.

Future research could also be conducted on additional cities in order to build the index for the difference in the bicycle mode share that cities experience. Because some of the cities in this thesis are located in similar geographical and cultural areas, further investigation of cities in different regions of the United States is warranted and may shed more light on the disparities of the bicycle commute mode share.

APPENDICES

APPENDIX A

Aurora, Colorado City Zonal Accessibility Maps

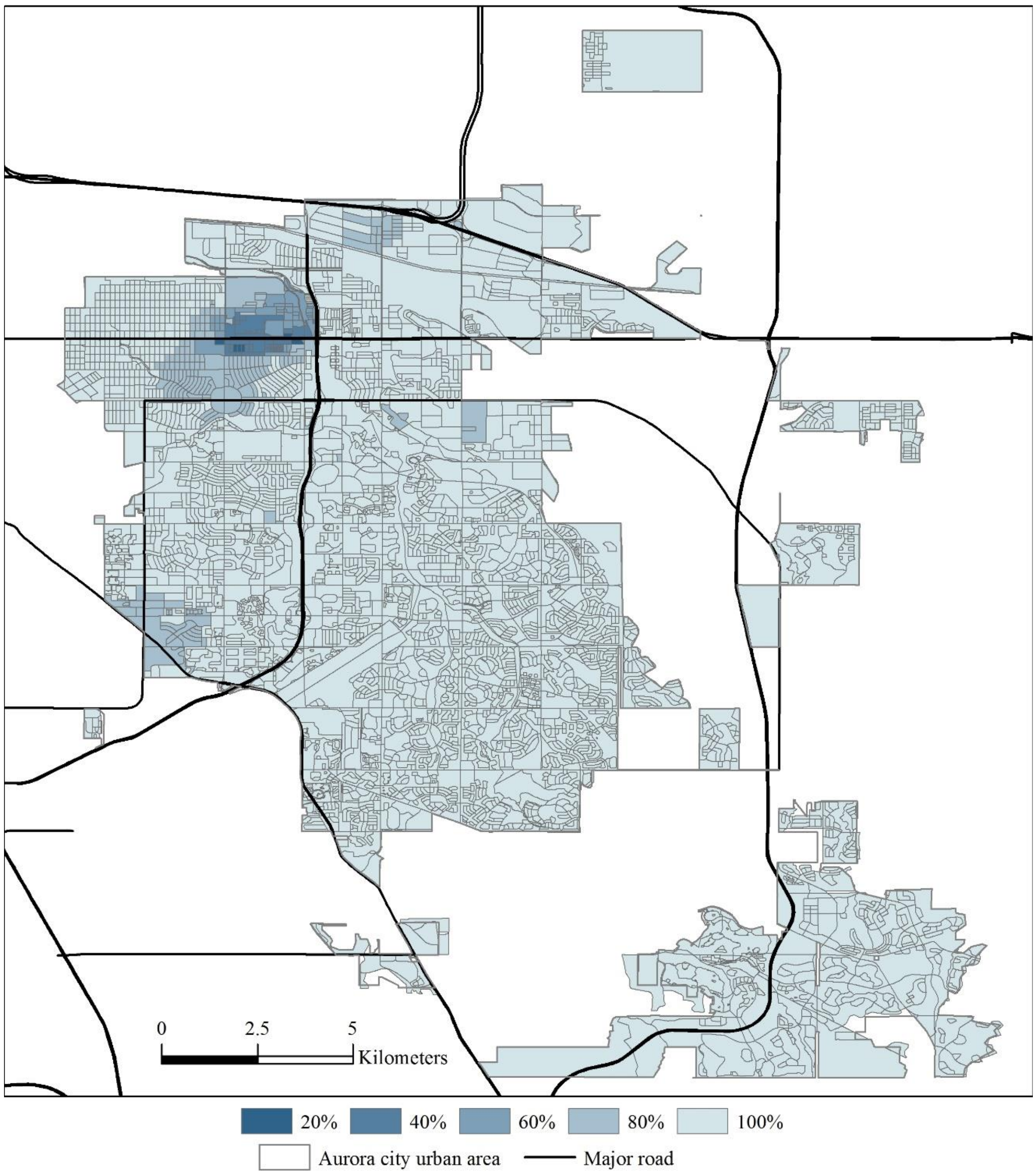

Figure 8. Aurora, Colorado 1-kilometer accessibility using roads

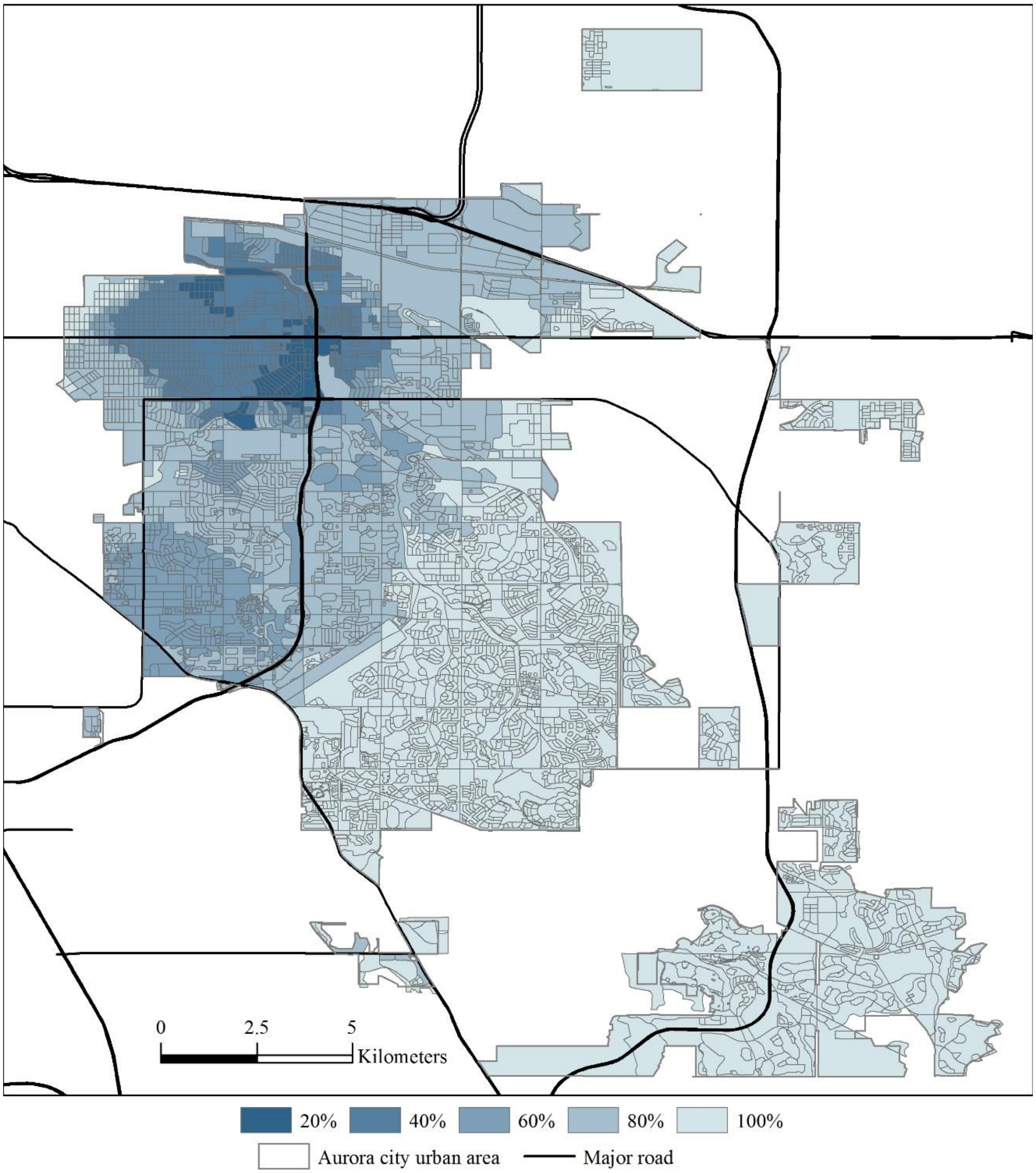

Figure 9. Aurora, Colorado 3-kilometer accessibility using roads

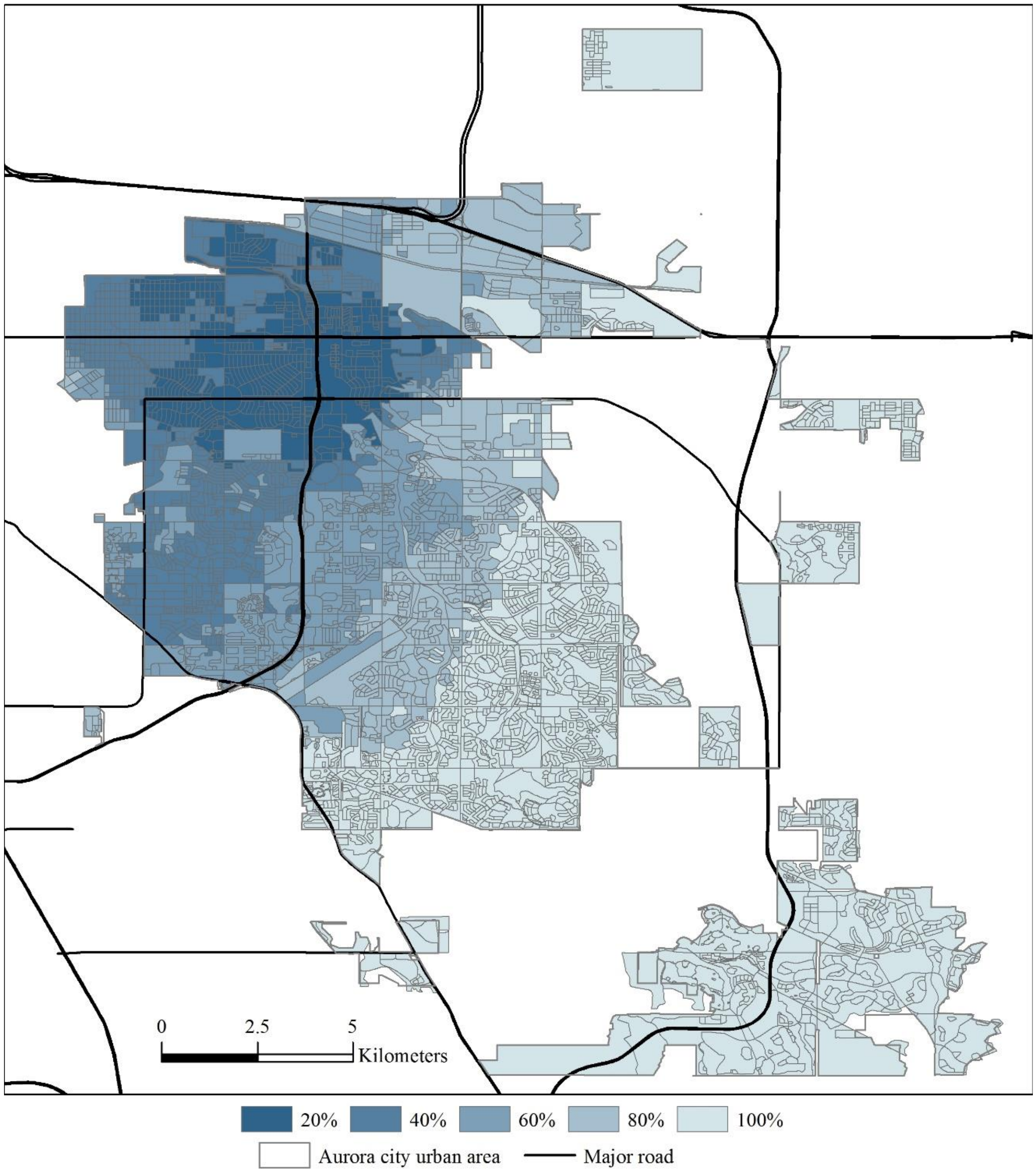

Figure 10. Aurora, Colorado 5-kilometer accessibility using roads

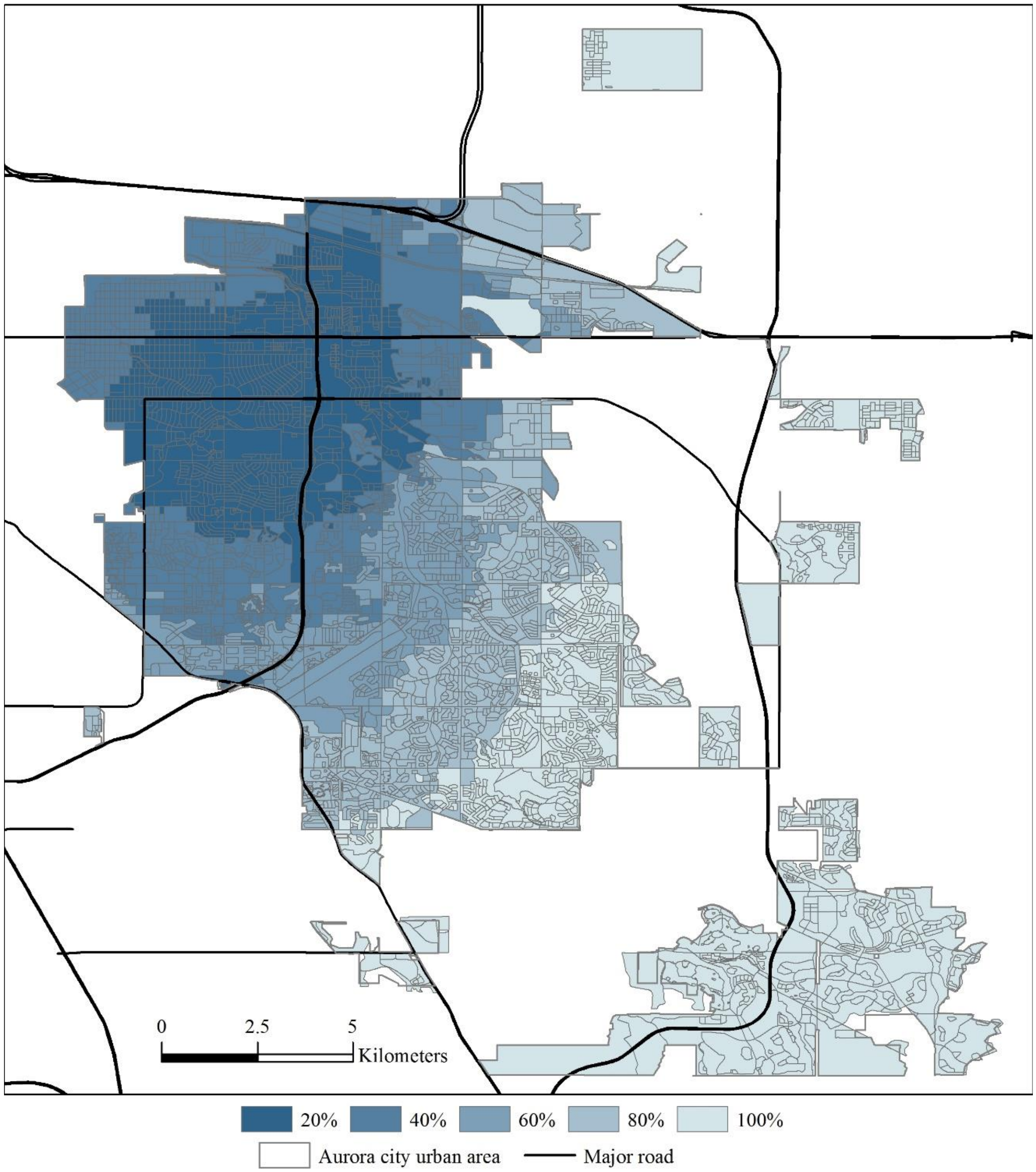

Figure 11. Aurora, Colorado 7-kilometer accessibility using roads

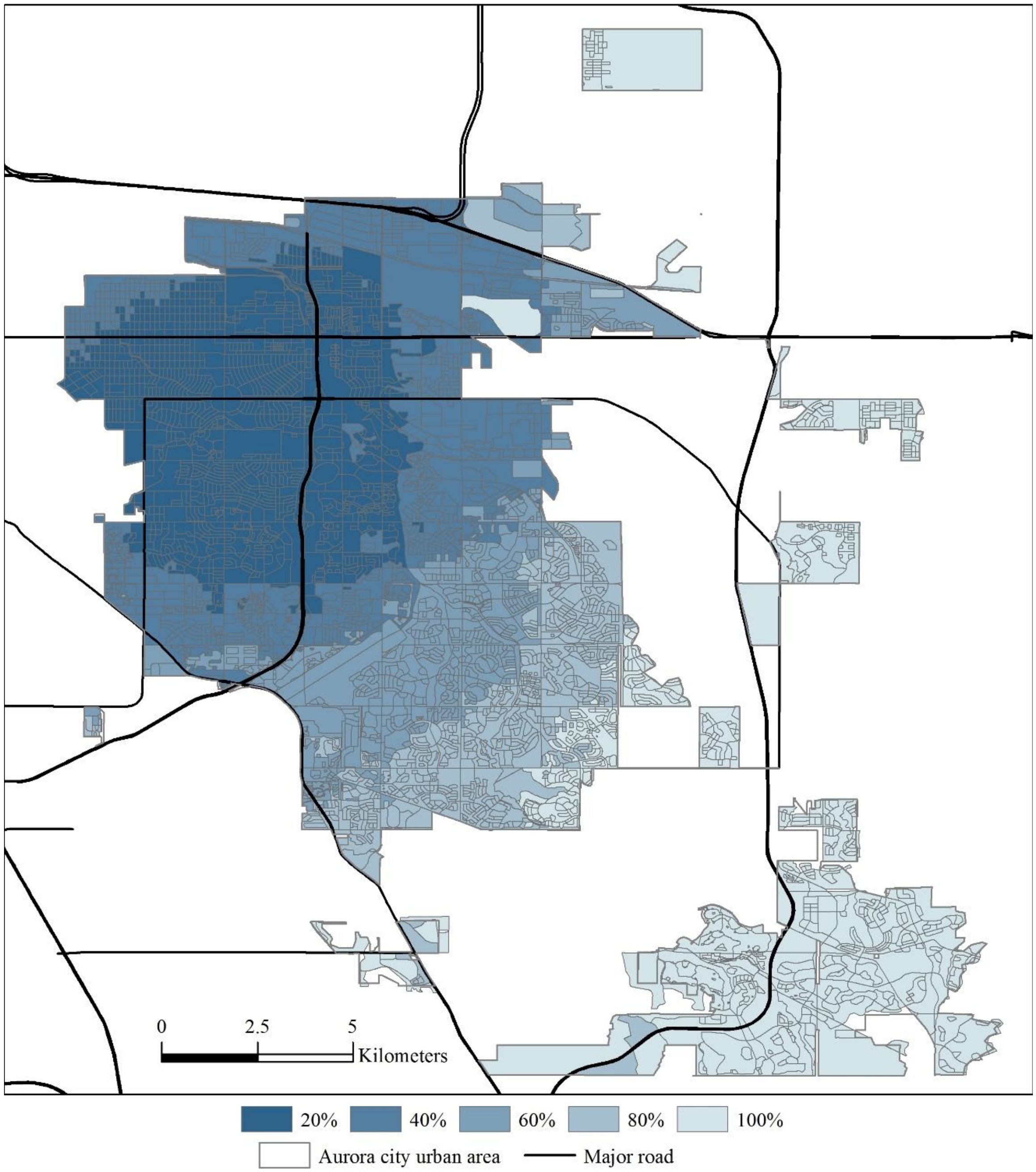

Figure 12. Aurora, Colorado 9-kilometer accessibility using roads

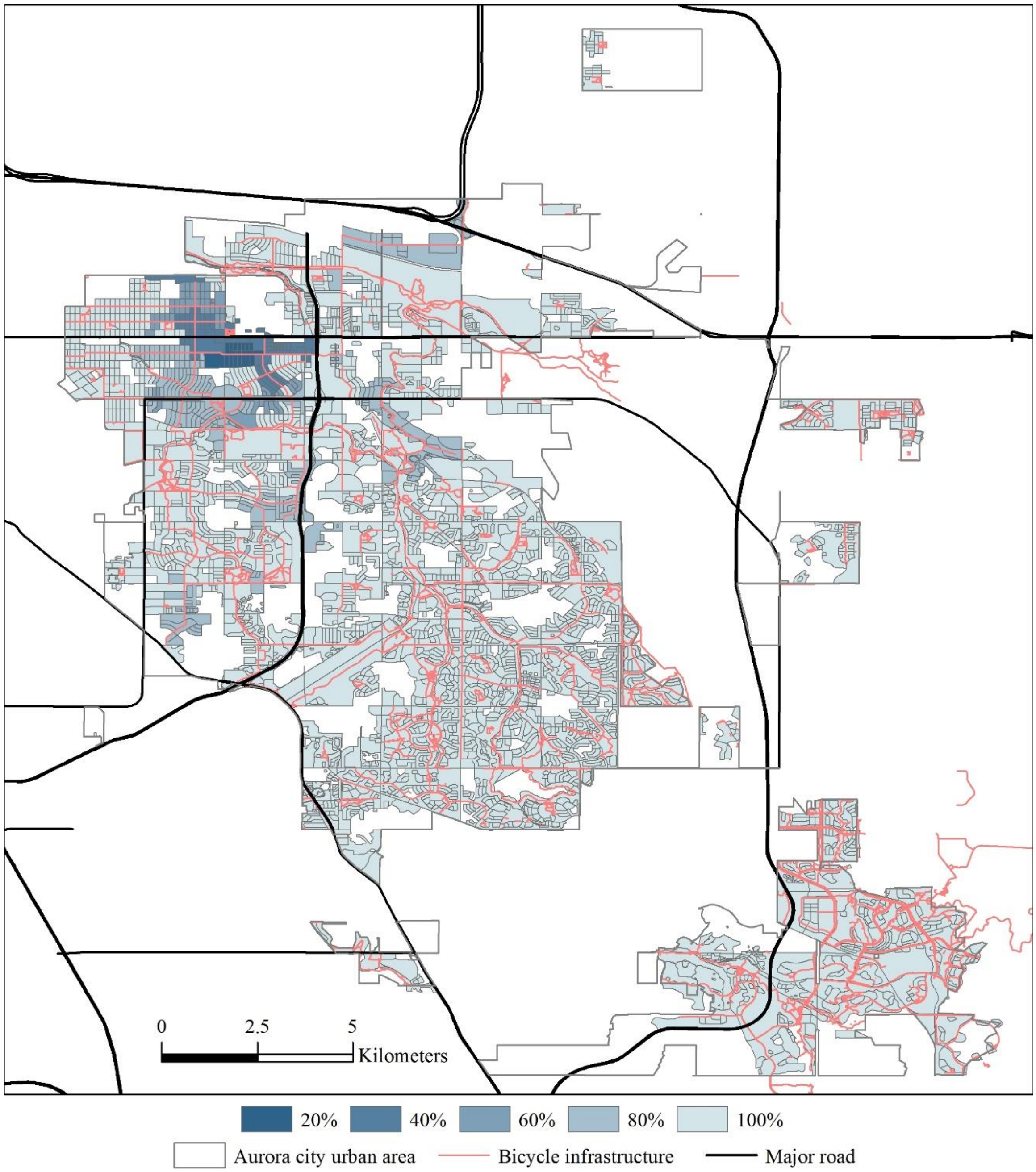

Figure 13. Aurora, Colorado 1-kilometer accessibility using all bicycle infrastructure

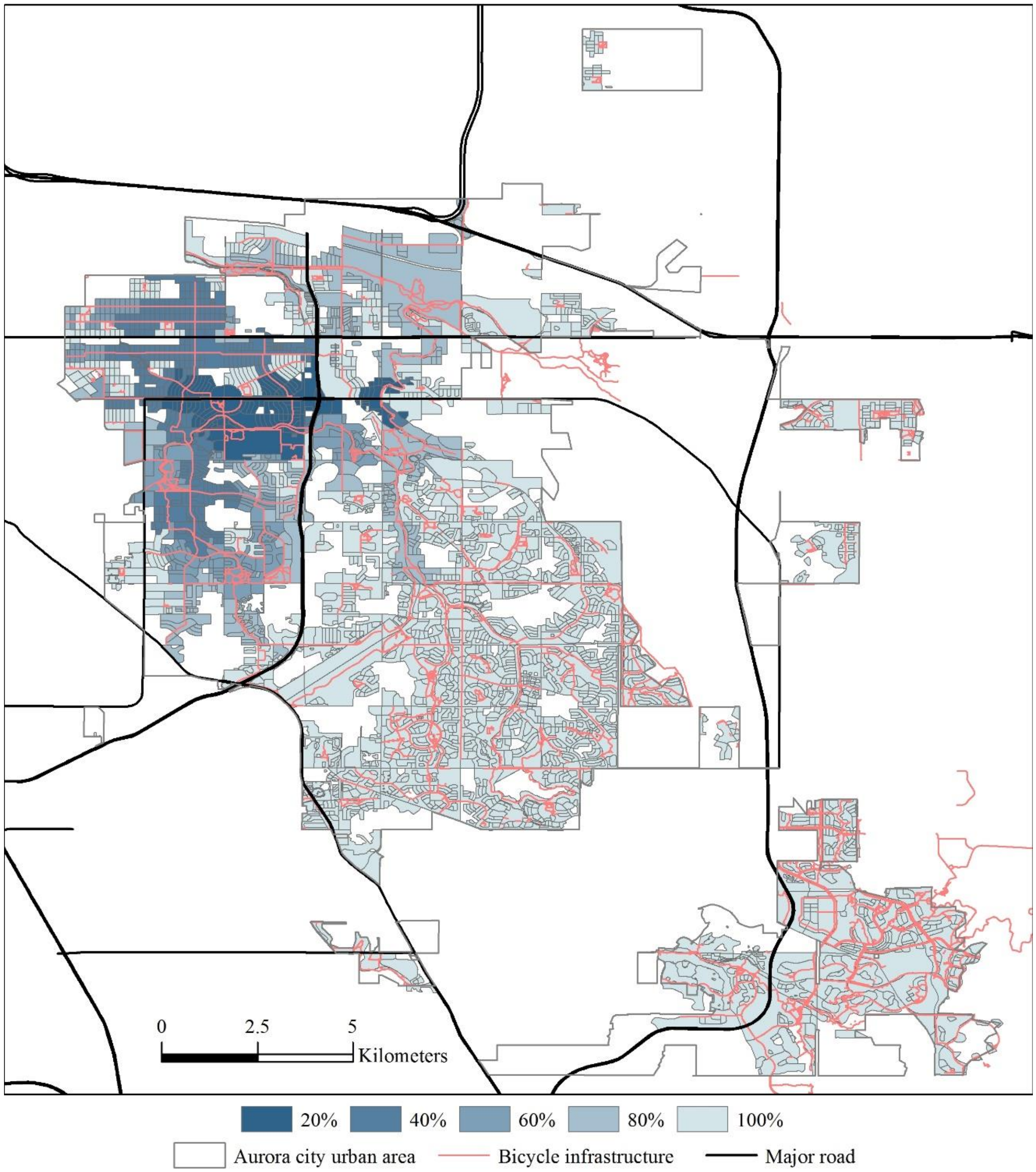

Figure 14. Aurora, Colorado 3-kilometer accessibility using all bicycle infrastructure

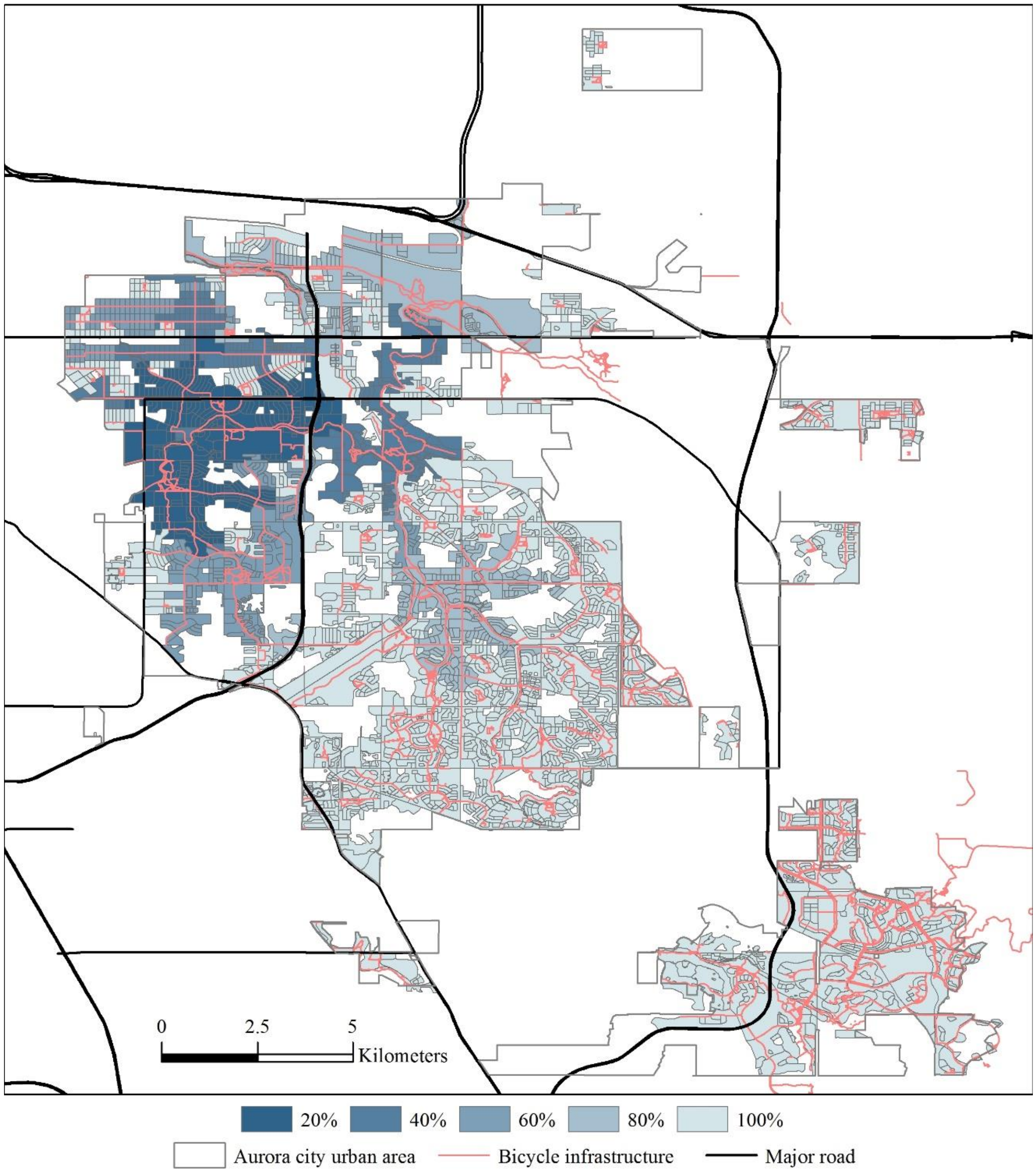

Figure 15. Aurora, Colorado 5-kilometer accessibility using all bicycle infrastructure

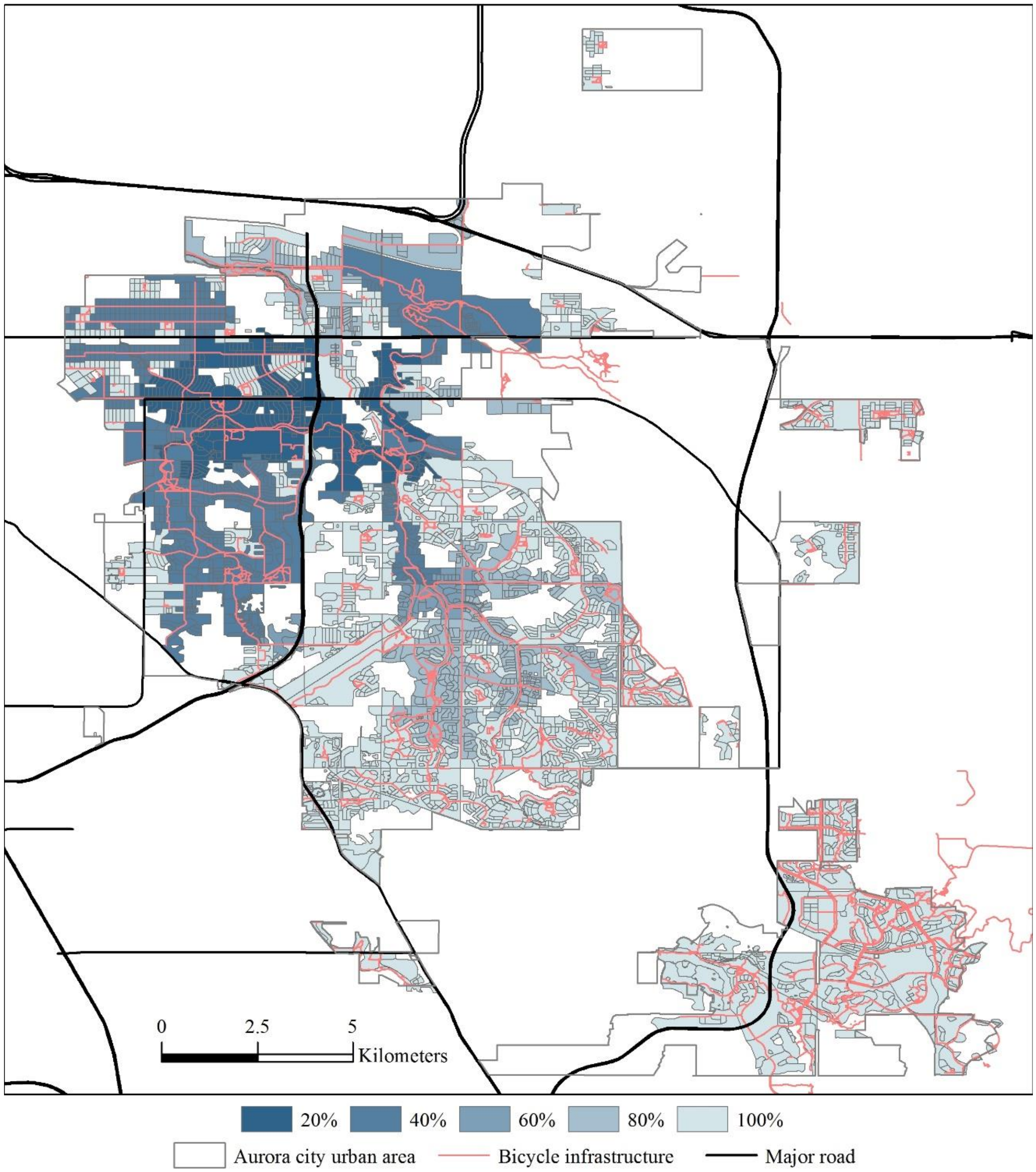

Figure 16. Aurora, Colorado 7-kilometer accessibility using all bicycle infrastructure

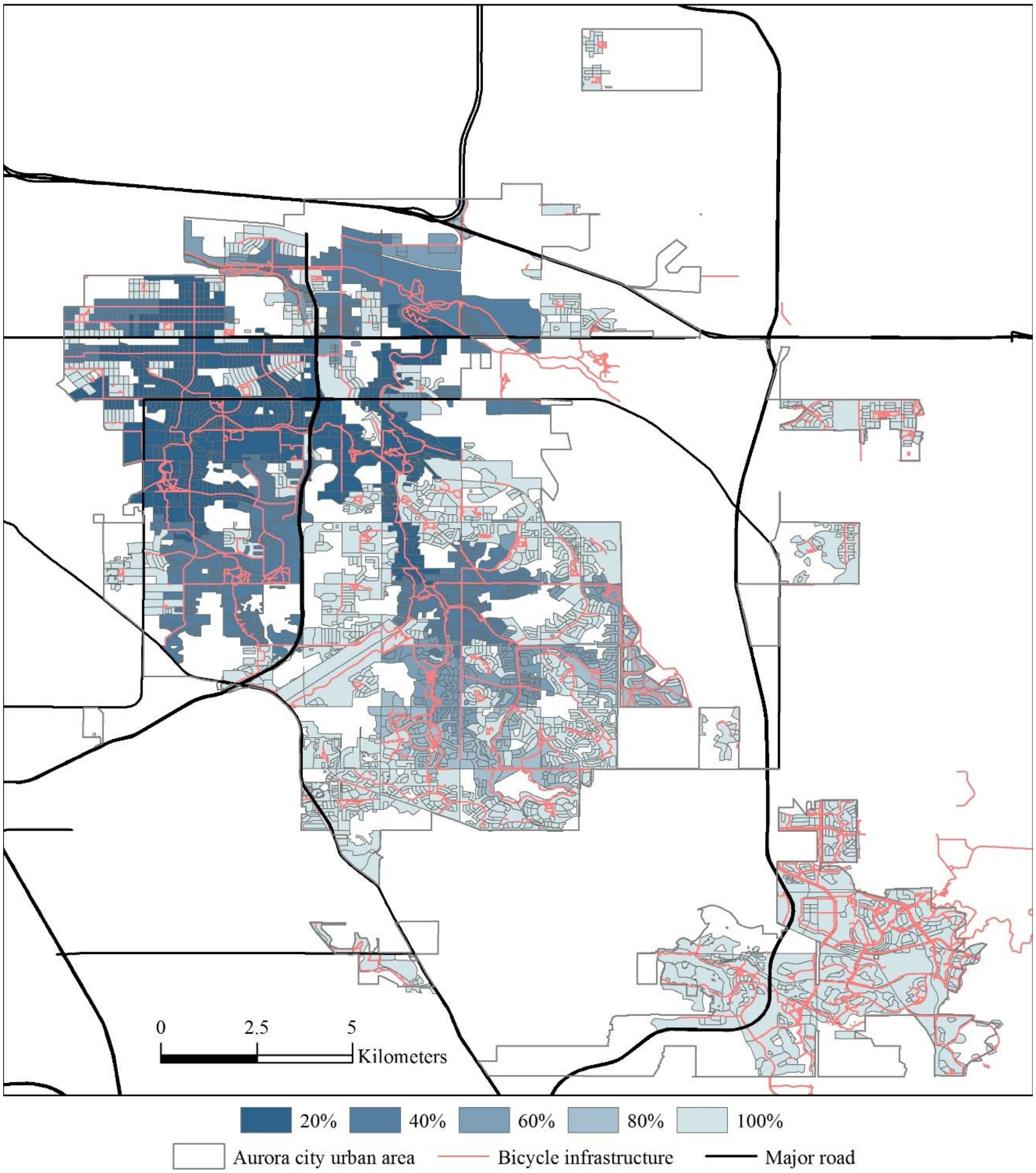

Figure 17. Aurora, Colorado 9-kilometer accessibility using all bicycle infrastructure

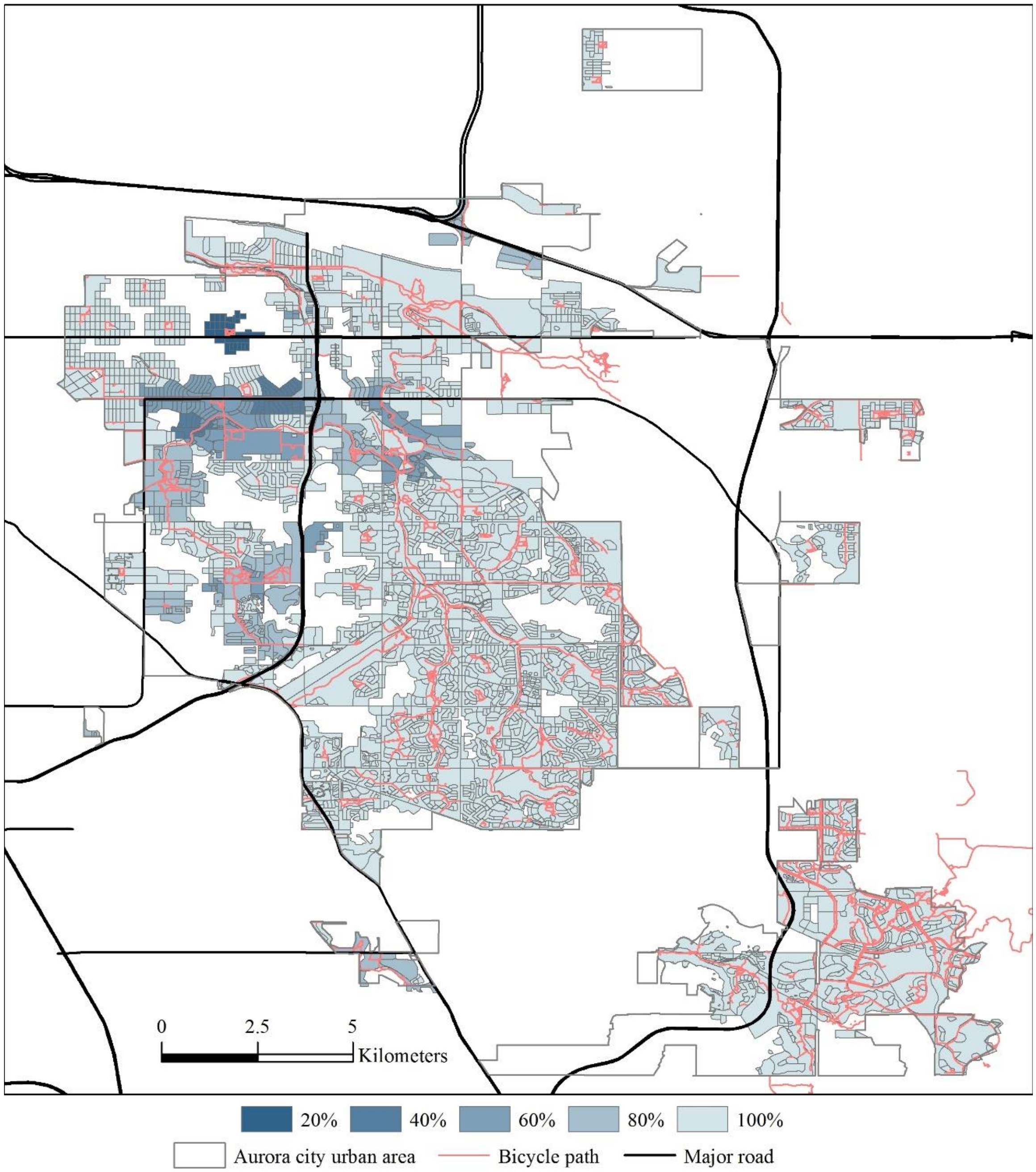

Figure 18. Aurora, Colorado 1-kilometer accessibility using bicycle paths

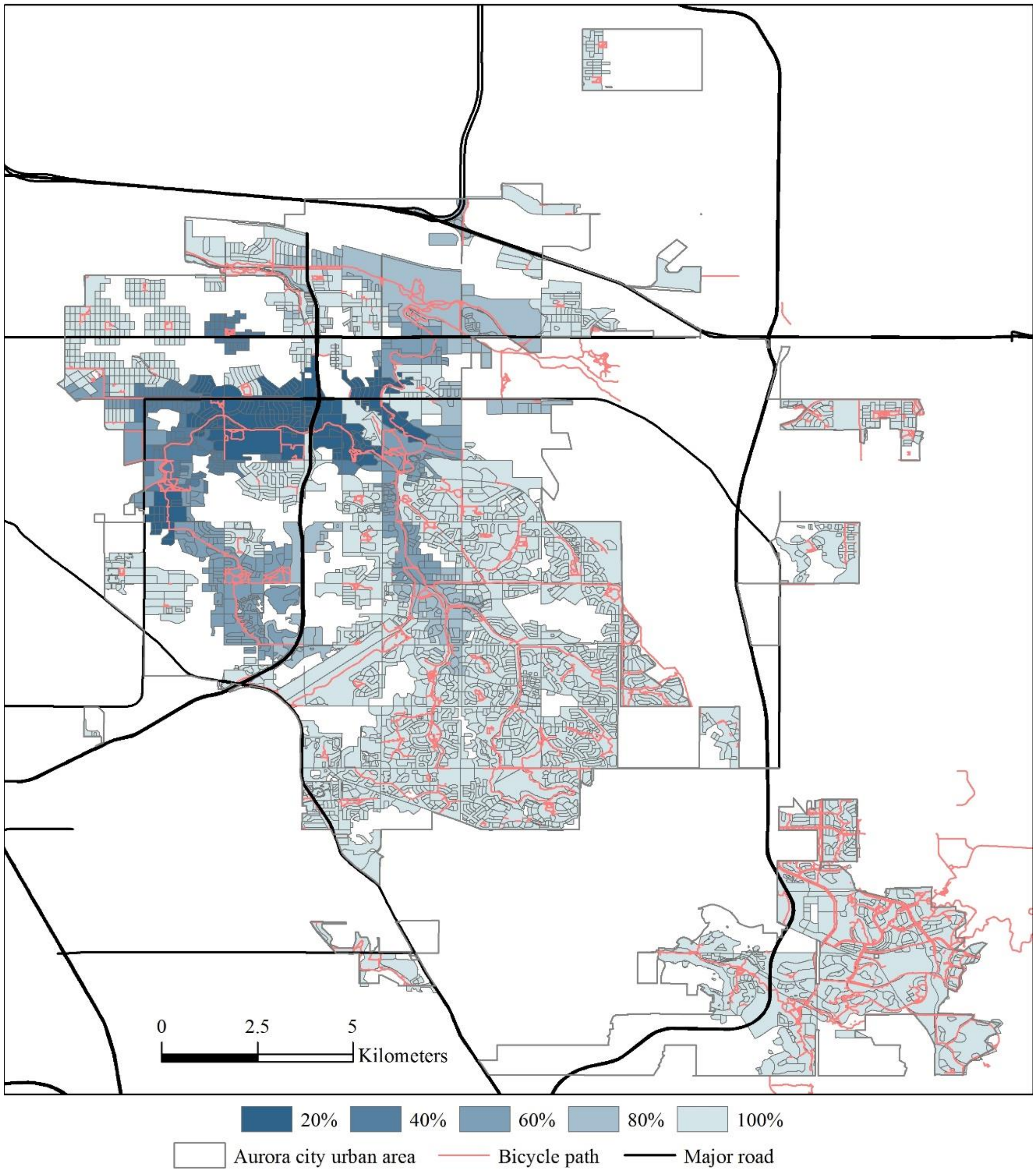

Figure 19. Aurora, Colorado 3-kilometer accessibility using bicycle paths

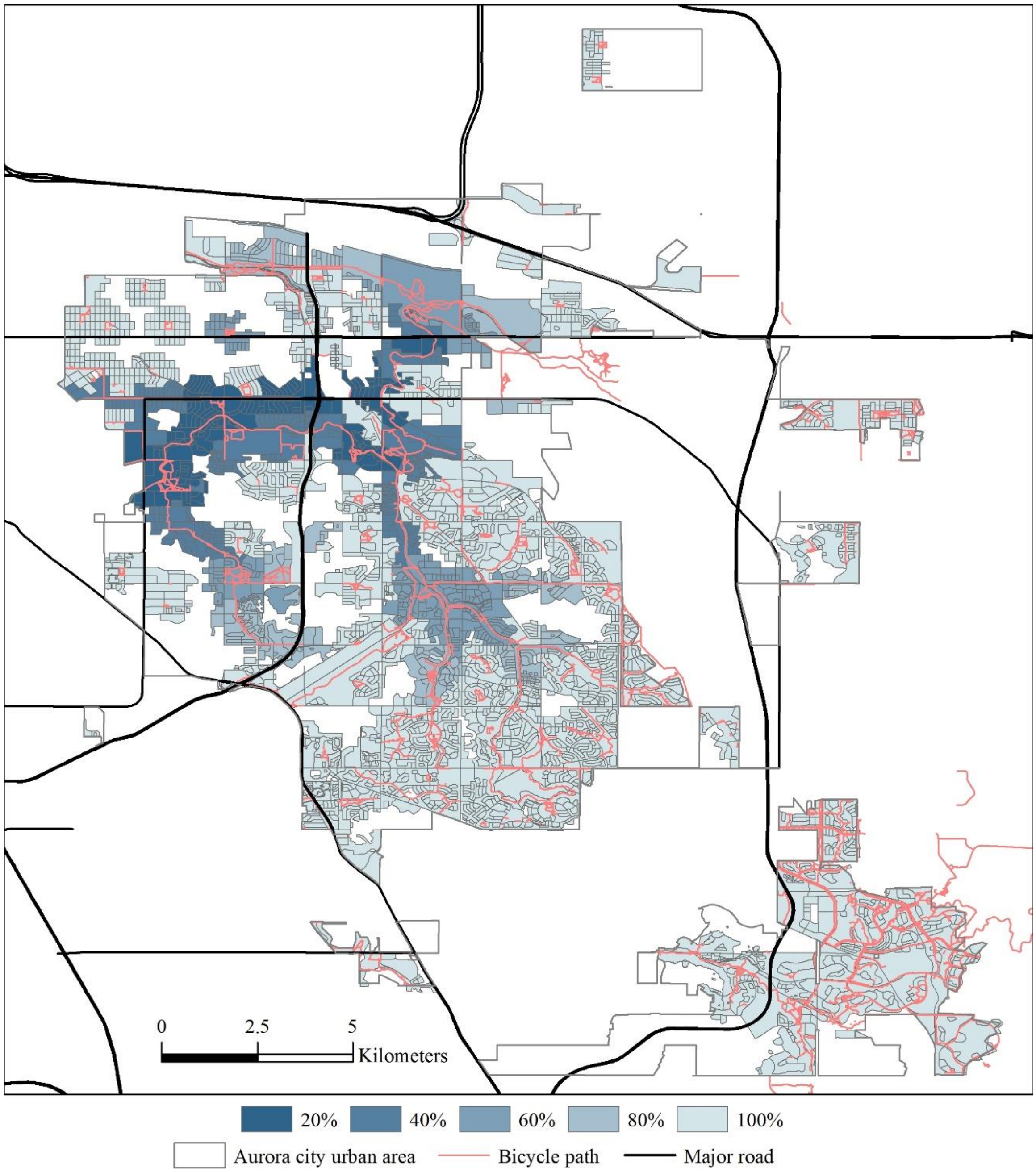

Figure 20. Aurora, Colorado 5-kilometer accessibility using bicycle paths

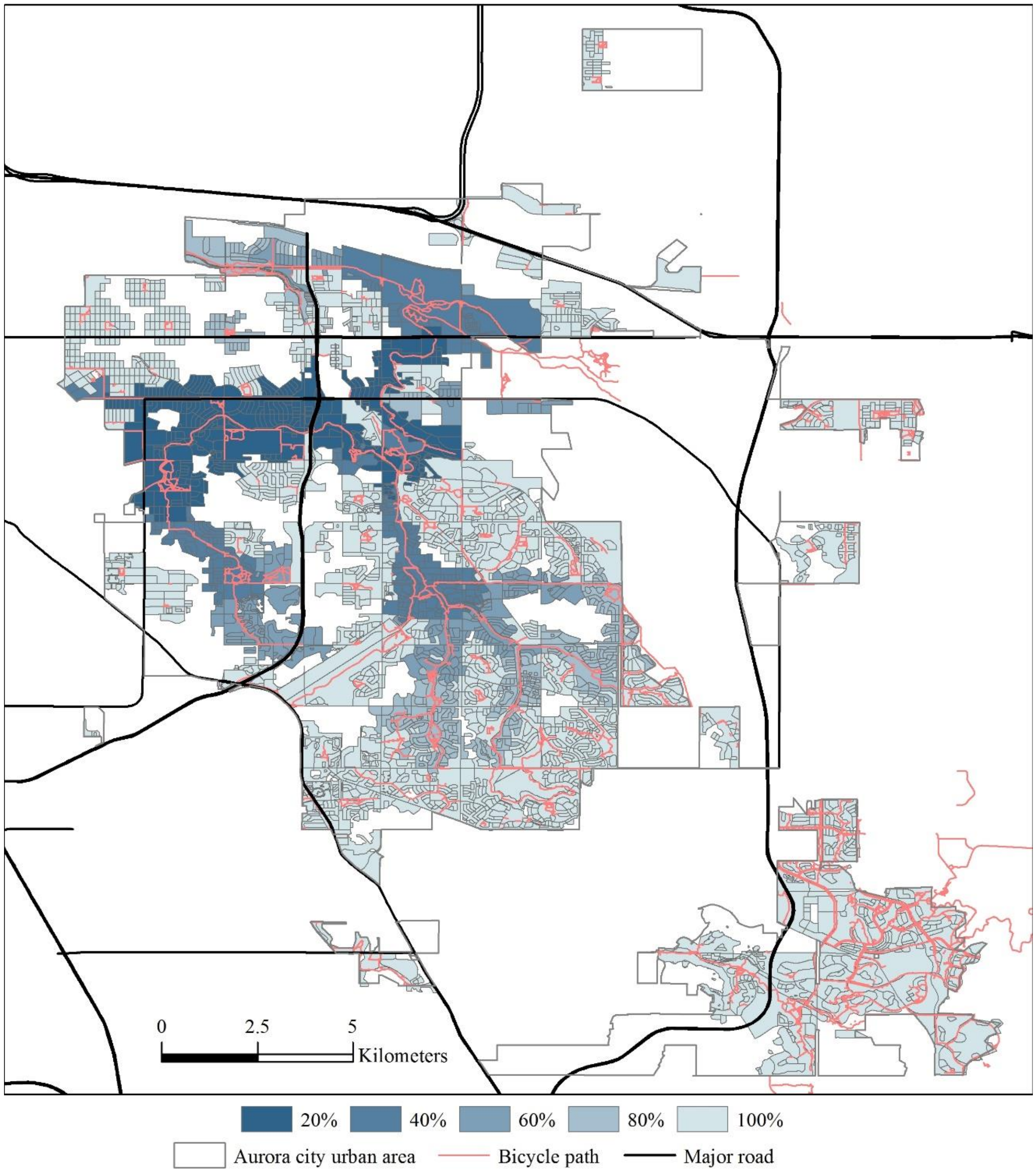

Figure 21. Aurora, Colorado 7-kilometer accessibility using bicycle paths

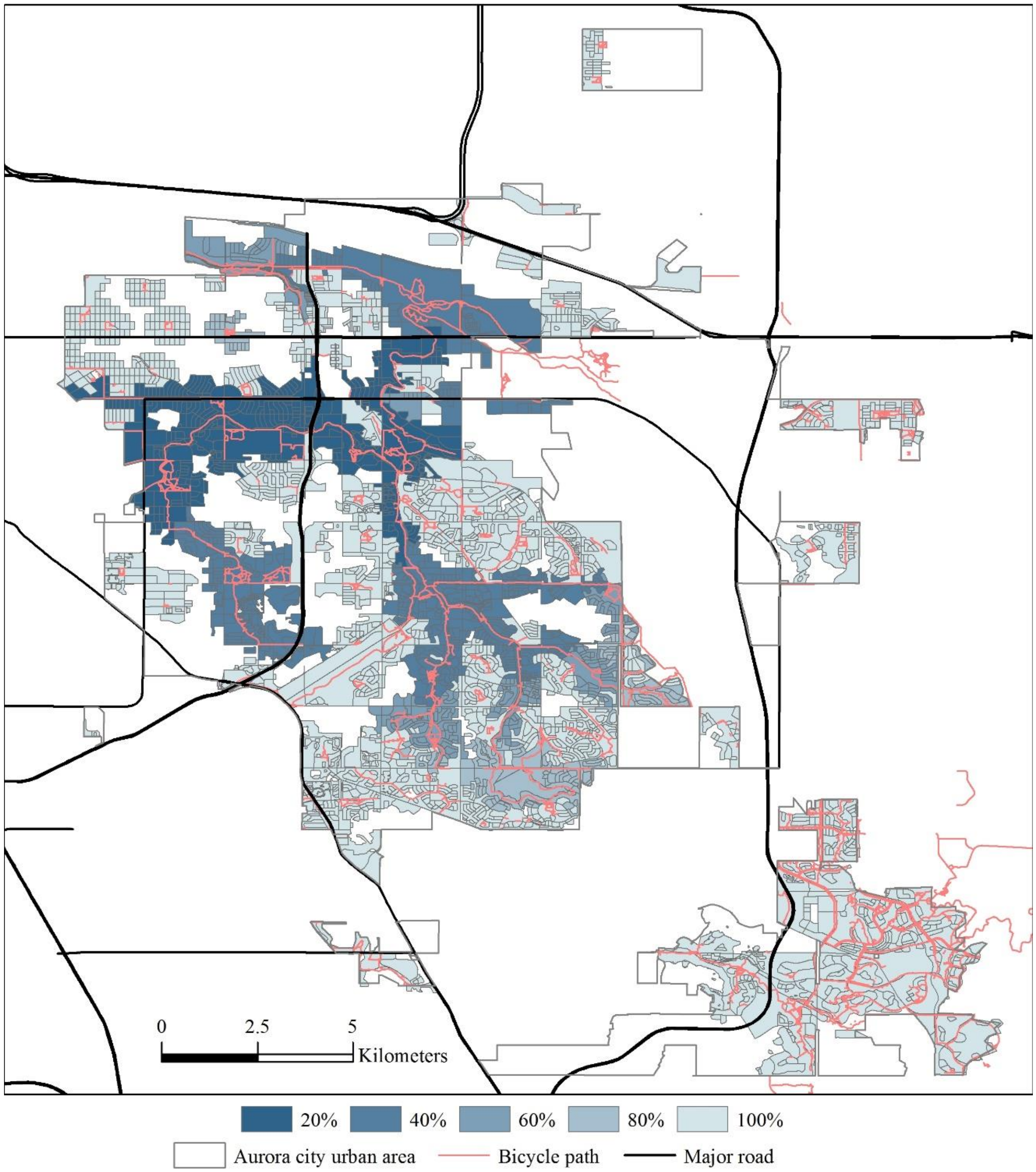

Figure 22. Aurora, Colorado 9-kilometer accessibility using bicycle paths

APPENDIX B

Corpus Christi, Texas City Zonal Accessibility Maps

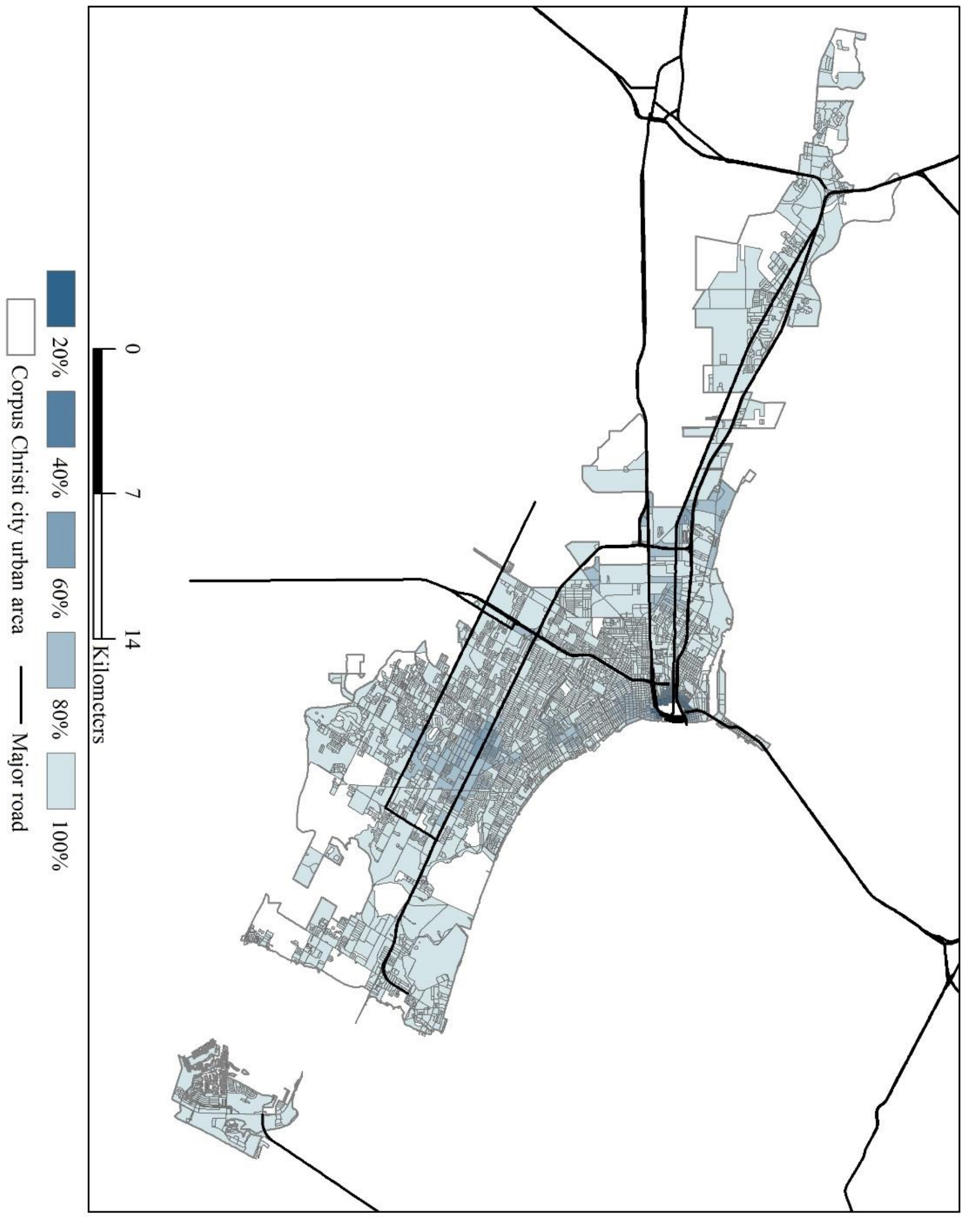

Figure 23. Corpus Christi, Texas 1-kilometer accessibility using roads

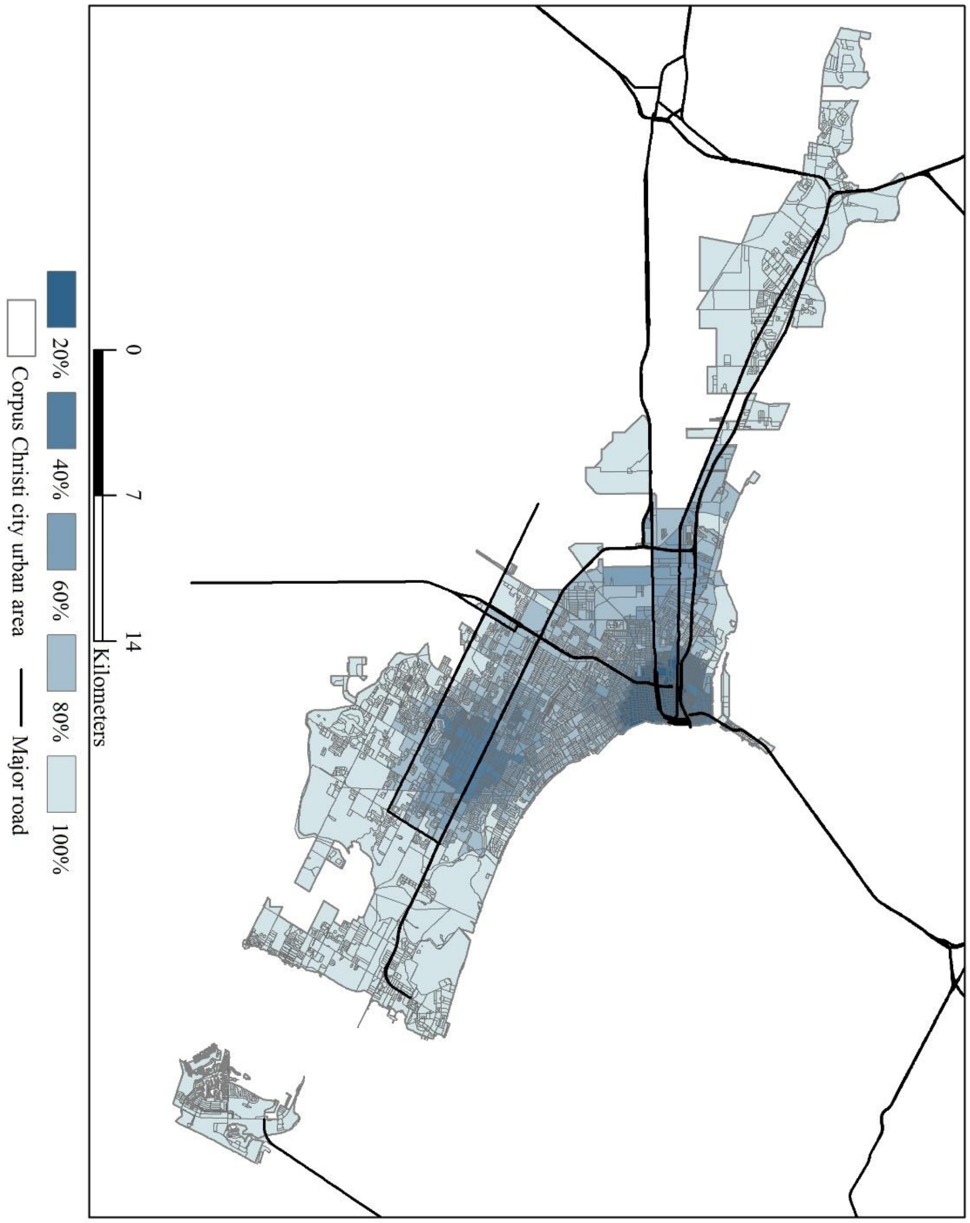

Figure 24. Corpus Christi, Texas 3-kilometer accessibility using roads

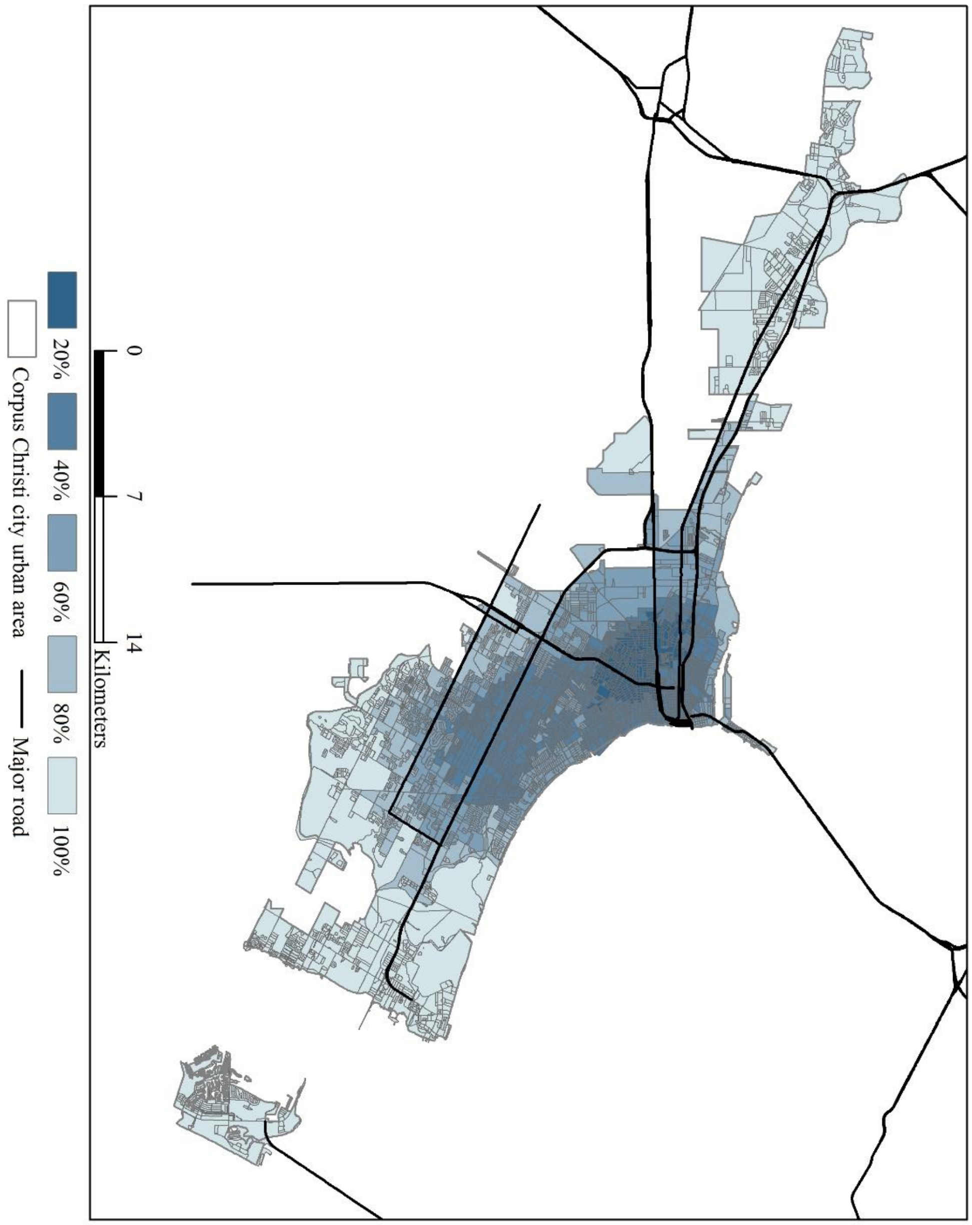

Figure 25. Corpus Christi, Texas 5-kilometer accessibility using roads

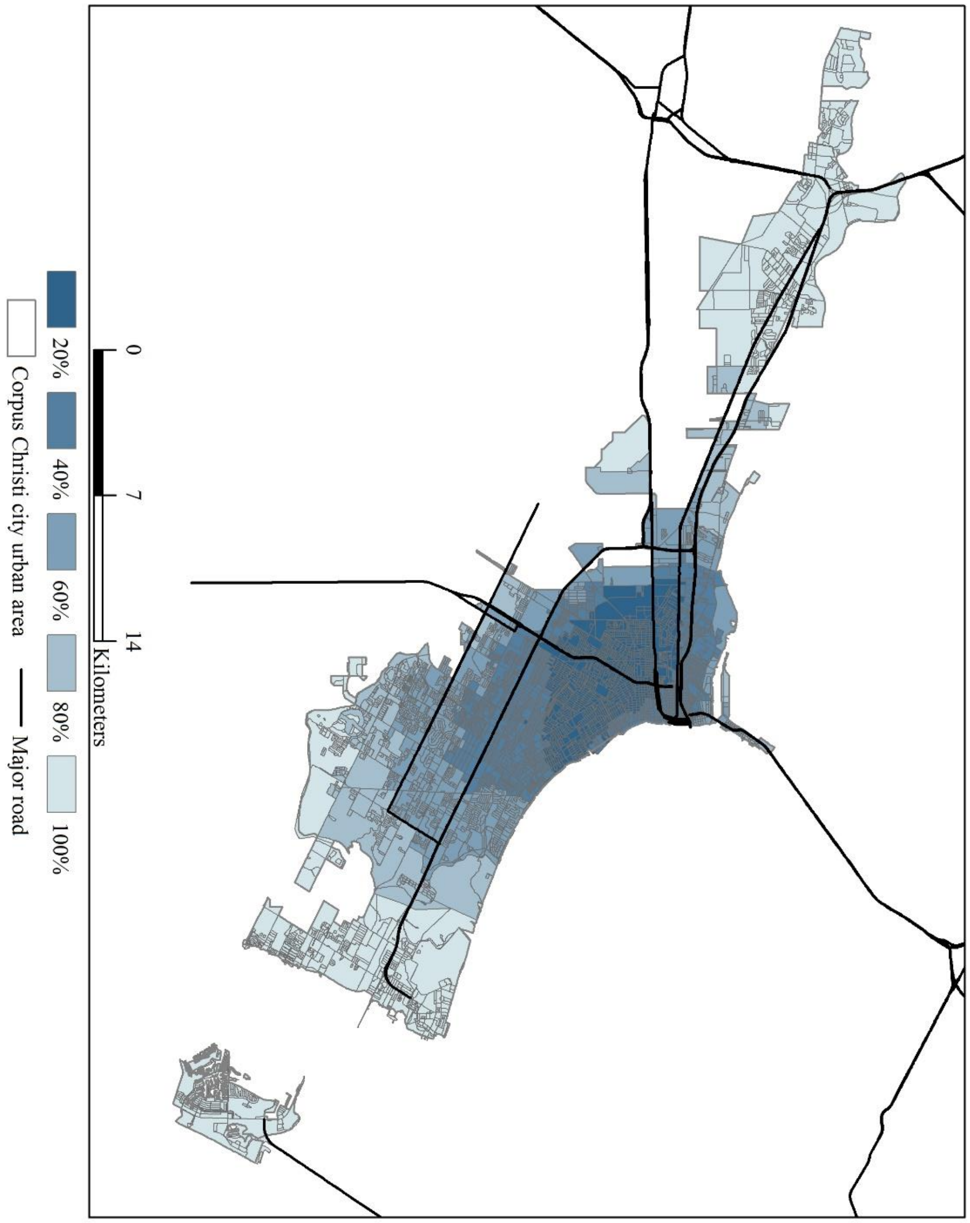

Figure 26. Corpus Christi, Texas 7-kilometer accessibility using roads

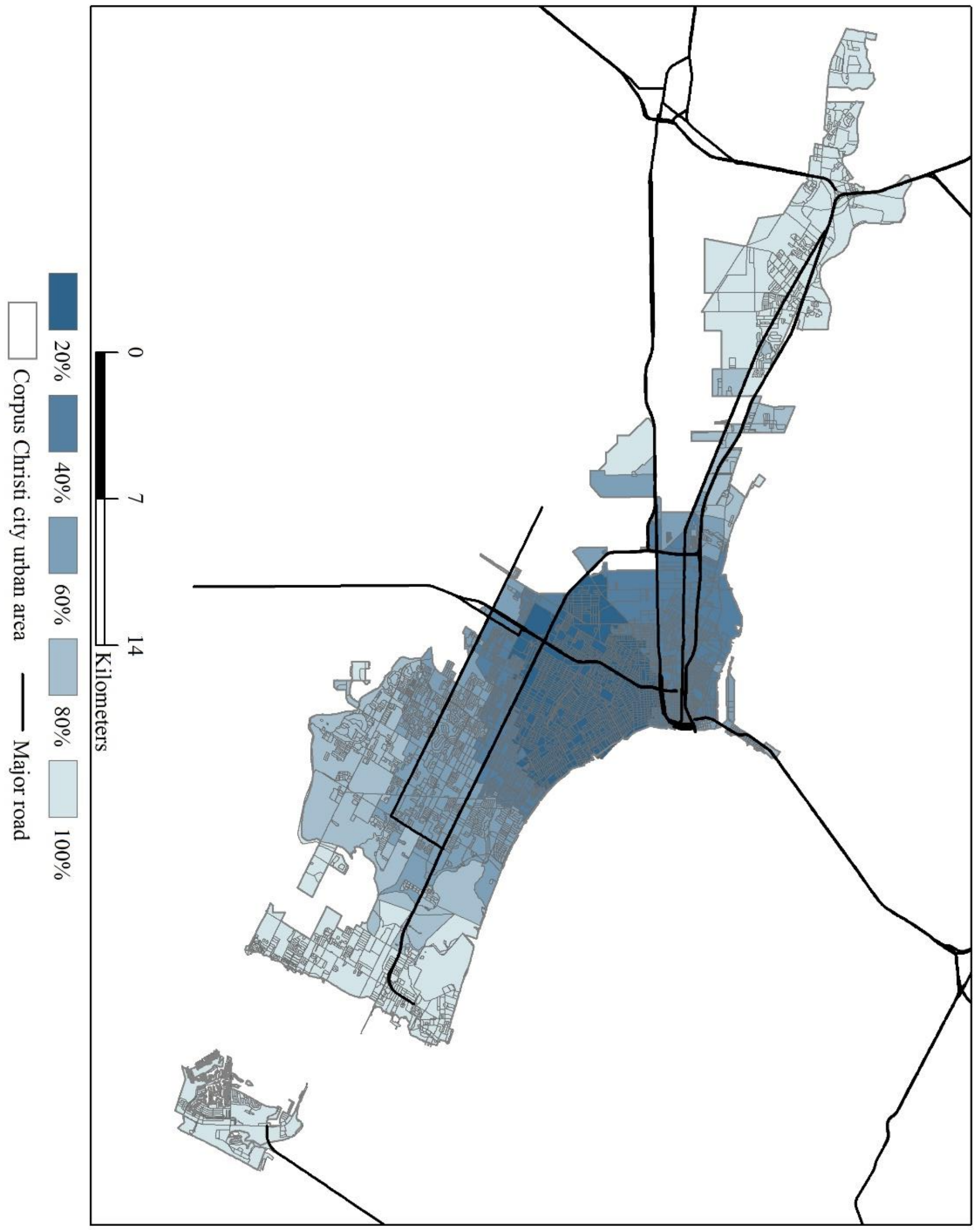

Figure 27. Corpus Christi, Texas 9-kilometer accessibility using roads

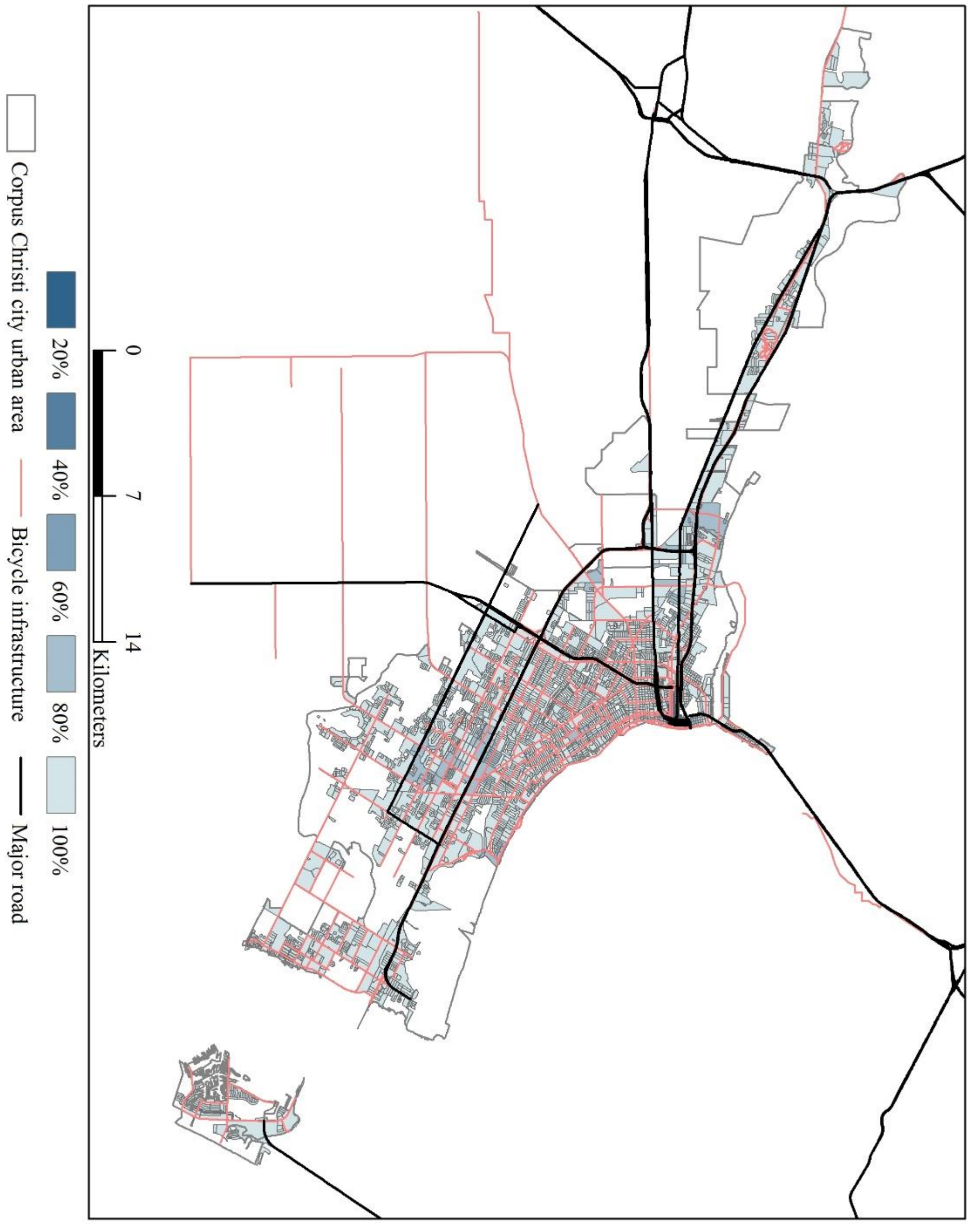

Figure 28. Corpus Christi, Texas 1-kilometer accessibility using all bicycle infrastructure

