Access to Destinations: Refining Methods for Calculating Non-Auto Travel Times

Report # 2 in the series

Access to Destinations Study

Report # 2007-24

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16. Abstract (Limit: 200 words)

The functioning of the system of land use and travel networks in a region can be encapsulated into measures of the ease of reaching destinations from various locations, often referred to as accessibility measures. Regardless of the form used to specify accessibility, all measures require as inputs travel times between the zones of a region. For most transportation planning purposes, these travel time calculations are limited to motorized modes (auto and public transit), since these modes carry the bulk of all urban travel. In this research study, attention is focused on developing methods for calculating travel times by non-auto modes, including walking, bicycling and public transit. Unique networks for each mode are developed, accounting for the presence of special facilities such as pedestrian or bicycle trails and on-street bike lanes. A statistical model is estimated to identify the influence of special bicycle facilities on travel speeds, using GPS data collected from bicyclists in a real-world setting. These methods are demonstrated with an application to a section of the Twin Cities metropolitan region encompassing parts of the cities of Minneapolis, St. Paul and Bloomington.

The output of the application of these methods are a set of maps depicting travel sheds from various locations within the study area. The data are displayed for three points in time: 1995, 2000 and 2005. Changes to these travel sheds over time are demonstrated with maps that show the difference in travel time between each set of origins and destinations for each pair of years. The research concludes with some suggestions about the uses of the travel time data, such as the calculation of multimodal, multipurpose measures of accessibility.

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Access to Destinations: Refining Methods for Calculating Non-Auto Travel Times

Final Report

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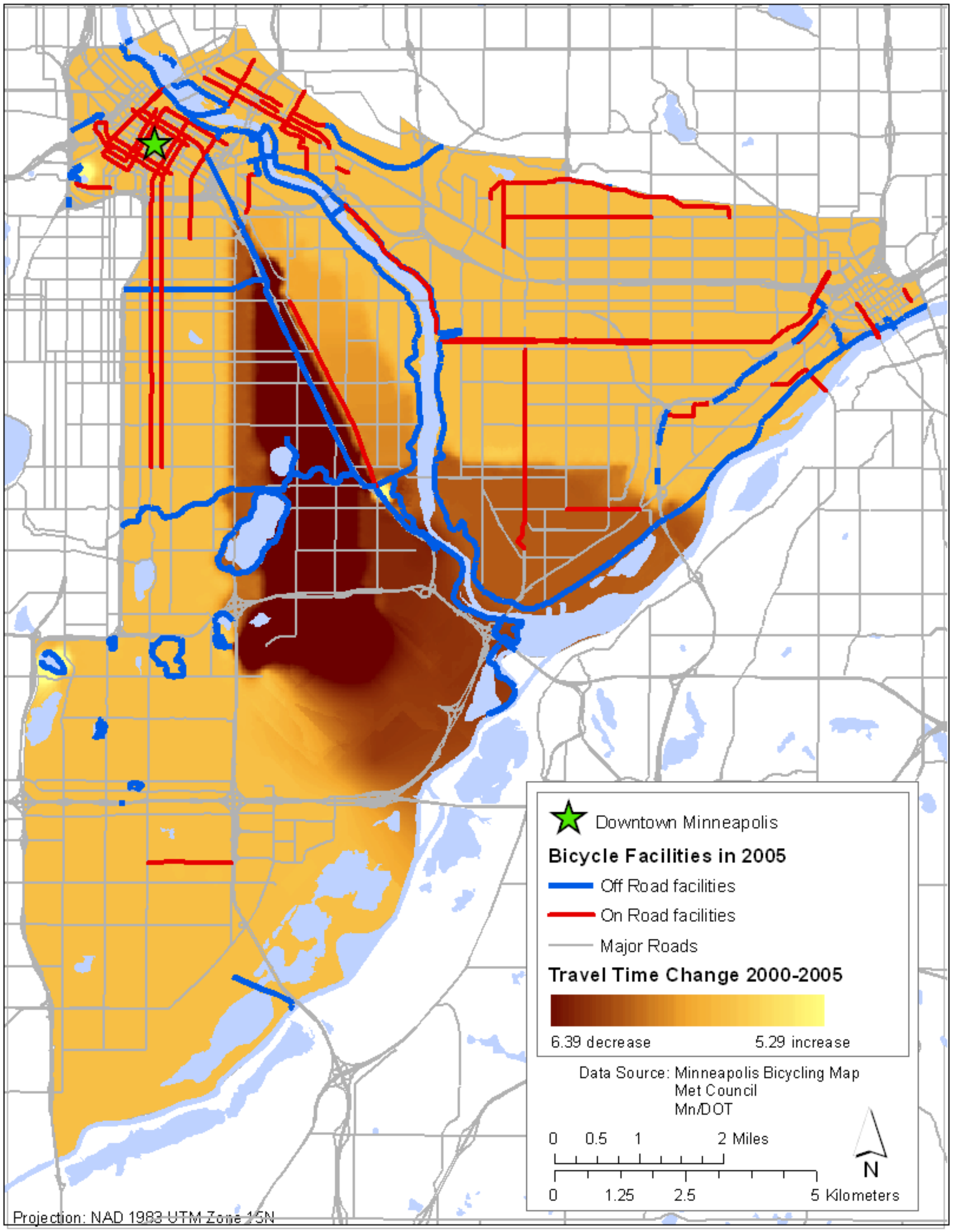
Executive Summary

The functioning of the system of land use and travel networks in a region can be encapsulated into measures of the ease of reaching destinations from various locations, often referred to as accessibility measures. Regardless of the form used to specify accessibility, all measures require as inputs travel times between the zones of a region. For most transportation planning purposes, these travel time calculations are limited to motorized modes (auto and public transit), since these modes carry the bulk of all urban travel. In this research study, attention is focused on developing methods for calculating travel times by non-auto modes, including walking, bicycling and public transit. These methods are demonstrated with an application to a section of the Twin Cities metropolitan region encompassing parts of the cities of Minneapolis, St. Paul and Bloomington.

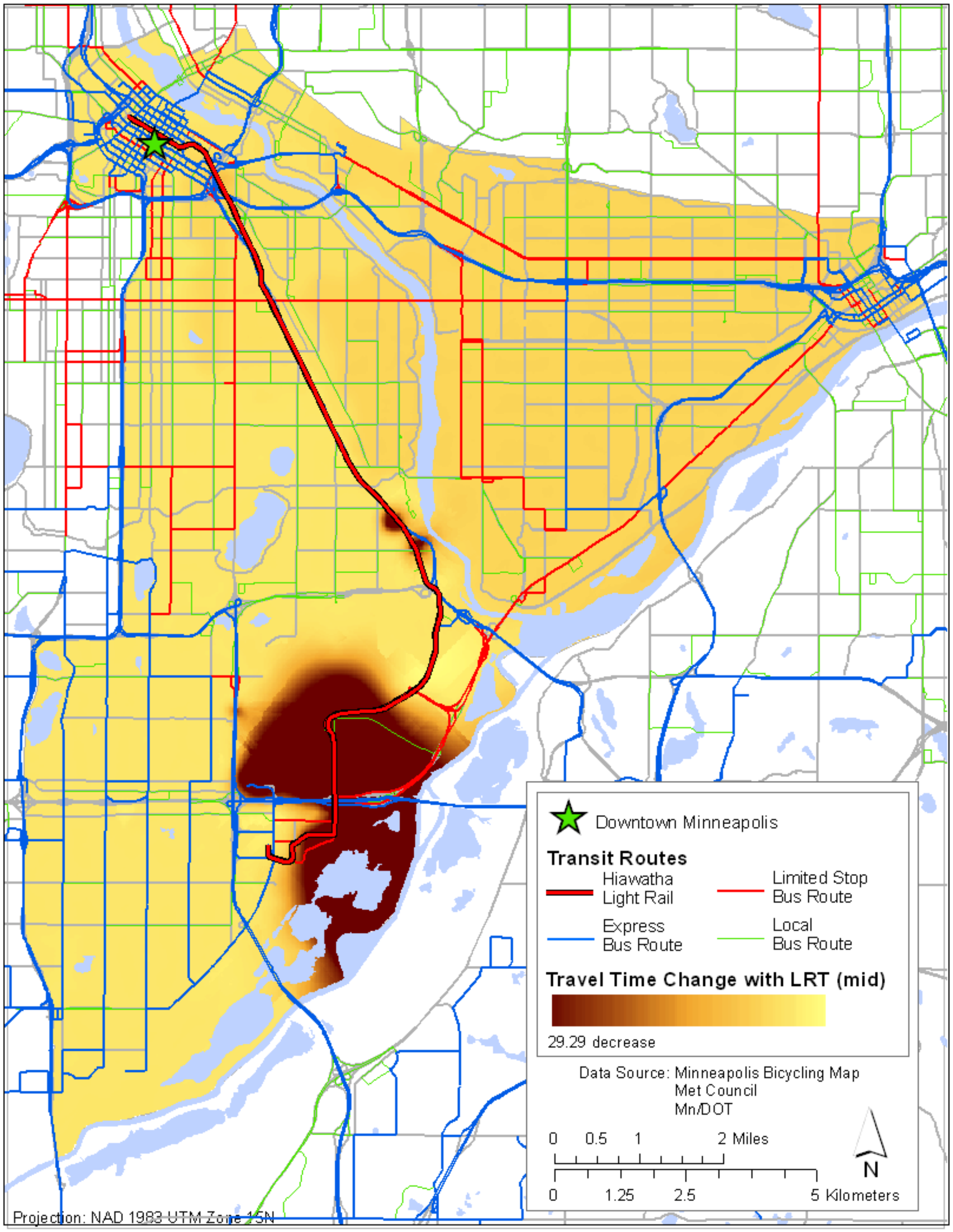
The calculation of travel times by mode requires two important inputs. First, unique networks need to be developed for each mode that reflect the provision of special facilities, such as sidewalks and on and off-street bicycle lanes and trails. Likewise, transit networks need to be developed with representation of travel times on specific links. Second, estimates of travel speeds by various modes need to be obtained. For pedestrian trips, travel speeds vary little and so we look to the literature on pedestrian travel for guidelines for our assumptions about travel speeds. In the case of bicycling, one might expect the presence of facilities such as on-street bike lanes and off-street trails to influence travel speeds. To account for this, a bicycle travel speed model is estimated to account for the influence of specific types of facilities on speeds, holding constant other factors that might be expected to influence travel speeds by bicycle, such as age and level of comfort with riding in mixed traffic. Data for this model are obtained from actual bicyclists outfitted with GPS receivers on their helmets. The influence of on and off-street facilities identified by the model are used to modify travel times on specific links in the bicycle network. Transit travel speeds can be calculated based on existing running times on bus and rail routes, but transit trips present some special challenges in determining overall trip times, since they represent not a single origin-destination pair, but a combination of shorter trip segments. In addition to time spent accessing transit and reaching a final destination, travel times must also account for the possibility of en-route transfers which may increase travel times. The methods used to account for these complications are detailed in a later section.

To apply these methods and view the effects of changes to travel networks on travel times, a series of maps are generated to depict the state of networks at three points in time, the years 1995, 2000 and 2005. In addition to depicting the extent of the networks, the maps show travel *sheds*, defined by travel times to various locations from a set of origins within the study area (such as downtown St. Paul and Minneapolis, South Minneapolis and Bloomington), and also changes in travel times between years, calculated by subtracting travel times between origins and destinations for successive points in time. Examples of these maps are provided below for the change in bicycle travel sheds between 2000 and 2005, and also for the change in travel sheds by public transit during the midday period (approximately 9:00 a.m. to 3:00 p.m.) of weekdays for 2000 and 2005, corresponding to the introduction of light rail transit and the restructuring of regional bus networks.

In summary, the results of this research demonstrate the potential of methods to calculate travel times for non-auto modes by developing specific methods for each mode and applying them in the context of a real-world urban setting. The travel time outputs by mode produced by this research can be integrated with detailed measures of land use to produce prototype measures of accessibility that can incorporate multiple modes and activity types (e.g. employment, shopping, education, etc.). This level of detail has rarely been reported in the published literature or in planning applications. This research takes the investigation of accessibility one step further by introducing temporal dynamics that allow for the tracking of changes in accessibility over time.



Change in bicycling travel time shed between 2000 and 2005



Change in transit travel time shed with LRT in 2005 (midday)

Introduction and Methods

Introduction

The functioning of the system of land use and travel networks in a region can be encapsulated into measures of the ease of reaching destinations from various locations, often referred to as accessibility measures. Regardless of the form used to specify accessibility, all measures require as inputs travel times between the zones of a region. For most transportation planning purposes, these travel time calculations are limited to motorized modes (automobile and public transit), since these modes carry the bulk of all urban travel. In this study, attention is focused on developing methods for calculating travel times by non-auto modes, including walking, bicycling, and public transit.

The study combines several methods for developing estimates of non-auto travel times. First, unique travel networks are defined for pedestrian, bicycle, and transit travel. These networks are updated over three points in time from 1995 to 2005. A novel approach is adopted to estimate bicyclist travel speeds incorporating the influence of different types of bicycle facilities on bicyclists' speeds via measurements obtained from global positioning system (GPS) receivers. Changes in travel time due to changes in the structure of travel networks for each mode are captured by generating maps highlighting changes in travel *sheds* (locations that can be reached within a given amount of time) for each mode between two points in time. These travel sheds are calculated for several origin points within the study area and, in the case of public transit, include differentiation of travel times by time of day.

Following a brief description of the study area and methods to be employed, a review of literature on travel speeds by pedestrians and bicyclists is presented, with additional material on the components of travel time by public transit and how these are measured. The development of networks for each mode is covered in the next section, including how the data for each network was acquired. Then, a detailed description of the bicycle speed model is presented, including the data collection process and estimation results. The latter sections of the study cover the data and assumptions that underpin the calculation of travel times by transit, followed by an analysis of the changes in travel time by each mode as a result of changes to the networks in the period between 1995 and 2005. Finally, the study concludes by noting the accomplishments and some of the difficulties encountered in calculating travel times for each mode, with ideas about how some of the ongoing concerns might be addressed in future efforts.

Research Goal

The objective of this research is to generate and refine methodologies for calculating non-auto (transit, bicycle, walking) travel times between origins and destinations within the Twin Cities. When married with detailed measures of land use activity, these derived travel times can then be used as required input parameters to calculate the accessibility to destinations within the metropolitan area using differing modes of transportation.

Study Area

The case study chosen for this application is shown in Figure 1 and includes downtown Minneapolis, downtown St. Paul, and the wedge stretching southwest to the Mall of America). The area includes the University of Minnesota (Minneapolis campus) and the area north of I-94 to just past University Avenue. The reasons for selecting this corridor are myriad; they include (but are not limited to) the fact that this area contains: (a) primary economic engines of the metropolitan area (e.g., downtown Minneapolis, the airport, the Mall of America), (b) several residential neighborhoods (e.g., southeast Minneapolis) and neighborhood commercial centers, and (c) the new Hiawatha Light Rail Line. It is ideal for an initial exploration of this type to consider different conditions when measuring transit attributes because each area has different reasons for travel, transit opportunities, and mode split.

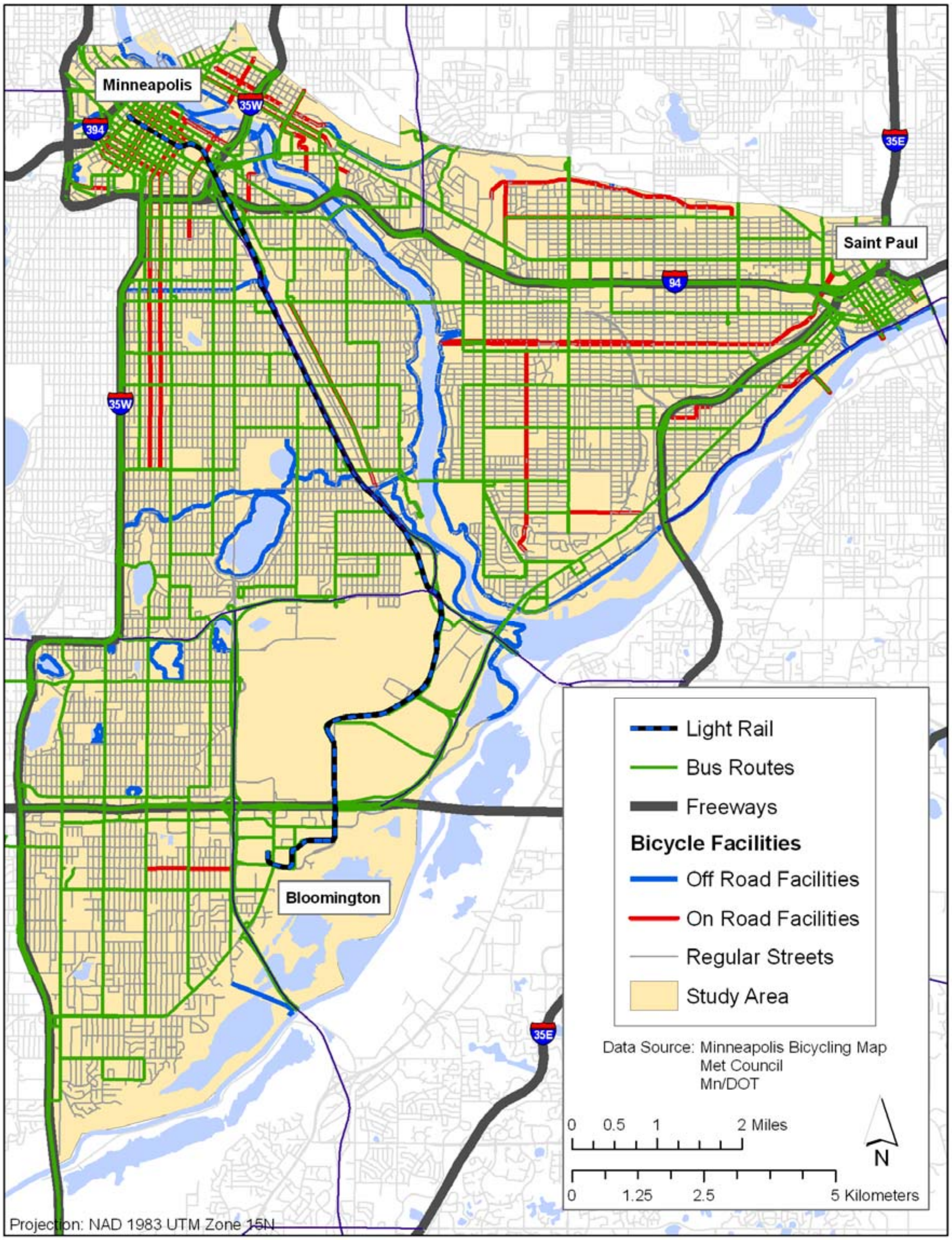


Figure 1. Study area

Methodology

For our analysis of non-auto travel time, we plan to aggregate data to the census block level. For the area shown in Figure 1.1, this includes 37,323 acres spread out over 6,555 blocks for an average area of over 6 acres per block. This represents an extremely detailed level of geography suitable for the fine level of analysis particularly required for studying walking distance. Obtaining the appropriate network for each non-auto mode in order to generate travel time between each census block and every other census block in the study area was the first step in our analysis.

Pedestrian networks consist mainly of all streets, trails, and special facilities designed especially to increase pedestrian access. Generating an accurate travel time matrix for a pedestrian network including all pedestrian bridges and short cuts is essential. It is important to note that such facilities are not incorporated in the general street layers and have to be added manually to the existing network. Travel time for pedestrians might vary by the type of facility and the purpose of the trip, yet incorporating such information from a secondary data set is not possible. A primary data collection effort would be required to obtain such information. In an ideal situation pedestrian travel time should incorporate delays associated with street intersections, either signalized or non-signalized, and also incorporate the presence or absence of sidewalks as part of travel time calculations. The availability of these datasets is the most limiting factor when generating accurate pedestrian maps.

Similarly, bicycling networks are composed from regular streets, off street bicycle facilities, on street bicycle facilities, and special facilities such as bridges and bicycle paths. To generate an accurate bicycling travel time matrix it is important to account for the variation in travel time along all these facilities. Also it is important to generate an accurate map that incorporates these facilities at various points in time to enable the quantification of benefits from adding a new facility or incorporating a bicycle lane along the new facility. The main source for obtaining bicycle networks are metropolitan planning agencies in a region and bicycling clubs. Maps from these sources require manual revision, due to errors in accuracy and in coding some of the facilities. Also some maps are generated based on the comfort of cyclists in using the facility rather than on facility type. The collection of primary data that accounts for the variance in travel time speeds and incorporating the effects of intersections on bicycling travel time is essential.

Regarding transit travel time it is important to understand the main components of a regular transit trip to enable modeling transit travel time in an accurate manner. In general, transit travel time can be divided into four main parts:

1- Access time
2- Wait Time
3- In vehicle travel time
4- Egress time

Access time is the time spent walking or bicycling from each origin to the nearest bus stop. Access time can also be the time spent in a vehicle en route to a bus stop, yet this type of access mode is not in the scope of the current study. Accordingly, this part of the trip should depend mainly on networks generated for bicycling and pedestrian travel time. Wait time is the time spent at the bus stop by each individual waiting for the bus. Wait time is usually half of the scheduled headway if the headway is less than or equal to roughly 15 minutes. In vehicle travel time is the time spent by the traveler in the vehicle and can be either obtained from published schedules or from archived automatic vehicle location system data, yet the second method is data intensive and hard to generalize. In vehicle travel time can be mainly obtained from transit agencies in various formats. Finally, egress time is the bicycling or walking time spent between when the person exits the bus or train at the nearest stop to his final destination and the arrival time at the final destination. Additional walking and waiting times can be added to the trip if a transfer was involved. For each transfer the walking distance between stops should be incorporated, along with the amount of time a person waits to ride the next bus or light rail train.

Background

Pedestrian Travel Time

Pedestrian speed study results have been widely reported and focus on several different aspects of pedestrian movement. Some focus on specific site conditions (e.g. geometric design), intersection control and location (midblock vs. corner), while others focus on the behavior of specific subgroups of the population (elderly, male/female, etc.). A brief cross-section of some recent studies is presented here, along with their primary findings.
Coffin and Morrall (1995) conducted a study of walking speeds of elderly pedestrians at intersections and midblock locations in Calgary, Alberta. Based on their findings, they recommend a 15th percentile design speed of 2.7 miles per hour (mph), or roughly 4.3 kilometers per hour (kph). Similarly, they report a design speed for midblock crosswalks and intersections near senior housing of 2.3 mph (3.7 kph). A study by Knoblauch et al. (1996) measured walking speeds at 16 intersections at signal-controlled intersections in four urban areas (Richmond, VA, Washington, D.C., Baltimore, MD, and Buffalo, NY), with the intention of providing empirical estimates of walking speeds for elderly pedestrians relative to other users. Results indicate that mean crossing speeds for pedestrians aged 14 to 64 were 3.4 miles per hour (mph), or 5.4 kilometers per hour (kph), while speeds for pedestrians 65 and over were recorded at 2.8 mph (4.5 kph). Recorded speeds among men and women were broadly similar, though age effects were detected in each group. Bennett et al. (2001) collected speed data for pedestrian crossings at four signalized intersections of four-lane roads in busy suburban shopping districts in Melbourne, Australia. Data were collected on weekdays as well as weekends, and included queued and unqueued pedestrians. A combined average of speeds at the four sites was reported as roughly 3.6 mph (5.8 kph), with a standard deviation of around 1.1 mph (1.8 kph).

Lam and Cheung (2000) report travel time estimates for pedestrians on different types of facilities in Hong Kong, including shopping and commercial areas, signalized crosswalks with and without midblock crossing, and signalized and non-signalized LRT crossings. The travel time function used to estimate speeds is a simple function of free-flow travel speeds and volume-to-capacity relationships for congested pedestrian areas. Their findings indicate speeds ranging from 1.6 mph (2.6 kph), for indoor walkways at shopping areas to 3.2 mph (5.2 kph) at signalized LRT crosswalks. Lindsey and Doan (2002) studied the use of multi-use urban greenway trails in Indiana by walkers, joggers, bikers, and skaters. While data were collected from users of multiple facilities, one trail was singled out for collection of speed measurements. Measured speeds on the Monon trail in November 2000 were 3.6 mph (5.8 kph) for walkers and 6.7 mph (10.8 kph) for runners.

These studies of pedestrian speed provide a reasonable cross-section of the estimates of pedestrian speed. The range of reported speeds of between 1.6 and 3.6 mph (2.6 and 5.8 kph) cover a wide range of locations and site conditions, as well as user groups, and provide a fairly robust interval of estimation for use in calculating pedestrian travel times.

Bicycling Travel Time

The available work on travel time and speed of cyclists reports only sporadic attempts to capture such phenomena. The cost and difficulty of collecting speed data for bicycle trips or facilities means that primary data collection efforts are uncommon. Bicycle speed data are often collected as a secondary consideration or as inputs for other related types of studies (e.g. level of service determination or bicycle traffic flow modeling). Below, we quickly review available efforts.

A comprehensive review by Allen et al. (1998) examines bicycling speed in general. They conclude that bicycle free-flow speed lies between 6.2 mph (10 km/h) and 17.4 mph (28 km/h) with a majority of the reported speeds in the literature being between 7.5 mph (12 km/h) and 12.4 mph (20 km/h). A study by Botma (1995) in the Netherlands uses a mean bicycle travel speed of 11.2 mph (18.0 km/h) to develop service flow rates for bicycles. Another study conducted by Thompson et al. (1997) used radar guns to detect speeds of adults and children while cycling along a closed road during a recreational event. In their study they found that the mean speed of all ages was around 9.2 mph (14.8 km/h). Khan and Raksuntorn (2001) employed video image data collection and analysis techniques to report speeds ranging from 10.7 to 22.3 mph (17.2 to 35.9 km/h) with a mean of 15.4 mph (24.8 km/h) on an exclusive bicycle path in Denver, Colorado, USA. Virkler and Balasubramanian (1998) collected speed data on bicyclists, along with hikers and joggers, as part of a study of flow on shared-use trail facilities in Columbia, Missouri, USA and Brisbane, Australia. Data in each location were collected manually by an observer with a stopwatch. Reported mean bicycle speeds in Columbia were 13.3 mph (21.4 km/h), while the Brisbane data indicated slightly lower speeds of 12.9 mph (20.7 km/h). As part of a study of urban greenway trails, Lindsey and Doan (2002) report mean speeds of 13 mph (20.9 km/h) for users of an urban greenway trail in Indianapolis, Indiana, USA. Other researchers concentrating on bicycle speed were mainly interested in speed at crossings and intersection points between trails and other types of networks (Pein 1997; Rubins and Handy 2005).

As is clear from the literature, reported bicycle speeds range from 6.3 mph (10km/h) to 22.3 mph (35.9 km/h), which is a wide range to generalize from. Also, classification along various types of facilities is not present. In addition, none of the previous studies account for route and user characteristics. Further, it is important to note that the majority of the studies mentioned previously were conducted prior the widespread use of GPS. Several technical and other advances in the past half-dozen years, however, now enable quick, reliable, and efficient collection of such data. For instance, in 2000 the U.S. government stopped its intentional degradation of the civilian GPS signal, called Selective Availability (SA), which was used to protect military operations. SA used to distort the accuracy of any GPS system, making it difficult to use a GPS to accurately locate a moving object such as vehicles on a road (Longley, Goodchild et al. 2001). Currently, off-the-shelf GPS systems have an accuracy range from three to ten meters that can be used to collect more accurate speed data.

Transit Travel Time

Calculating transit travel time is an especially difficult task. This is because trips by transit tend to be a composite of several smaller trips and trip components comprising access, egress, line-haul, and waiting or transfer times at stops/stations. Each component tends to be perceived differently by travelers and common metrics are often needed to simply the contribution of each.

One critical component of travel time calculations is the treatment of transfers between routes or modes, a critical function in most urban transit systems. The reluctance of potential users to endure transfers can present constraints on the design of transit services. Little empirical evidence is available on the number of transfers used by transit patrons in completing their daily trips. Requirements for transit agency reporting to the Federal Transit Administration do not include the reporting of *linked* transit trips (e.g. whole trips from the point of origin to final destination), only the provision of the number of unlinked *boardings,* which are tallied each time a passenger boards a bus or train (including transfers). Since there is no real incentive for most transit agencies to report linked boardings, such data is not typically made available on a consistent basis.

Data from a recent survey of transit users in the Twin Cities region suggests that the system-wide transfer rate is around 36 percent, that is, 36 percent of all system-wide boardings represent transfers (2006). This value varies by type of service (local bus users versus express bus or light rail users), with local bus users transferring more frequently than light rail and express bus users, respectively. Pisarski (2003) reports that historically, the average transfer rate for transit systems in the U.S. has been around 30 percent, though this number has been increasing in recent years due to a variety of factors, such as the introduction of flat fare policies, free transfers, and the redesign of routes and networks from a radial system to a decentralized, hub-and-spoke system. The most profound influence on the transfer rate though, has been the addition of rail systems in many U.S. cities. Kain (1997), in a study of the MARTA heavy rail system in Atlanta, reports that the introduction of heavy rail service and associated redesign of local bus networks to serve as rail feeder routes increased the transfer rate from 29 percent in May 1979 to 40 percent in May 1980. The continued restructuring of the route network led to a system-wide transfer rate that reached a maximum of 125 percent in fiscal year 1984. Kain also reports that the transfer rate has reached at least 99 percent in each year since. This is confirmed for more recent data published in MARTA's annual financial reports. Data for fiscal years 1996 and 2005 indicate that system-wide transfer rates for these years were 115 percent and 122 percent, respectively (Authority 2005).

The effect of transfers on transit use and their subjective valuation by travelers provide indicators of the relative value of various components of transit trips. Estimation results from empirical mode (Liu, Pendyala et al. 1997) or route choice (Han 1987; Hunt 1990; Guo and Wilson 2004) models are commonly used to estimate the values of various components of transit travel time. In the choice models, a utility function is specified expressing the utility of an alternative (route or mode) in terms of a set of attributes of the choice, such as walk time, wait time, in-vehicle and out-of-vehicle time, and fare (for competing modes or services). Using the estimated coefficients from the utility function, comparisons of relative utility can be made that allow the calculation of the value of each component in terms of a common unit of cost (e.g. in-vehicle time or fare). The utility-based approach is conceptually similar to studies using generalized cost measures, where coefficients of a linear cost function are estimated, and the coefficient of the fare or in-vehicle time variable is normalized to equal 1.0. The values of walking, waiting and transfer times are often found to be between two and three times the value of in-vehicle time (Ortuzar and Willumsen 2001), and thus can be scaled accordingly. Since the observation and accurate measurement of some of the components of transit travel time is sometimes difficult, experimental approaches have also been developed using stated preference (Liu, Pendyala et al. 1997) and psychological scaling (Horowitz 1981) techniques.

Data on transit access time is also somewhat difficult to obtain. In practice, transportation planning models sometimes assume a default value for access time throughout a particular travel zone (Ortuzar and Willumsen 2001). However, the increasing presence of transportation GIS applications (GIS-T) allows for more accurate measures of access distance via travel networks using some common functions of GIS software packages (Dueker and Ton 2000).

Modeling the behavior of transit users en route, including at transfer points, requires some assumptions about how users will respond to different levels of service and accordingly adjust their behavior. Transit passengers will typically adjust their arrival time at a stop or transfer point in response to changes in operations. For routes characterized by long headways, schedule adherence is the most important operations objective. Passengers will attempt to time their arrivals with that of the bus based upon a given probability of missing the departure (Turnquist 1978; Bowman and Turnquist 1981). In these circumstances average wait times are less than one-half of the scheduled headway. Schedule adherence is also an important objective at timed transfer locations. Alternatively, for routes that operate at headways of 10 minutes or less, headway maintenance is the most important operations objective. This is because passengers do not find it advantageous to time their arrivals with that of the schedule, and are thus assumed to arrive at stops randomly. The aggregate wait time of passengers is minimized when buses are evenly spaced on routes operating at high frequencies. (Strathman, Dueker et al. 1999).

Waiting time is usually modeled as half the headway in transportation planning models. Yet this assumption is true only when short headways are present. For routes with longer headways, passengers will limit their waiting time, indicating some arbitrary upper bound (perhaps around 10 minutes). Within this limit, assumptions about waiting time can be further generalized to include measures of service reliability (Ortuzar and Willumsen 2001) and issues of congestion (De Cea and Fernandez 2000). In this research we use half the headway as the wait time for routes with headway less than 15 minutes. While all other routes we assume people consult schedules and we use 7.5 minutes as an average waiting time.

Networks

Data requests and communication

The research team contacted various agencies in the Twin Cities region to obtain the required data to generate travel time for the various modes. Problems did exist in various aspects of the data obtained. This section documents mainly the contacts and the problems being faced by the research team in term of obtaining the data needed and/or data quality. Appendix A includes copies of the communication being conducted with various agencies in the Twin Cities region to obtain the appropriate data needed to conduct the analysis

Pedestrian networks

As is mentioned in the methodology section, obtaining accurate sidewalk and street intersections are very important to accurately model pedestrian travel time. Since it is expected that travel time will vary with the quality of the sidewalk and with its presence or absence, obtaining sidewalk data was one of the first steps the research team took. Several agencies were contacted and a final data set was obtained. Figure 2 shows a sample of the sidewalk data. The data displayed here is not useful for generating a travel time matrix. There are several reasons for this. First, sidewalk data are not linked to the street centerline; accordingly, measurements of sidewalk connectivity are not possible. Second the data lack alignment with the existing centerline files obtained from the Met Council. In addition, the presence of curb cuts in the dataset made it even harder to generalize a sidewalk layer from the data. For the years 1995 and 2000 we mainly used the existing street centerline files combined with off-street bicycle and pedestrian facilities obtained from various historical maps. For the year 2005 we incorporated various bridges and walking amenities being constructed in the period between 2000 and 2005. Such facilities were incorporated based on discussions with several planners at various municipalities in the Twin Cities region about the locations of such facilities. These facilities were then incorporated manually in the network.

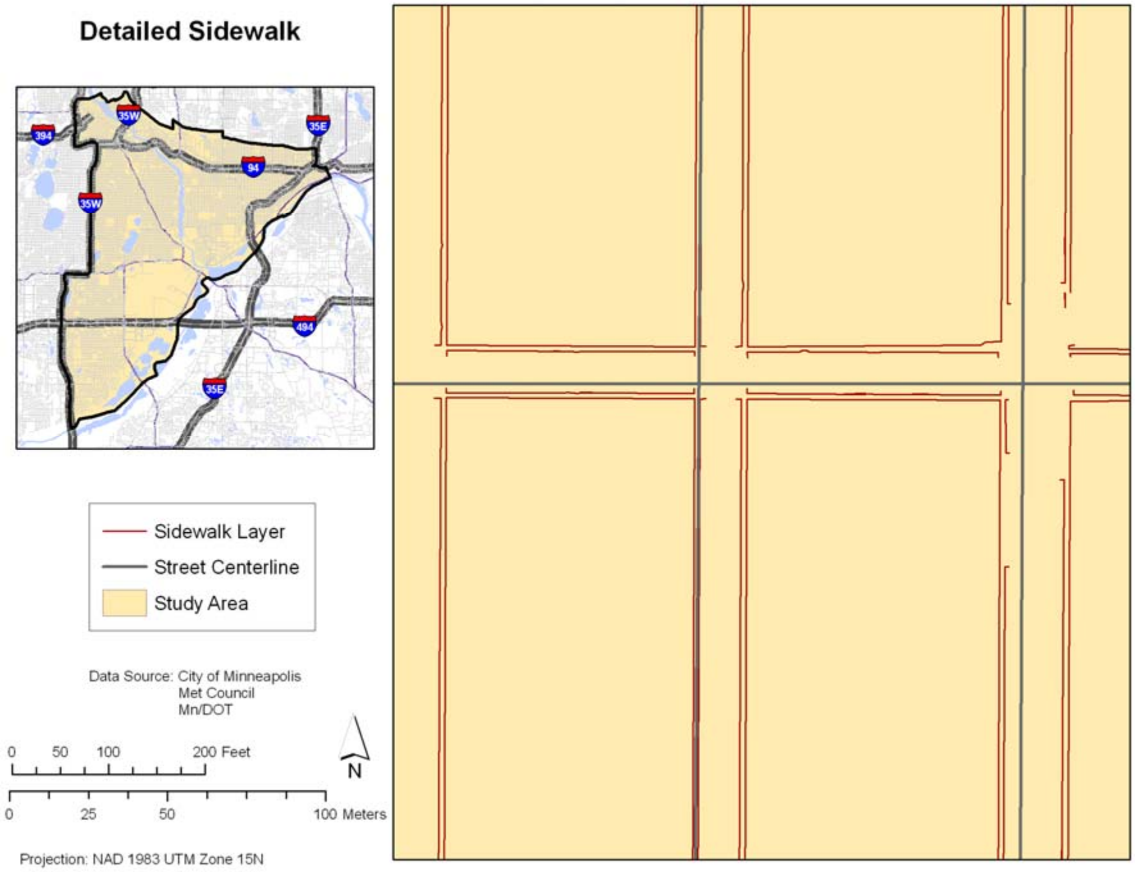


Figure 2. Accuracy of sidewalk data

Figures 3, 4, and 5 show the pedestrian networks being used in the study for the years 1995, 2000 and 2005, respectively. It is important to note that all freeway segments are removed from the pedestrian networks. Several errors were noticed in the coding of the freeways where local streets were coded as freeways. These errors were adjusted manually.