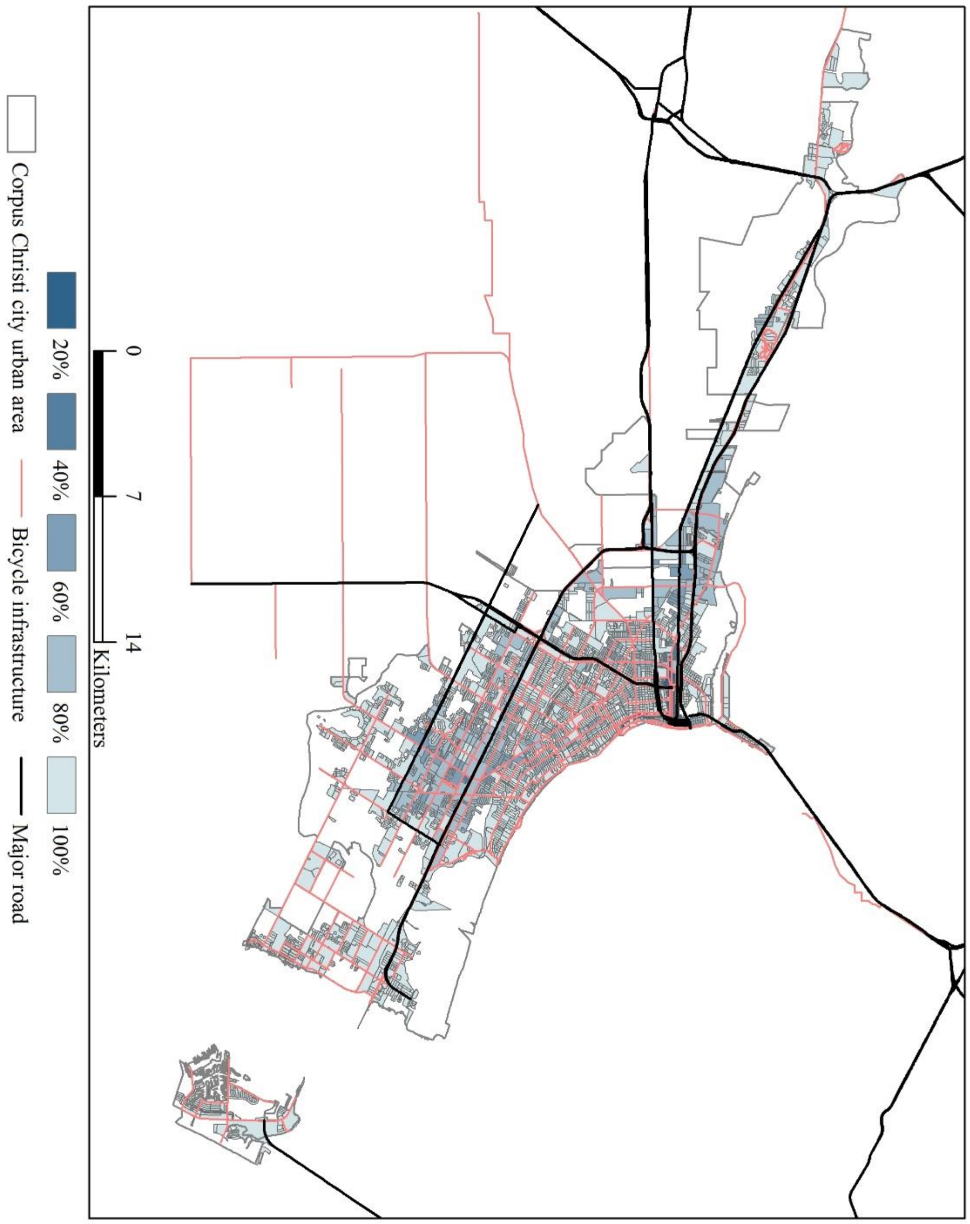

Figure 29. Corpus Christi, Texas 3-kilometer accessibility using all bicycle infrastructure

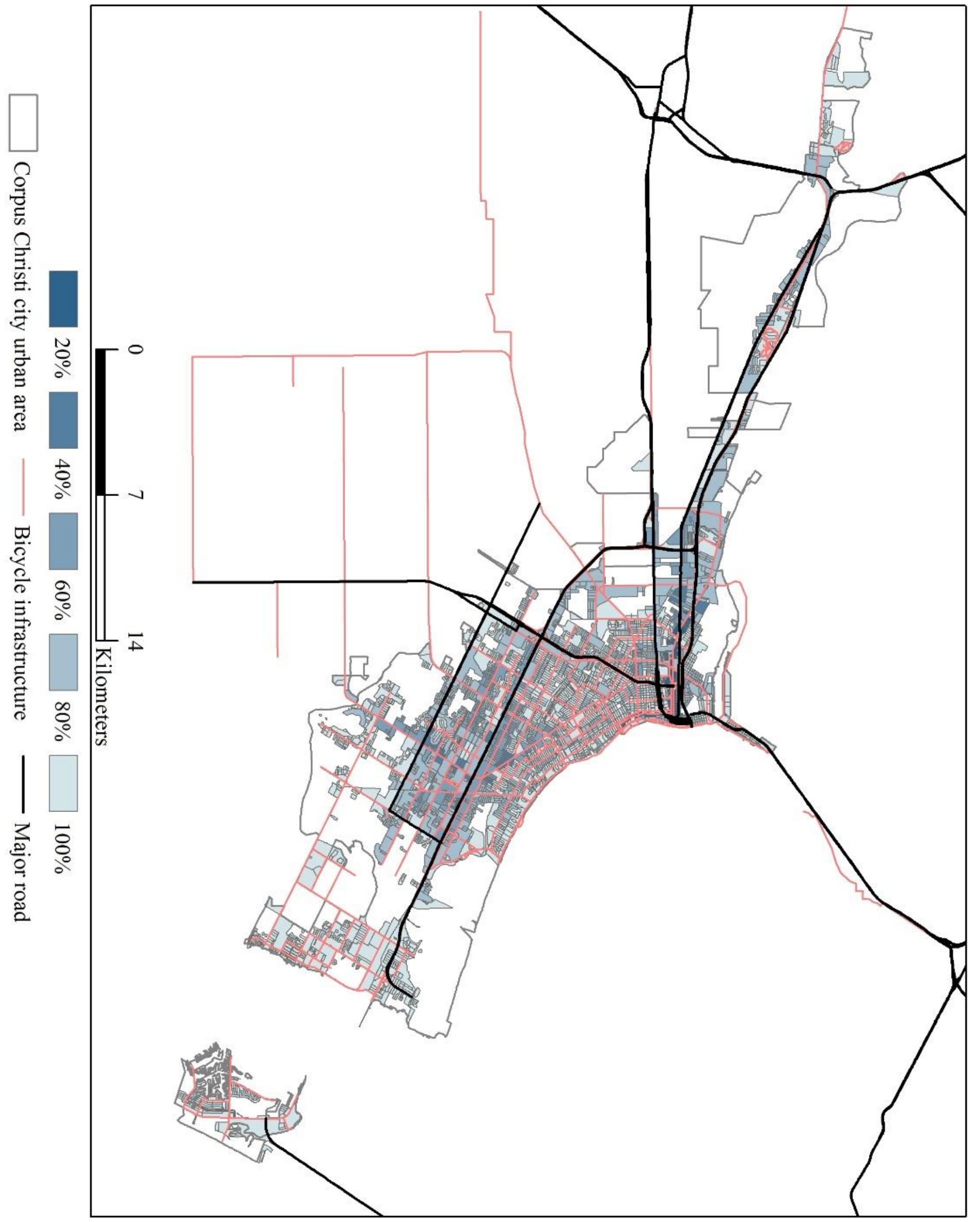

Figure 30. Corpus Christi, Texas 5-kilometer accessibility using all bicycle infrastructure

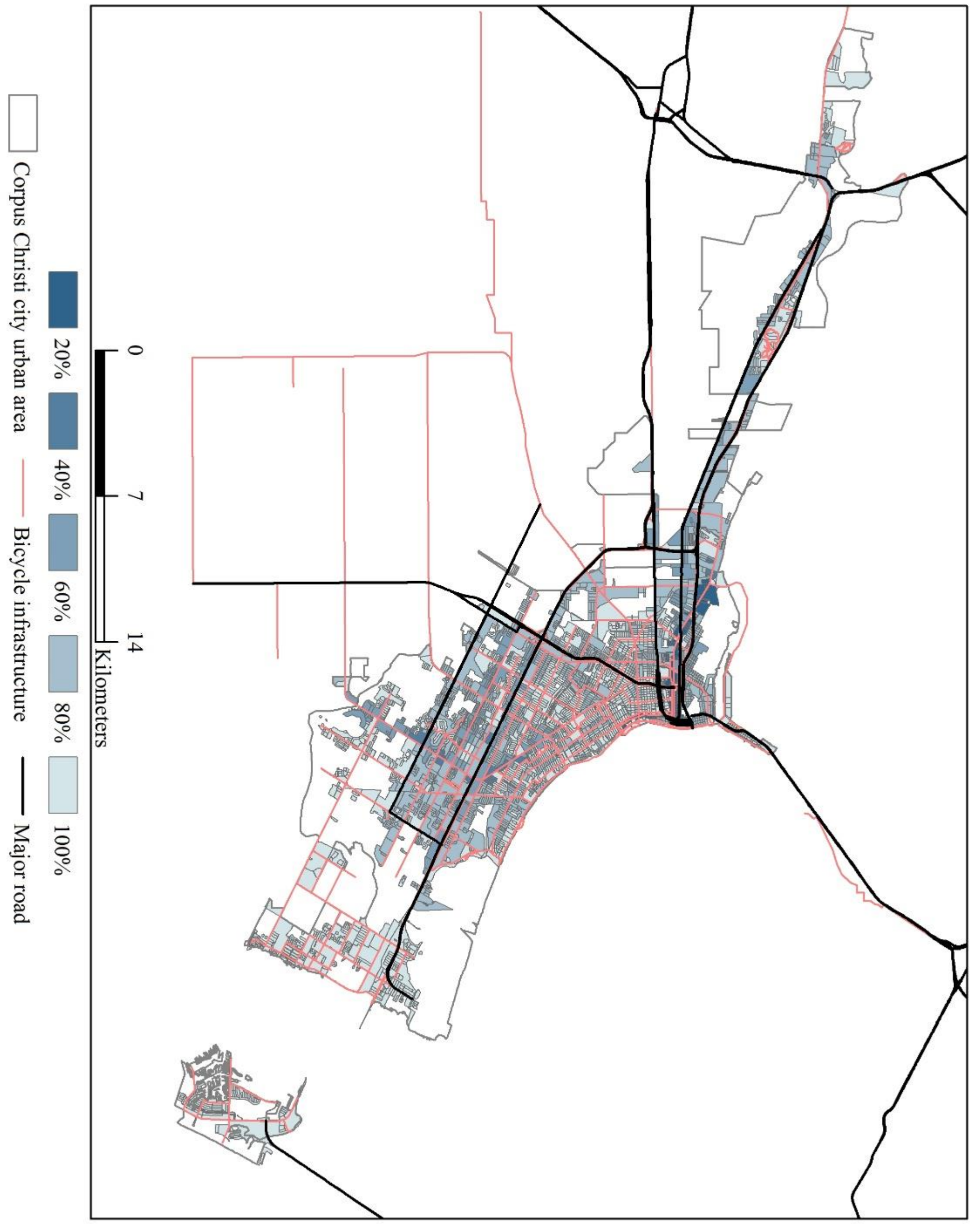

Figure 31. Corpus Christi, Texas 7-kilometer accessibility using all bicycle infrastructure

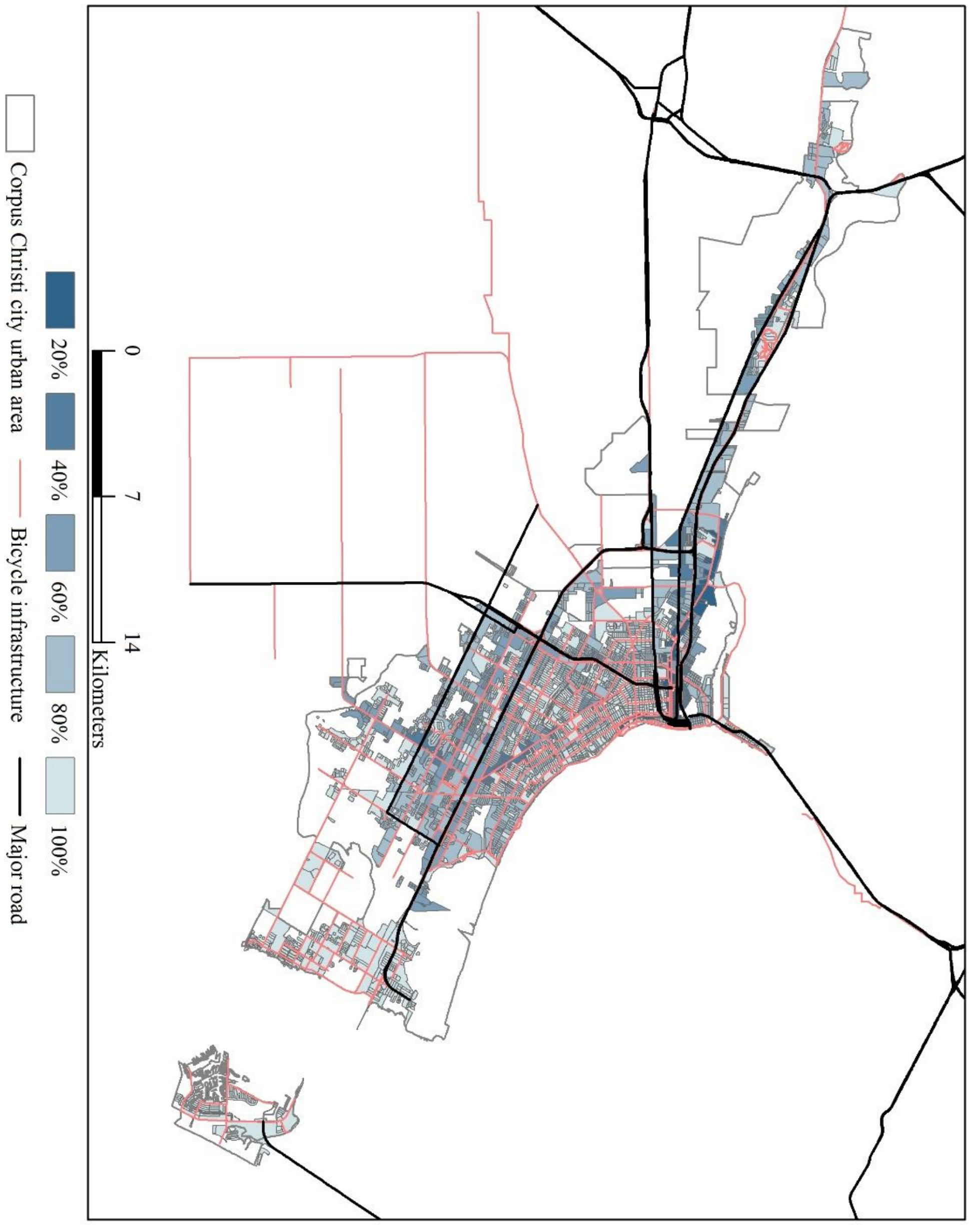

Figure 32. Corpus Christi, Texas 9-kilometer accessibility using all bicycle infrastructure

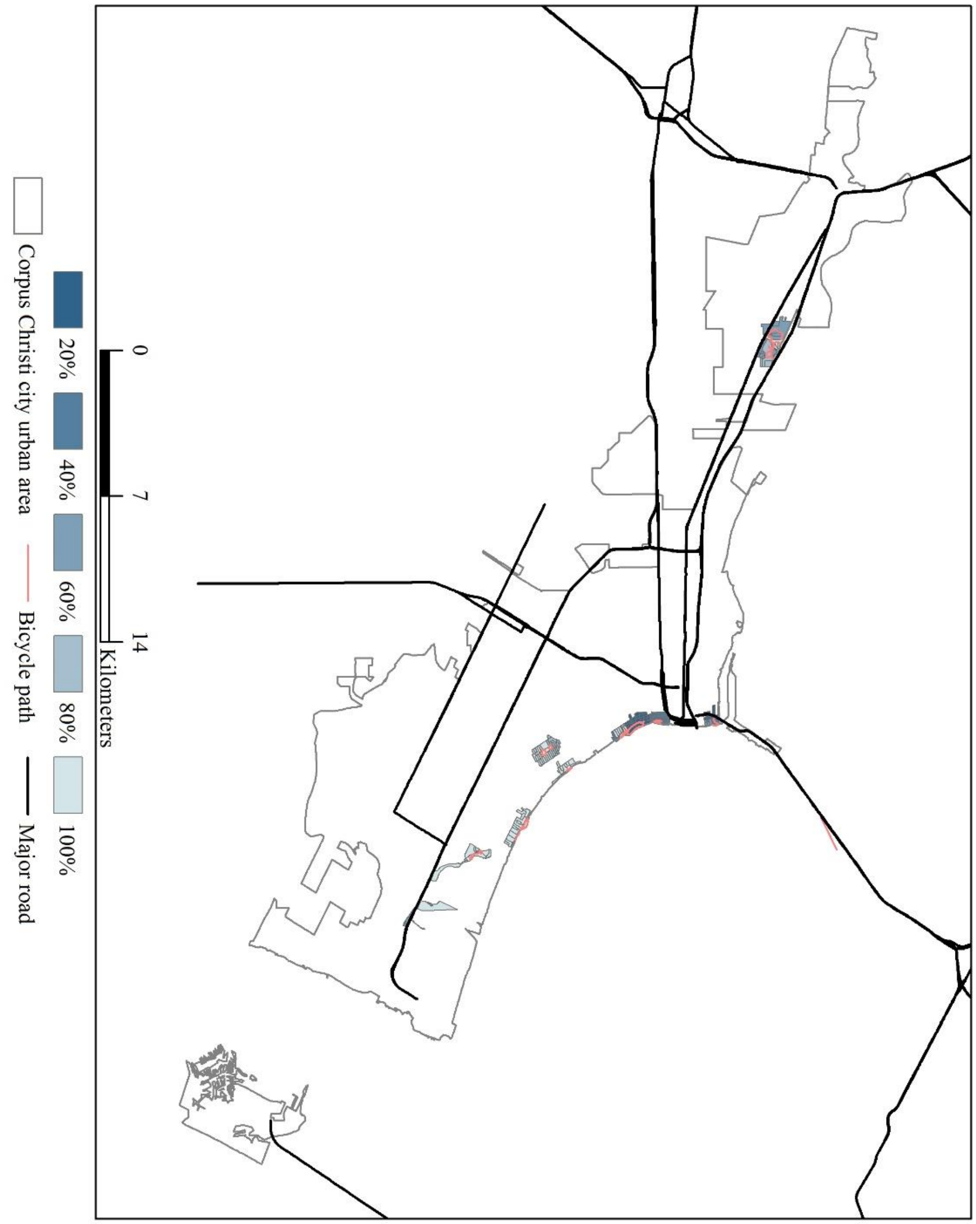

Figure 33. Corpus Christi, Texas 1-kilometer accessibility using bicycle paths

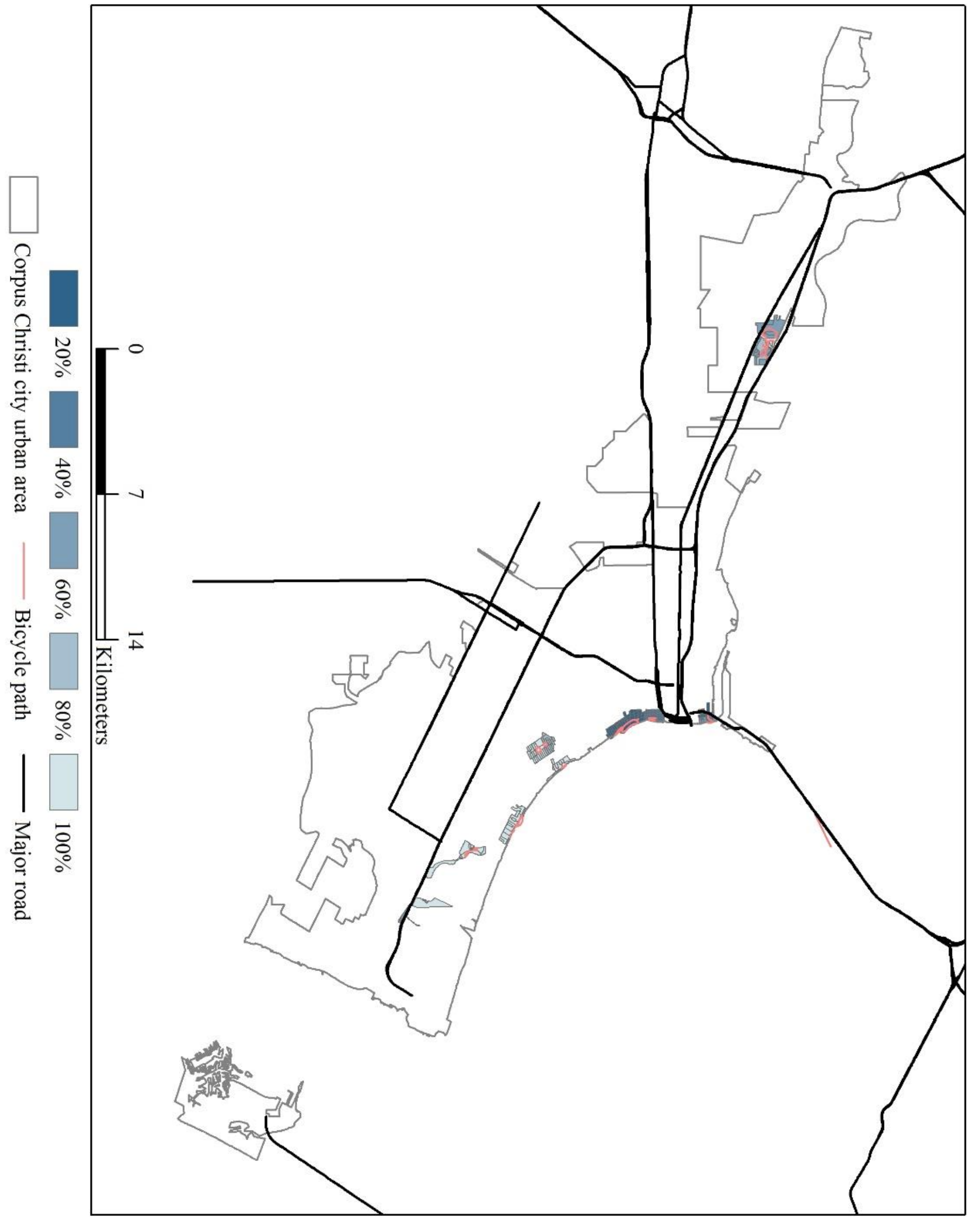

Figure 34. Corpus Christi, Texas 3-kilometer accessibility using bicycle paths

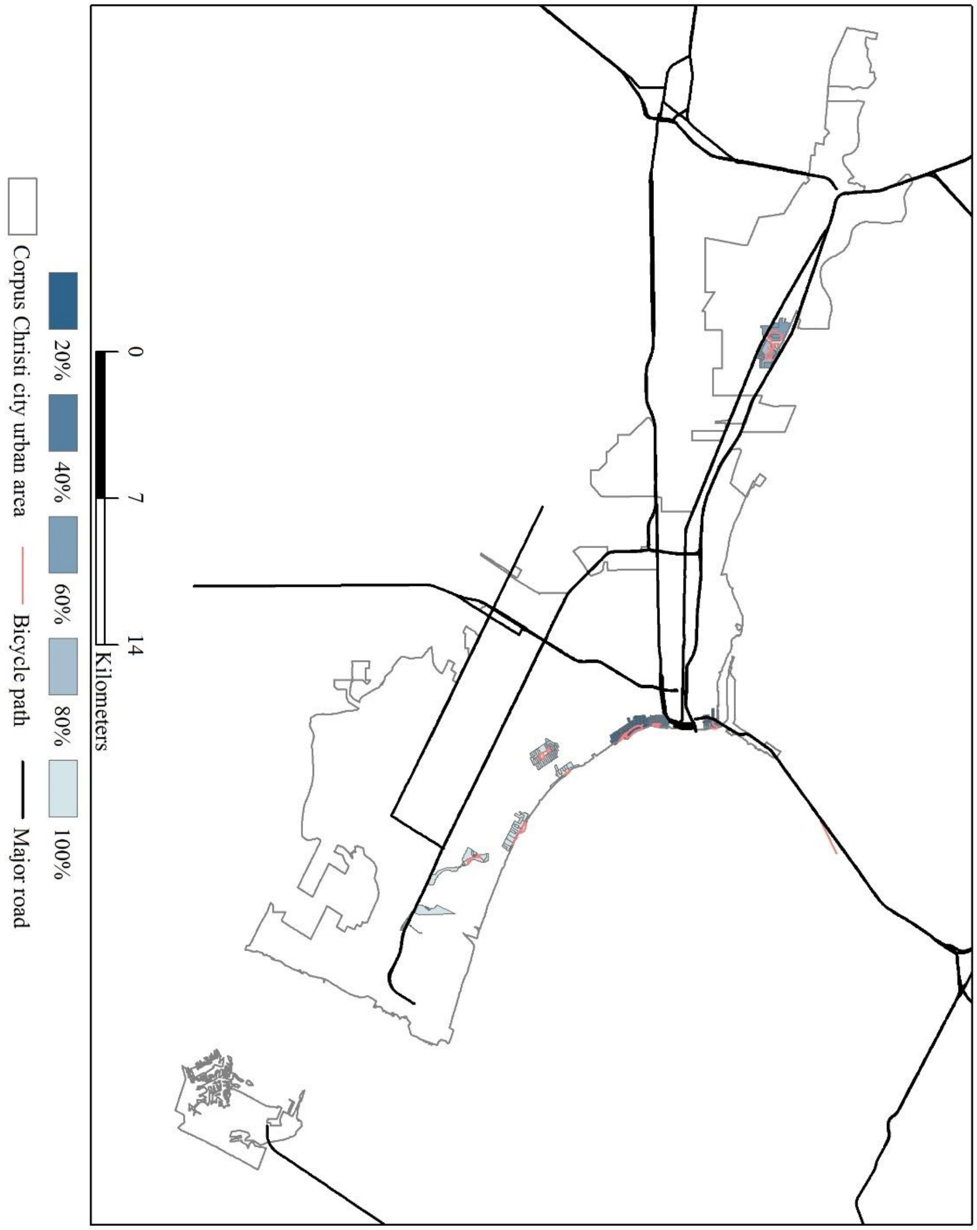

Figure 35. Corpus Christi, Texas 5-kilometer accessibility using bicycle paths

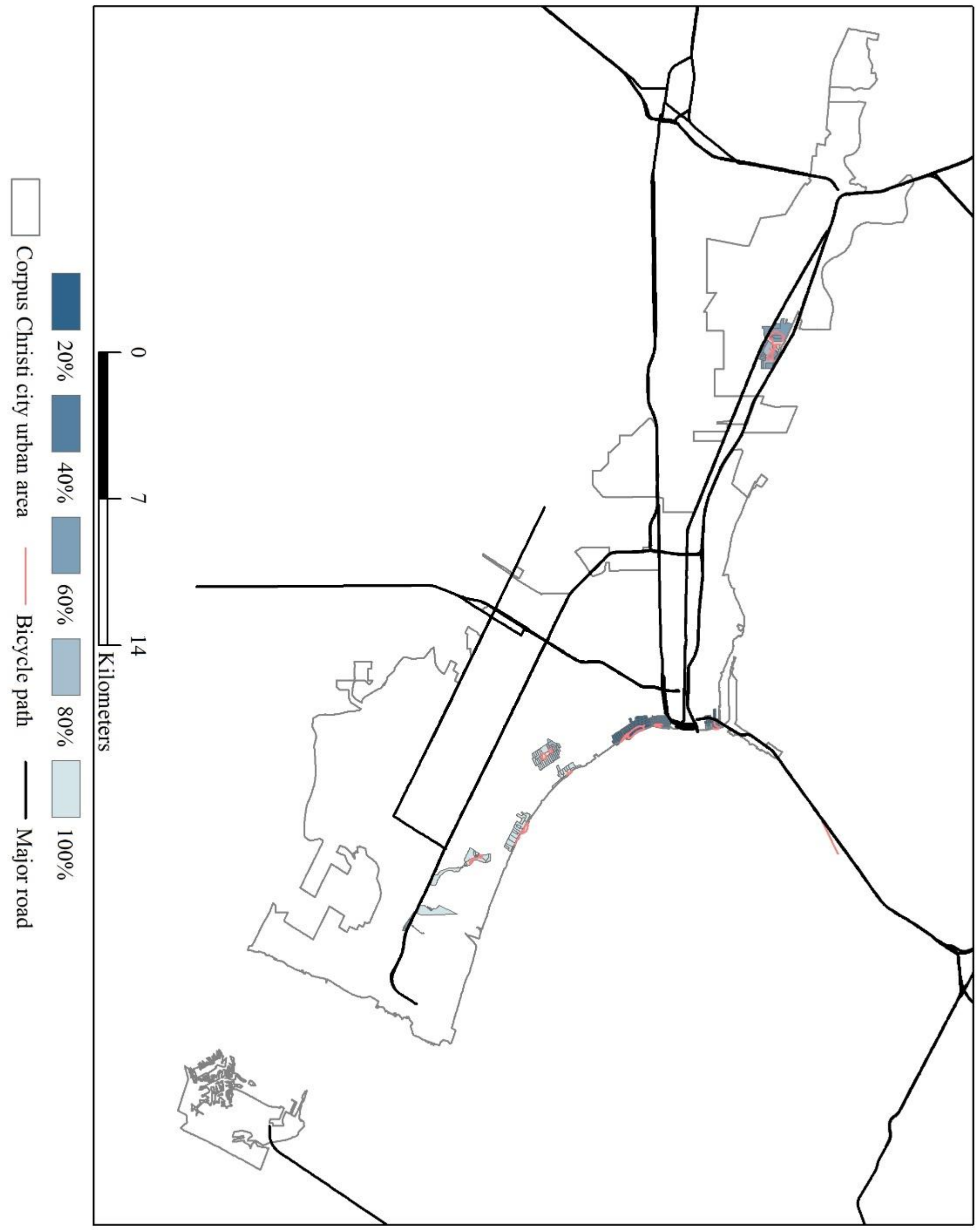

Figure 36. Corpus Christi, Texas 7-kilometer accessibility using bicycle paths

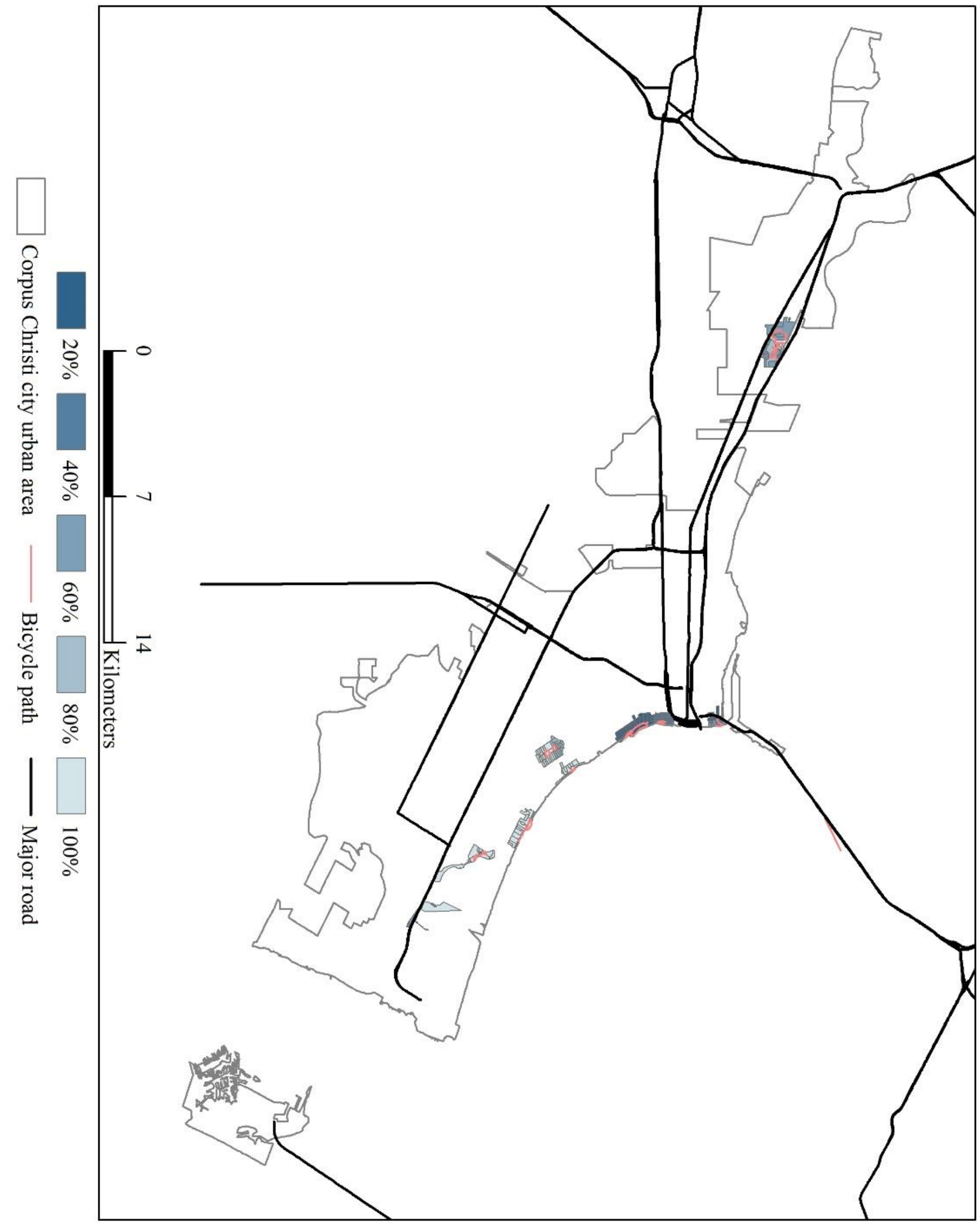

Figure 37. Corpus Christi, Texas 9-kilometer accessibility using bicycle paths

APPENDIX C

Denver, Colorado City Zonal Accessibility Maps

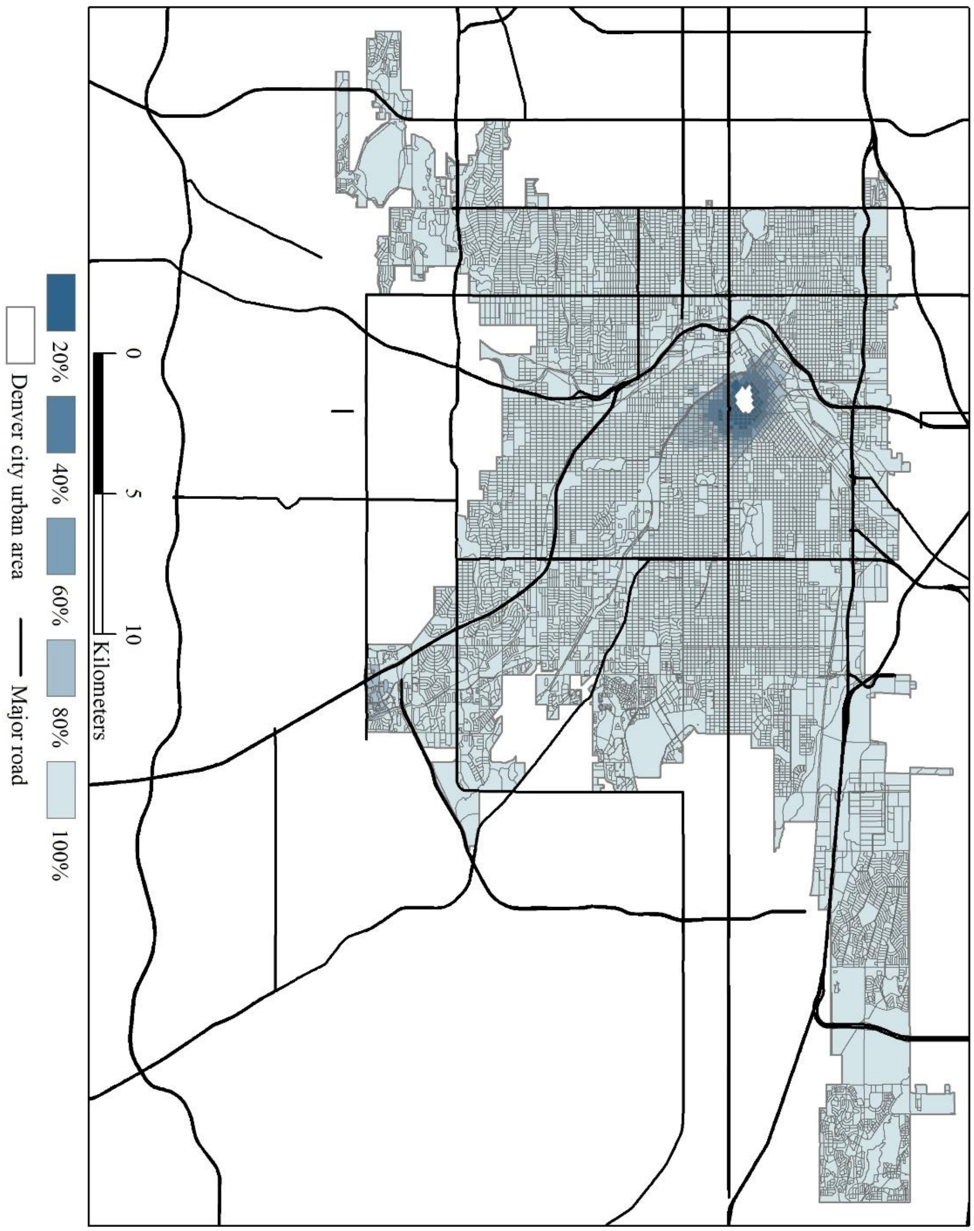

Figure 38. Denver, Colorado 1-kilometer accessibility using roads

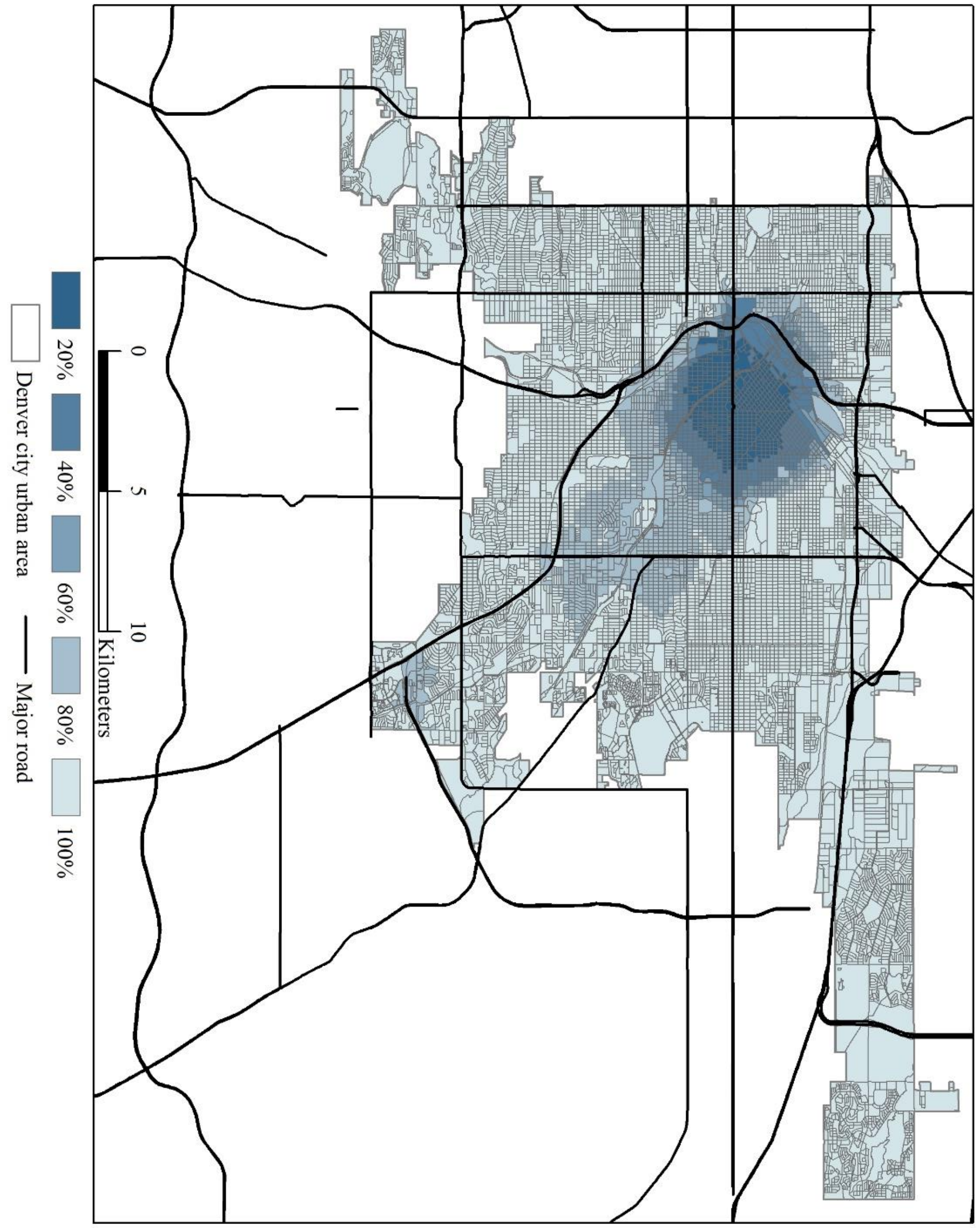

Figure 39. Denver, Colorado 3-kilometer accessibility using roads

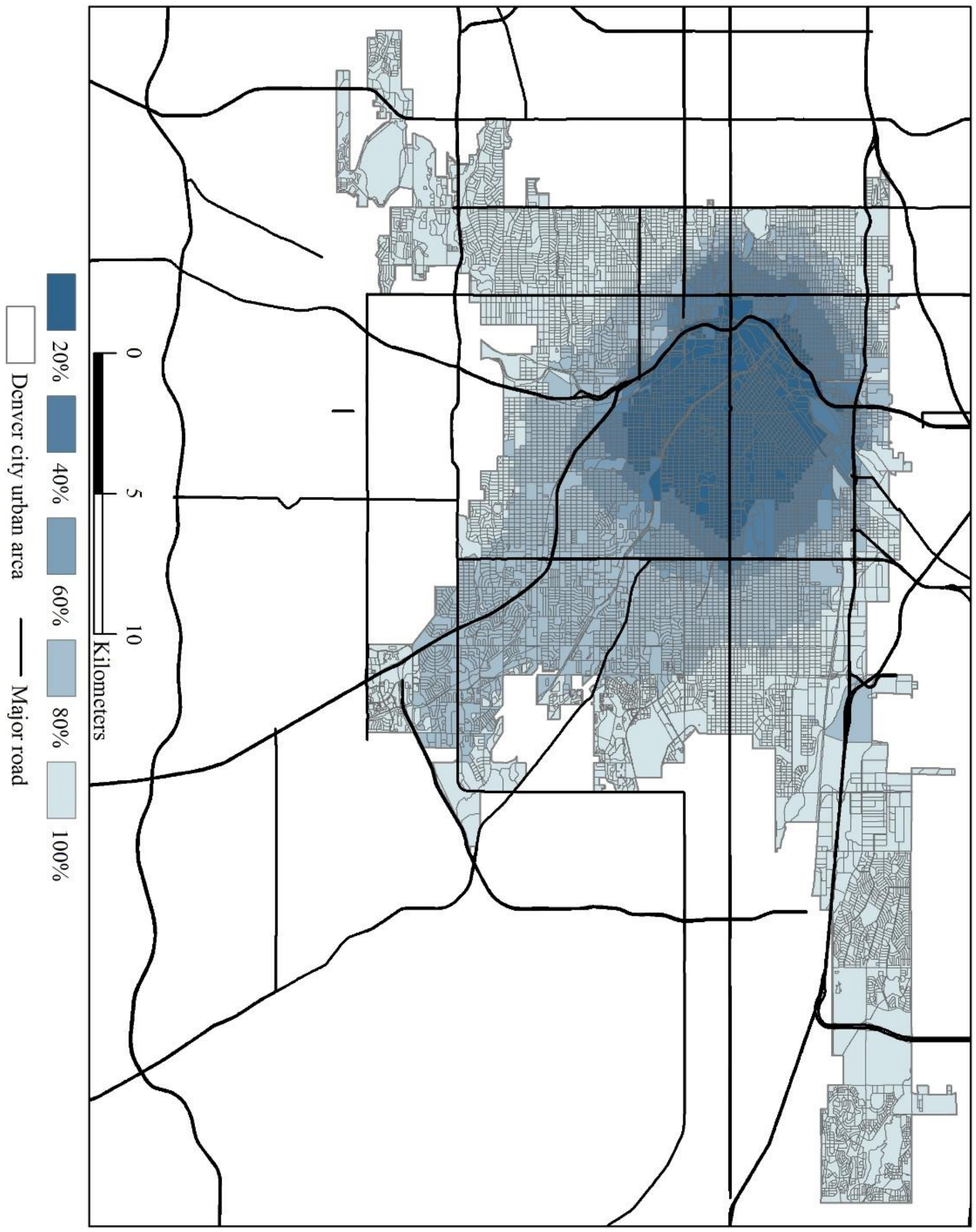

Figure 40. Denver, Colorado 5-kilometer accessibility using roads

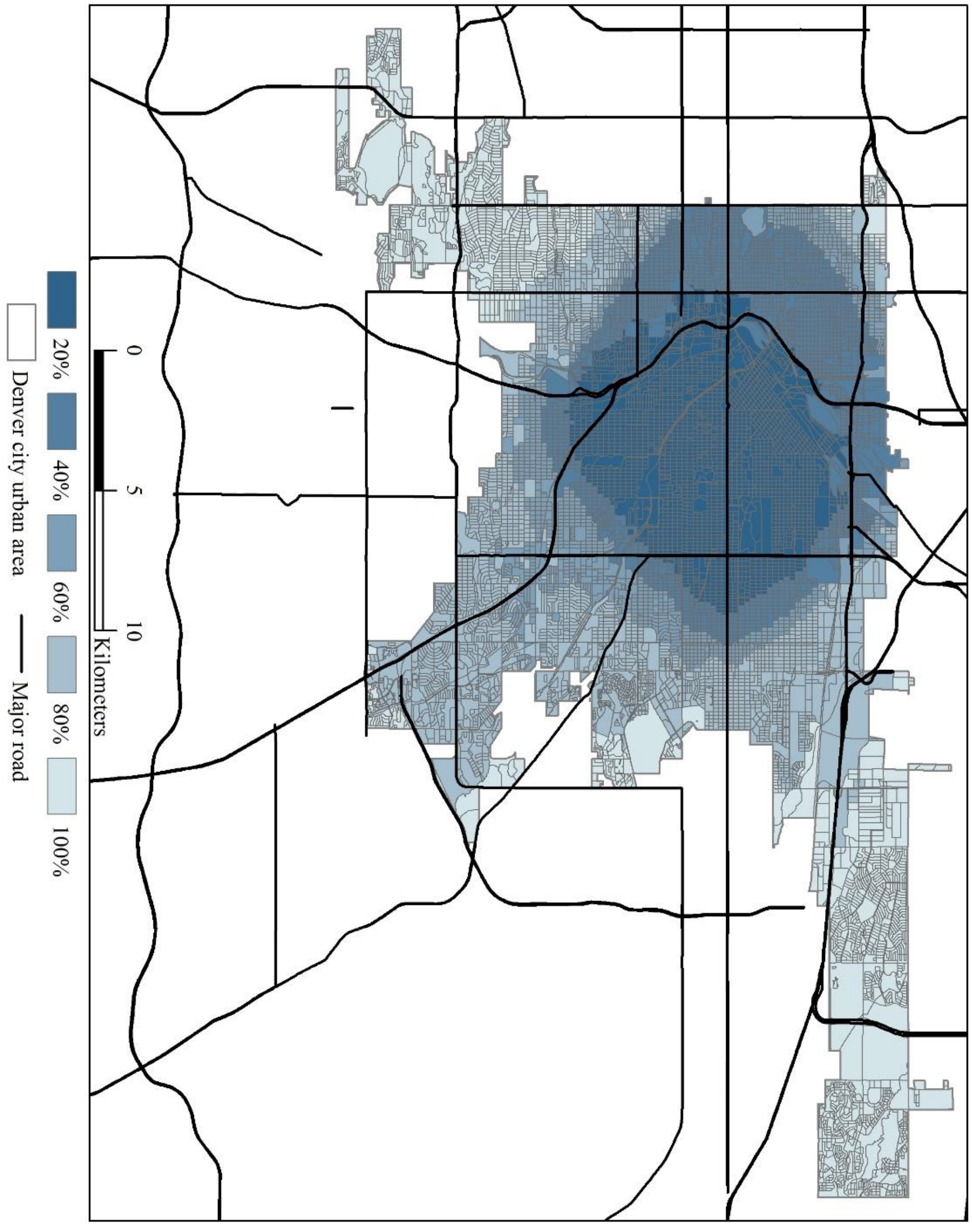

Figure 41. Denver, Colorado 7-kilometer accessibility using roads

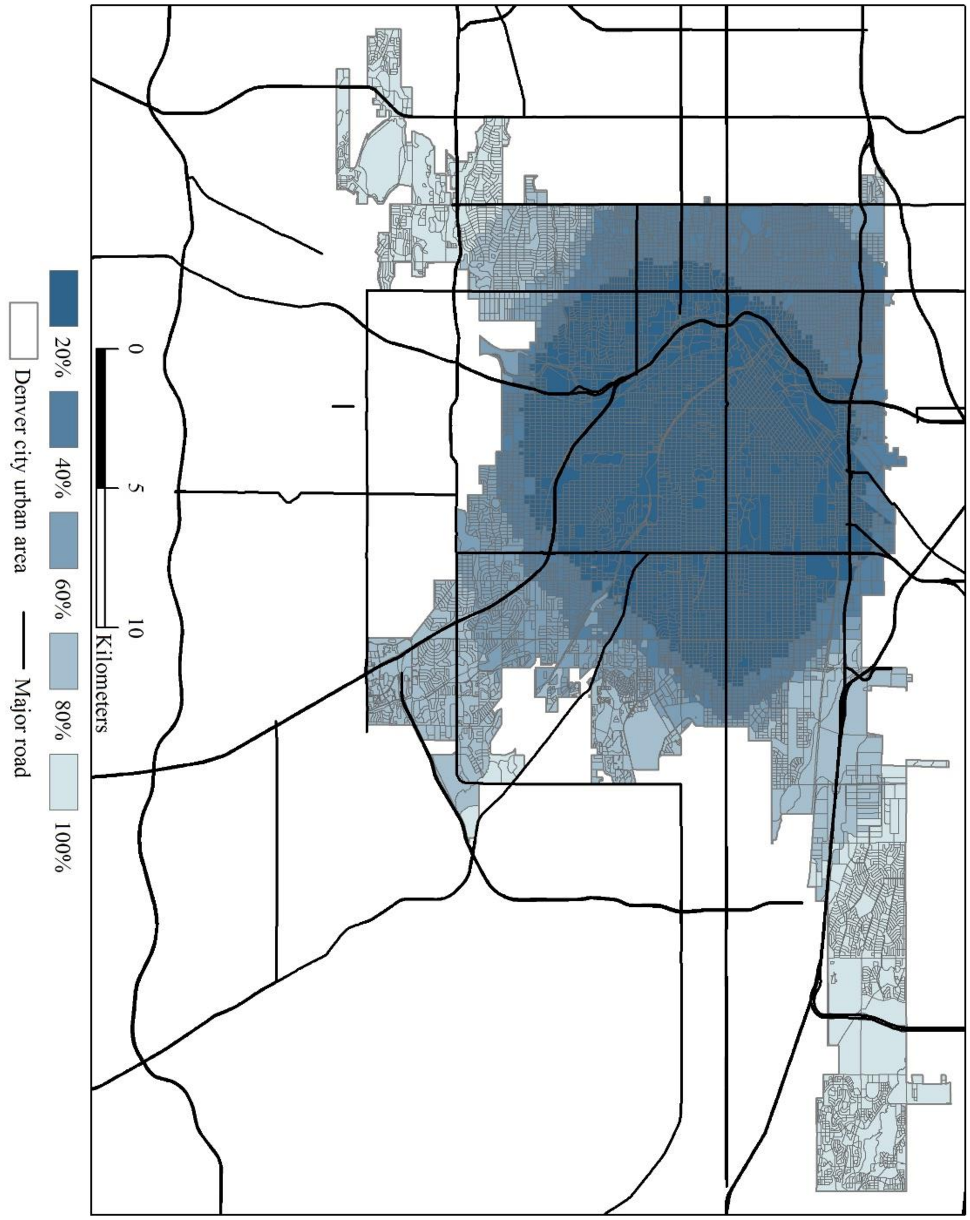

Figure 42. Denver, Colorado 9-kilometer accessibility using roads

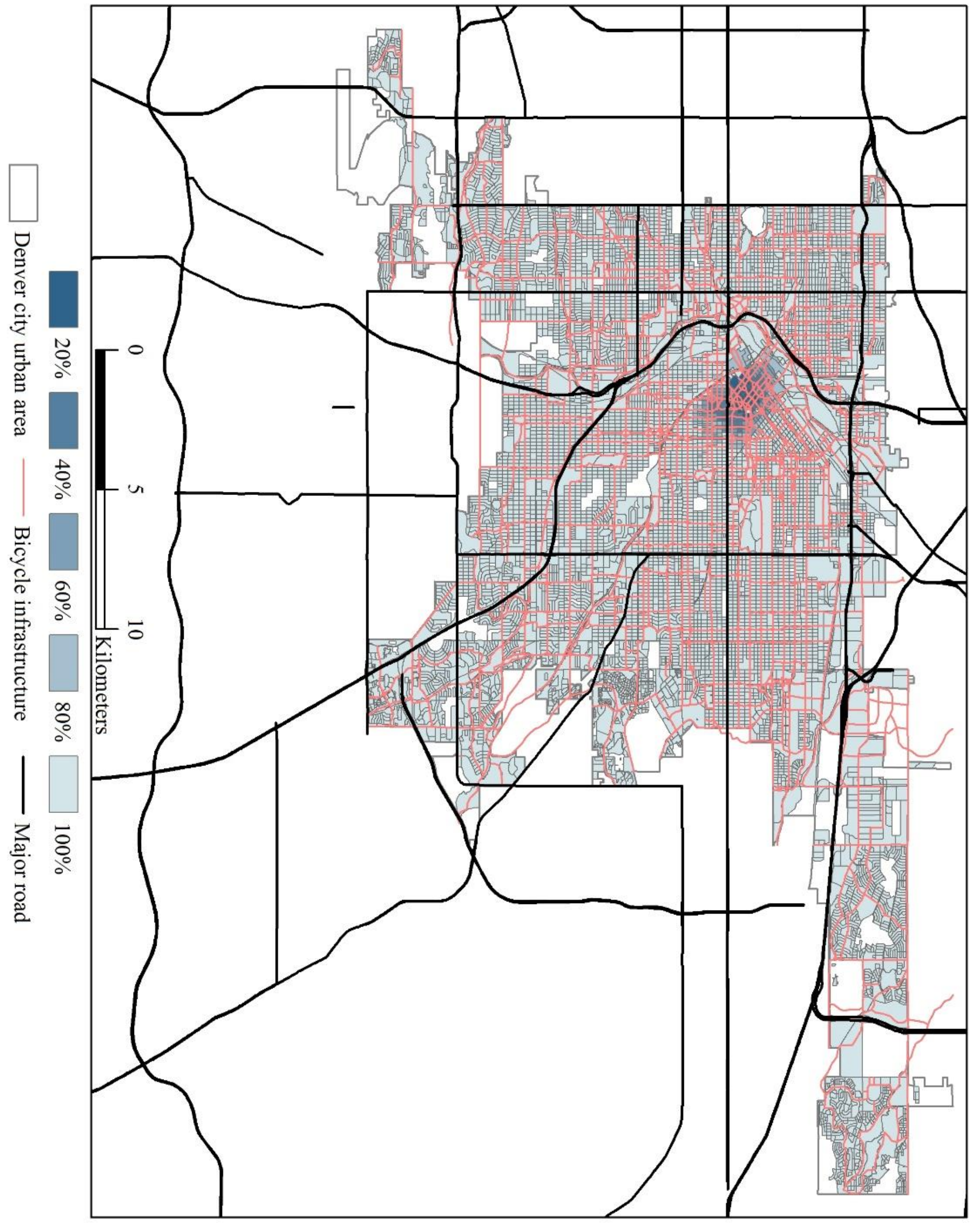

Figure 43. Denver, Colorado 1-kilometer accessibility using all bicycle infrastructure

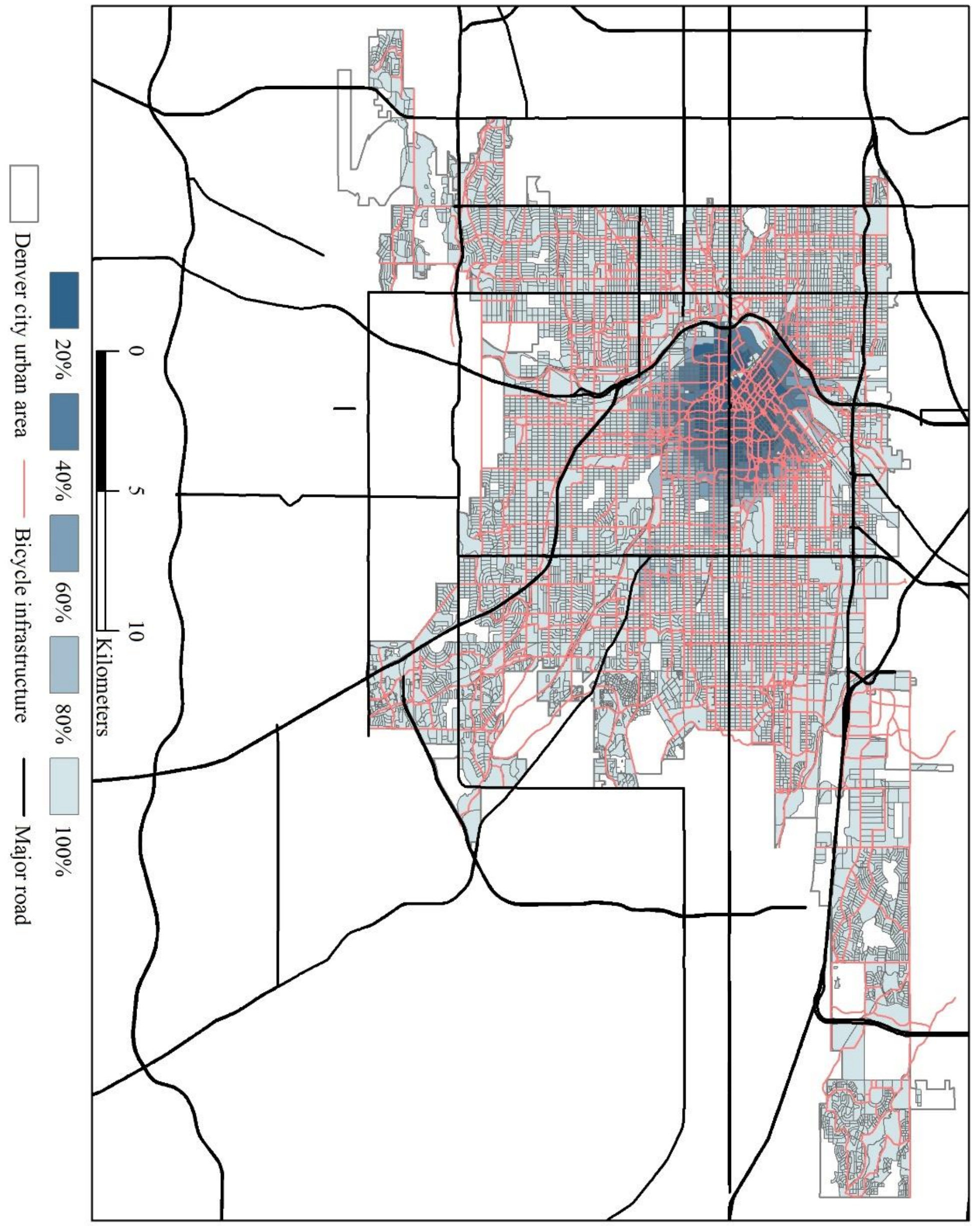

Figure 44. Denver, Colorado 3-kilometer accessibility using all bicycle infrastructure

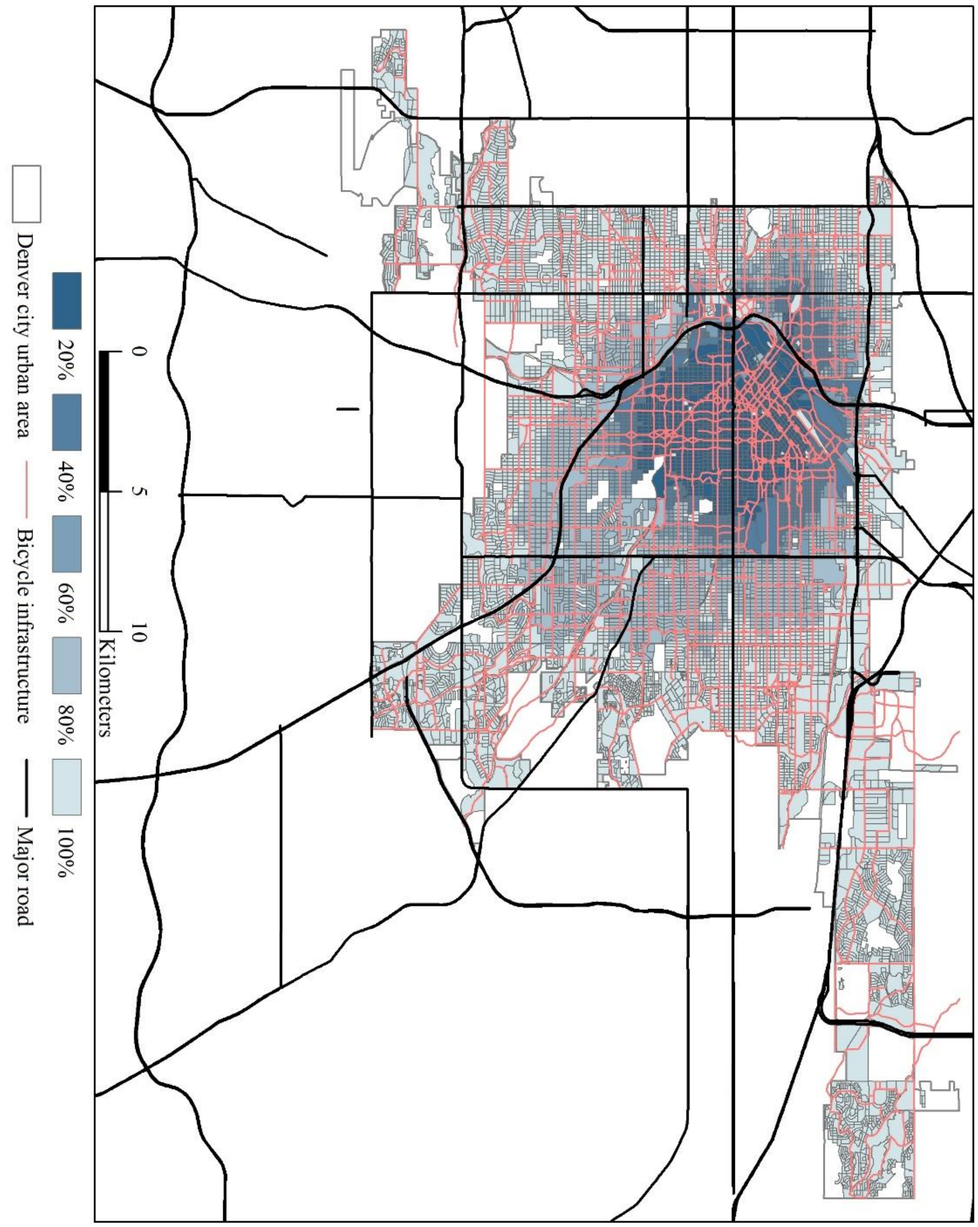

Figure 45. Denver, Colorado 5-kilometer accessibility using all bicycle infrastructure

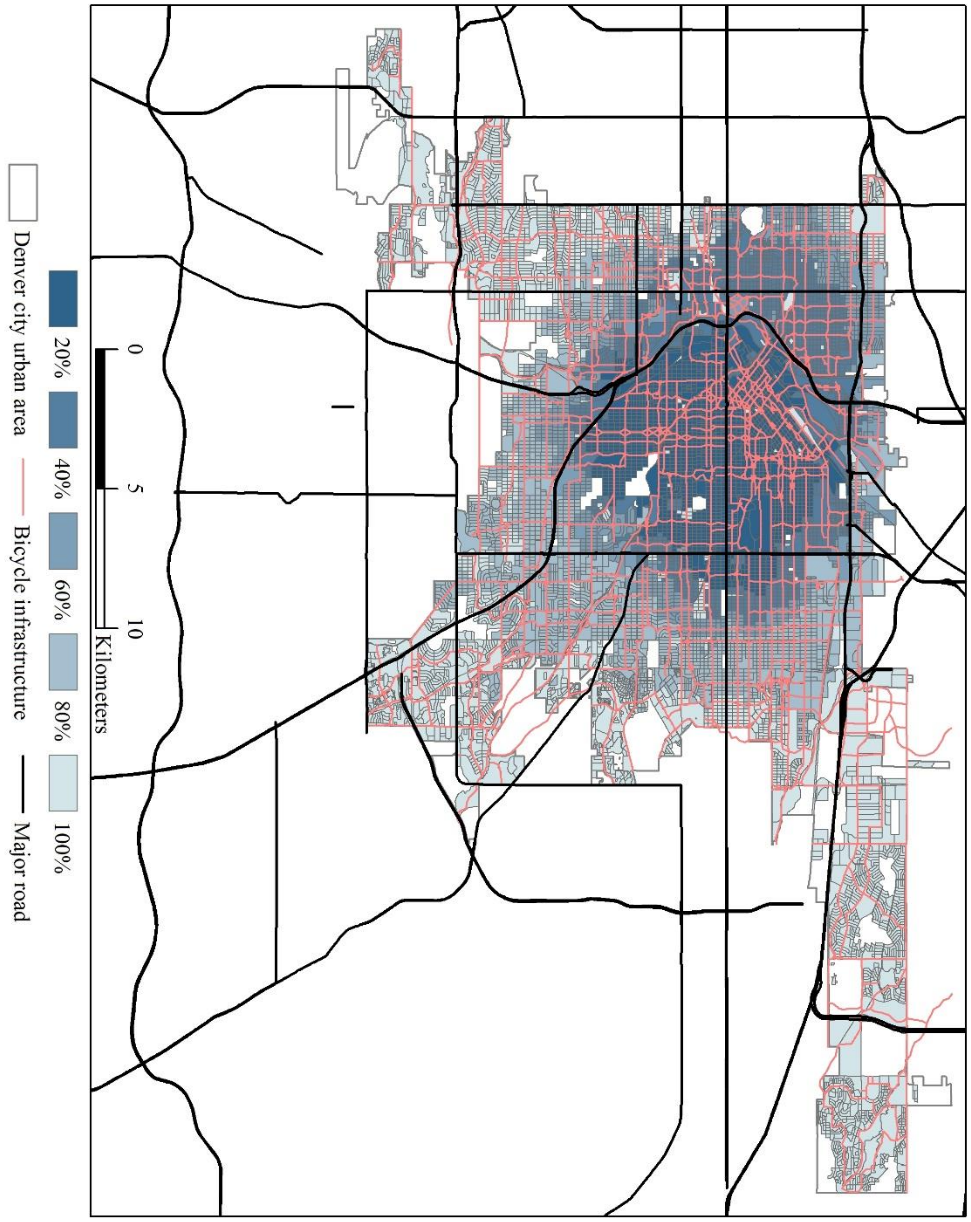

Figure 46. Denver, Colorado 7-kilometer accessibility using all bicycle infrastructure

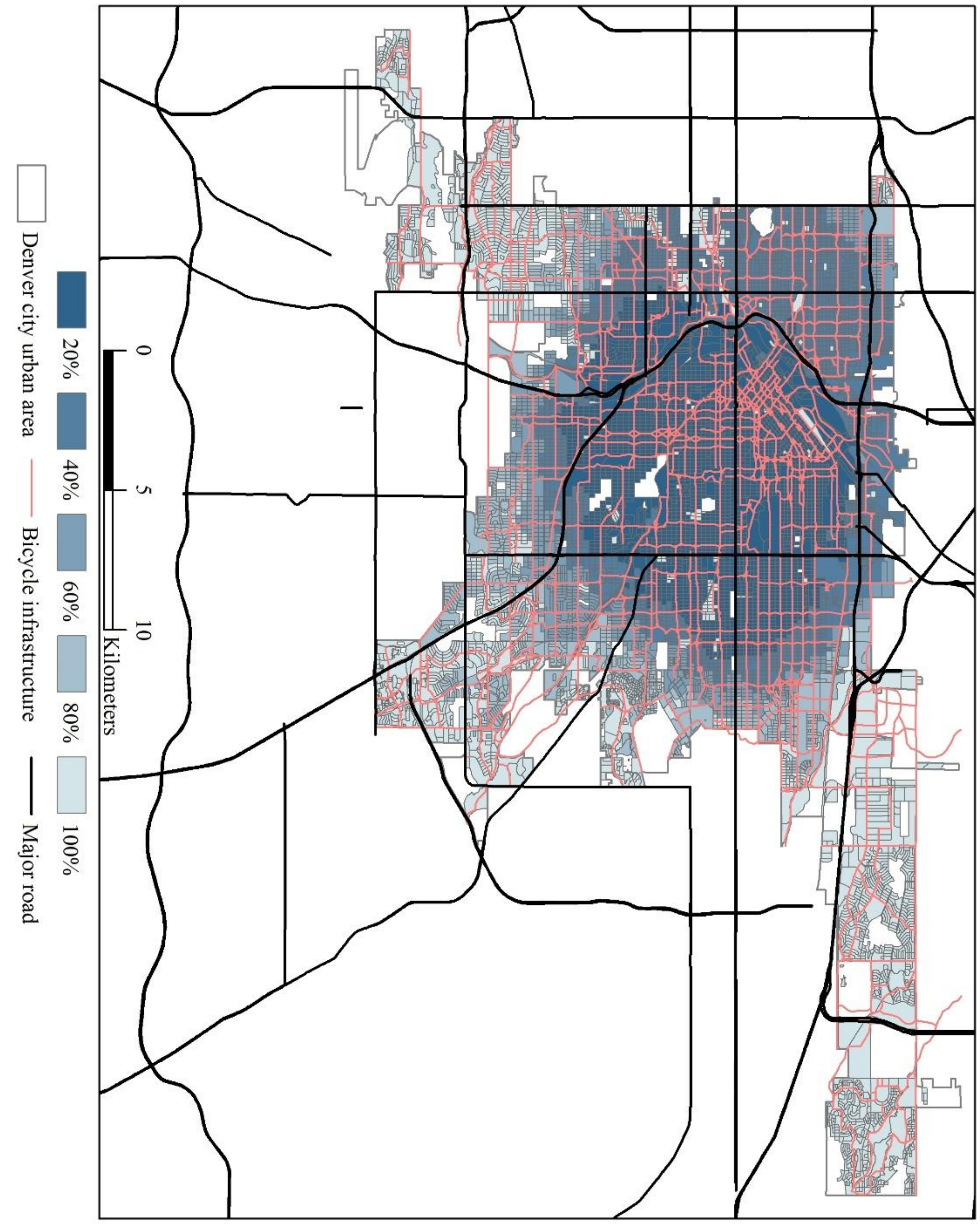

Figure 47. Denver, Colorado 9-kilometer accessibility using all bicycle infrastructure

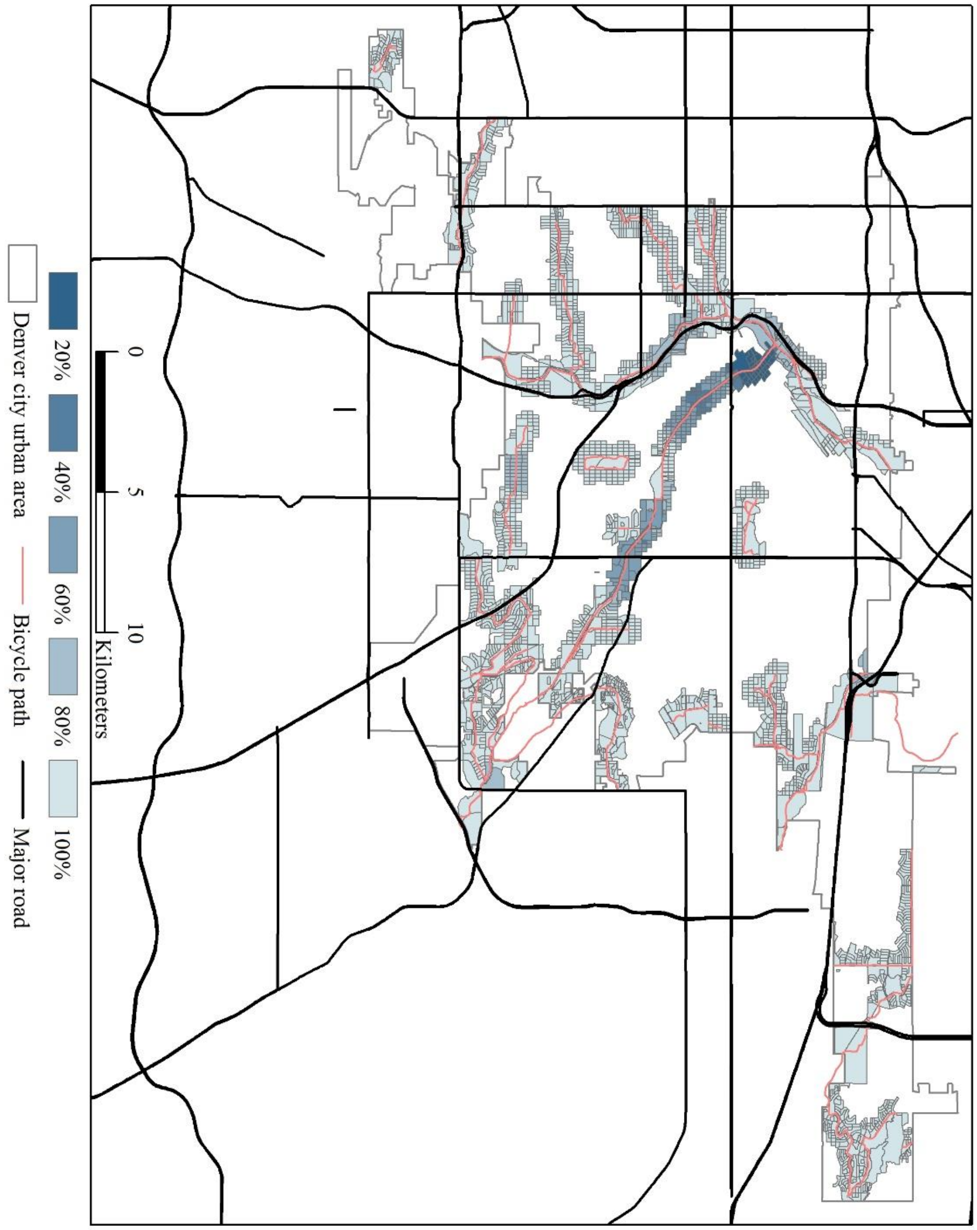

Figure 48. Denver, Colorado 1-kilometer accessibility using bicycle paths

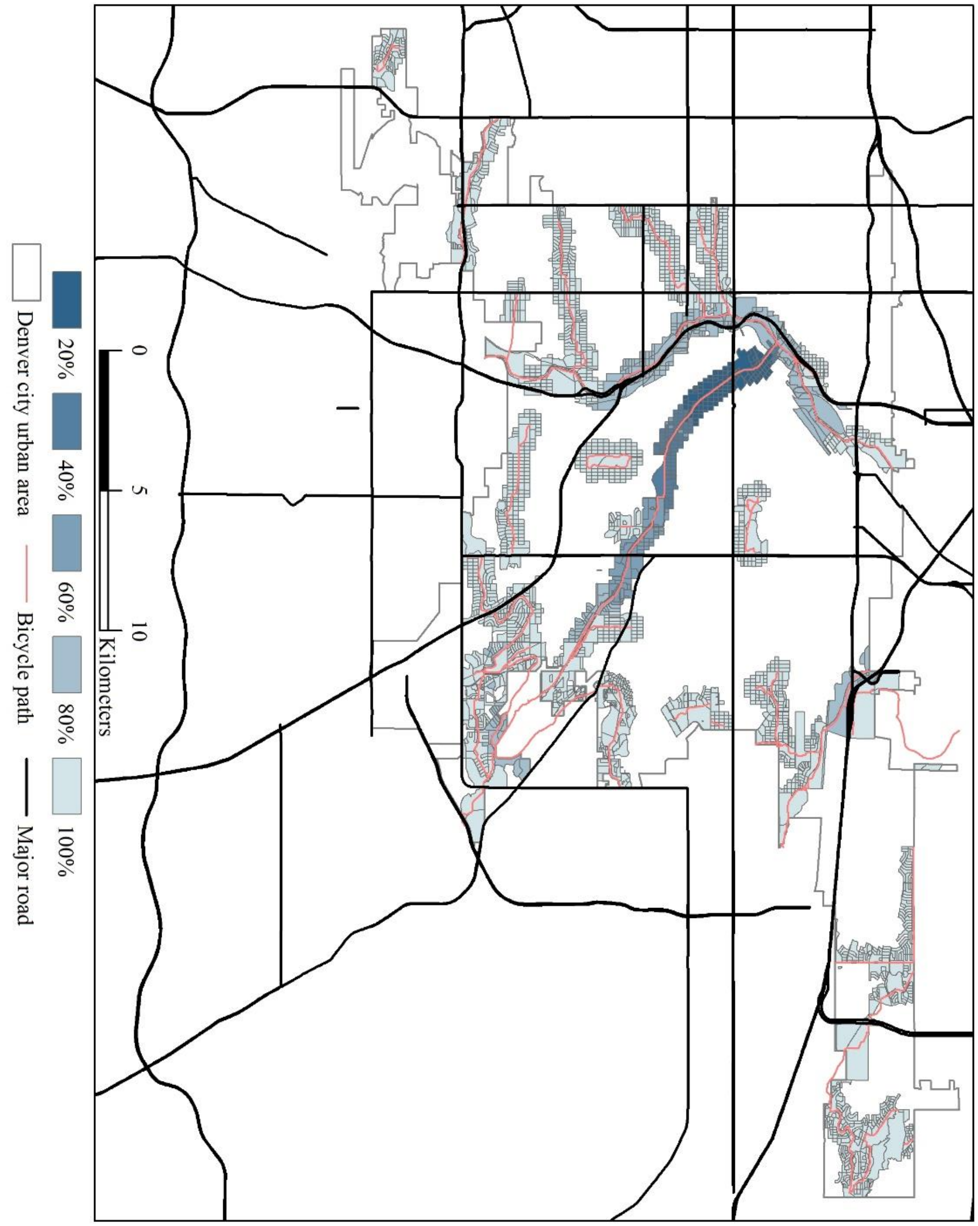

Figure 49. Denver, Colorado 3-kilometer accessibility using bicycle paths

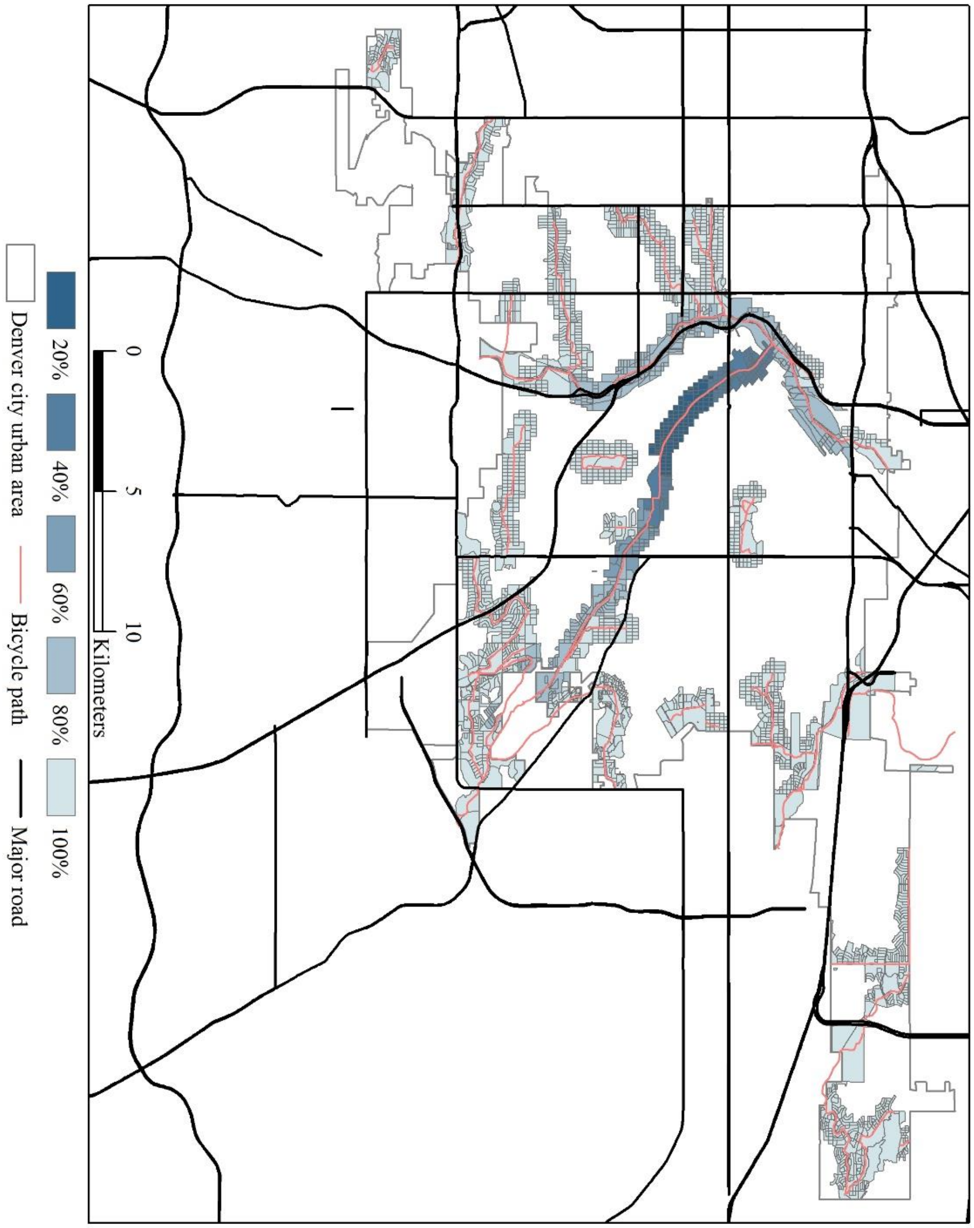

Figure 50. Denver, Colorado 5-kilometer accessibility using bicycle paths

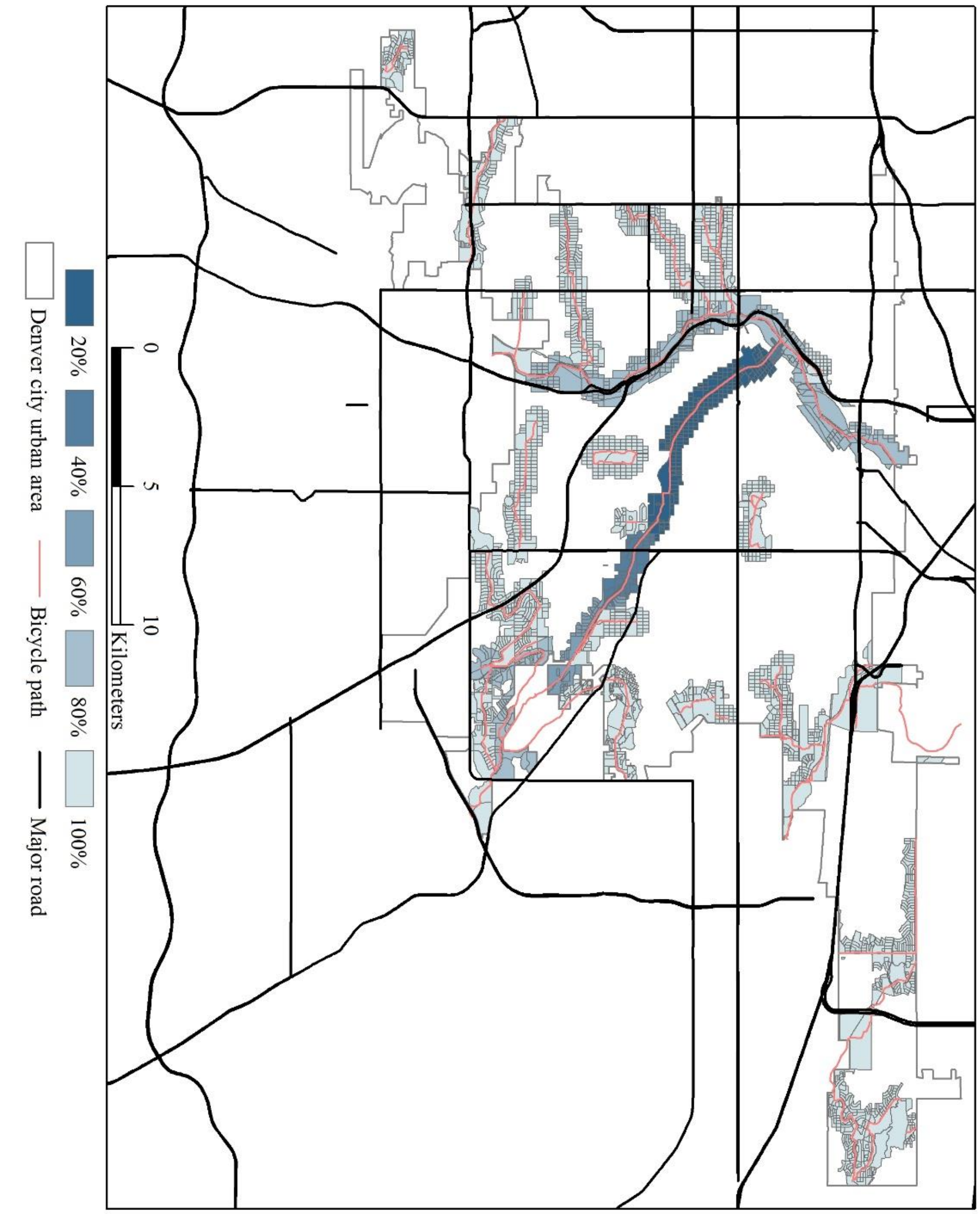

Figure 51. Denver, Colorado 7-kilometer accessibility using bicycle paths

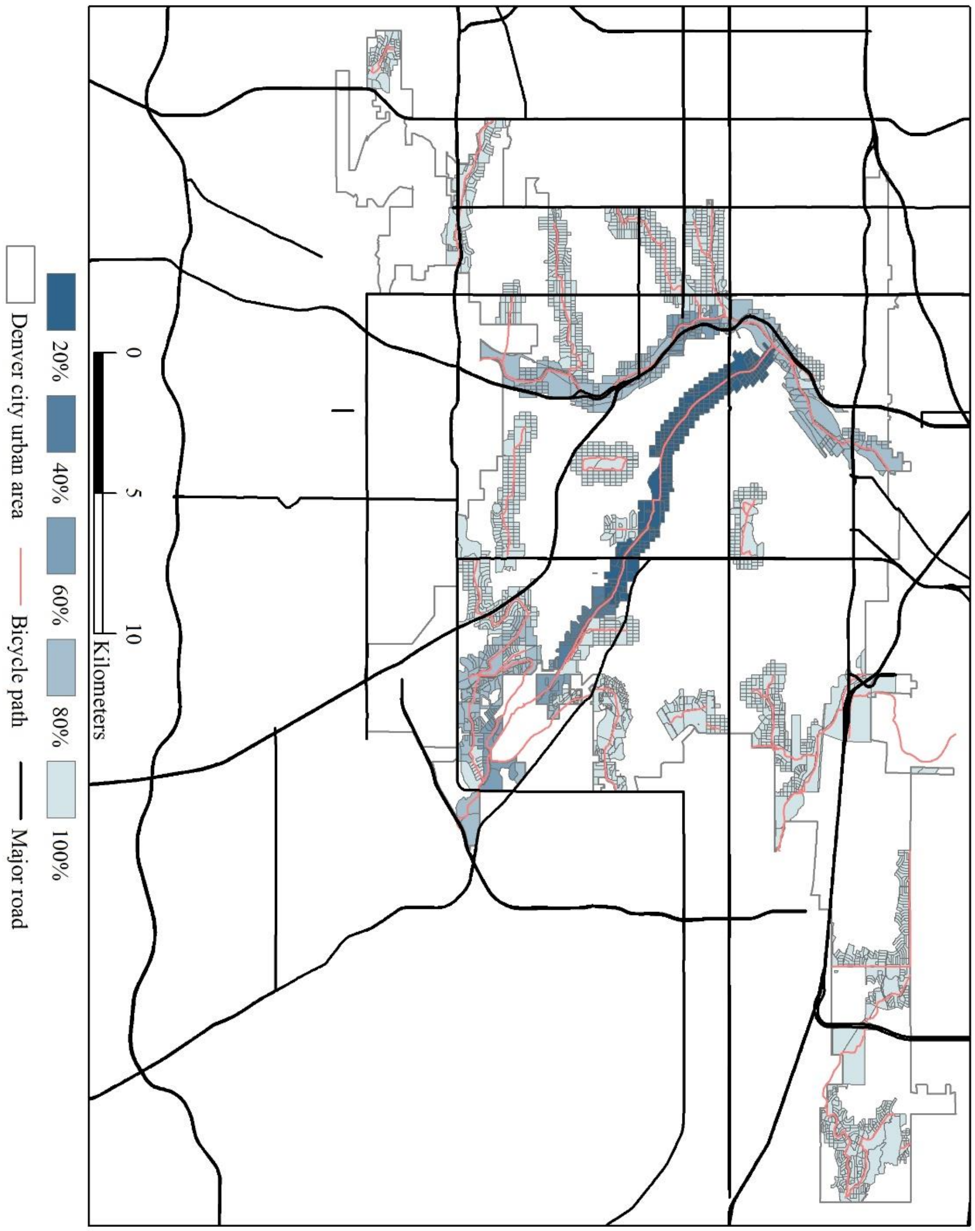

Figure 52. Denver, Colorado 9-kilometer accessibility using bicycle paths

APPENDIX D

Detroit, Michigan City Zonal Accessibility Maps

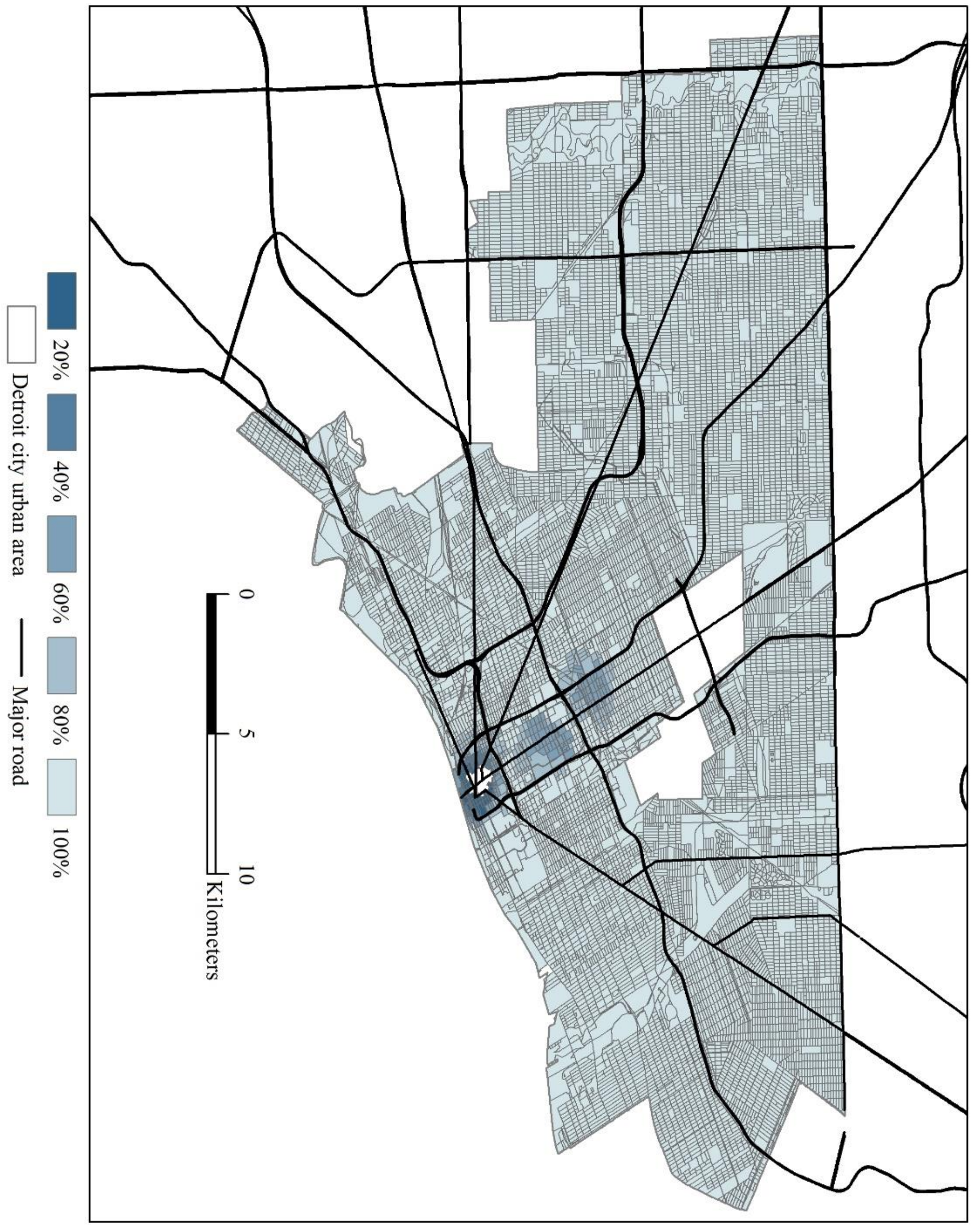

Figure 53. Detroit, Michigan 1-kilometer accessibility using roads

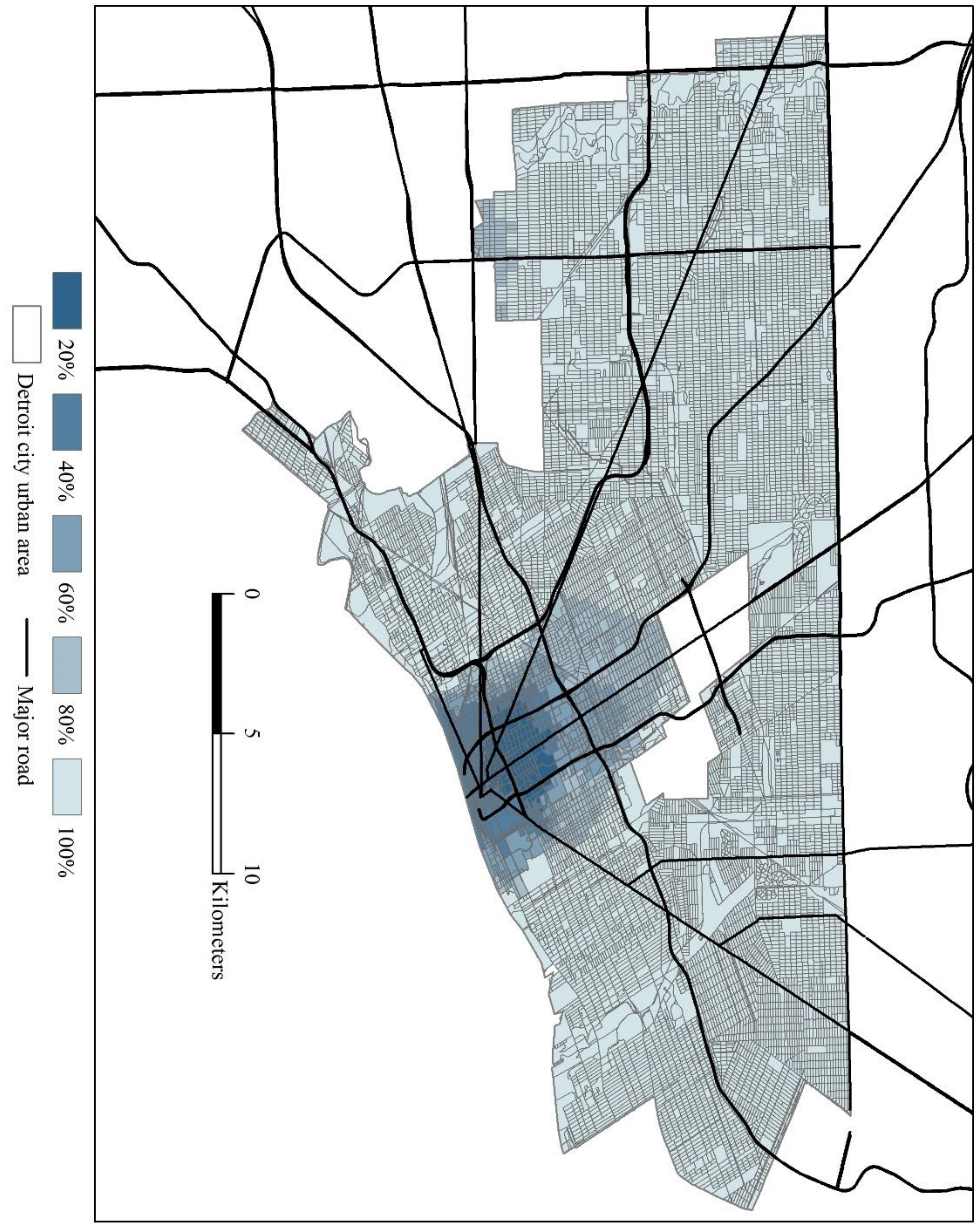

Figure 54. Detroit, Michigan 3-kilometer accessibility using roads

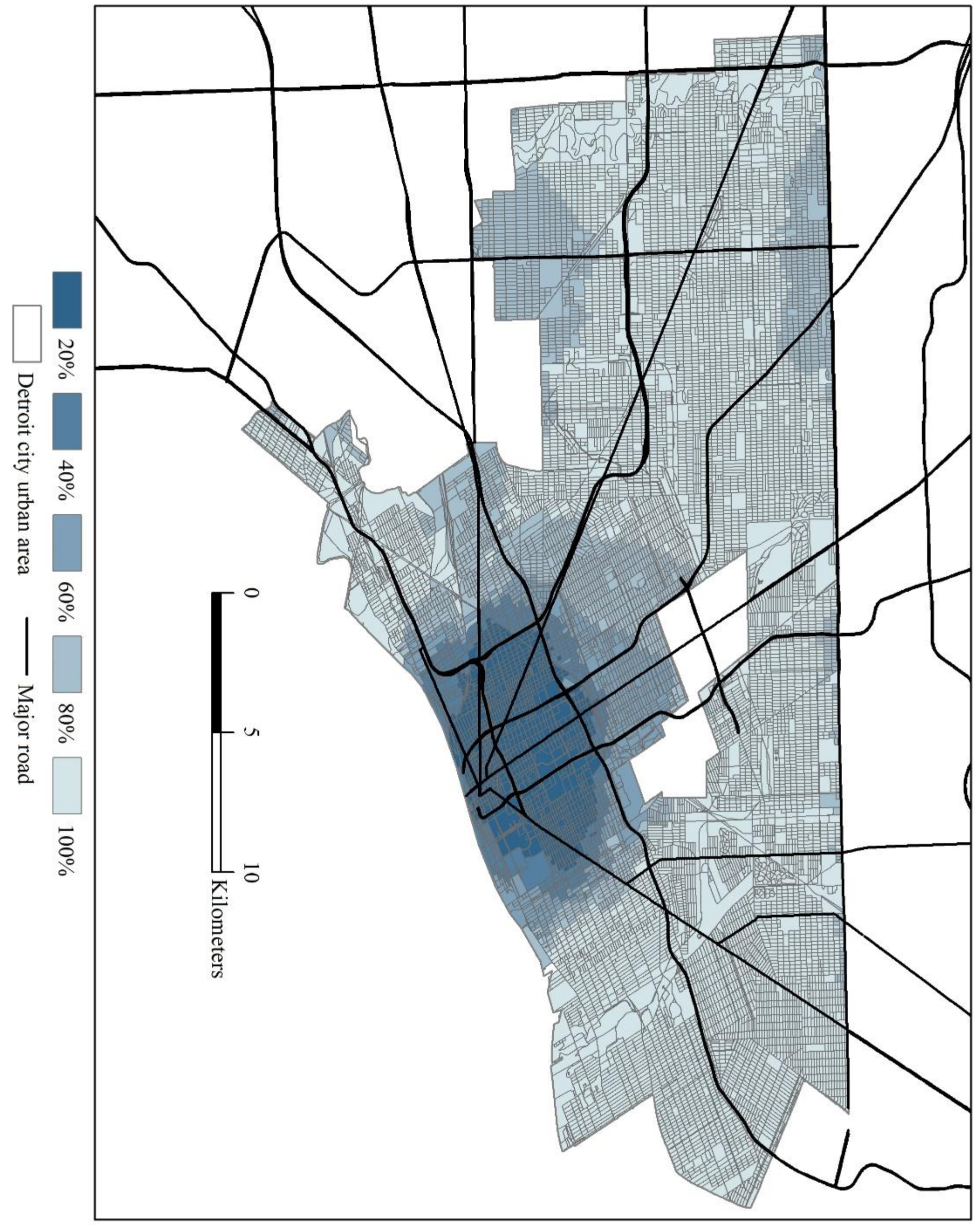

Figure 55. Detroit, Michigan 5-kilometer accessibility using roads

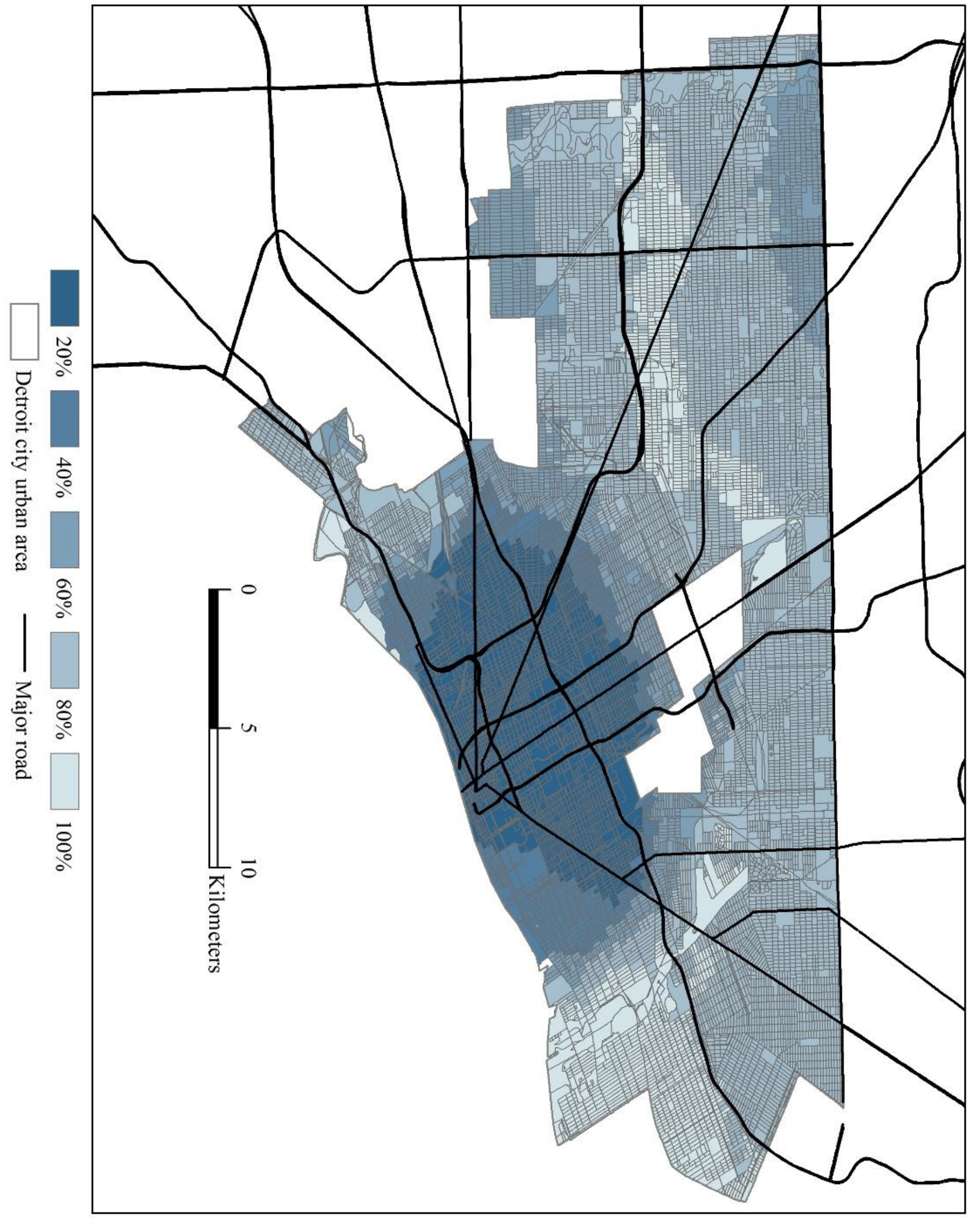

Figure 56. Detroit, Michigan 7-kilometer accessibility using roads

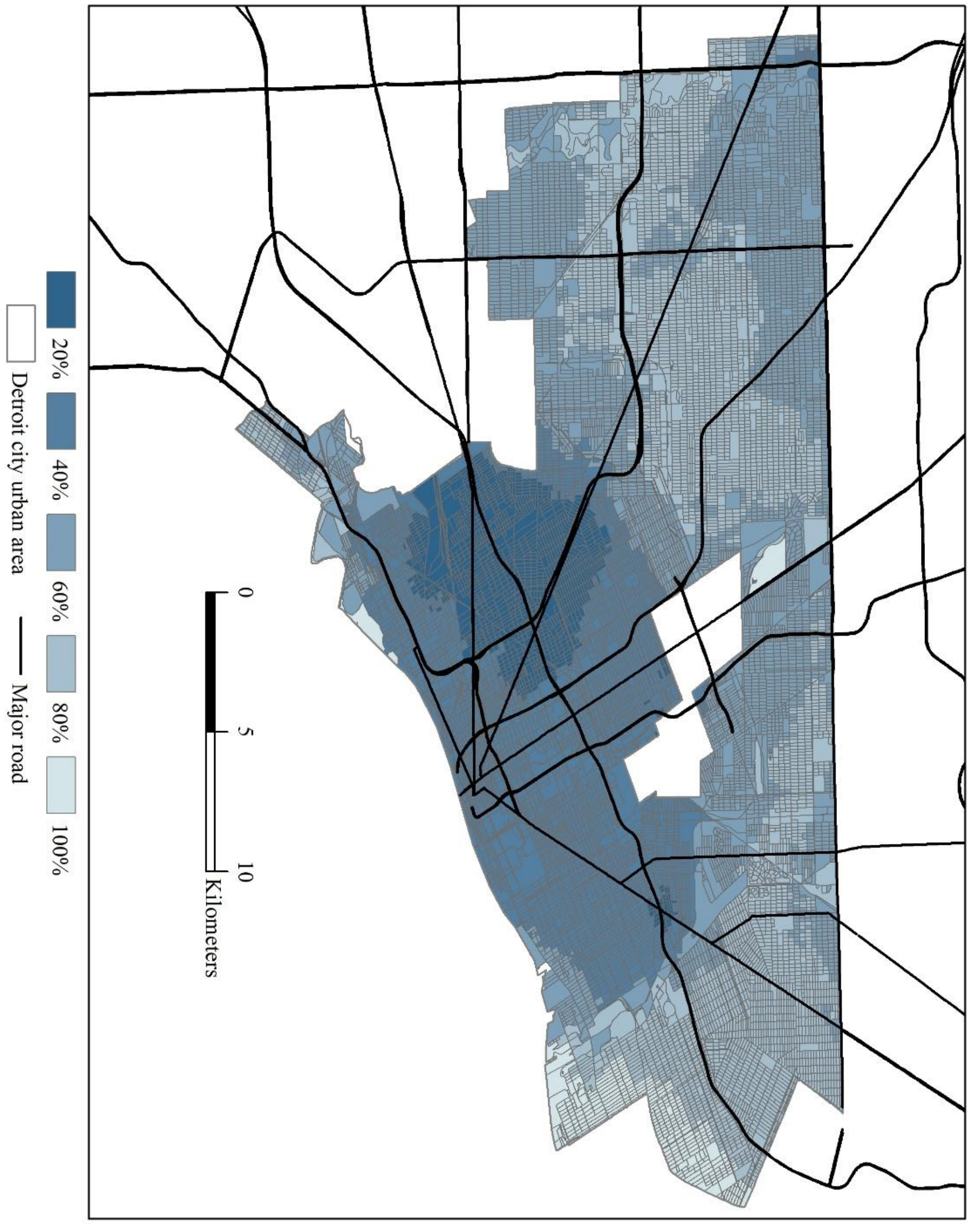

Figure 57. Detroit, Michigan 9-kilometer accessibility using roads

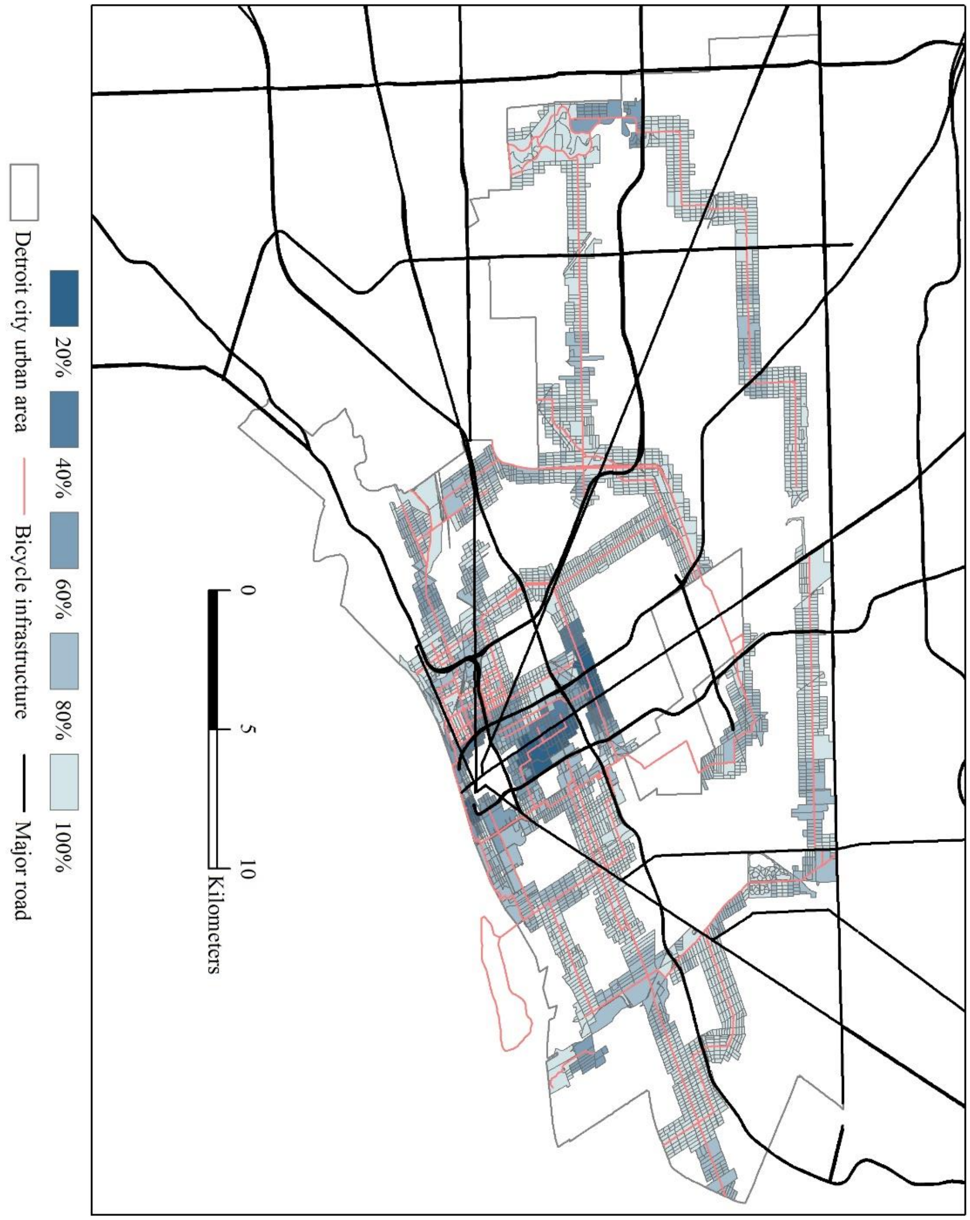

Figure 58. Detroit, Michigan 1-kilometer accessibility using all bicycle infrastructure

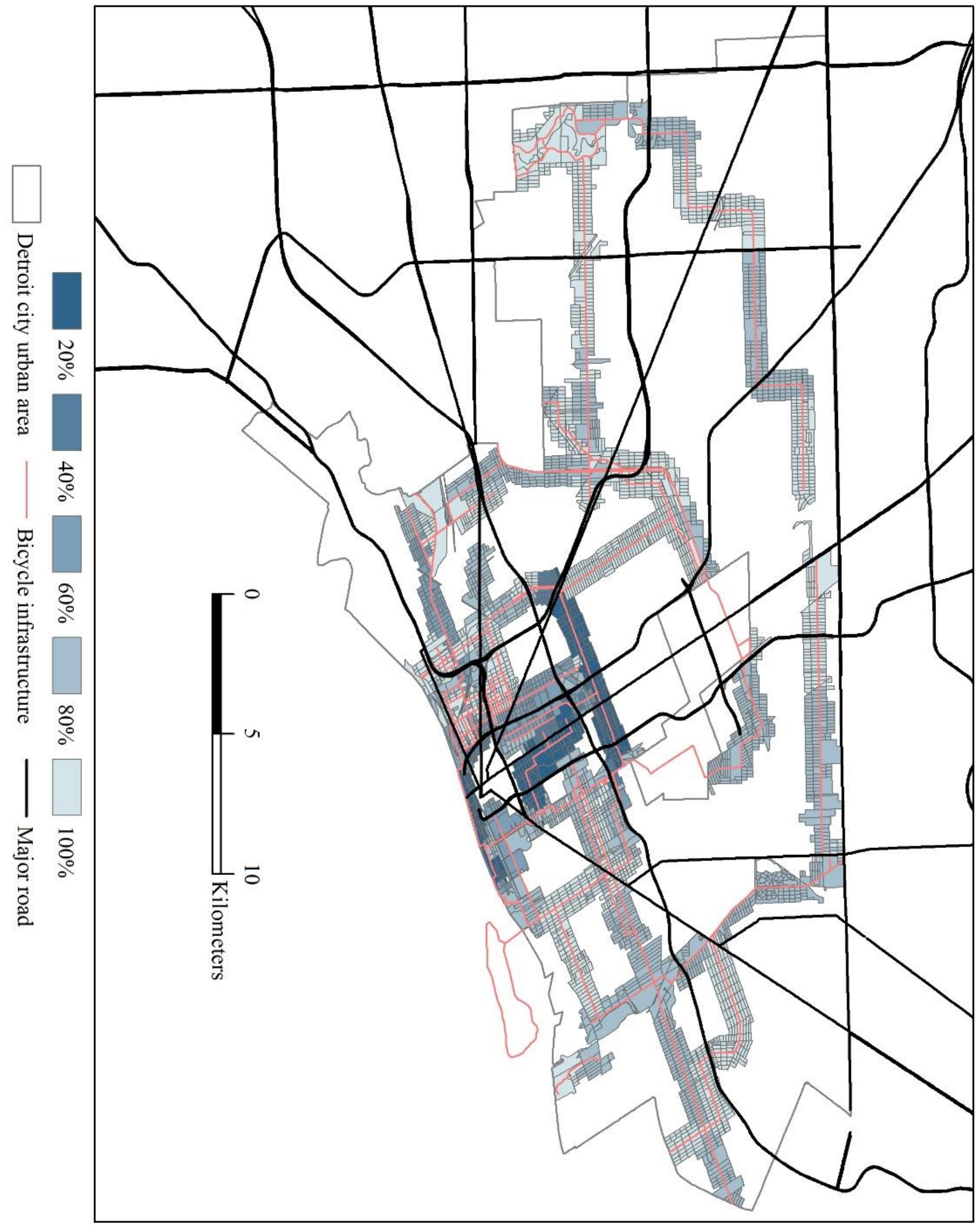

Figure 59. Detroit, Michigan 3-kilometer accessibility using all bicycle infrastructure

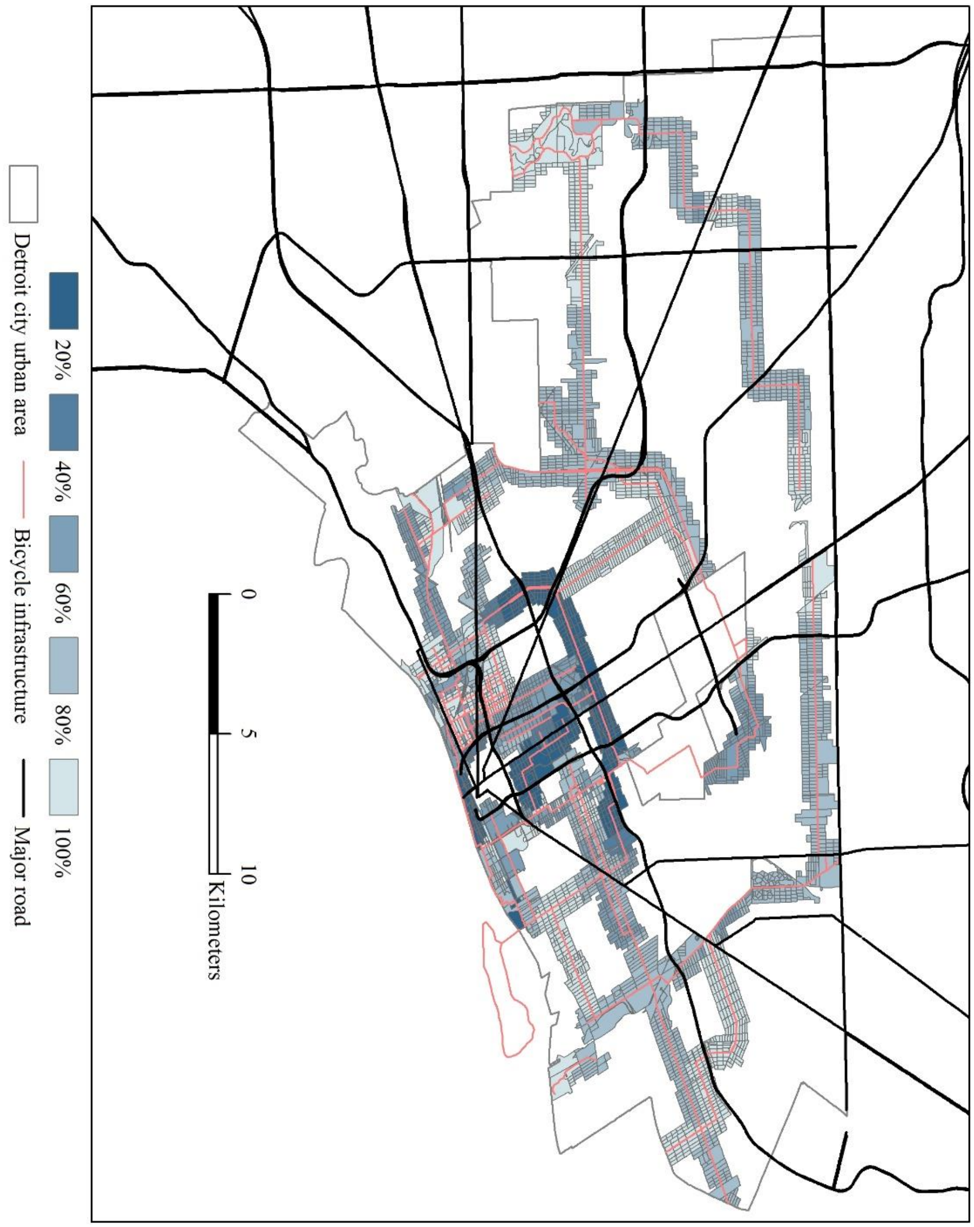

Figure 60. Detroit, Michigan 5-kilometer accessibility using all bicycle infrastructure

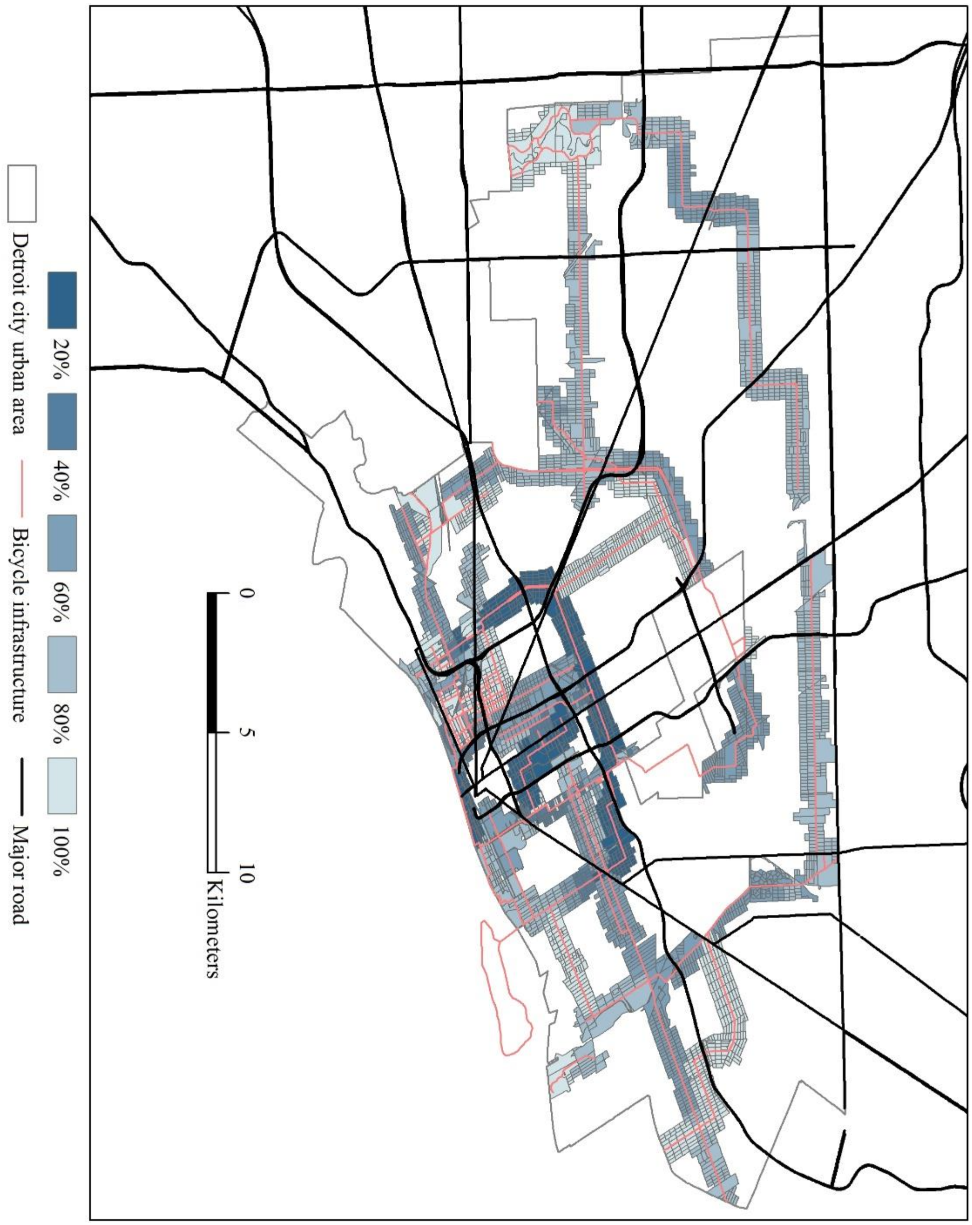

Figure 61. Detroit, Michigan 7-kilometer accessibility using all bicycle infrastructure

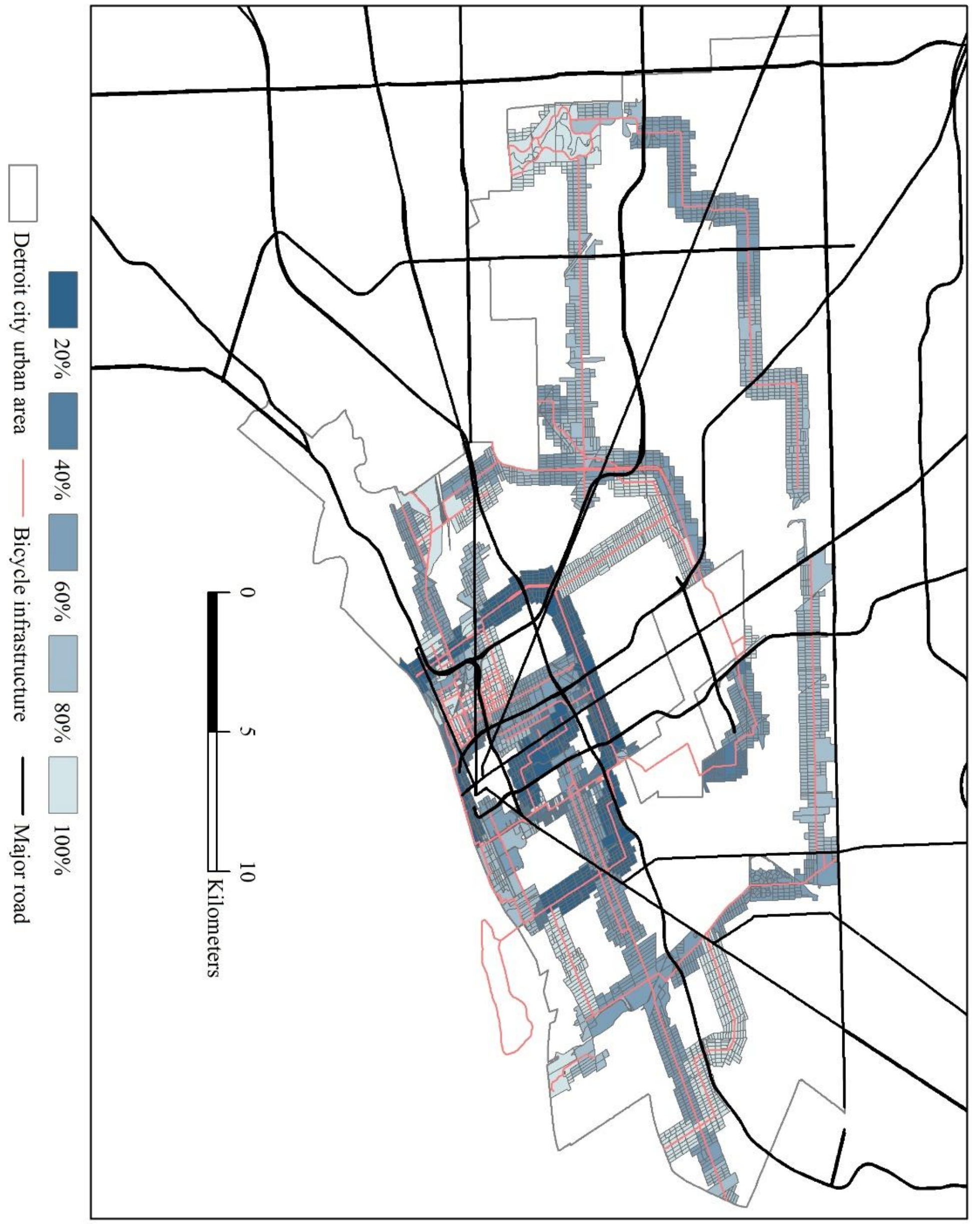

Figure 62. Detroit, Michigan 9-kilometer accessibility using all bicycle infrastructure