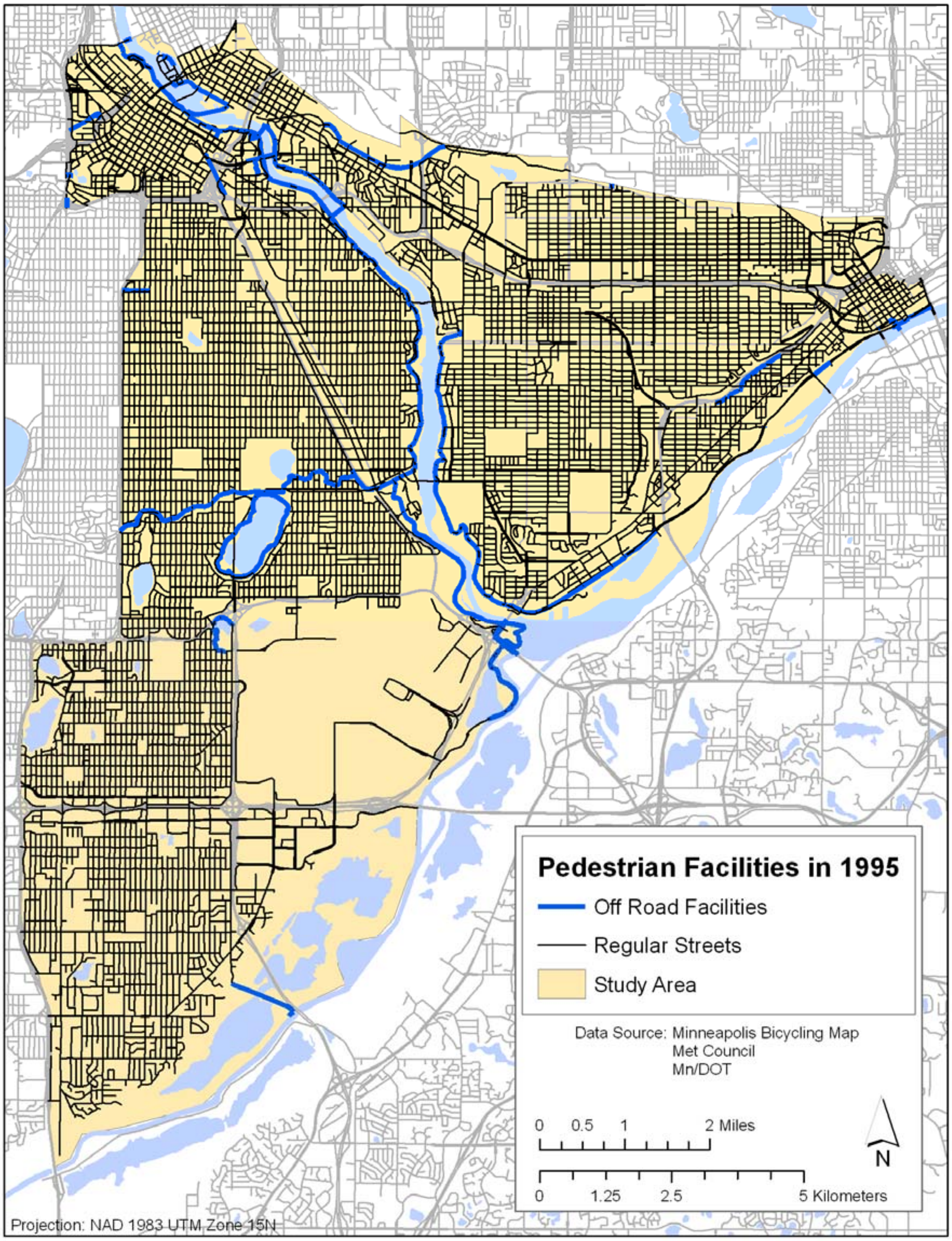


Figure 3. Pedestrian network in 1995

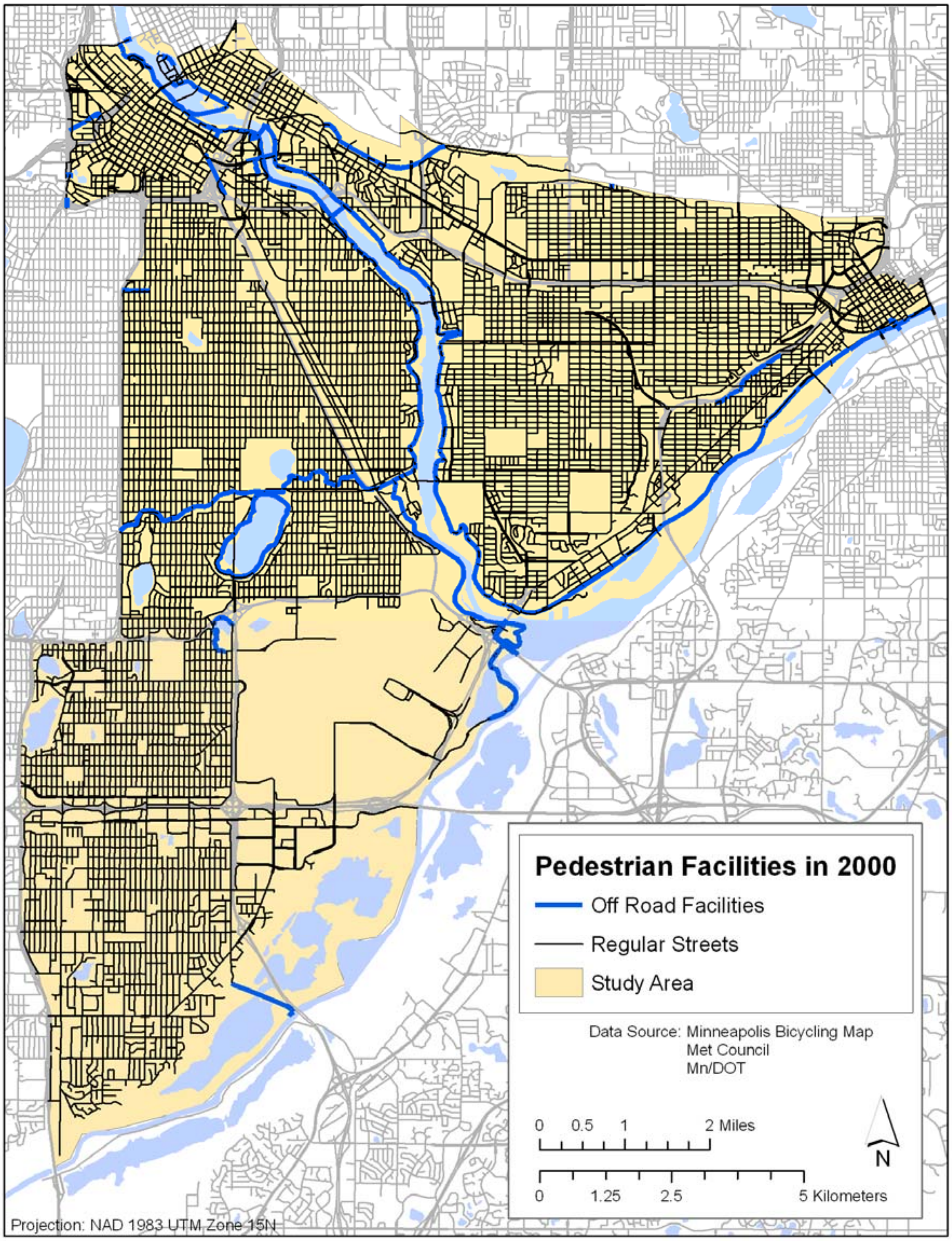


Figure 4. Pedestrian network in 2000

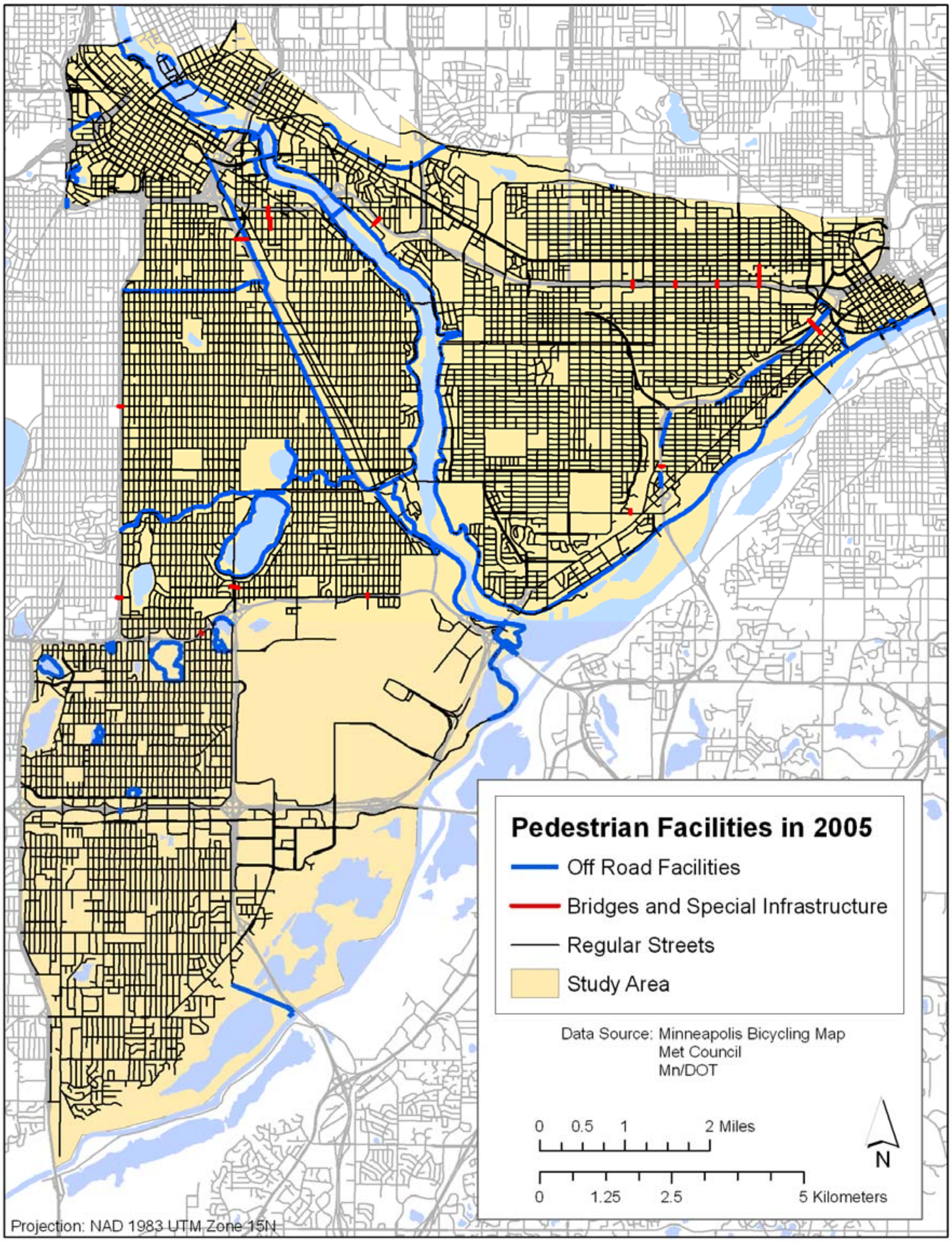


Figure 5. Pedestrian network in 2005

Bicycling Network

Off and on street facility layers were obtained from various sources. These networks were edited manually to accurately represent the studied dates. Figures 6, 7, and 8 show the bicycling networks used in the study for the years 1995, 2000 and 2005, respectively. It is important to note that all freeway segments are removed from the pedestrian networks. Several errors were noticed in the coding of the freeways where several local streets were coded as freeways. These errors were adjusted manually.

To generate the bicycling maps we used base bicycling GIS layers obtained from Mn/DOT, which mainly includes both off-street and on-street bicycling facilities. These GIS layers were then manually reviewed with various paper copies of bicycling maps. Then integration between this GIS layer and the existing street centerline file was done in a GIS environment. A base map for 2005 was generated as a start, then this map was manually edited to exclude off-street and/or on-street facilities that did not exist in previous years (2000 and 1995). The revision of the facility layers was done through observing bicycling maps for the years 2000 and 1984.

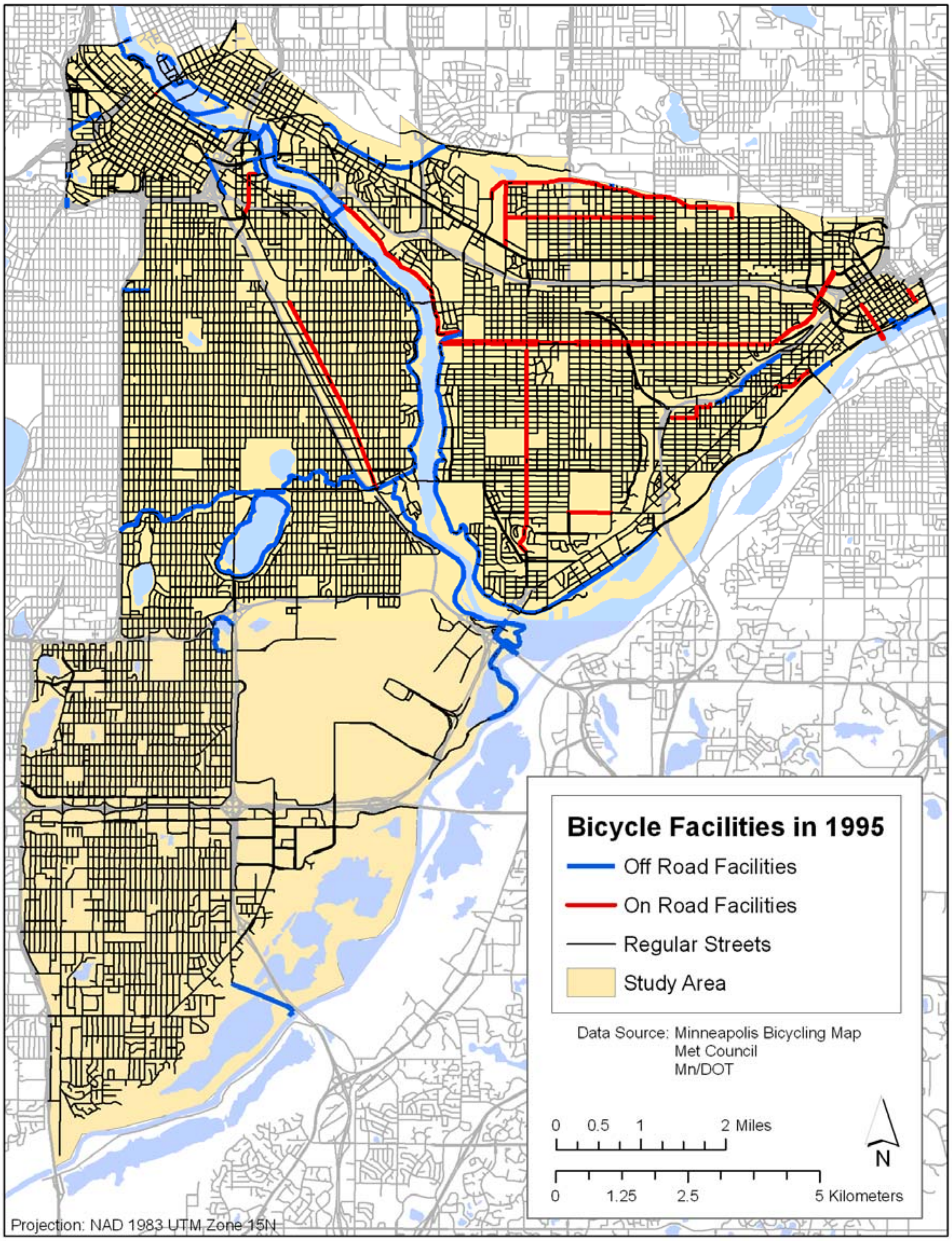


Figure 6. Bicycle network in 1995

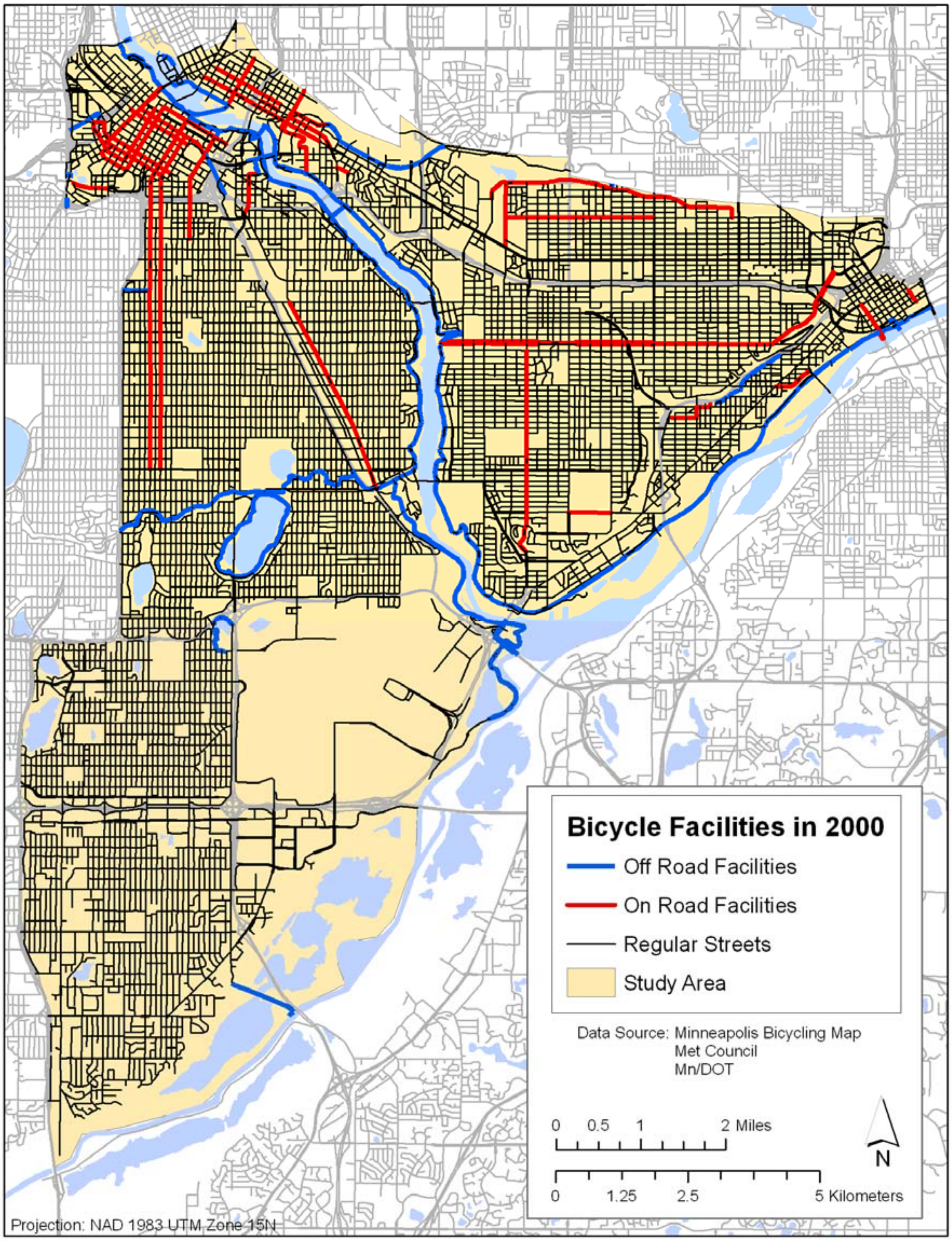


Figure 7. Bicycle network in 2000

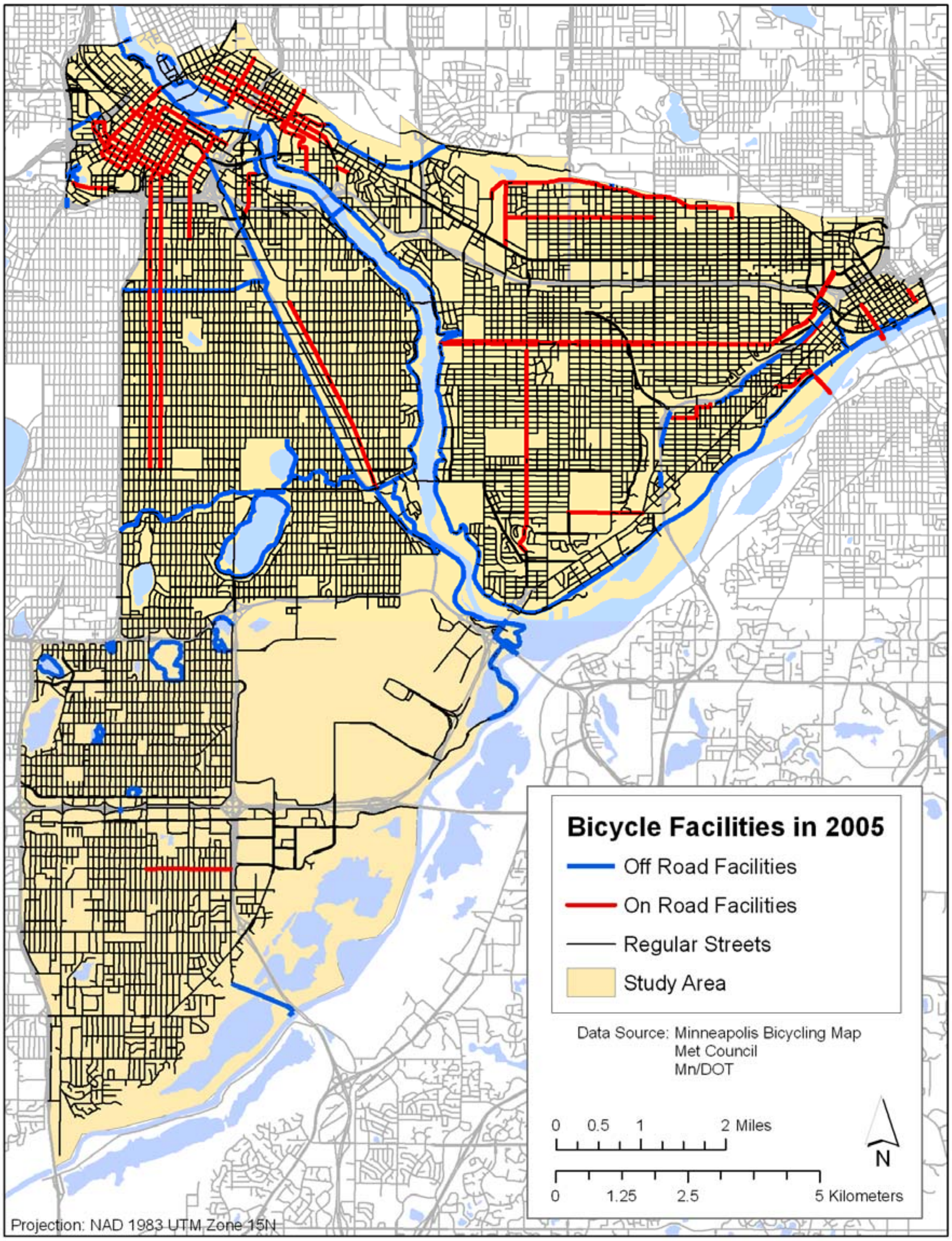


Figure 8. Bicycle network in 2005

Transit Network

The research team contacted Metro Transit through various sources to obtain schedules in electronic format for the desired time periods. Jason Podany, a GIS/ Transit planner at Metro Transit expressed to us that obtaining historical data in an electronic format would be difficult for the desired years. He directed the research team to the Metropolitan Council GIS database where information related to transit travel time and schedules could be obtained for the year 2005. He also provided the research team with an incomplete transit network for the years 1996, 1997 and 1998. The problem is that these networks did not include any information that could help in generating travel times for am, pm, and midday periods.

Regarding the data available from the Metropolitan Council websites, several issues were found in the data related to its quality. The following is a list of the available GIS files:

1- Bus Routes,
   The Bus Routes layer contains all bus routes in the seven-county Twin Cities metropolitan area. One shape and one corresponding record exists for each individual bus route. Attributes include Line_id, Segments, Route type, Weekday/Saturday/Sunday Trips, CBD Service and garage.

2- Bus Routes Segments
   The Bus Route Segments layer contains all segments that compose all bus routes in the seven-county metropolitan area. A bus segment is defined as a specific set of contiguous street centerlines with a defined Line-ID, Direction, From Node, To Node, and Variant. Several segments make up a bus route. Attributes include Segid, Line_id, Direction, From_node and To_node, Miles, Weekday/Saturday/Sunday Trips, and a decimal time for the first and last trip during Weekday/Saturday/Sunday service, average daily minutes of running time and miles per hour for Weekday/Saturday/Sunday service.

3- Bus Service
   The Bus Service layer contains all street centerlines with bus service in the seven- county metropolitan area. Attributes include road name, Id, Length in meters, Routes, Number of Routes, trips for weekday, weekday morning, weekday midday, weekday afternoon, weekday evening, Midday Saturday, and Sunday service, average run time and miles per hour for weekday, weekday morning, weekday midday, weekday afternoon, weekday evening, Midday Saturday, and Sunday service.

4- Bus Stops
   The Bus Stops layer contains over 17,000 active bus stops in the seven-county metropolitan area. Attributes include Siteid, transit control center id, Siteon, Siteat, Corner Number, Corner Description, Bustop_yn, X and Y coordinates and Nodeid, the number of trips, first and last stops during weekdays, Saturdays, and Sundays and Routes serving each stop

The bus service information represents the best available data for generating travel times during peak and off-peak time periods. Yet generating travel time directly from this layer is not robust, since it is segmented by streets. Accordingly, each street will be considered as an intersection or a transfer point even though it might not be a transfer point. Therefore, the bus service layer has to be spatially joined to the bus routes layer. The spatial join had to be based on a point join to avoid joining intersecting routes.

Problems do exist in the bus service layer. For example, the running time along some segments were recorded to be higher than 3,000 minutes which cannot be true for any segment. Running times along some of these segments were revised based on online schedule information available from the Metro Transit website. Others were removed form the network. On the other hand, some segments had running times equal to zero during the morning peak, yet a value during the evening peak. Similarly, running time was revised for these parts of the network and removed for the network used to generate travel time during the morning peak. Another example is the Hiawatha light rail line, where travel time was recorded as zero. In a similar fashion, schedule revisions and assignments of travel time between stations were done manually based on the schedules for light rail service. Figure 9 shows the transit network used for the morning peak period. In addition, parts of the network that had either a zero value or a high value for travel time are also displayed.

The network had to be revised, so random segments were selected for revision to ensure accuracy. Although the source for the bus service layer is the same as the route layer, differences did exist between the two networks. Some routes did not have a corresponding segment and other segments did not have a corresponding route. These were revised and removed from the data if an accuracy problem was noticed by the research team.

Due to the various problems the research team noticed in the bus service layer, the research team contacted Jason Podany at Metro Transit, who provided the research team with a bus route segments layer which included morning peak period running time, mid day running time and evening running time, along with accurate transfer points to be incorporated when modeling transit running time. Transfer points are identified as the intersection between any two routes. Modeling transfer time in the network and using ArcGIS software still proved to be problematic. The research team contacted the ESRI help line to provide support on how transfers can be incorporated in the analysis. The ESRI support team provided a solution included in Appendix B. This solution is workable only for small systems where a person can model each transfer manually. In addition, headway information is not available directly and had to be calculated for each segment based on three hours of service divided by the number of trips in the period of study.

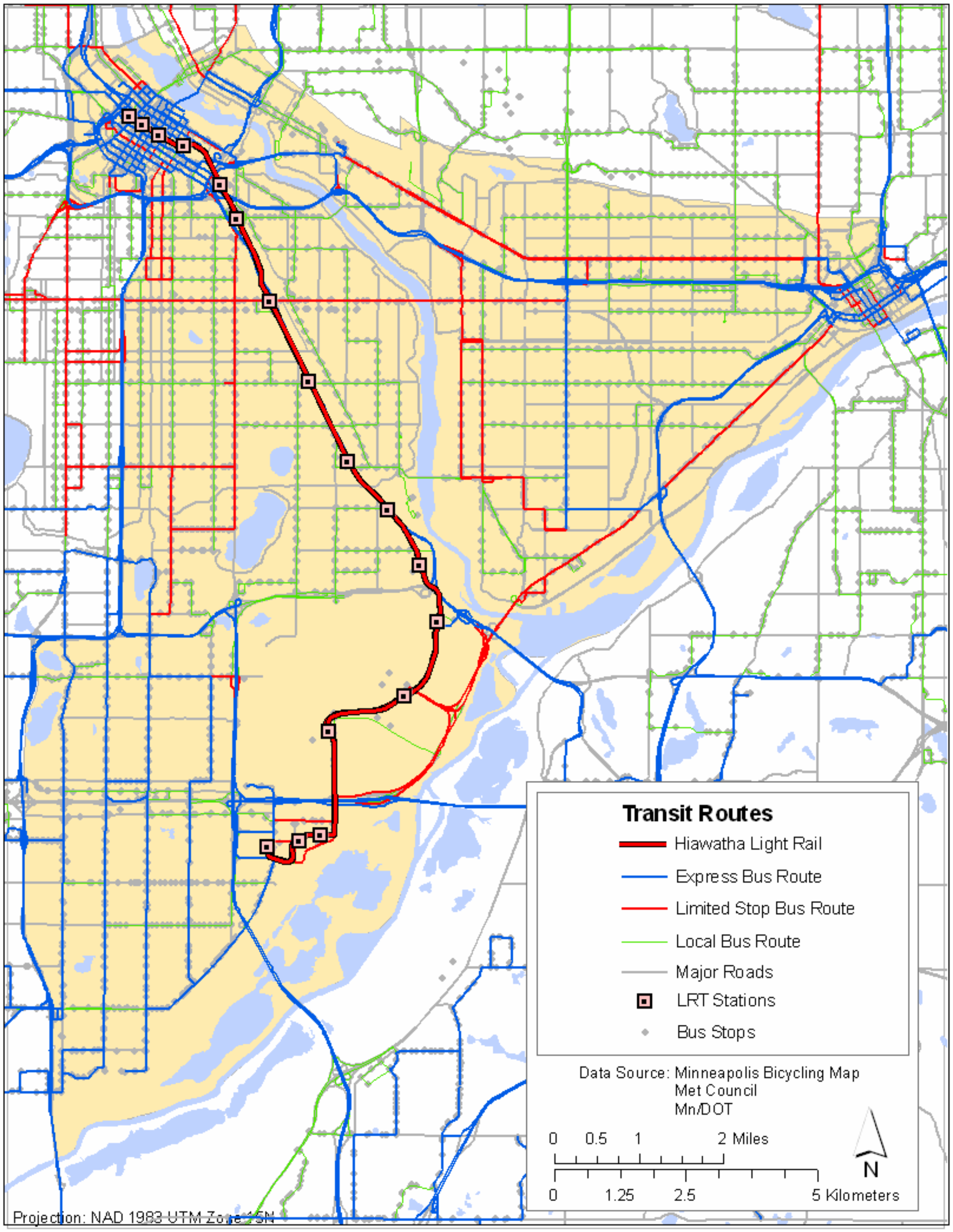


Figure 9. Transit network in 2005

Obtaining historical transit network data in an electronic format that could be linked to a GIS through Metro Transit was not possible. Instead, Mark Filipi from the Met Council provided the research team with data used by the Metropolitan Council in their travel demand forecasting model for the years 1990 and 2000. Unfortunately, the way this data is structured it cannot be used in GIS to generate travel times using ArcGIS, though it can be used with the Cube Voyager software package from Citilabs© to do so. Cube Voyager is commercially available software and is being sold for $13,500. This software enables a full control on the number of transfers and adding penalties related to transfers.

Initial communications with Citilabs personnel are documented in Appendix C.

Bicycling Travel Time Model

The aim of this research is to develop a model to predict the speed at which different types of users travel along different types of bicycle facilities. In order to generate a reliable model that can accurately predict bicycling speeds, data should be collected along the various transportation facilities that permit cycling. Many urban areas, particularly in the USA, have generally three types of facilities for cyclists. The first is an off-street facility, a dedicated path for bicycling only (although sometimes for bicycling and walking), with minimal to non-existent interaction with motor traffic. The Minneapolis-St. Paul region, the geographic location of our research, boasts a system of off-street bike paths unparalleled among major metropolitan areas in the USA, totaling over 1,692 miles (2,722 kilometers). The second type of facility, striped on-street bike lanes, are not nearly as extensive. Cyclists travel along these facilities to the side of regular traffic, yet in a dedicated lane where they have the right of way. These facilities have higher levels of interaction with traffic compared with off-street facilities. The last type of facility cyclists use are regular streets. Regular streets have the highest level of interaction between cyclists and traffic; cyclists must travel in mixed traffic. Figure 10 shows example images of the first two types of bicycling facilities.

Figure 10. Examples of types of bicycling facilites: Off-street and on-street

Figure 11 shows an example of a typical trip between points A and B. The person traveling from point A has passed through three different facilities to reach his destination at point B. Accordingly, the trip is divided into three different sections. Segment 1 presents the traveler cycling along an on-street facility to segment 2, where he travels on an off-street facility, and finally onto segment 3 where the traveler uses the network of regular streets. Accordingly, speed along each segment is expected to vary due to the nature and characteristics of the segment. Differentiating between these types of facilities by splitting the trip into segments is essential to generating a more accurate speed model. The trip segment is used as our main unit of analysis for the study. Each trip segment includes only one type of facility.

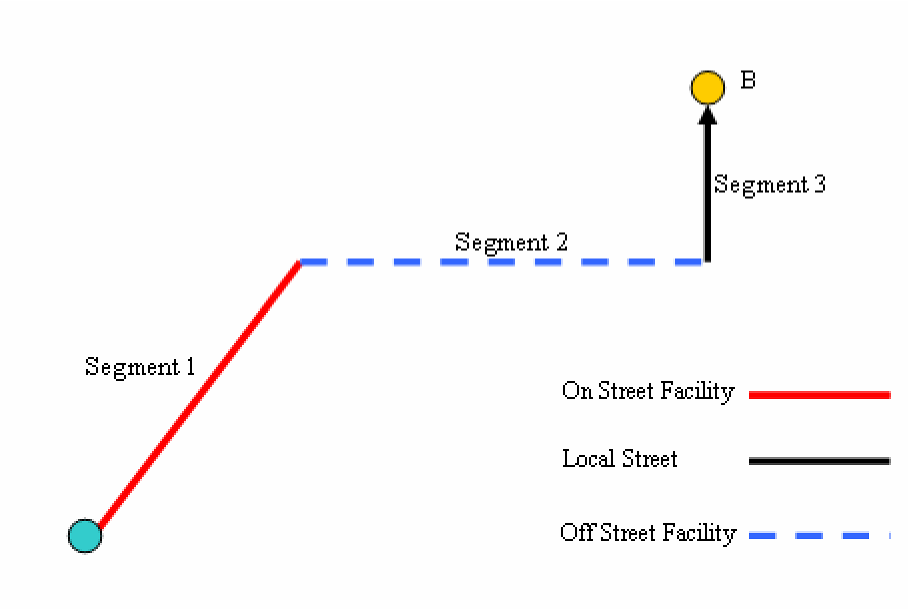


Figure 11. Unit of analysis

We expect the speed of bicycling to vary based on the cycling facility being traveled (e.g., transportation network of off-street facilities, on-street facilities, and regular streets), characteristics of the route, and characteristics of the user. Route characteristics include the total length of the trip (one may have slower speeds for longer travel distances), time of day (travelers may be more time-pressed in the morning), number of signalized intersections along the segment, number of crossing streets, and the average daily traffic along the segment. User characteristics include gender, age, and comfort with traveling in various types of facilities. Including these personal characteristics should account for the variance between individuals collecting the data.

The generalized relationship we used to measure speed along a segment is represented as follows:

Speed along segment = f (type of facility, segment length, trip length, number of signalized intersections, average daily traffic, time of day, personal characteristics)

The main policy-relevant variable we focused on in this application is the type of facility. The segment length variable will provide a generalized average speed while controlling for other factors affecting bicycling speed at its mean value. The type of facility is also a key variable since it provides us with estimates of the effects of specialized facilities on bicycling speed.

Data

In order to develop an accurate bicycle travel speed model, primary data collection is an important first step. In October 2005 the Active Communities Research Group (ACT) at the University of Minnesota conducted a pilot study to measure the effects of route choice on cyclists. This study required recruiting cyclists and equipping them with GPS units to monitor their travel patterns and speed. Eight cyclists who both live and work in Minneapolis were recruited for the pilot study. None of the cyclists knew that a speed model would be generated from the data they were collecting; communication regarding the purpose of the exercise was kept at a very general level, primarily focusing on route decisions. Table 1 includes information related to each respondent volunteer showing the age, gender, and frequency of cycling per week for each participant.

Table 1. Characteristics of respondents

ID	Age	Gender	Frequency of Cycling Per Week
1	50	Male	3.67
2	43	Male	5.00
3	60	Female	2.33
4	28	Male	6.00
5	55	Female	3.75
6	47	Female	0.50
7	58	Male	3.25
8	30	Female	1.75

A GPS unit was attached to each respondent's handlebar to collect their location every two seconds. Three weeks worth of data were collected per respondent and they were asked to vary their path and to use various facilities during their daily trips. An abundant number of GPS points were collected. The high level of resolution required a thorough cleaning process. For example, figure 12 shows a snapshot of GPS data collected during the course of a trip, the cluster in the centre depicting an origin location of one of the cyclists. Many similar points exist at other locations, for example, while waiting at a traffic light or reaching the destination. Such extraneous data had to be removed. Figure 12 also shows that it is difficult to discern among the transitional points between the different types of facilities. Accordingly, all transitional points were also removed from the data. It is important to note that only GPS points that can be clearly associated to a facility were used in the analysis. Each GPS point was snapped to the centre line for one of the transportation facilities. It is also important to note that, as observed in figure 12, some travel occurred in small alleys. Since these alleys are not part of the formally recognized transportation network, these observations were also removed in the interest of parsimony.

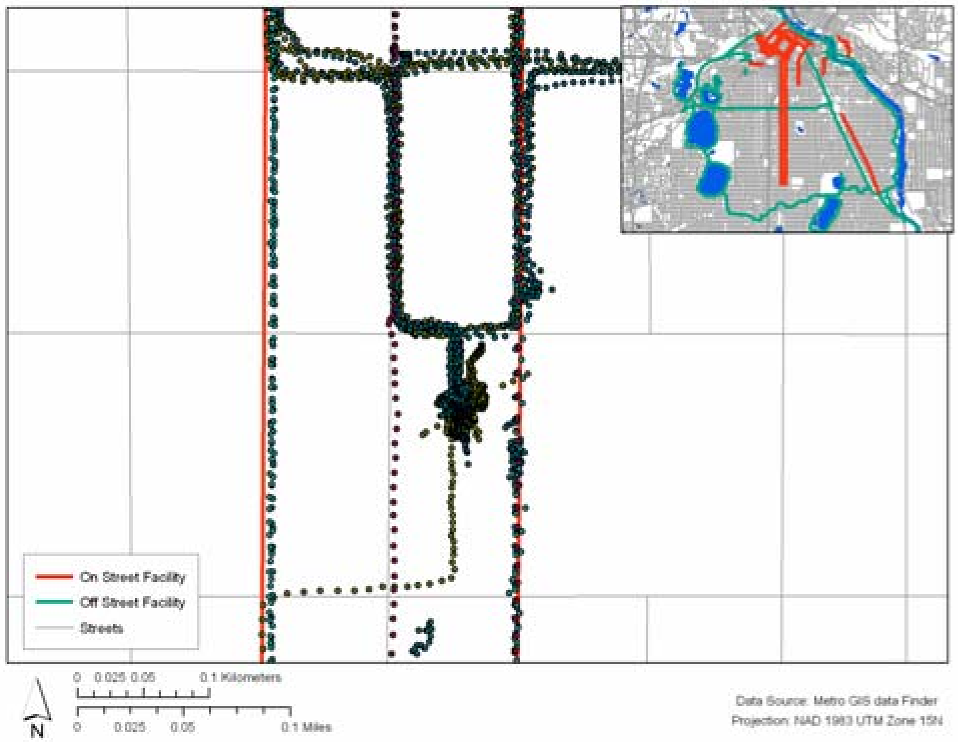


Figure 12. Snapshot of GPS collected data at the origin of a respondent's trip

We took additional strides to manually clean the data to decrease the amount of error, and to be sure that all points were to be assigned to one type facility and to the segment that was actually being traveled along. Figure 13 shows the distribution of the study routes. Study segments are defined based on the observation of continuous GPS points along a facility. A total of 315 study segments emerged as clean segments: 102 off-street, 81 on-street, and 132 local street segments.

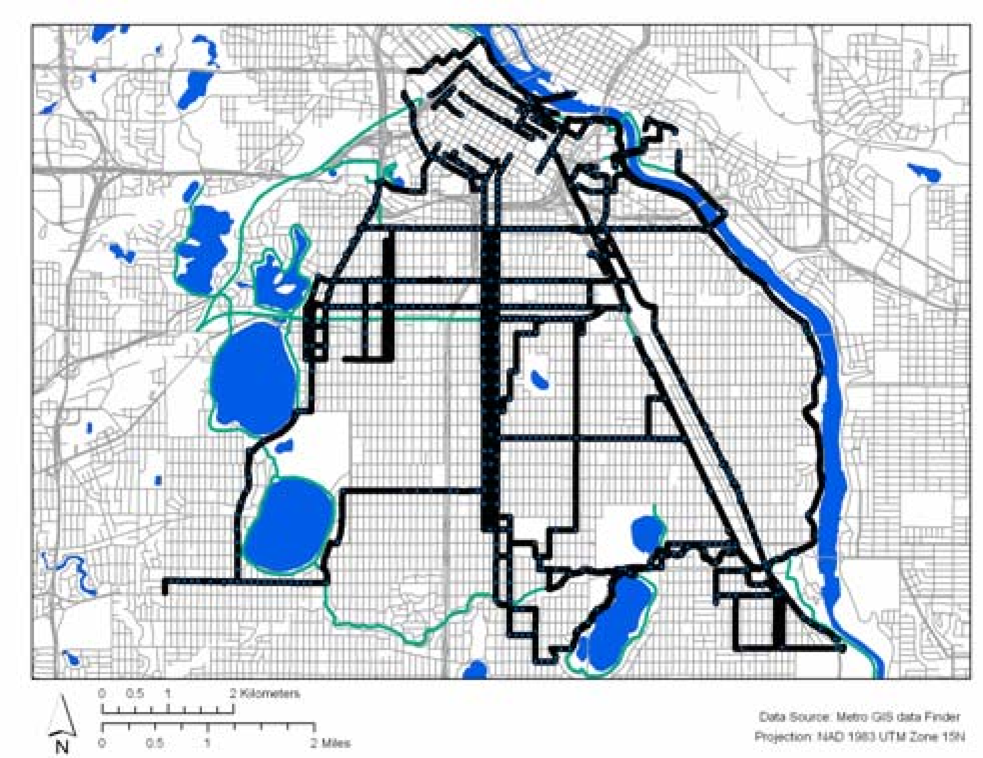


Figure 13. Study routes

GPS points were used to derive several variables related to the trip and the segment such as speed, segment length, total trip length, and other characteristics of the trip. All data were assigned to individual segments. Meanwhile, other characteristics of the segments, including type of facility, number of signalized intersections, and average daily traffic were obtained from secondary data sources including the Metropolitan Council (regional planning agency for the Minneapolis-St. Paul region) geographic information system (GIS) database, Minnesota Department of Transportation, and the City of Minneapolis, respectively. All cyclists were required to complete a survey at the end of the data collection process. This survey included various questions to help control for the variation among the respondents. Table 2 includes a summary of the descriptive statistics of each variable used in the speed model.

Table 2. Descriptive statistics

Variable	Min	Max	Mean	Std. Dev.
On Street Facility (1 or zero)	0.00	1.00	0.26	0.44
Off Street Facility (1 or zero)	0.00	1.00	0.32	0.47
Distance Traveled Till Segment (Miles)	0.00	10.12	2.61	2.30
Total Trip Length (Miles)	0.08	10.62	5.51	1.82
Segment Length	0.05	6.29	1.20	1.40
Average Daily Traffic (Vehicles/ Day)	0.00	28174.68	4497.52	5474.38
Number of Signalized Intersections	0.00	17.00	0.78	1.89
Morning Commute (1 or zero)	0.00	1.00	0.63	0.48
Speed (Miles/Hour)	0.00	20.74	10.02	2.87
Age	28.00	60.00	47.92	11.86
Male (1 male or zero female)	0.00	1.00	0.53	0.50
Comfort in traveling in light Traffic (1 or zero)	0.00	1.00	0.54	0.50
Comfort in traveling in heavy Traffic (1 or zero)	0.00	1.00	0.41	0.49

Analysis

Our first approach is to develop an ordinary least squares regression model that can control for variation among cyclists (table 3). Therefore, speed is used as the dependent variable in the model, while a set of independent variables included the type of facility, trip and segment characteristics, and seven dummy variables representing each cyclist. The seven dummy variables are included to account for the variation between the cyclists and their experience in using bicycling facilities. The reference level user was the average in terms of age and frequency of bicycling.

Table 3. Ordinary least squares regression model predicting bicycle speed

	Coefficients	t-stat	Significance
Constant	**9.38**	**12.84**	**0.00**
On Street Facility (1 or zero)	-0.35	-0.93	0.35
Off Street Facility (1 or zero)	**0.71**	**1.69**	**0.09**
Distance Traveled To Segment (Miles)	-0.08	-1.18	0.24
Total Trip Length (Miles)	**0.24**	2.54	0.01
Segment Length (Miles)	**0.32**	**2.55**	**0.01**
Average Daily Traffic (Vehicles/ Day)	0.00	0.43	0.67
Number of Signalized Intersections	-0.14	-1.5	0.13
Morning Commute (1 or zero)	-0.15	-0.48	0.63
Traveler 1 relative to Traveler 2 (1 or zero)	-0.36	-0.67	0.50
Traveler 3 relative to Traveler 2 (1 or zero)	**-1.99**	**-4.04**	**0.00**
Traveler 4 relative to Traveler 2 (1 or zero)	-0.94	-1.71	0.09
Traveler 5 relative to Traveler 2 (1 or zero)	0.5	0.44	0.66
Traveler 6 relative to Traveler 2 (1 or zero)	**-2.05**	**-2.6**	**0.01**
Traveler 7 relative to Traveler 2 (1 or zero)	0.78	0.92	0.36
Traveler 8 relative to Traveler 2 (1 or zero)	0.95	1.31	0.19

Adjusted R^2 = 0.25
N = 315
Variables in bold significant at the 0.10 level

Observing the first key variables (type of facility) which are represented as dummy variables, it is clear that speed along off-street bicycling facilities shows a positive and statistically significant effect on bicycling speed along the segments relative to the reference variable (regular streets). A person cycling along an off-street bicycling facility is expected to be faster by 0.71 mph (1.14 km/h), holding all other variables at their mean values. No statistical difference was found between the speed along on-street bicycling facilities and regular streets. The distance traveled to the segment did appear to have a negative effect on the general speed (-0.08 mph). Meanwhile, the total trip length did appear to have a statistically significant and positive effect on speed. For each mile added to the total trip length the cyclist is expected to be around 0.24 mph (0.38 km/h) faster while keeping all other variables at their mean value. This can be related to the experience of the cyclist.

The second key variable, segment length, has a positively and statistically significant effect on average speed. For each mile of increase in the segment length cyclists tend to travel faster by around 0.32 mph (0.51 km/h) while keeping all other variables at their mean values. Surprisingly, the effects of average daily traffic, morning commute, and number of signalized intersections did not appear to have a clear effect on speed. The signs of these variables follow an expected trend. For example, the increase in the number of signalized intersections leads to a decrease in the average speed along the segment by 0.14 mph (0.22 km/h) while keeping all the other variables at their mean value. This effect follows the expected hypothesis in terms of the sign. Signalized intersections add some delay to cyclists and accordingly, decrease their speed along the segments.

Observing the seven dummy variables representing the cyclists, it is clear that only two of the respondents, 3 and 6, are slower than the reference category (cyclist 2). From Table 1 it can be observed that cyclist 3 was a 60 year old female that tended to travel by bicycle around 2.3 times per week. Cyclist 3 travels slower than cyclist 2 by 1.99 mph (3.2 km/h). Meanwhile, cyclist 6 is a 47 year old female with the least level of frequency in cycling. Cyclist 6 tends to be slower than cyclist 2 by 2.05 mph (3.30 km/h).

We developed a second model using the same variables but excluding the seven dummy variables. The dummies were replaced with other independent variables to control for the variance among the travelers. Such variables include age, gender, and a couple of variables describing whether the traveler feels comfortable when traveling along light or heavy traffic relative to no traffic (the reference variable). Table 4 includes the output of the generalized speed model. It is clear from the table that most variables from the previous model maintain their statistical significance and explanatory power in the model.

Table 4. Generalized speed model

	Coefficients	t-stat	Significance
Constant	**6.48**	**4.65**	**0.00**
On Street Facility (1 or zero)	-0.32	-0.84	0.40
Off Street Facility (1 or zero)	**0.94**	**2.22**	**0.03**
Distance Traveled To Segment (Miles)	-0.09	-1.31	0.19
Total Trip Length (Miles)	**0.31**	**3.37**	**0.00**
Segment Length (Miles)	**0.23**	**1.85**	**0.07**
Average Daily Traffic (Vehicles/ Day)	0.00	0.37	0.71
Number of Signalized Intersections	-0.01	-0.08	0.94
Morning Commute (1 or zero)	-0.33	-1.05	0.30
Age	0.01	0.66	0.51
Male	**0.67**	**1.83**	**0.07**
Comfort in traveling in light Traffic (1 or zero)	0.16	0.21	0.84
Comfort in traveling in heavy Traffic (1 or zero)	**1.41**	**1.83**	**0.07**

Adjusted R^2 = 0.17
N = 315
Variables in bold significant at the 0.10 levels

Among the variables controlling for the variance in travelers, gender has a positive and statistically significant effect on bicycle speed. Being male increases the speed along the segment by 0.67 mph (1.07 km/h) while keeping all the other factors at their mean value. Age is found to have a small, positive effect on the speed measured along the segments. Evidence from the eight study participants suggests that cyclists comfortable with traveling in heavy traffic tend to have statistically significantly higher speeds than people who are only comfortable traveling in no traffic. People who are comfortable cycling on streets with higher traffic cycle faster than those more comfortable traveling along off-street facilities by 1.41 mph (2.26 km/h).

Discussion

Observing the two models we see that travel speed hovers around 10 mph (16 km/h), though there are statistically significant differences in each cycling environment. Cyclists traveling on off-street facilities move faster than on all the other facilities when keeping all other variables at their mean values. On average, speed along off-street facilities is observed to be around 10.1 mph (16.25 km/h) (this may in part be influenced by the marked 10 mph (16.25 km/h) speed limit notices along such facilities). Speed along on-street facilities is slightly lower at 9.71 mph (15.62 km/h). Finally, when the eight participants rode on regular streets, their average speed was observed to be 9.79 mph (15.75 km/h). Figure 14 shows the predicted speed along each type of facility with all variables held at the mean values. Similarly, Figure 15 shows the predicted speed compared to comfort level with all variables held at the mean. The study participants who reported being more comfortable riding in heavy traffic tended to have higher average speeds than cyclists who reported being less comfortable in heavy traffic. They tend to travel on average around 10.79 mph (17.36 km/h).

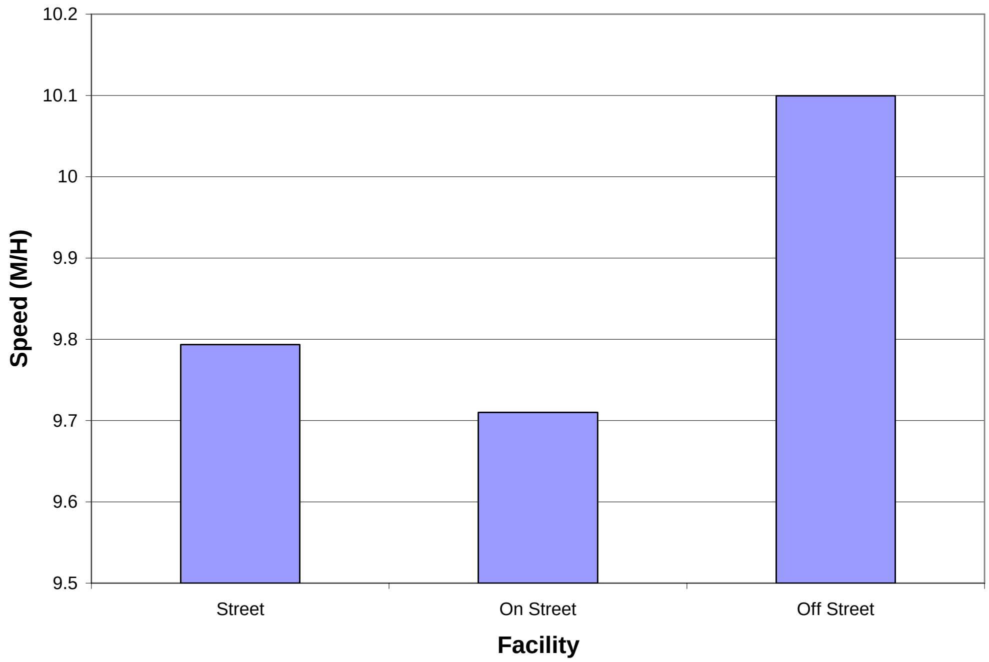


Figure 14. Predicted speed along each type of facility with all variables held at the mean

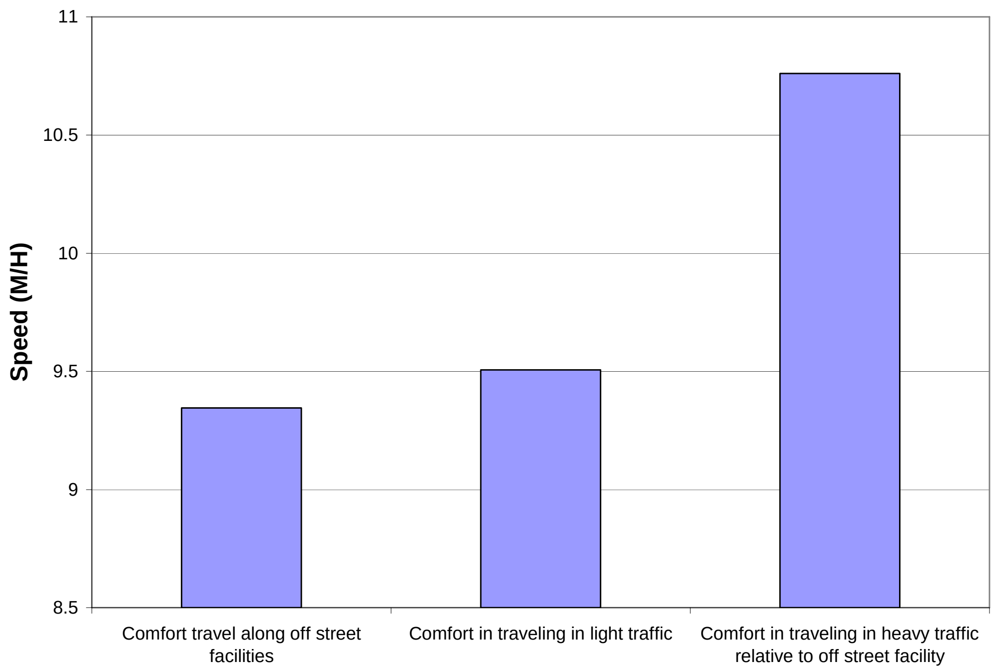


Figure 15. Predicted speed compared to comfort with all variables held at the mean

Two key variables, when interpreted together, can help in better understanding cyclists' behavior and how they distribute their efforts along the trip. The first is the trip length and the second is the distance traveled to the segment starting point. These two variables indicate that cyclists making longer trips tend to be faster than others, and that, as expected, their speeds decline toward the end of their trips.

Conclusions

This research presents a proof-of-concept method to model bicycle travel speed along different types of facilities often found in urban areas. Using primary data collected with commercially available GPS technology, regression models were estimated to predict travel speeds on both off-street and on-street bicycle facilities as well as regular streets. Results showed that, all else equal, cyclists tend to travel along various types of facilities at different speeds. On average, their speed ranges between 9.71 mph and 10.8 mph (15.62 km/h and 16.25 km/h) while keeping all other variables at their mean values. Predicted travel speeds on off-street facilities are slightly higher than those for on-street and mixed traffic facilities. However, it is difficult to determine whether the slower observed speeds on on-street facilities were due to congestion or other factors such as fatigue or pavement conditions. While these average speeds fail to account for a number of individual-specific factors, such as age, they are acceptable for basic planning and modeling purposes. While trip characteristics and gender were also shown to influence travel speeds, an important predictor is the cyclist's level of comfort with traveling in heavy traffic.

An important outgrowth of this study is that the findings of the estimated models can be used to apply impedances to each type of facility to generate more accurate accessibility measures, an increasing aim of municipalities worldwide. Understanding the impedances faced by cyclists in the form of travel speeds allows planners to better estimate the range of destinations that might reasonably be reached by bicycle travel in a given amount of time.

The specific findings of this study need to be tempered by the limitations inherent to the data collected. While a large number of observations were gathered, such data was acquired from relatively few respondents. An important aspect of the study was to isolate the effects of specific facility types on travel speeds, apart from individual and sociodemographic factors. Beginning with a larger sample of individuals would allow greater confidence in the effects of factors such as age, gender, and skill or comfort level, and would make the results more generalizable. Such extensive data collection efforts are often costly.

An additional measurement concern involves the effect of the GPS units on the research subjects, themselves. One might hypothesize that the mere presence of the GPS unit and the knowledge that the individual is being continually monitored would have an effect on the individual's cycling behavior.

With the amount of attention and resources now being directed towards improving the quality of bicycle and pedestrian facilities, improved research and data collection methods should become more of a priority. Approaches such as the one described herein can be further refined to produce more robust results and also to be used to develop measures of accessibility that are consistent with those being developed for other modes. By doing so, this research addresses a critical—and emerging—gap in providing transportation methods for non-motorized modes on par with those currently being used in mainstream applications for automobile and transit travel.

Transit Travel Time

Transit assumptions and definitions

As Table 5 indicates, the vast majority of trips by transit involve walking as their access mode. Nearly five-sixths of all transit trips in the Twin Cities region are accessed on foot. By contrast, access by bicycle is a rare occurrence, with less than one percent of all transit trips involving bicycle access. Around 13 percent of transit trips are accessed by automobile, with the remainder being either dropped off at their boarding point or choosing some other access mode (e.g. taxi, dial-a-ride, etc.).

Table 5. Mode of access for transit trips

Access Mode	Percent
Walk	83.2
Drove or rode with someone	2.1
Bicycle	0.6
Dropped off	2.9
Drove alone and parked	10.8
Other	0.5

Source: Metropolitan Council (2006)

A significant number of transit users must transfer between buses or trains in order to complete their journey. Table 6 indicates that just over 30 percent of all users must transfer at least once during their trip. Around 25 percent of all users transfer once, fewer than five percent transfer twice, and trips involving three or more transfers are extremely rare.

Table 6. Total number of transfers per transit trip

Number of Transfers	Percent of Passengers
0	69.5
1	25.6
2	4.5
3	0.3
4+	0.0

Source: Metropolitan Council (2006)

The data presented in Table 6 are aggregated to include all trips and mask some variation in transfer rates by service type. Local bus trips tend to require the most transfers, followed by light rail trips and express or commuter bus trips.

Transit travel time is calculated in four steps. The first involves using the pedestrian network to measure the walking travel time to the nearest bus stop. The second is adding waiting time to each walking distance based on the current headway. Third is calculating the in-vehicle travel time through the available transit network. Finally, we added walking time from the nearest bus stop to the destination. No transfer time has been added and no limits were set on the number of transfers due to the limitations in the software.

Analysis

Pedestrian analysis

Using the pedestrian networks described earlier in this report, the research team generated a pedestrian travel time matrix for the study area in the years 1995, 2000, and 2005. Since the research team was unable to find reliable data on improvements to pedestrian infrastructure between 1995 and 2000 the pedestrian travel times generated for these two time periods are identical. The travel time matrix was created using the Network Analyst extension in the ArcGIS 9.2 software suite. The matrix assumes a constant walking speed of 3.4 miles per hour throughout the study area. This is the mean walking speed for pedestrians age 14-64 found by Knoblauch et al. (1996) and is within the range of average walking speeds found in the literature discussed earlier.

Figures 16 and 17 show the travel time sheds for pedestrians traveling from downtown St. Paul in 1995-2000 and 2005. These maps were created using the kriging function in the Geostatistical Analyst extension to ArcGIS 9.2 and then transformed into a 30 meter grid cell raster format. In these maps areas shown in light yellow could be reached by foot within a relatively short travel time, whereas areas shown in dark brown would take over 5 hours to reach on foot using the existing pedestrian network. Between 2000 and 2005 relatively little change took place in the pedestrian travel shed from downtown St. Paul. Travel times decreased slightly in the area immediately southwest of downtown St. Paul where several off-street bicycle and pedestrian facilities were added to the network. Pedestrian travel times also decreased slightly in Minneapolis immediately north of the phase two extension of the Midtown Greenway.

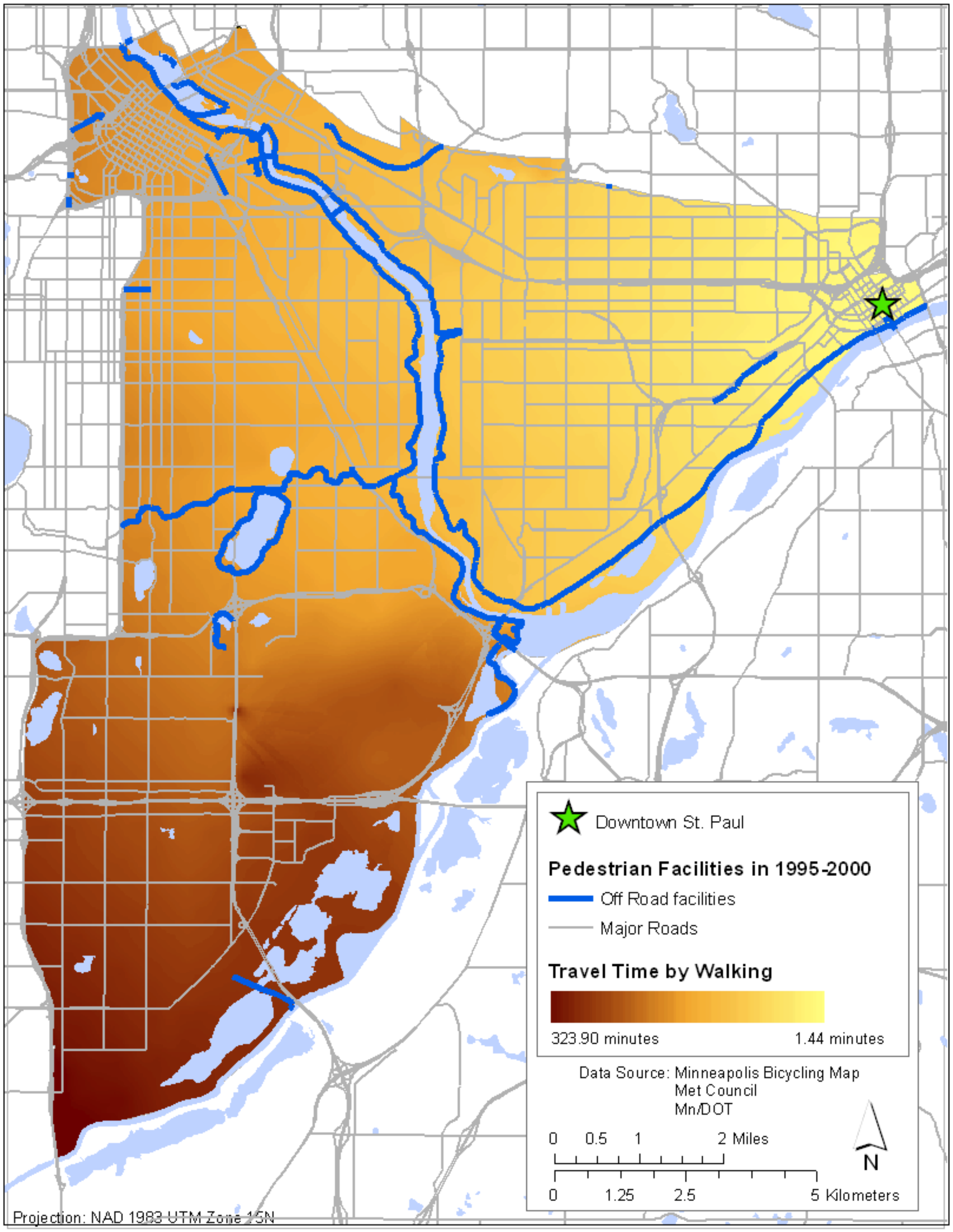


Figure 16. Pedestrian travel time shed from downtown St. Paul in 1995 and 2000

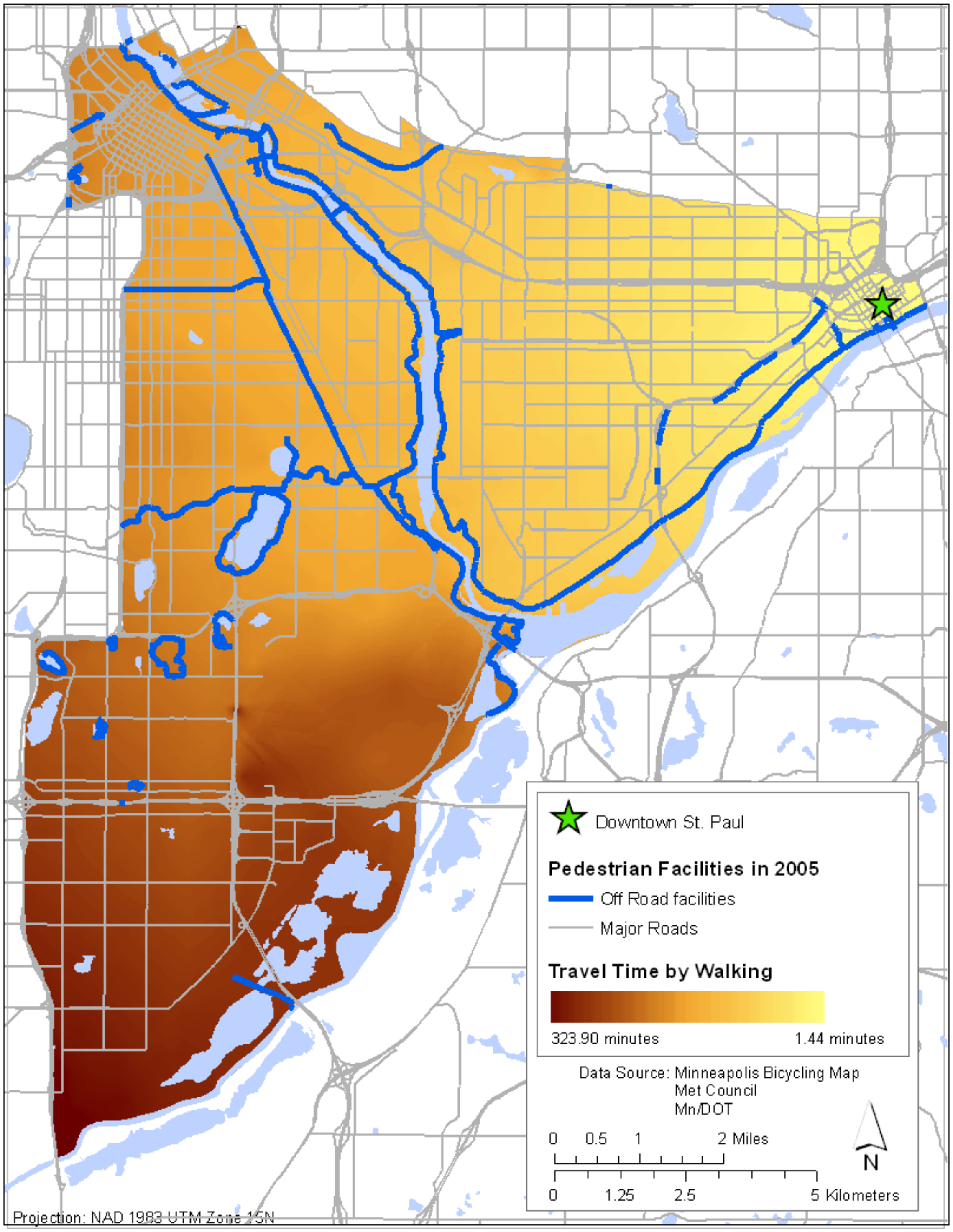


Figure 17. Pedestrian travel time shed from downtown St. Paul in 2005

Pedestrian travel shed maps for additional origins (Downtown Minneapolis, Central Minneapolis, South Minneapolis, Bloomington, and the Minneapolis/St. Paul International Airport) are included in Appendix D.

Bicycling Analysis

Using the bicycling networks described earlier in this report, the research team generated a bicycling travel time matrix for the study area in the years 1995, 2000, and 2005. Similar to the pedestrian travel time matrix, the bicycling matrix was created using the Network Analyst extension in the ArcGIS 9.2 software suite. Different bicycling networks were used to calculate travel times for each time period. These different networks account for new bicycling infrastructure built during each time period and the different travel speeds along these routes. The average bicycling speeds along different types of facilities (regular streets, on-street and off-street trails) determined by the bicycle travel time study presented earlier were used to calculate the travel times from six different origins to points throughout the study area.

Figures 18, 19, and 20 show the travel time sheds for cyclists traveling from downtown Minneapolis in 1995, 2000, and 2005. These maps were created using the kriging function in the Geostatistical Analyst extension to ArcGIS 9.2 and then transformed into a 30 meter grid cell raster format. In these maps areas shown in light yellow could be reached by bicycle within a relatively short travel time, whereas areas shown in dark brown would take slightly over an hour to reach using the existing bicycling network.

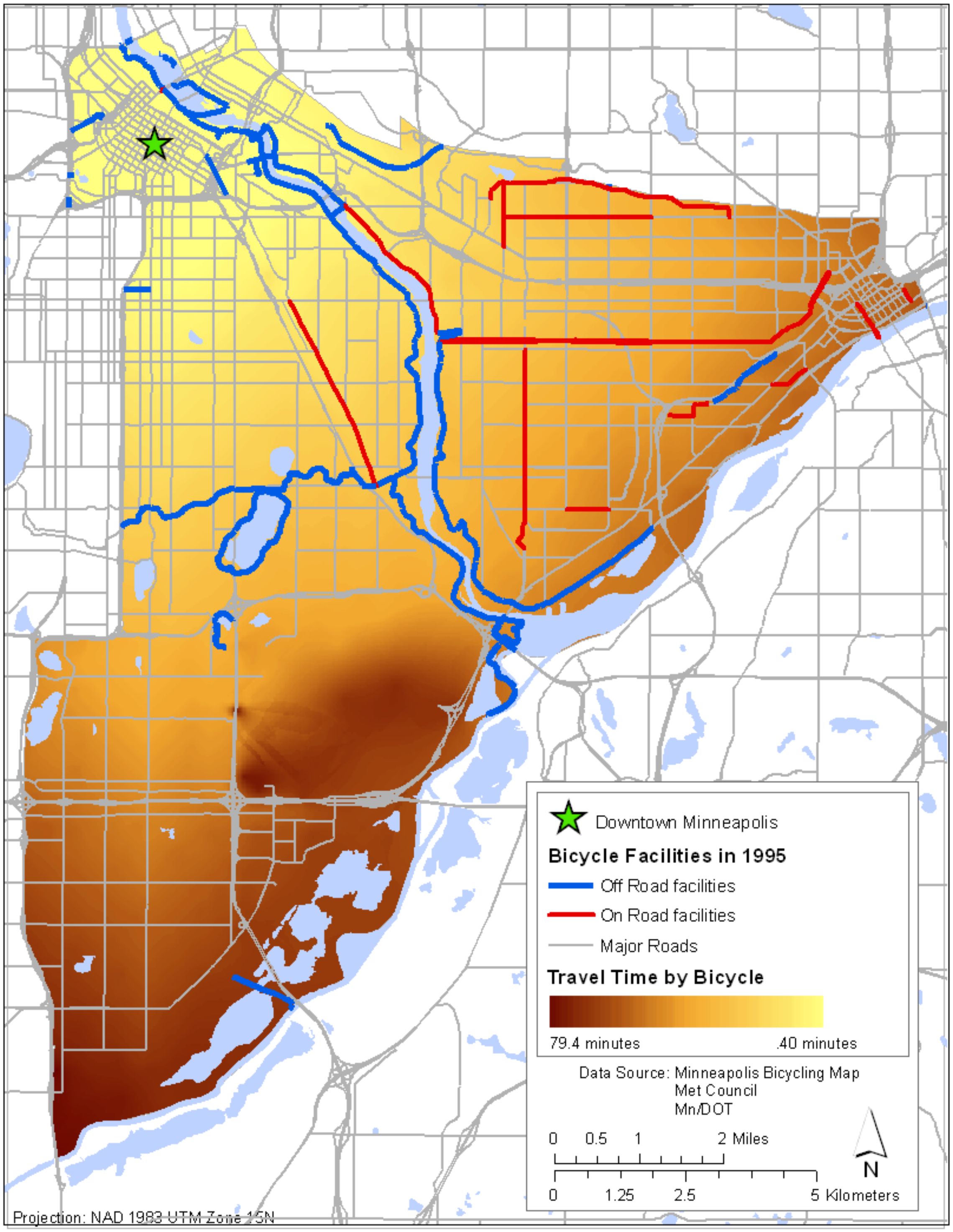


Figure 18. Bicycling travel time shed from downtown Minneapolis in 1995

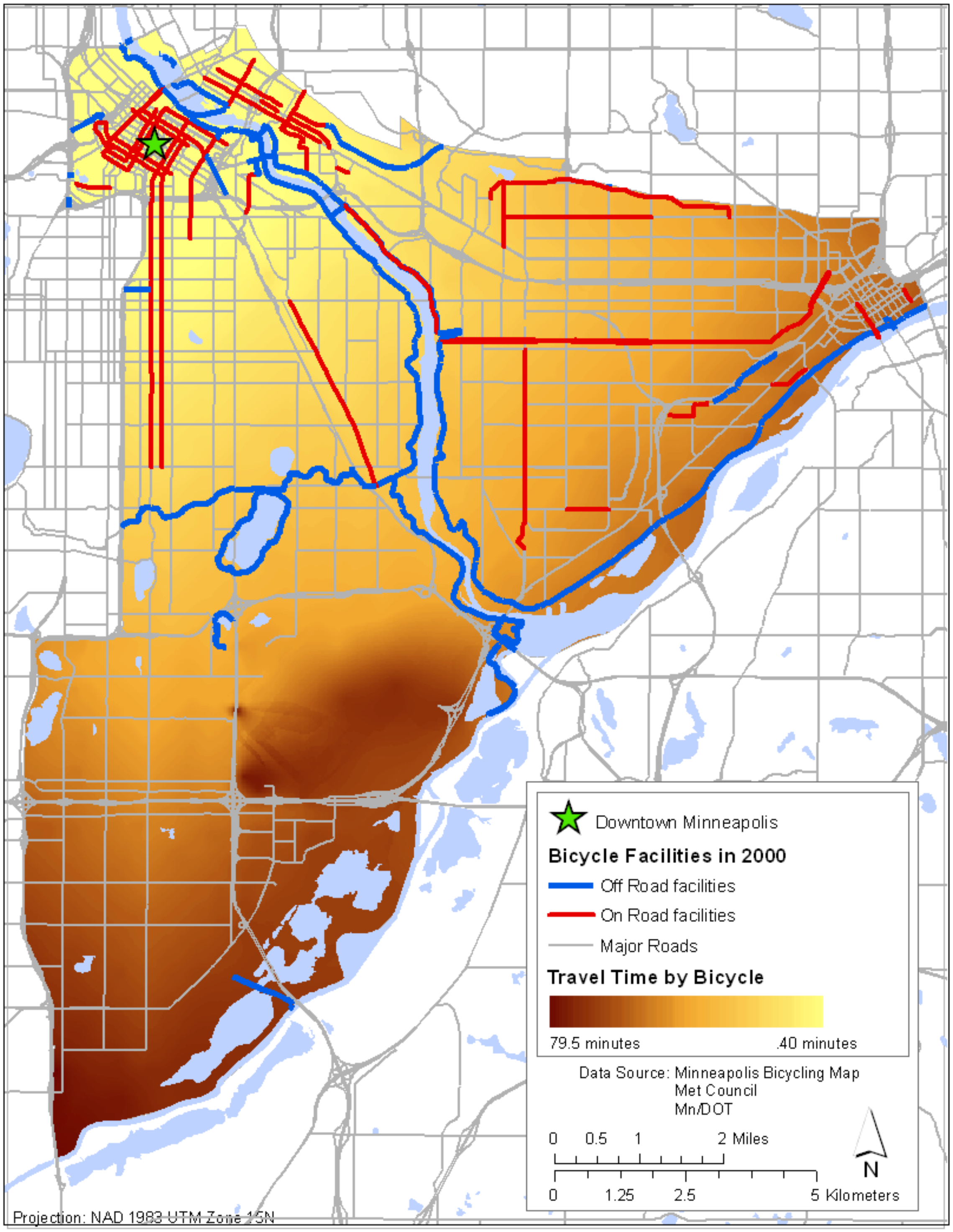


Figure 19. Bicycling travel time shed from downtown Minneapolis in 2000

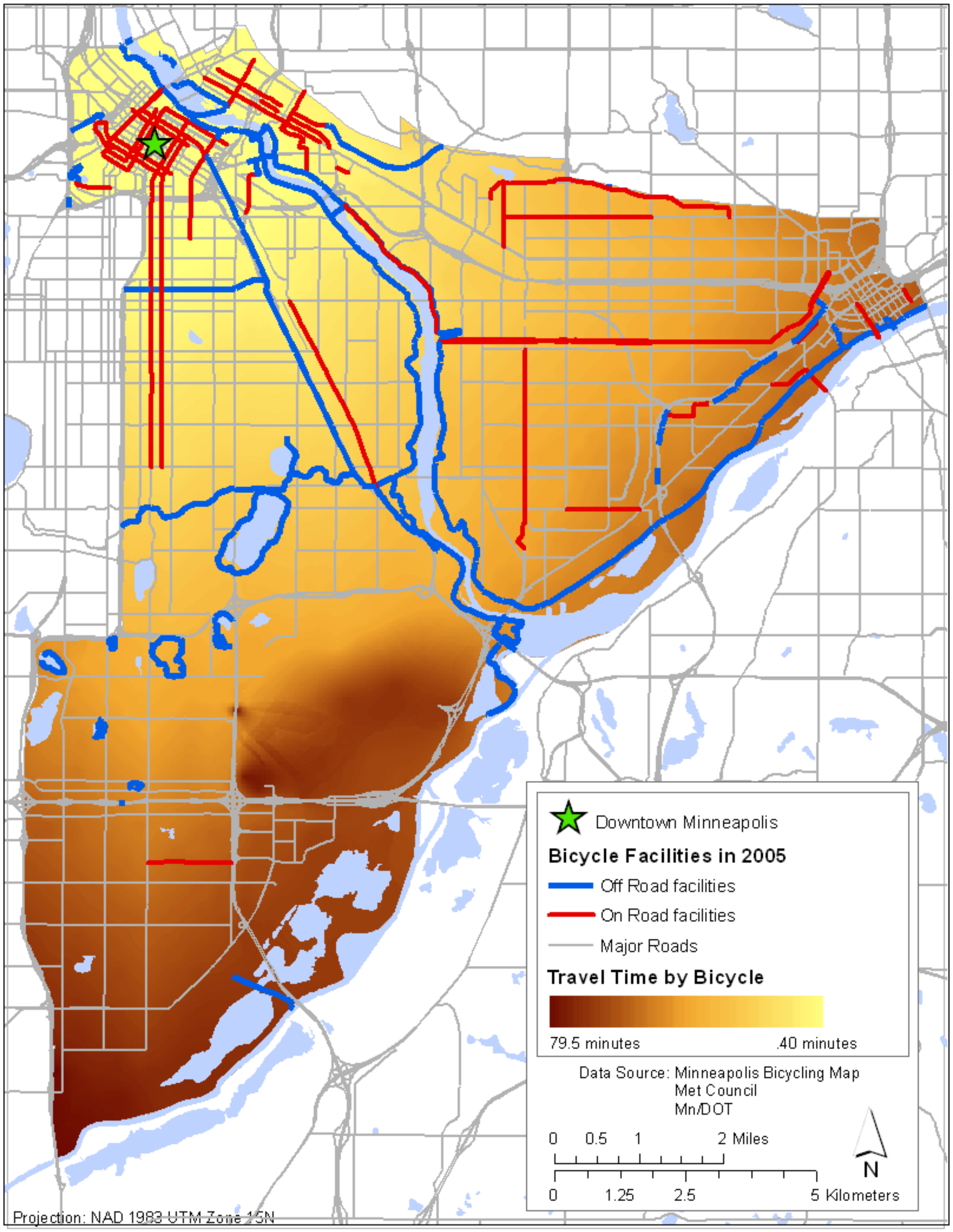


Figure 20. Bicycling travel time shed from downtown Minneapolis in 2005

The bicycling network in the study area underwent significant changes between 1995 and 2005 that reduced bicycling travel time in multiple areas. Between 1995 and 2000, a large number of on-street bike lanes were added throughout downtown Minneapolis and the University of Minnesota area. Two north-south on-street bike lanes were also added connecting downtown and south Minneapolis, and the off-road path connecting the Fort Snelling area to downtown St. Paul was also completed. The latter facility caused a noticeable reduction in travel time from downtown Minneapolis to areas in St. Paul along the Mississippi River. Between 2000 and 2005, the second phase of the Midtown Greenway was completed as well as the Hiawatha LRT bike trail and several off-street paths in Richfield. As Figure 21 shows, these investments led to noticeable reductions in bicycling travel time throughout southeastern Minneapolis and southwestern St. Paul. Along the Hiawatha LRT trail, estimated travel time decreased by up to 6.39 minutes.