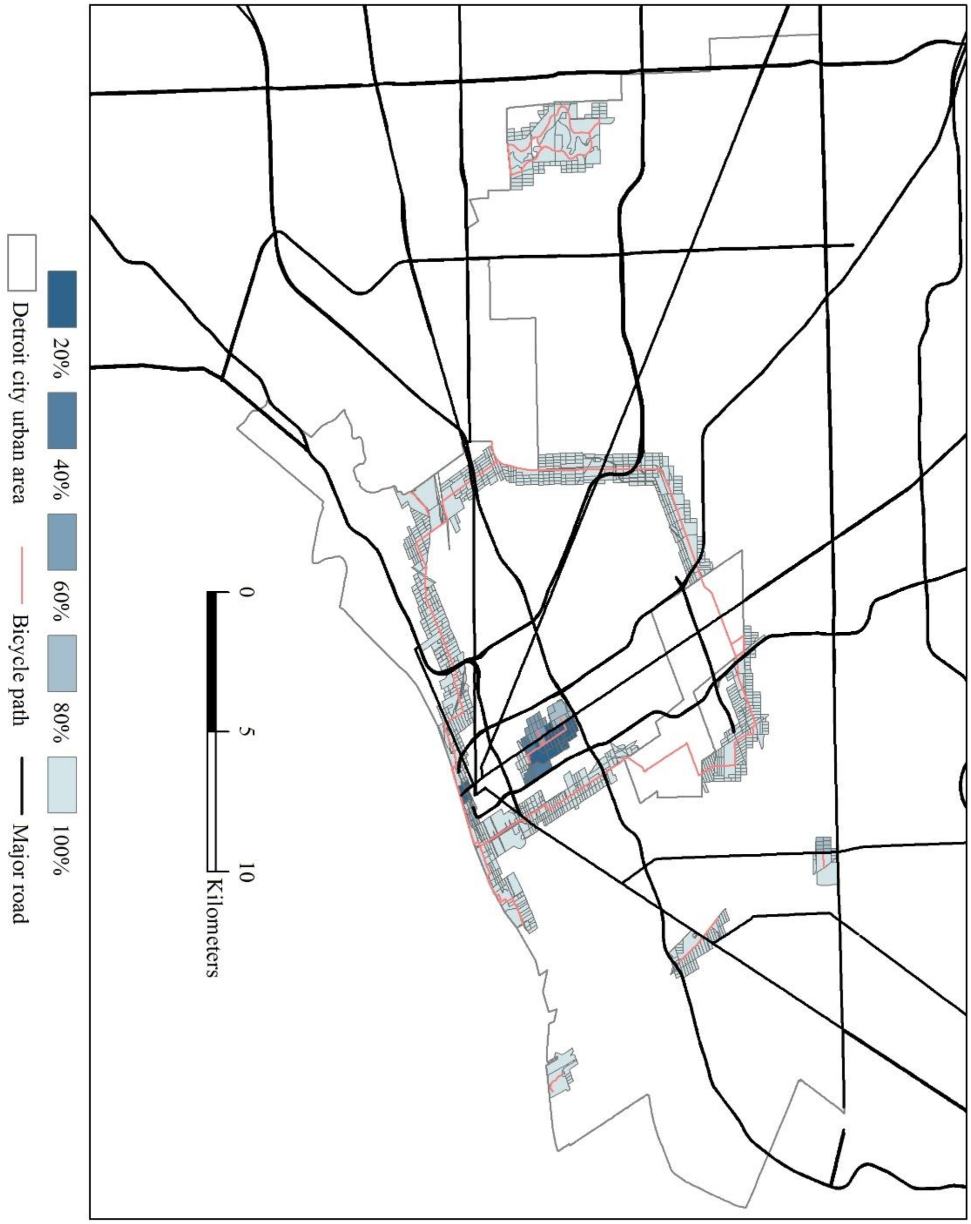

Figure 63. Detroit, Michigan 1-kilometer accessibility using bicycle paths

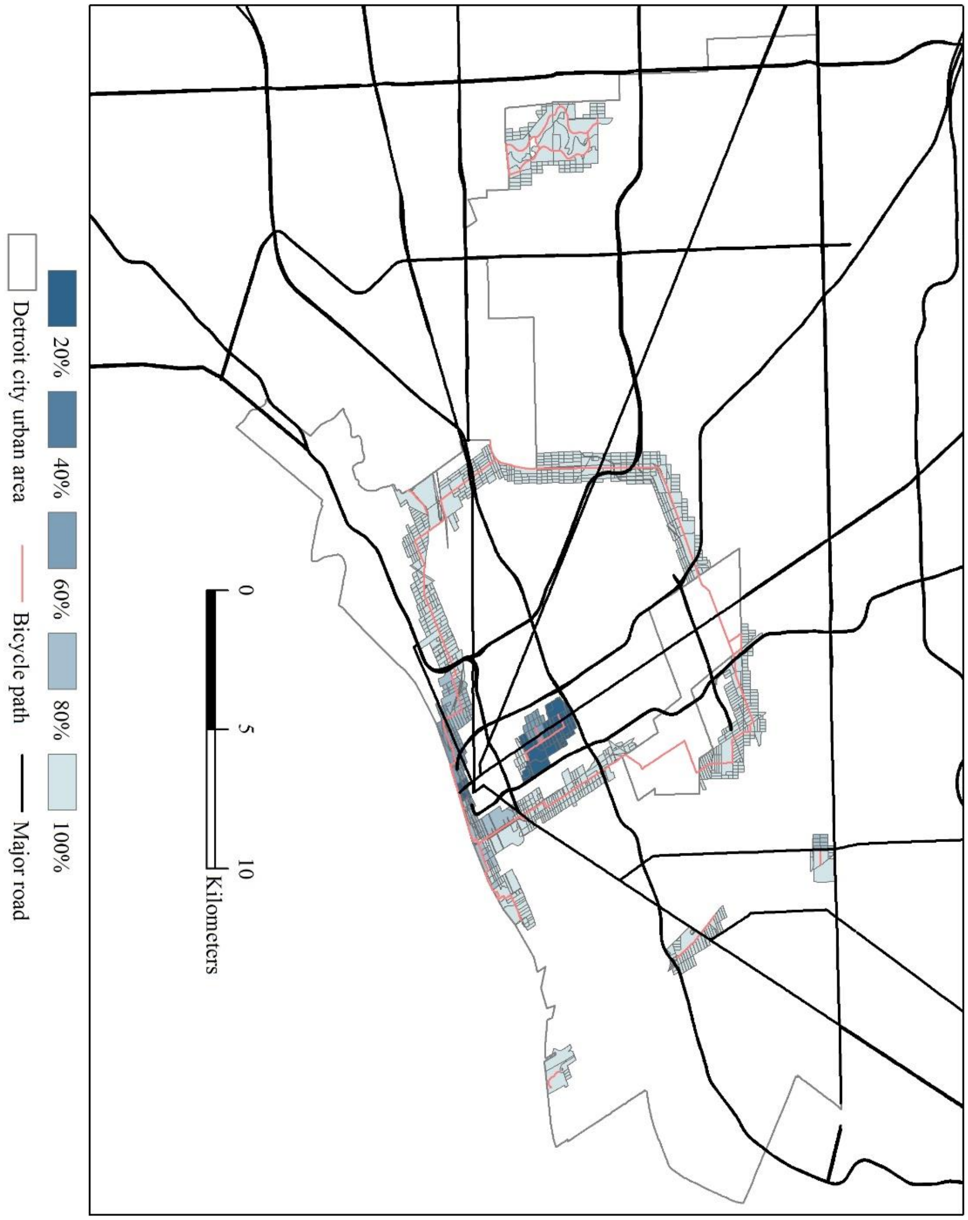

Figure 64. Detroit, Michigan 3-kilometer accessibility using bicycle paths

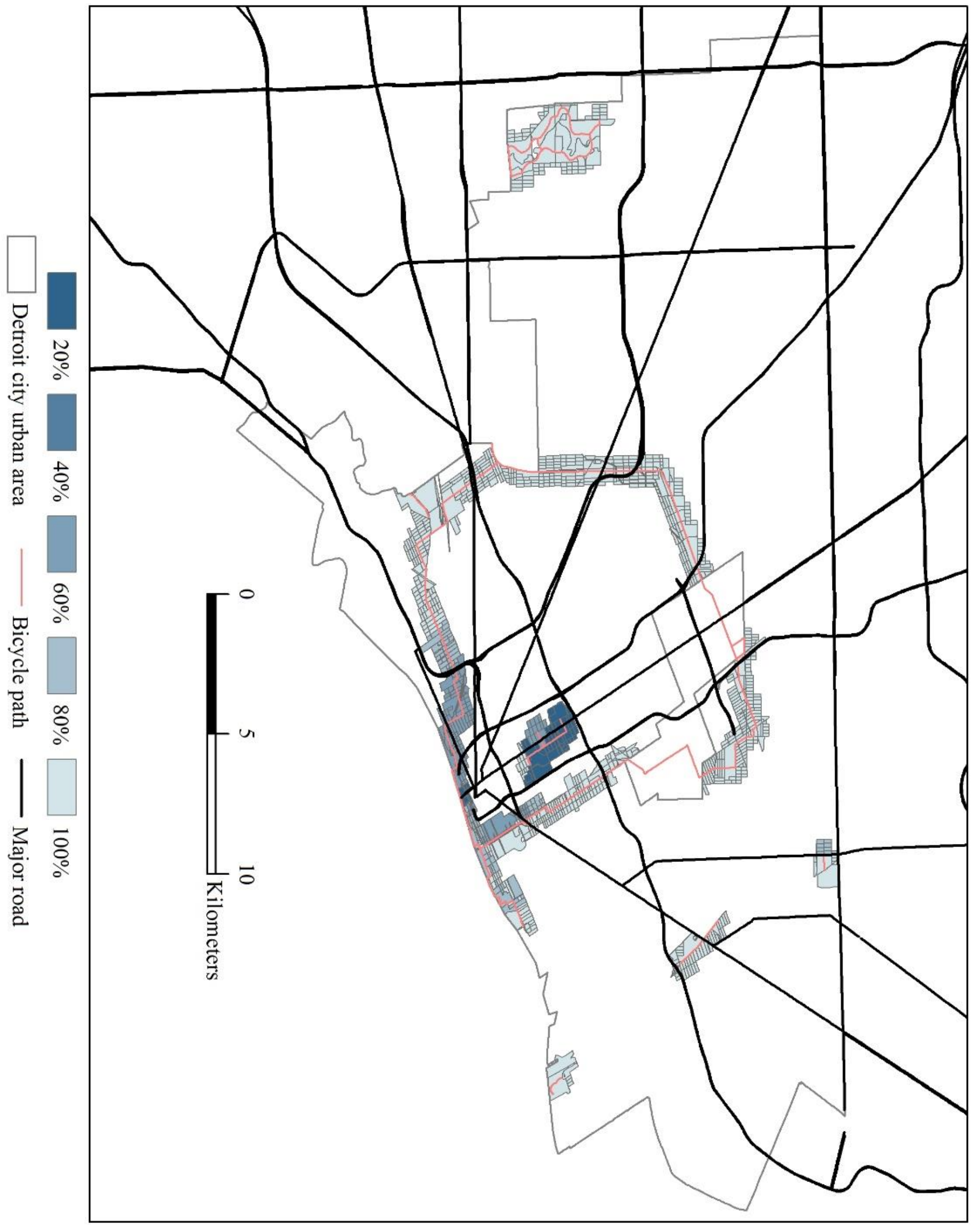

Figure 65. Detroit, Michigan 5-kilometer accessibility using bicycle paths

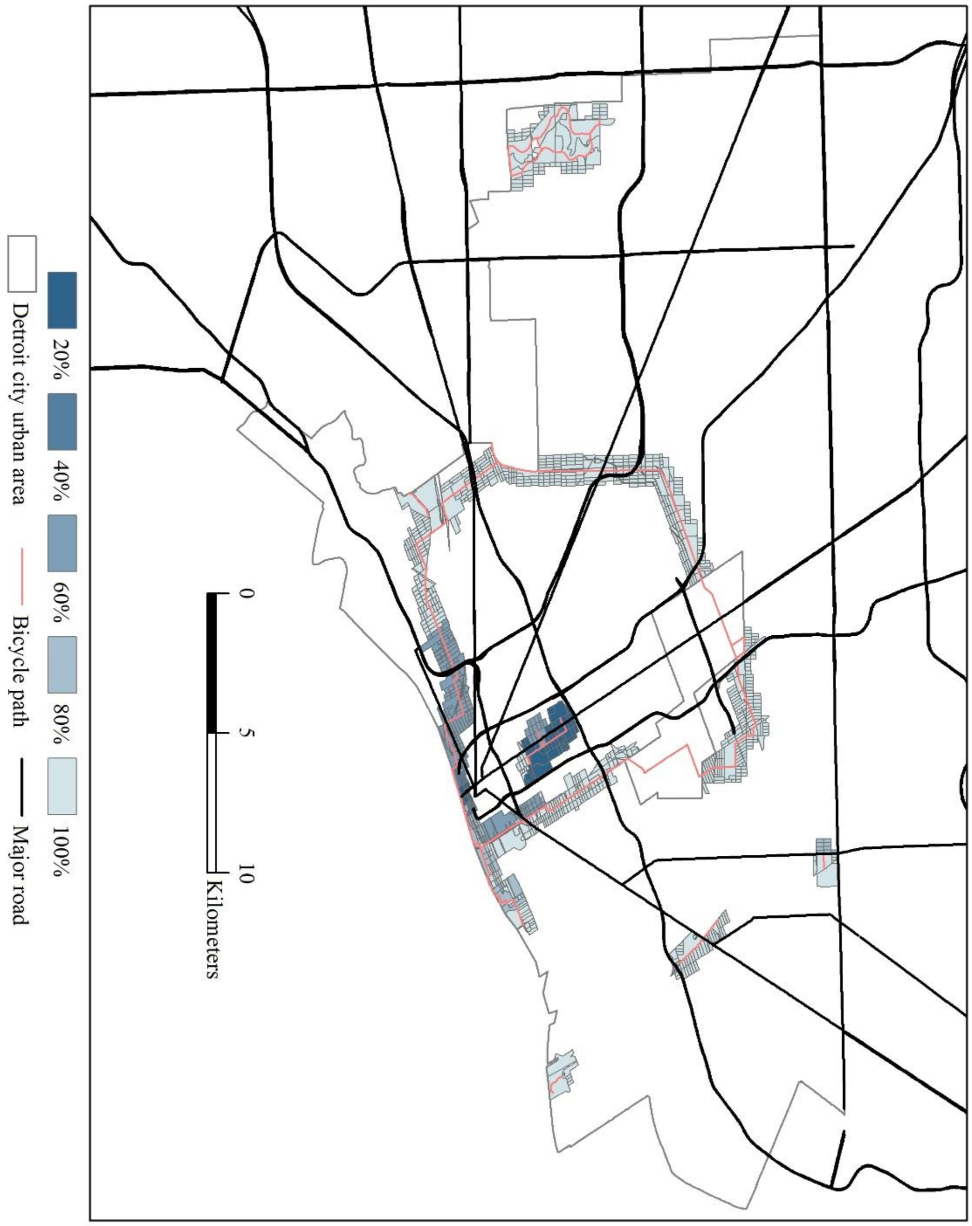

Figure 66. Detroit, Michigan 7-kilometer accessibility using bicycle paths

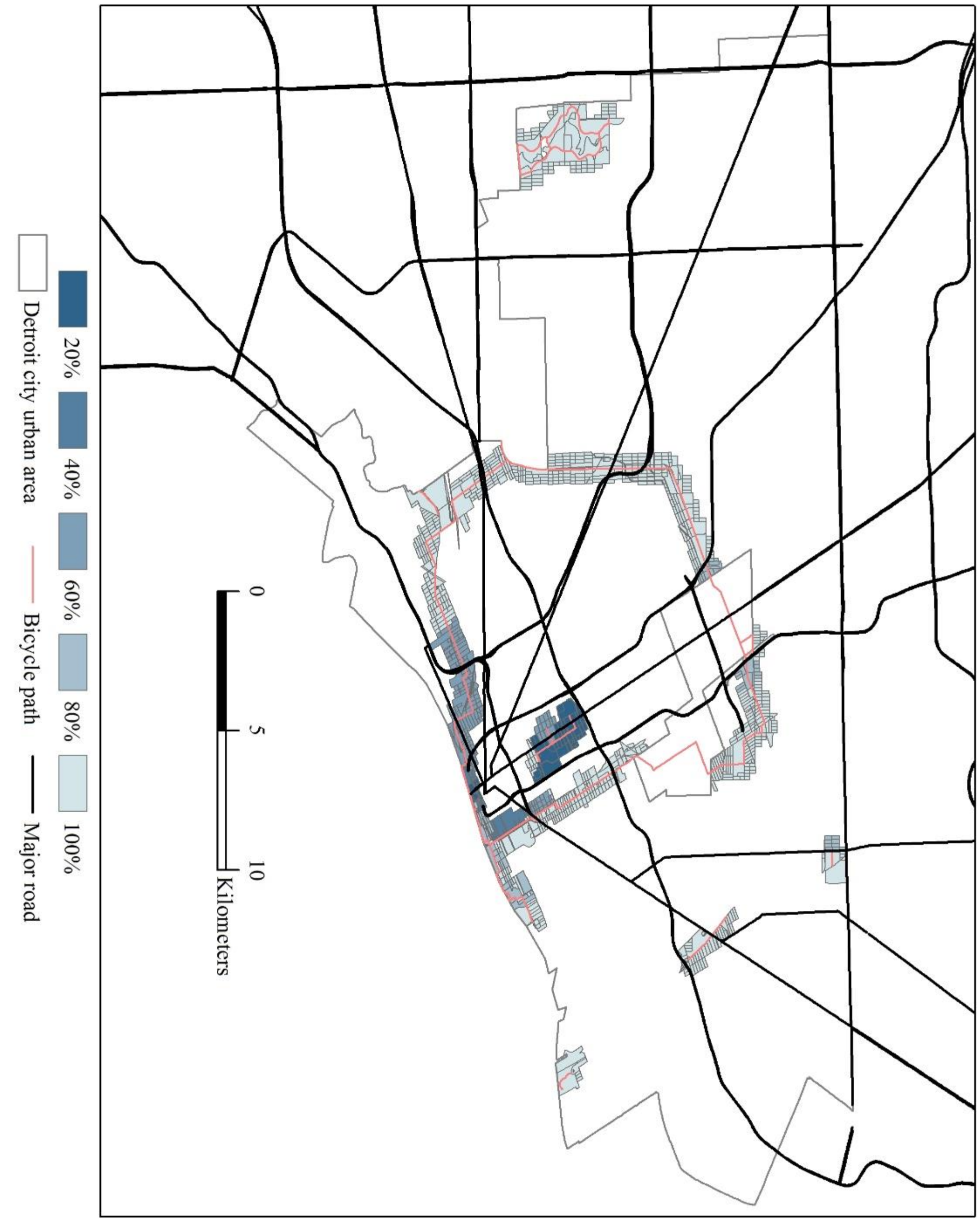

Figure 67. Detroit, Michigan 9-kilometer accessibility using bicycle paths

APPENDIX E

Fort Worth, Texas City Zonal Accessibility Maps

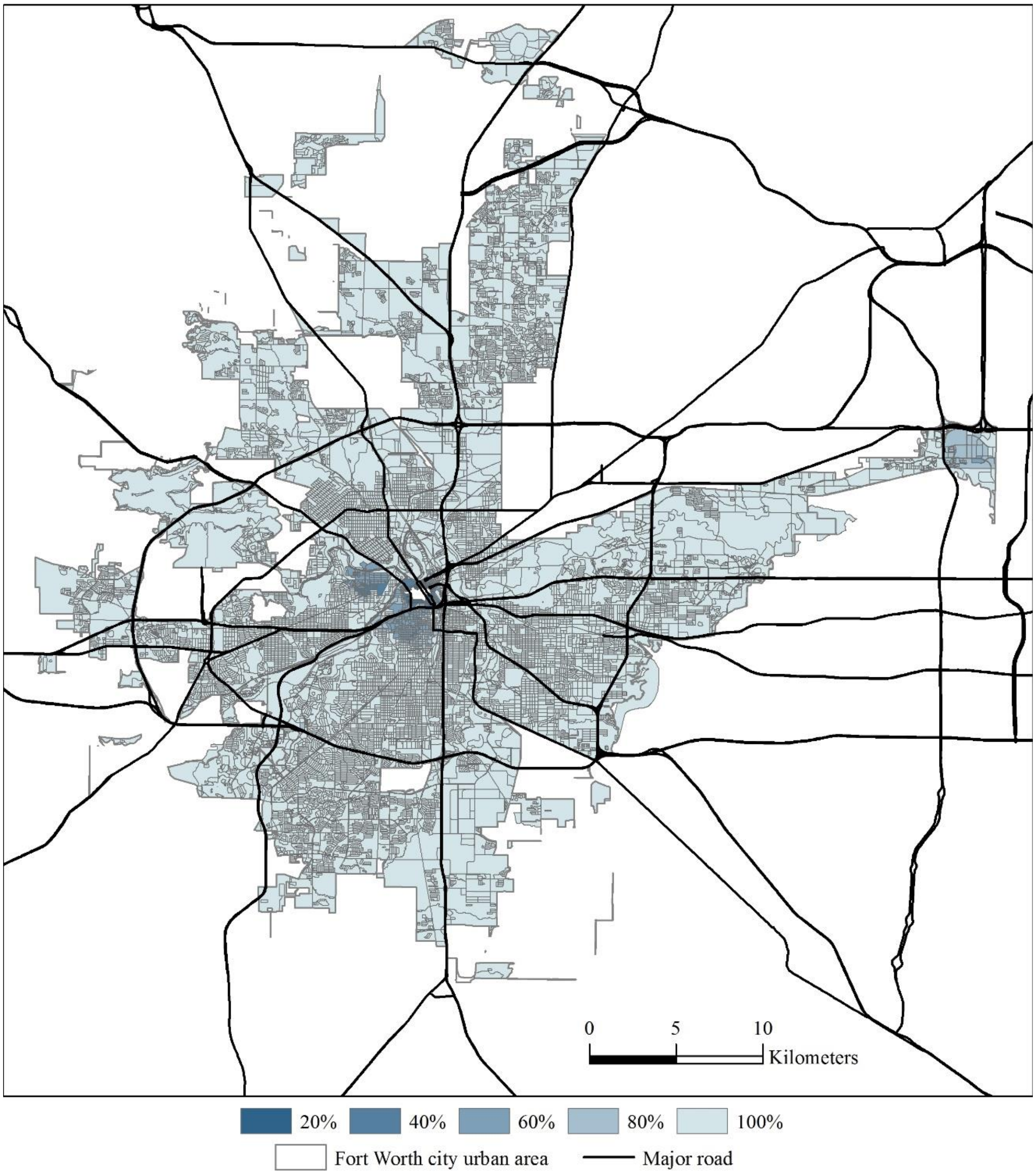

Figure 68. Fort Worth, Texas 1-kilometer accessibility using roads

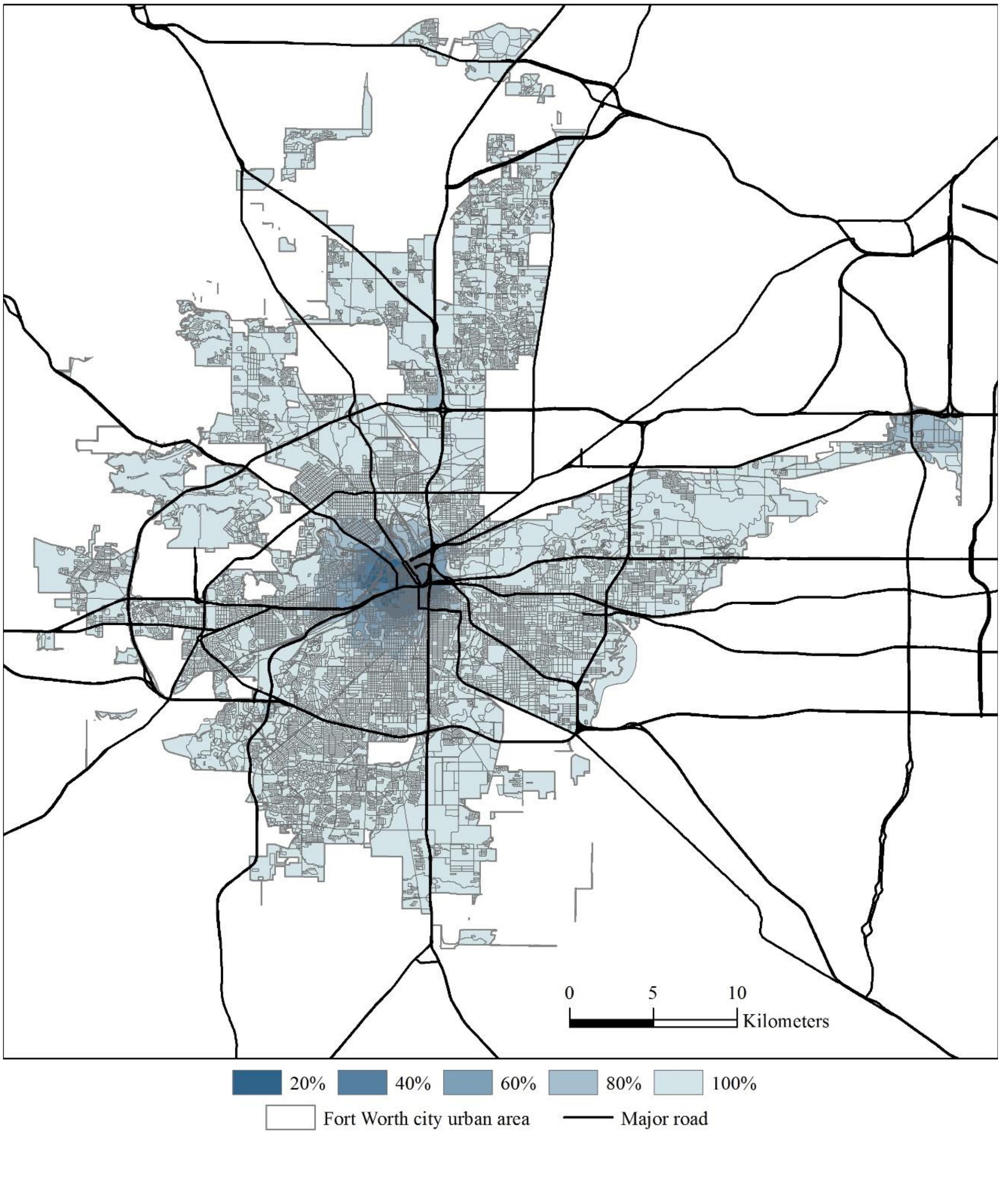

Figure 69. Fort Worth, Texas 3-kilometer accessibility using roads

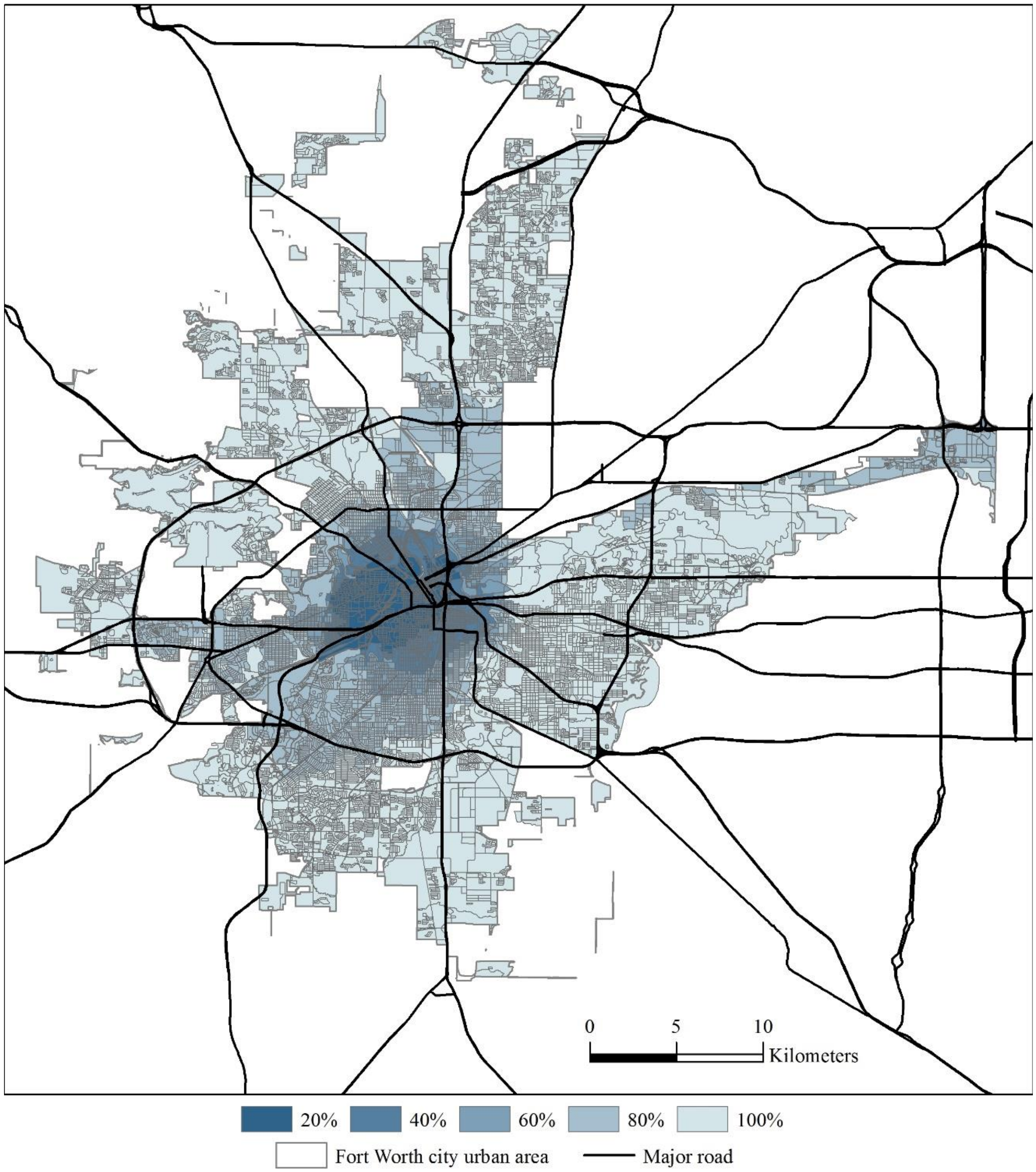

Figure 70. Fort Worth, Texas 5-kilometer accessibility using roads

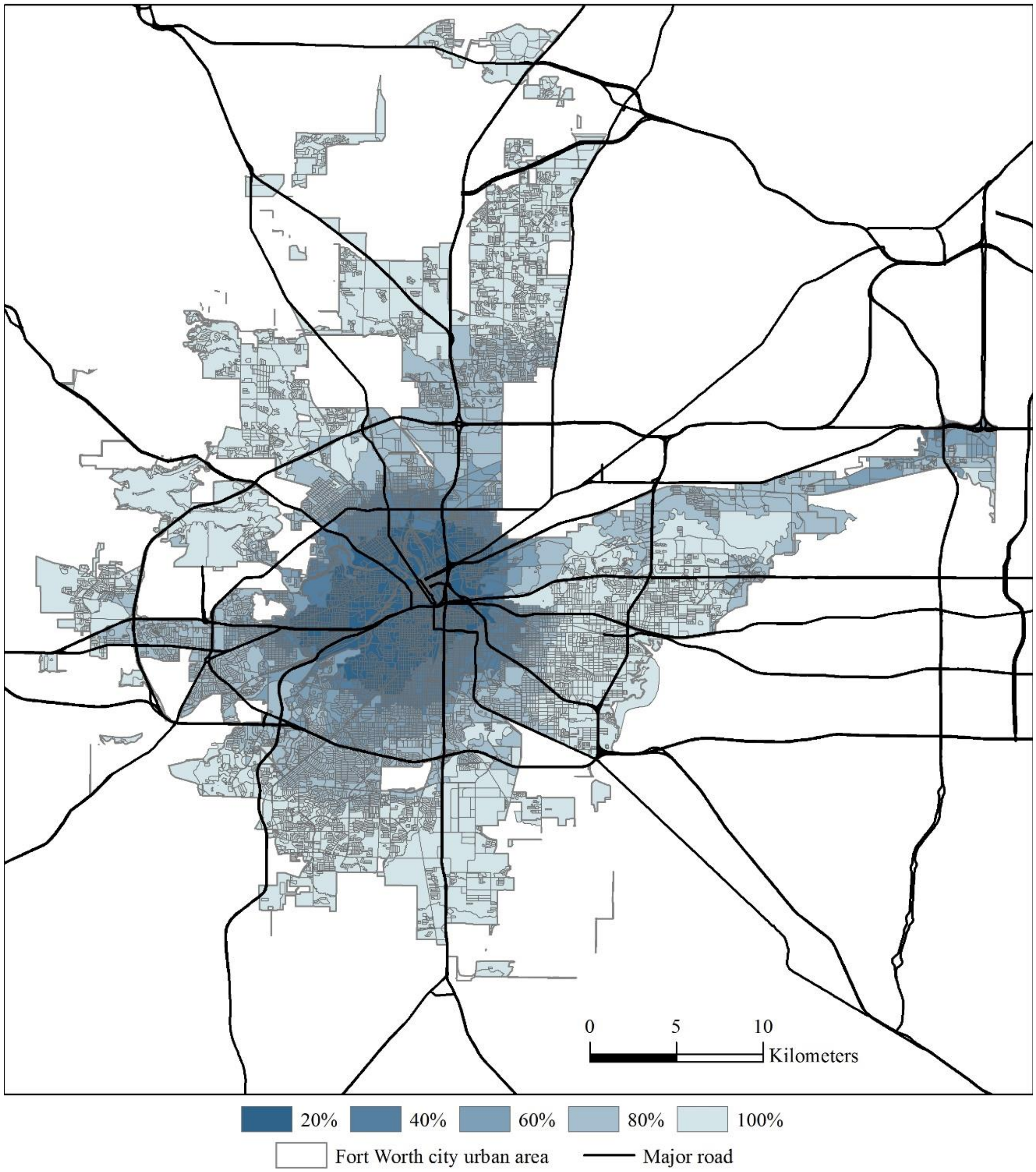

Figure 71. Fort Worth, Texas 7-kilometer accessibility using roads

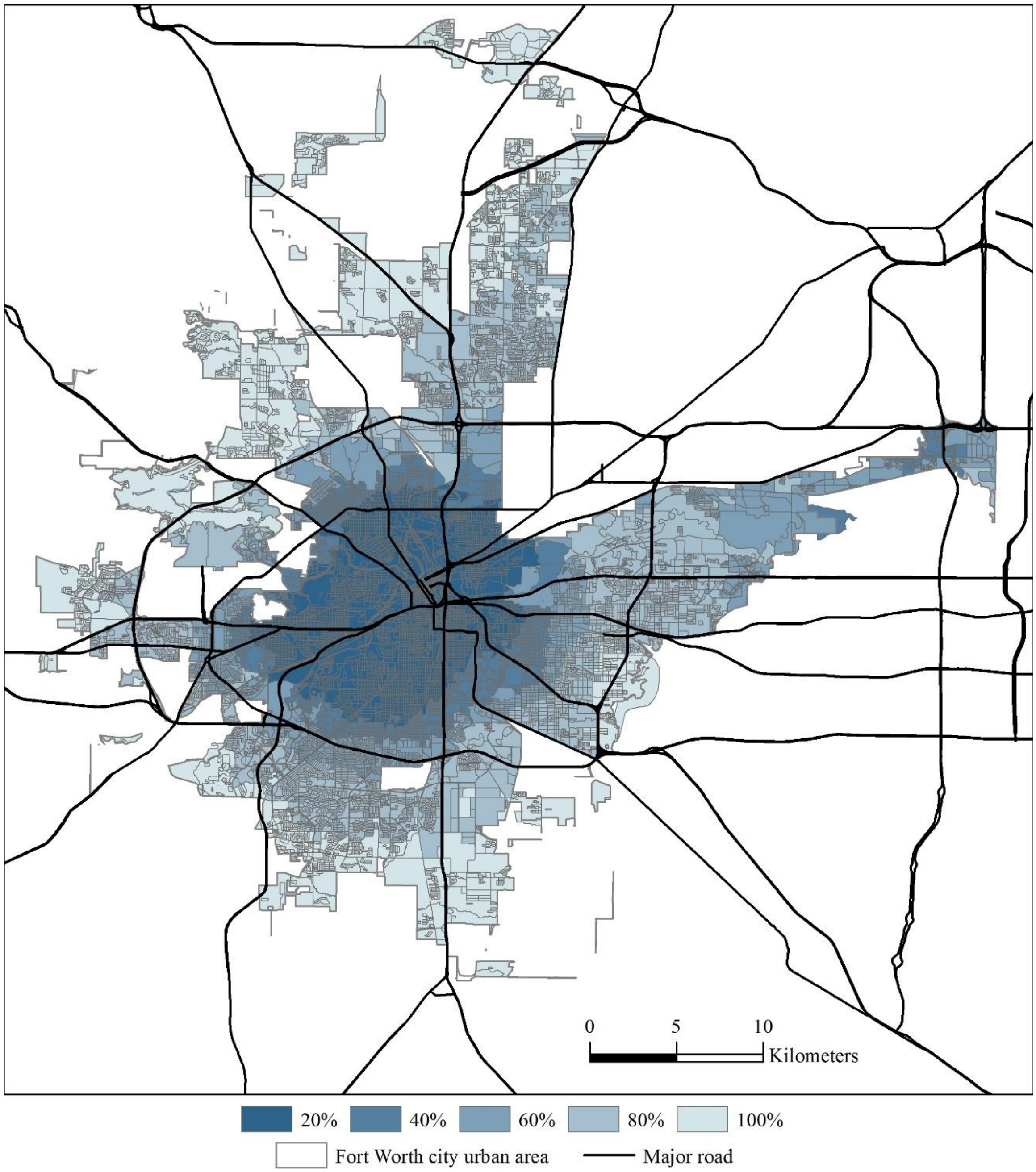

Figure 72. Fort Worth, Texas 9-kilometer accessibility using roads

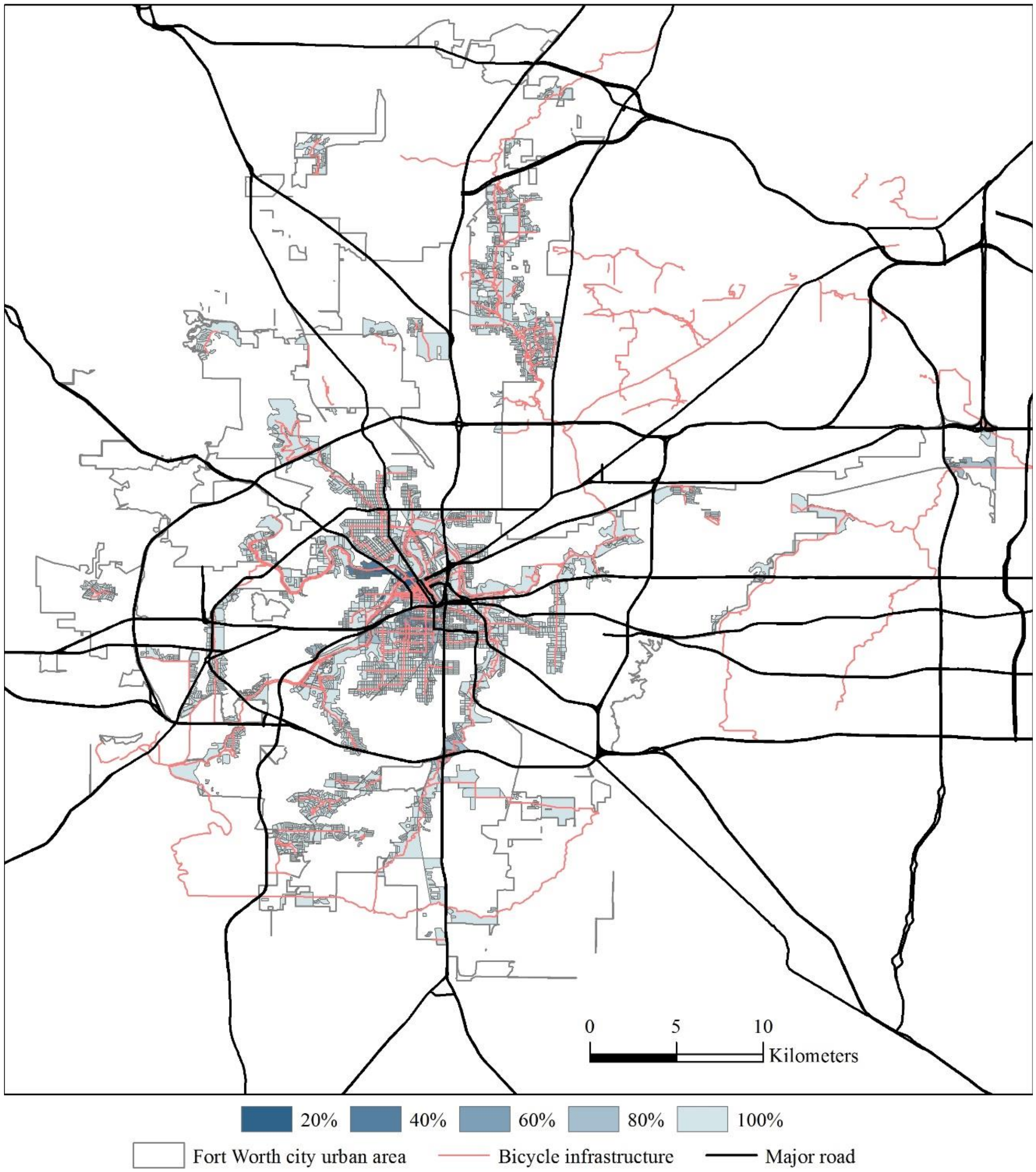

Figure 73. Fort Worth, Texas 1-kilometer accessibility using all bicycle infrastructure

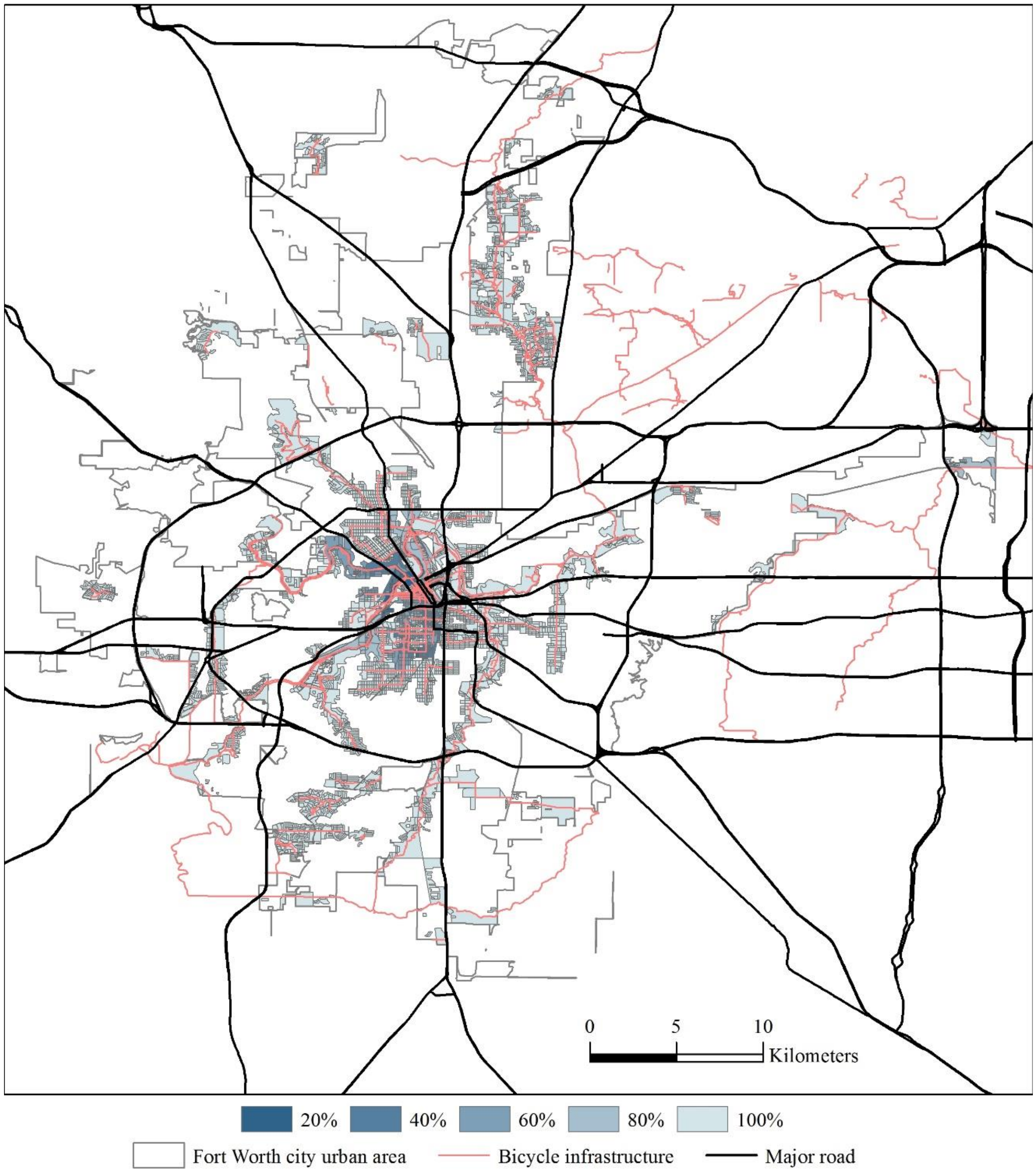

Figure 74. Fort Worth, Texas 3-kilometer accessibility using all bicycle infrastructure

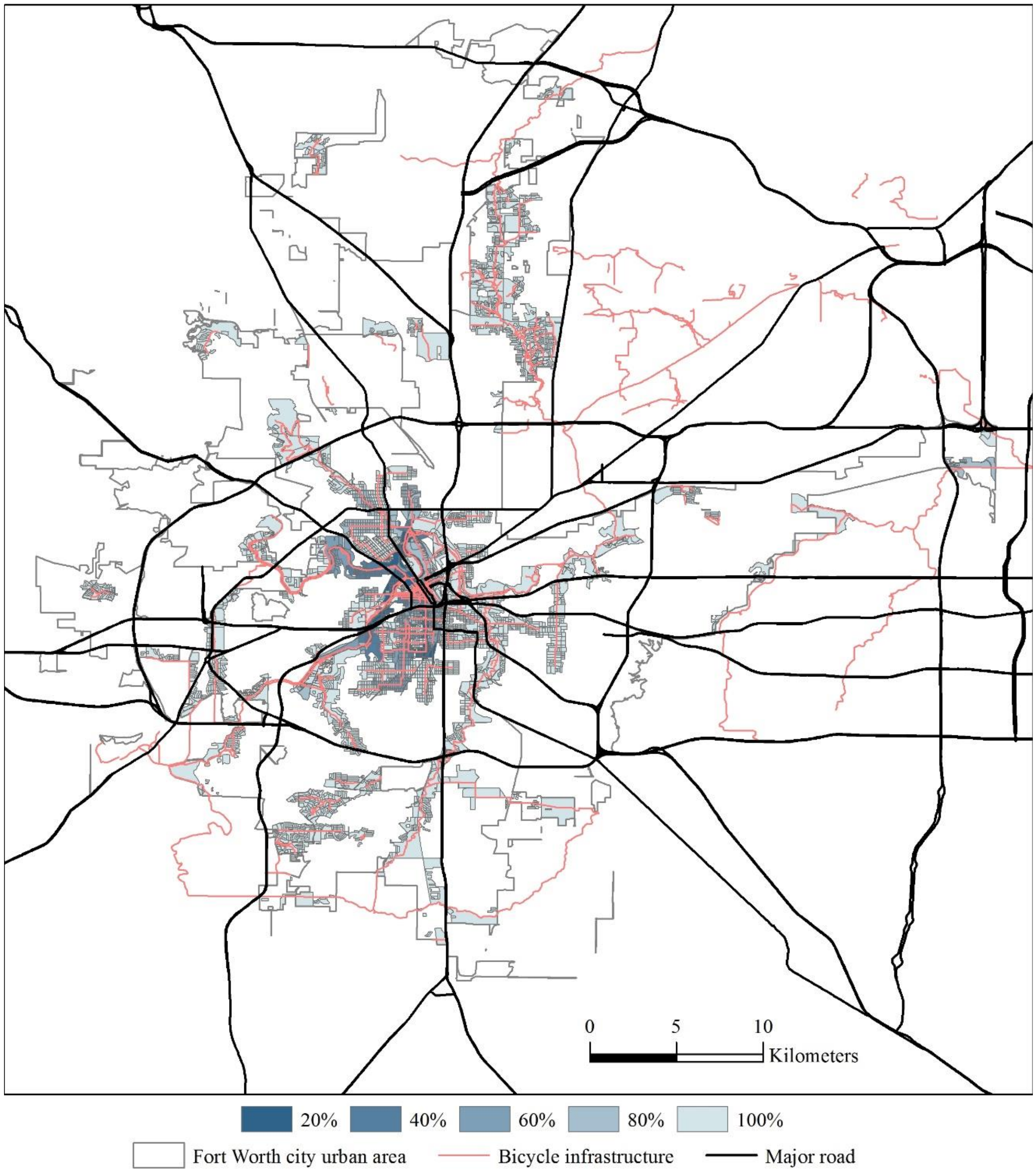

Figure 75. Fort Worth, Texas 5-kilometer accessibility using all bicycle infrastructure

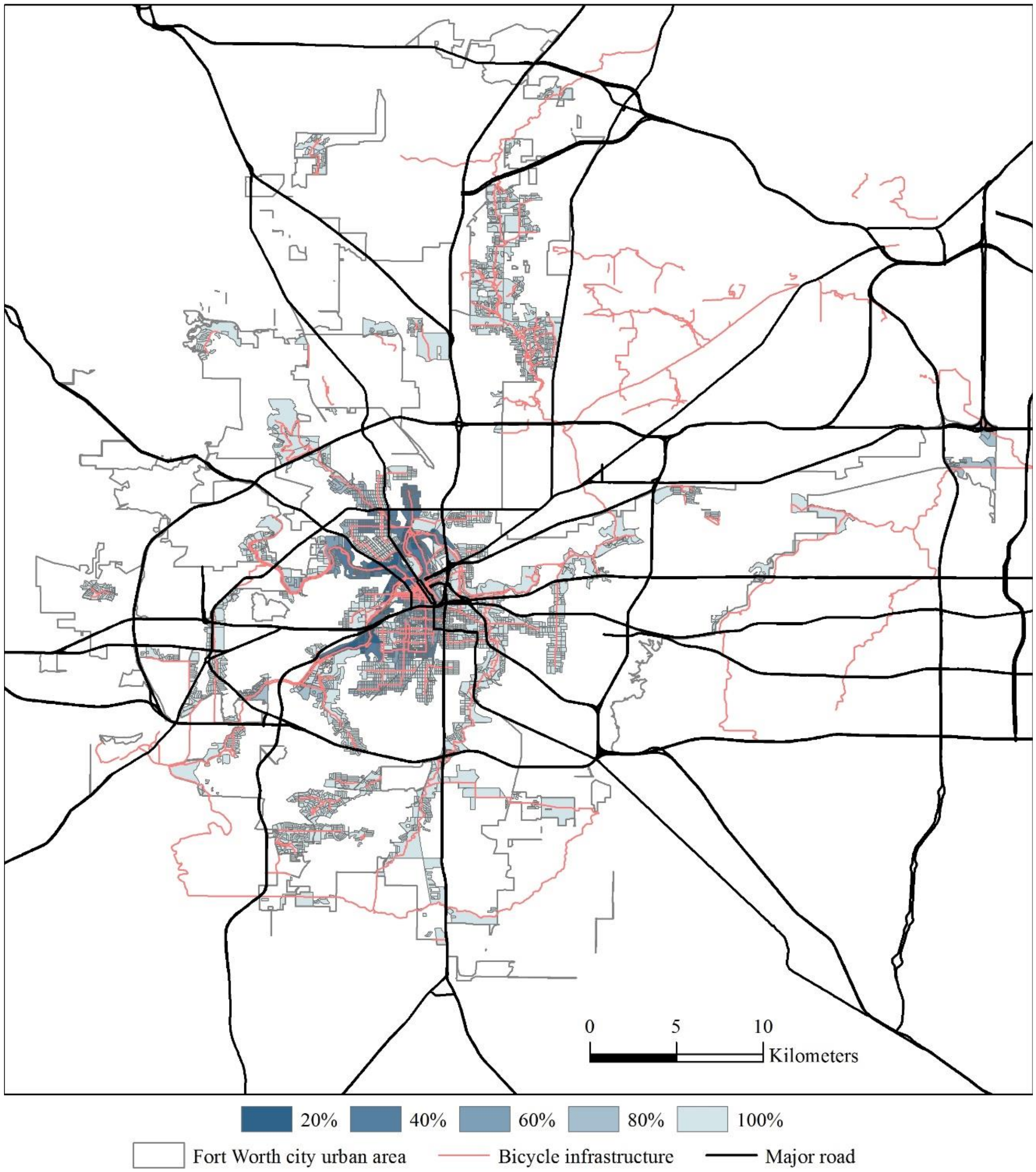

Figure 76. Fort Worth, Texas 7-kilometer accessibility using all bicycle infrastructure

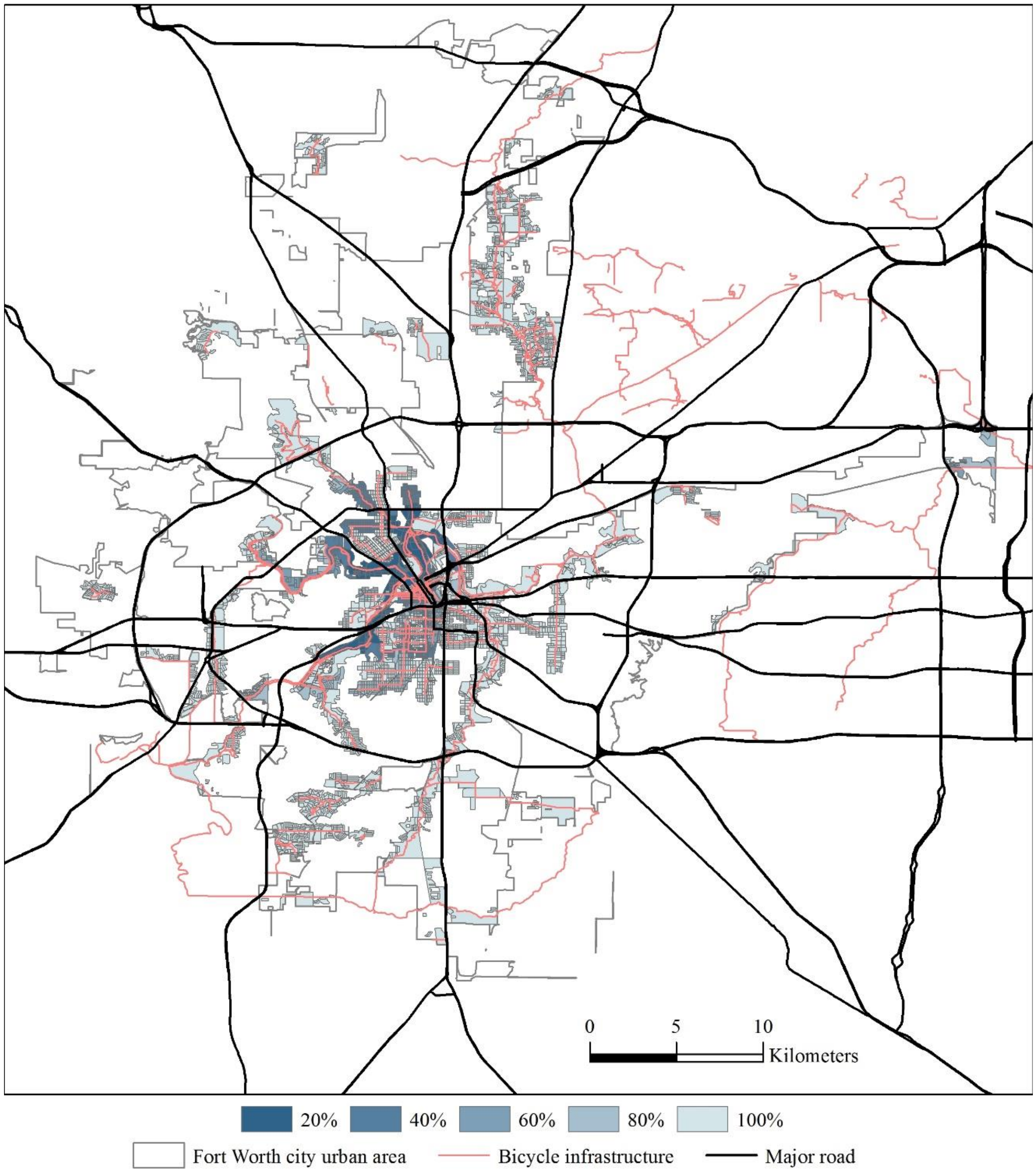

Figure 77. Fort Worth, Texas 9-kilometer accessibility using all bicycle infrastructure