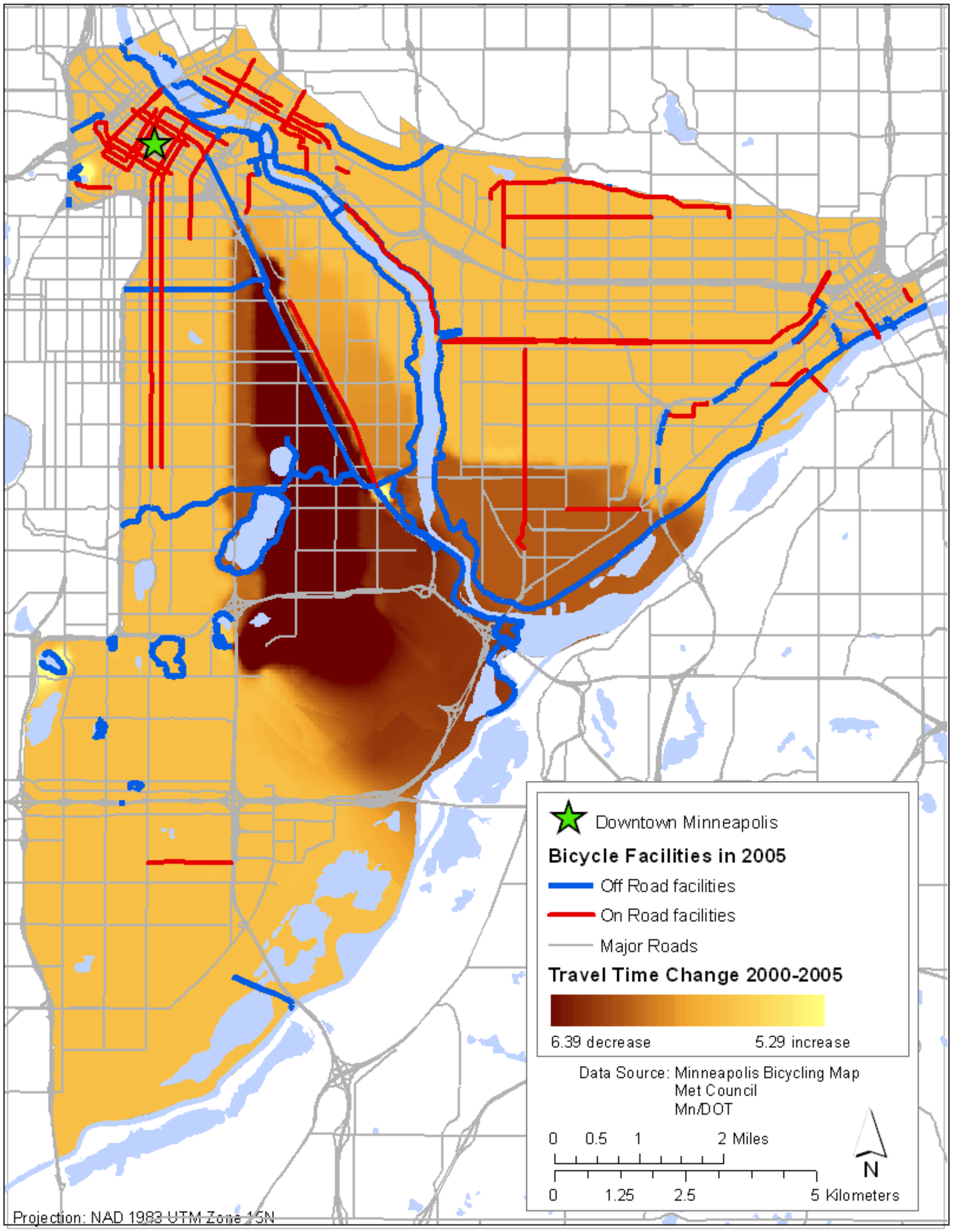


Figure 21. Change in bicycling travel time from downtown Minneapolis between 2000 and 2005

Bicycling travel shed maps for additional origins (Downtown St. Paul, Central Minneapolis, South Minneapolis, Bloomington, and the Minneapolis/St. Paul International Airport) as well as additional maps of bicycling travel time change are included in Appendix E.

Transit Analysis

Using the transit networks provided by MetroTransit and the Metropolitan Council, the research team generated a transit travel time matrix for the study area in the years 2000 and 2005. Similar to the pedestrian and bicycling travel time matrix, the transit matrix was created using the Network Analyst extension in the ArcGIS 9.2 software suite. Due to the fact that detailed historical transit data is not available, travel times for 2000 represent the average transit travel time from each origin to destination throughout the day. For 2005, much more detailed transit travel time information was available, so the research team calculated travel times using three separate networks modeling transit headways and speeds at am, pm, and midday service levels.

Figure 22 shows the average daily travel time shed for transit riders traveling from downtown Minneapolis in 2000 (before the construction of the Hiawatha LRT). Figures 23, 24, and 25 show the travel time sheds for transit riders traveling from downtown Minneapolis in 2005 using am, pm, and midday bus or LRT transit service. These maps were created using the kriging function in the Geostatistical Analyst extension to ArcGIS 9.2 and then transformed into a 30 meter grid cell raster format. In these maps areas shown in light yellow could be reached by transit within approximately five minutes, whereas areas shown in dark brown would take about one hour to reach using the existing transit network. Between 2000 and 2005, there is a general decrease in transit travel time across the study area. The most notable increase in accessibility and decrease in transit travel time between 2000 and 2005 occurs in and around the Minneapolis/St. Paul International Airport.

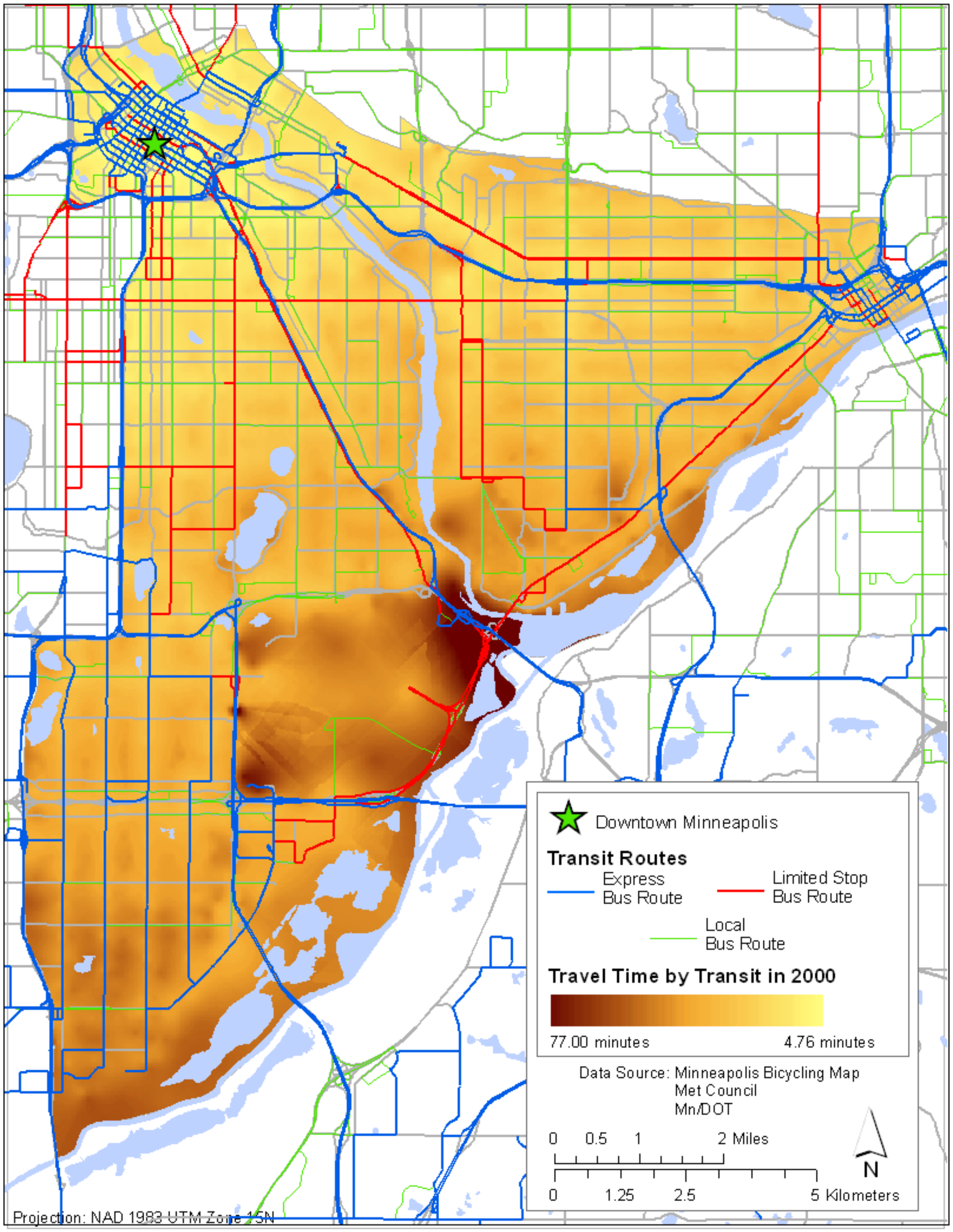


Figure 22. Transit travel time shed from downtown Minneapolis in 2000

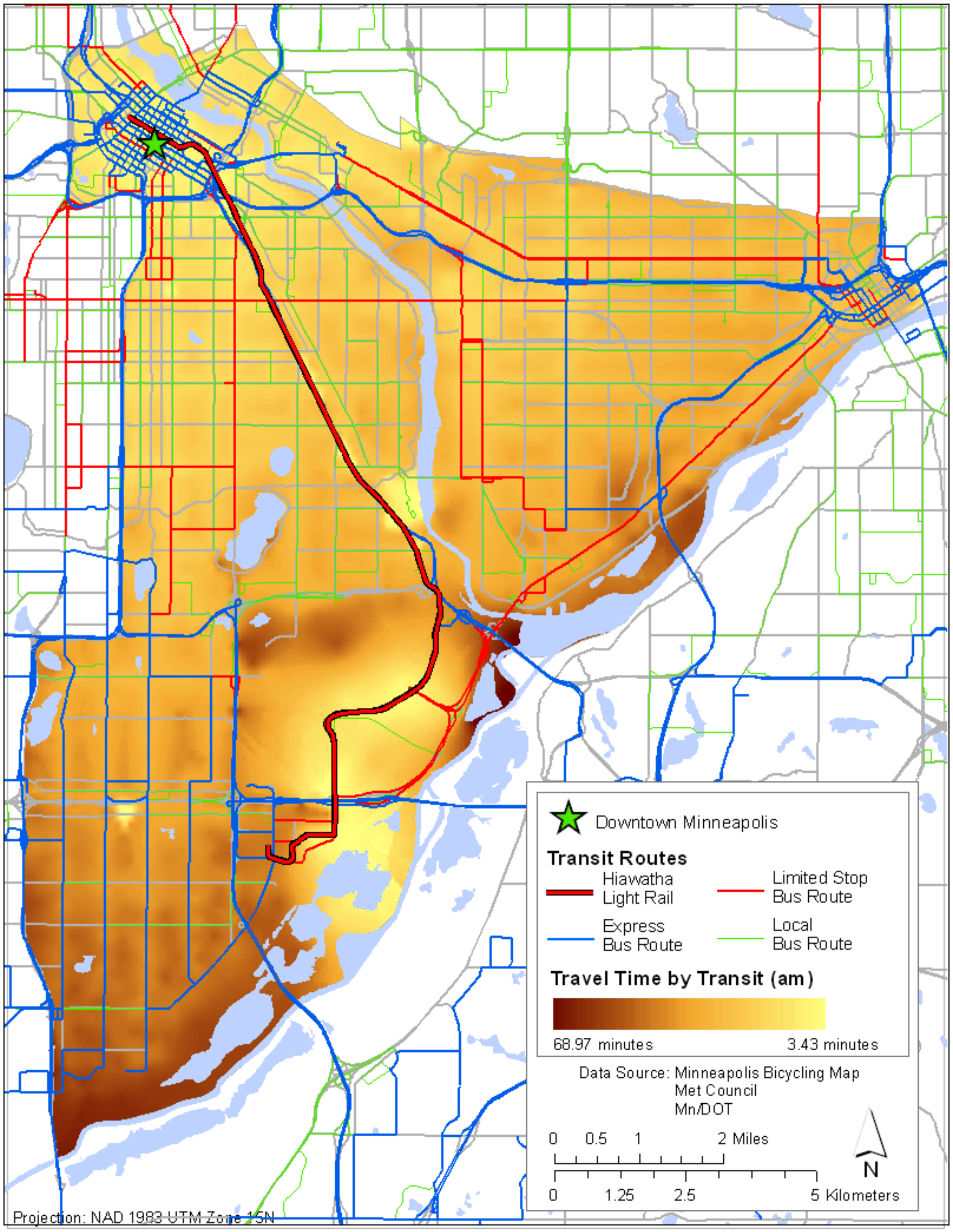


Figure 23. Transit travel time shed from downtown Minneapolis in 2005 (am)

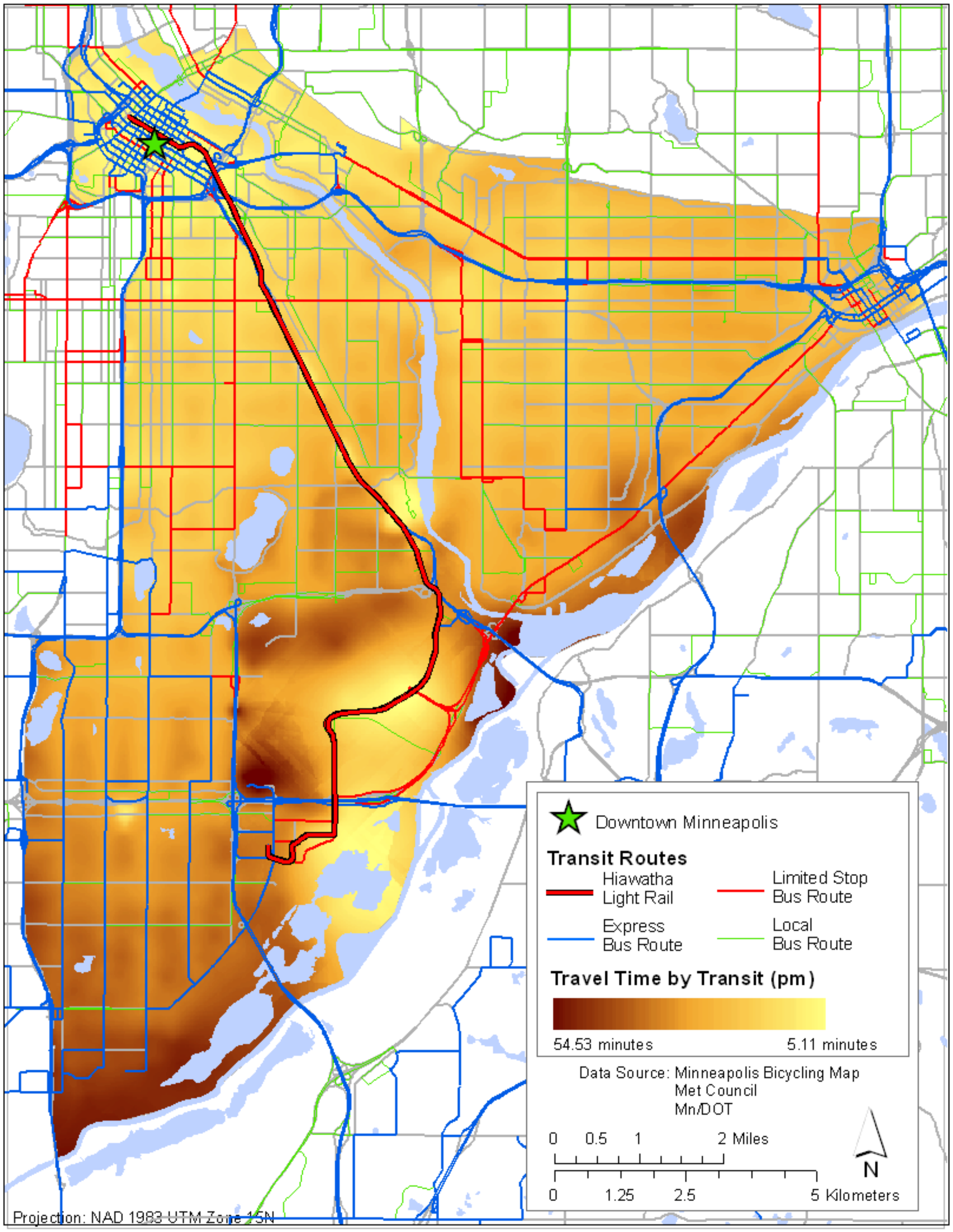


Figure 24. Transit travel time shed from downtown Minneapolis in 2005 (pm)

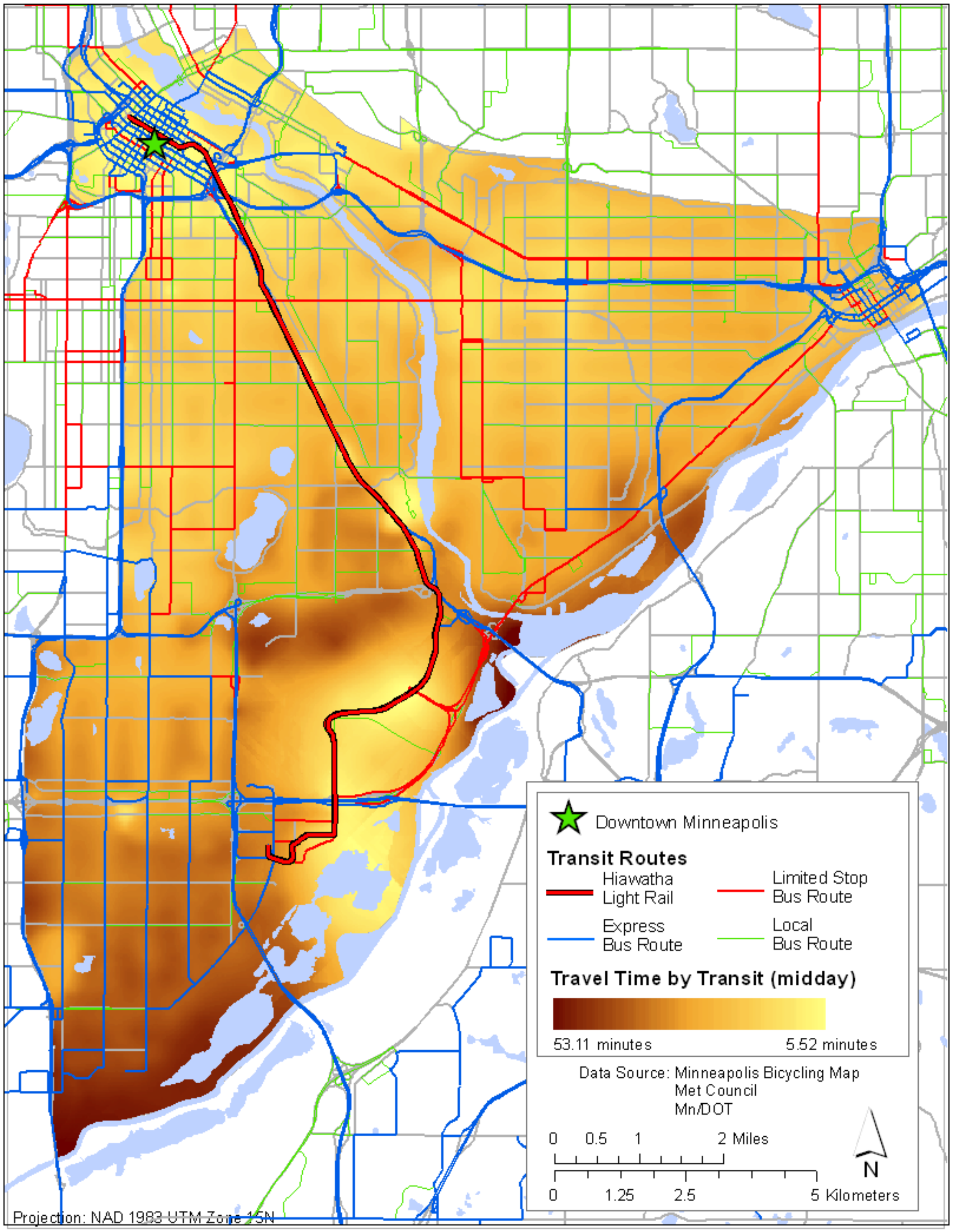


Figure 25. Transit travel time shed from downtown Minneapolis in 2005 (midday)

Figures 26, 27, and 28 show the change in transit travel time in 2005 caused solely by the addition of the Hiawatha LRT line. The Hiawatha LRT has drastically decreased the travel time to the Minneapolis/St. Paul International Airport as well as the areas surrounding the 50th Street, 46th Street, and Bloomington Central stations. This decrease is fairly consistent throughout the day and ranges from a 38 minute travel time decrease during the am peak to a 27 minute travel time decrease during the pm peak period.

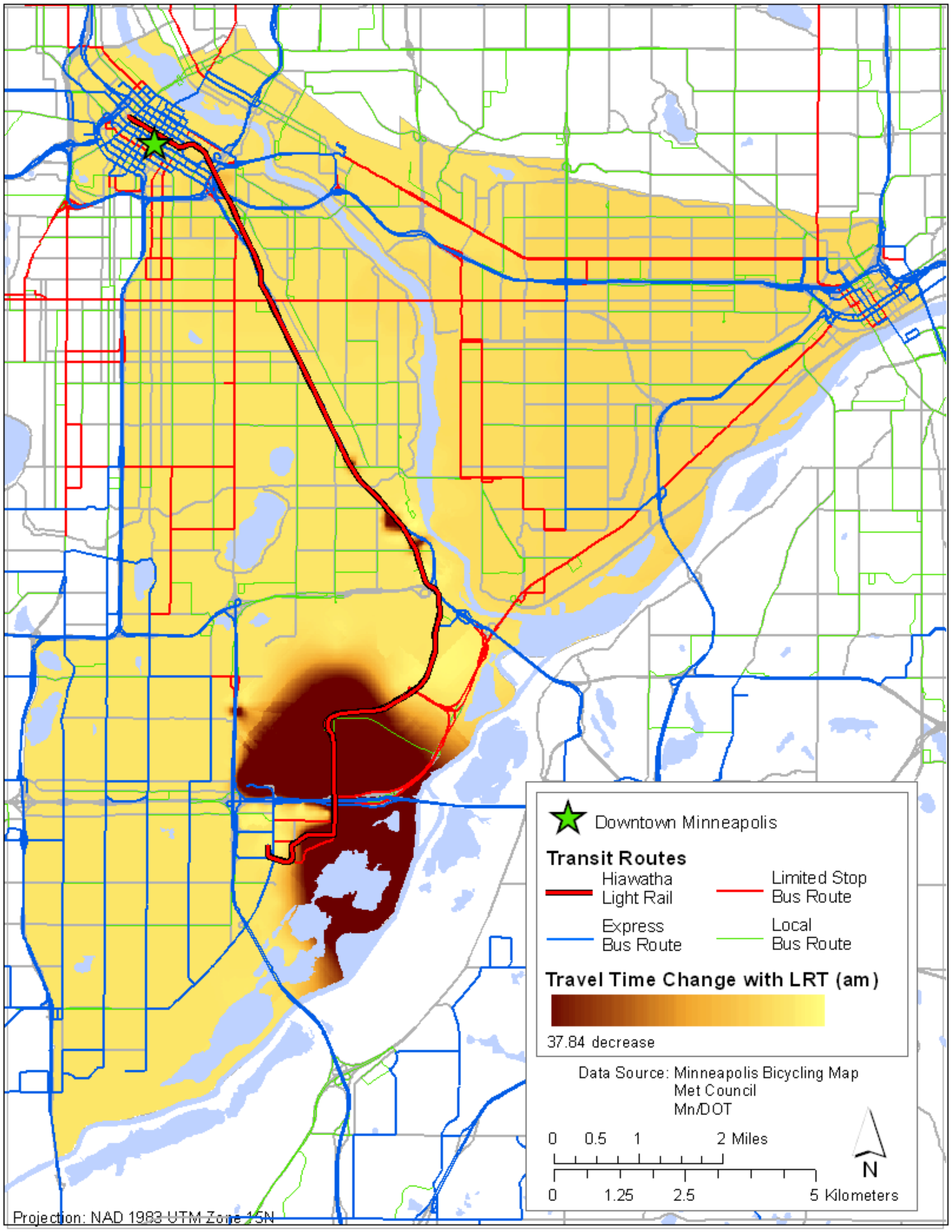


Figure 26. Change in transit travel time from downtown Minneapolis with LRT (am)

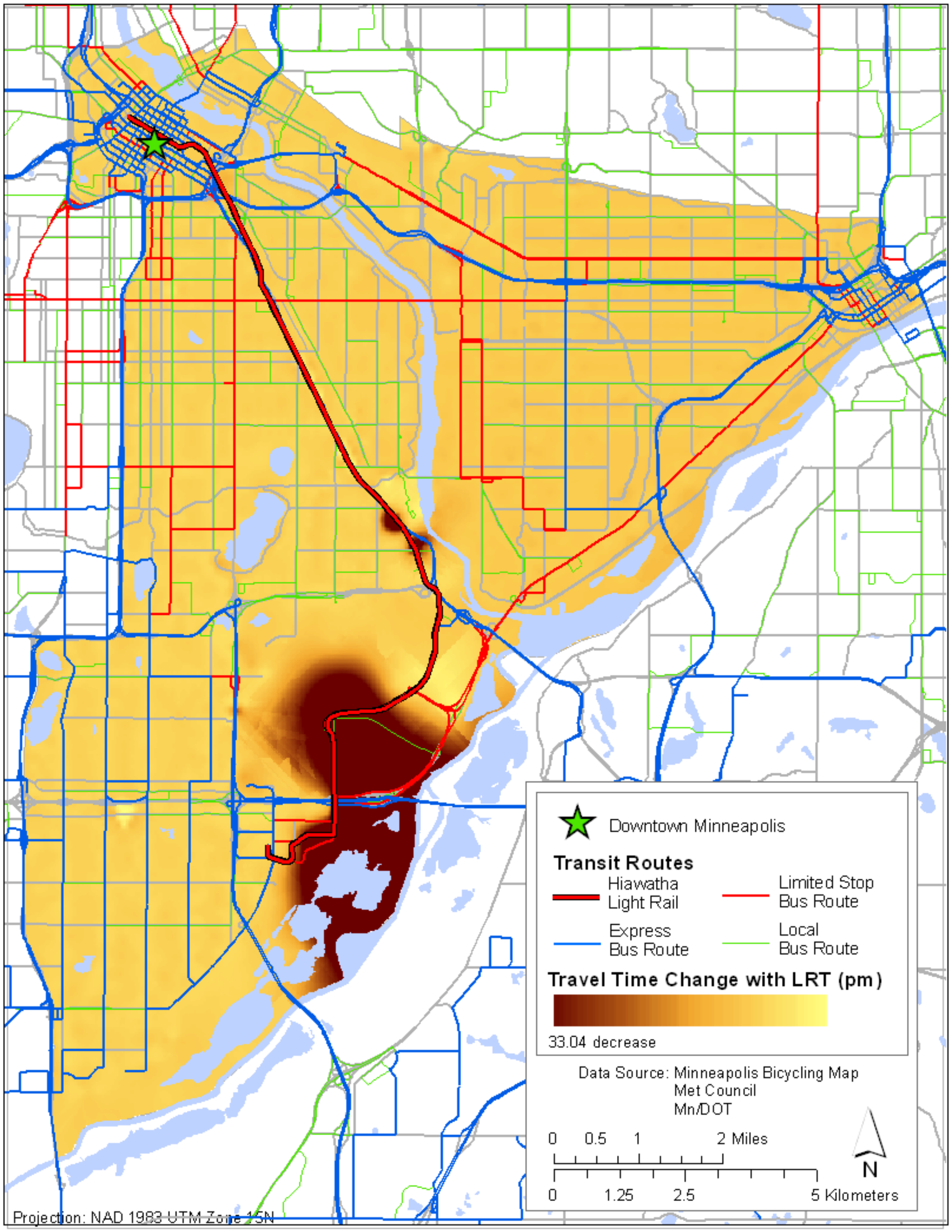


Figure 27. Change in transit travel time from downtown Minneapolis with LRT (pm)

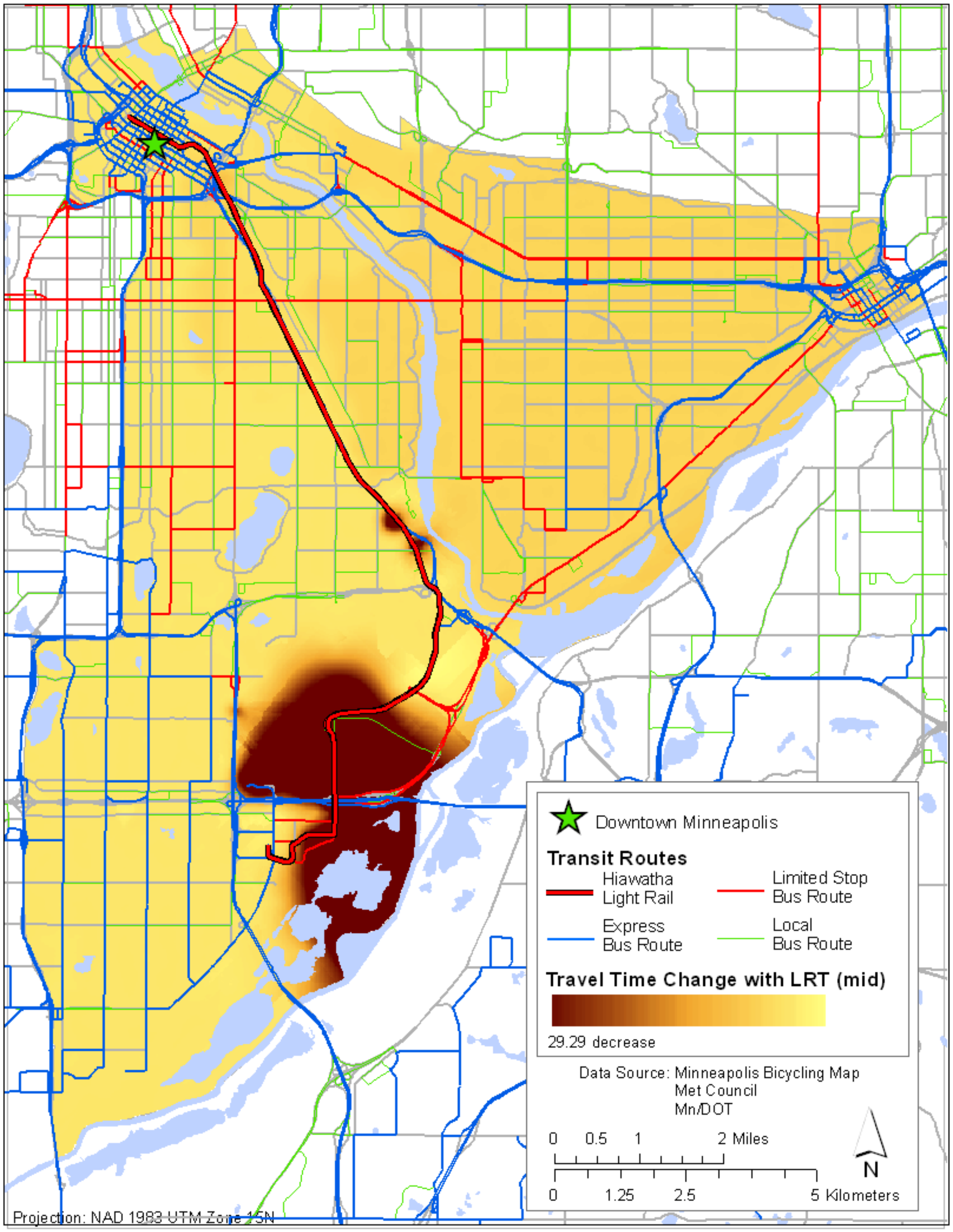


Figure 28. Change in transit travel time from downtown Minneapolis with LRT (midday)

Transit travel shed maps for additional origins (Downtown St. Paul, Central Minneapolis, South Minneapolis, Bloomington, and the Minneapolis/St. Paul International Airport) as well as additional maps of transit travel time changes caused by the addition of the Hiawatha LRT line are included in Appendix F.

Conclusions

This study has demonstrated the validity of methods for calculating travel times for modes other than automobile. The methods developed here can be applied in other settings, given the availability of appropriate network and travel behavior data. The results of this study include origin-destination travel time matrices for pedestrian and bicycle modes for the years 1995, 2000, and 2005. With the available transit network and link travel time data, average travel times by transit were calculated for the year 2000, and travel times for 2005 were generated for am peak, pm peak, and midday periods, with and without the light rail link.

Some problems were encountered in the analysis that could not be addressed in the current study. For example, dealing with transit trips involving transfers was a difficult matter. The ArcGIS Network Analyst extension used for walking and bicycle modes could not as easily manage the complex trip patterns characterizing transit travel. Transfers on transit trips were not dealt with explicitly, except to assume an approximate time penalty for each transfer. In future applications, we recommend the use of travel modeling software, such as Citilabs© Voyager to deal with transit trips involving two or more transfers.

While they did not perform as well for calculating transit travel time, ArcGIS applications were able to effectively model paths for pedestrian and bicycle travel. Still, the calculation of bicycle travel speeds and times could be improved. One of the most important steps to be taken is to find accurate historical maps of bicycle facilities. These facilities are not as well documented as other types of infrastructure networks, making the task of tracking their extent over time more difficult. A secondary concern related to the calculation of accurate bicycle travel times is the estimation of a more robust travel speed model. The example provided in this study partially validates the method of using GPS traces from actual cyclists to measure various influences on speeds. However, the limited number of cyclists employed in the sample leaves open some questions regarding whether the heterogeneity in bicyclist behavior related to social and demographic factors has effectively been captured. Nonetheless, the speeds predicted by the model fall within a reasonable range of those found in the empirical literature.

The calculation of travel times for transit and non-motorized modes also has enabled a demonstration of the effects of new links on the utility of a network. The availability of data for a series of points in time allows changes in travel time by a particular mode to be depicted in visual form as changes to the travel shed of the mode. An example of this was the change in travel times by bicycle attributed to the addition of an off-street trail along Hiawatha Avenue. By subtracting travel times calculated for the period following the completion of this link from travel times calculated for the preceding period, reduced travel times to the neighborhoods south and west of Hiawatha Avenue from downtown Minneapolis became readily apparent. Similar effects were demonstrated for the addition of the Hiawatha light rail line in terms of reducing travel times to locations near the Mall of America and the airport from downtown Minneapolis. These measures are an effective way to demonstrate the potential improvements from new infrastructure projects.

With the calculation of travel times for various modes having been demonstrated as possible, it is now reasonable to focus attention on the use of these measures. Accessibility measures provide a fundamental understanding of the performance of the system of land use and travel networks serving an urban area. Measures of accessibility have previously been limited in large part to automobile and in some cases, transit networks. The collection of input data on travel times by non-motorized modes has typically not been considered in great detail, given the limited markets these modes often serve. Now that such data has been made available, the use of accessibility measures can be broadened to include a greater range of modes within urban transportation systems.

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Appendix A: Data Requests and Communication

Data Request for Traffic Signals from Mn/DOT

To: <geneidy@UMN.EDU>
Cc: <dallas.hildebrand@ci.minneapolis.mn.us>,
<Scott.Tacheny@ci.minneapolis.mn.us>,
<steve.mosing@ci.minneapolis.mn.us>,
"Steve Misgen" <Steve.Misgen@dot.state.mn.us>,
Kevin J Krizek <kjkrizek@tc.umn.edu>,
<henryliu@UMN.EDU>,
<levin031@UMN.EDU>
Subject: Re: Traffic Signals

Ahmed,
I do not have the GIS file you have requested. I do not believe MN/DOT has such a file. Steve Misgen would be your best contact for Metro area traffic signals. Steve, any comments???
For Minneapolis traffic signals(they operate all signals within the city limits), you can contact Steve Mosing or Scott Tacheny who are CC'd on this note.

Jerry Kotzenmacher
Minnesota Department of Transportation
Office of Traffic, Security & Operations - Roseville
Office: 651-634-5463
Cell: 612-202-6802

An email from Bob Basques whom we obtained sidewalk data for the City of Saint Paul.

bob.basques@ci.stpaul.mn.us (Bob Basques)
To: "Ahmed M. El-Geneidy" <geneidy@umn.edu>
Subject: Re: Do you have a FAX number I can use?

Ahmed M. El-Geneidy wrote:

Bobb,
I just sent you the fax regarding the redistribution of the sidewalk data.
I got it.

Here you go.

From: "Brian Balfanz" <Brian.Balfanz@ci.stpaul.mn.us>
To: "Ahmed El-Geneidy" <geneidy@umn.edu>
Subject: Re: Sidewalk Data

Glad I could point you in the right direction.

Have a great day, Brian

>>> "Ahmed M. El-Geneidy" <geneidy@umn.edu> 11/04/05 11:13 AM >>>
Thanks Brain we will try and contact Bob and see if he can help us.

Thanks again for your help

Ahmed

>I'm sorry, but after a long look, I cannot locate a sidewalks file
>within my area of our City Network.
>
>I hate to pass you off to yet another City Staff person, but I think
>you'll need to connect with Bob Basques, in our Public Works department.
>
>Bob works on both GIS and AutoCAD systems, so you will need to
>specify to him your data preferences.
>
>Mr Basques can be reached at:
>
>651-266-6188
><mailto:Bob.Basques@ci.stpaul.mn.us>Bob.Basques@ci.stpaul.mn.us
>
>THanks, good luck with your project, and have a great day.
>
>Brian

>
>
>Brian Balfanz
>GIS Research Analyst
>City of St. Paul, Parks & Recreation
>1100 Hamline Ave., St. Paul. MN 55108
><mailto:brian.balfanz@ci.stpaul.mn.us>brian.balfanz@ci.stpaul.mn.us
>Phone: 651-632-2453
>
> >>> "Ahmed M. El-Geneidy" <geneidy@umn.edu> 11/04/05 12:19 AM >>>
>Dear Mr Brian,
>
>My name is Ahmed El-Geneidy I work for the Center for Transportation
>Studies at the University of Minnesota with Kevin Krizek measuring
>accessibility for the twin cities region using various modes of
>transportation. I got your contact from Mary Jackson who attended our
>TAP meeting and suggested contacting you since we are looking for a
>clean sidewalk GIS layer and she suggested that you might have one or
>know how to direct us. Our study area includes cities of Minneapolis,
>St Paul, and part of Richfield. We are trying to model travel time
>for pedestrians while controlling for the presence or absence of
>sidewalks on both sides of streets.
>
>Thanks
>
>Ahmed El-Geneidy

Appendix B: ESRI Communication

Hi Ahmed,

With the new data, I got this working correctly. Here are the steps you will need to take:

1. Create a personal geodatabase and feature dataset within this geodatabase

2. Import the feature classes within the feature dataset

3. Create a Network Dataset with a Time and Distance cost attribute

4. Build the network

5. After it is finished being built, right-click on the feature dataset > New > Feature class. Give this feature class a name, then choose the second bullet under Type. Hit the dropdown and choose ESRI Turn Feature. Set the maximum number of edges to 2

6. Hit Next > Next > Finish

7. Add the Network Dataset and turn feature class to ArcMap. Set the primary display field for Bus_Segments_I to be the LINE_ID (Properties > Fields tab)

8. Start an edit session for the Turn Feature class

9. Set up the snapping to snap to the bus route feature class

10. Zoom to a transfer point and begin digitizing a turn starting at one route type and ending at another. Double-click to finish the segment

11. A dialog will pop-up saying Multiple Features Found (multiple.bmp)

12. Choose the first bus segment (ie 5) then hit Next

13. Choose the second bus segment (ie 2) then hit Finish (multiple2.bmp).

You will have to digitize a line segment and repeat this so that each route has a turn for each different route. You can see for the included turn feature class, there are six different turn features for one turn.

Once your turns are finished being digitized, close ArcMap and go back to ArcCatalog. Right-click on the network dataset > Properties. Select the Turns tab. The new feature class should automatically be added. Then select the Attributes tab. Select the Time attribute and click Evaluators. You will see the turn feature class there. Click under Type and choose Constant. Set this to your desired minutes (evaluator.bmp). Then re-build your network.

Finally add your network back to ArcMap and you can solve for a route. You will want to make sure that you are solving for the Distance impedance, and that you have U-Turns specified for 'Nowhere' (Properties.bmp).

I've uploaded an example of this on our ftp site:

ftp://ftp.esri.com/

Once there, go to File > Login As:

username: JSkinn3
password: Hockey

The username and password are case sensitive. You will see a folder there called Ahmed.zip.

Please let me know if you need any help with this.

Regards,

Jake S.

To contact ESRI Support Services (USA only):
Tel: (888)377-4575   Fax: (909)792-0960   E-mail: support@esri.com

Appendix C: Citilabs Communication

From: "Mark Filipi" <Mark.Filipi@metc.state.mn.us>
To: <geneidy@umn.edu>
Subject: Re: Request Reminder

I will get back to work on getting the data to you. I use citlab's Voyager to generate the travel time skims. They do have educational licensing, but I don't know how much it is. I expect that a commercial license would be too expensive for your project. Their webiste is at:

www.citilabs.com

Mark Filipi, AICP
Transportation Forecast/Analyst
Metropolitan Council
230 E. 5th St.
St. Paul, MN 55101-1626

Phone: 651-602-1725
Fax: 651-602-1739

From: "Derek Miura" <dmiura@citilabs.com>
To: <geneidy@umn.edu>
Subject: Price Quote
Date: Tue, 19 Dec 2006 09:11:12 -0600
X-Mailer: Microsoft Office Outlook 11
Thread-Index: Accjf+uj3q3EPJFiRRqQs5BuipREZA==

Hi Dr. El-Geneidy,

The academic price for Cube Voyager is $ 6,750 (50% of $13,500). Software maintenance costs an additional $1,312 for one year of tech support and software upgrades. The total cost with maintenance comes to $8,062.

I have included a summary of Public Transit's functions, inputs and outputs for your review. I will be contacting you shortly.
Thanks
Derek

Derek Miura
Citilabs - Transportation Engineer
227 Chestnut St E, Suite 3
Stillwater, MN 55082 USA
Tel: +1 651-351-0886
Fax: +1 651-389-9144

Public Transport Overview

PUBLIC TRANSPORT is the Public Transport Data Preparation and Modeling program. The main capabilities of the program are:

- User control over all aspects of the Public Transport model;
- True multi-routing between zone pairs, or alternatively single best-path routes may be used;
- Demand stratification by user class with variations in the behavior of classes represented by different cost functions;
- Comprehensive Fares Modeling;
- Preparation of a Public Transport Network for PUBLIC TRANSPORT's modeling functionality;
- Generation of the non-transit element of the Public Transport network, ie access, egress, transfer and park and ride legs;
- Skimming, network-wide and mode specific, composite and average journey costs, and components of costs;
- Two methods (Service Frequency and Service Frequency & Cost based) for loading demand on to transit choices at stops;
- Analyses of loaded trips - transfers between modes, operators, lines, a variety of stop-to-stop movements, select-link/line outputs;
- Reporting of input data, model infrastructure, multiple routes with probability of use, line and link loads, secondary analyses

PUBLIC TRANSPORT requires as input:

- A highway or Public Transport network;
- PT System data;
- Line data;
- Fare data;
- Non-transit legs (developed externally or by PUBLIC TRANSPORT)
- Generalized cost information;
- Demand.

PUBLIC TRANSPORT produces:

- Non-transit legs;
- Enumerated Routes;
- Skim and select-link matrices;
- Loaded lines and non-transit legs;
- Transfer matrices - results of Loading Analyses;
- A variety of reports of input data and model results;

- A Public Transport network that can be displayed by Cube and used as an input network for further modeling.

Appendix D: Pedestrian Maps

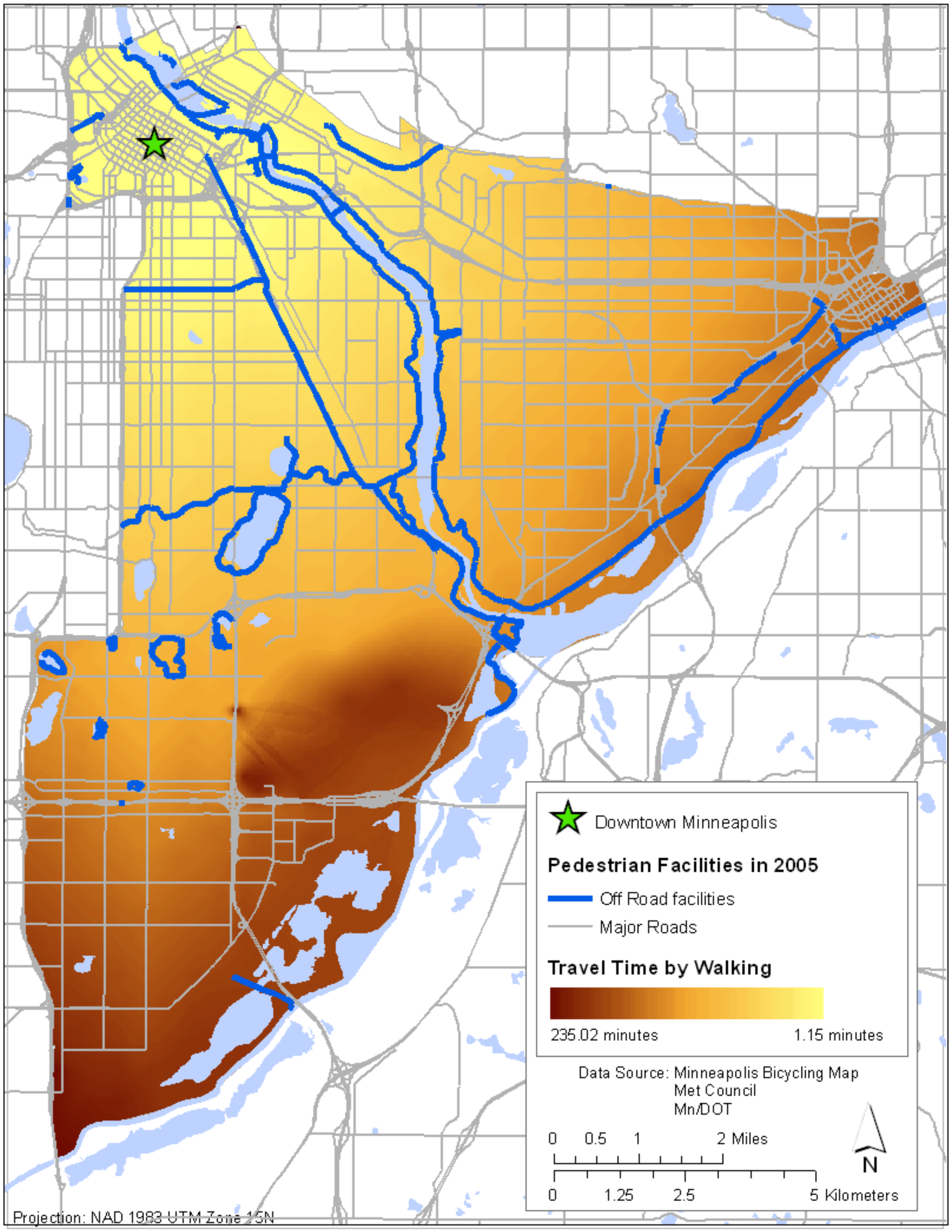

Figure 29. Pedestrian travel time shed from downtown Minneapolis in 2005

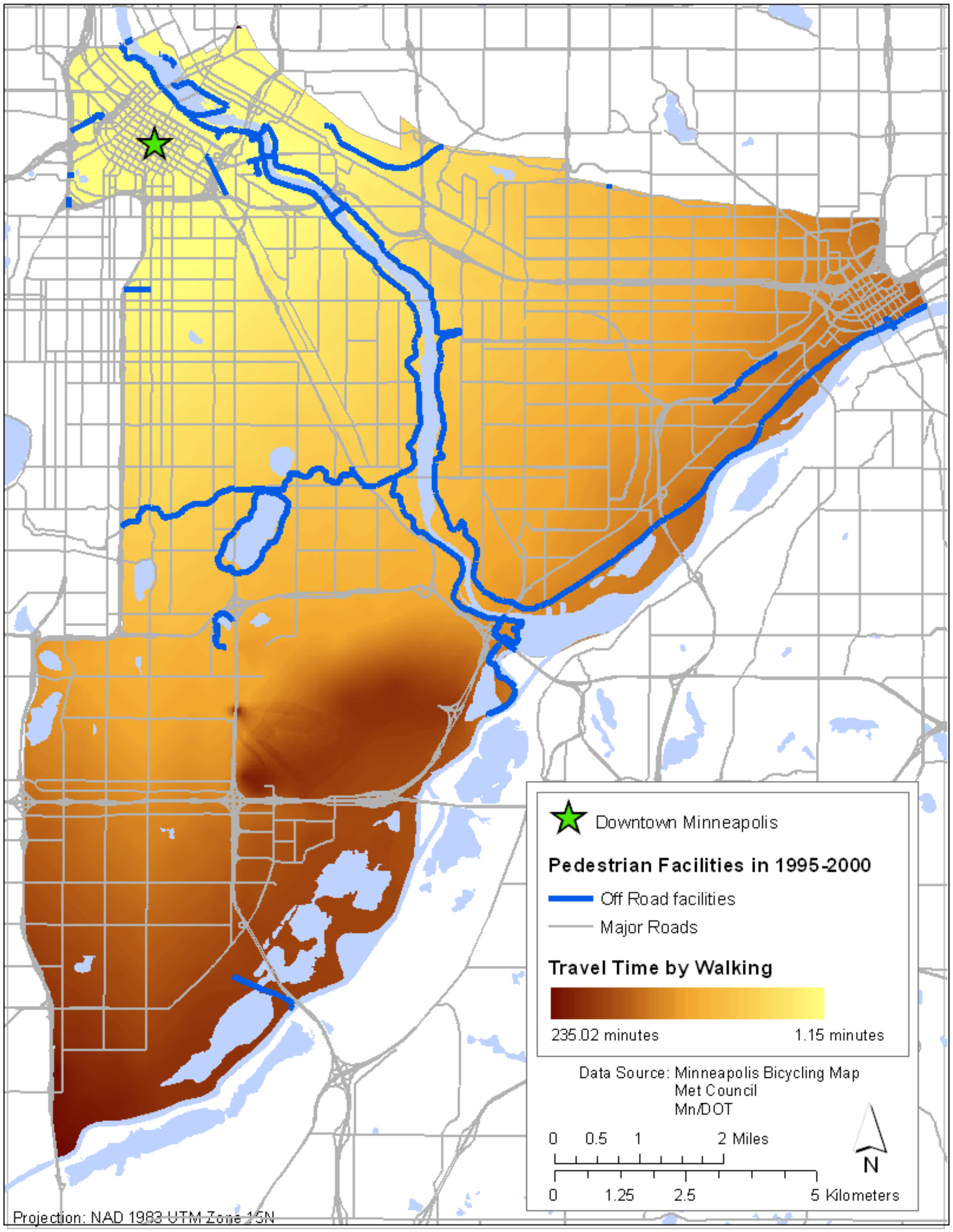

Figure 30. Pedestrian travel time shed from downtown Minneapolis in 1995-2000

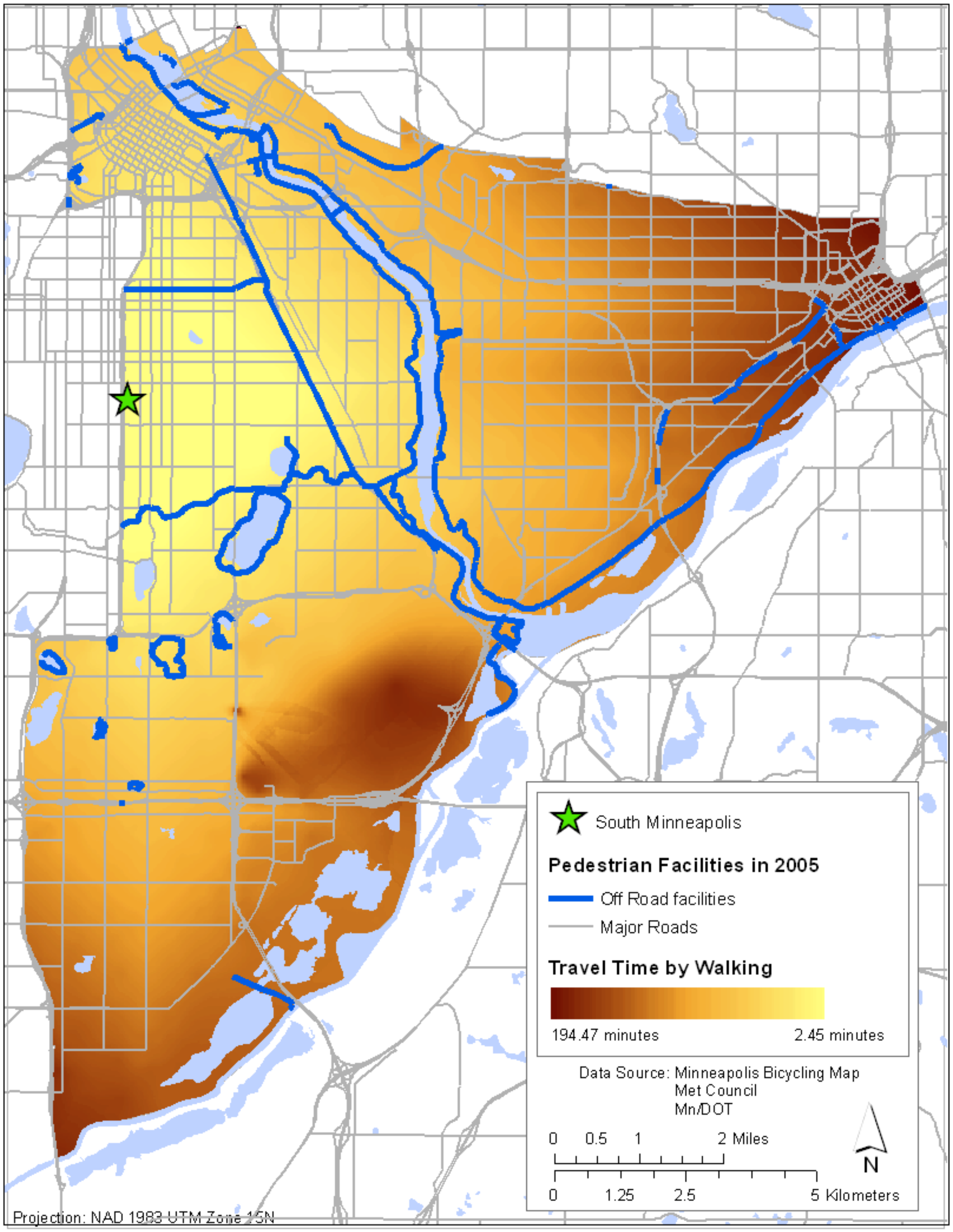

Figure 31. Pedestrian travel time shed from south Minneapolis in 2005

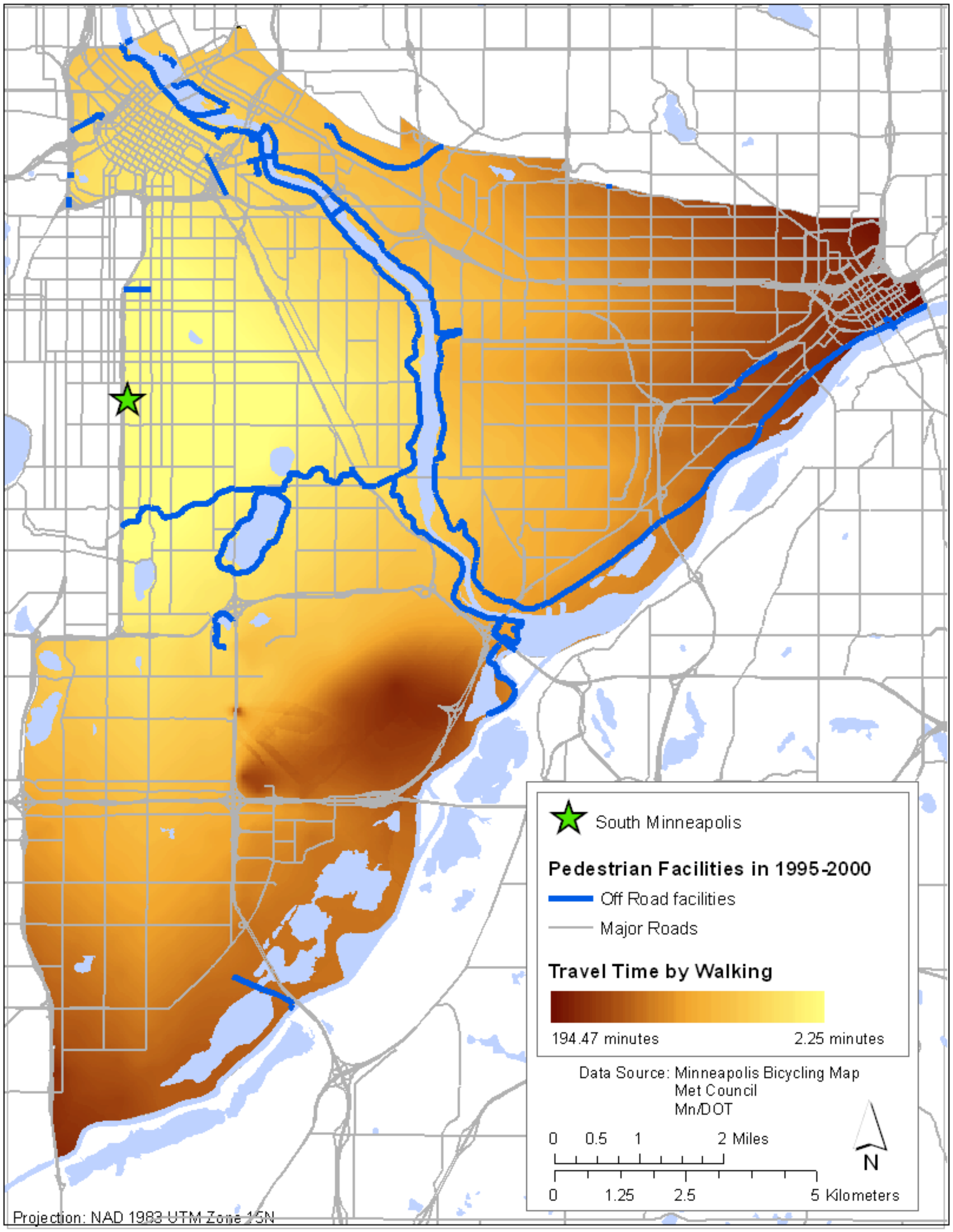

Figure 32. Pedestrian travel time shed from south Minneapolis in 1995 - 2000

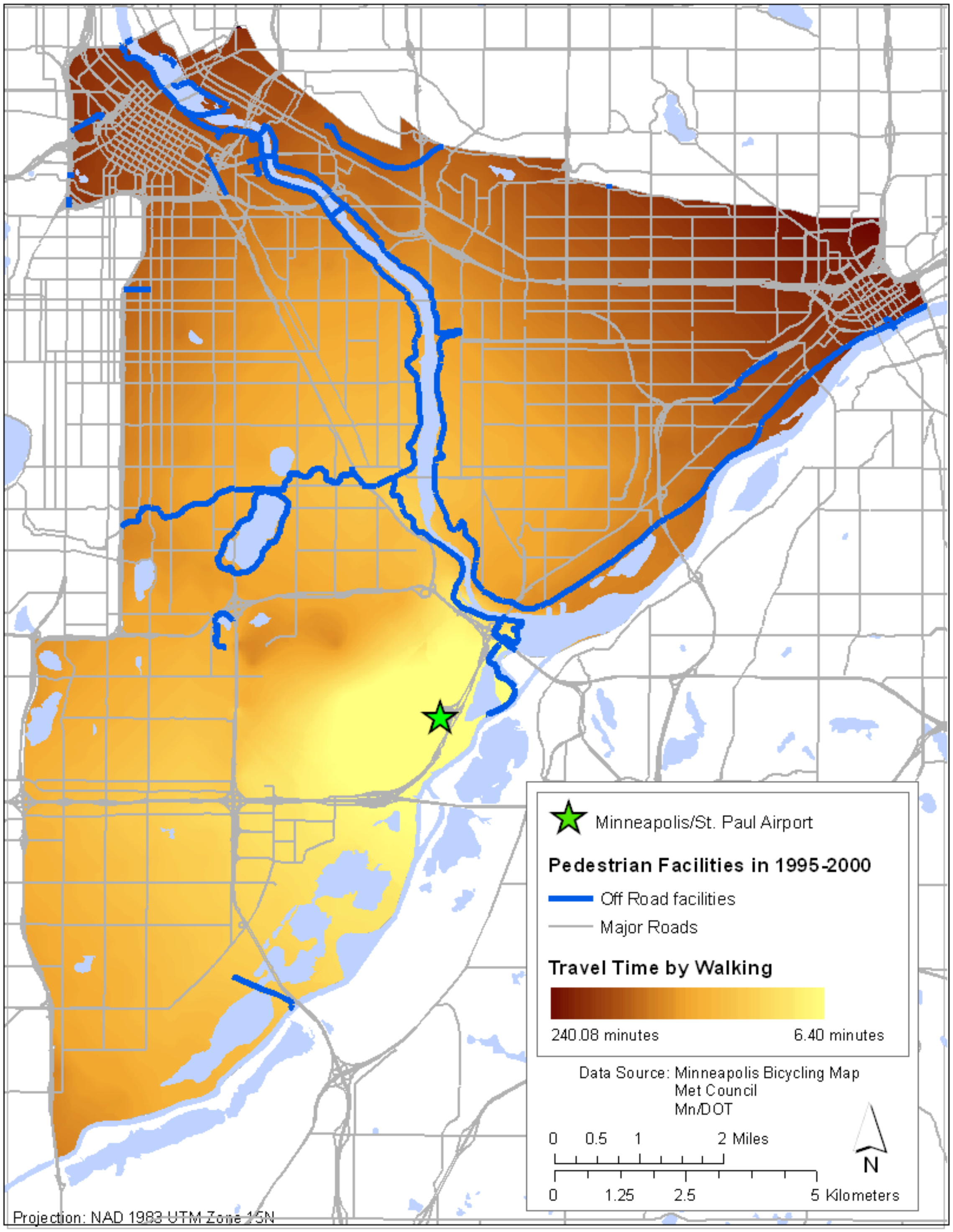

Figure 33. Pedestrian travel time shed from the Minneapolis/St. Paul Airport in 1995-2000

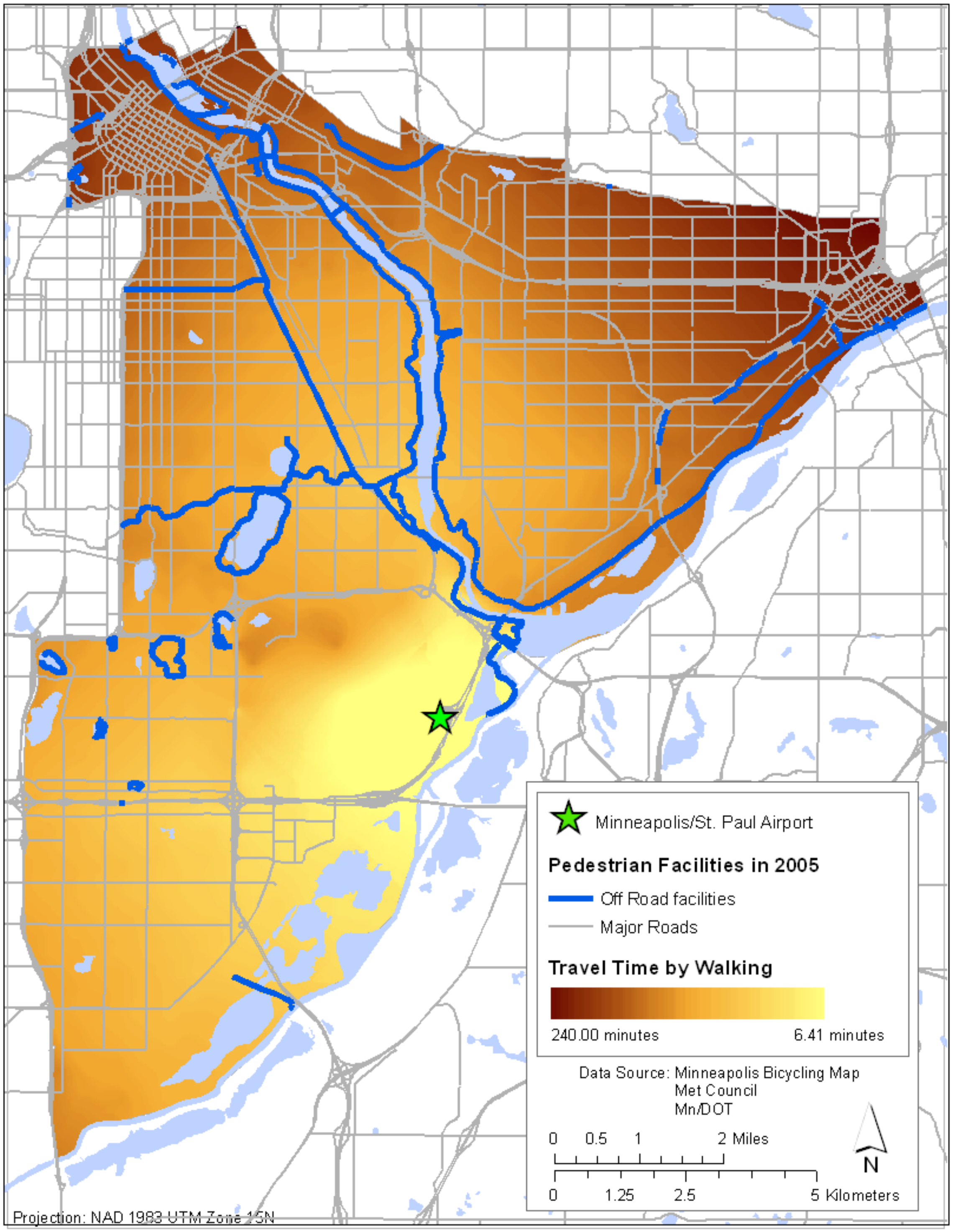

Figure 34. Pedestrian travel time shed from the Minneapolis/St. Paul Airport in 2005