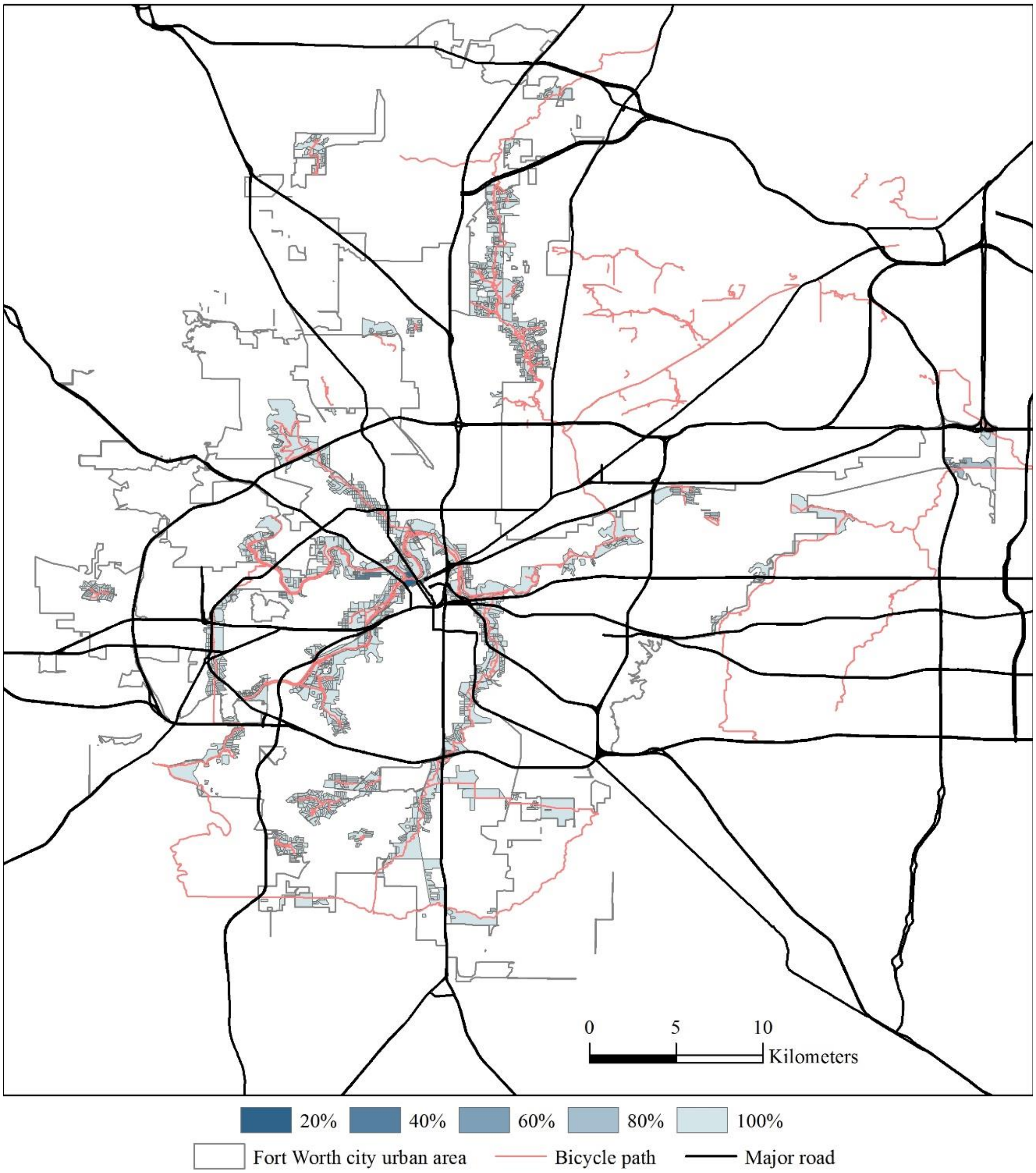

Figure 78. Fort Worth, Texas 1-kilometer accessibility using bicycle paths

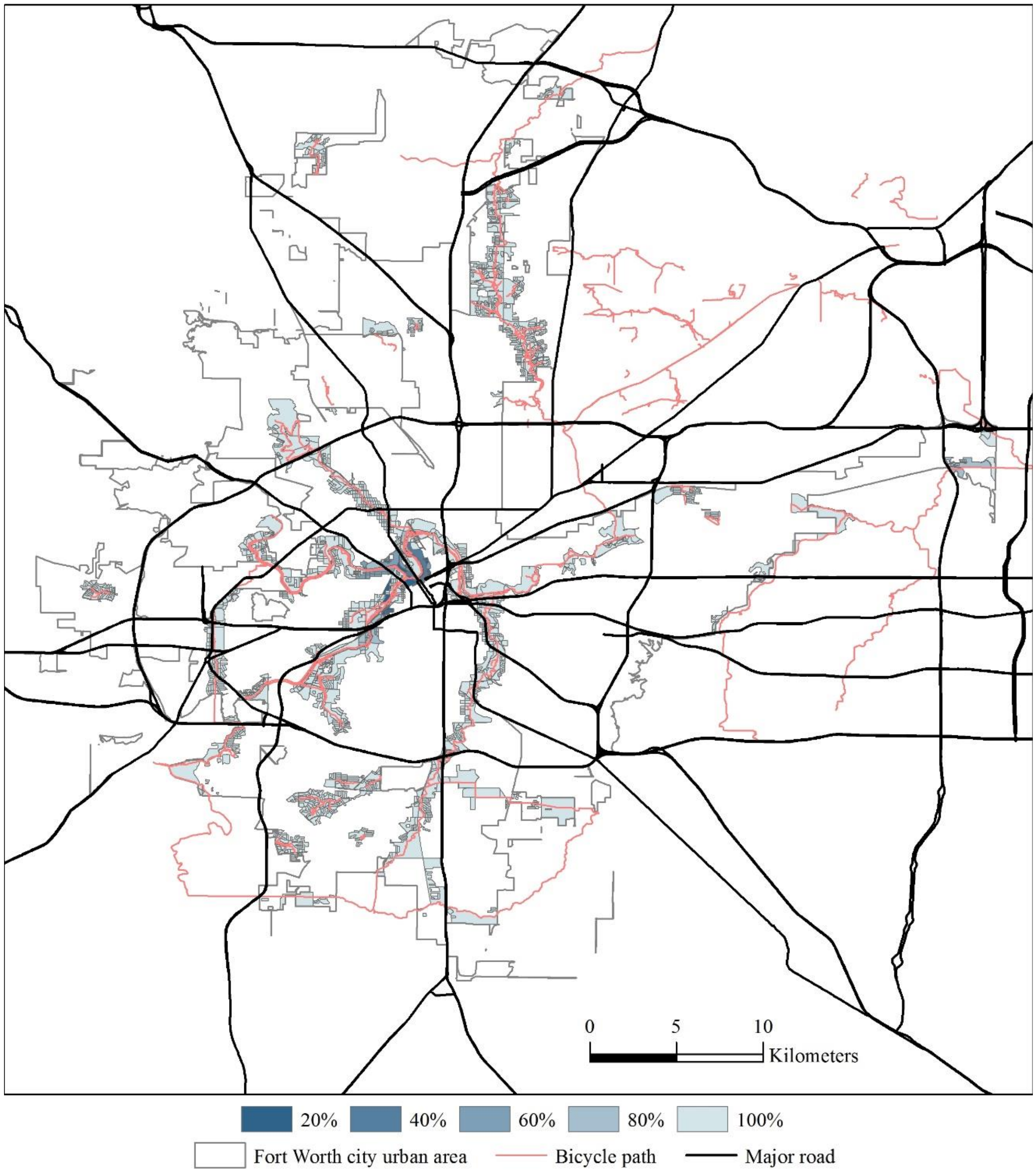

Figure 79. Fort Worth, Texas 3-kilometer accessibility using bicycle paths

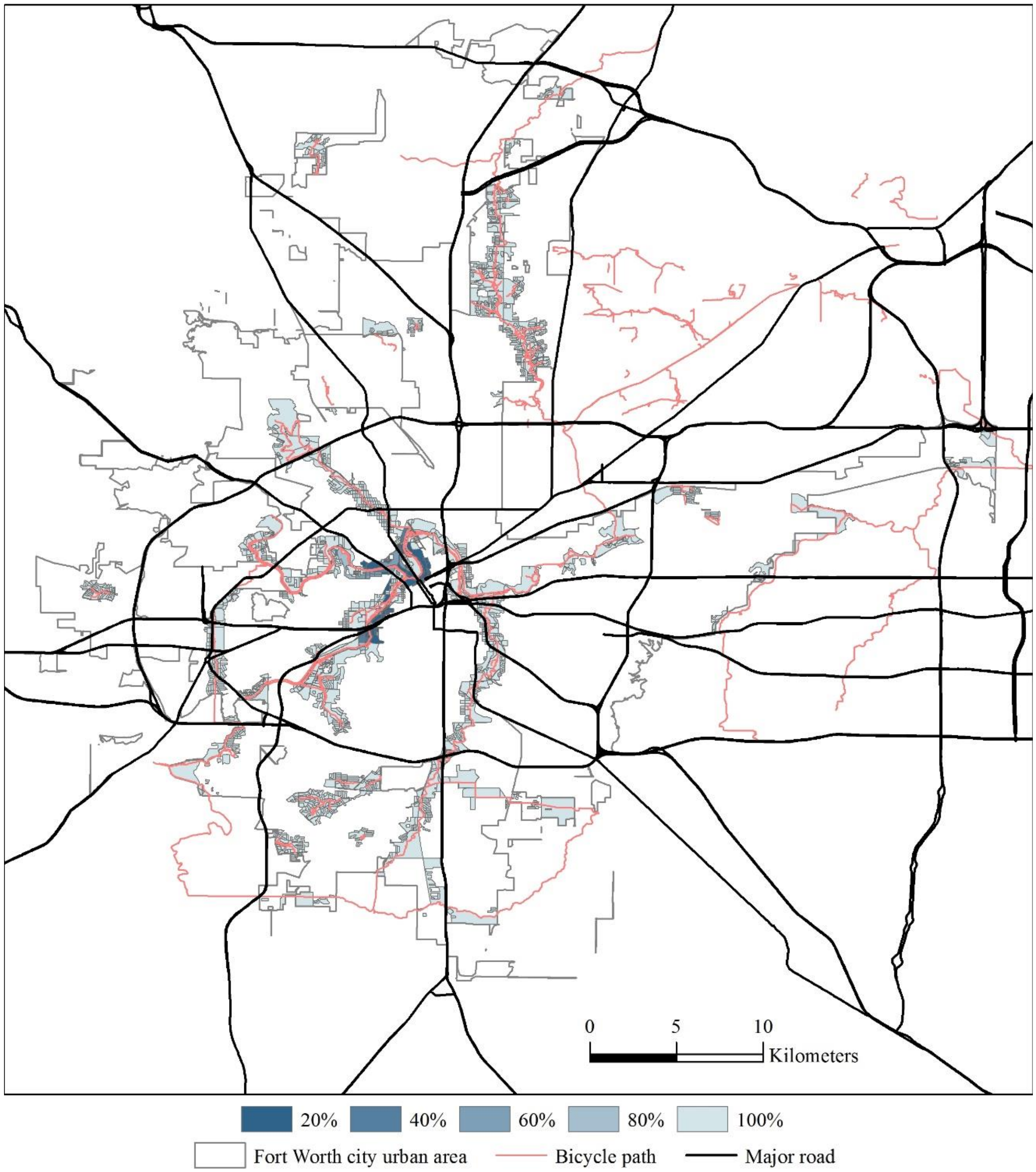

Figure 80. Fort Worth, Texas 5-kilometer accessibility using bicycle paths

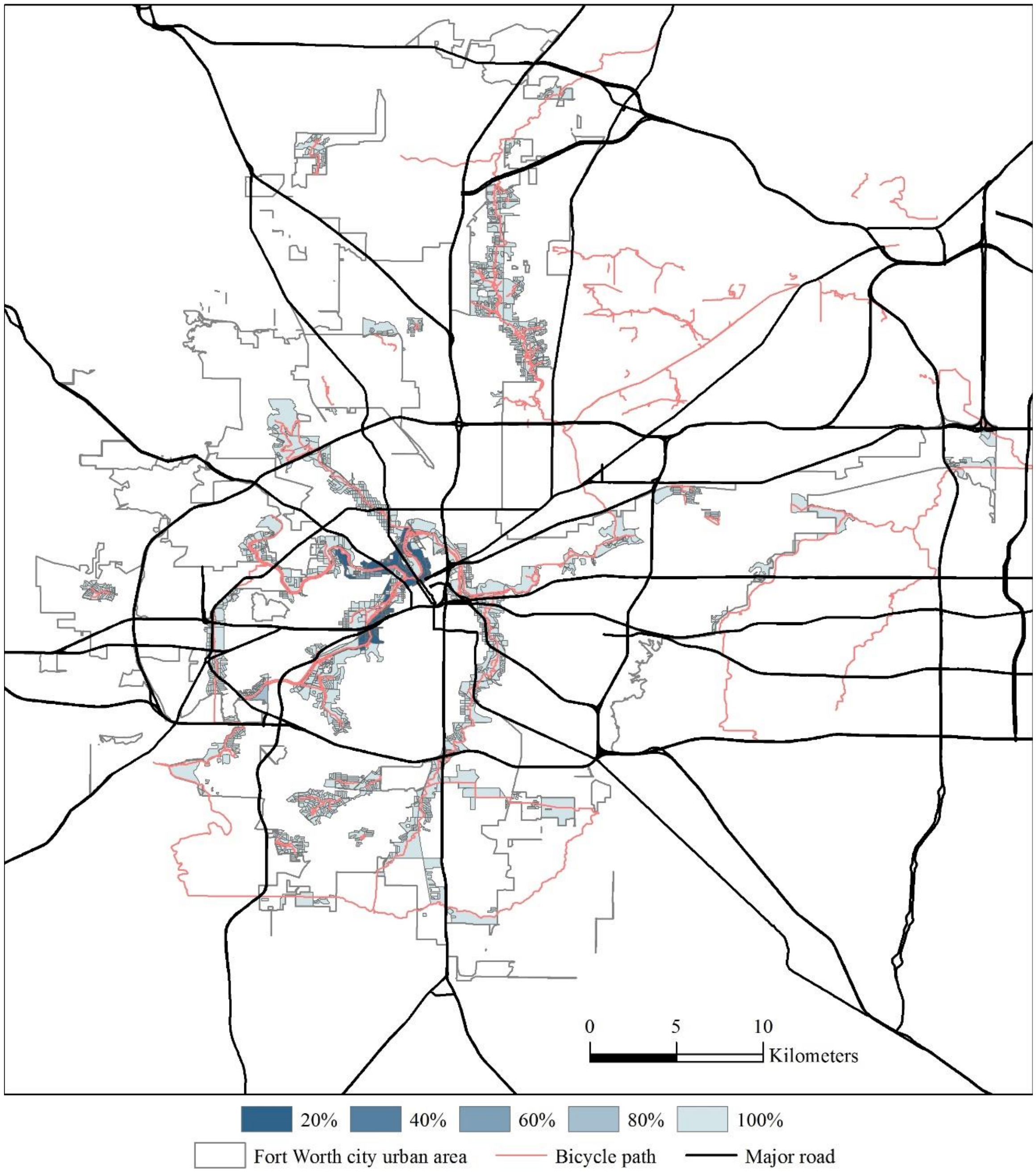

Figure 81. Fort Worth, Texas 7-kilometer accessibility using bicycle paths

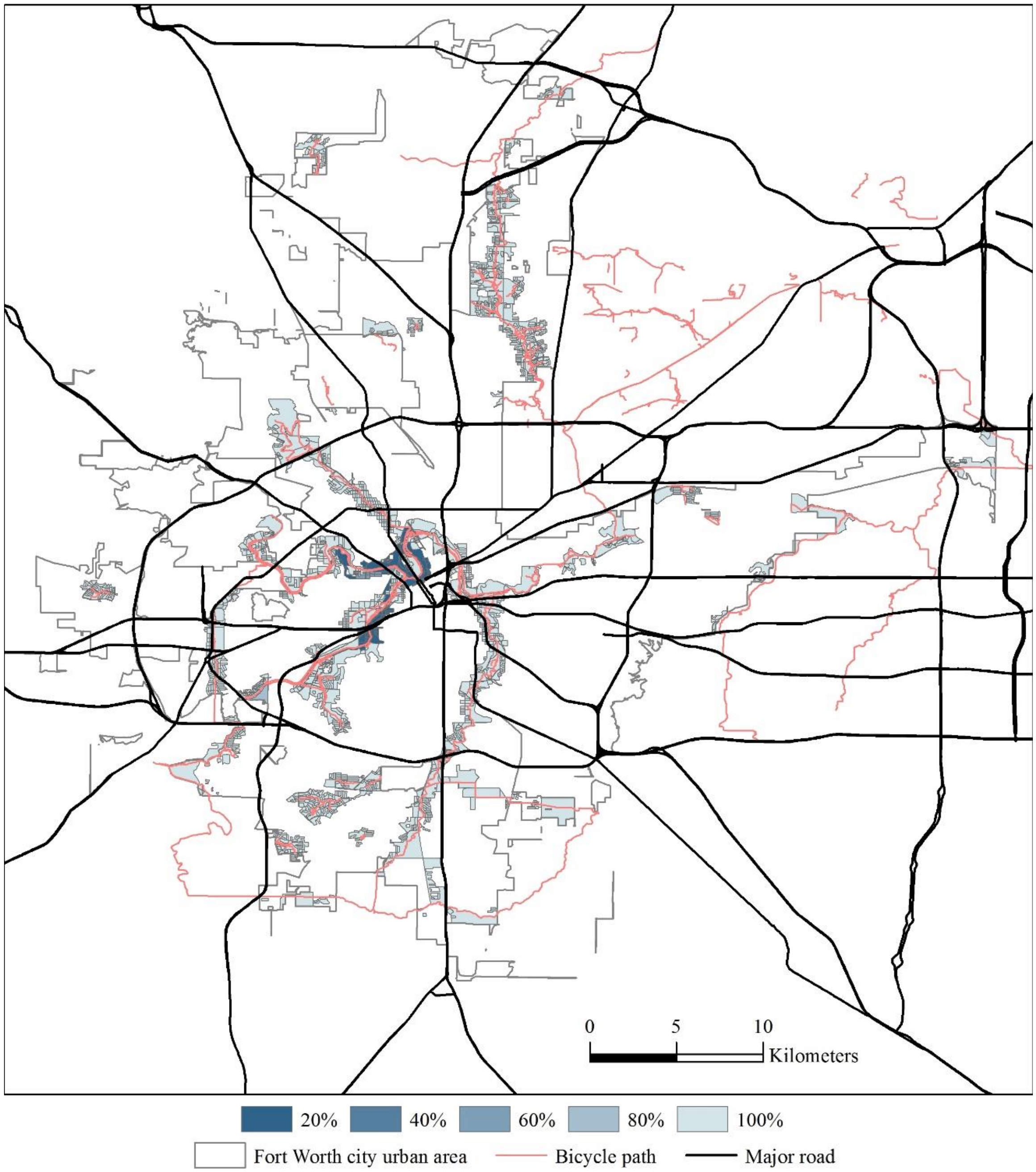

Figure 82. Fort Worth, Texas 9-kilometer accessibility using bicycle paths

APPENDIX F

Omaha, Nebraska City Zonal Accessibility Maps

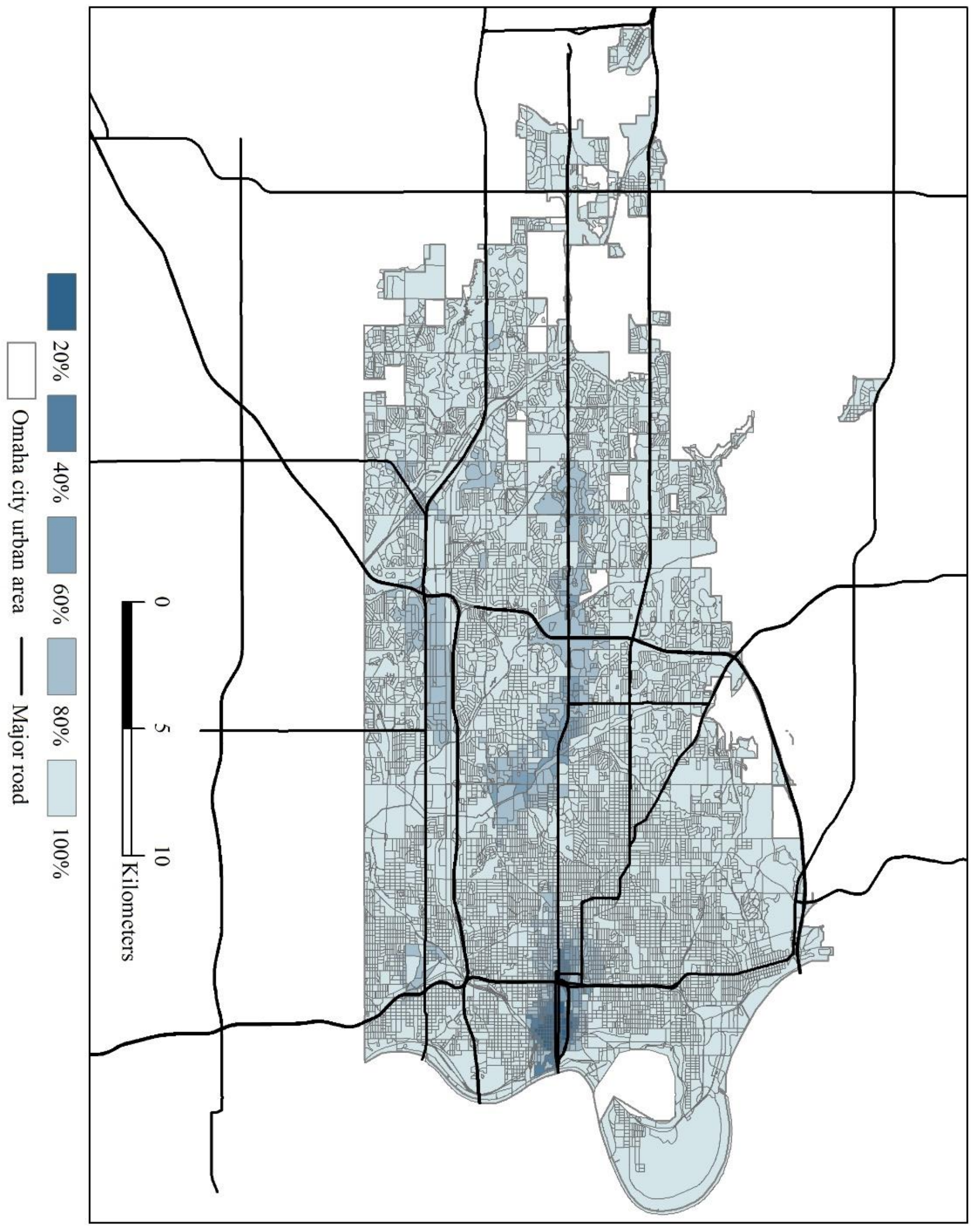

Figure 83. Omaha, Nebraska 1-kilometer accessibility using roads

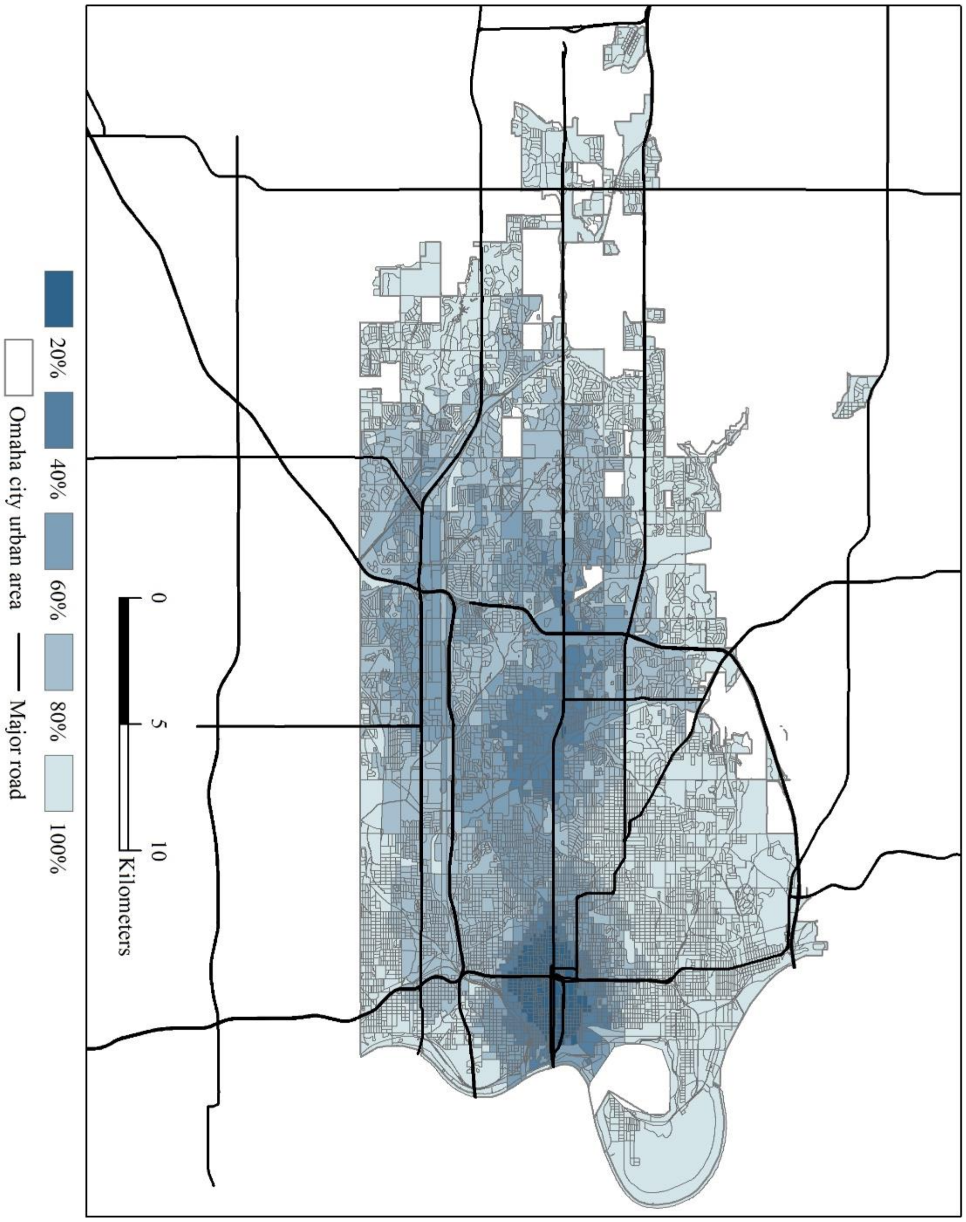

Figure 84. Omaha, Nebraska 3-kilometer accessibility using roads

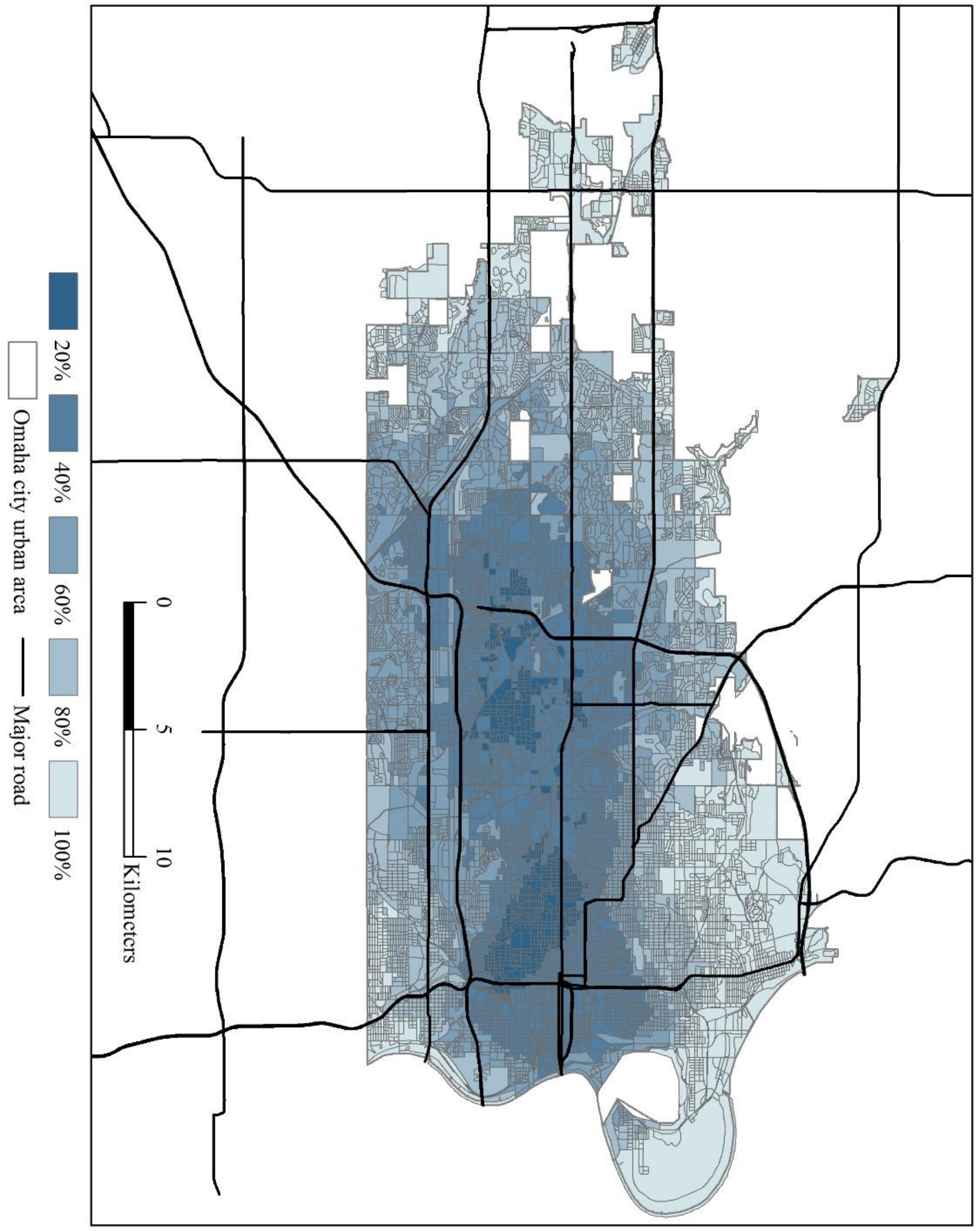

Figure 85. Omaha, Nebraska 5-kilometer accessibility using roads

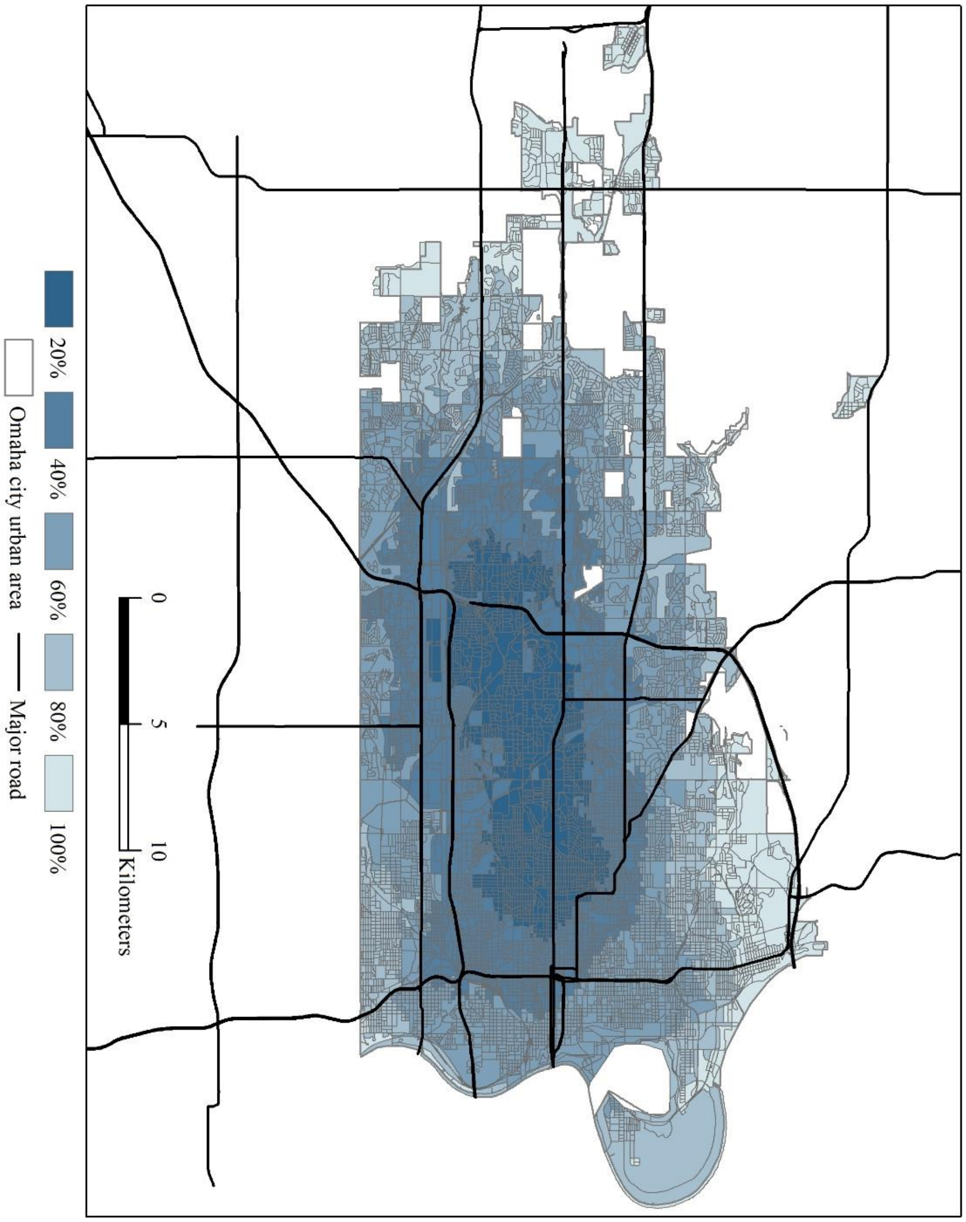

Figure 86. Omaha, Nebraska 7-kilometer accessibility using roads

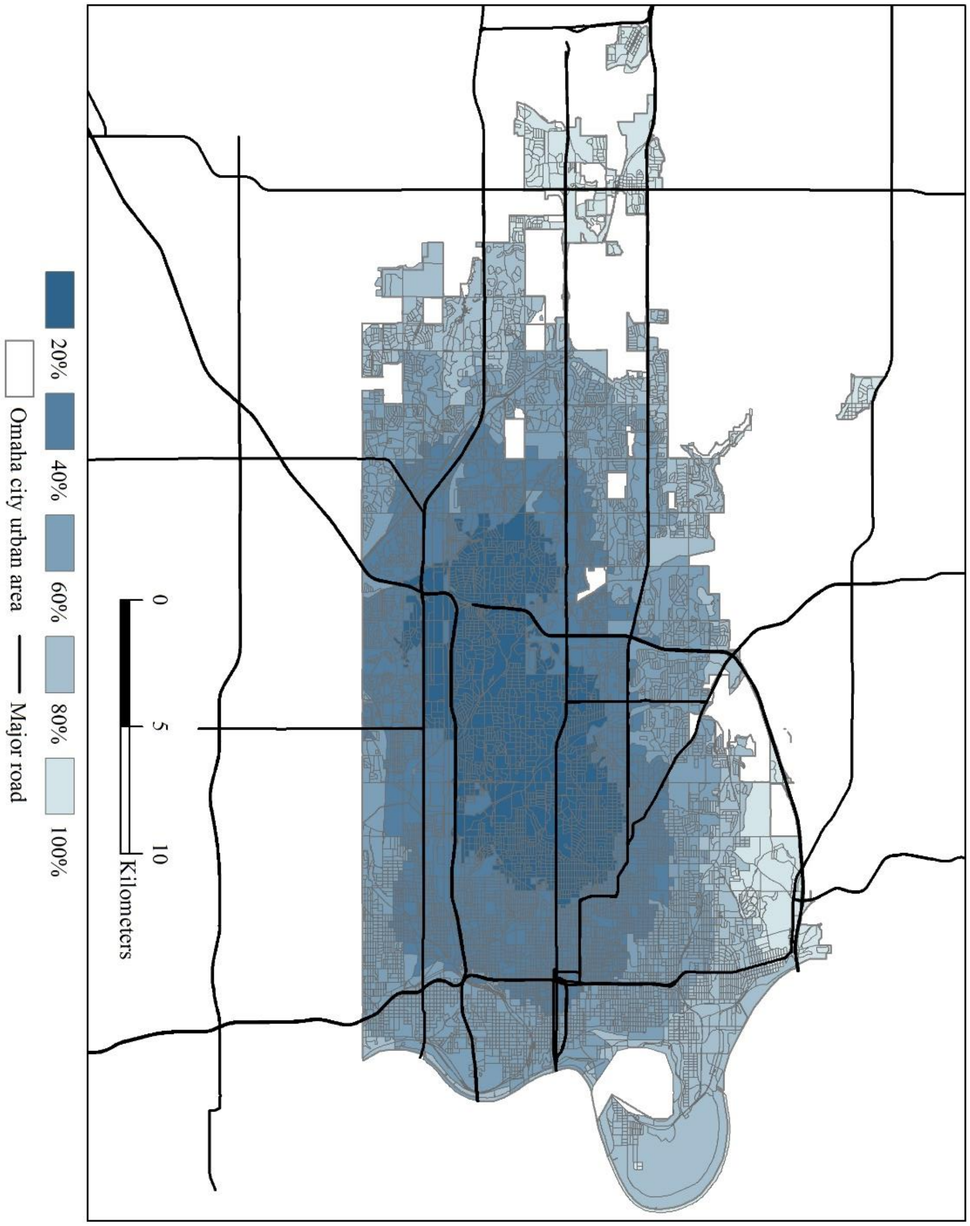

Figure 87. Omaha, Nebraska 9-kilometer accessibility using roads

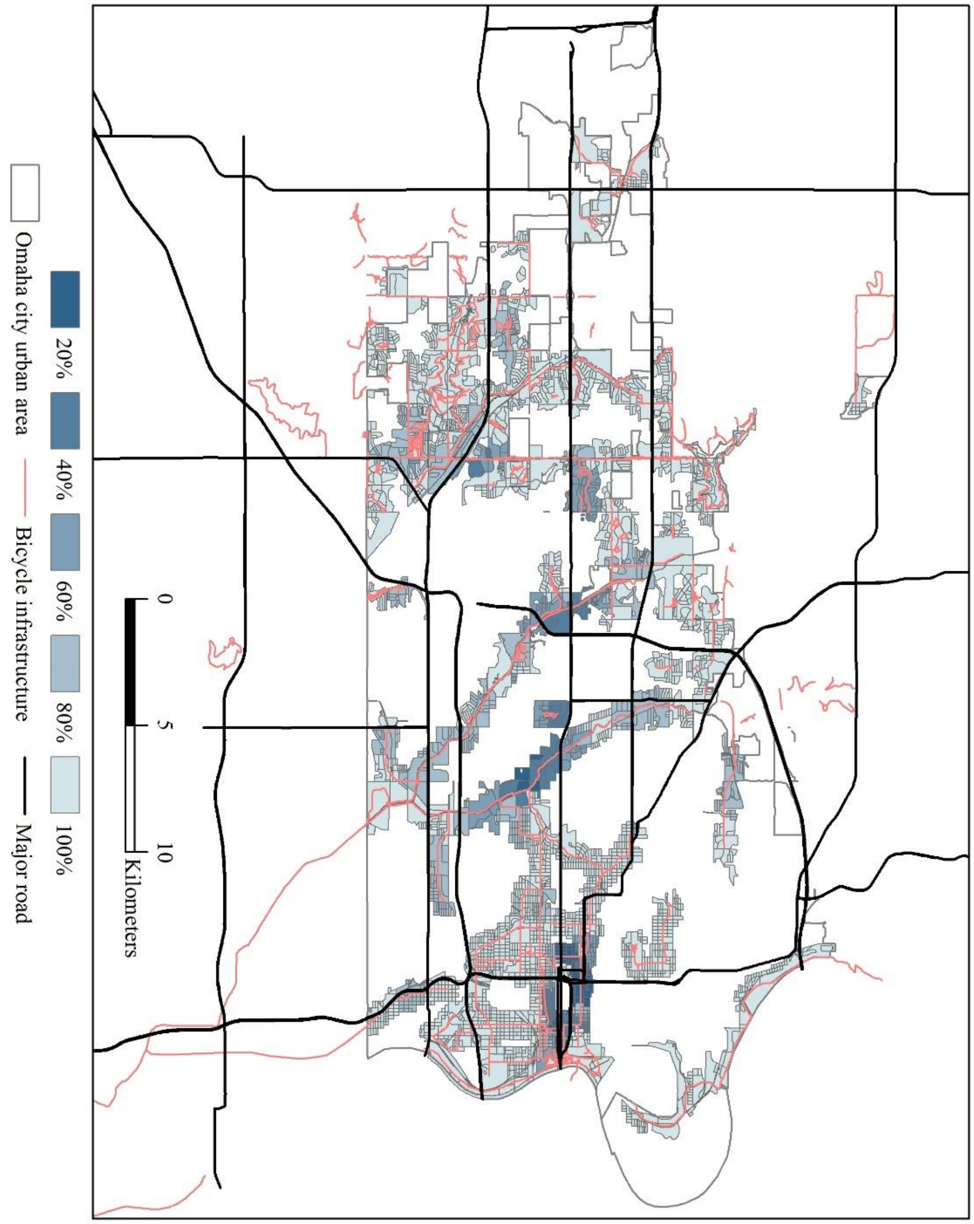

Figure 88. Omaha, Nebraska 1-kilometer accessibility using all bicycle infrastructure

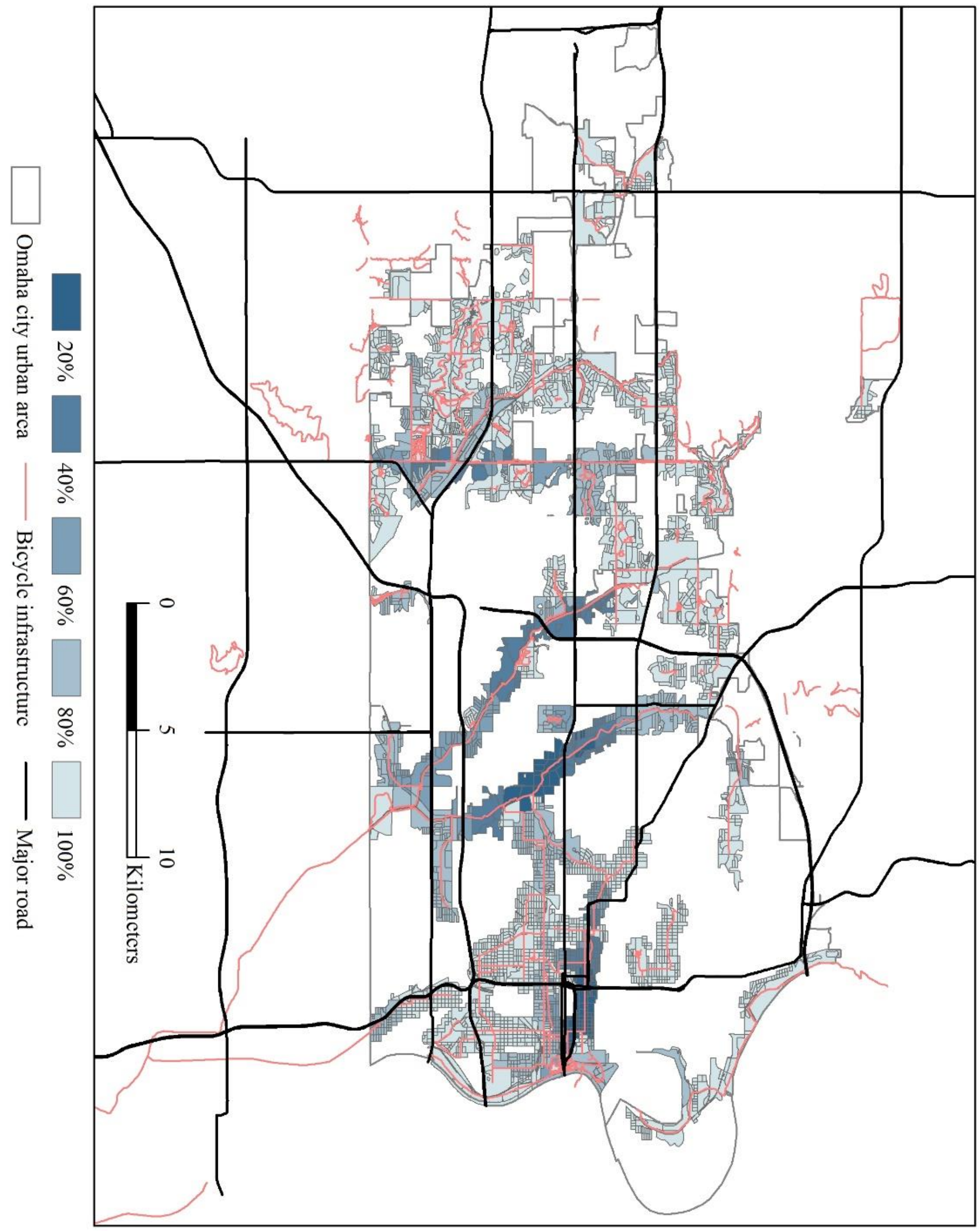

Figure 89. Omaha, Nebraska 3-kilometer accessibility using all bicycle infrastructure

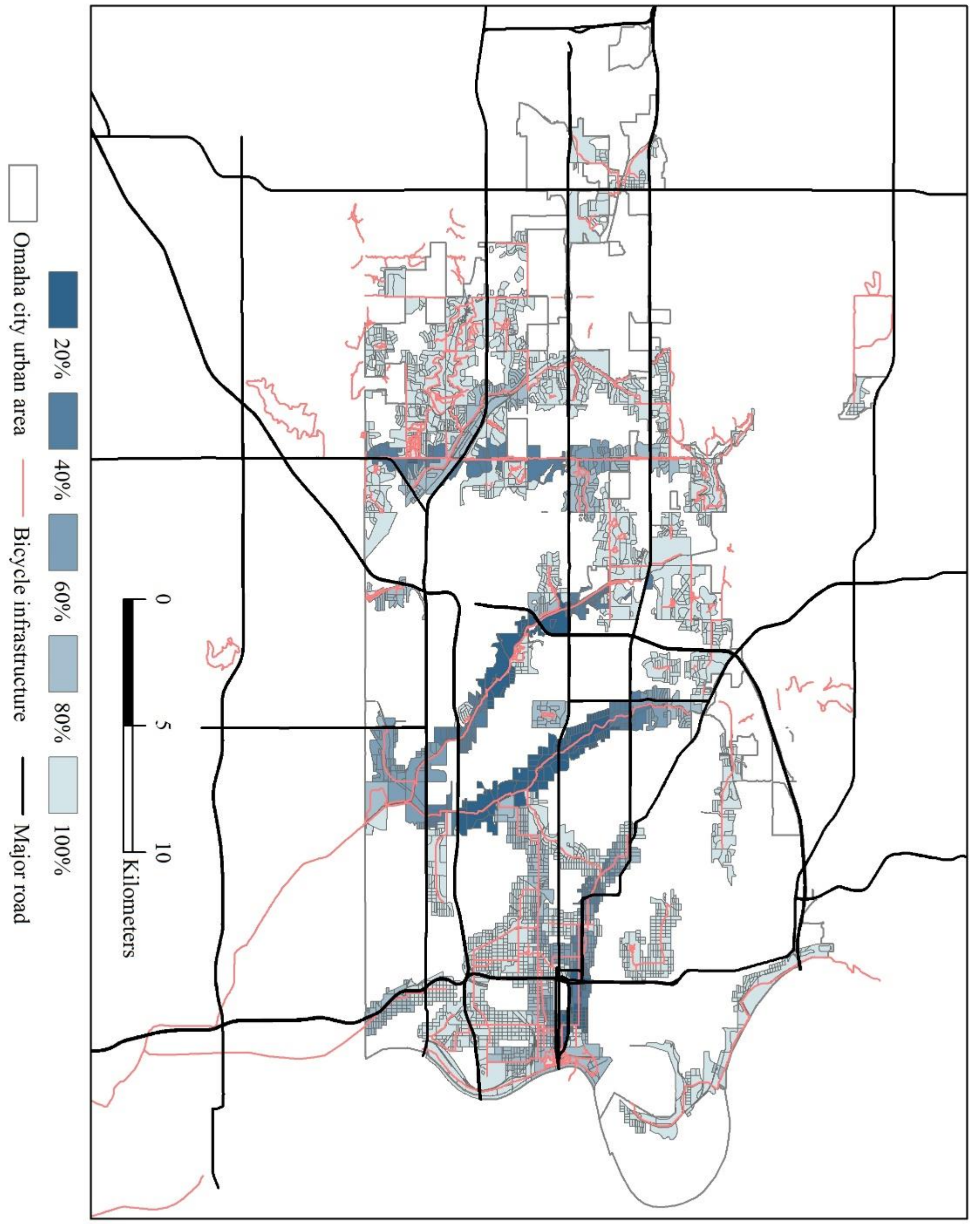

Figure 90. Omaha, Nebraska 5-kilometer accessibility using all bicycle infrastructure

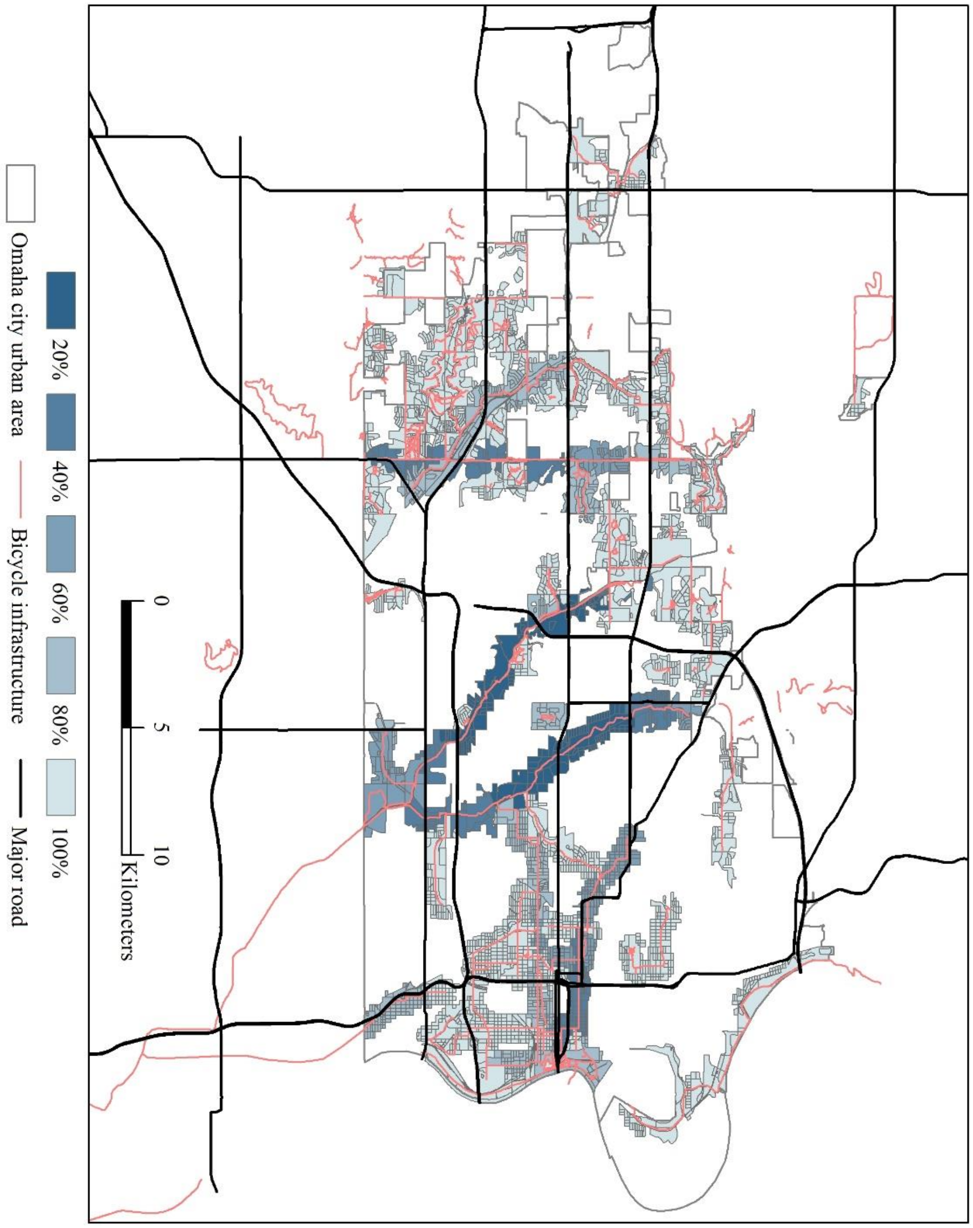

Figure 91. Omaha, Nebraska 7-kilometer accessibility using all bicycle infrastructure

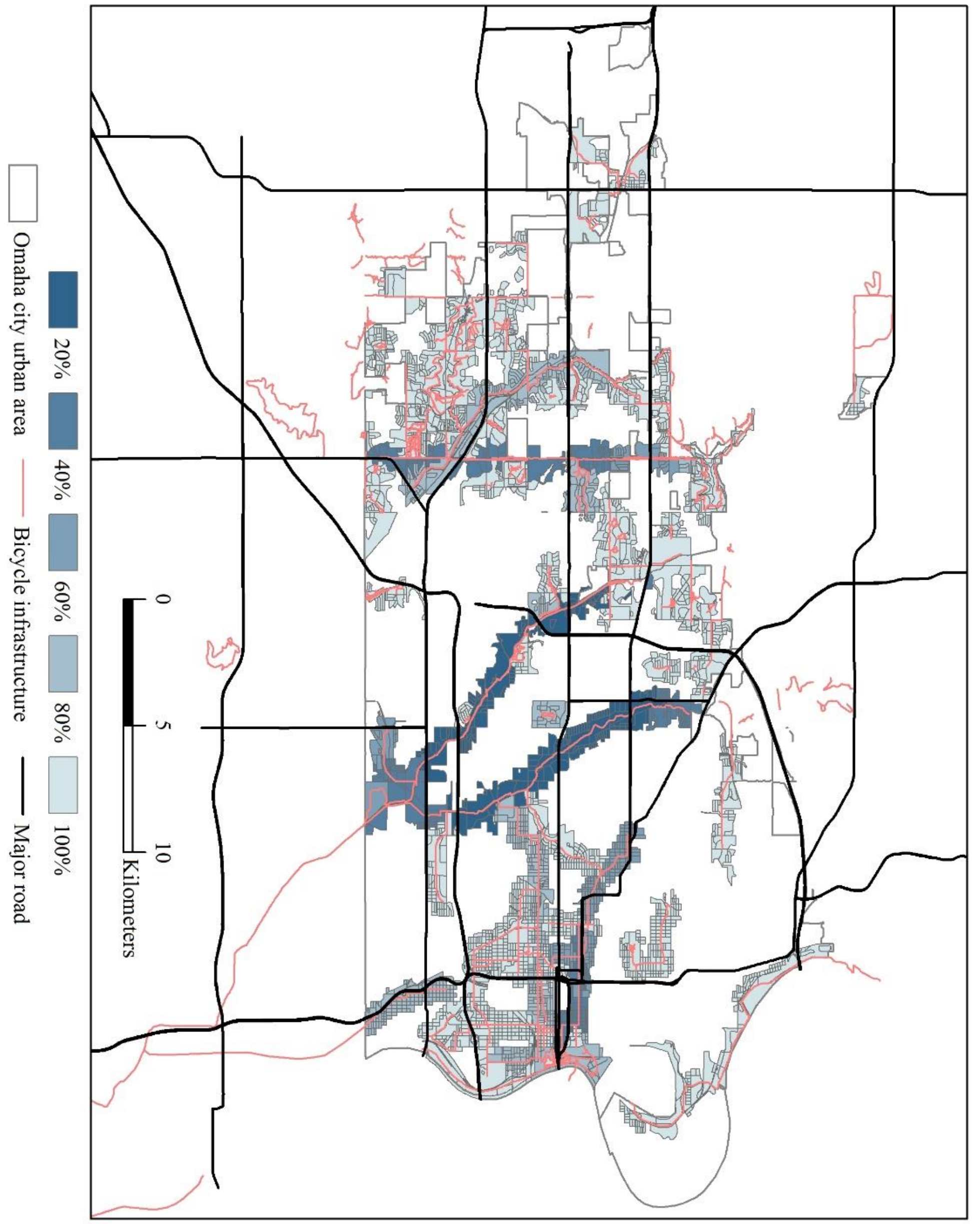

Figure 92. Omaha, Nebraska 9-kilometer accessibility using all bicycle infrastructure