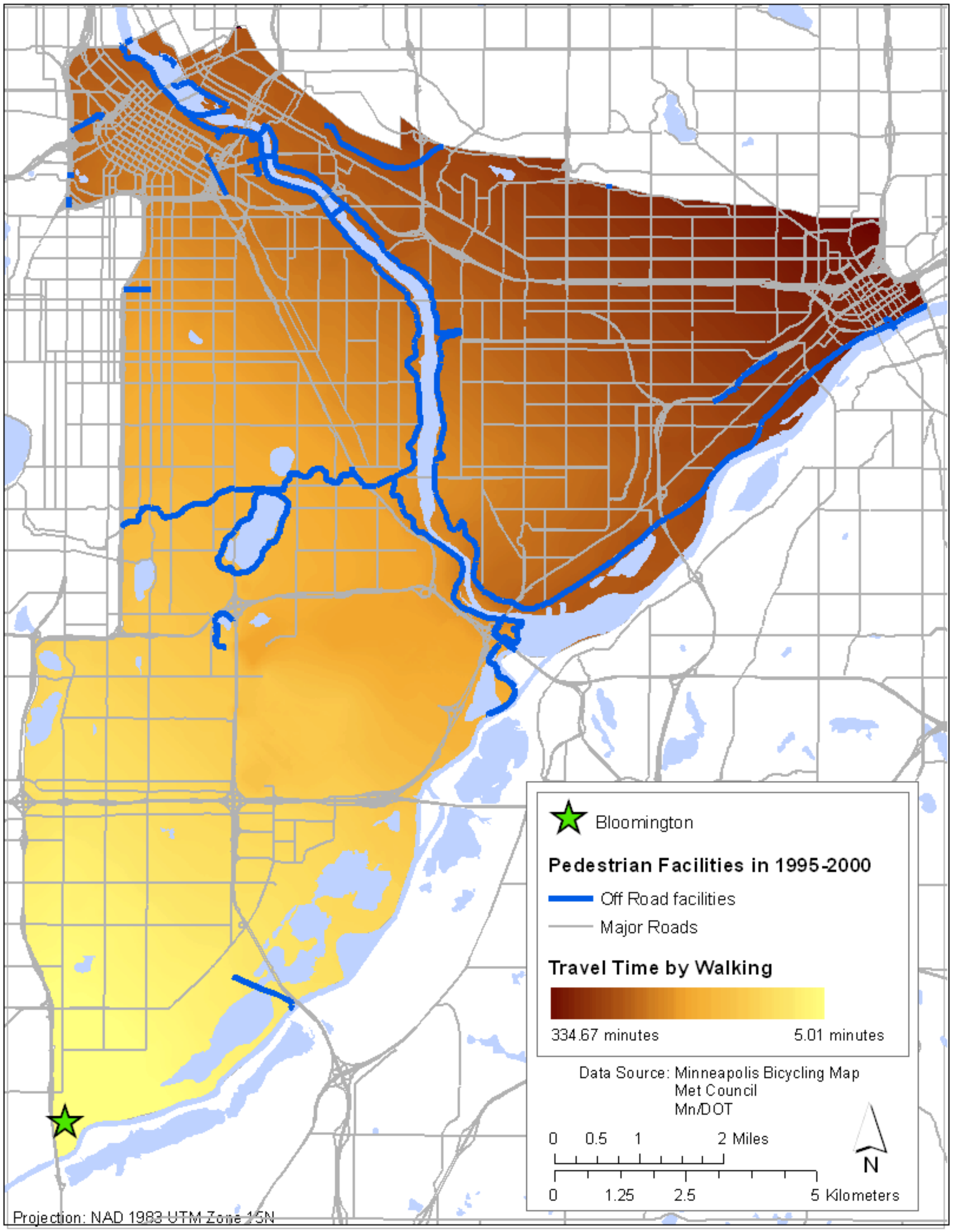

Figure 35. Pedestrian travel time shed from Bloomington in 1995-2000

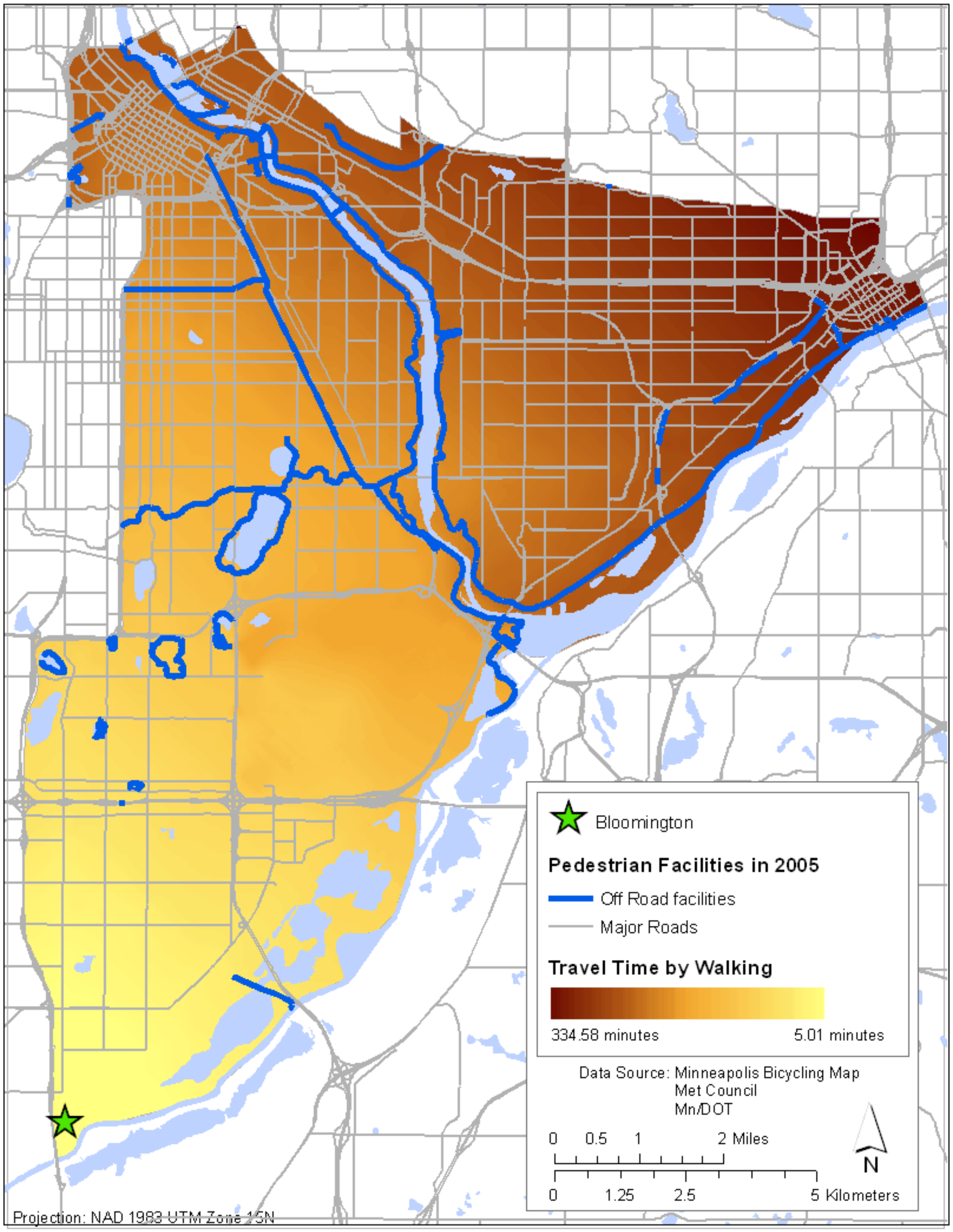

Figure 36. Pedestrian travel time shed from Bloomington in 2005

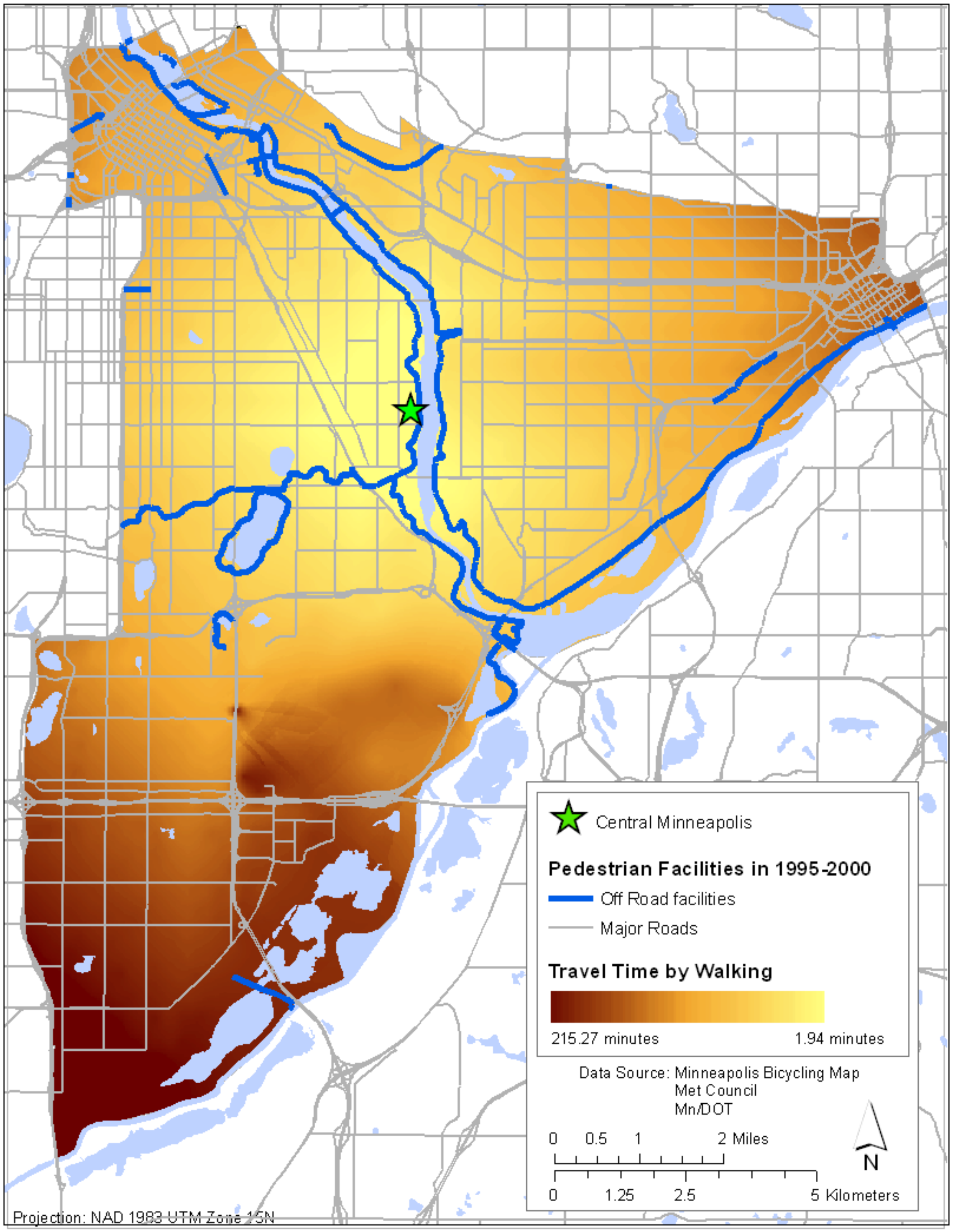

Figure 37. Pedestrian travel time shed from central Minneapolis in 1995-2000

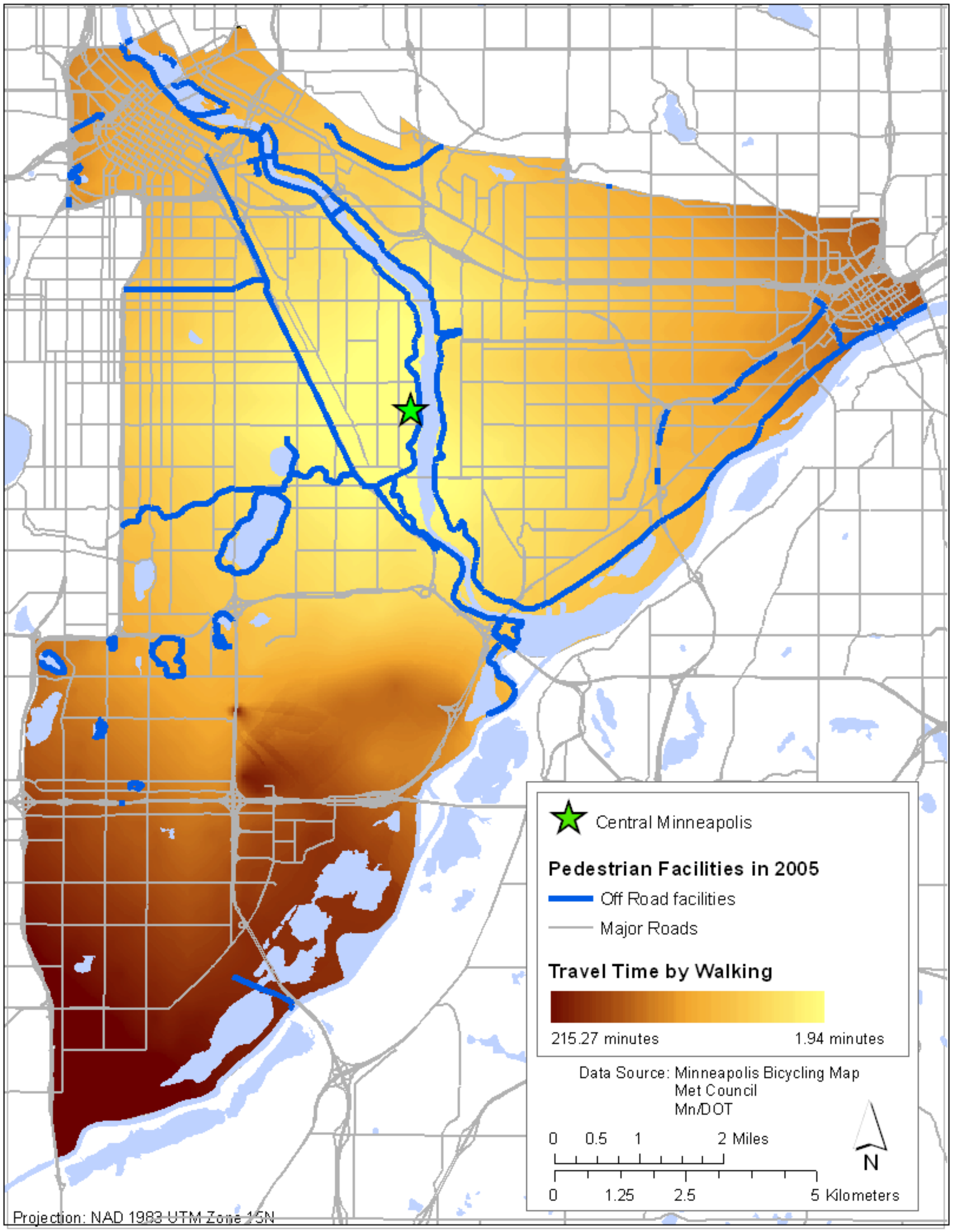

Figure 38. Pedestrian travel time shed from central Minneapolis in 2005

Appendix E: Bicycling Maps

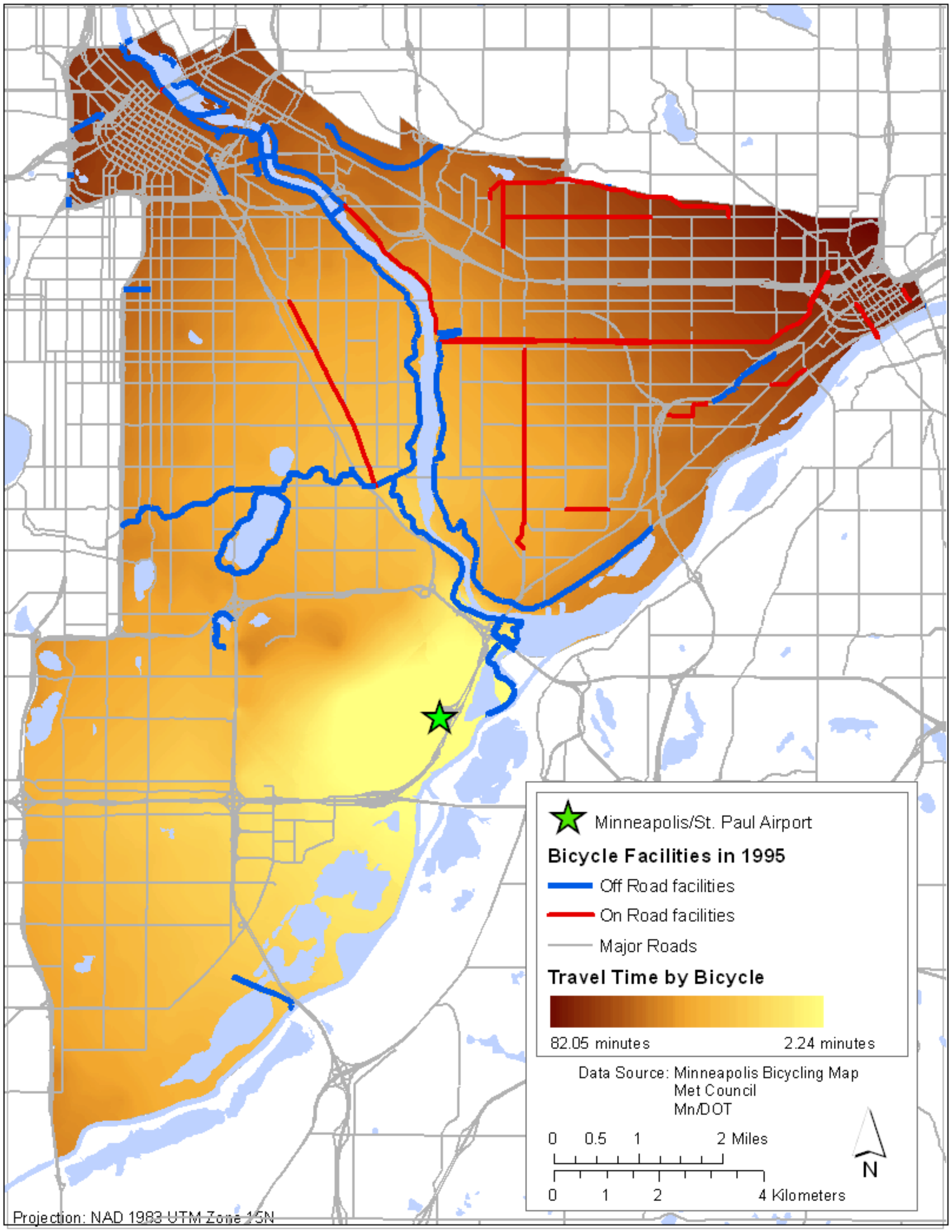

Figure 39. Bicycling travel time shed from the Minneapolis/St. Paul Airport in 1995

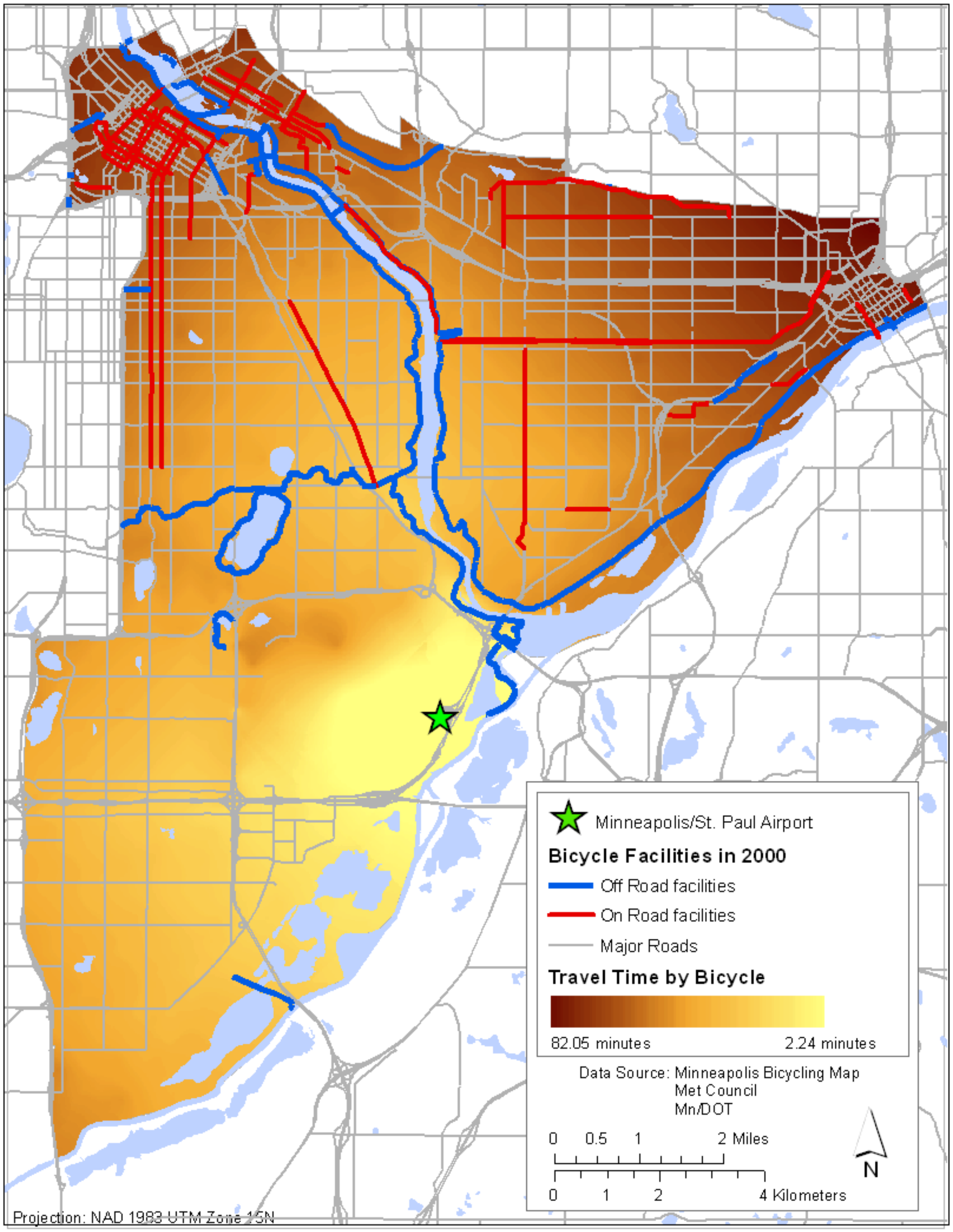

Figure 40. Bicycling travel time shed from the Minneapolis/St. Paul Airport in 2000

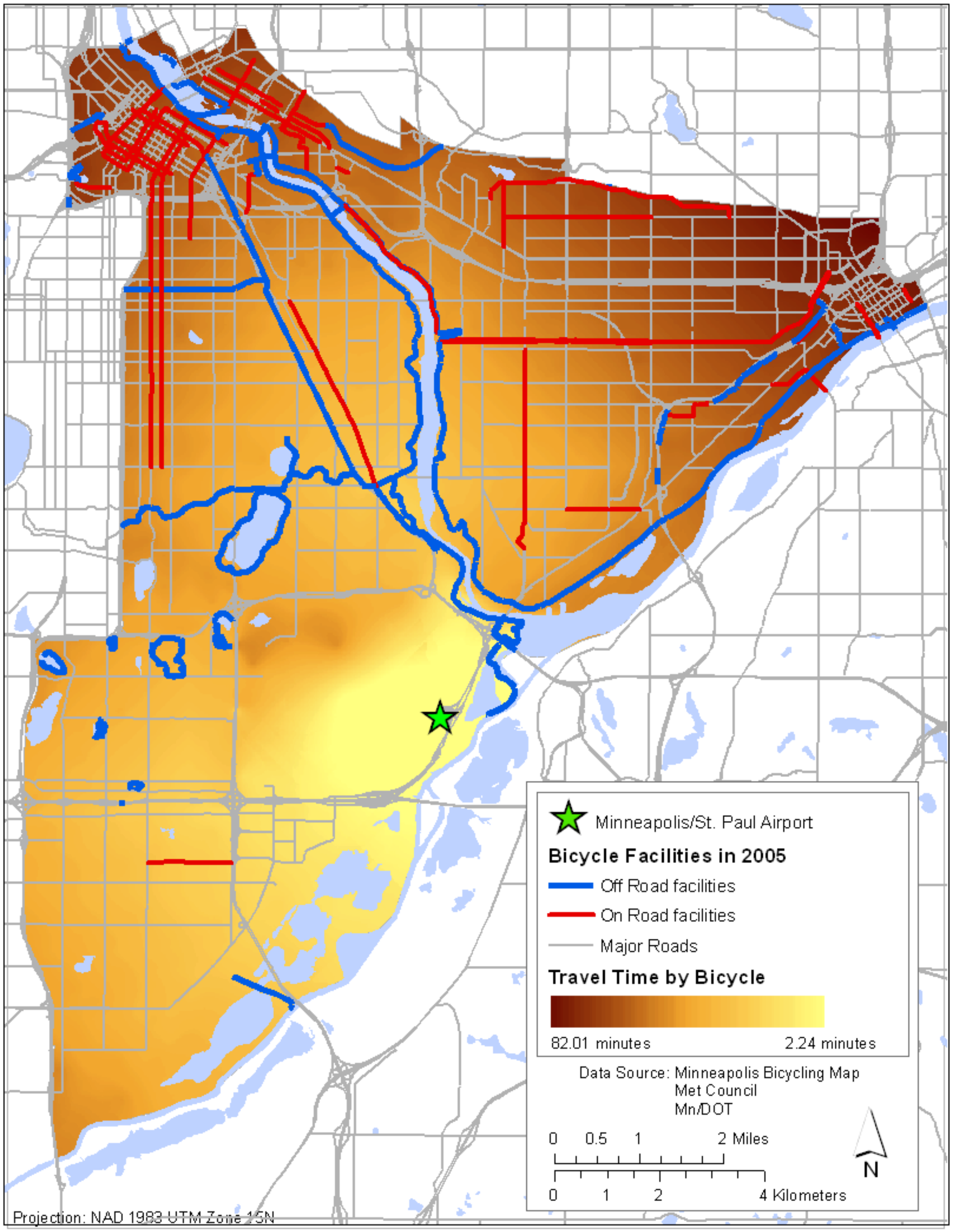

Figure 41. Bicycling travel time shed from the Minneapolis/St. Paul Airport in 2005

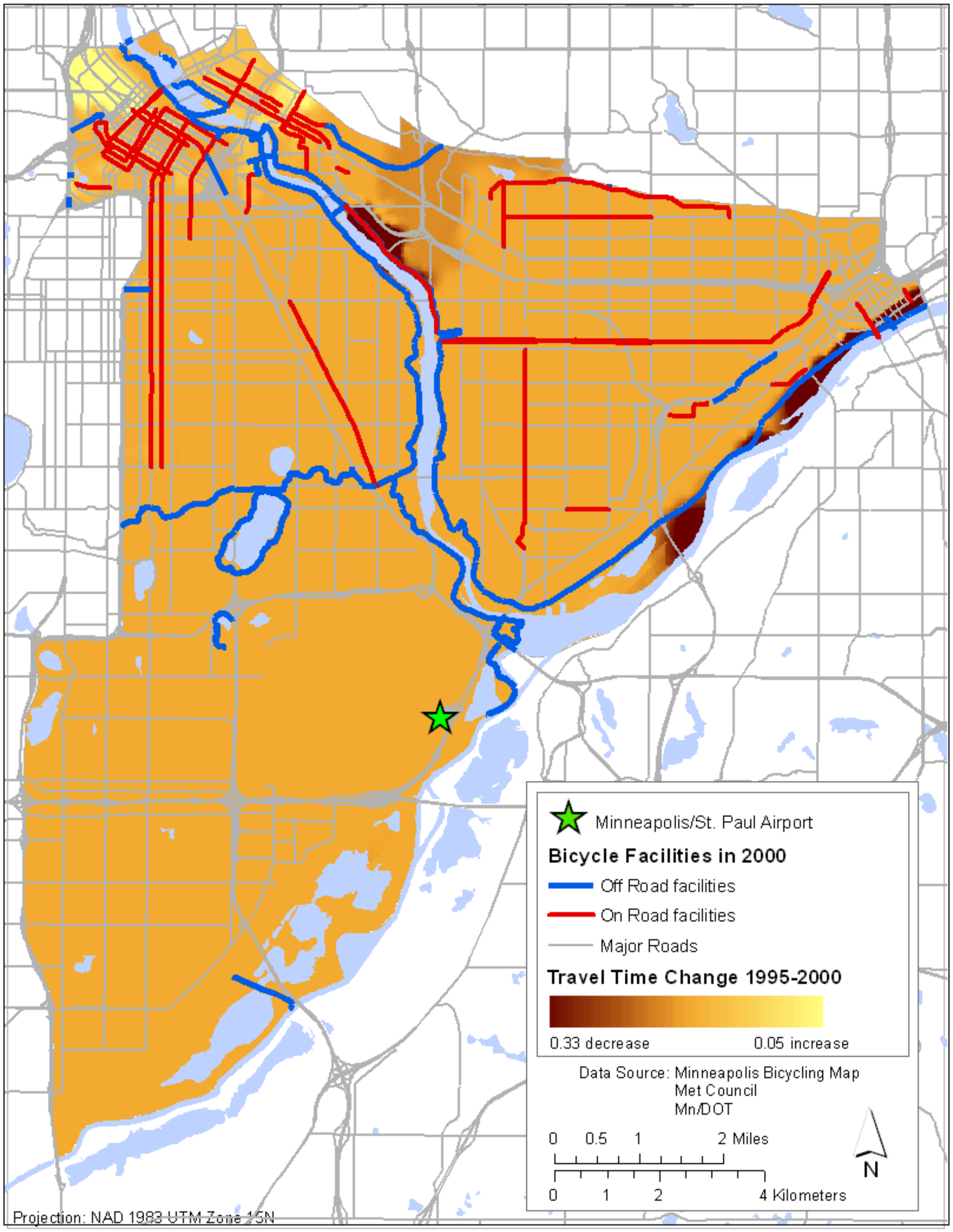

Figure 42. Change in bicycling travel time from the Minneapolis/St. Paul Airport between 1995 and 2000

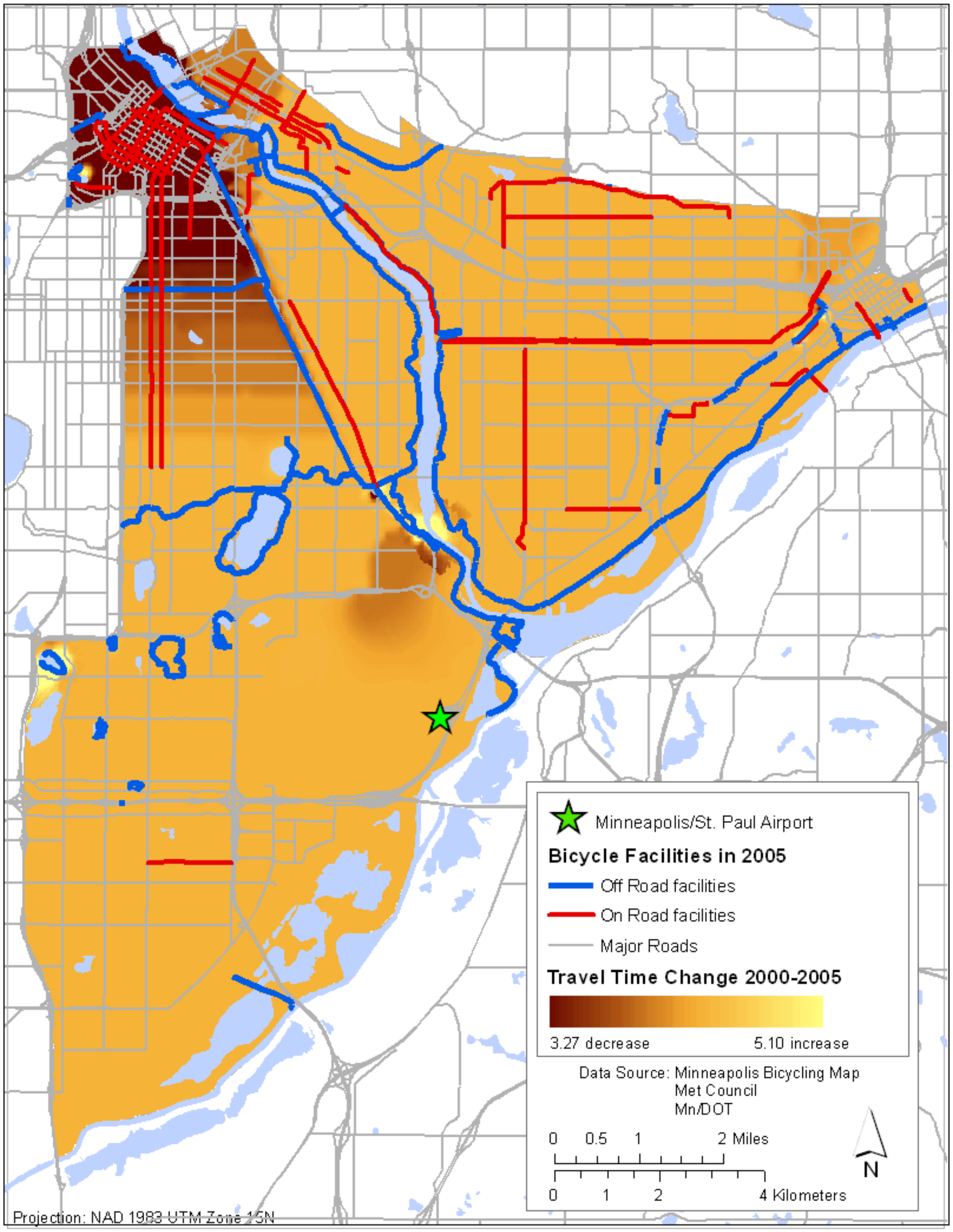

Figure 43. Change in bicycling travel time from the Minneapolis/St. Paul Airport between 2000 and 2005

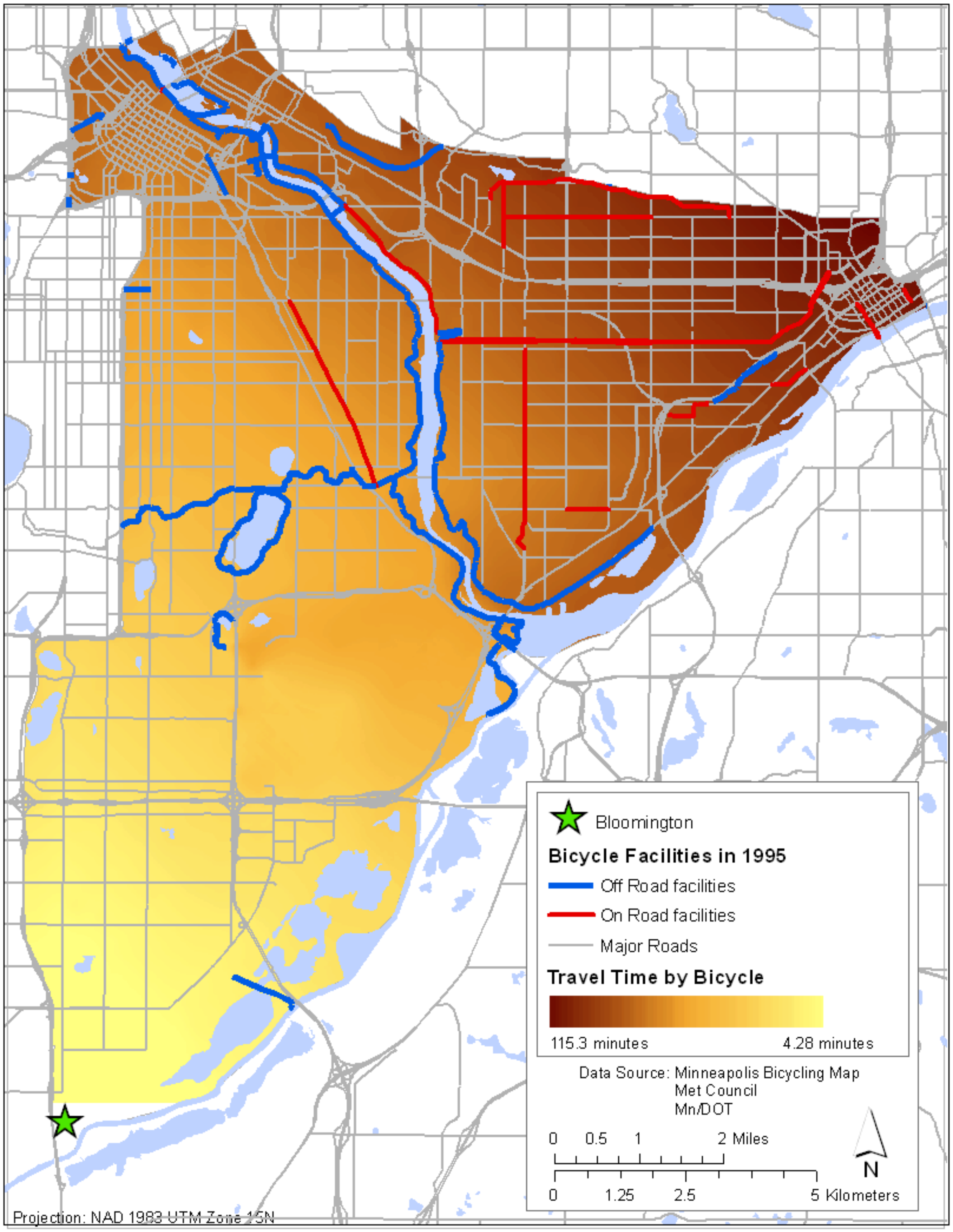

Figure 44. Bicycling travel time shed from Bloomington in 1995

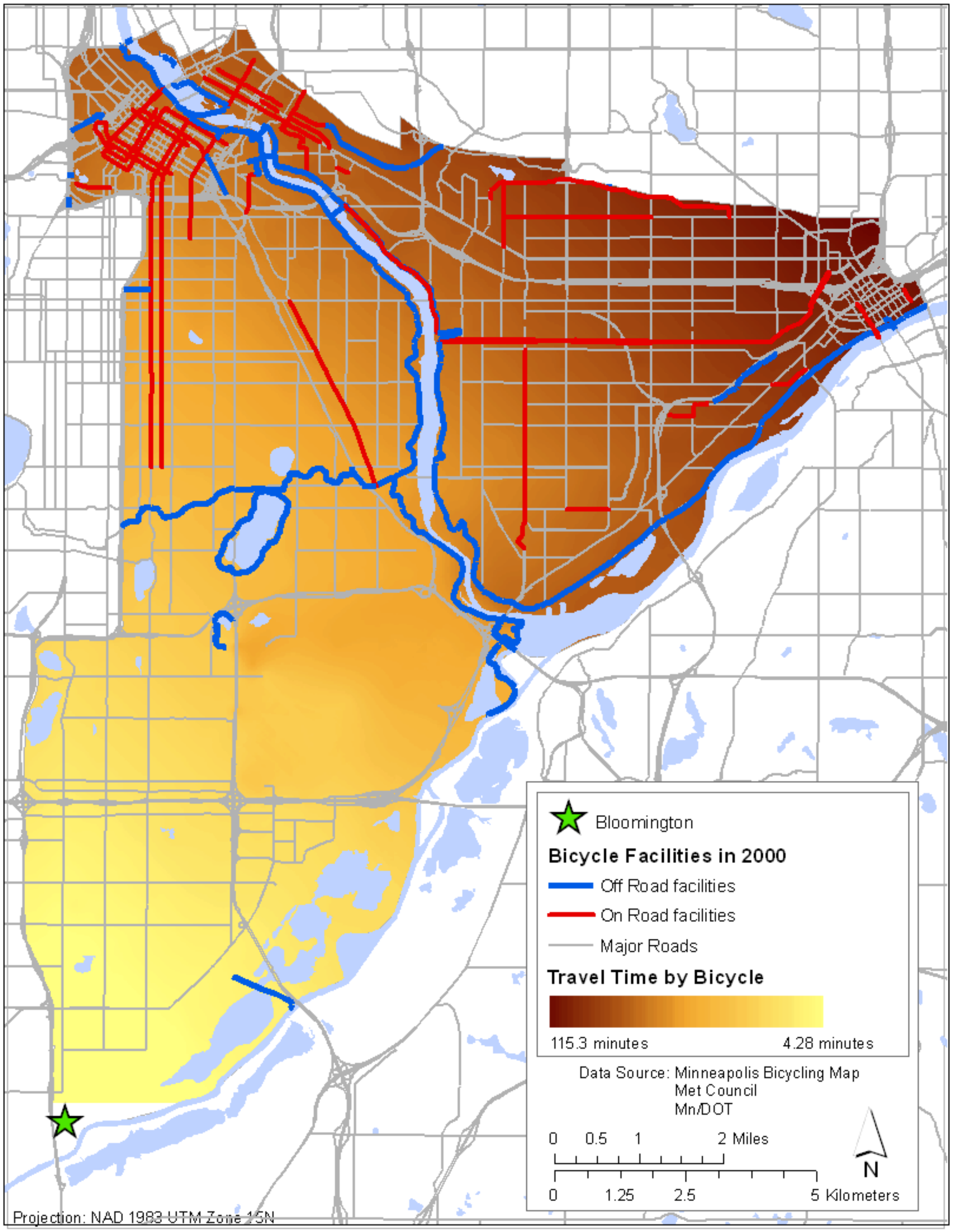

Figure 45. Bicycling travel time shed from Bloomington in 2000

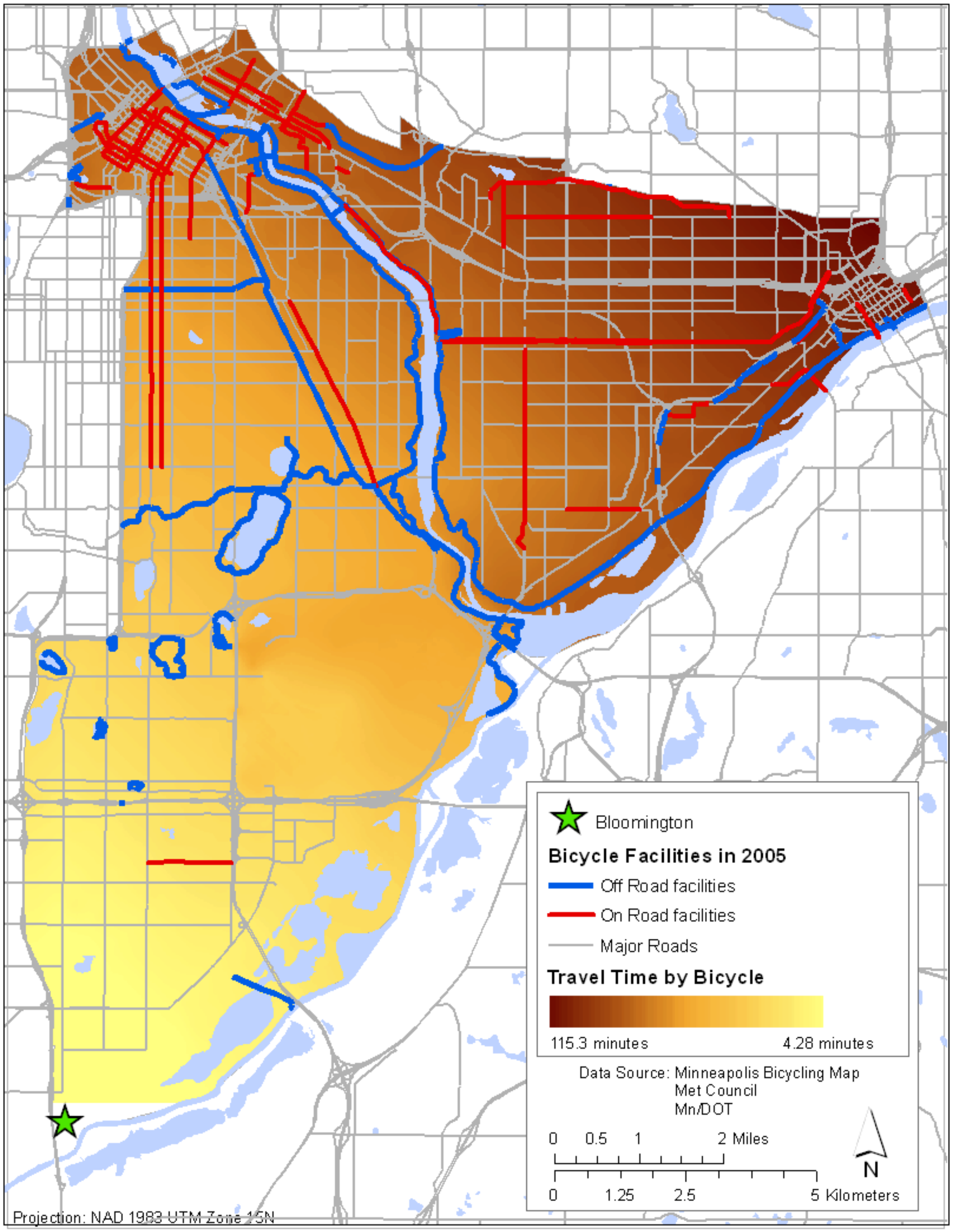

Figure 46. Bicycling travel time shed from Bloomington in 2005

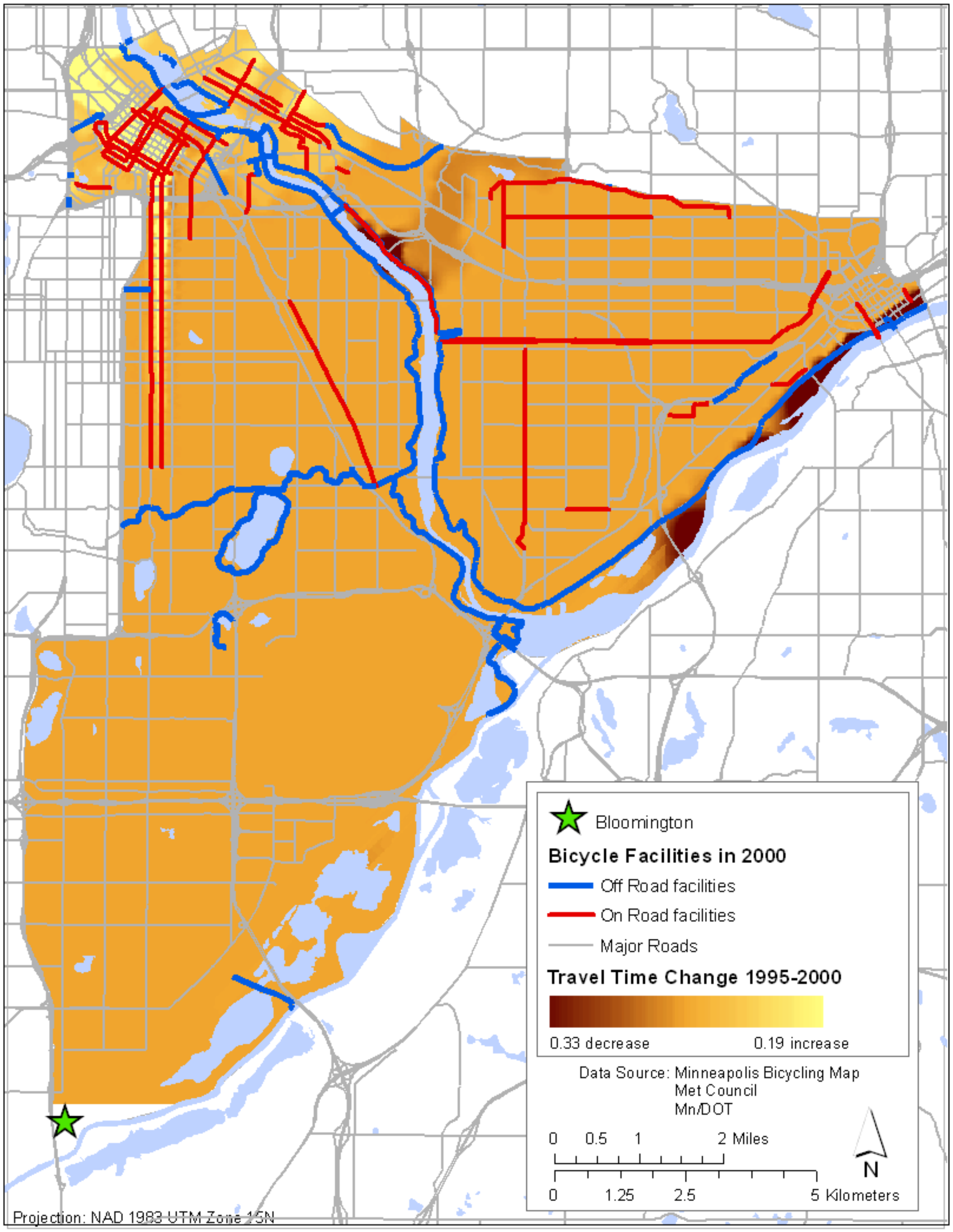

Figure 47. Change in bicycling travel time from Bloomington between 1995 and 2000

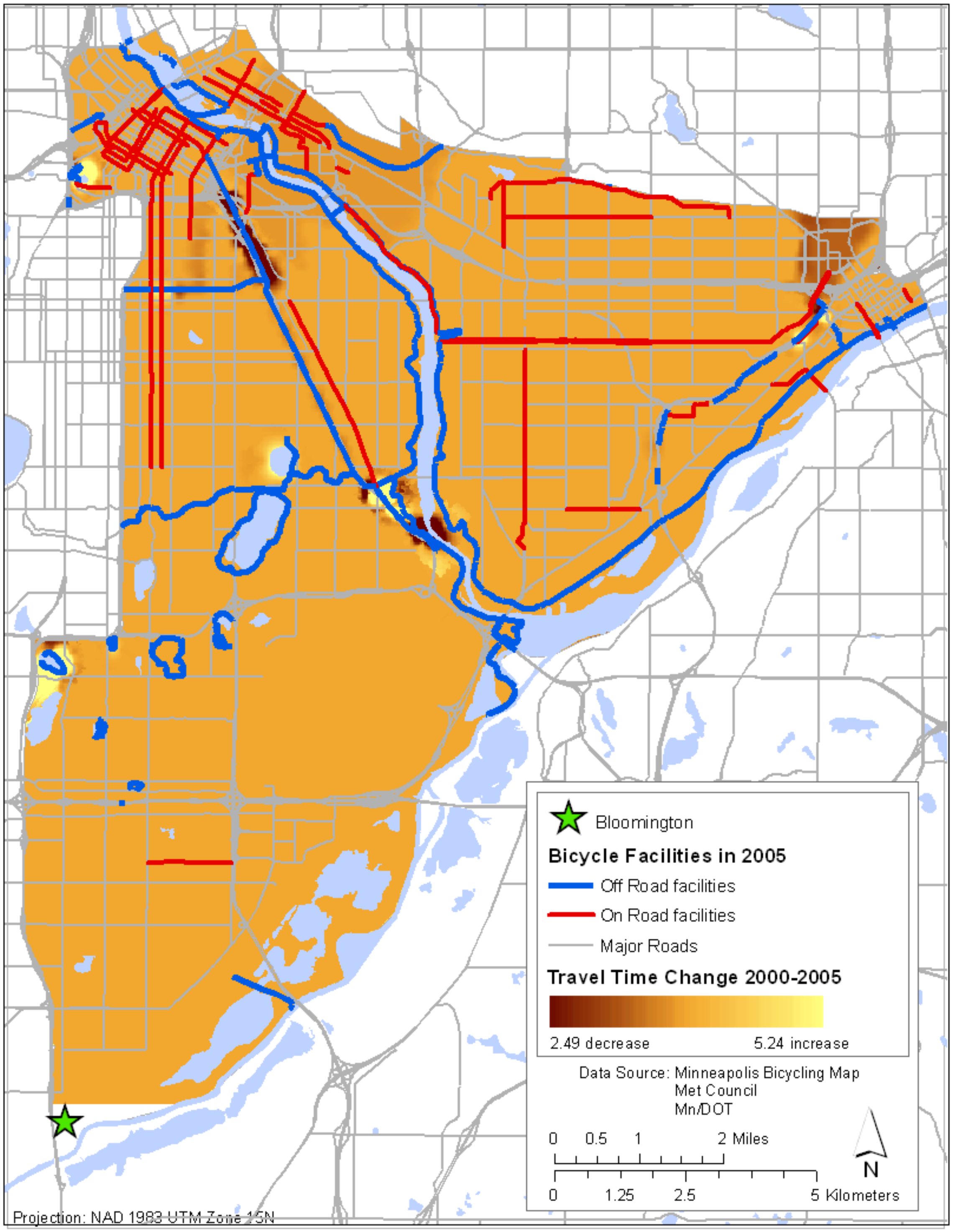

Figure 48. Change in bicycling travel time from Bloomington between 2000 and 2005

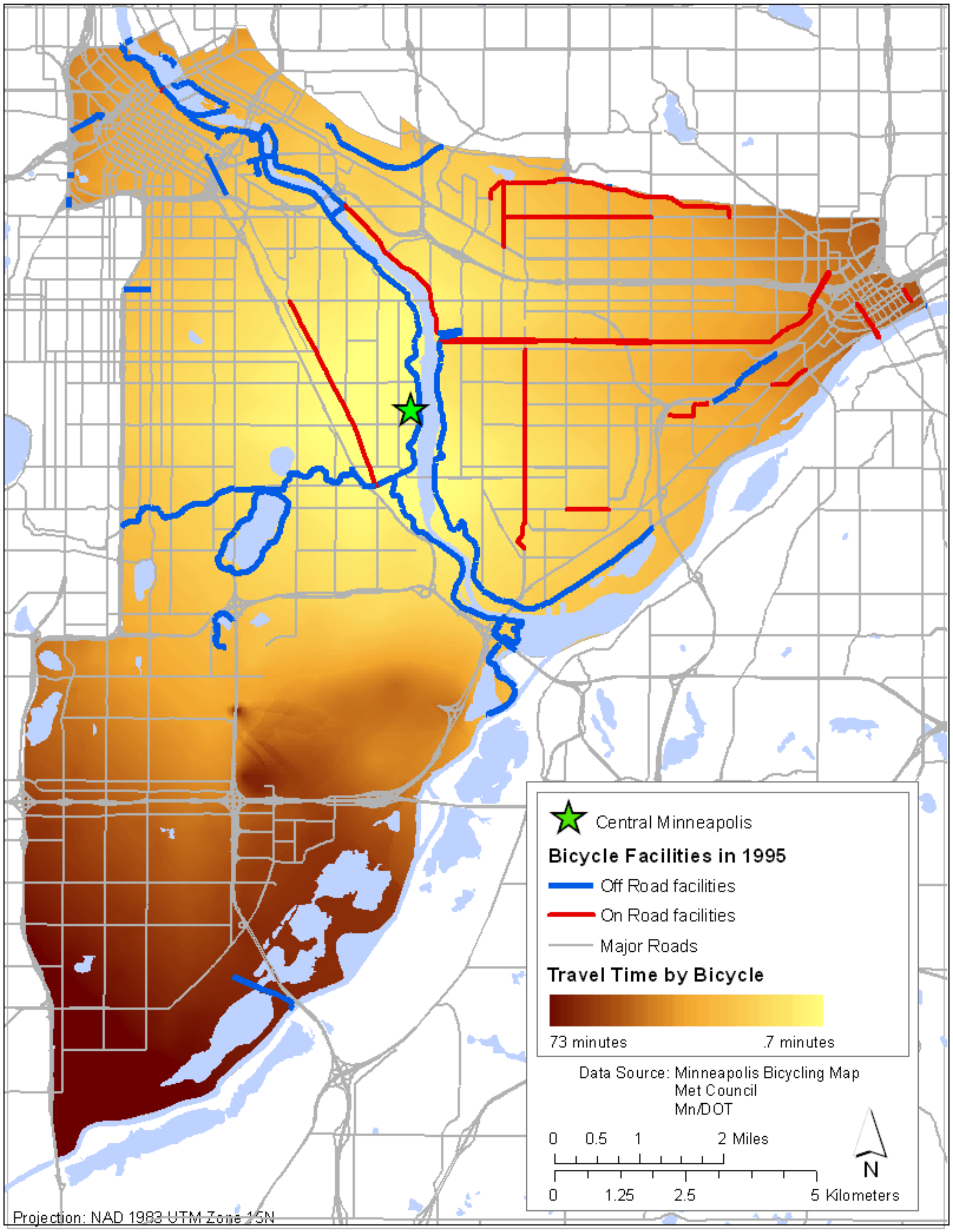

Figure 49. Bicycling travel time shed from central Minneapolis in 1995

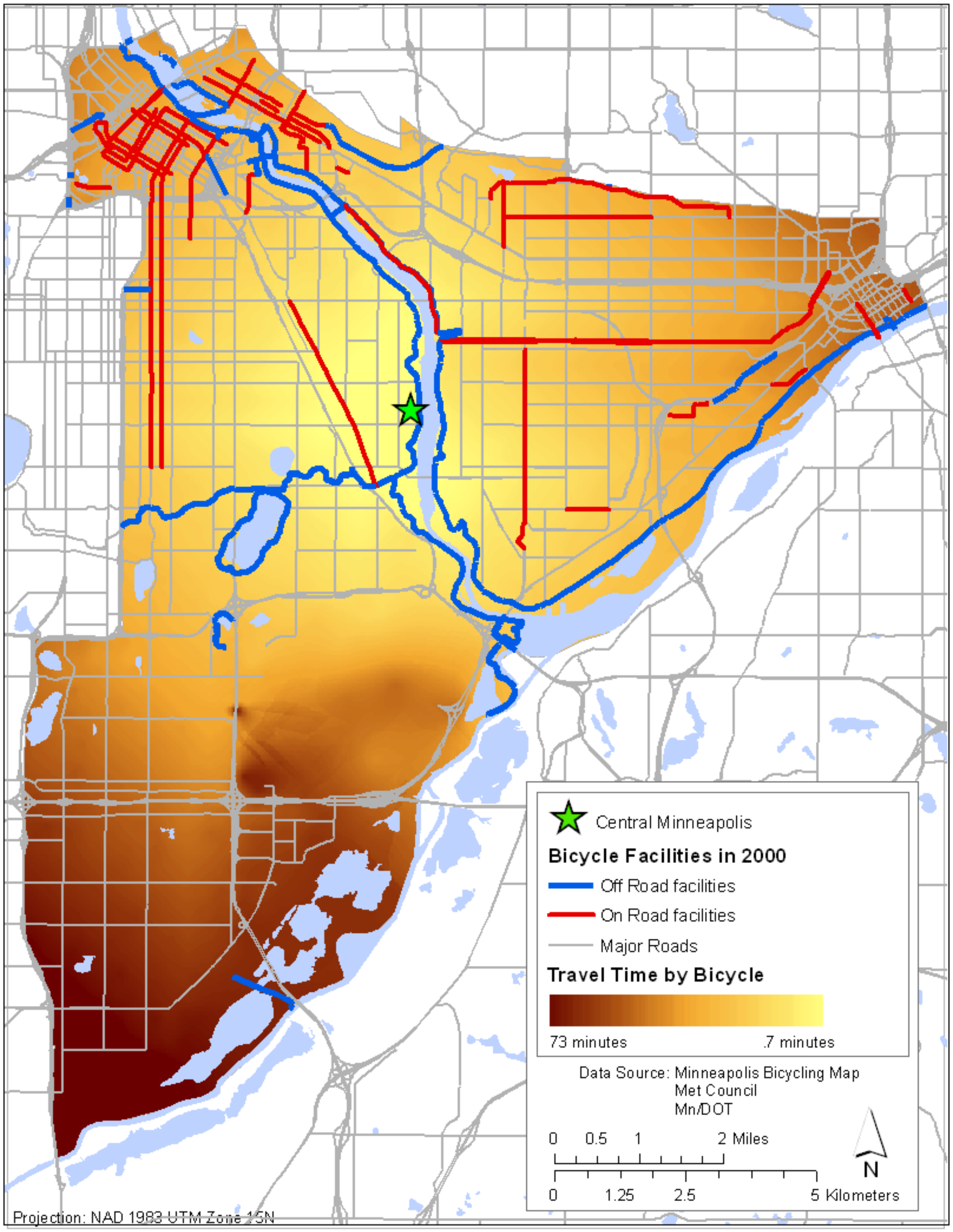

Figure 50. Bicycling travel time shed from central Minneapolis in 2000

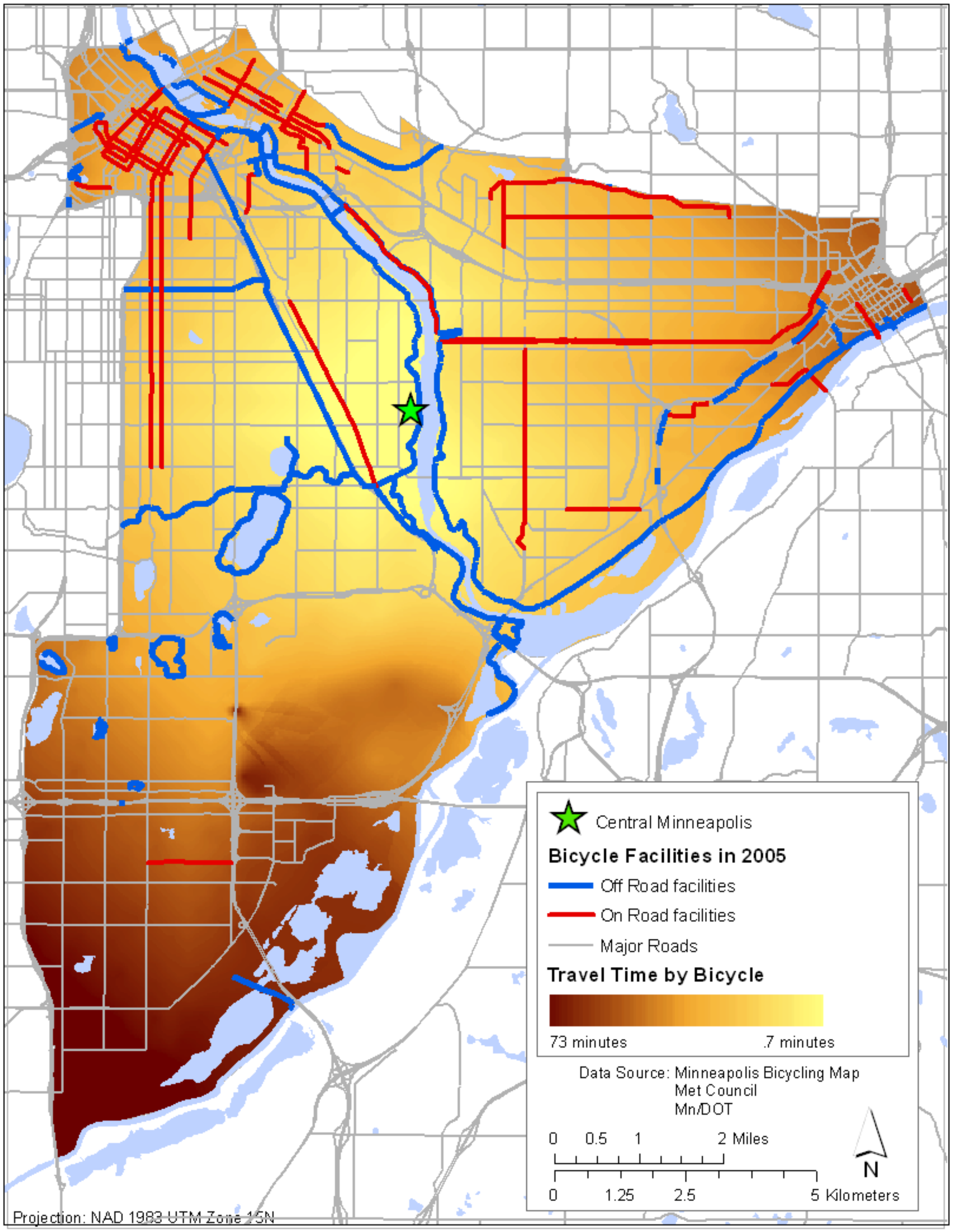

Figure 51. Bicycling travel time shed from central Minneapolis in 2005

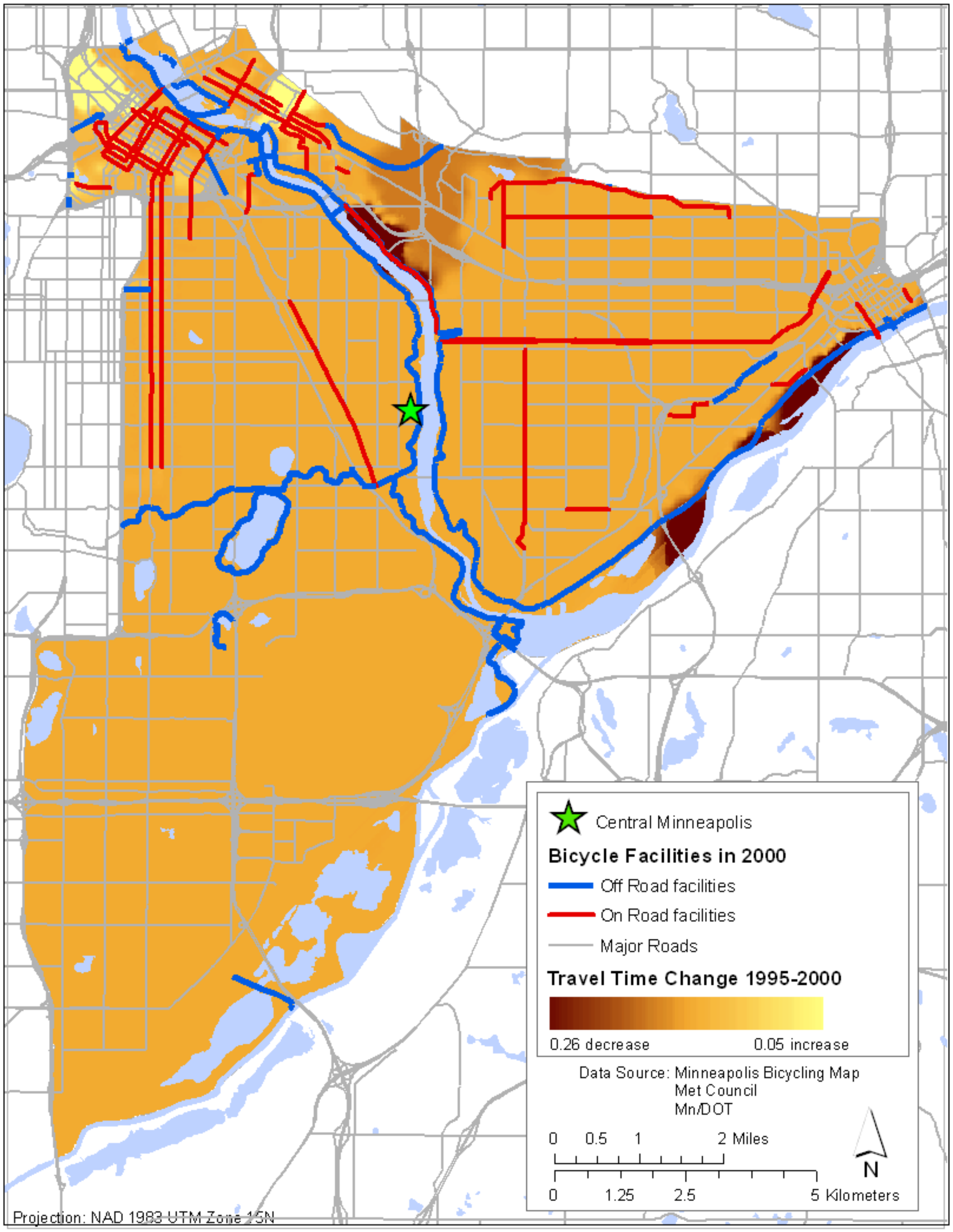

Figure 52. Change in bicycling travel time from central Minneapolis between 1995 and 2000

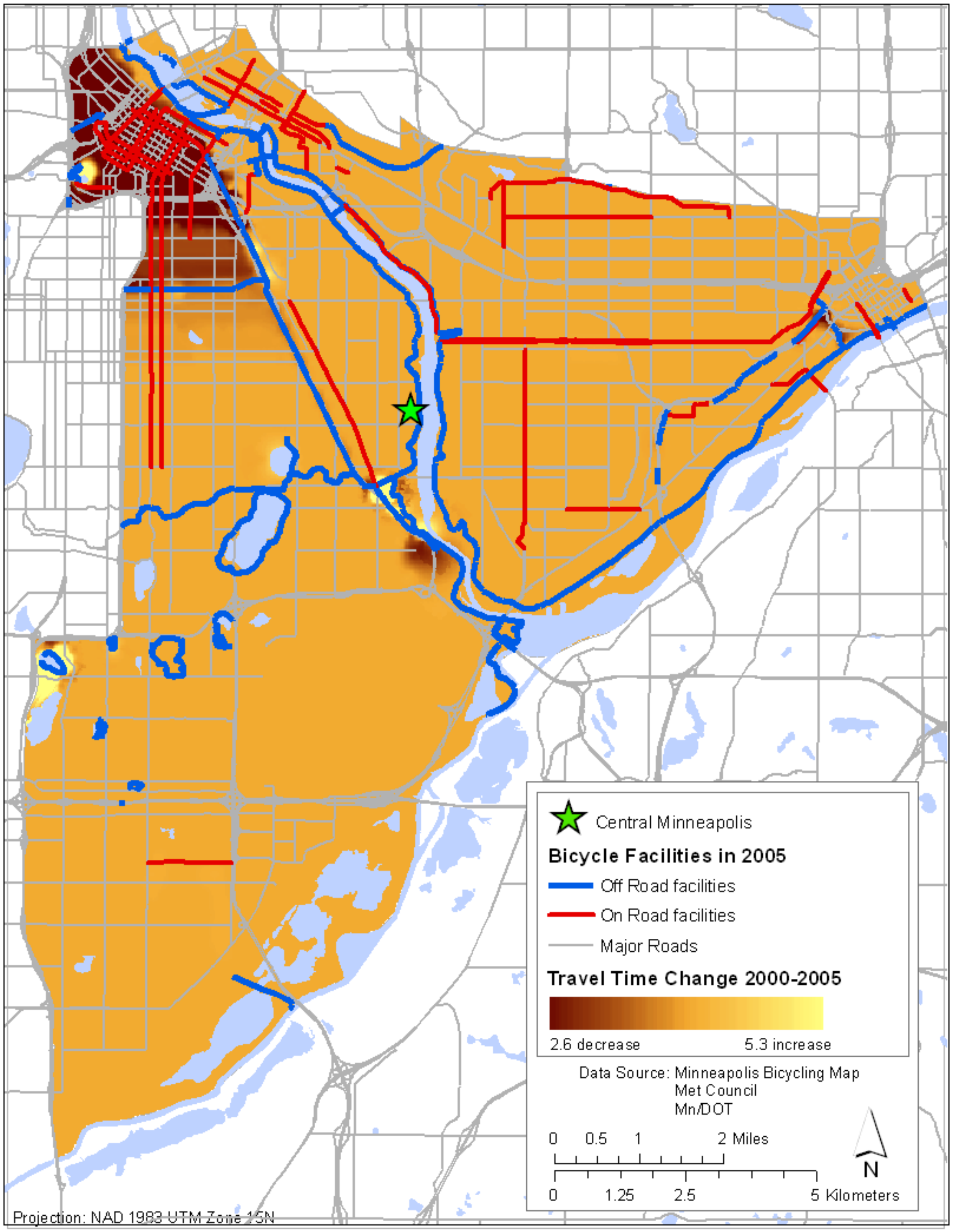

Figure 53. Change in bicycling travel time from central Minneapolis between 2000 and 2005

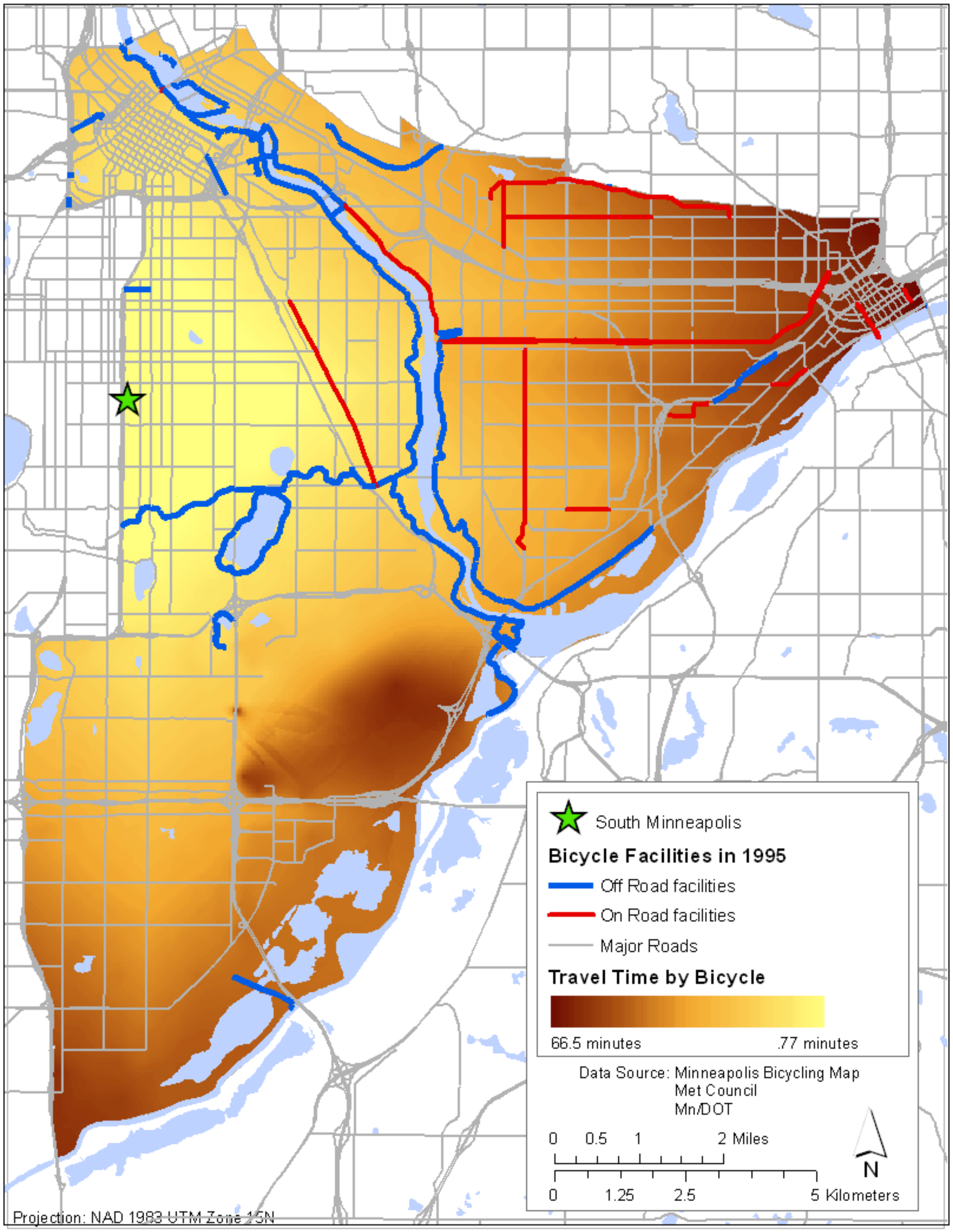

Figure 54. Bicycling travel time shed from south Minneapolis in 1995

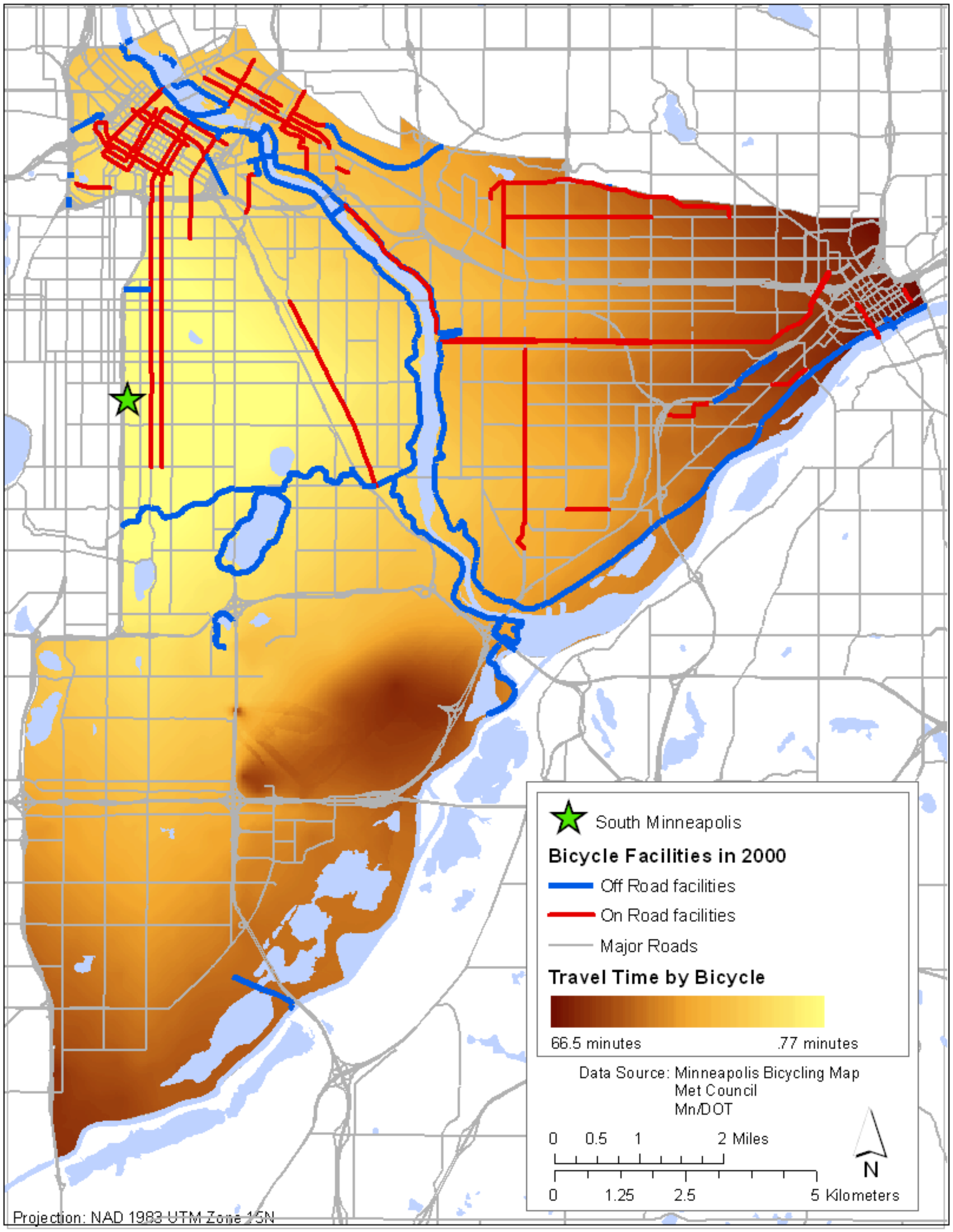

Figure 55. Bicycling travel time shed from south Minneapolis in 2000

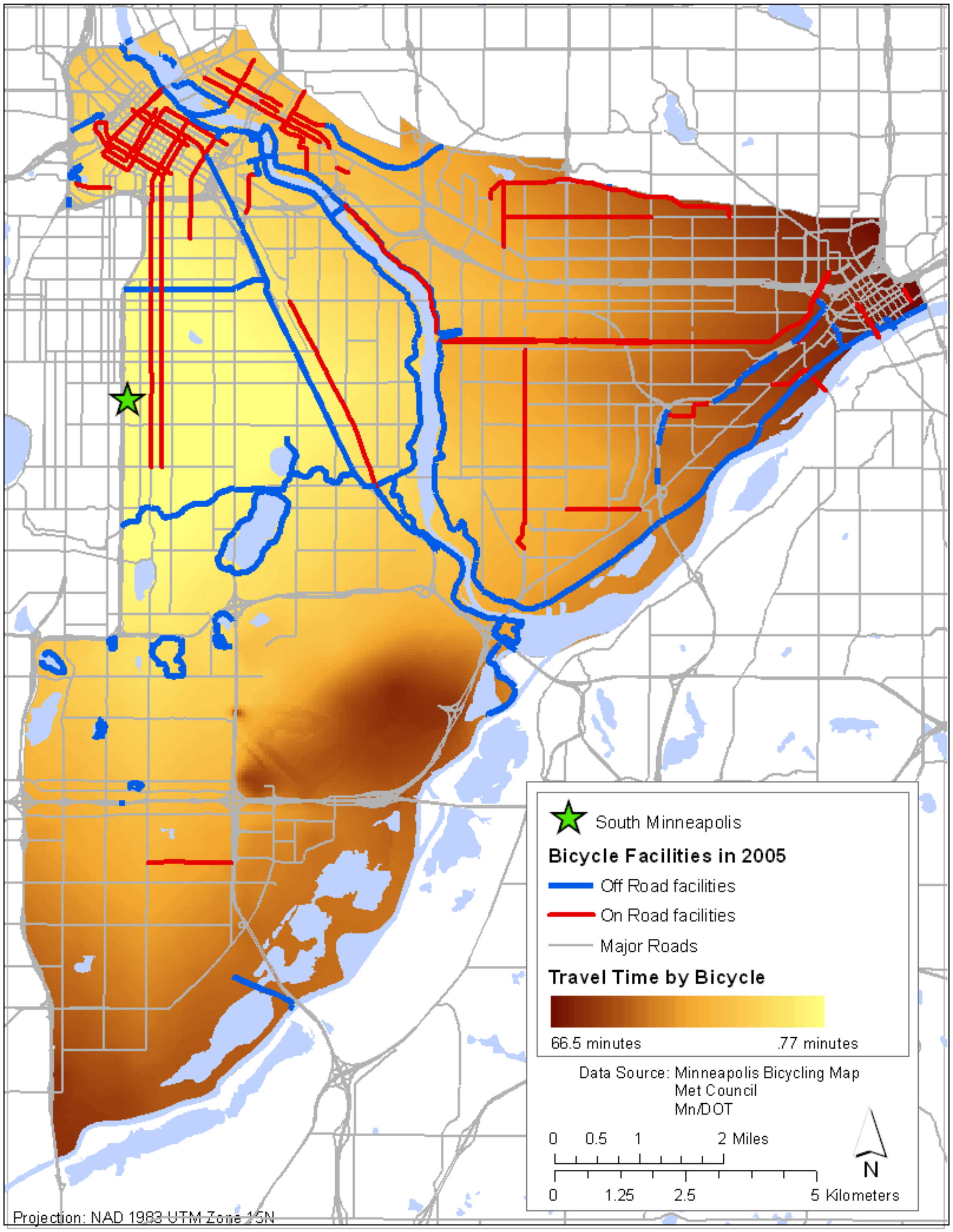

Figure 56. Bicycling travel time shed from south Minneapolis in 2005

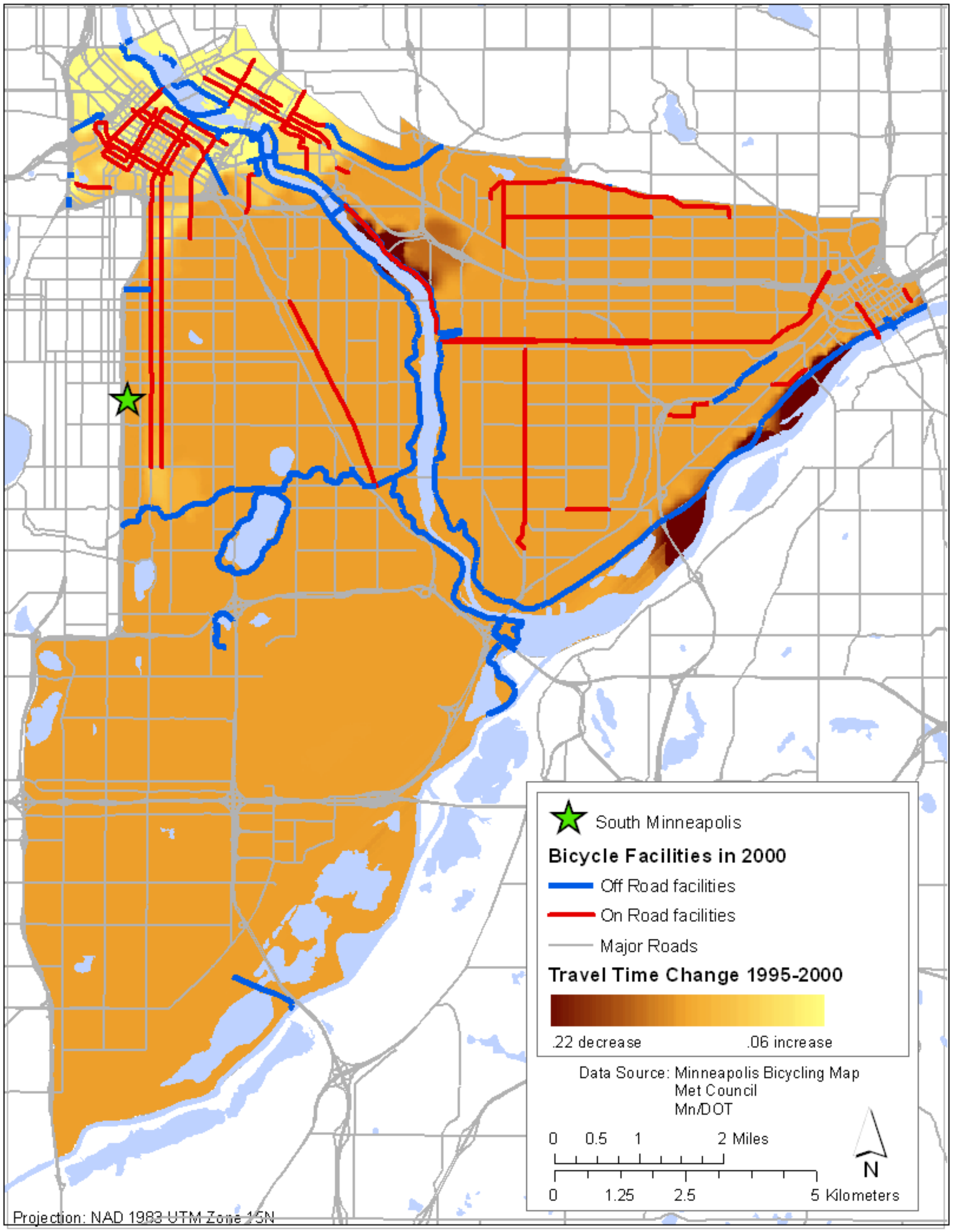

Figure 57. Change in bicycling travel time from south Minneapolis between 1995 and 2000

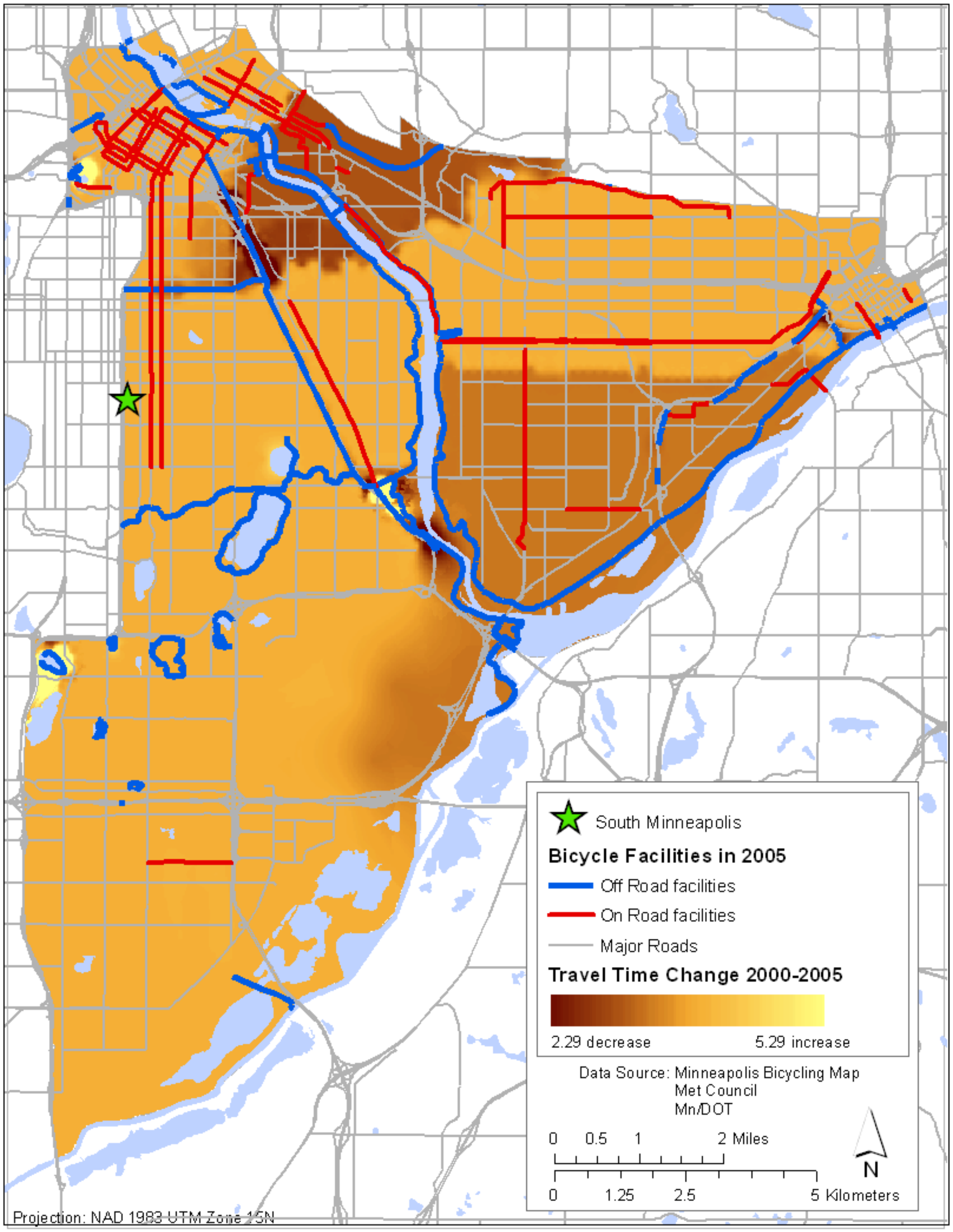

Figure 58. Change in bicycling travel time from south Minneapolis between 2000 and 2005