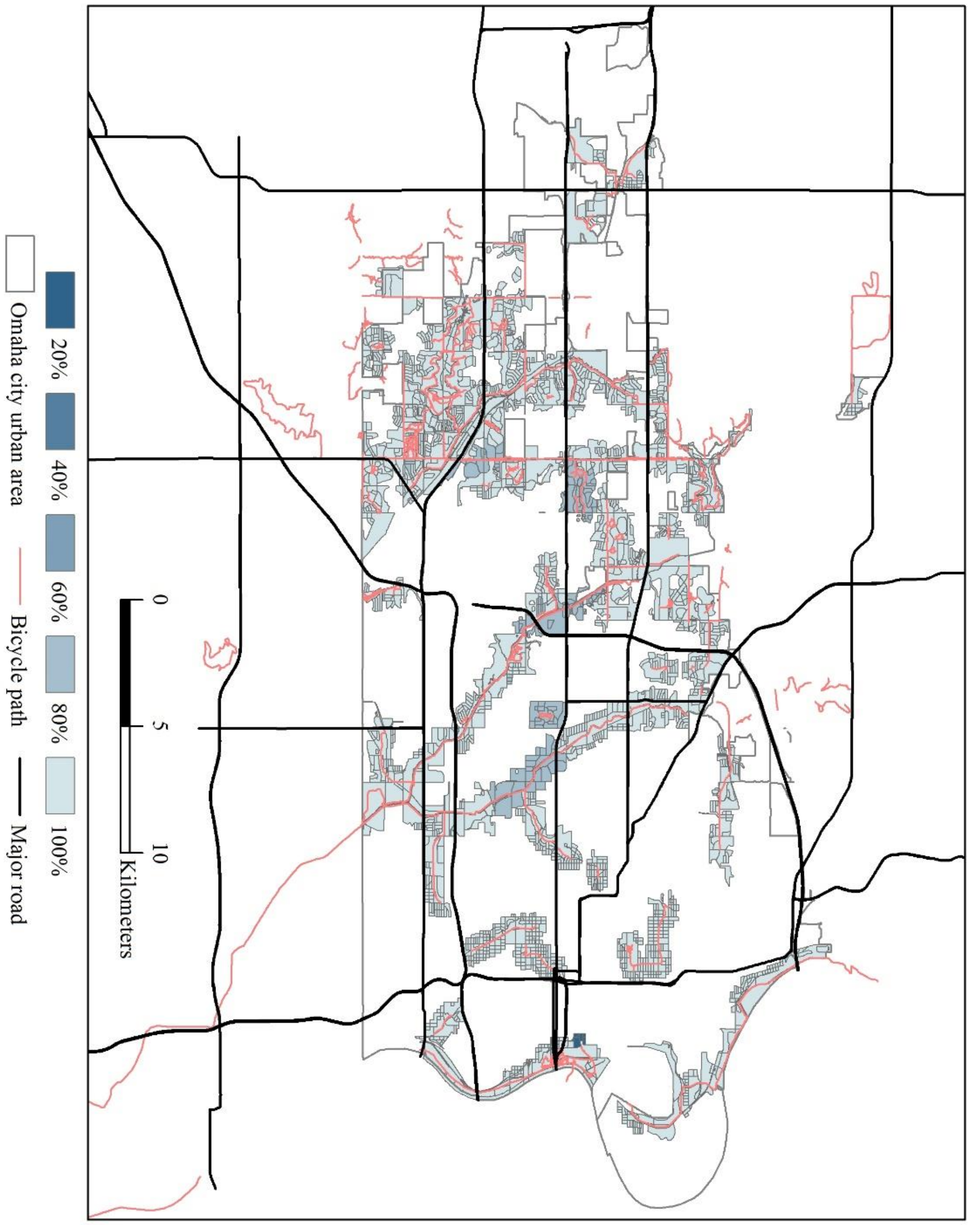

Figure 93. Omaha, Nebraska 1-kilometer accessibility using bicycle paths

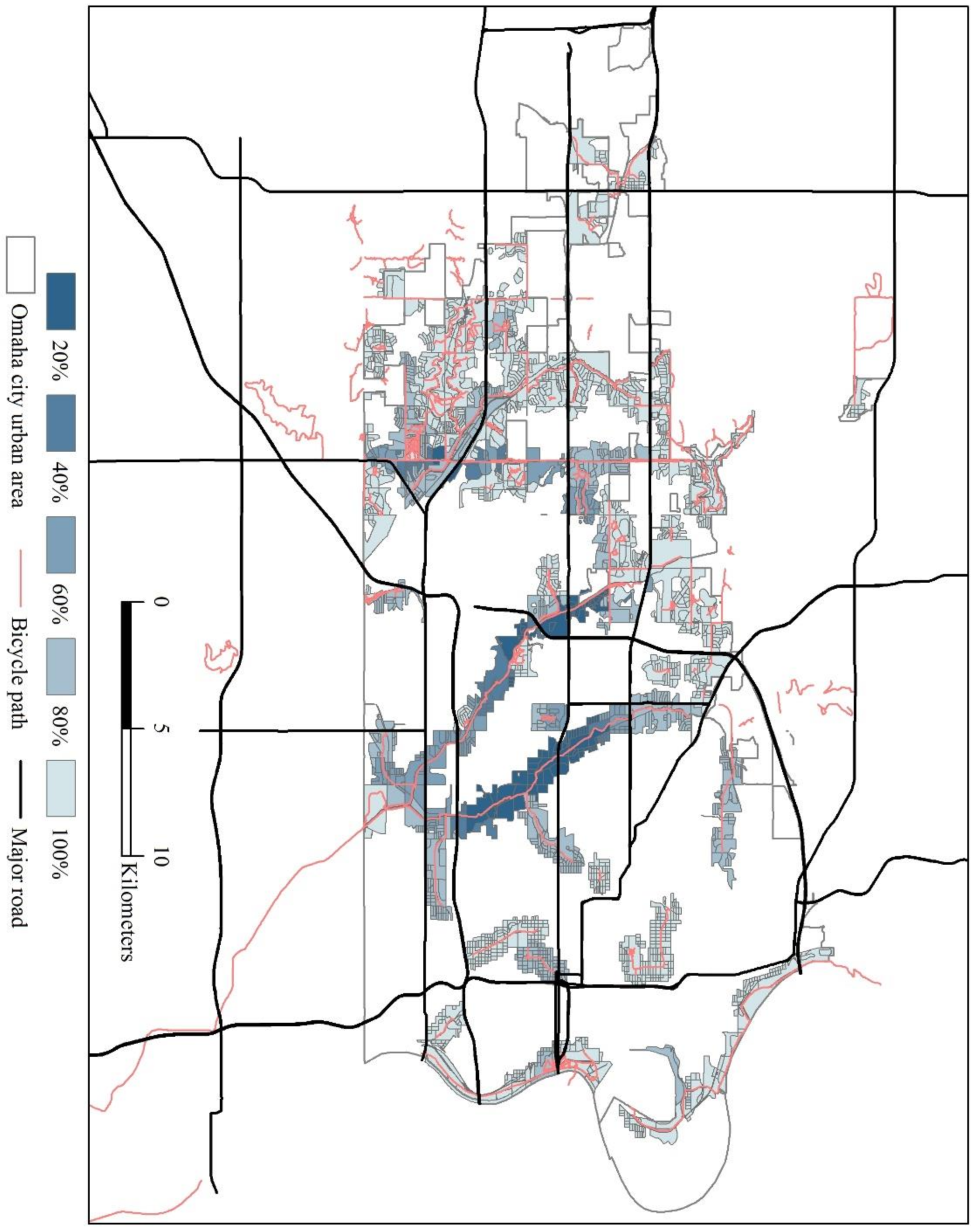

Figure 94. Omaha, Nebraska 3-kilometer accessibility using bicycle paths

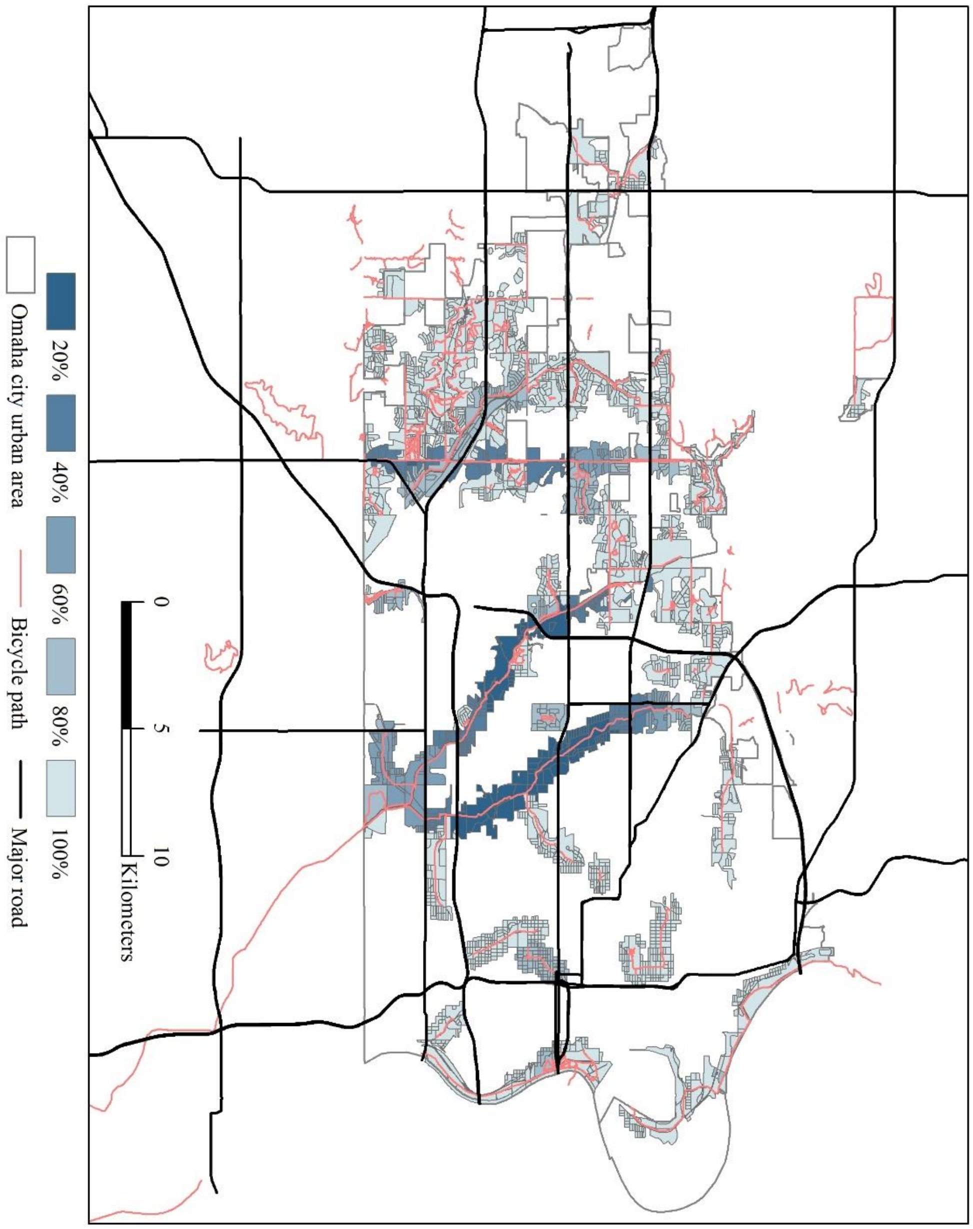

Figure 95. Omaha, Nebraska 5-kilometer accessibility using bicycle paths

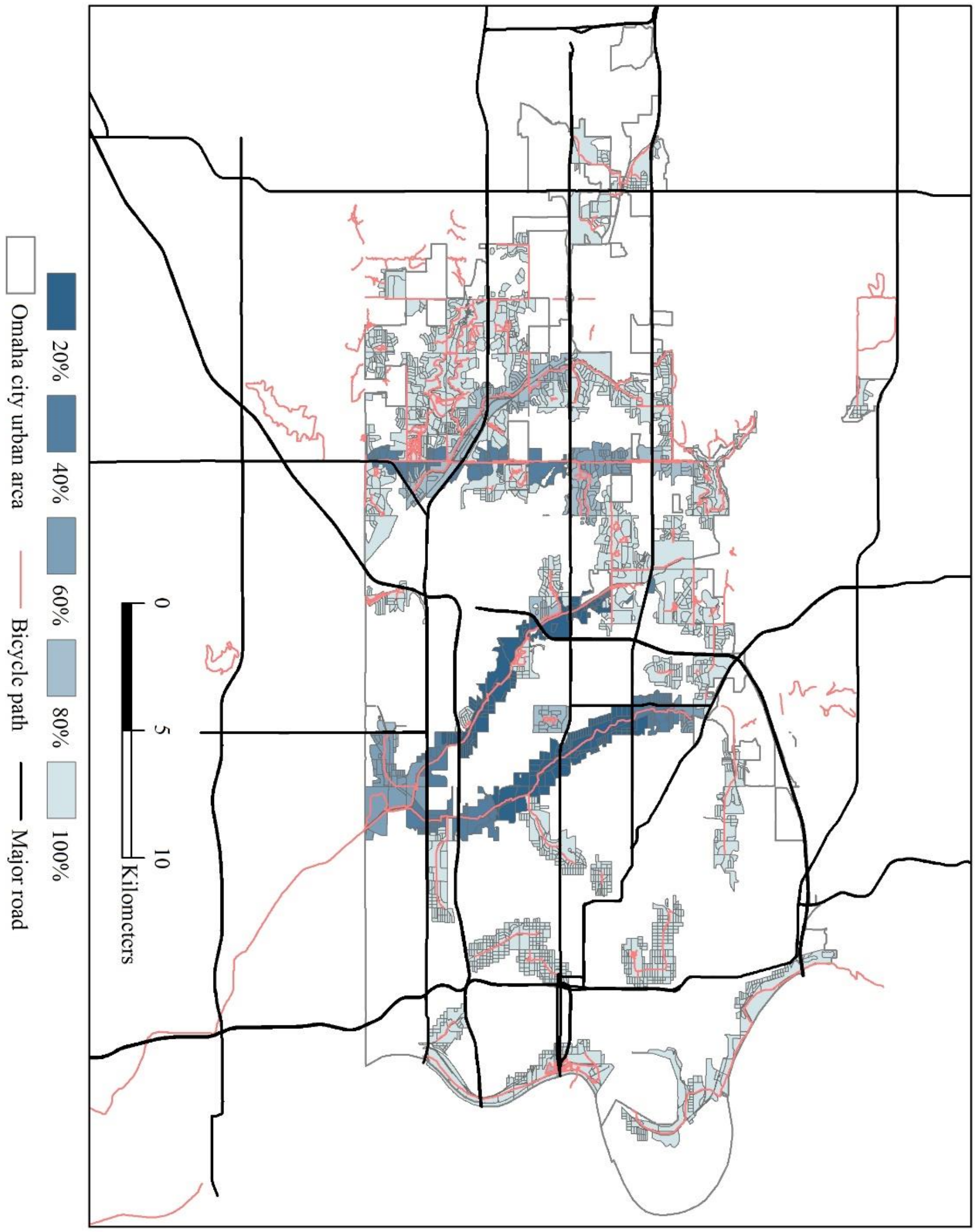

Figure 96. Omaha, Nebraska 7-kilometer accessibility using bicycle paths

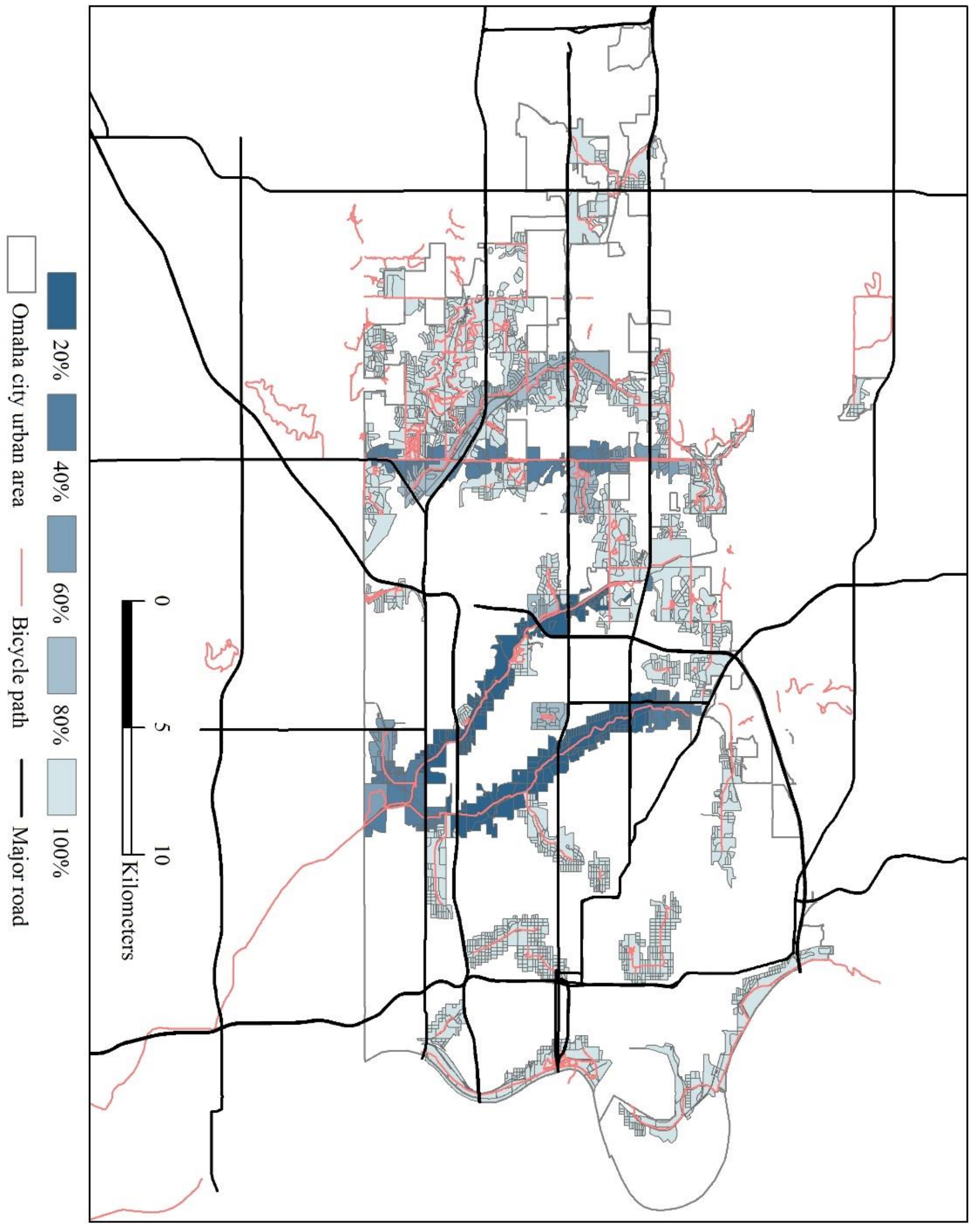

Figure 97. Omaha, Nebraska 9-kilometer accessibility using bicycle paths

APPENDIX G

Pittsburgh, Pennsylvania City Zonal Accessibility Maps

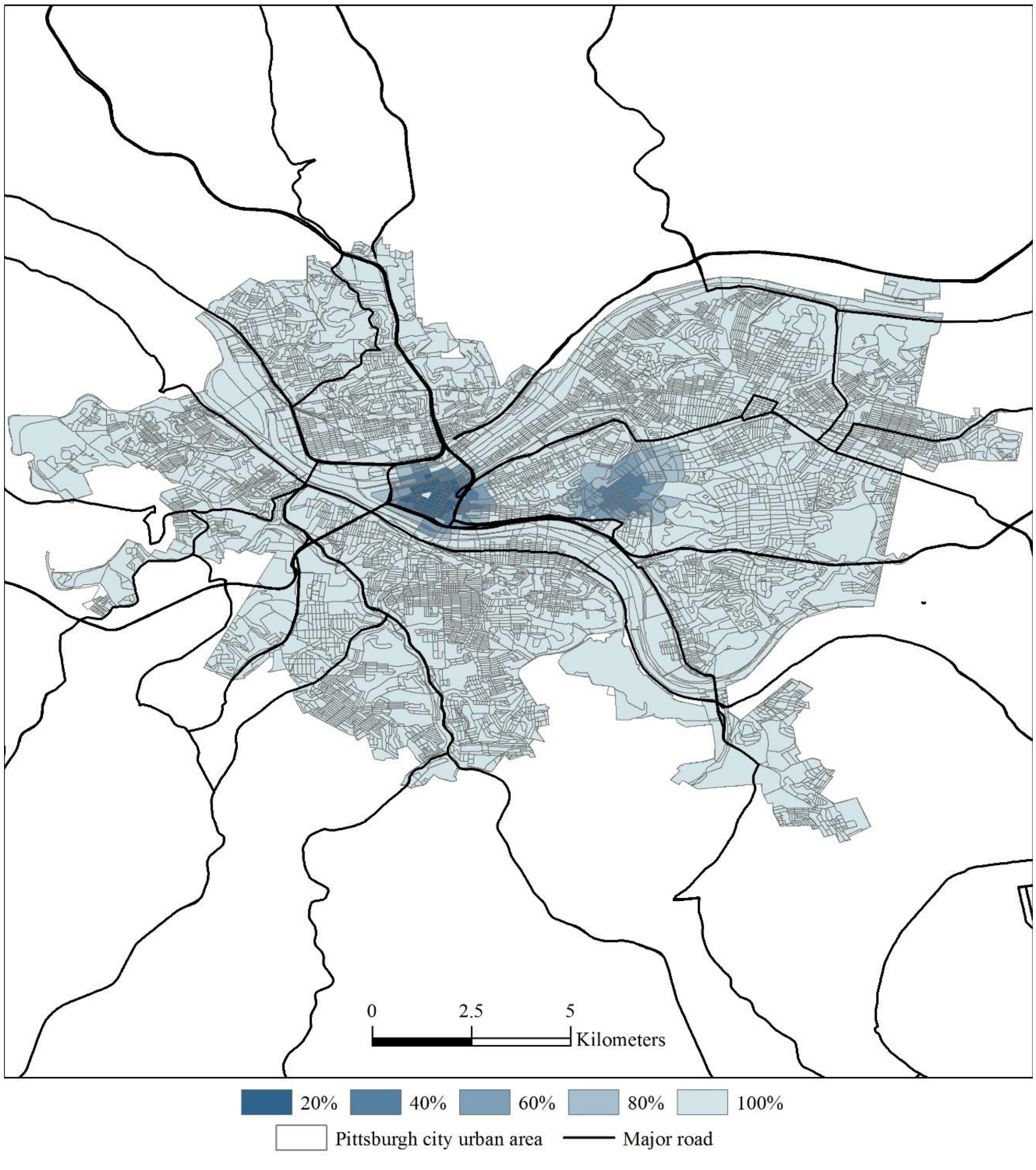

Figure 98. Pittsburgh, Pennsylvania 1-kilometer accessibility using roads

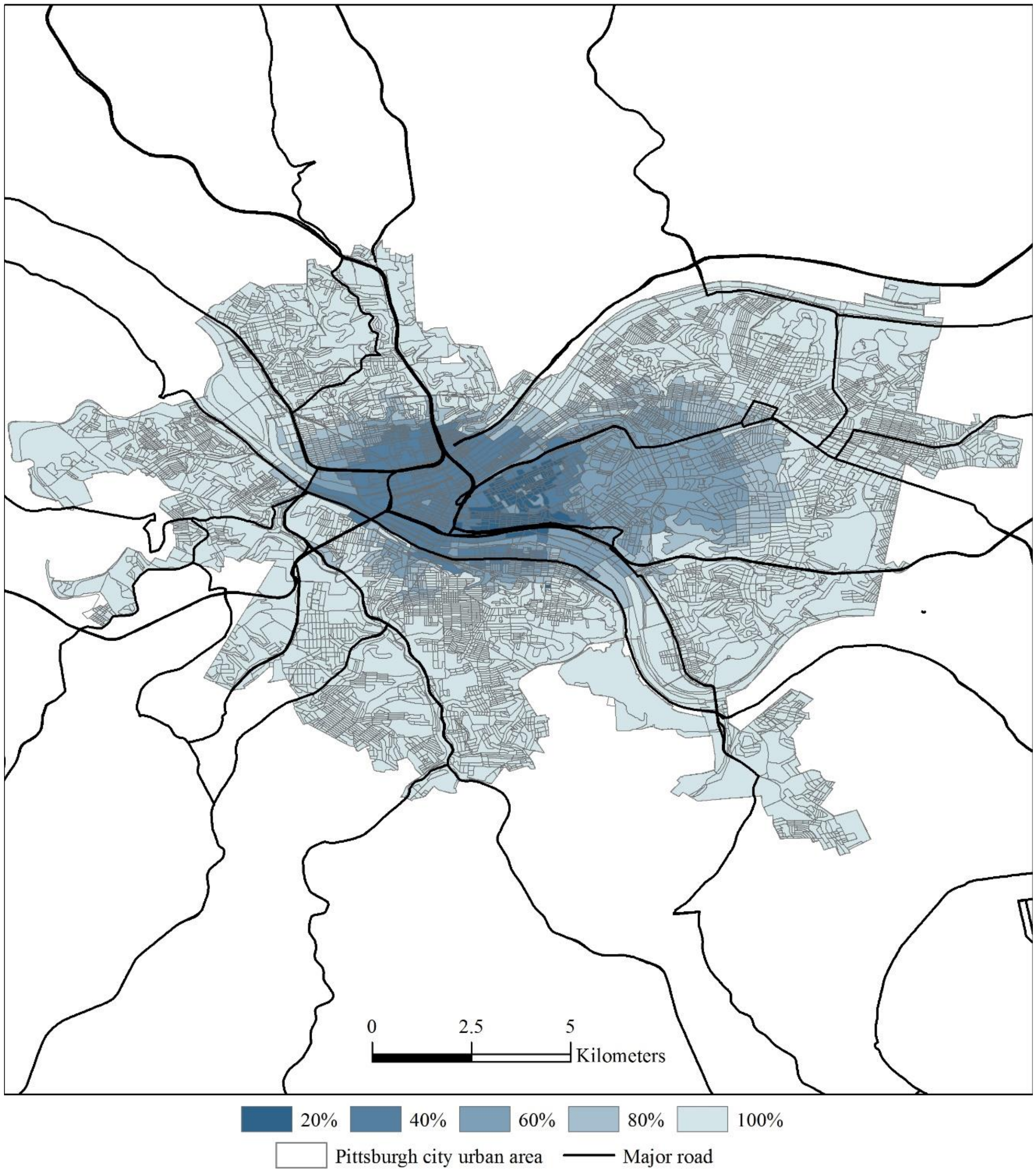

Figure 99. Pittsburgh, Pennsylvania 3-kilometer accessibility using roads

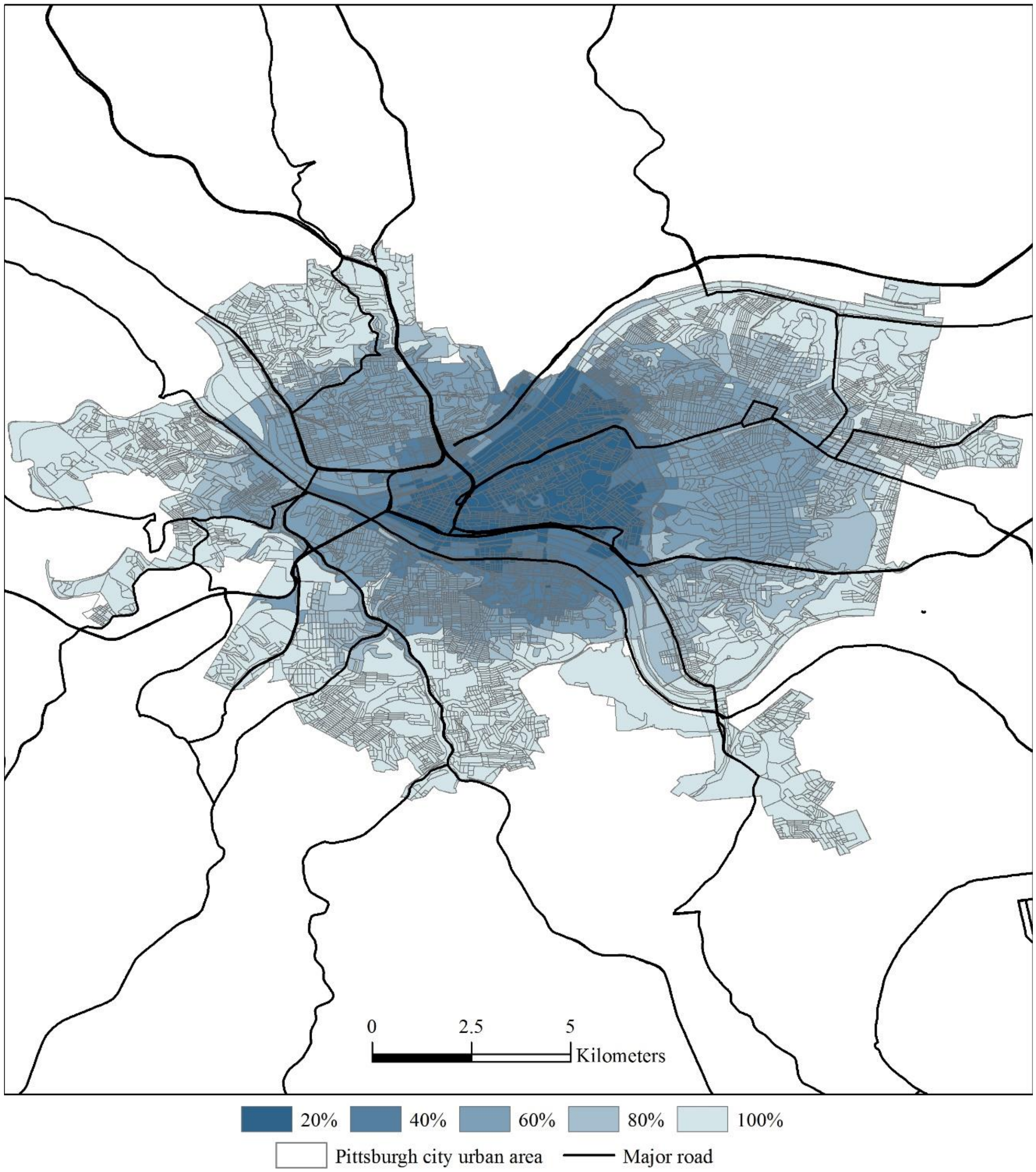

Figure 100. Pittsburgh, Pennsylvania 5-kilometer accessibility using roads

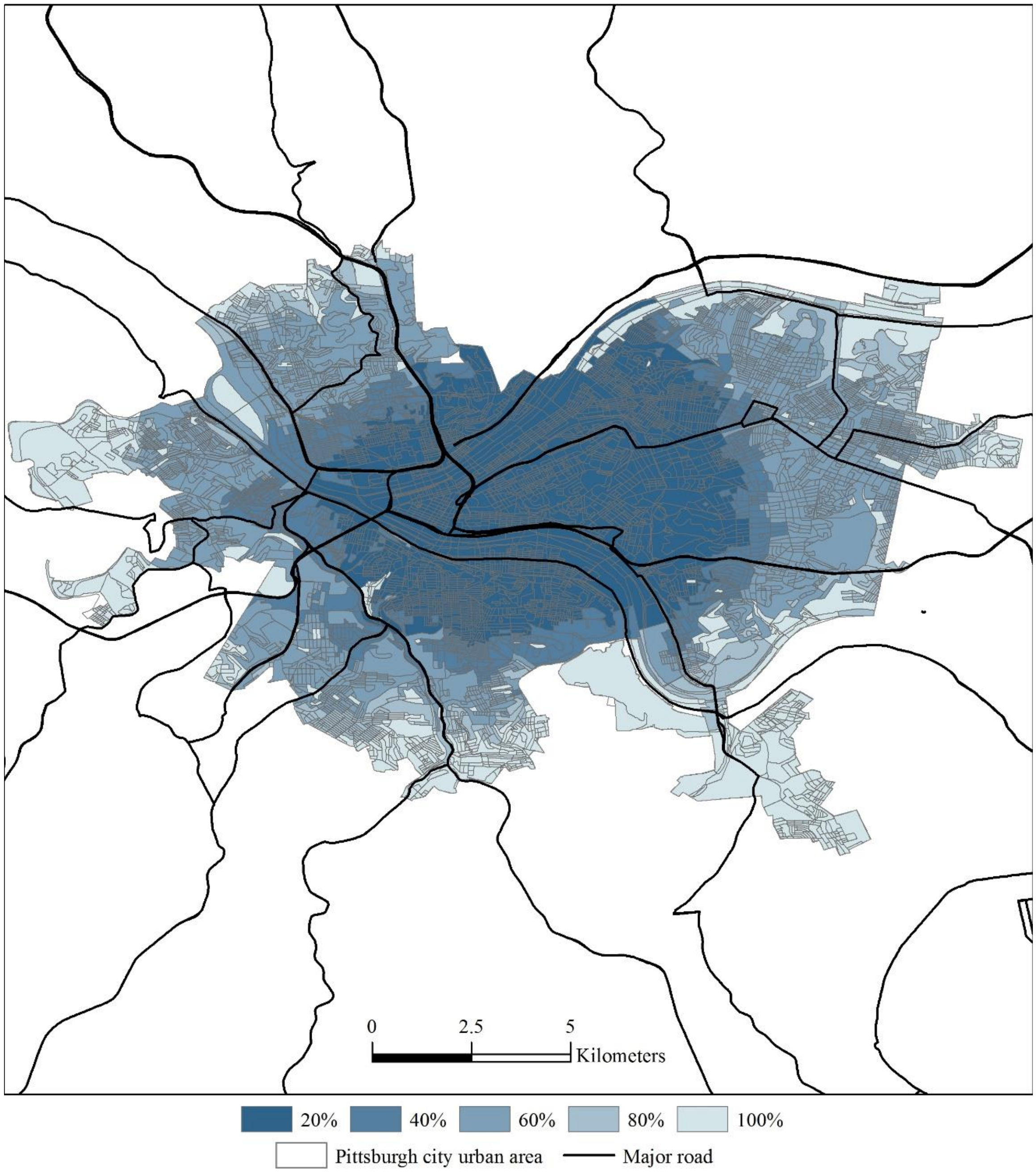

Figure 101. Pittsburgh, Pennsylvania 7-kilometer accessibility using roads

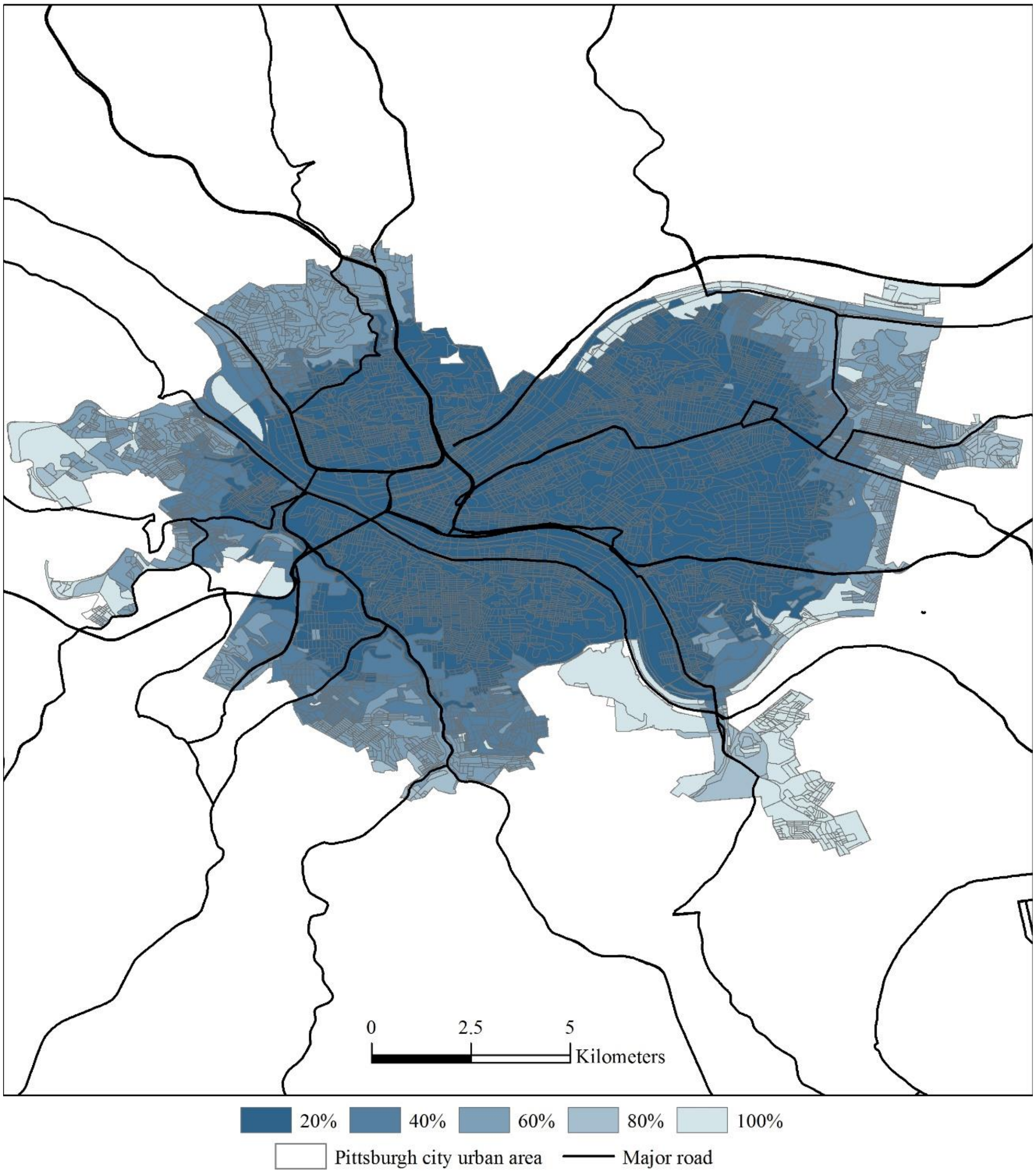

Figure 102. Pittsburgh, Pennsylvania 9-kilometer accessibility using roads

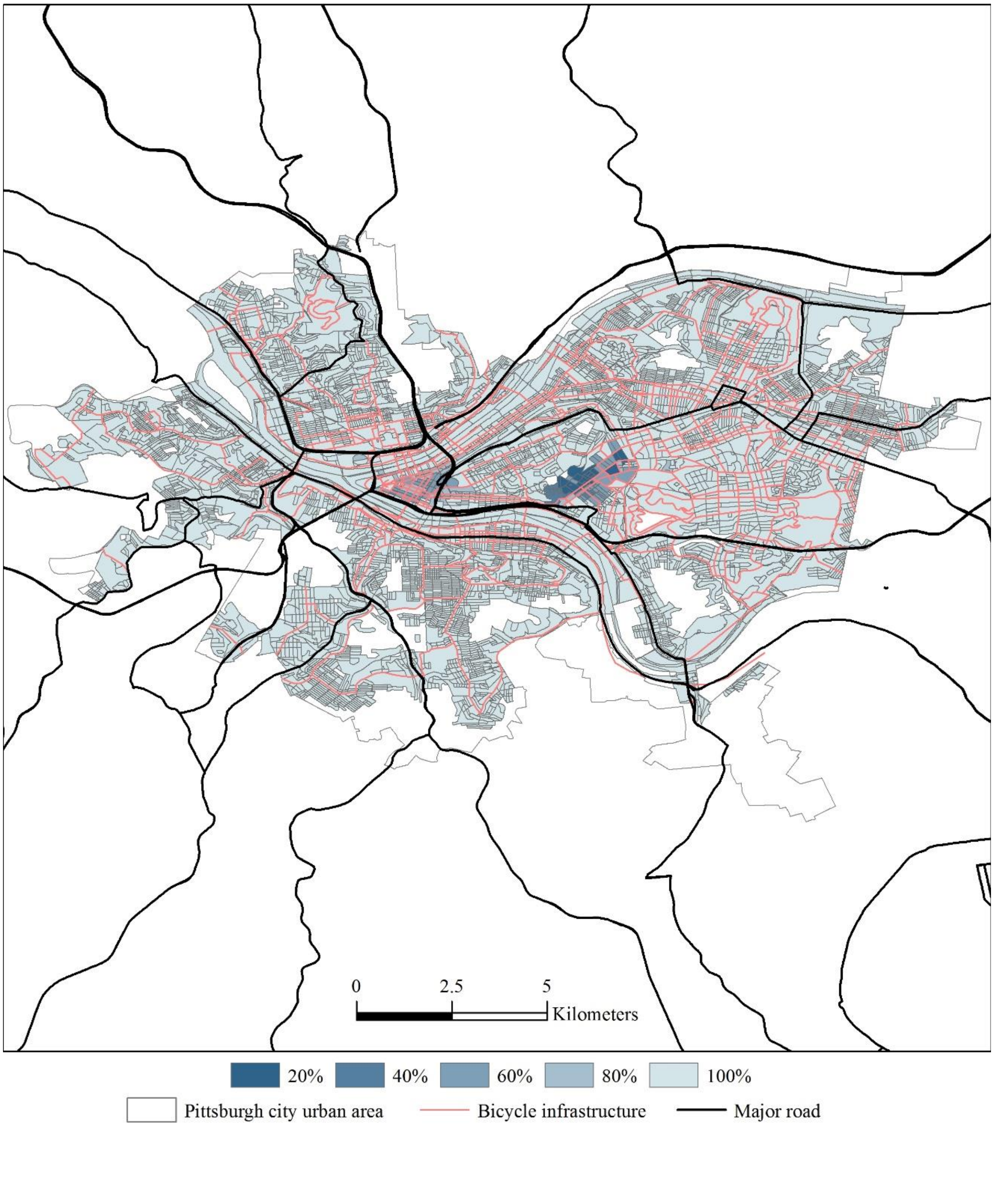

Figure 103. Pittsburgh, Pennsylvania 1-kilometer accessibility using all bicycle infrastructure

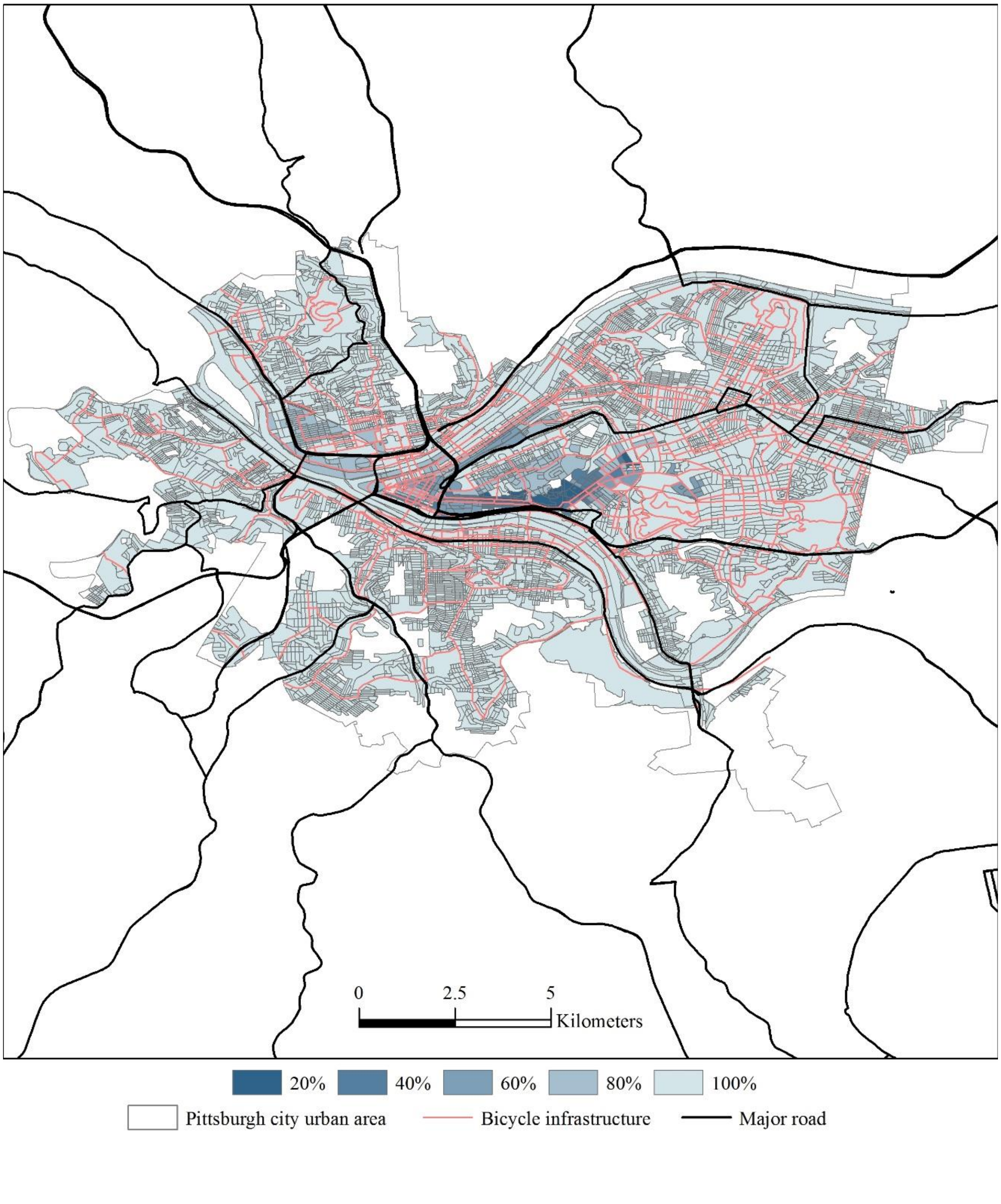

Figure 104. Pittsburgh, Pennsylvania 3-kilometer accessibility using all bicycle infrastructure

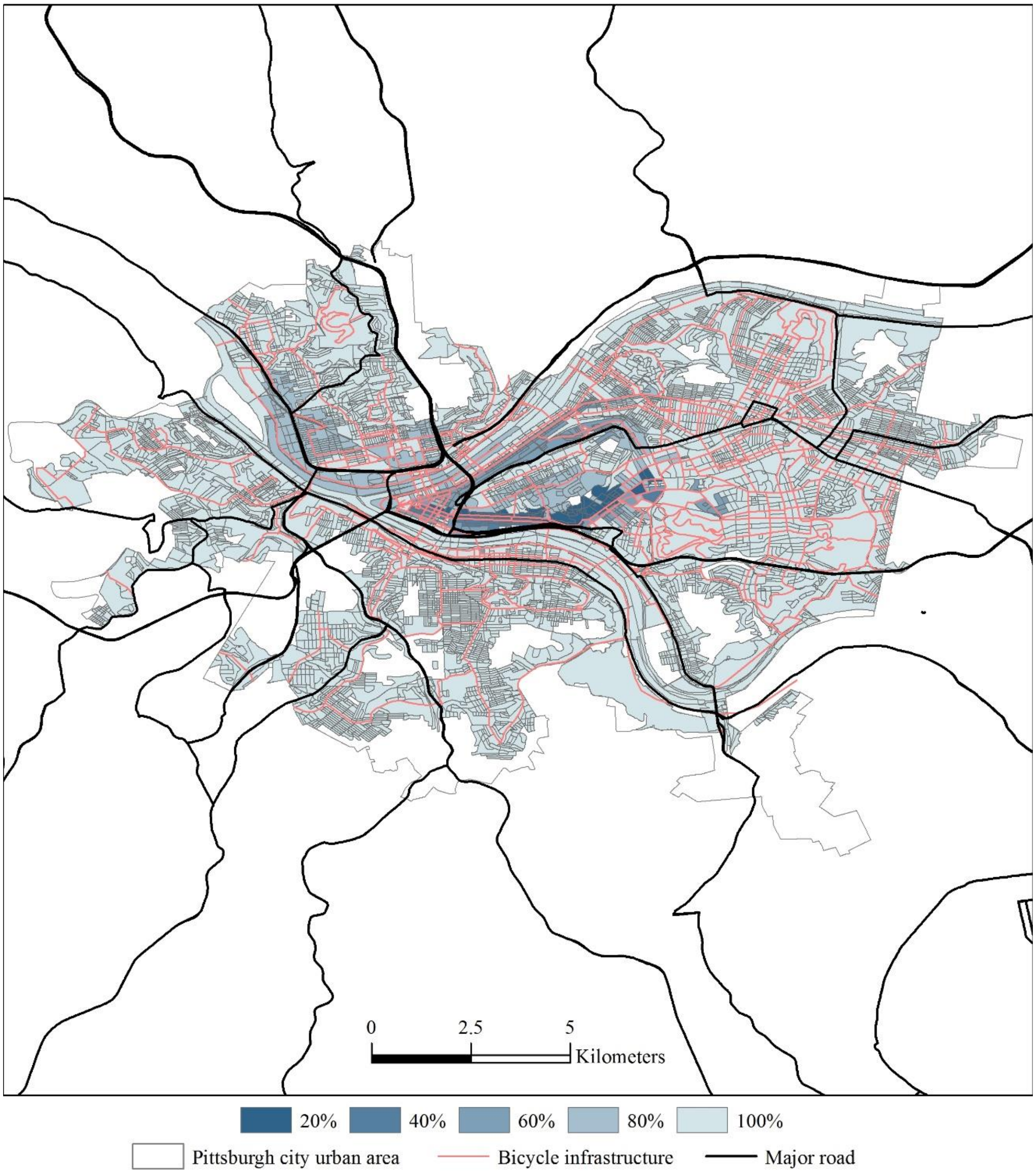

Figure 105. Pittsburgh, Pennsylvania 5-kilometer accessibility using all bicycle infrastructure

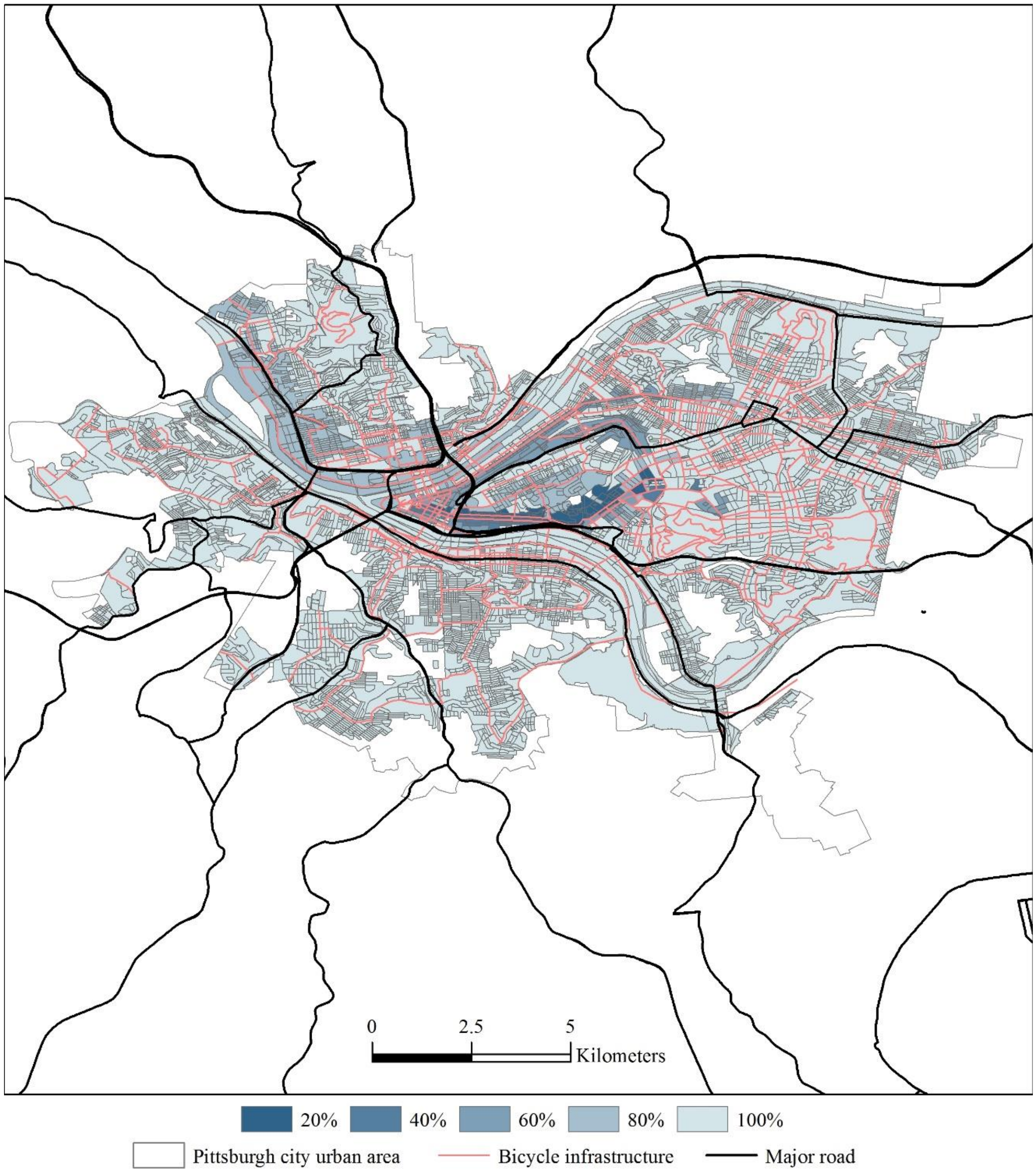

Figure 106. Pittsburgh, Pennsylvania 7-kilometer accessibility using all bicycle infrastructure

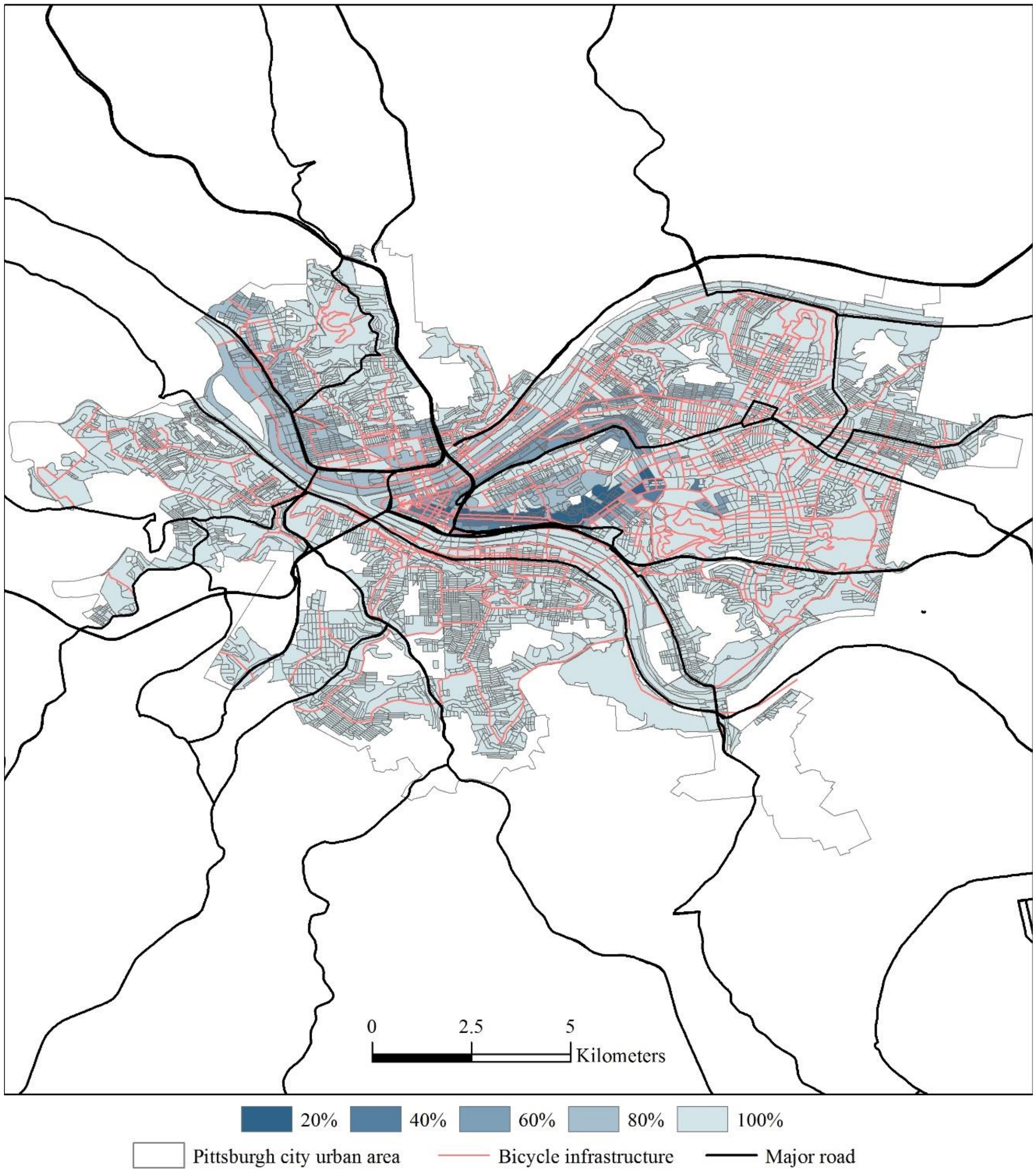

Figure 107. Pittsburgh, Pennsylvania 9-kilometer accessibility using all bicycle infrastructure

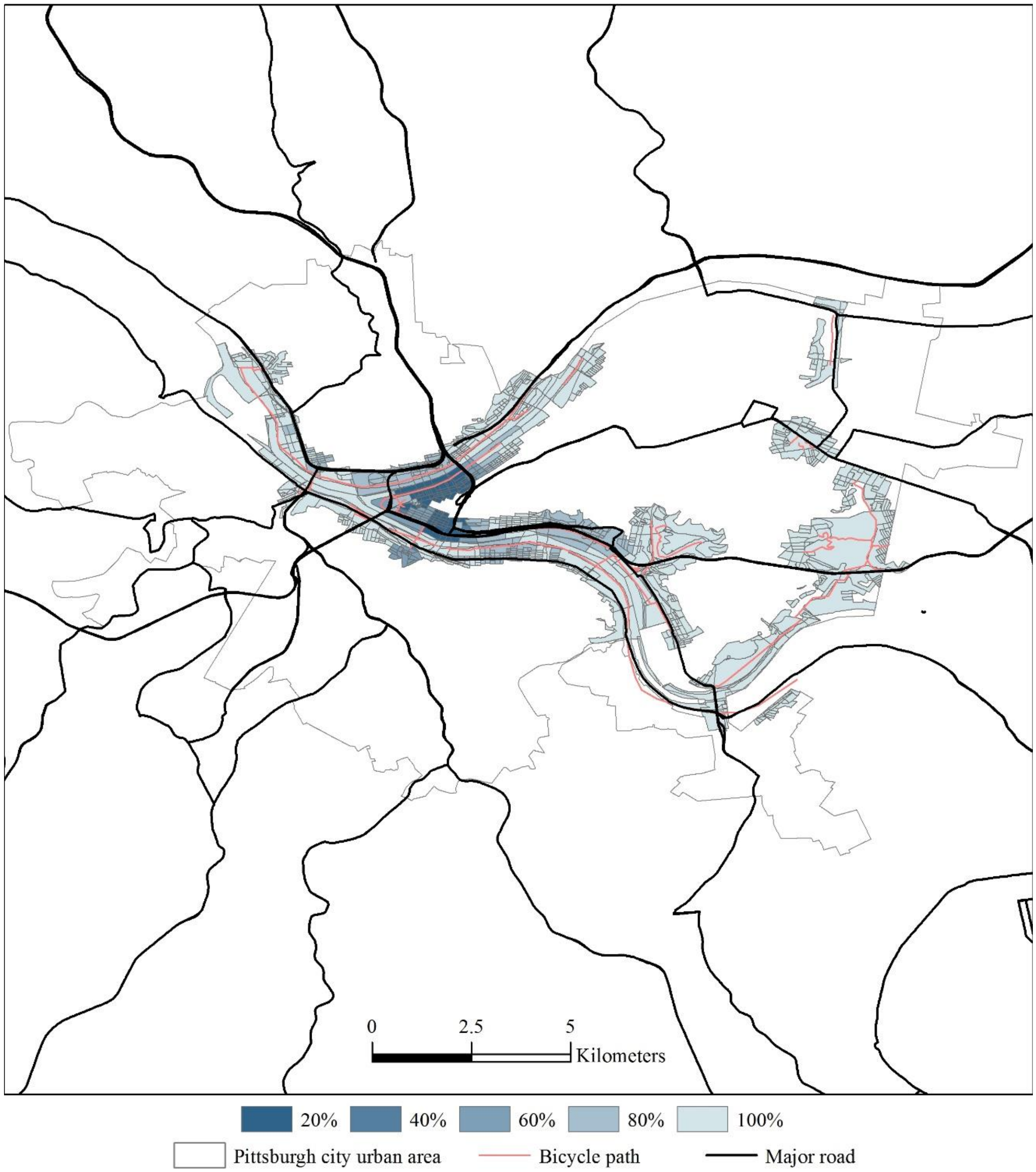

Figure 108. Pittsburgh, Pennsylvania 1-kilometer accessibility using bicycle paths

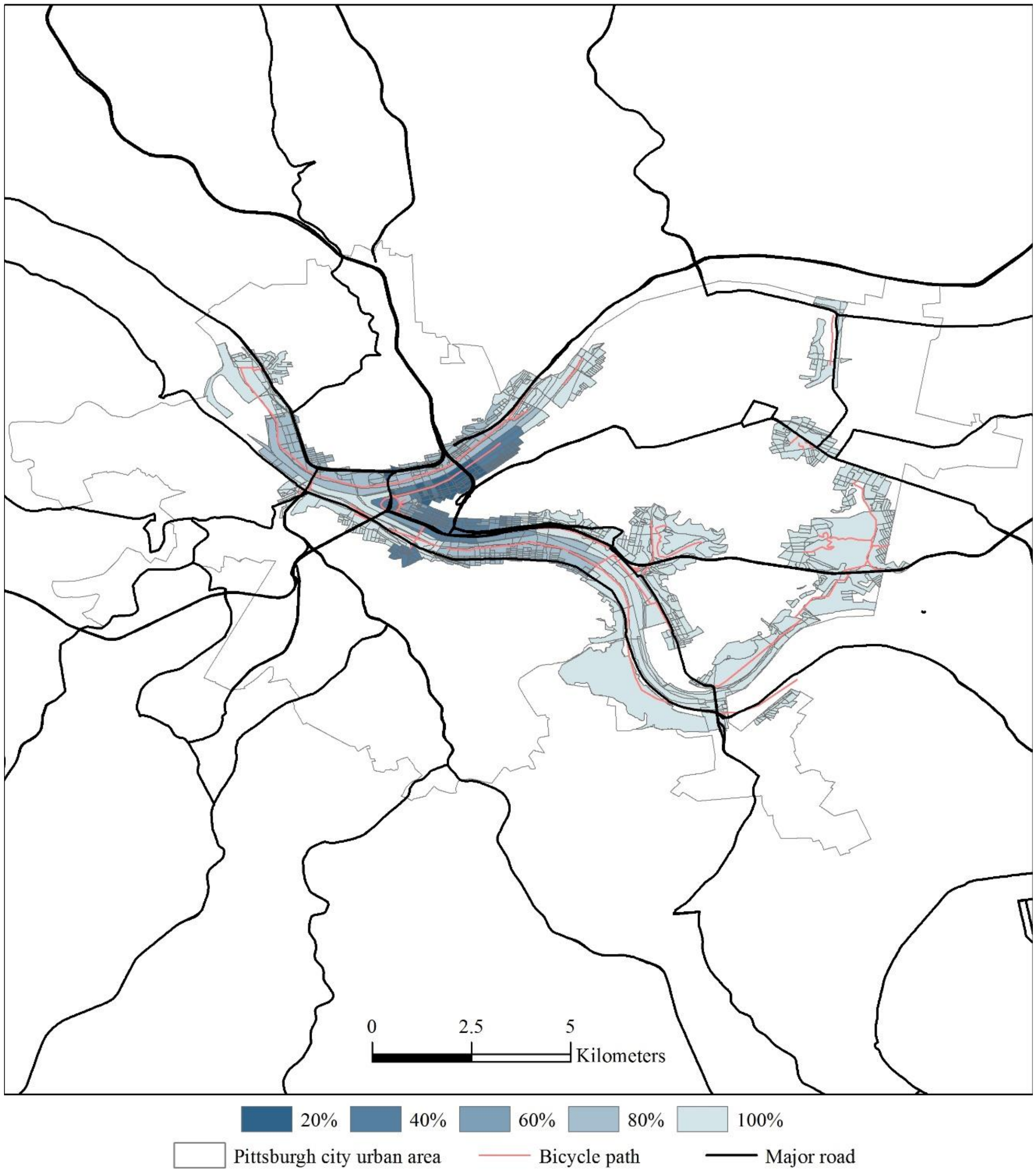

Figure 109. Pittsburgh, Pennsylvania 3-kilometer accessibility using bicycle paths

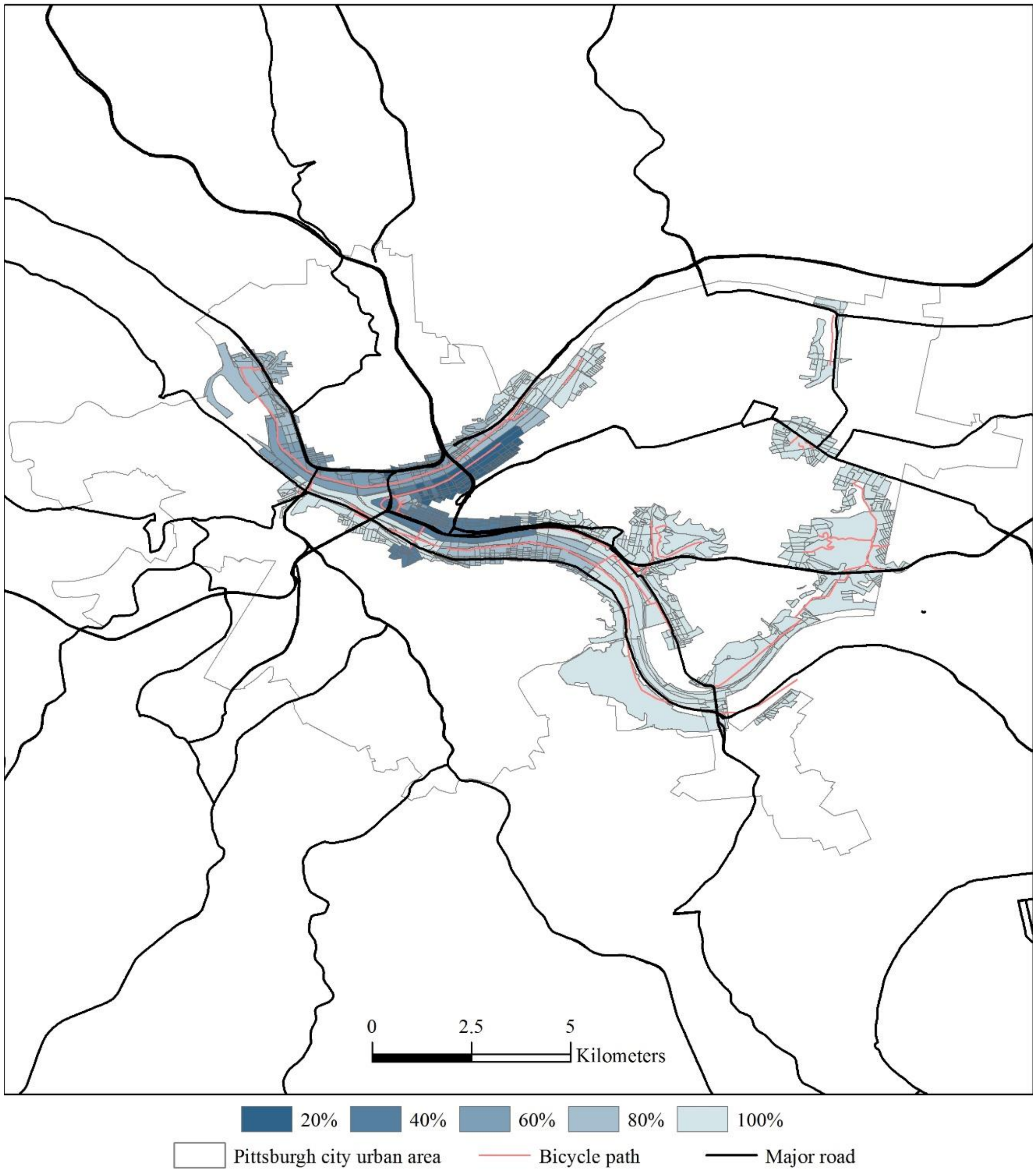

Figure 110. Pittsburgh, Pennsylvania 5-kilometer accessibility using bicycle paths

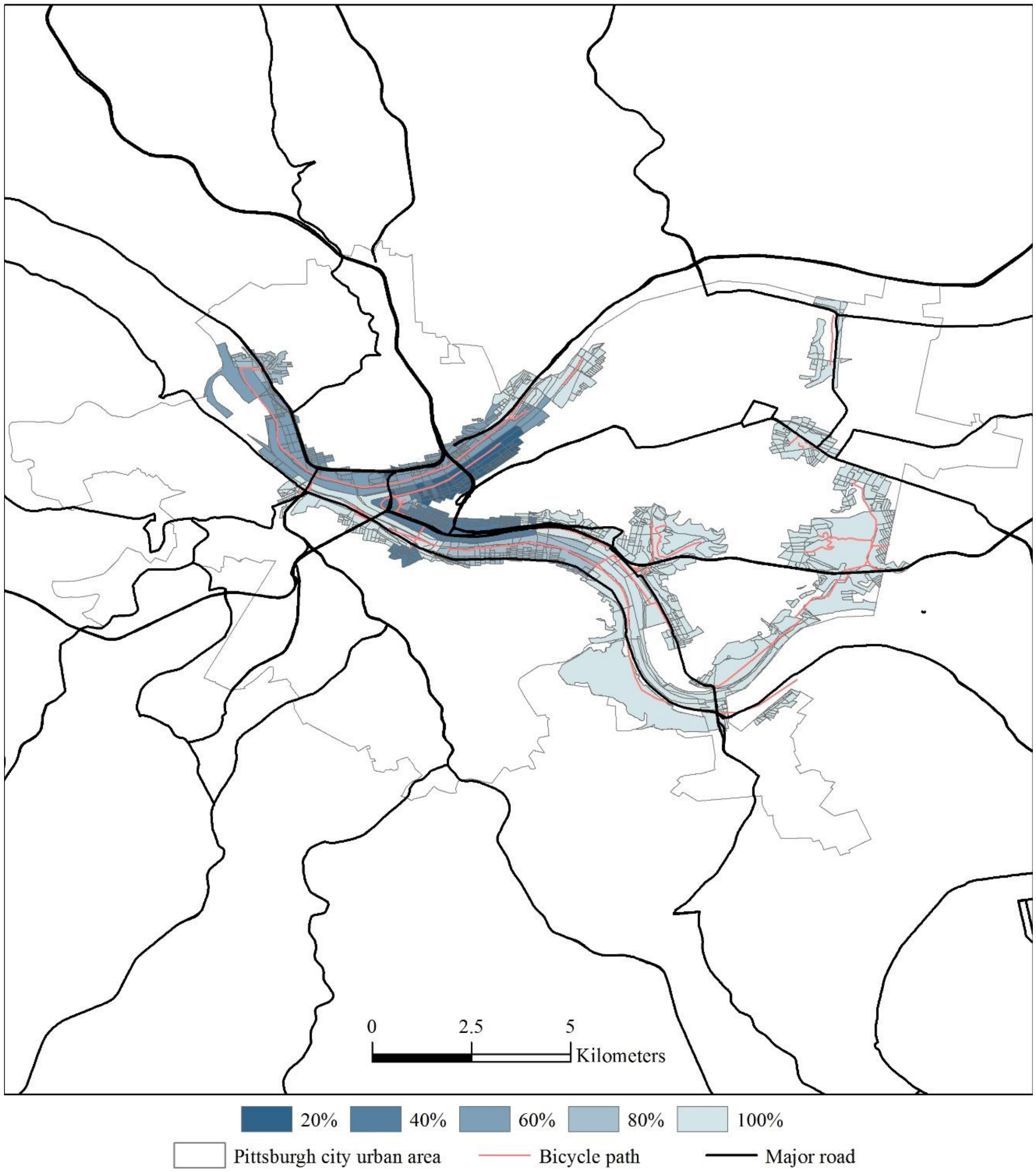

Figure 111. Pittsburgh, Pennsylvania 7-kilometer accessibility using bicycle paths

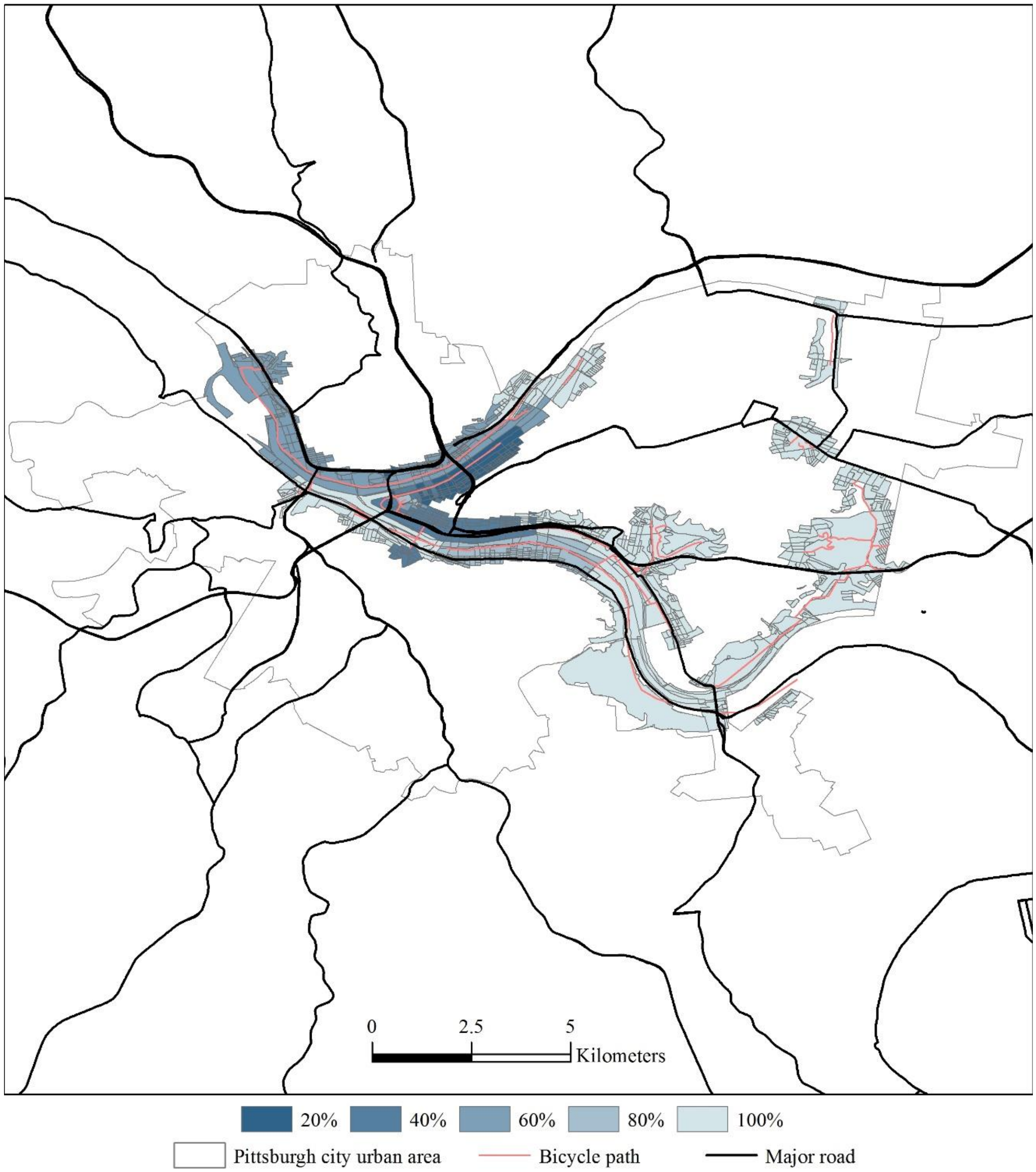

Figure 112. Pittsburgh, Pennsylvania 9-kilometer accessibility using bicycle paths

APPENDIX H

Portland, Oregon City Zonal Accessibility Maps

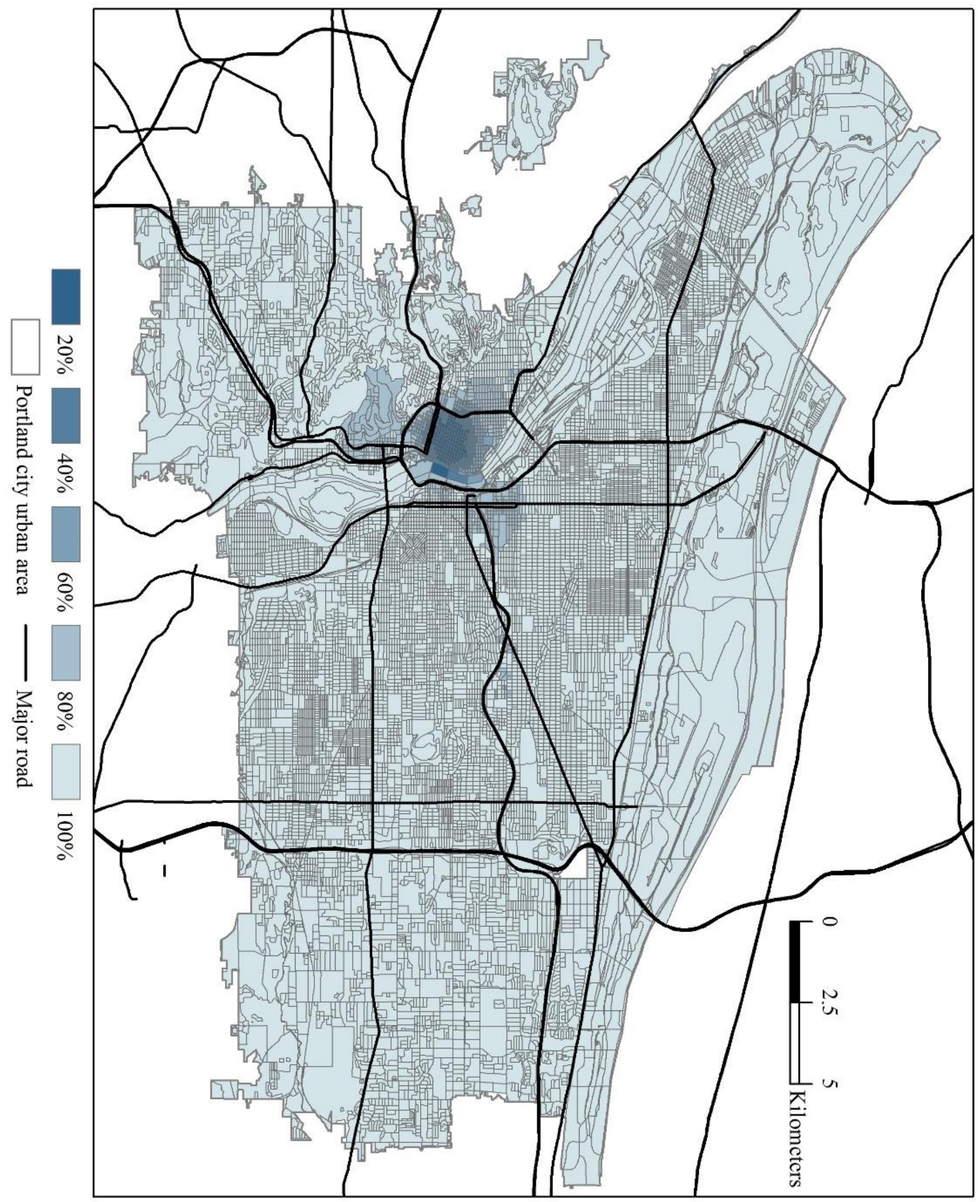

Figure 113. Portland, Oregon 1-kilometer accessibility using roads

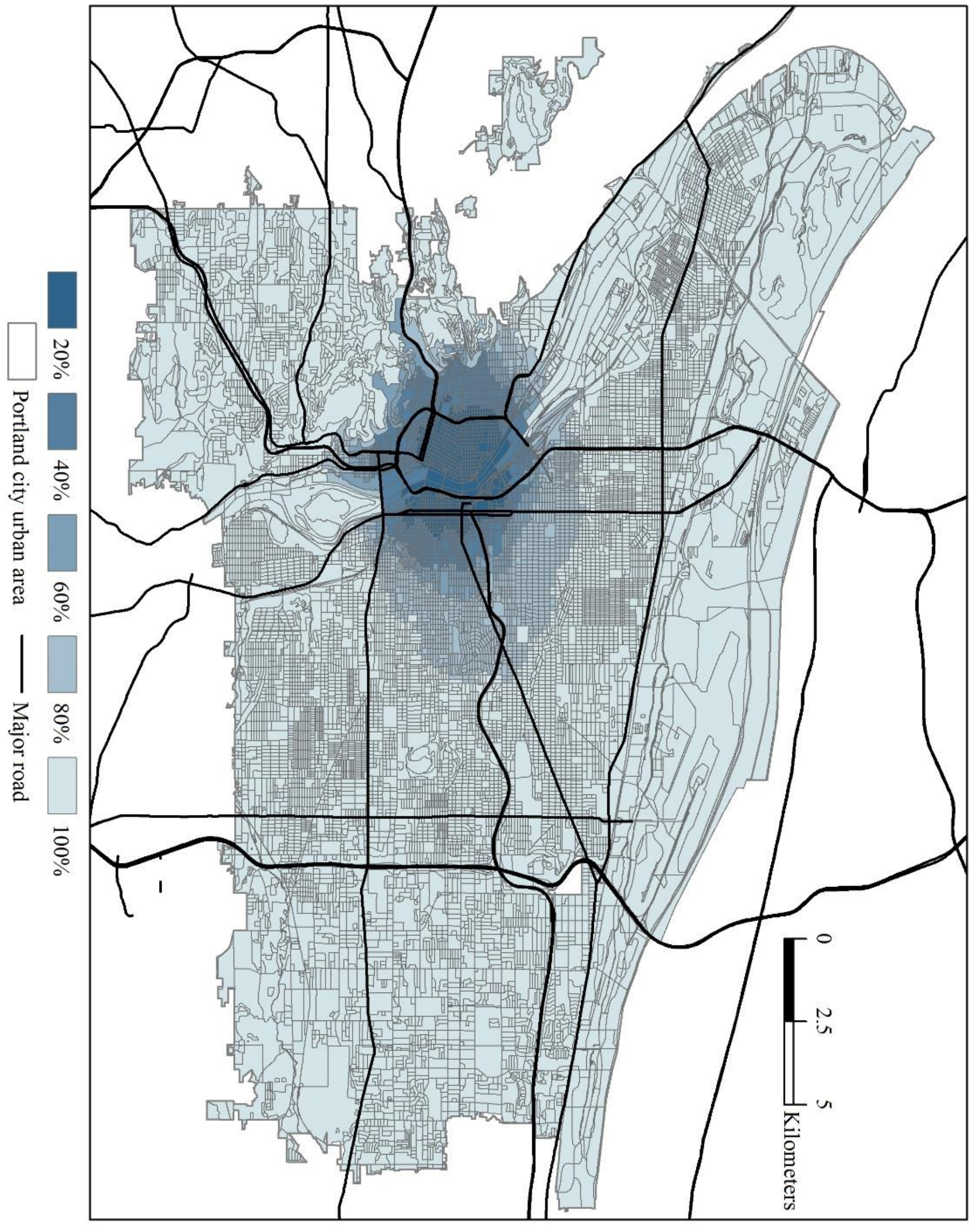

Figure 114. Portland, Oregon 3-kilometer accessibility using roads

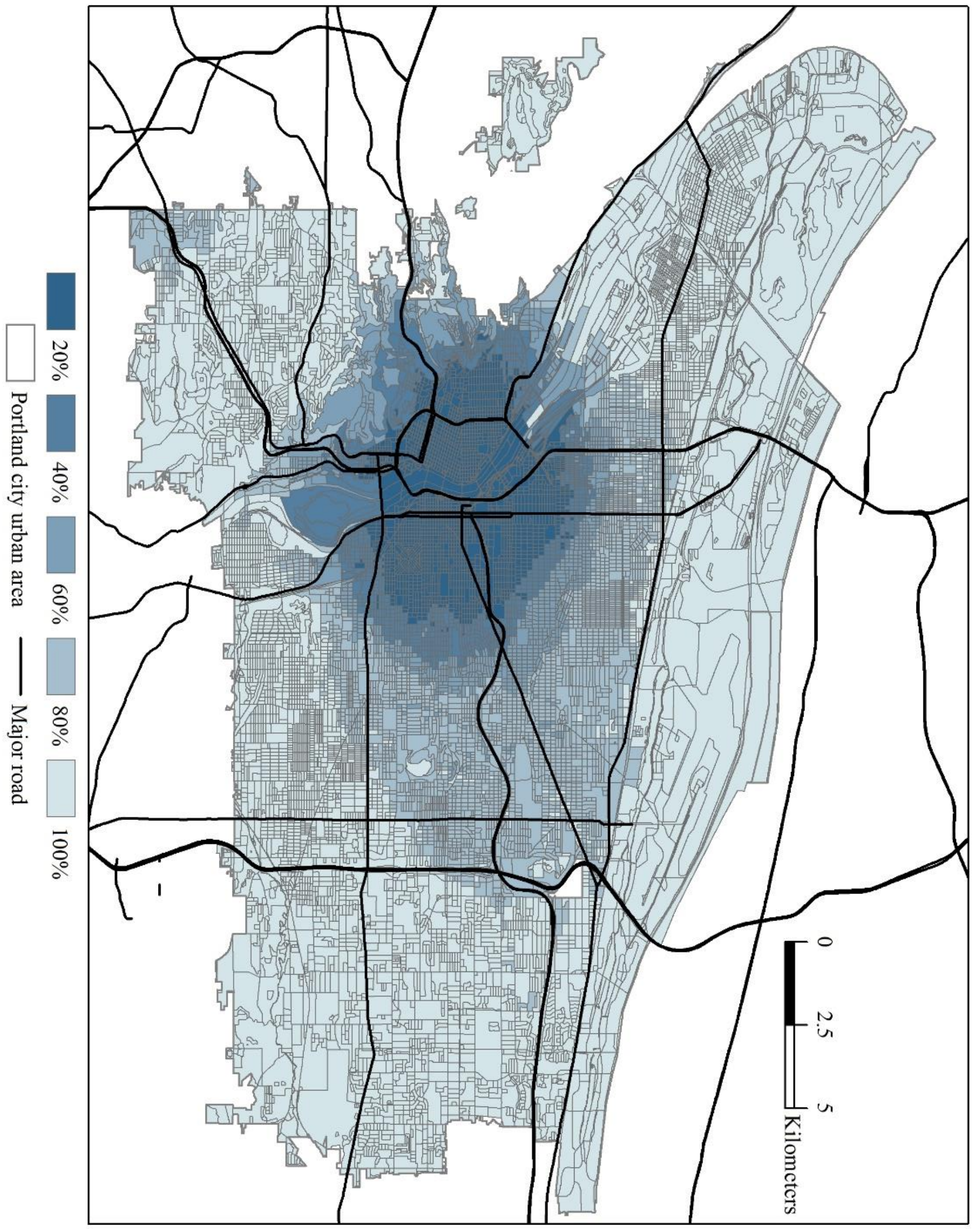

Figure 115. Portland, Oregon 5-kilometer accessibility using roads

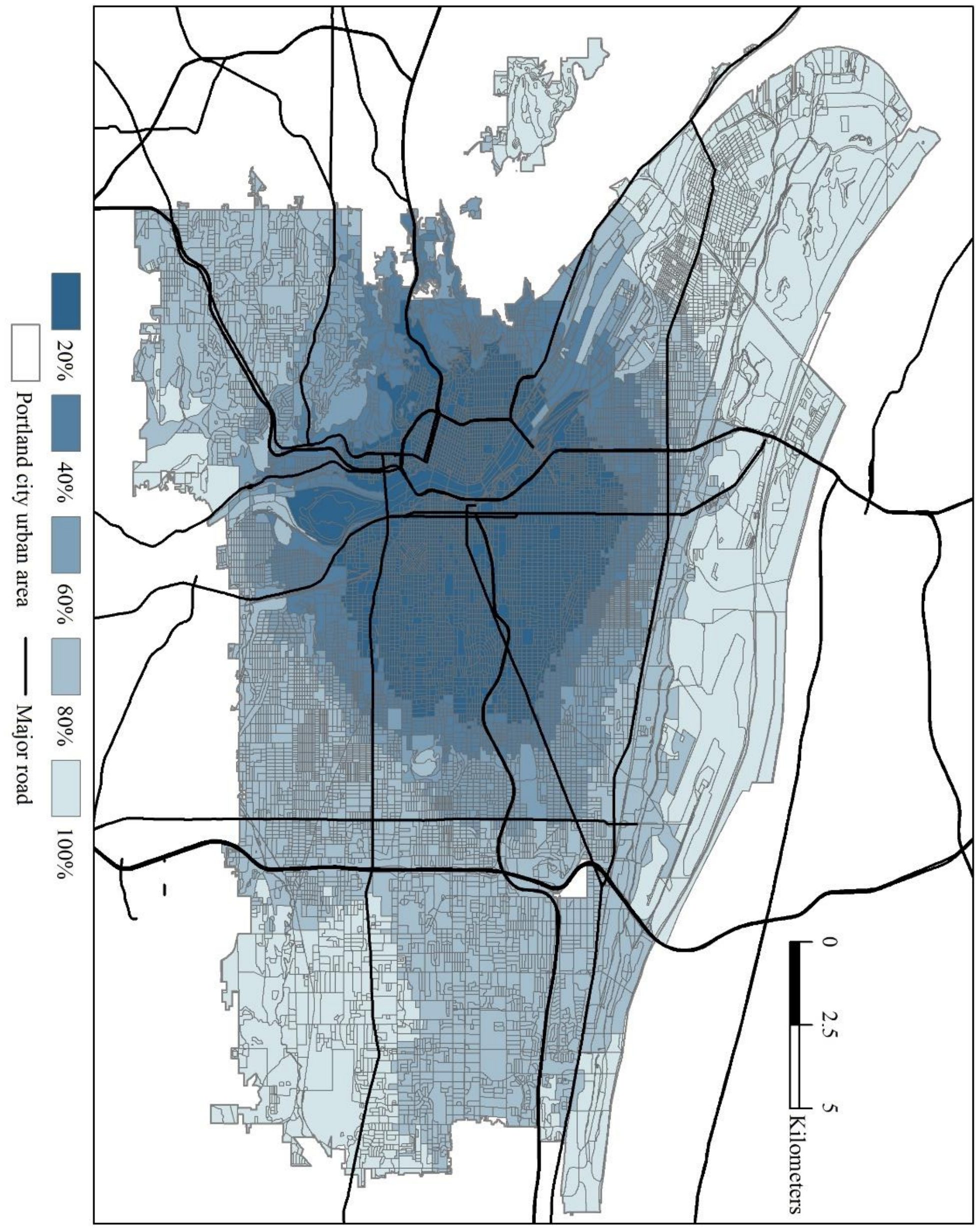

Figure 116. Portland, Oregon 7-kilometer accessibility using roads

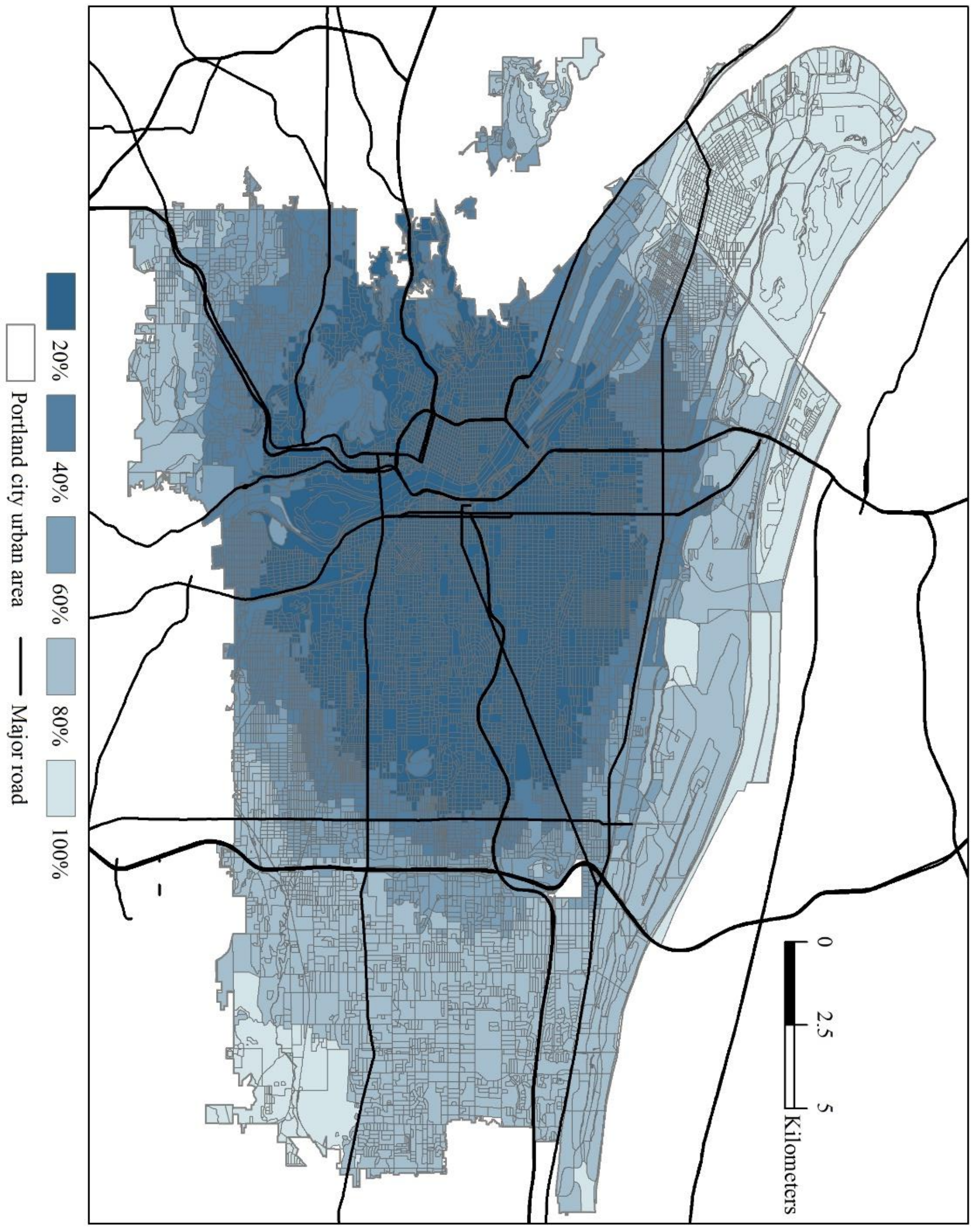

Figure 117. Portland, Oregon 9-kilometer accessibility using roads

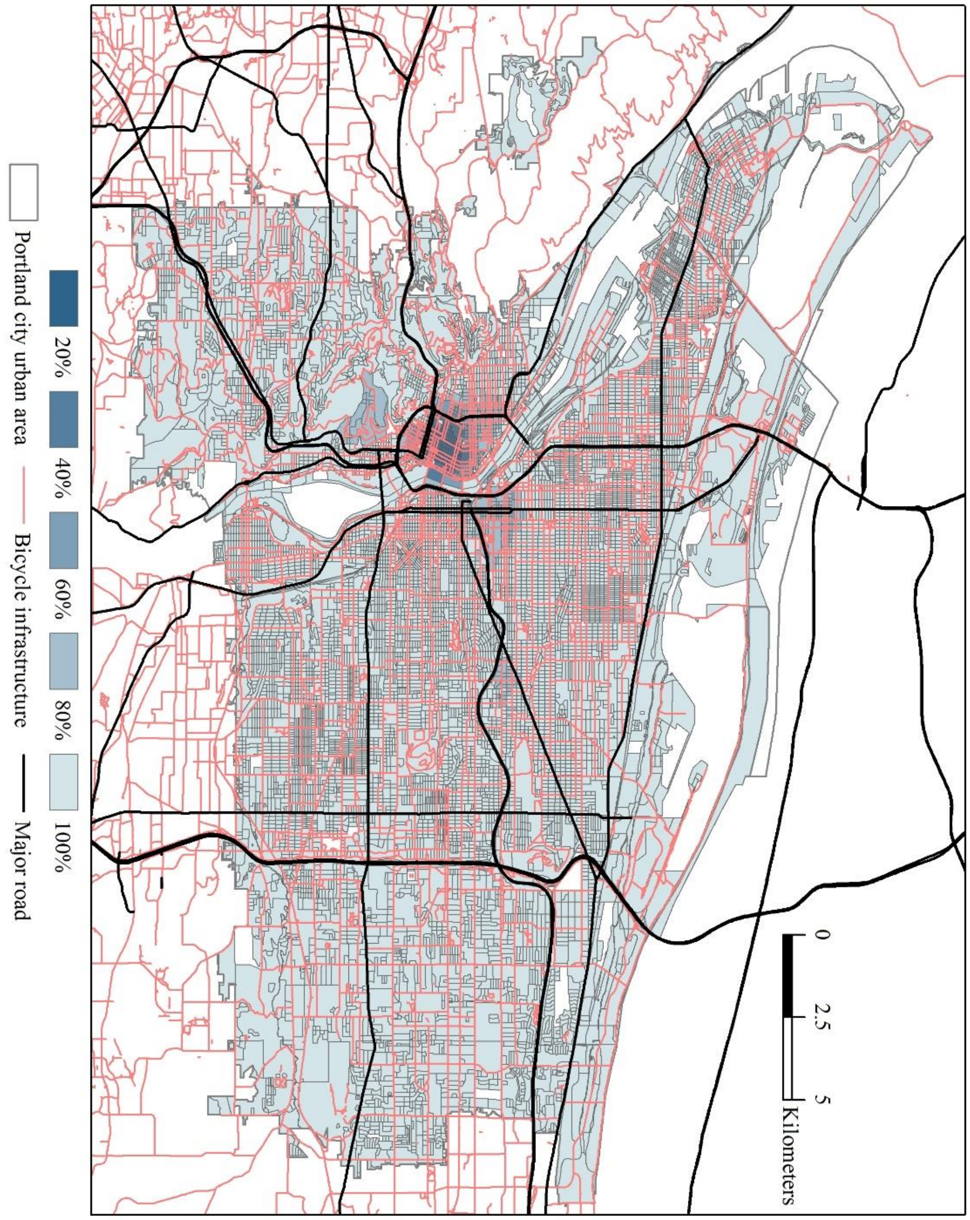

Figure 118. Portland, Oregon 1-kilometer accessibility using all bicycle infrastructure

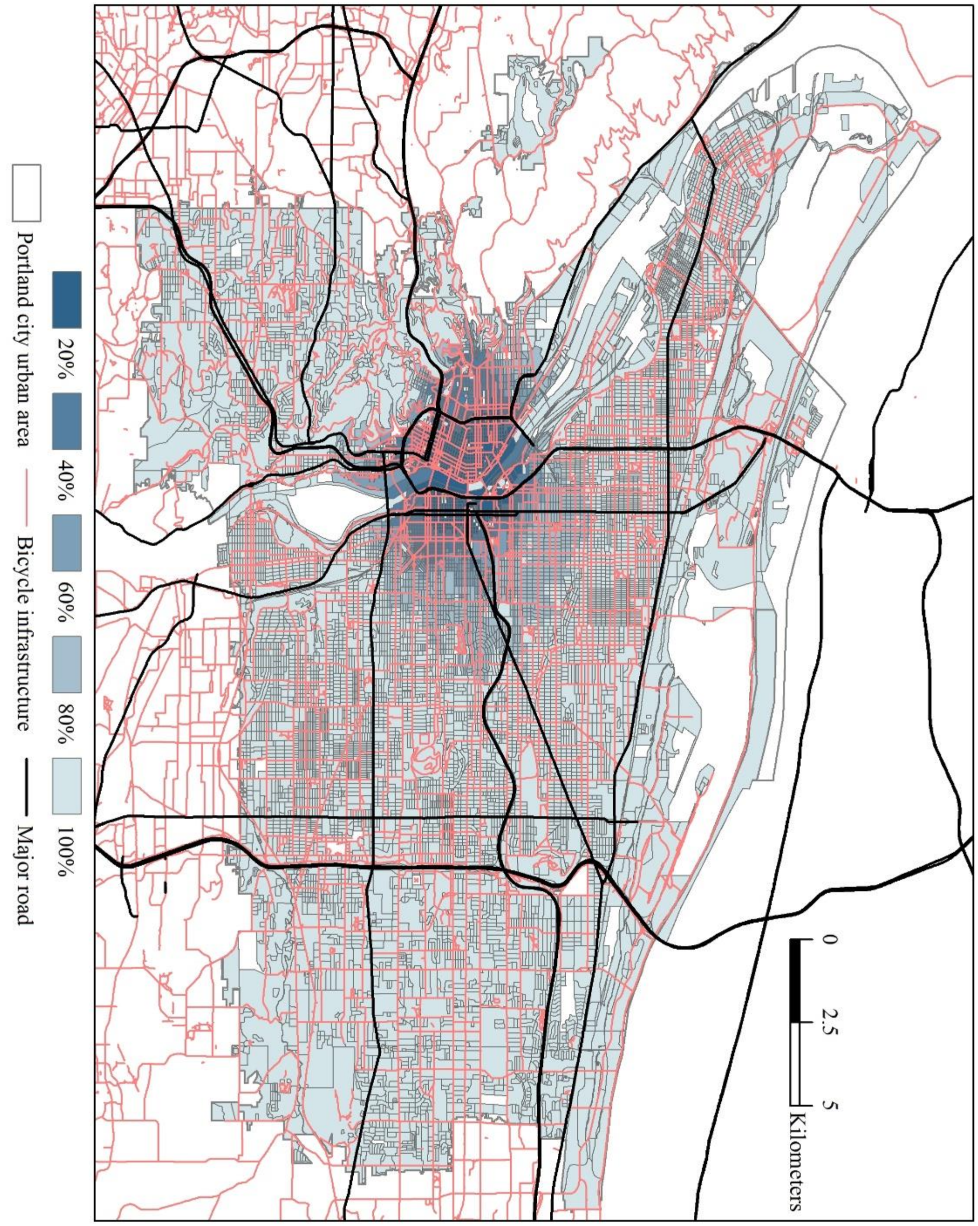

Figure 119. Portland, Oregon 3-kilometer accessibility using all bicycle infrastructure

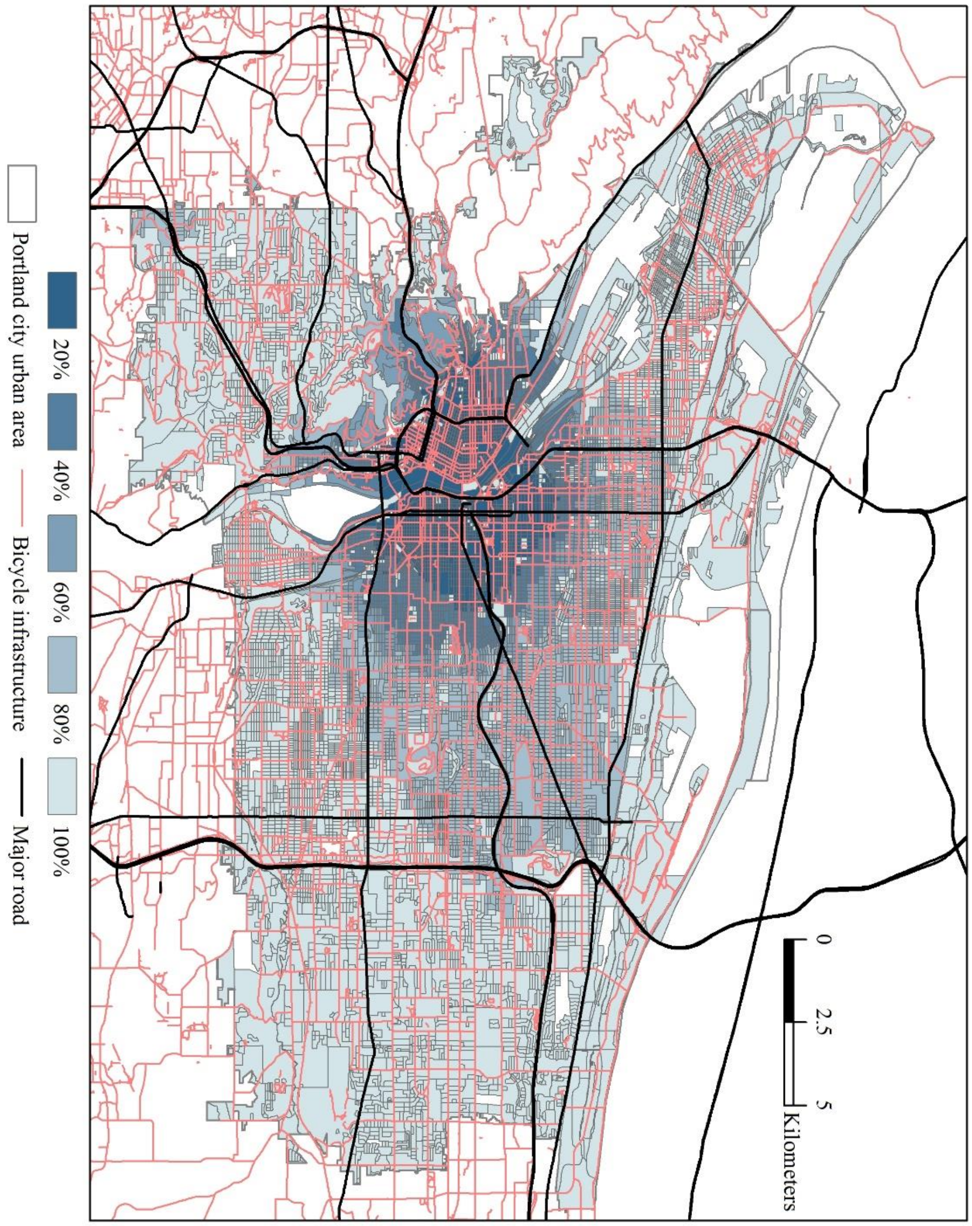

Figure 120. Portland, Oregon 5-kilometer accessibility using all bicycle infrastructure

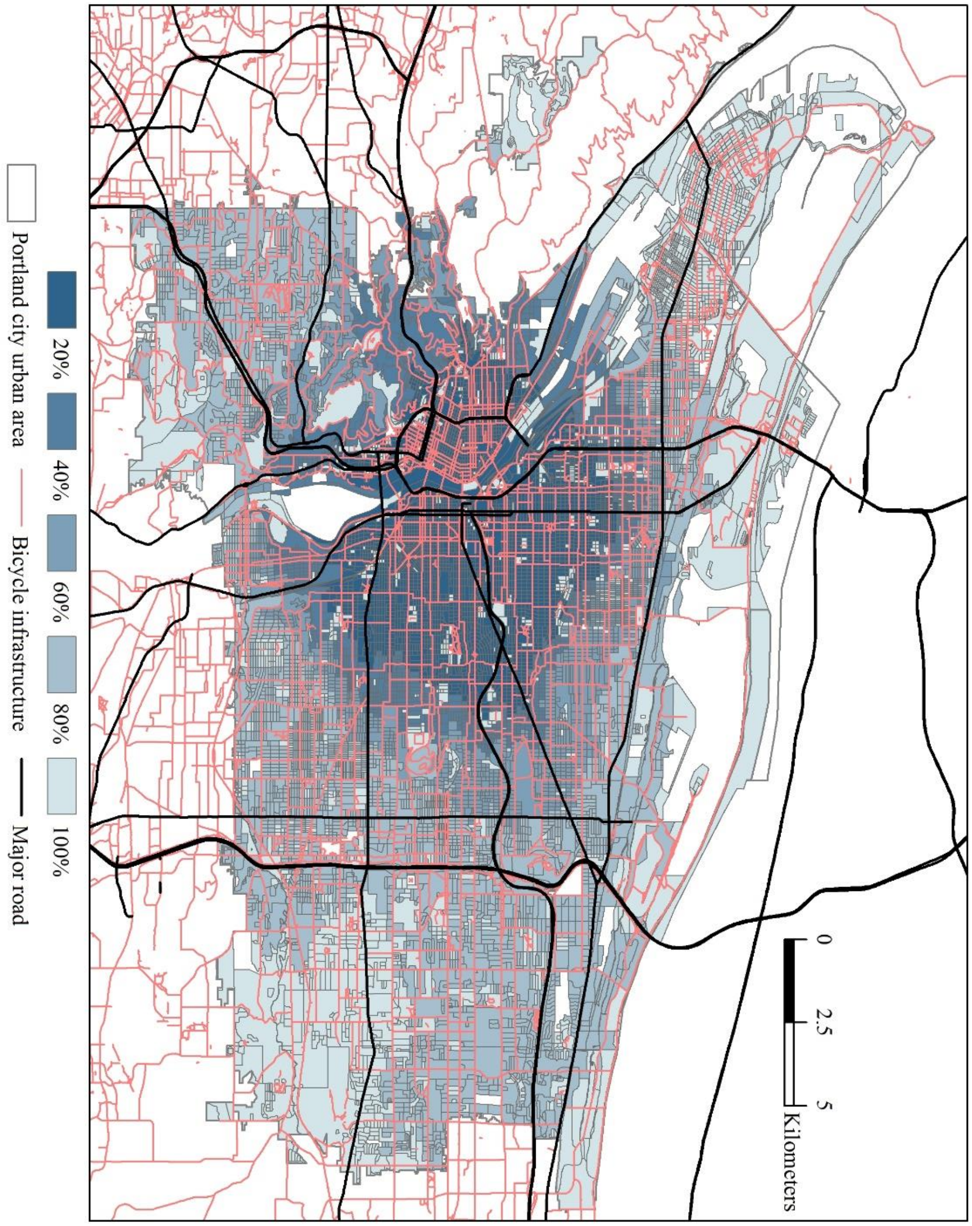

Figure 121. Portland, Oregon 7-kilometer accessibility using all bicycle infrastructure

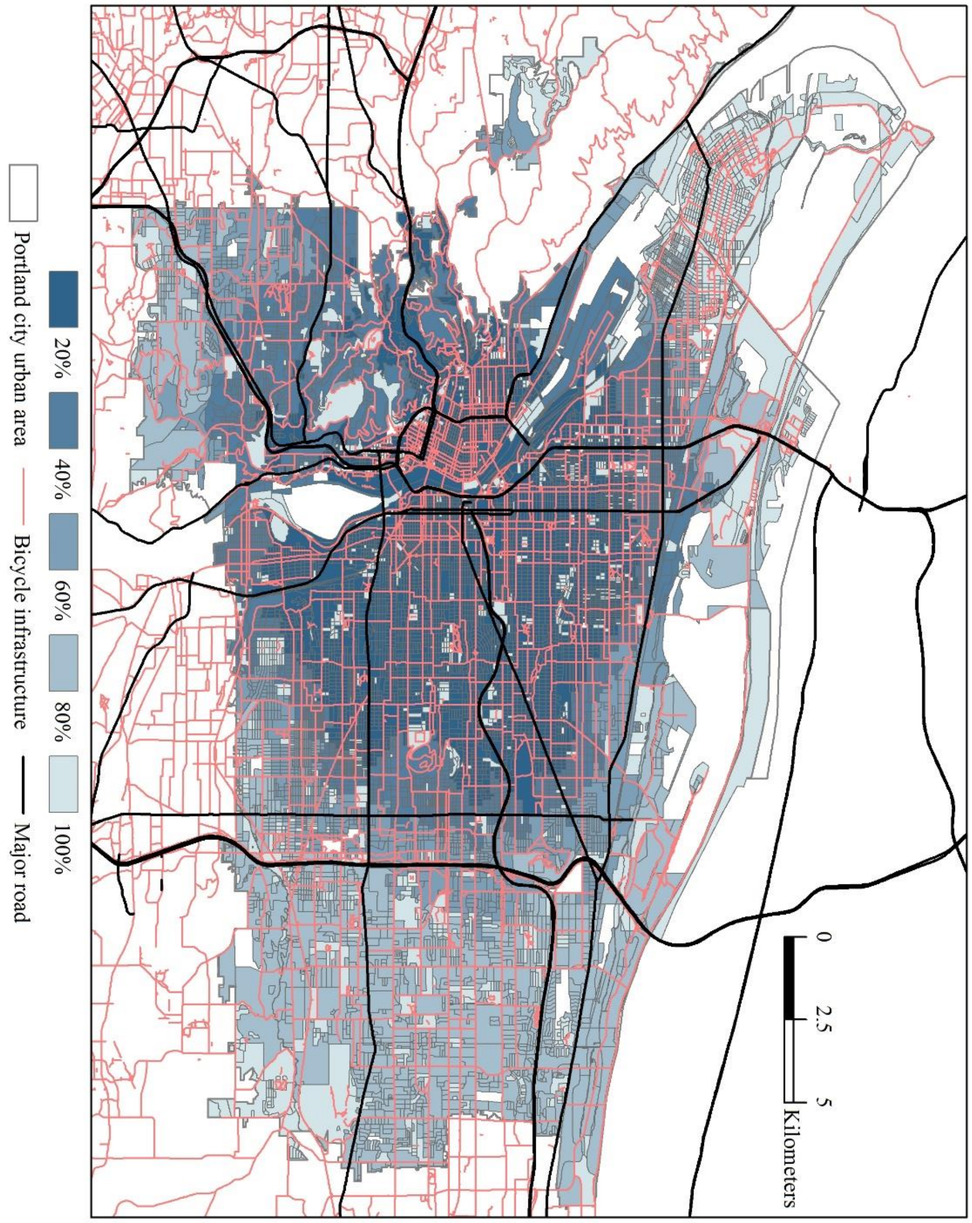

Figure 122. Portland, Oregon 9-kilometer accessibility using all bicycle infrastructure

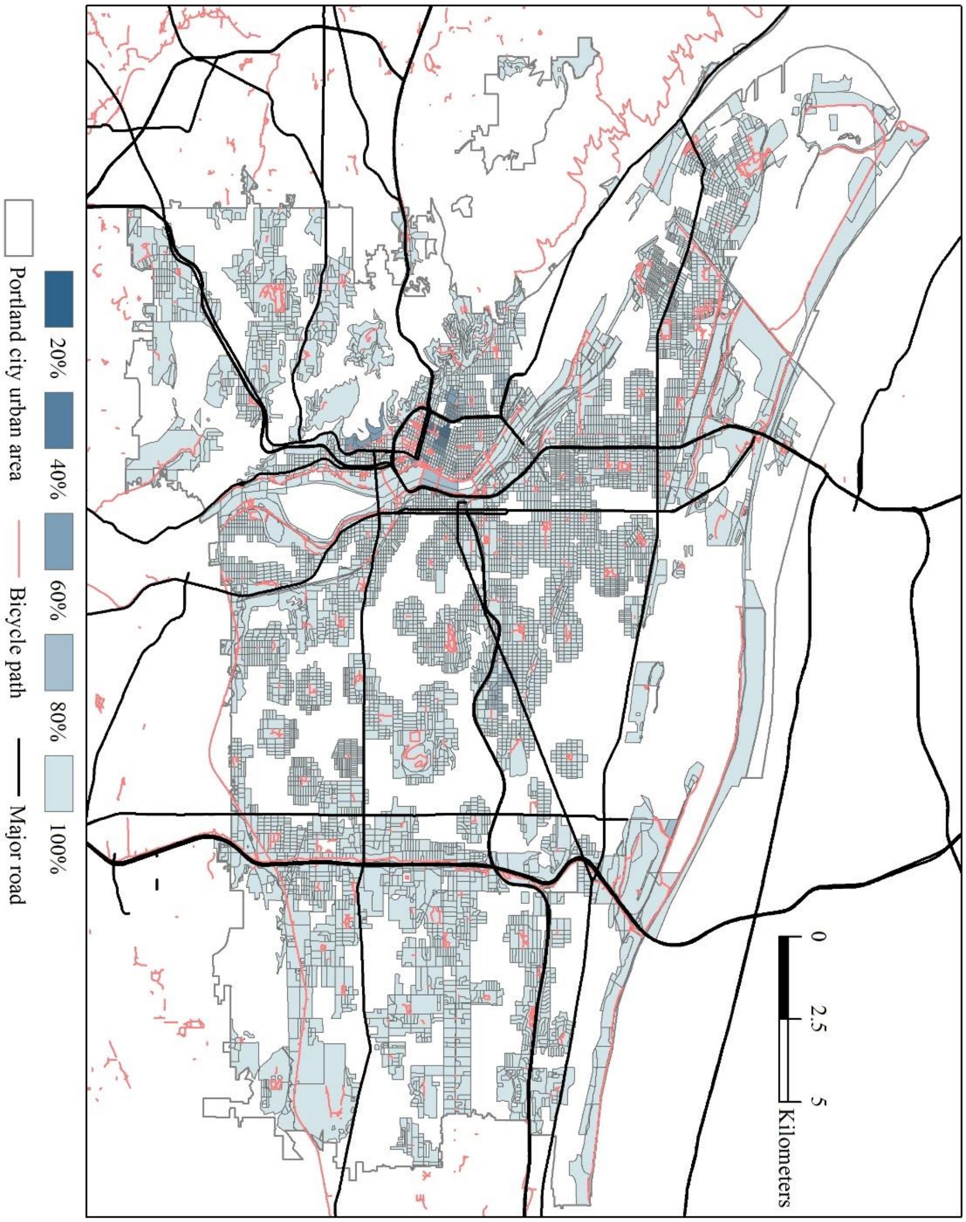

Figure 123. Portland, Oregon 1-kilometer accessibility using bicycle paths

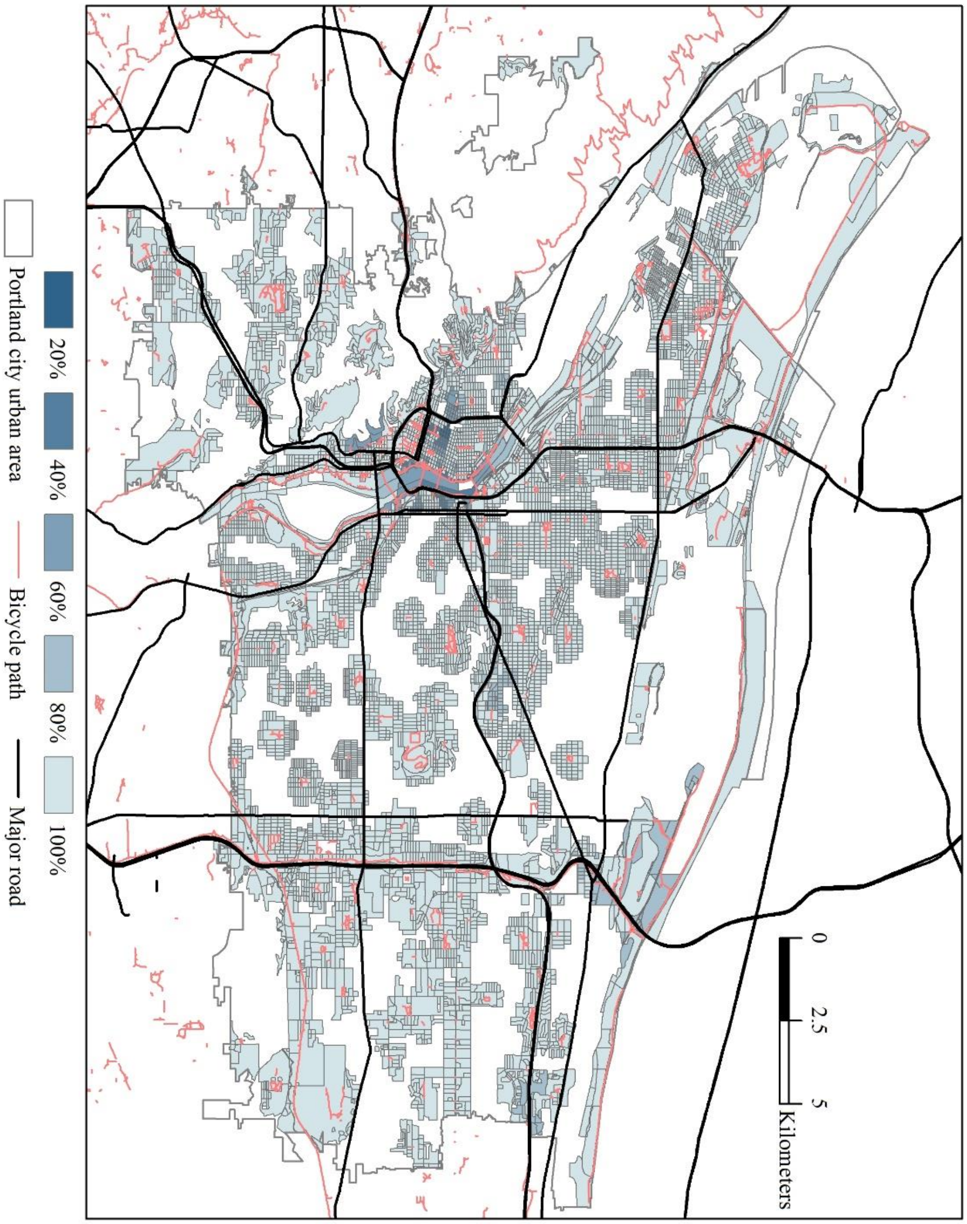

Figure 124. Portland, Oregon 3-kilometer accessibility using bicycle paths

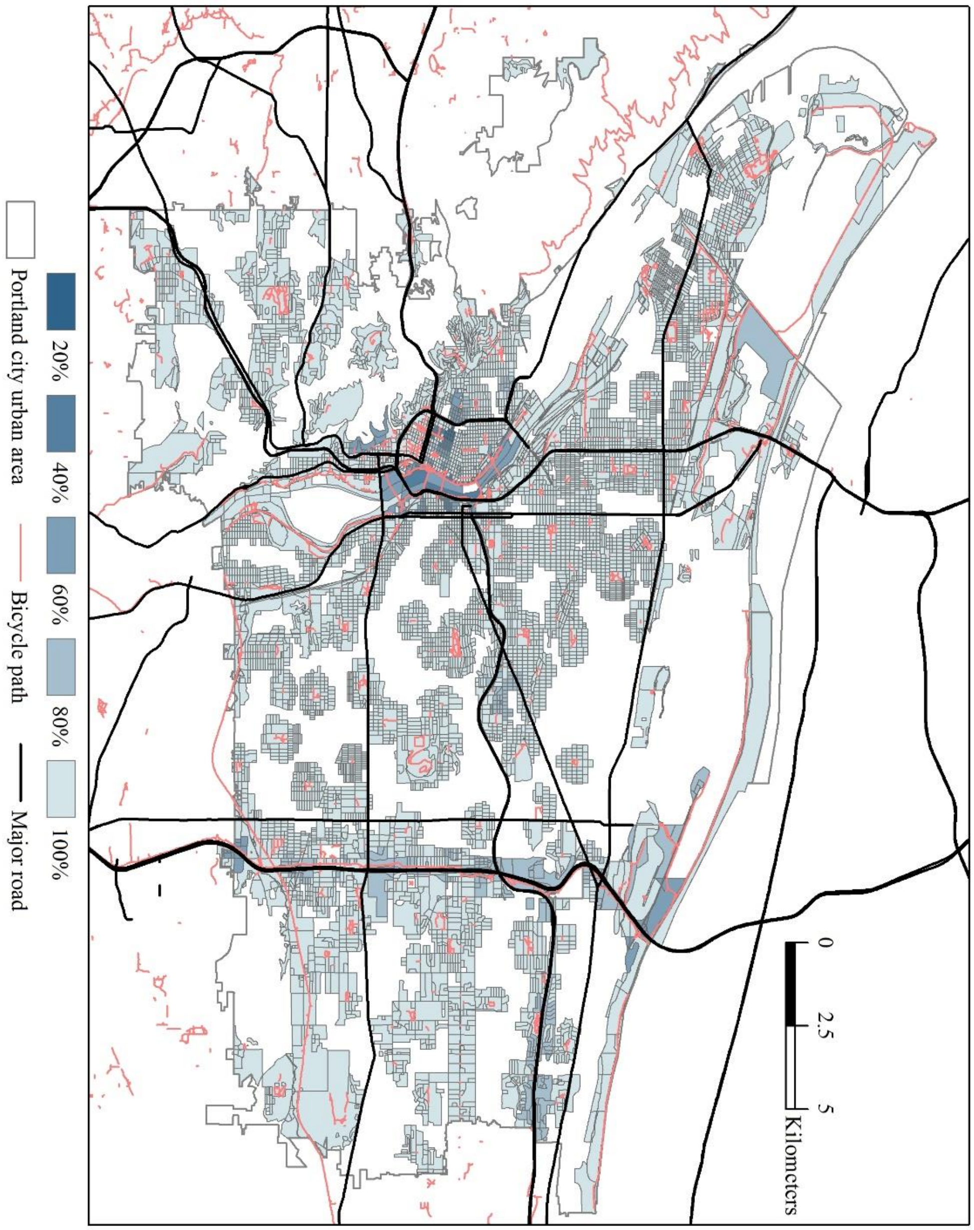

Figure 125. Portland, Oregon 5-kilometer accessibility using bicycle paths

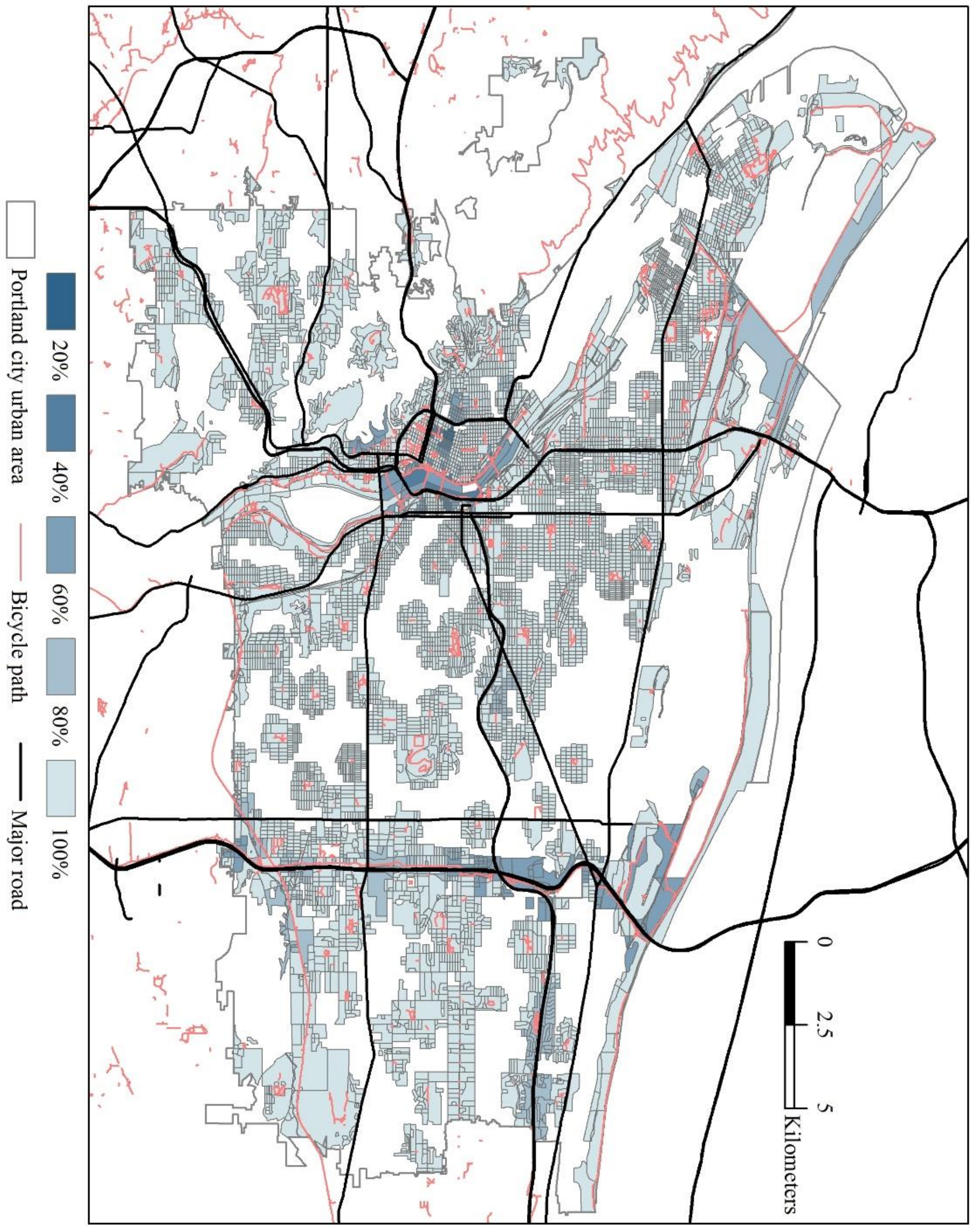

Figure 126. Portland, Oregon 7-kilometer accessibility using bicycle paths

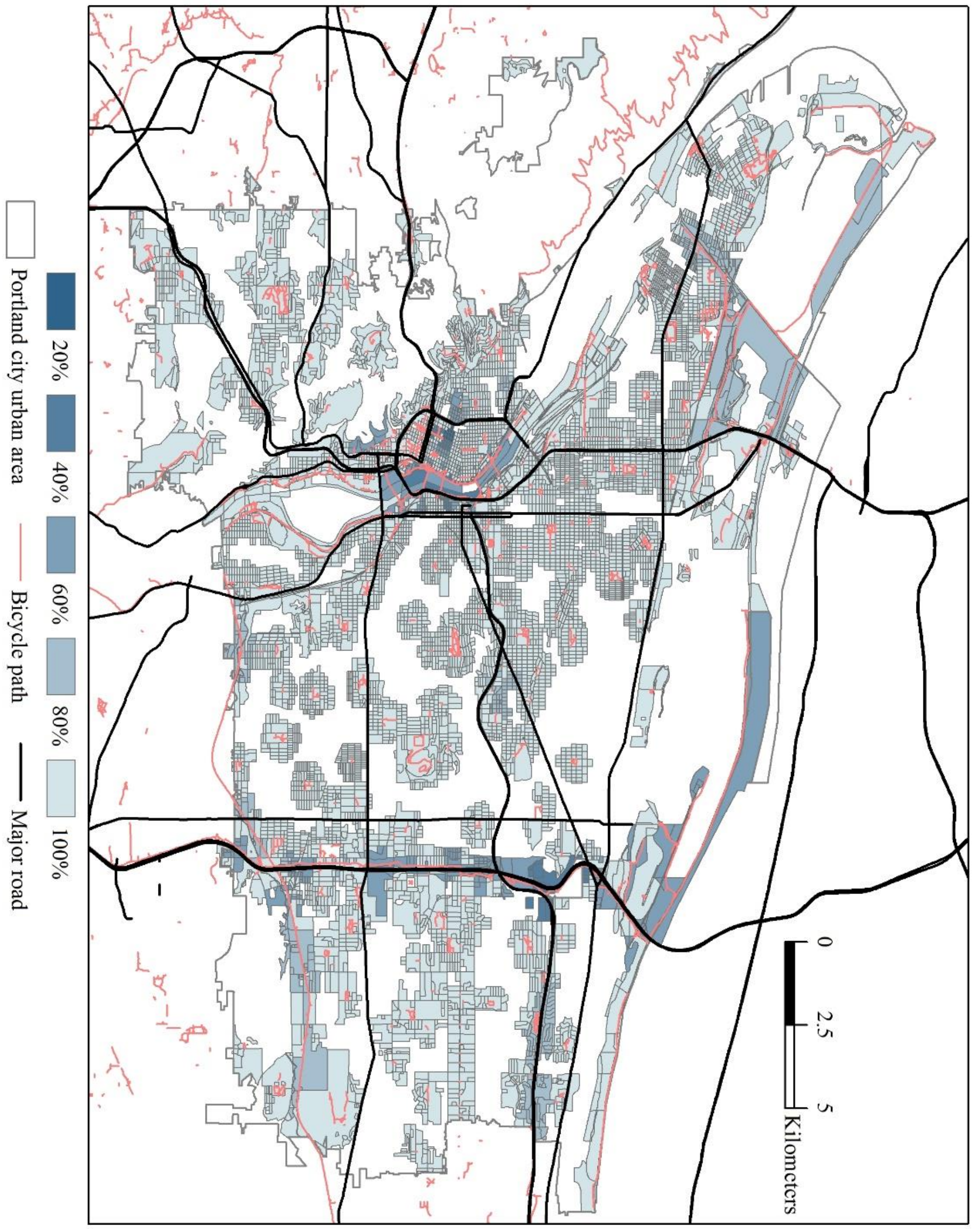

Figure 127. Portland, Oregon 9-kilometer accessibility using bicycle paths

APPENDIX I

San Antonio, Texas City Zonal Accessibility Maps

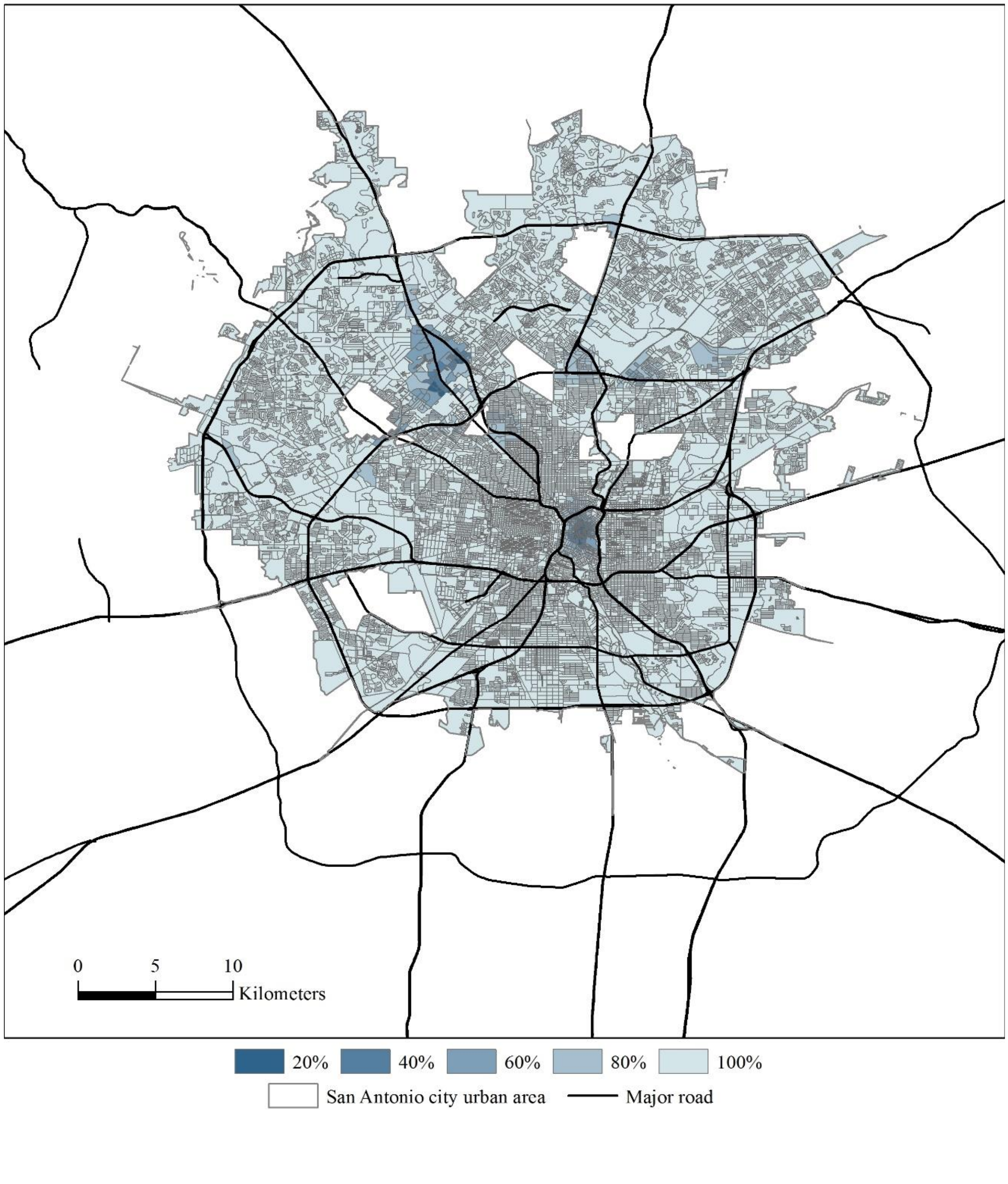

Figure 128. San Antonio, Texas 1-kilometer accessibility using roads

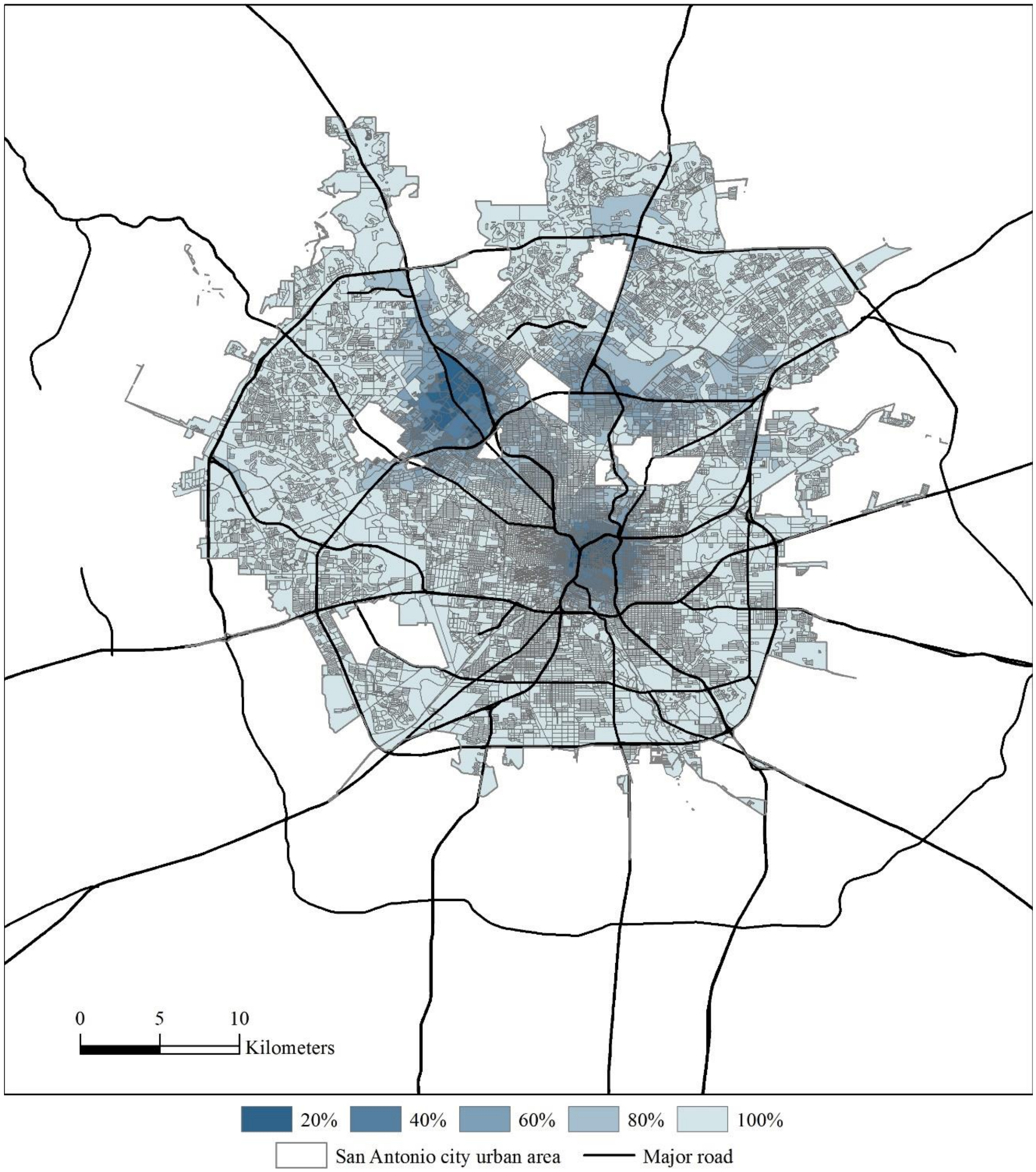

Figure 129. San Antonio, Texas 3-kilometer accessibility using roads

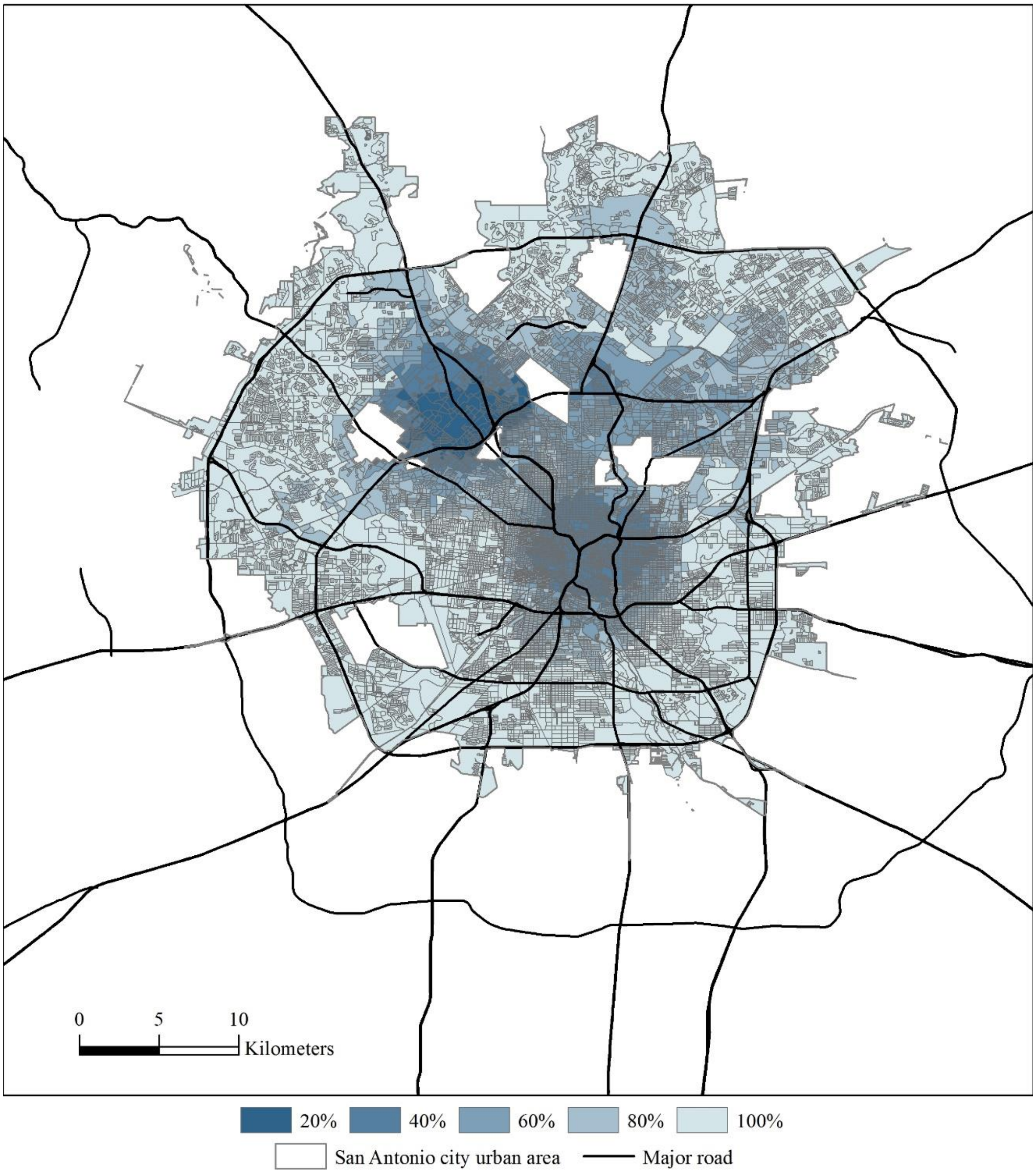

Figure 130. San Antonio, Texas 5-kilometer accessibility using roads

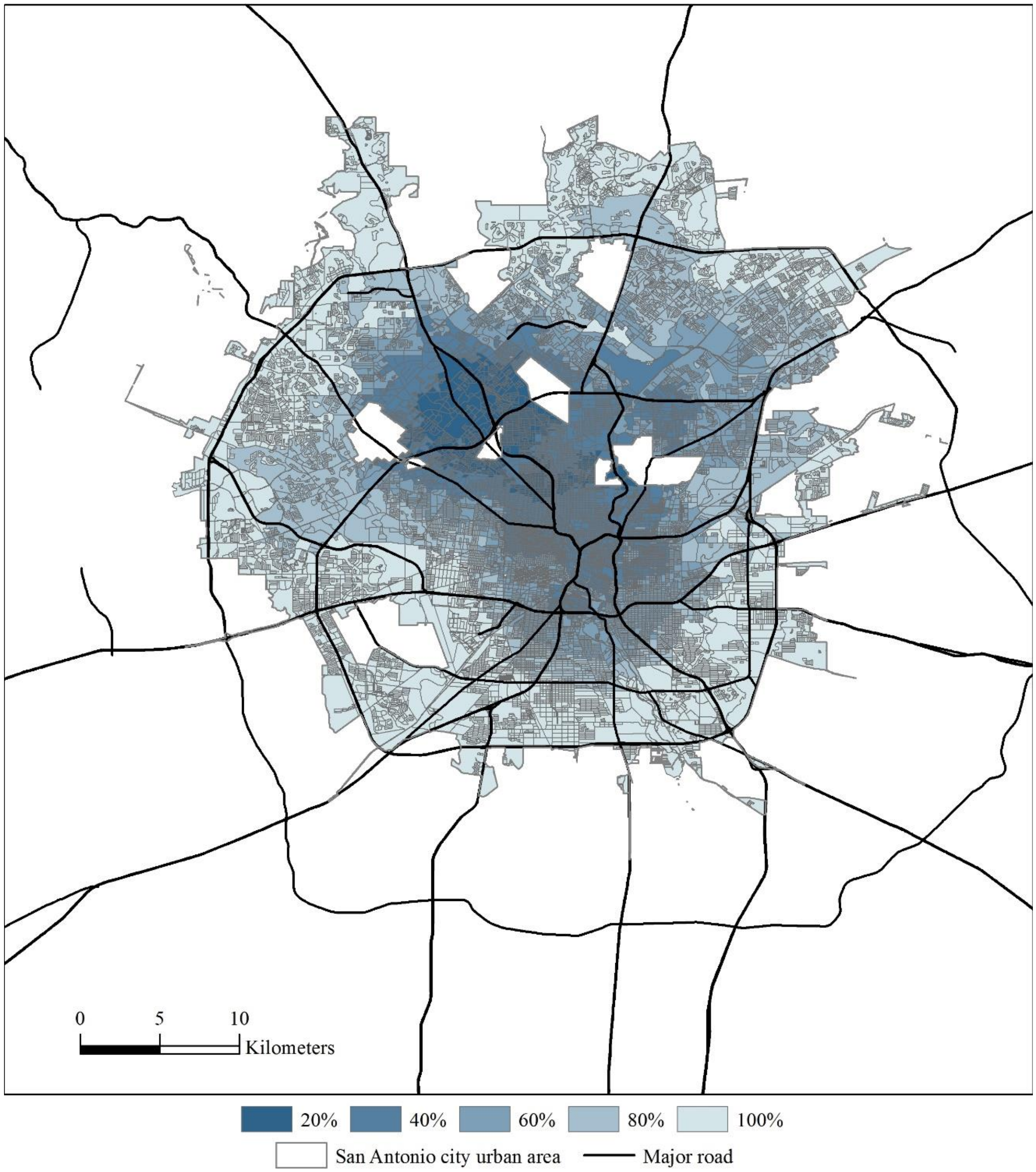

Figure 131. San Antonio, Texas 7-kilometer accessibility using roads

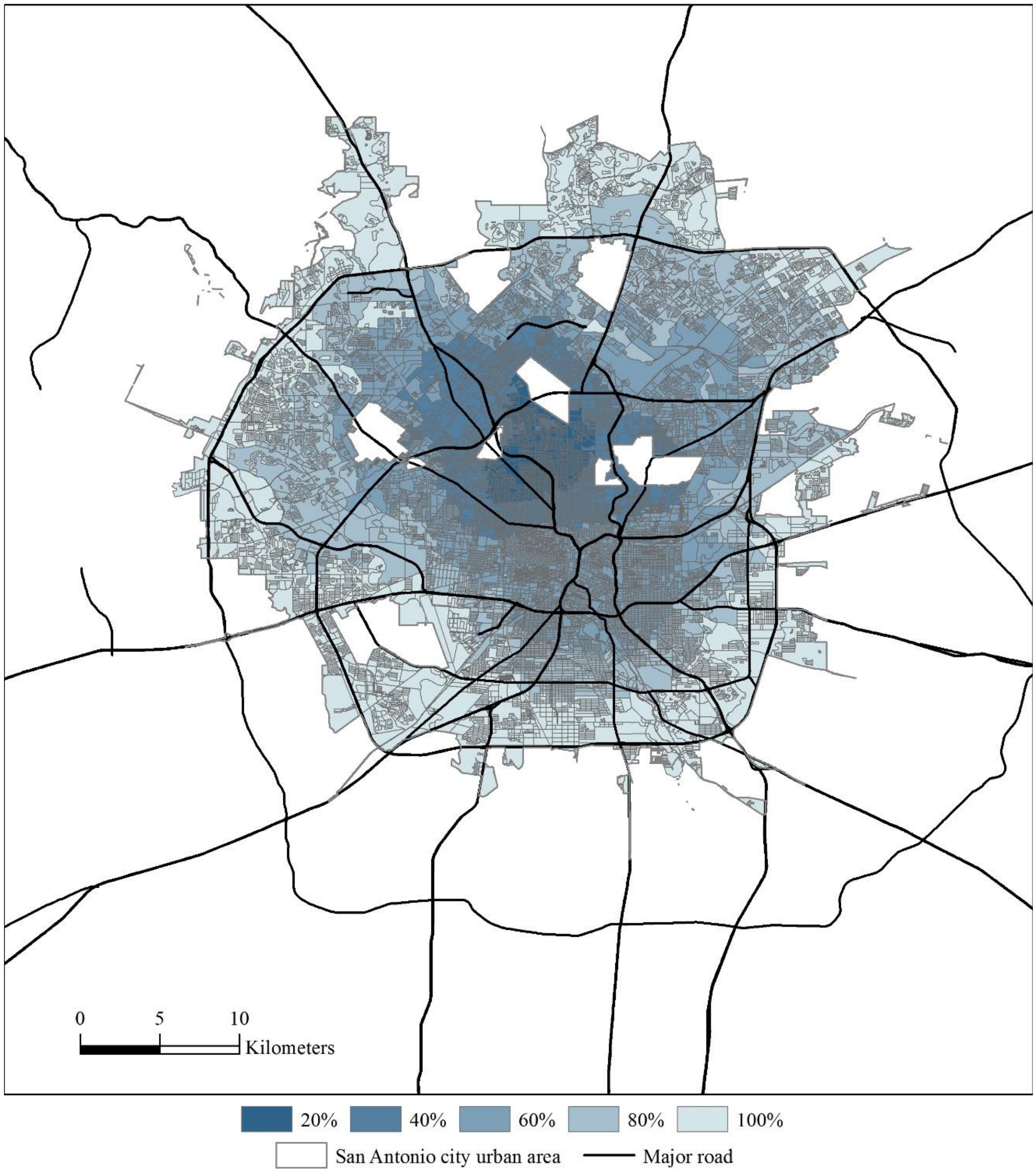

Figure 132. San Antonio, Texas 9-kilometer accessibility using roads

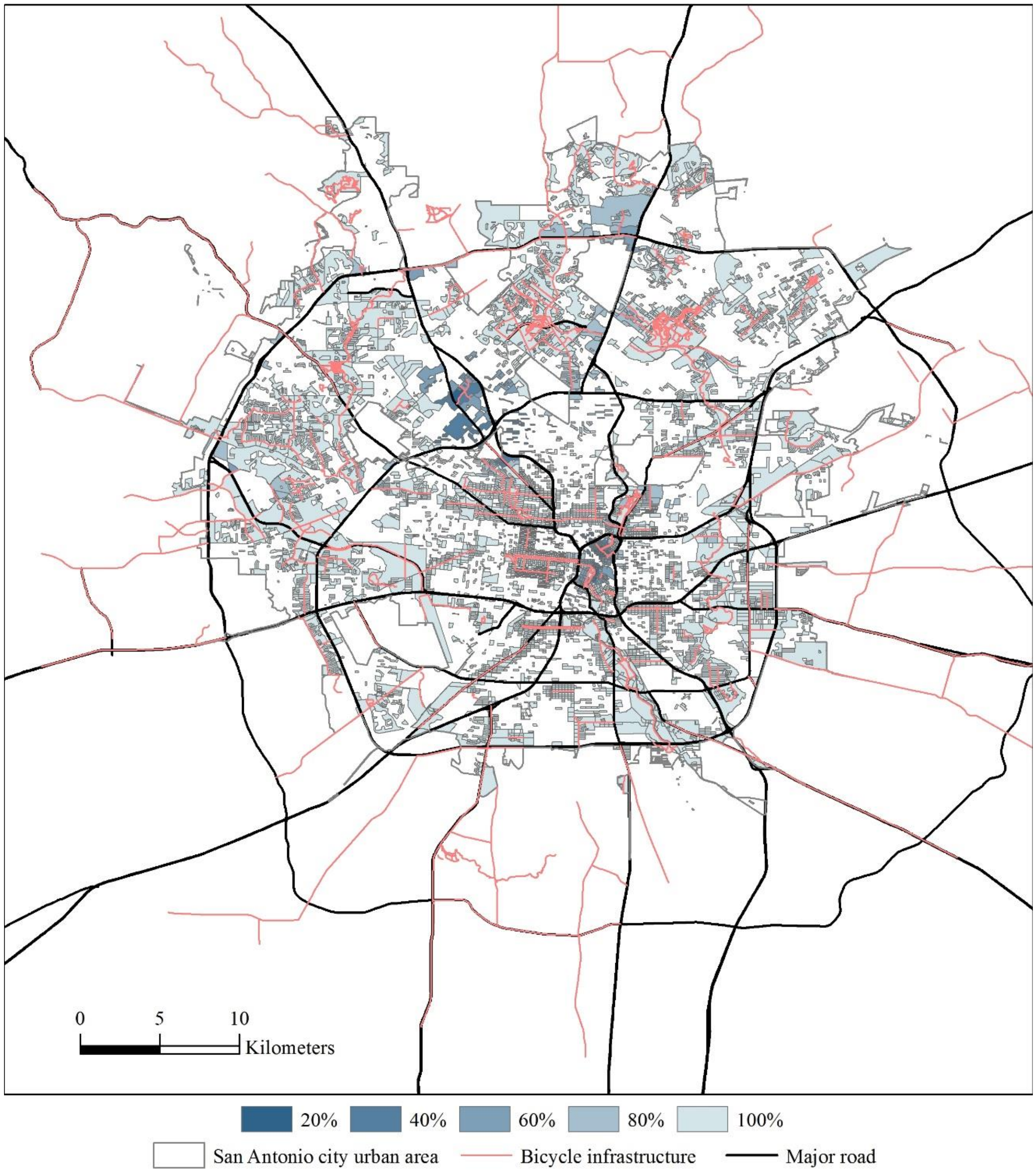

Figure 133. San Antonio, Texas 1-kilometer accessibility using all bicycle infrastructure

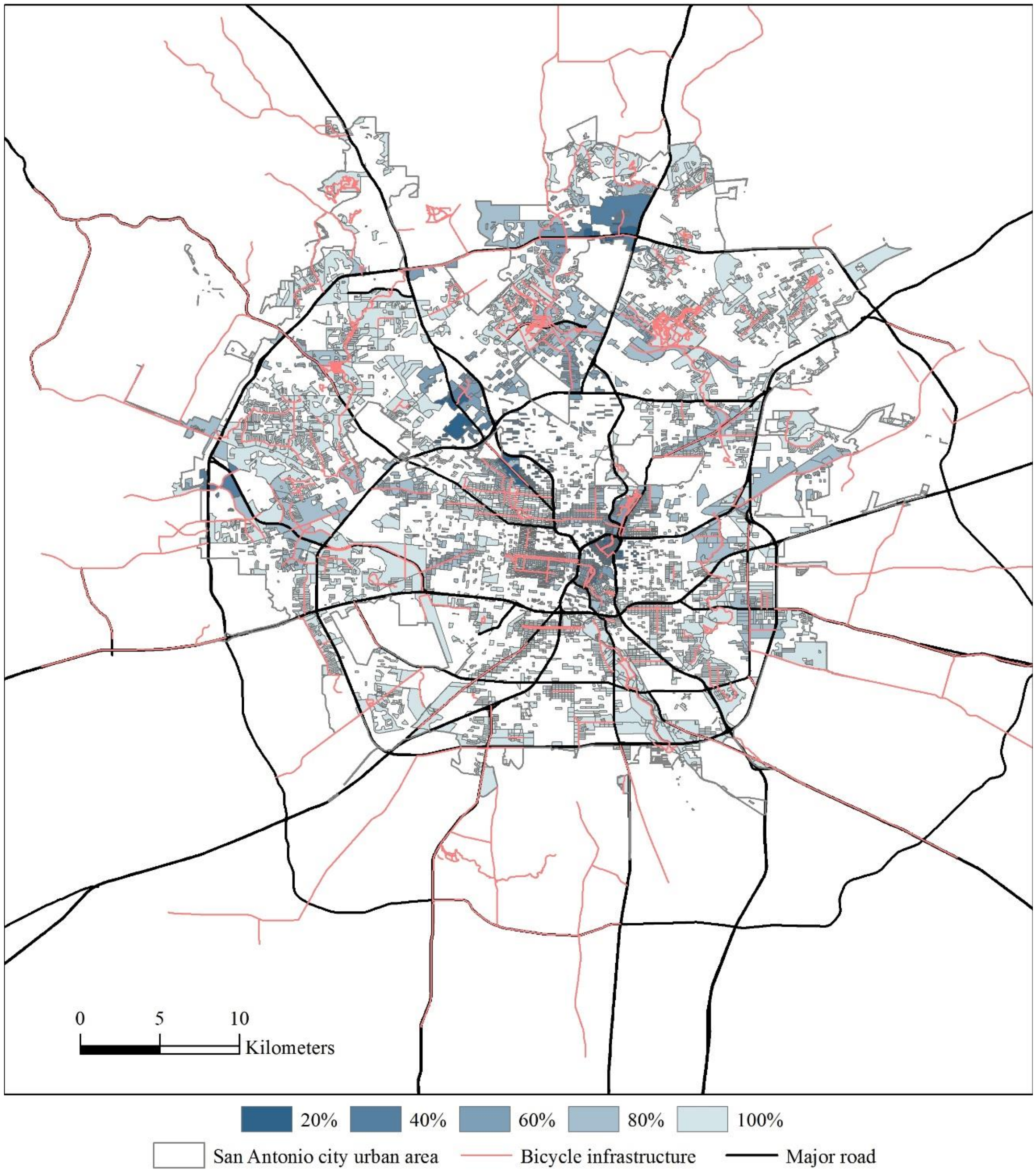

Figure 134. San Antonio, Texas 3-kilometer accessibility using all bicycle infrastructure

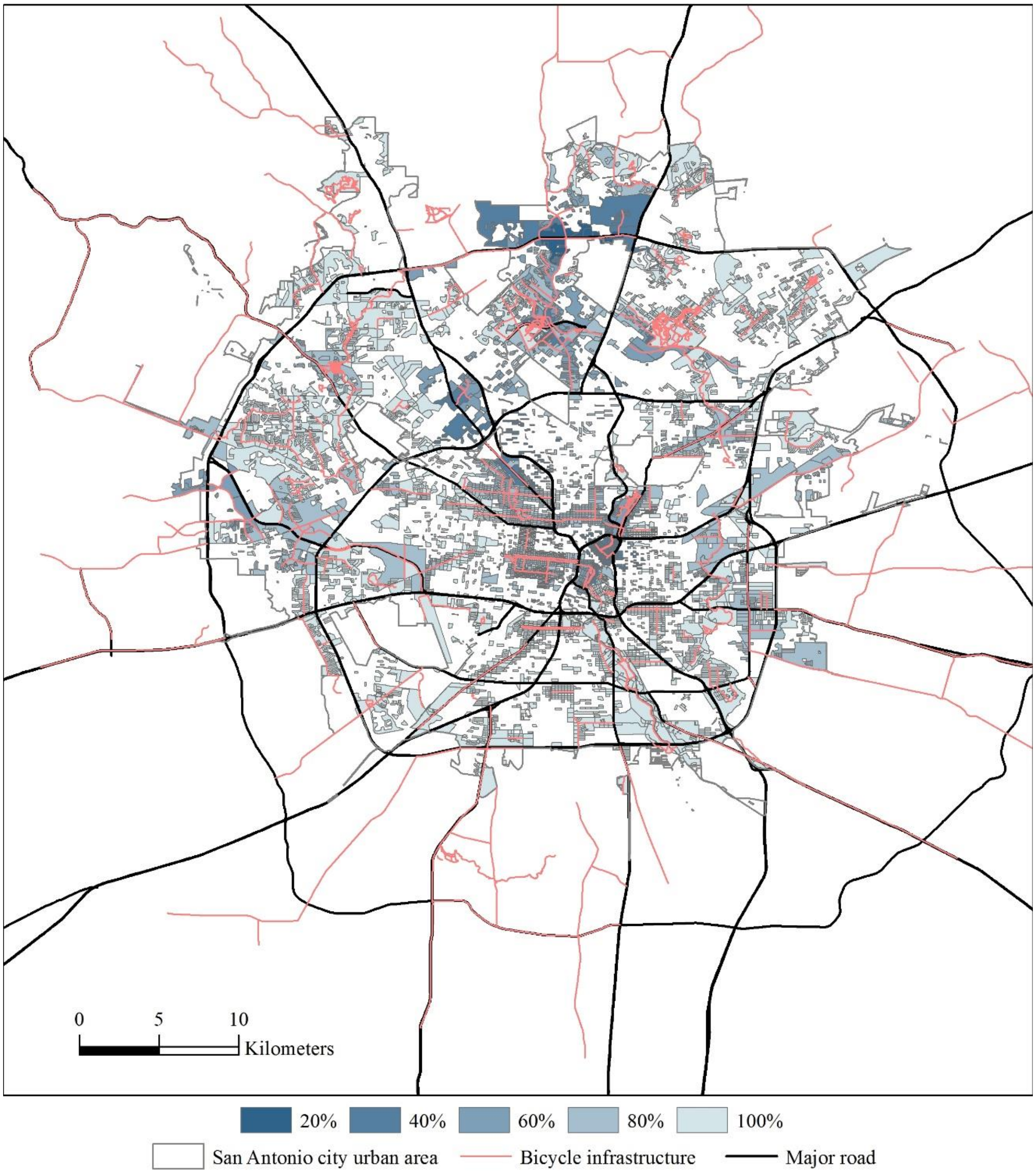

Figure 135. San Antonio, Texas 5-kilometer accessibility using all bicycle infrastructure

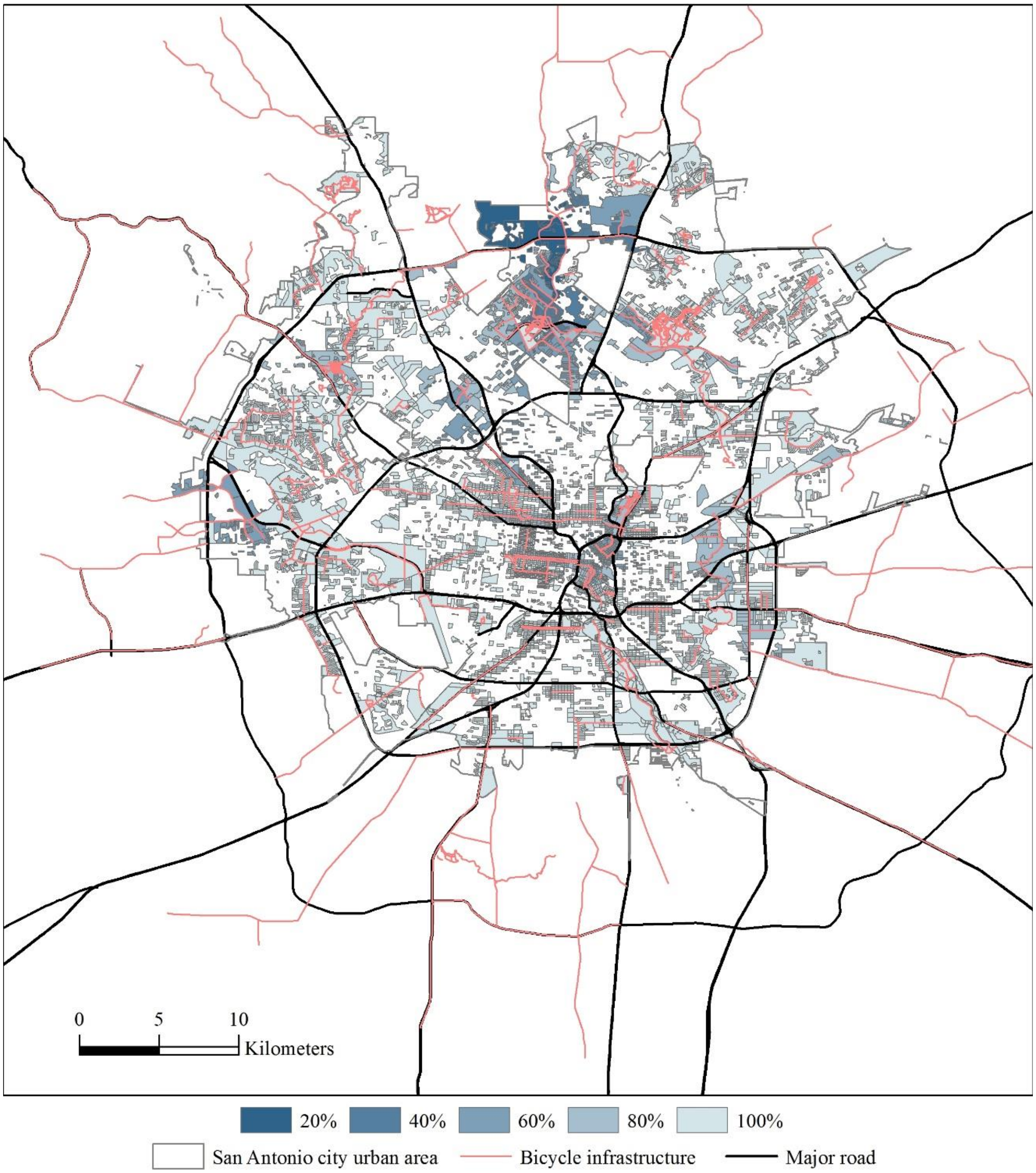

Figure 136. San Antonio, Texas 7-kilometer accessibility using all bicycle infrastructure

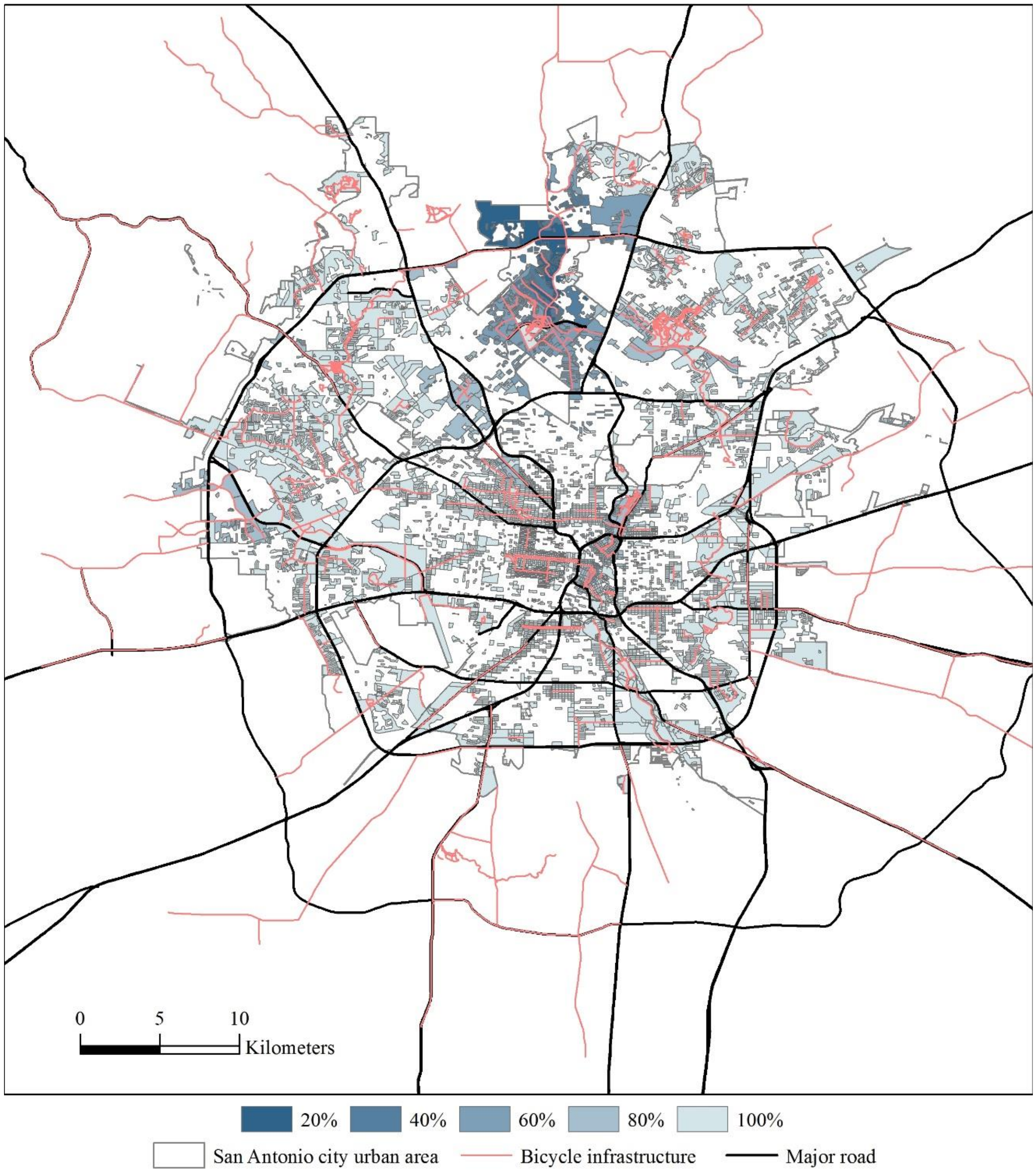

Figure 137. San Antonio, Texas 9-kilometer accessibility using all bicycle infrastructure

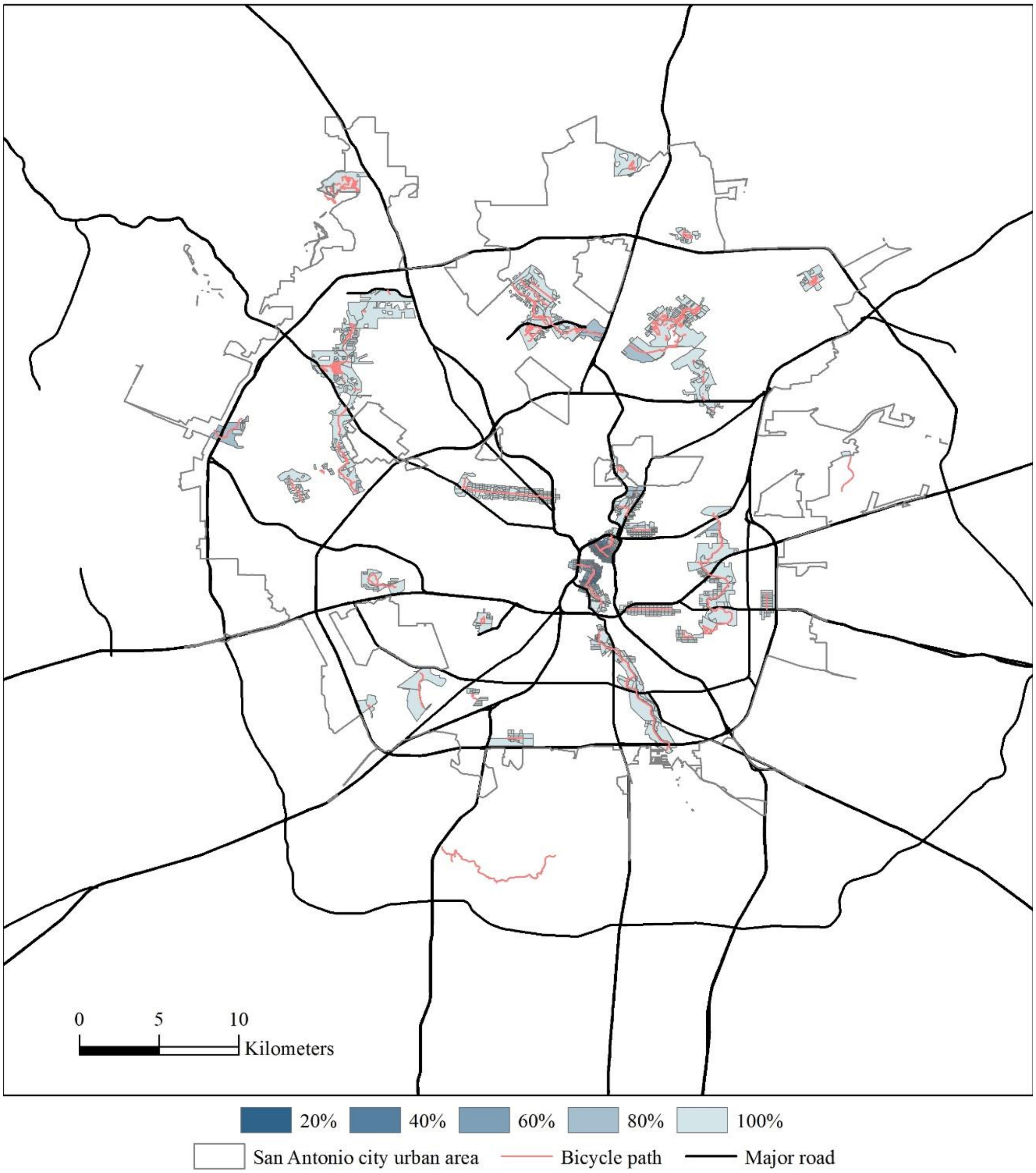

Figure 138. San Antonio, Texas 1-kilometer accessibility using bicycle paths

Figure 139. San Antonio, Texas 3-kilometer accessibility using bicycle paths

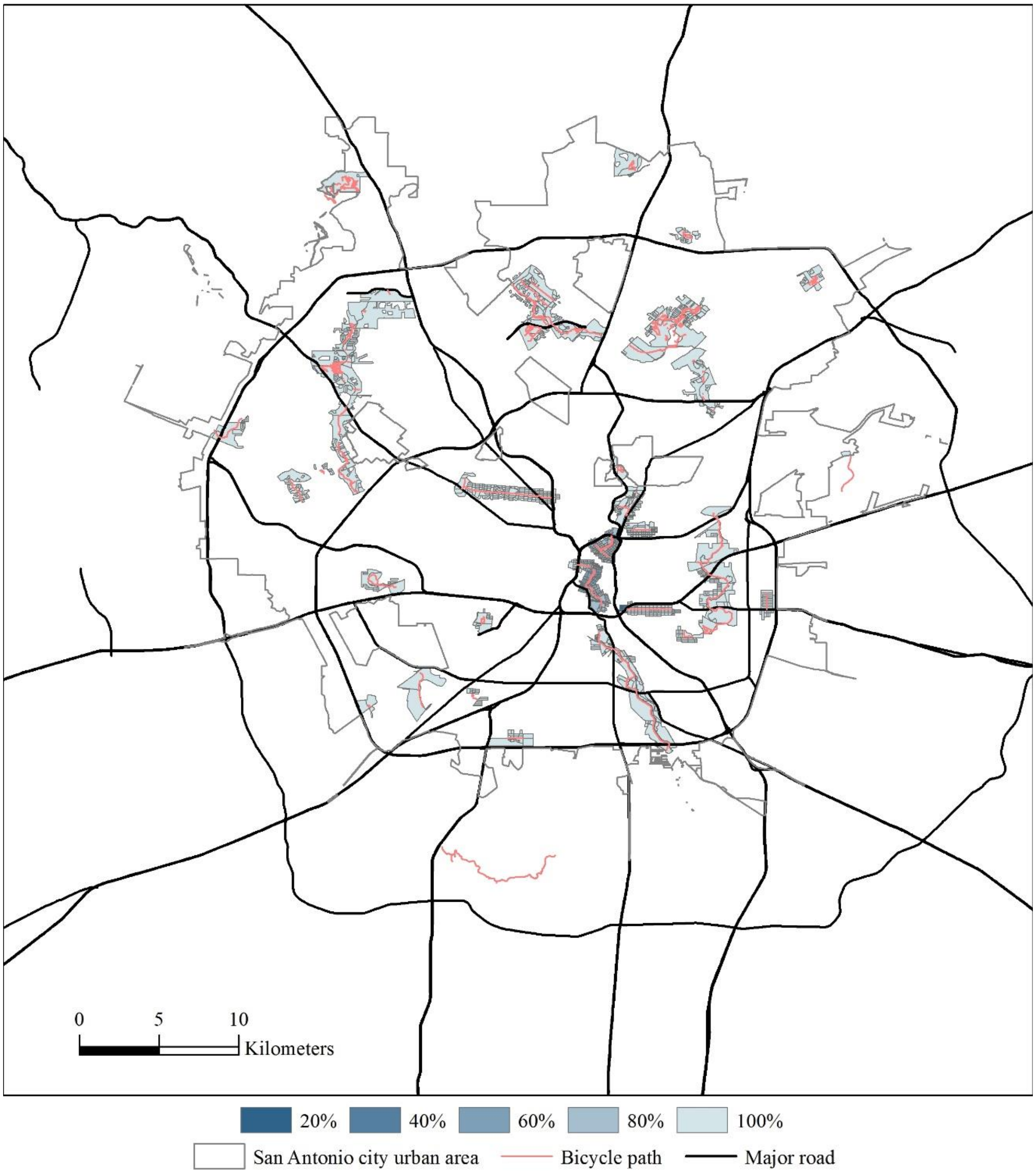

Figure 140. San Antonio, Texas 5-kilometer accessibility using bicycle paths

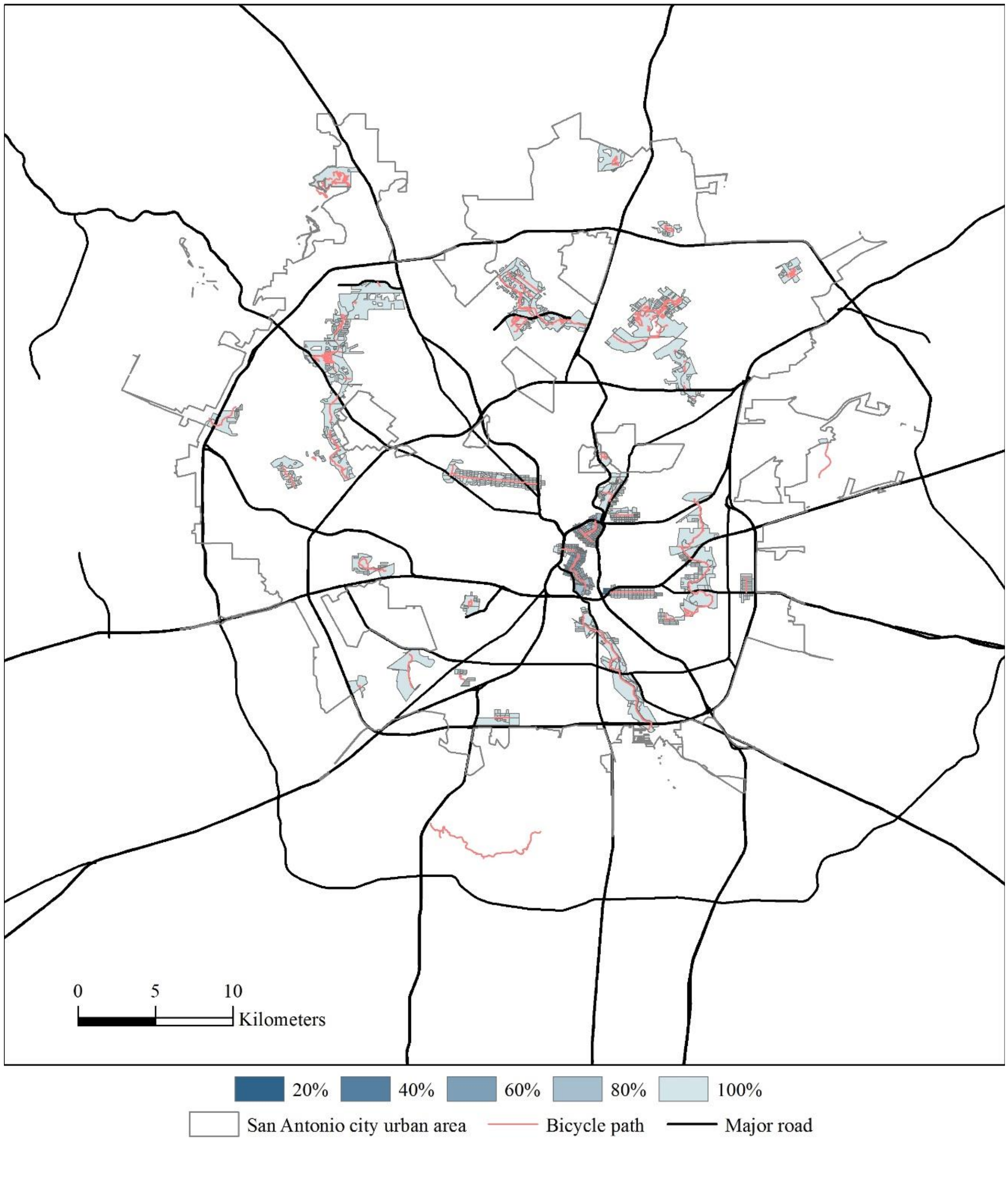

Figure 141. San Antonio, Texas 7-kilometer accessibility using bicycle paths

Figure 142. San Antonio, Texas 9-kilometer accessibility using bicycle paths

APPENDIX J

Washington, D.C. City Zonal Accessibility Maps

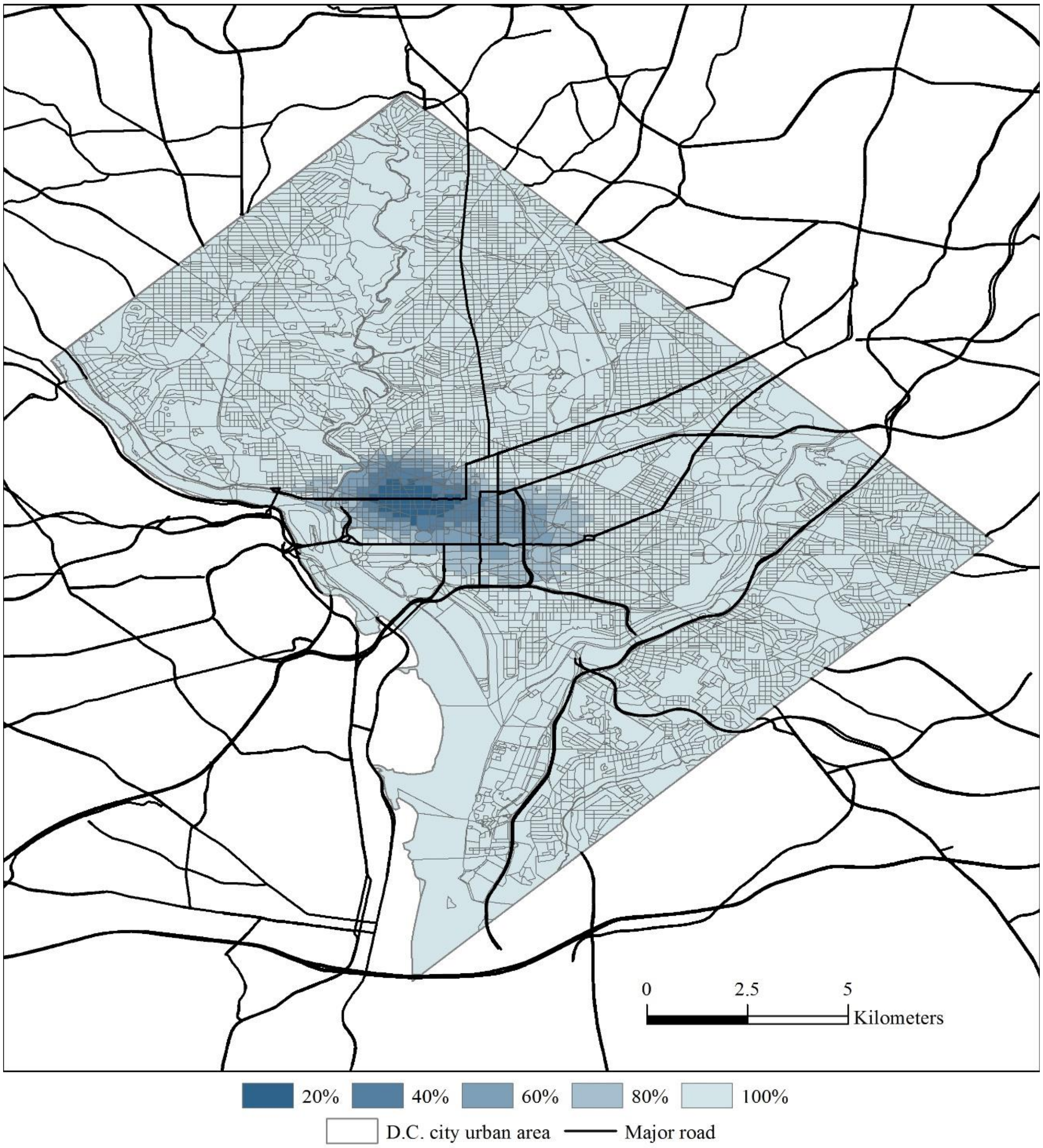

Figure 143. Washington, D.C. 1-kilometer accessibility using roads

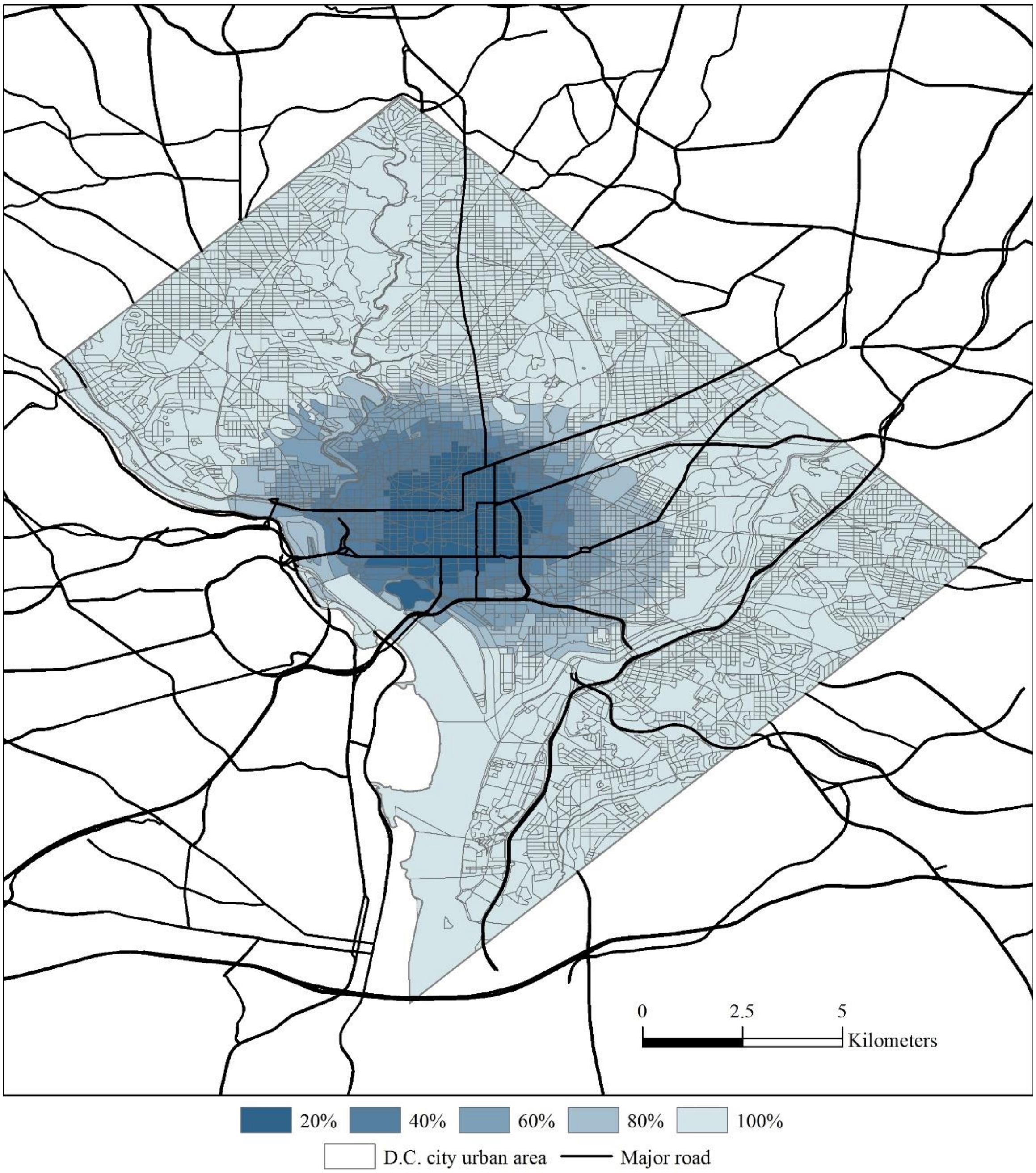

Figure 144. Washington, D.C. 3-kilometer accessibility using roads

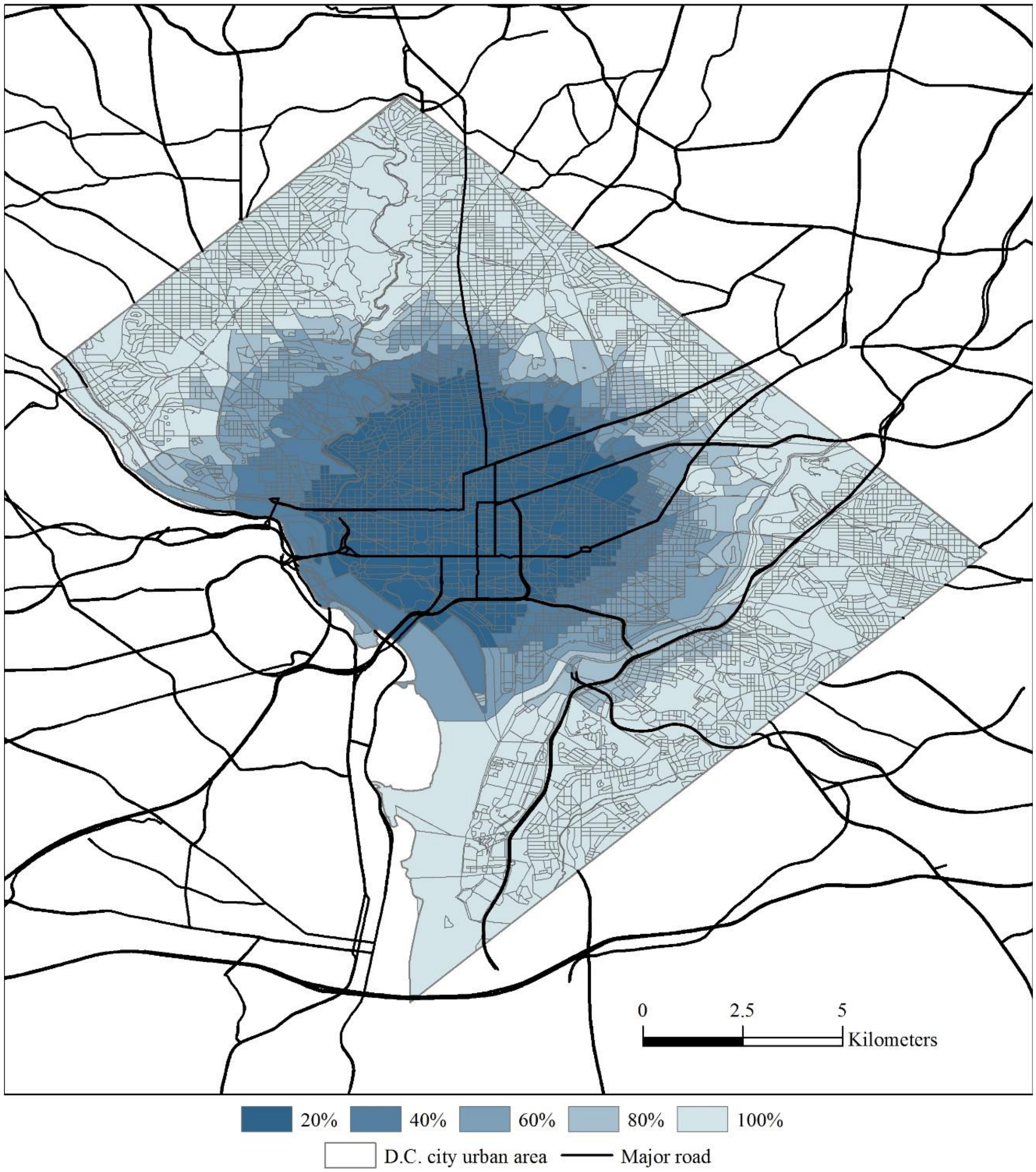

Figure 145. Washington, D.C. 5-kilometer accessibility using roads

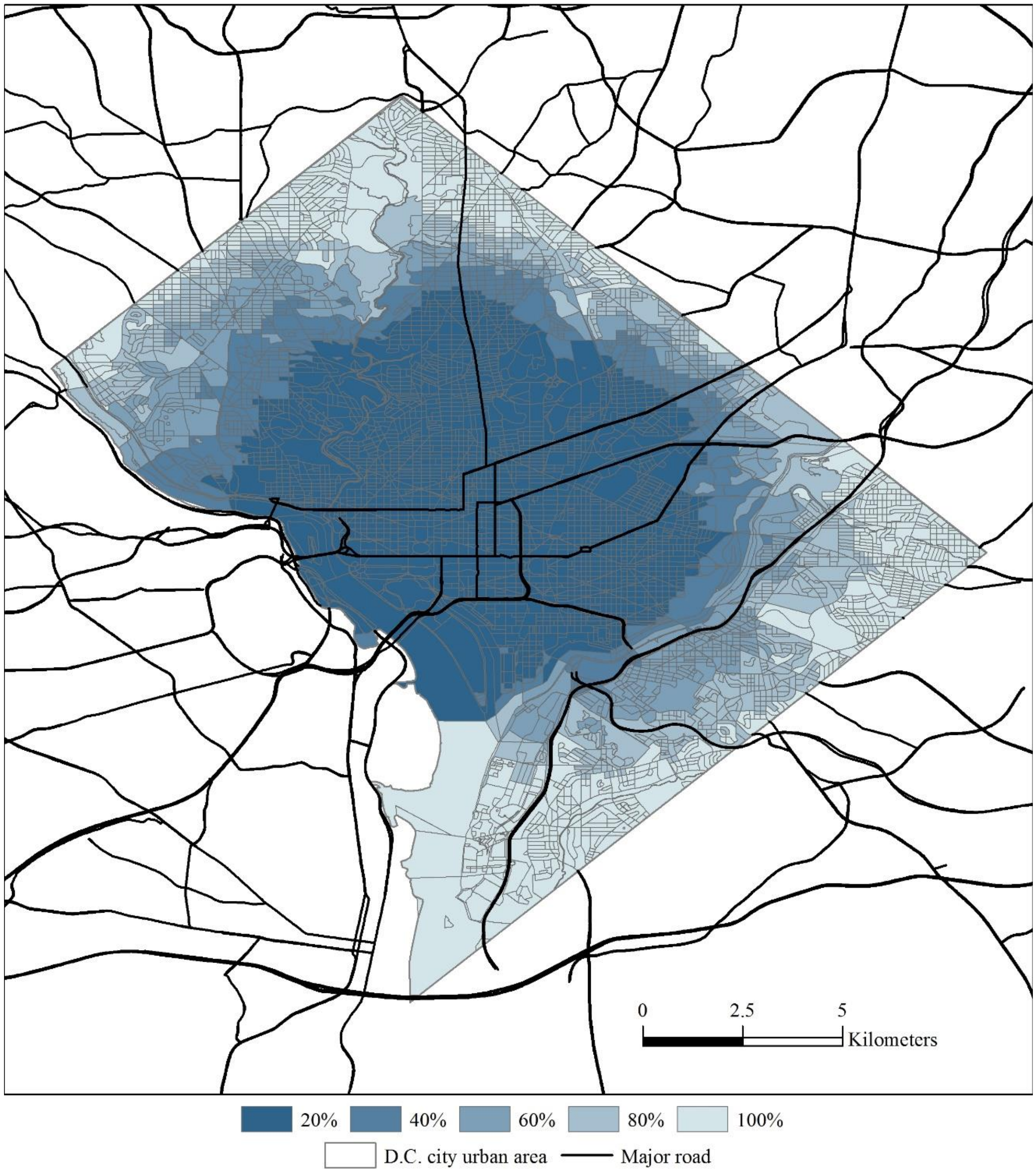

Figure 146. Washington, D.C. 7-kilometer accessibility using roads

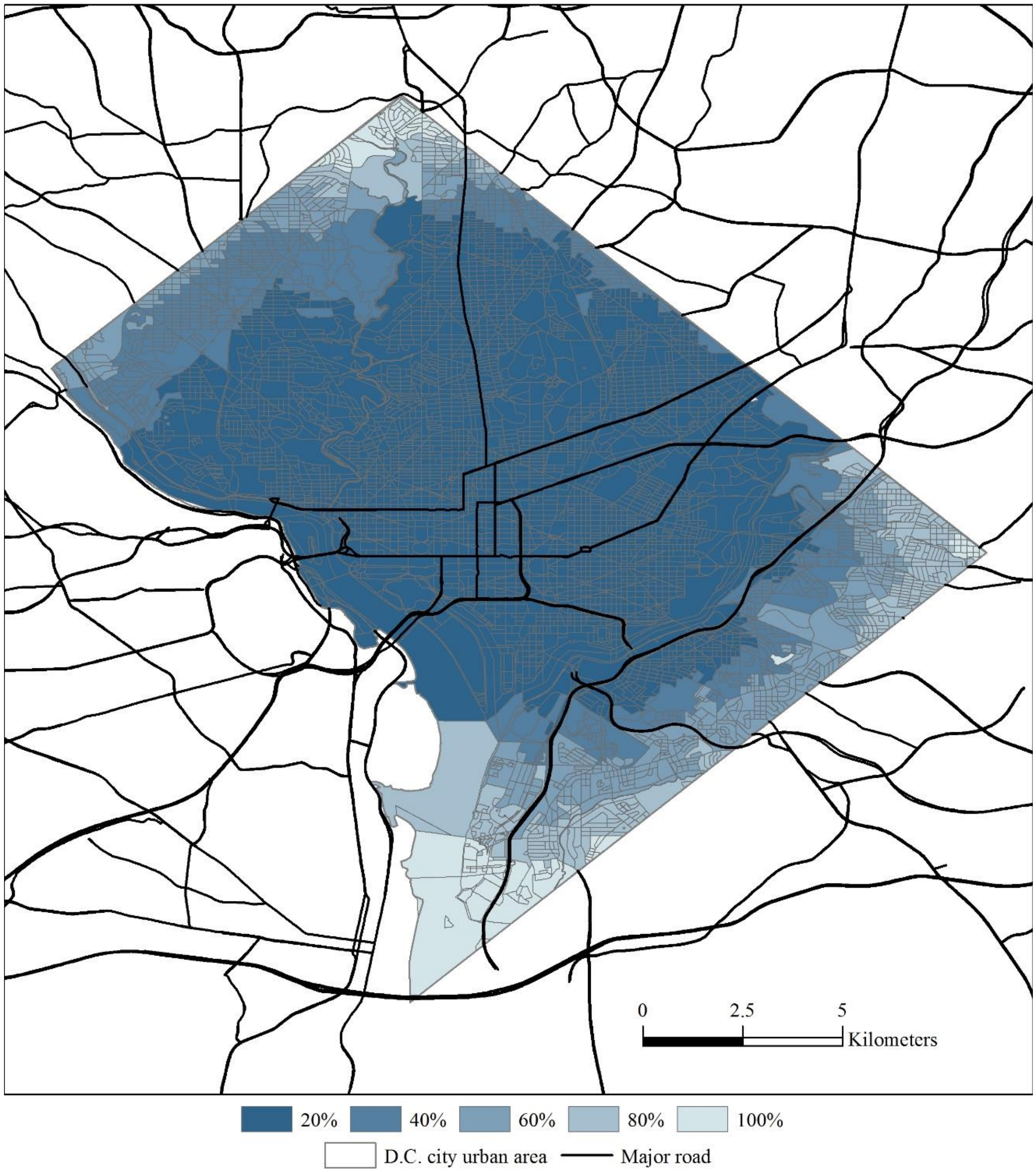

Figure 147. Washington, D.C. 9-kilometer accessibility using roads

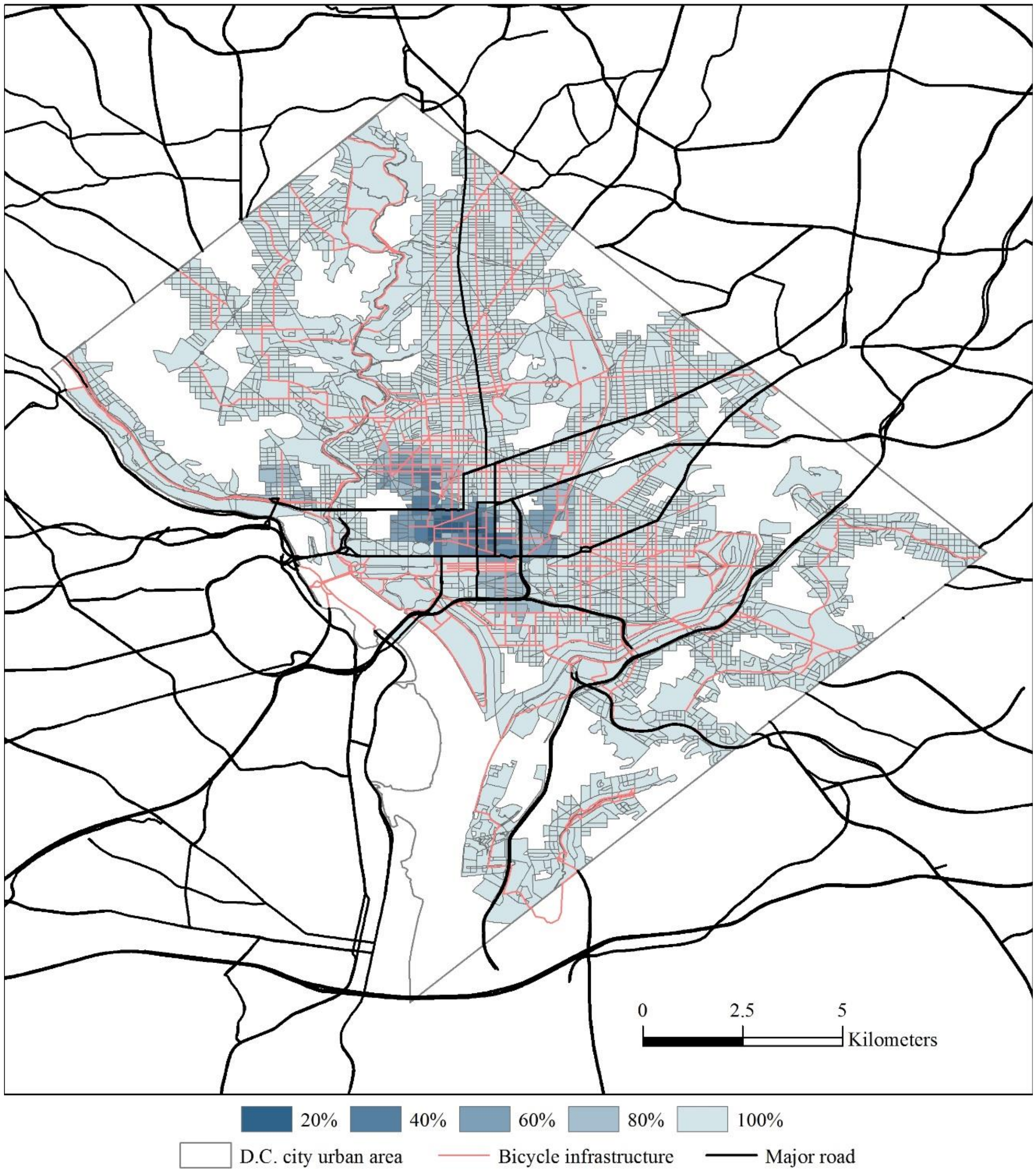

Figure 148. Washington, D.C. 1-kilometer accessibility using all bicycle infrastructure

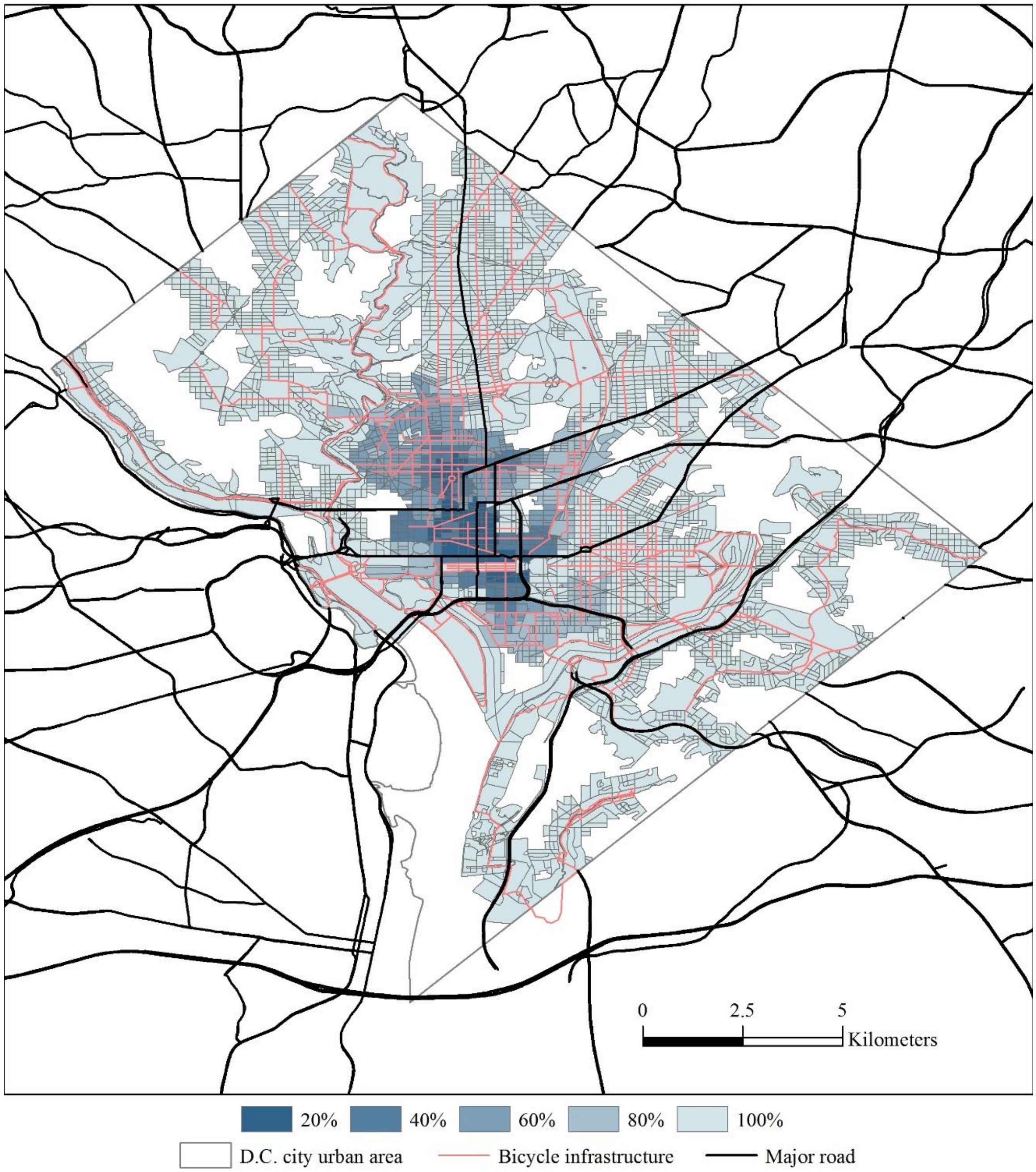

Figure 149. Washington, D.C. 3-kilometer accessibility using all bicycle infrastructure

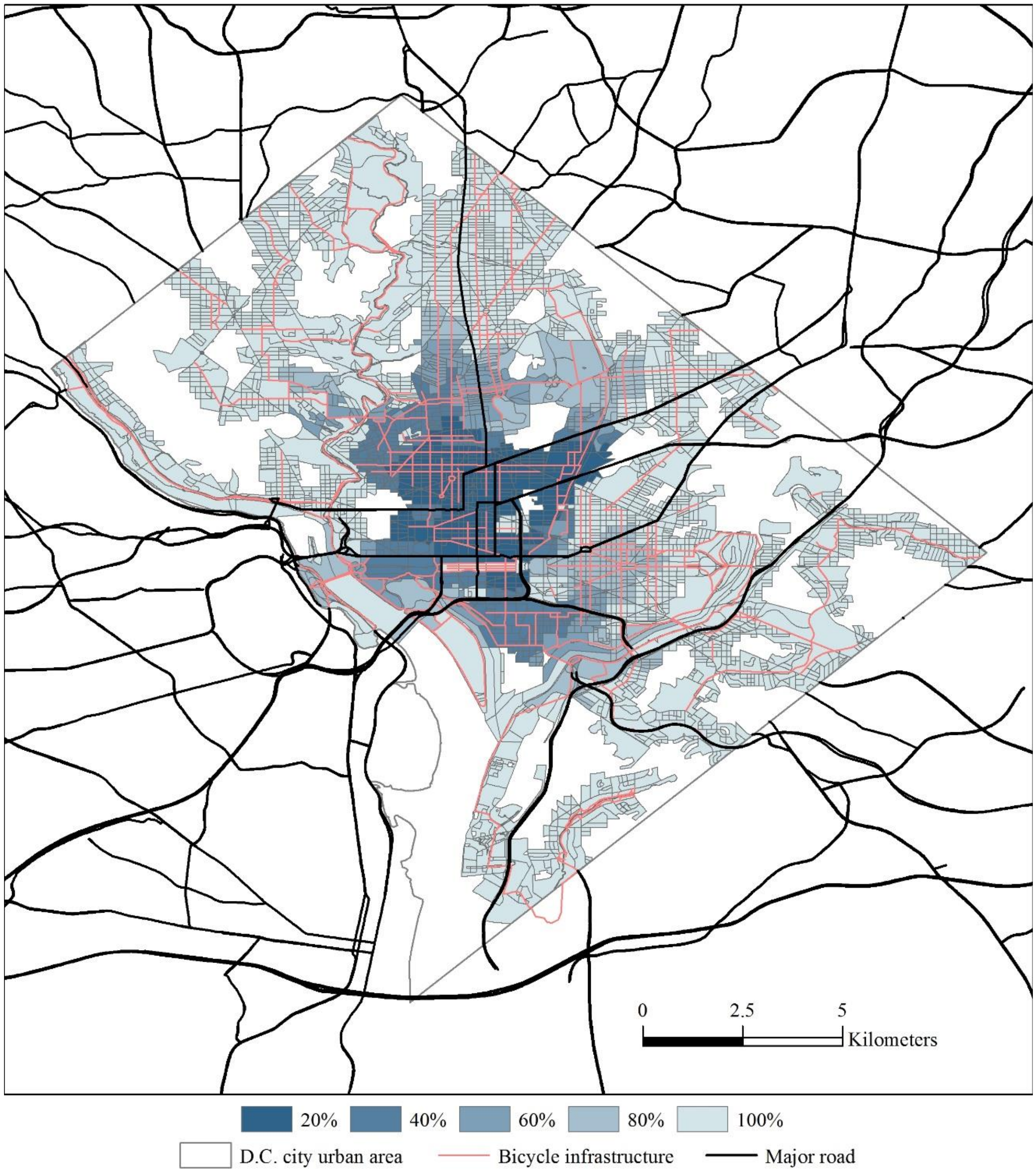

Figure 150. Washington, D.C. 5-kilometer accessibility using all bicycle infrastructure

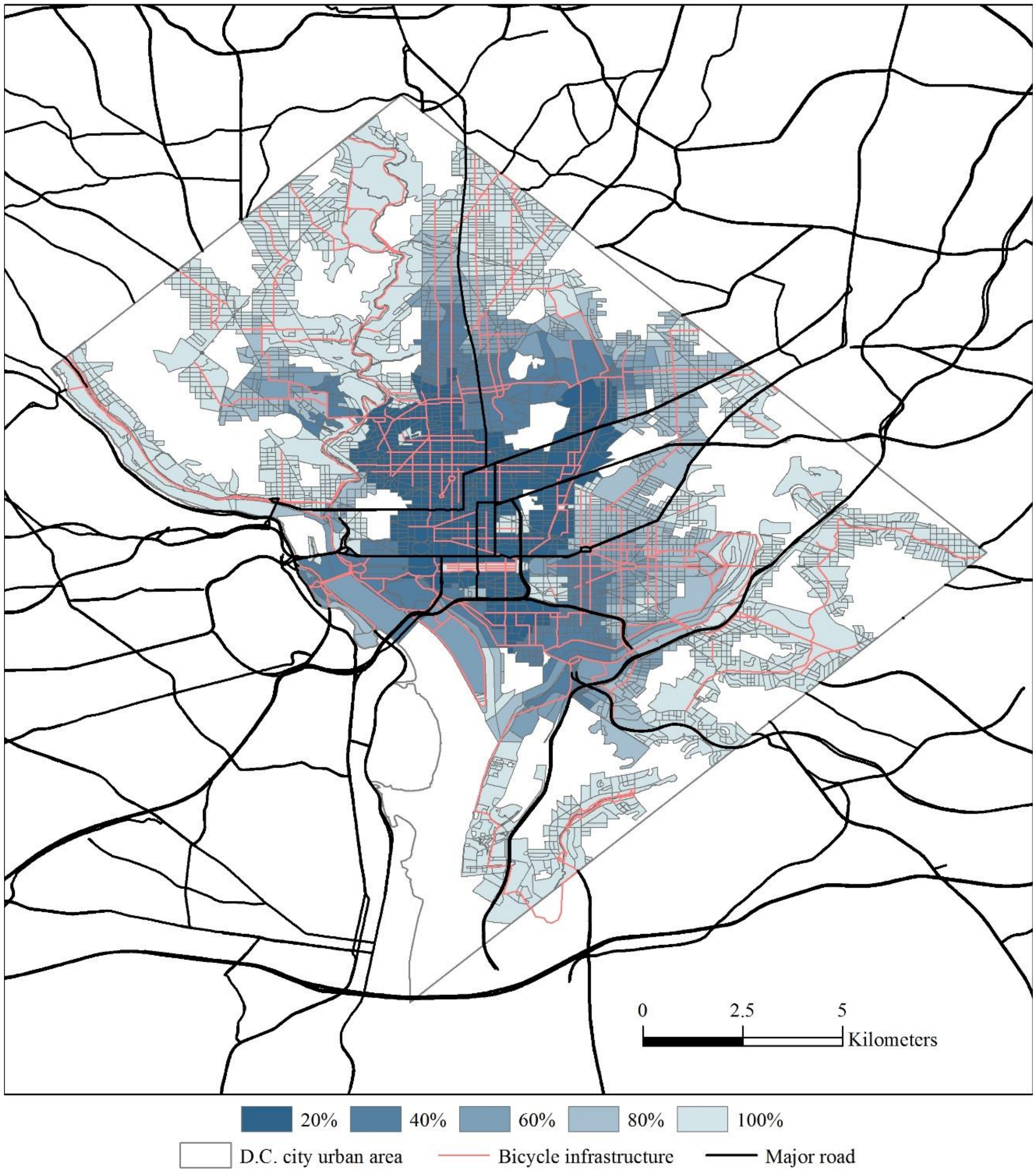

Figure 151. Washington, D.C. 7-kilometer accessibility using all bicycle infrastructure

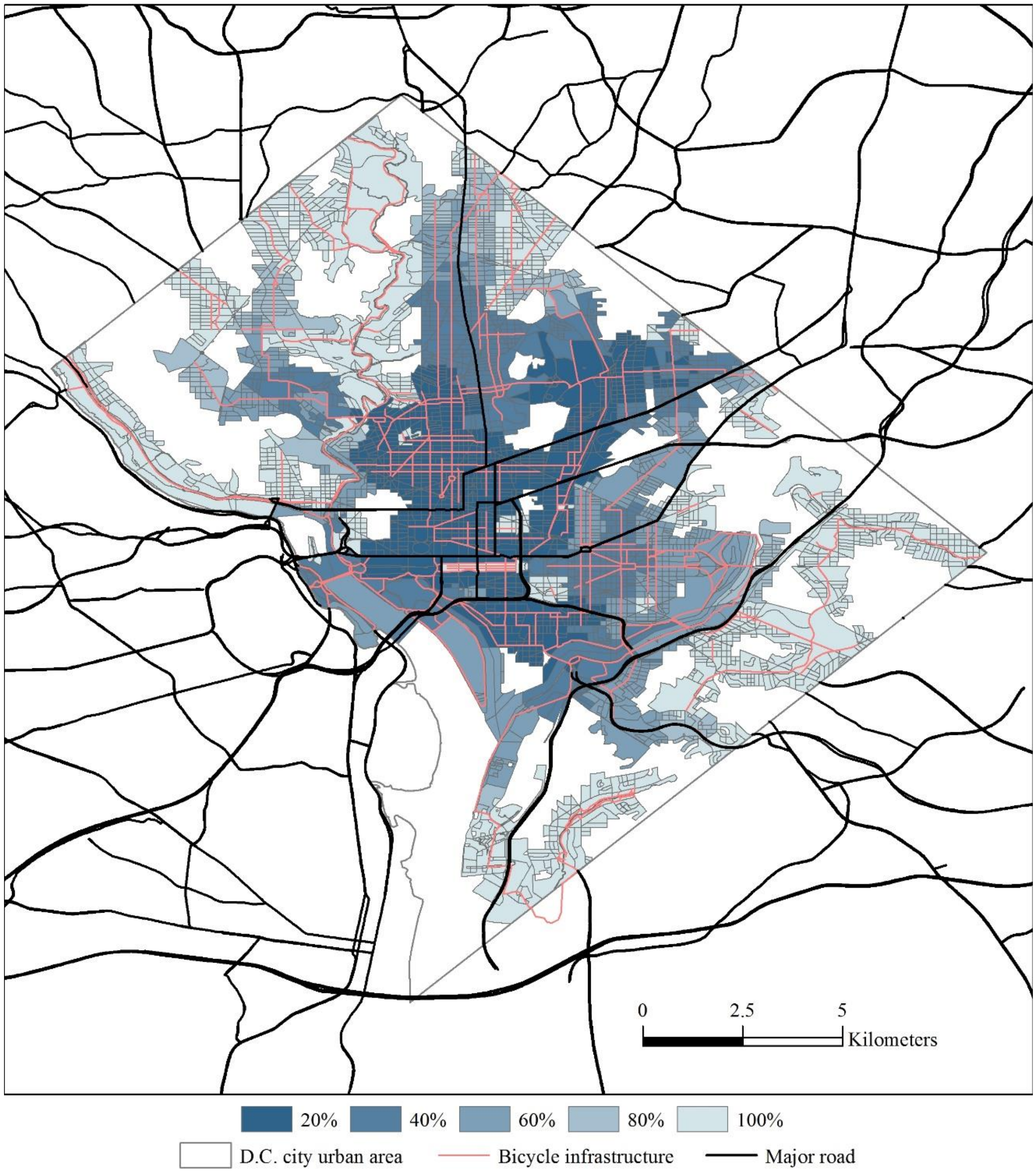

Figure 152. Washington, D.C. 9-kilometer accessibility using all bicycle infrastructure

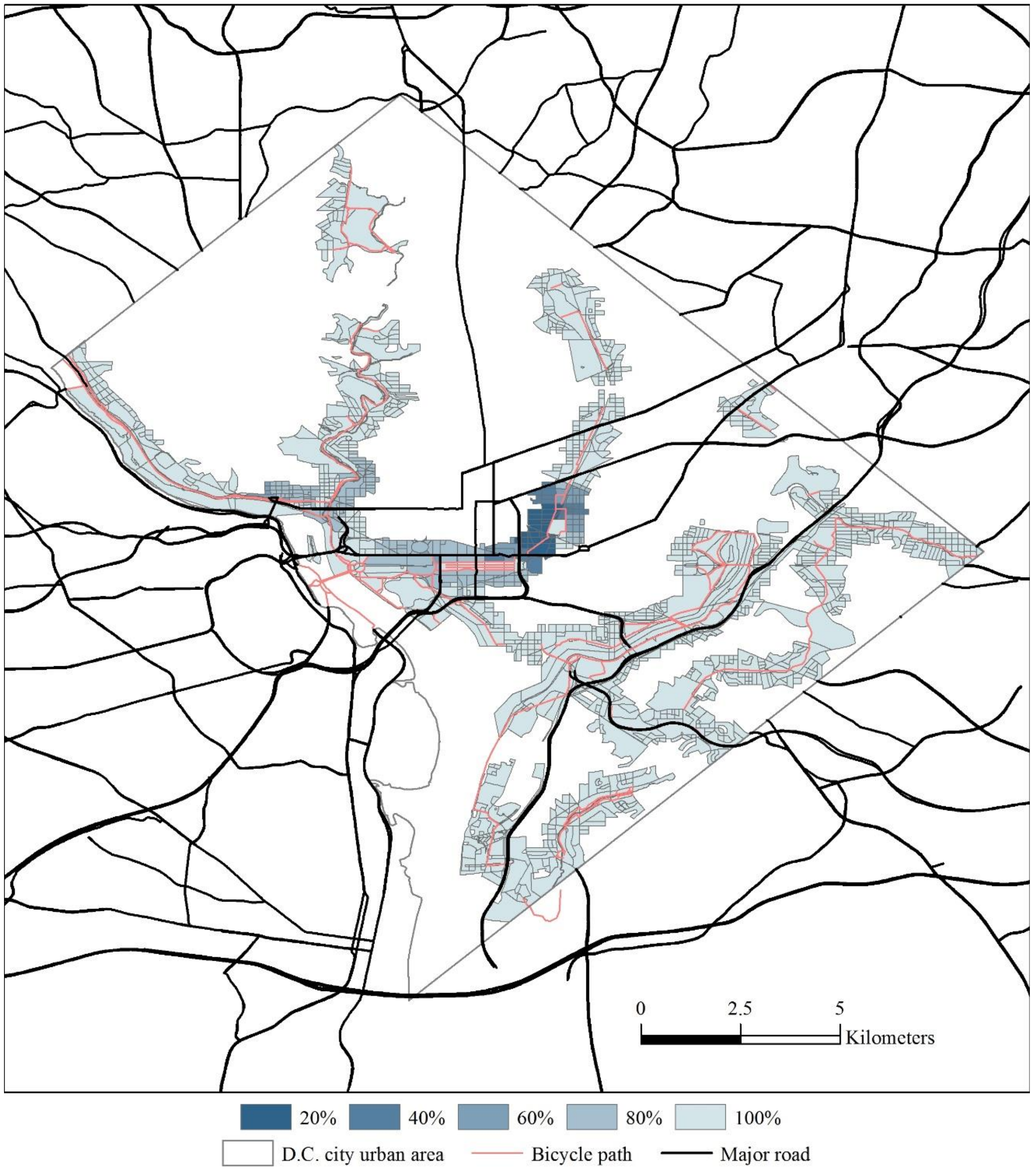

Figure 153. Washington, D.C. 1-kilometer accessibility using bicycle paths

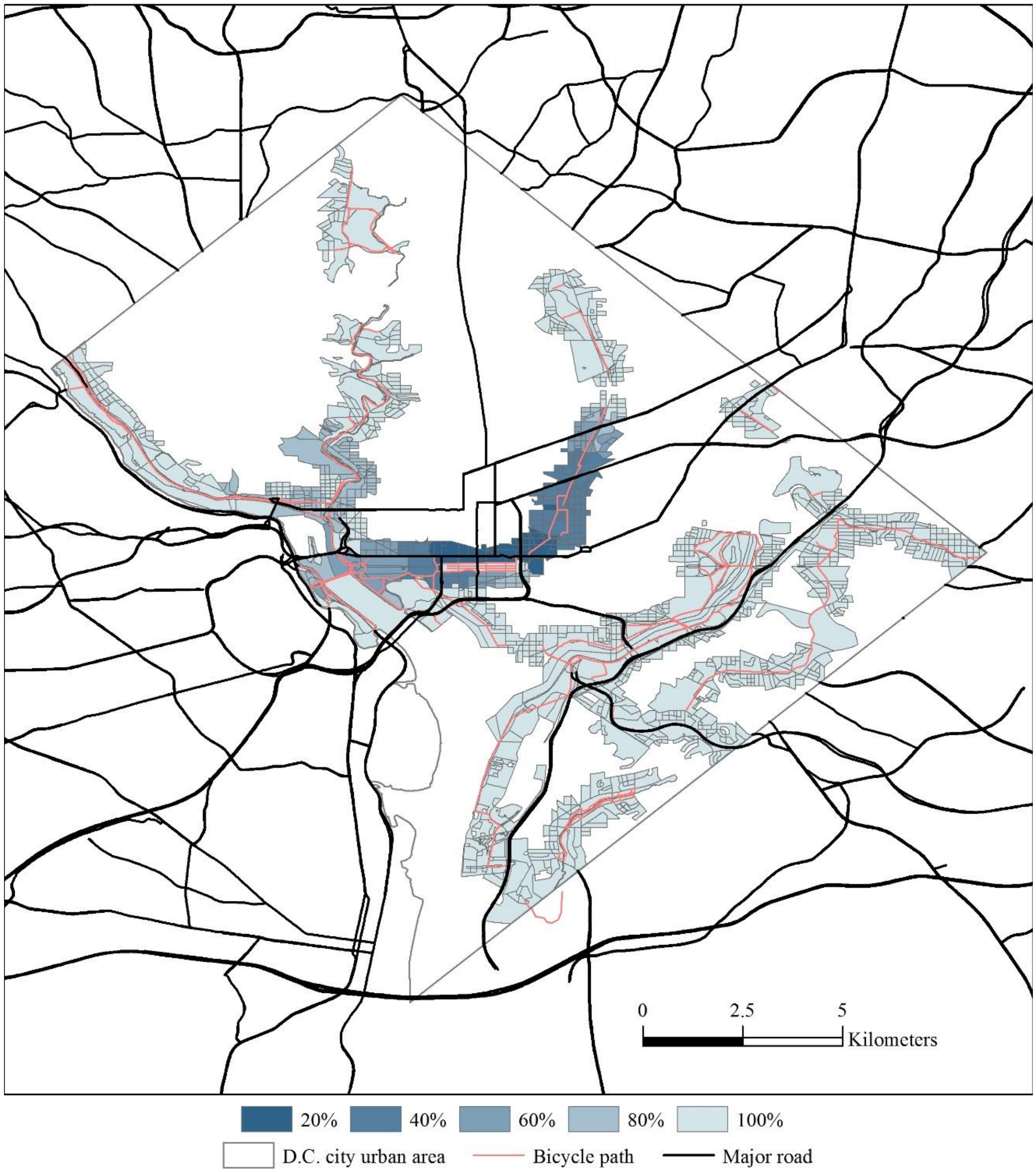

Figure 154. Washington, D.C. 3-kilometer accessibility using bicycle paths

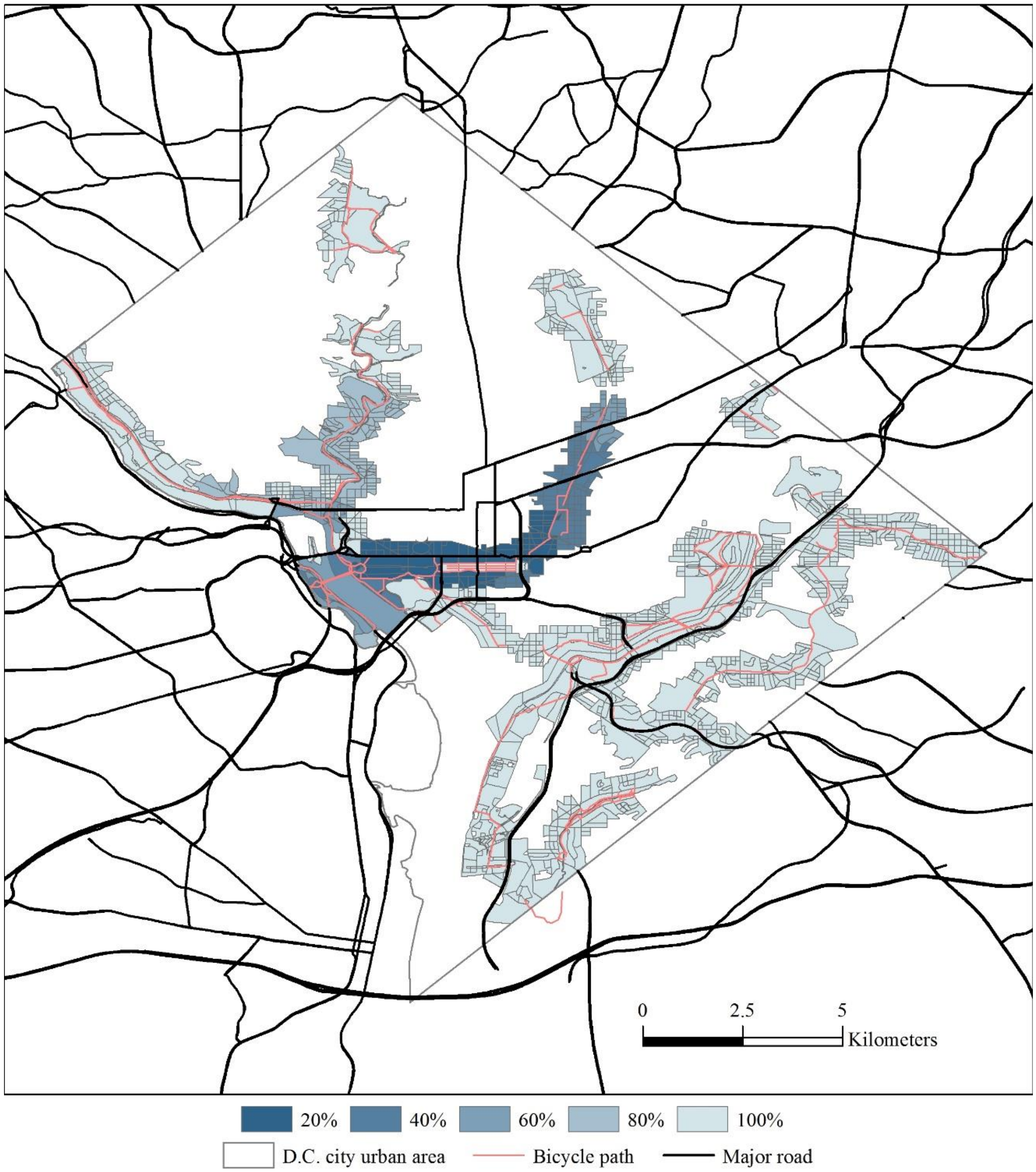

Figure 155. Washington, D.C. 5-kilometer accessibility using bicycle paths

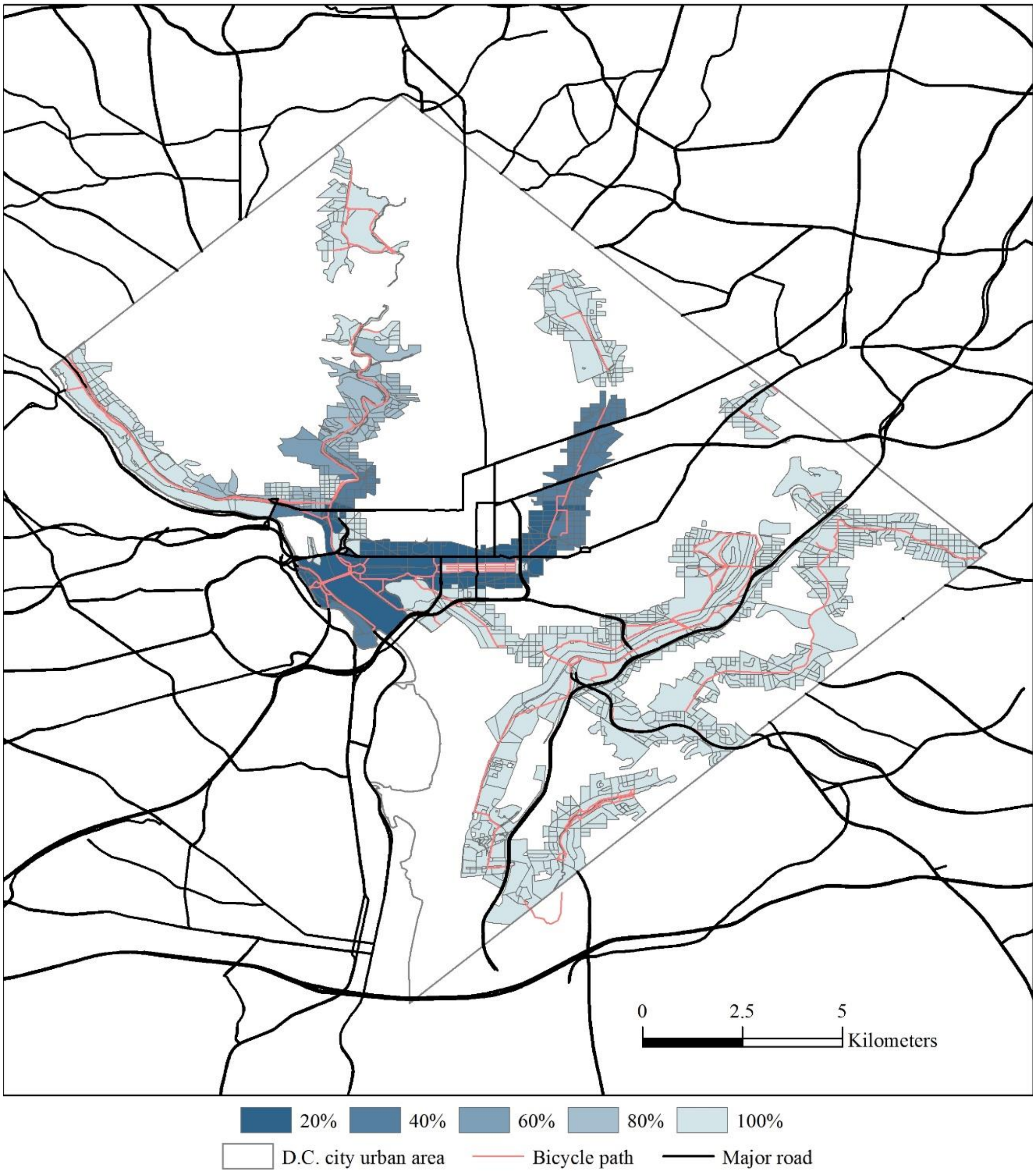

Figure 156. Washington, D.C. 7-kilometer accessibility using bicycle paths

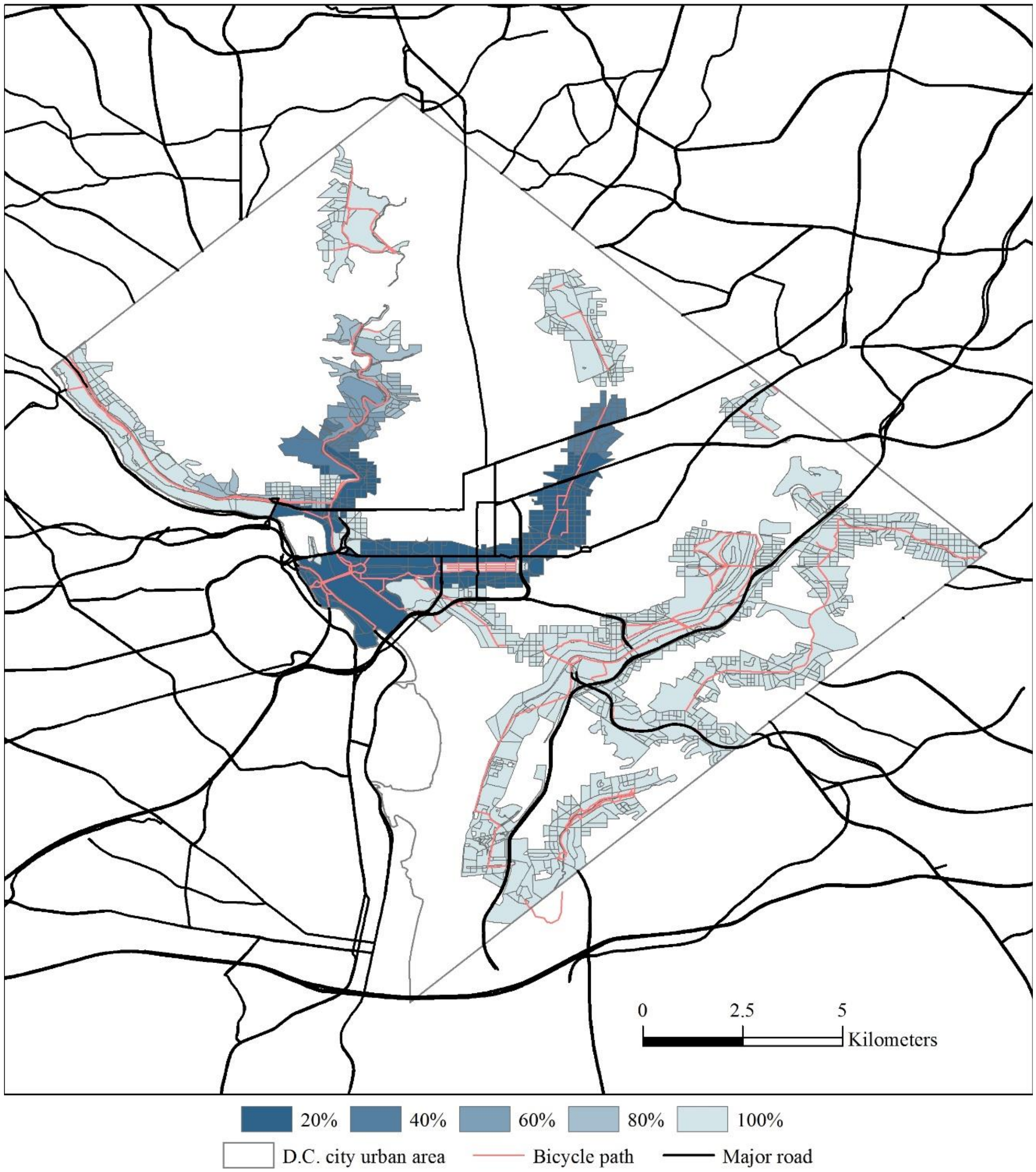

Figure 157. Washington, D.C. 9-kilometer accessibility using bicycle paths

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