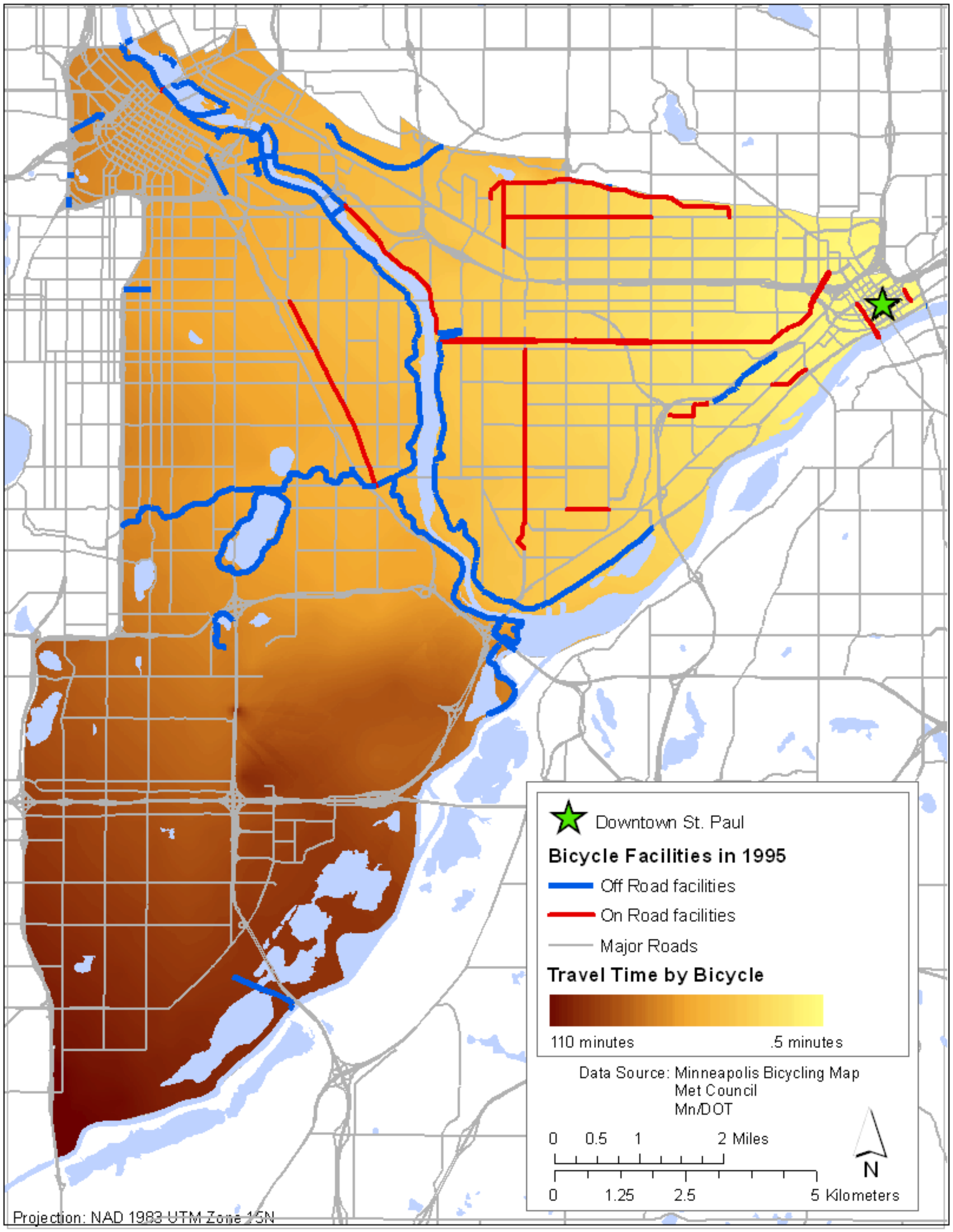

Figure 59. Bicycling travel time shed from downtown St. Paul in 1995

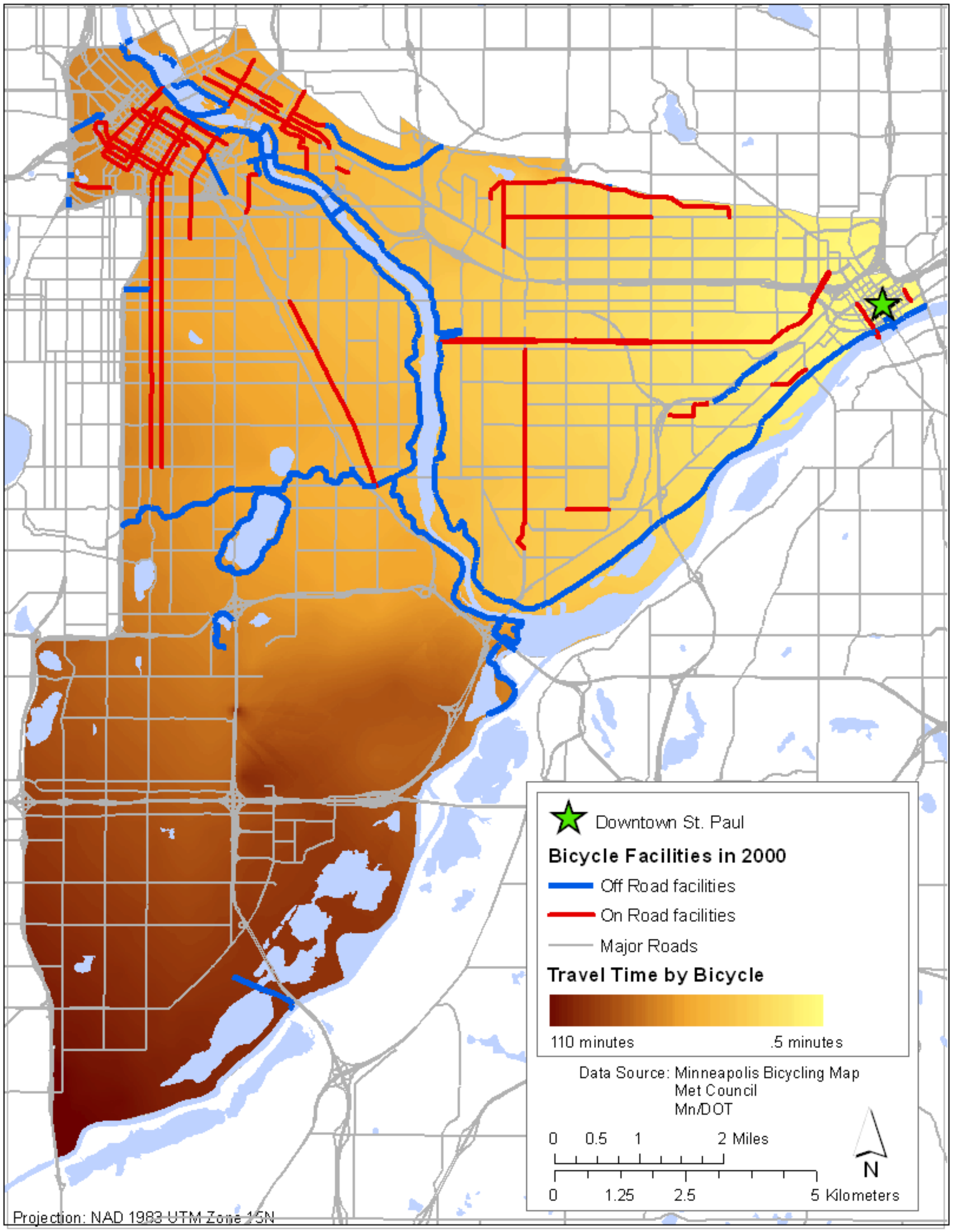

Figure 60. Bicycling travel time shed from downtown St. Paul in 2000

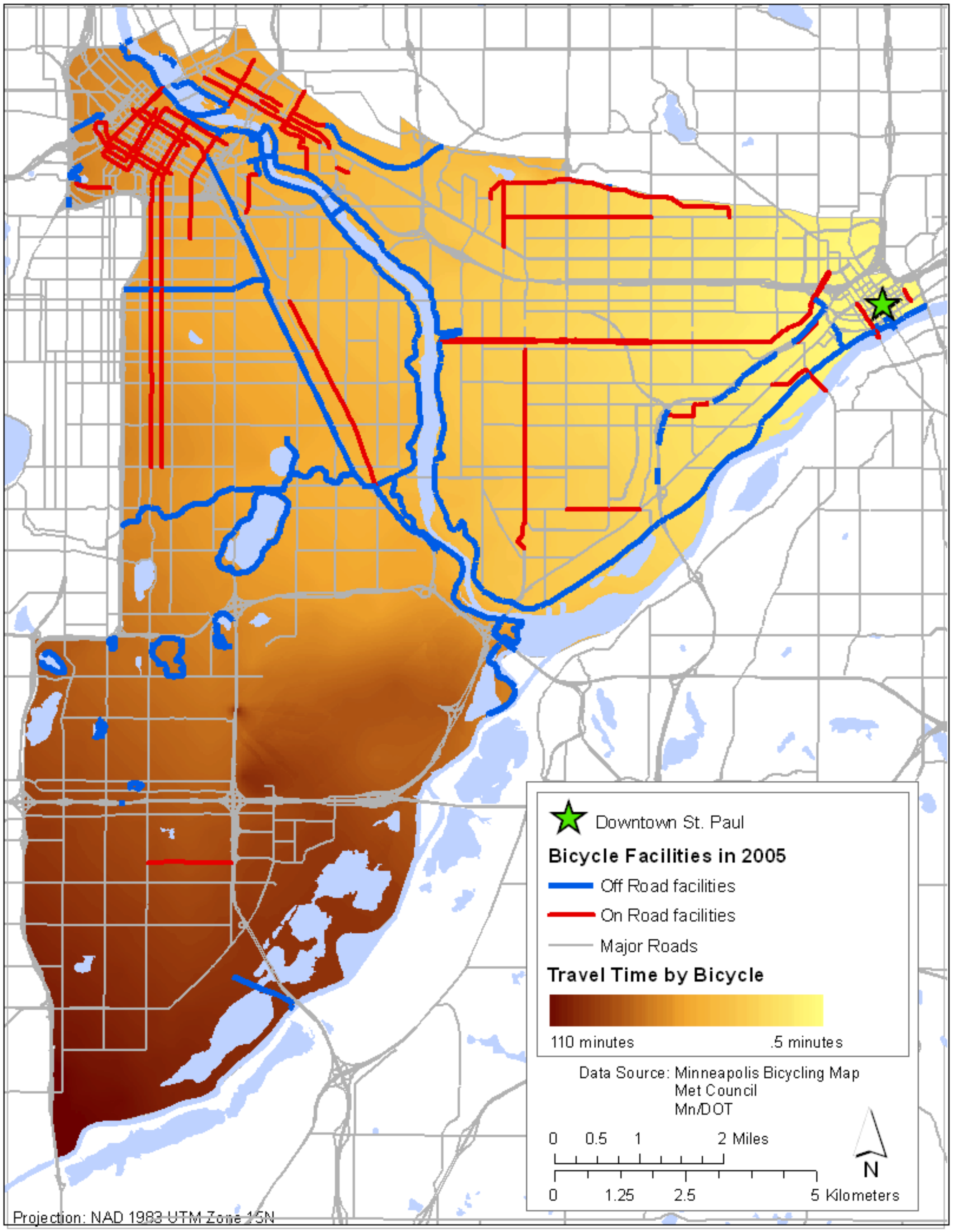

Figure 61. Bicycling travel time shed from downtown St. Paul in 2005

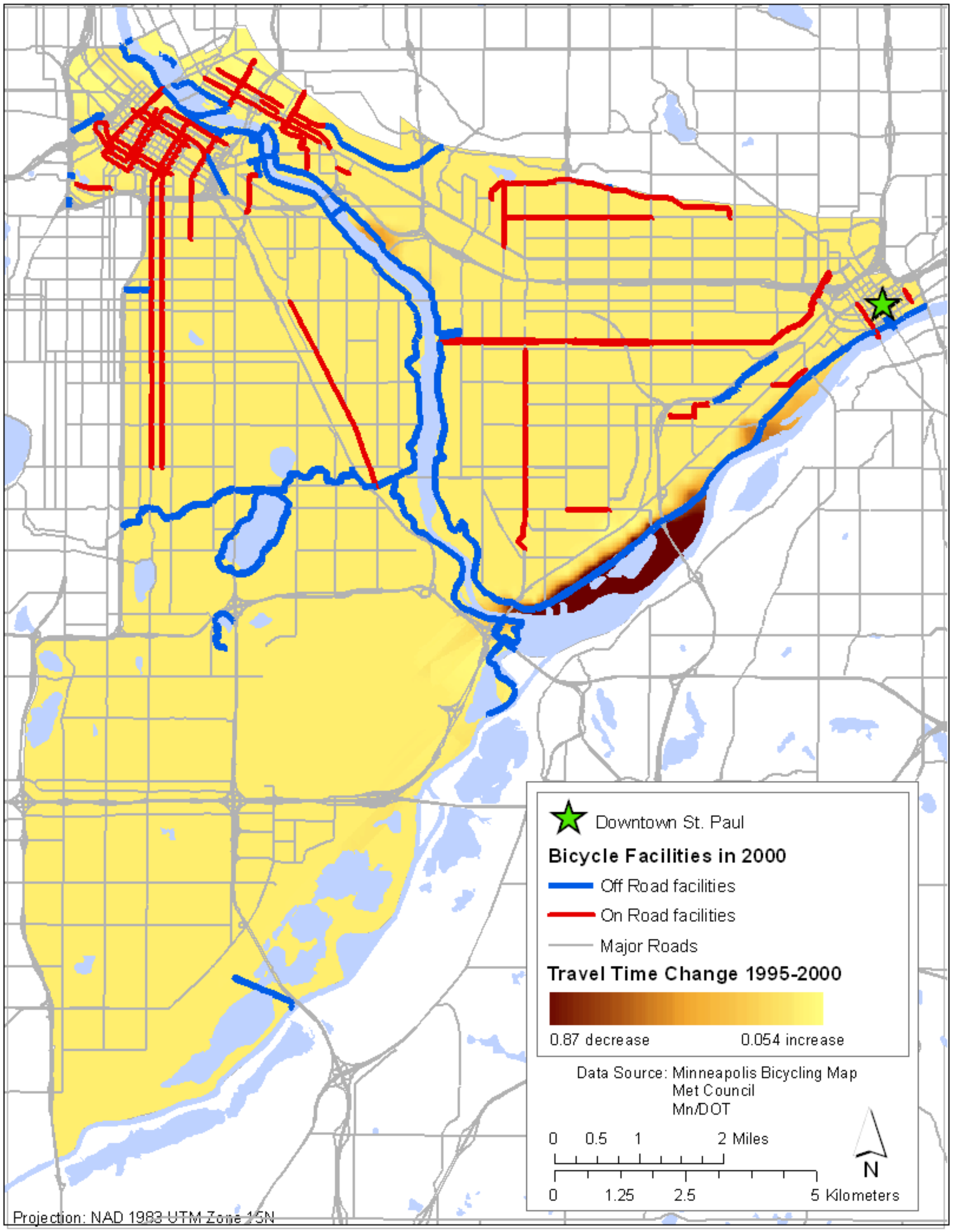

Figure 62. Change in bicycling travel time from downtown St. Paul between 1995 and 2000

Appendix F: Transit Maps

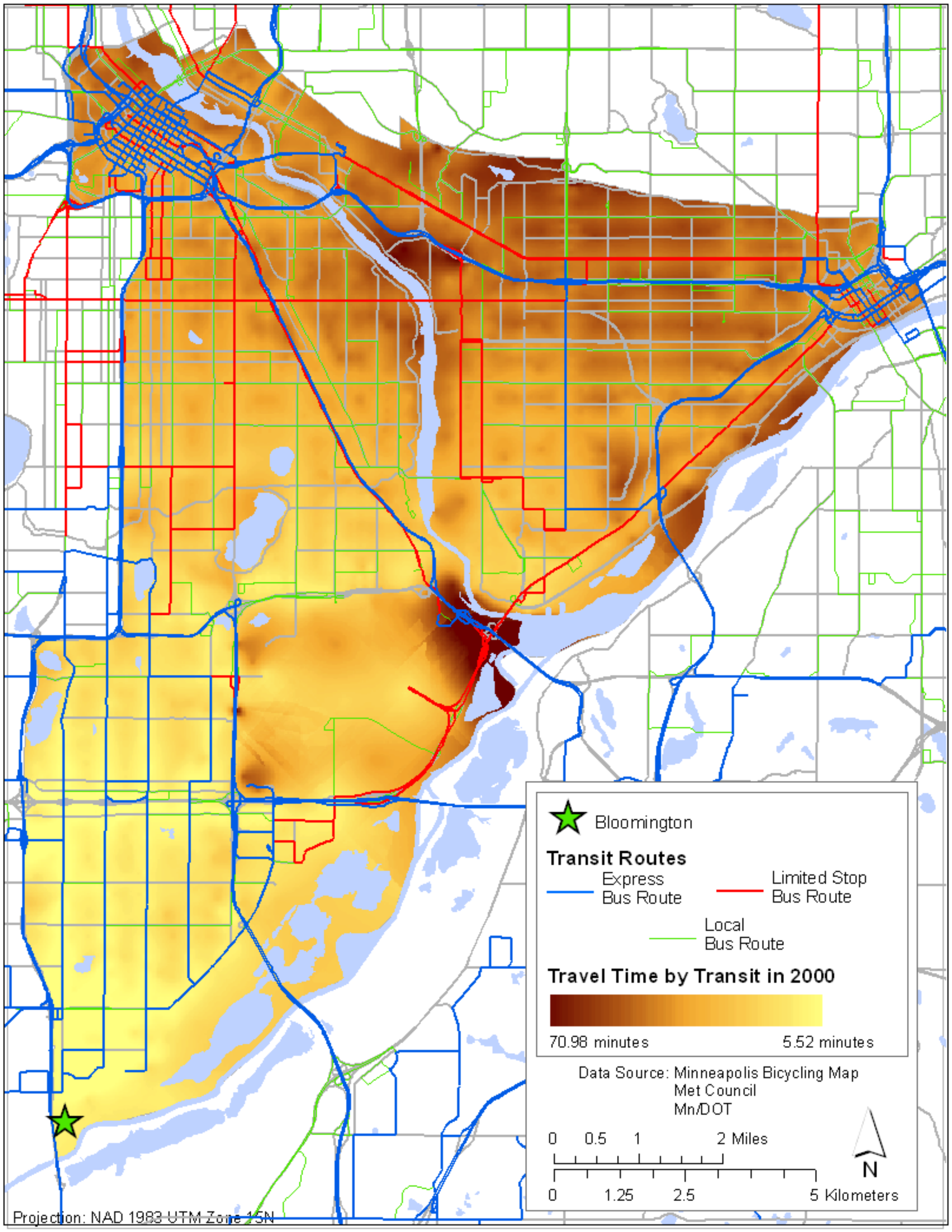

Figure 63. Transit travel time shed from Bloomington in 2000

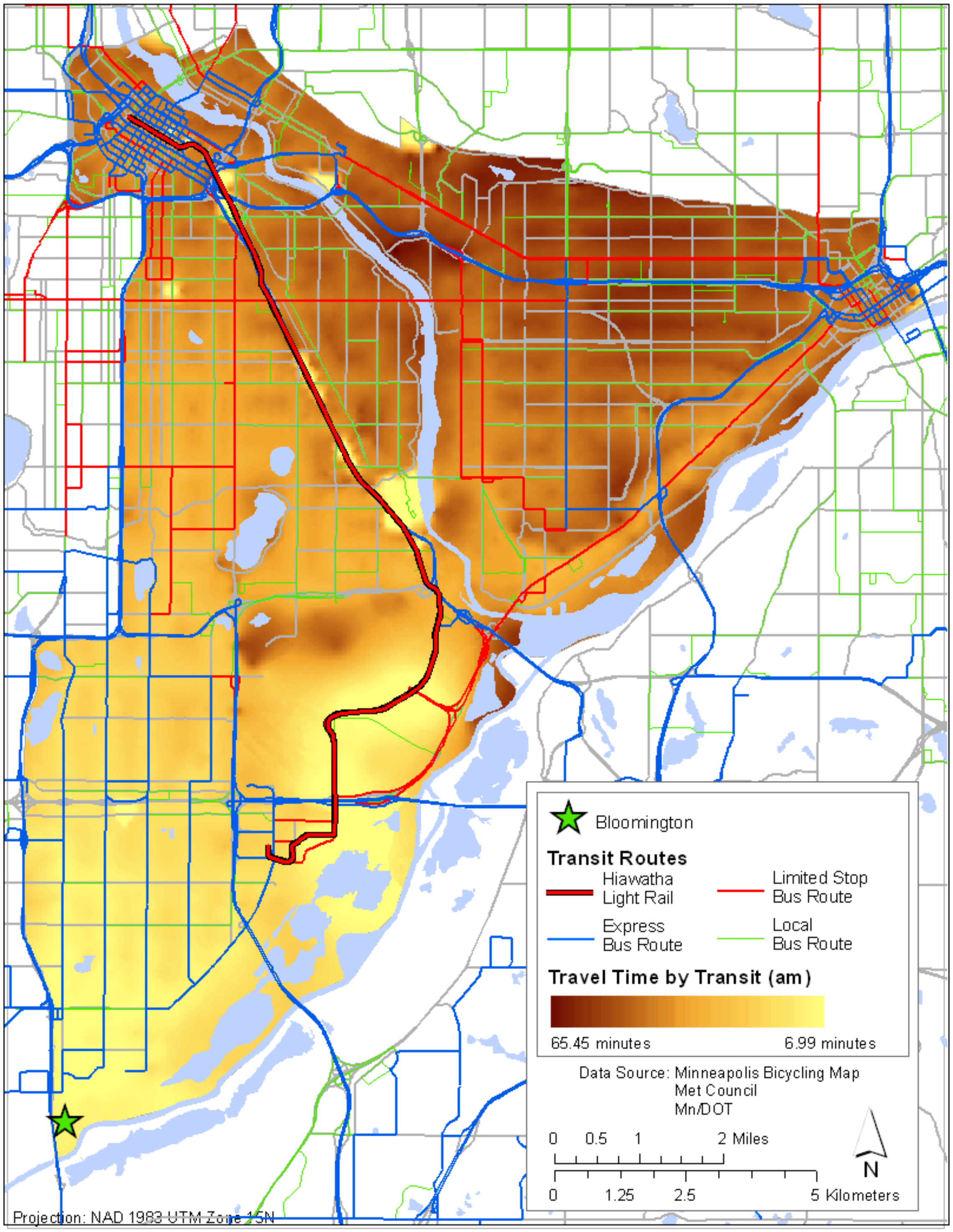

Figure 64. Transit travel time shed from Bloomington in 2005 (am)

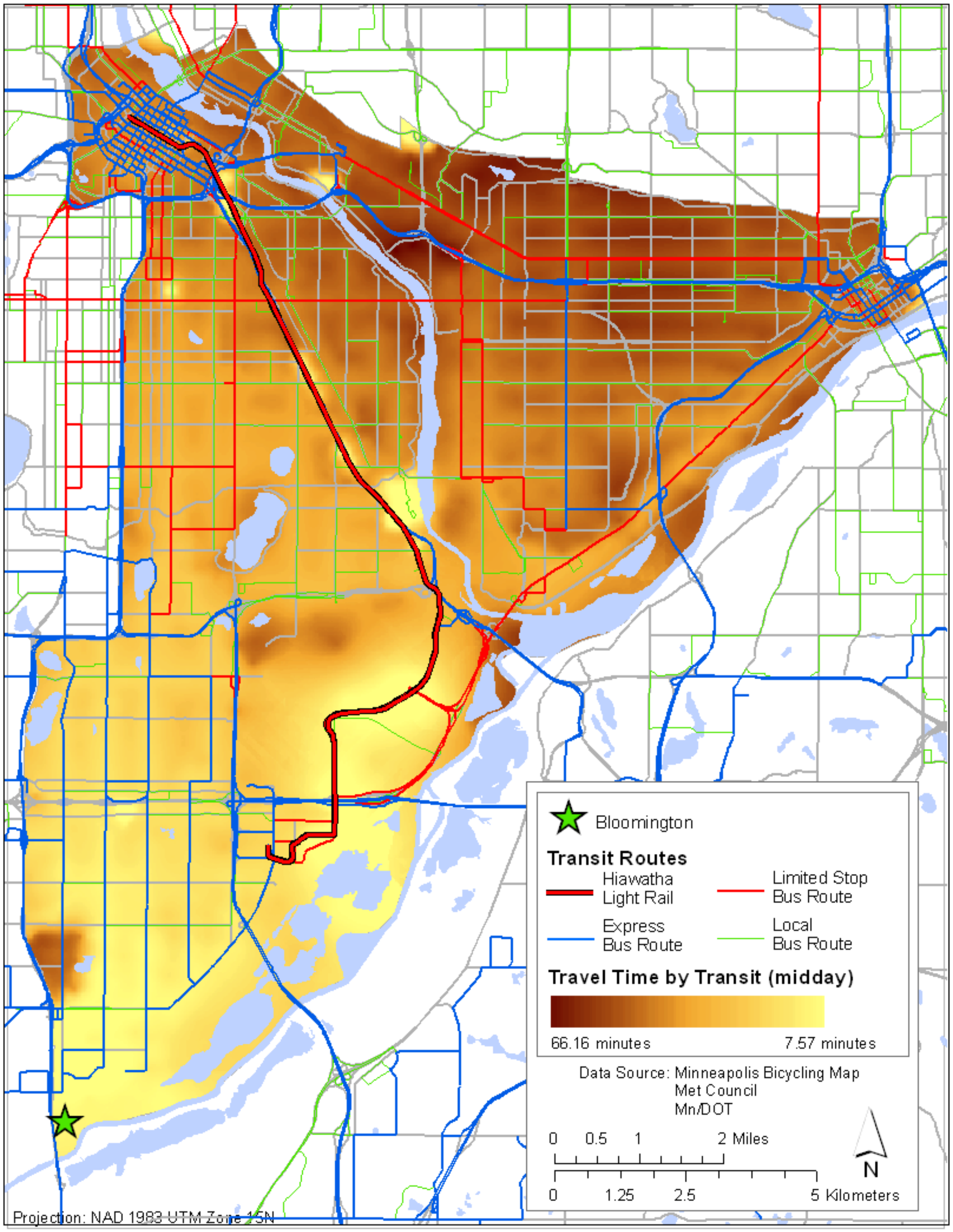

Figure 65. Transit travel time shed from Bloomington in 2005 (midday)

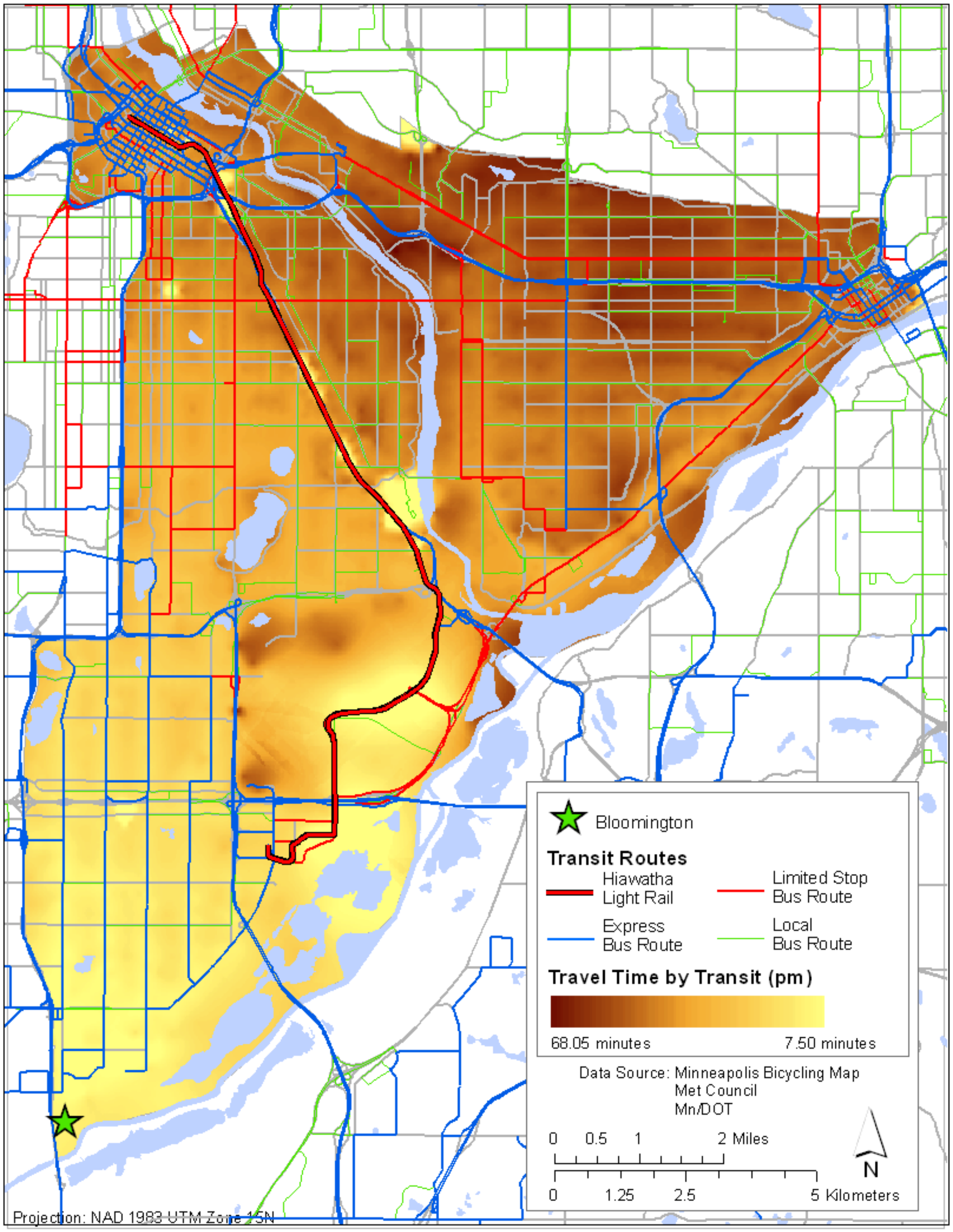

Figure 66. Transit travel time shed from Bloomington in 2005 (pm)

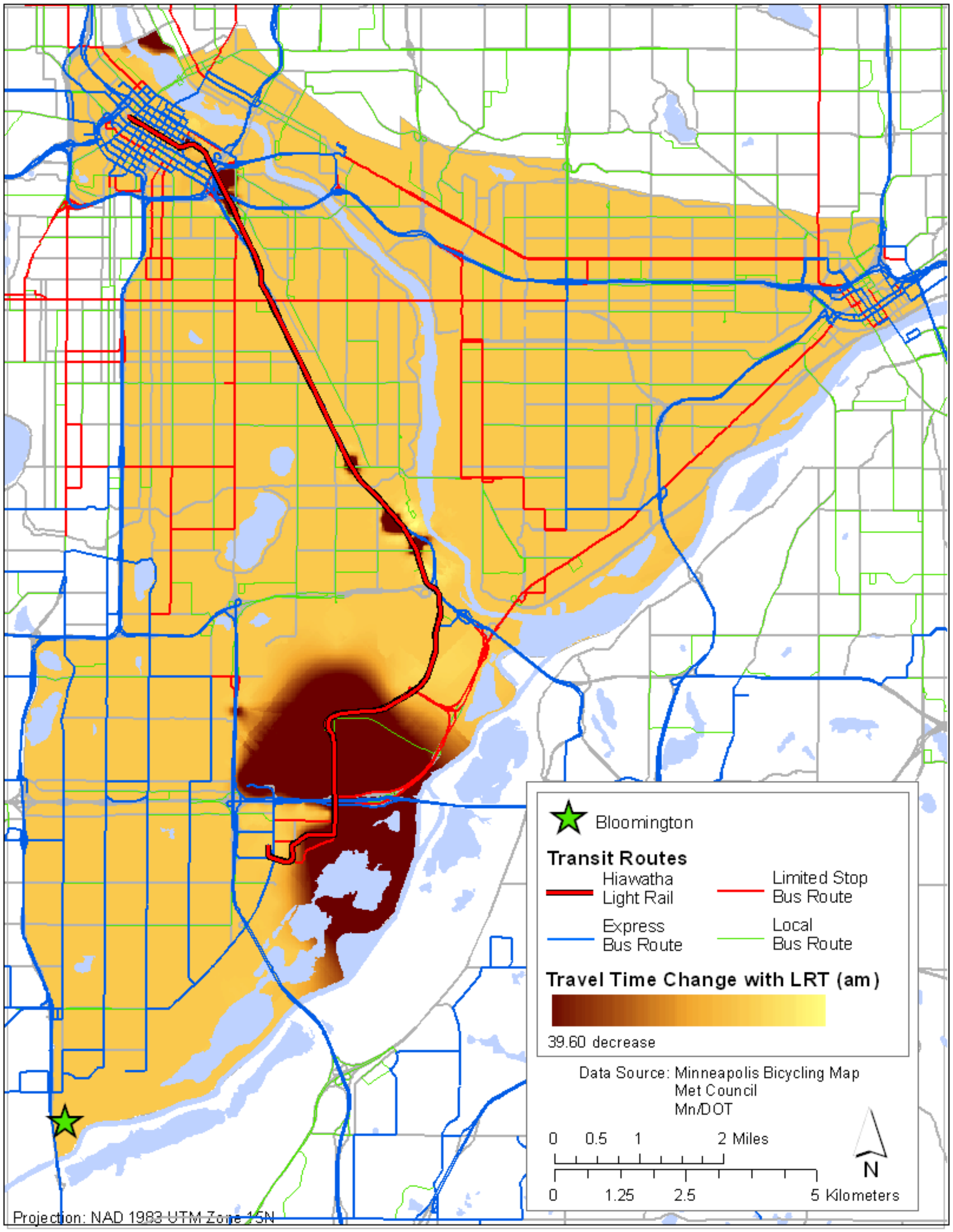

Figure 67. Change in transit travel time from Bloomington with LRT (am)

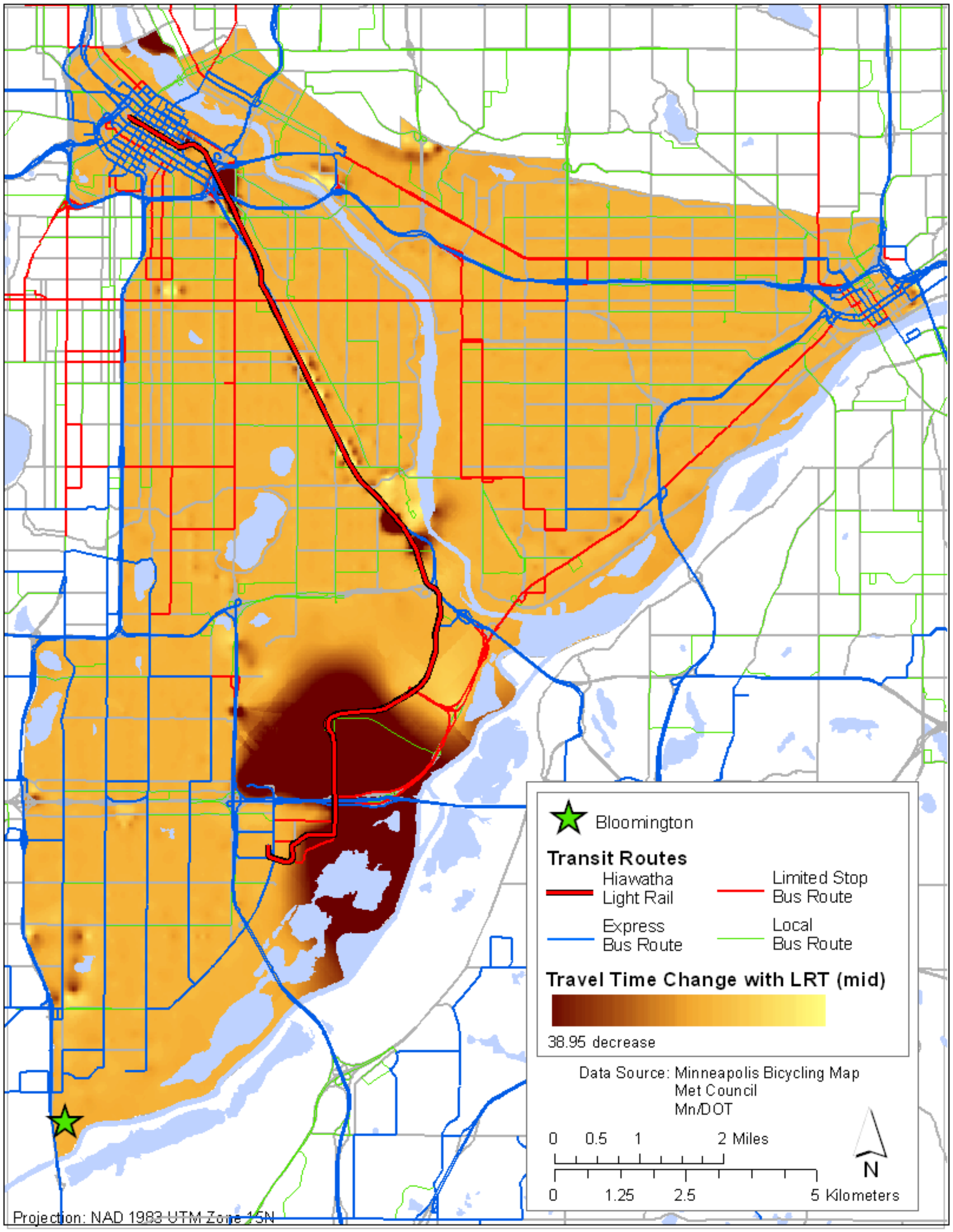

Figure 68. Change in transit travel time from Bloomington with LRT (midday)

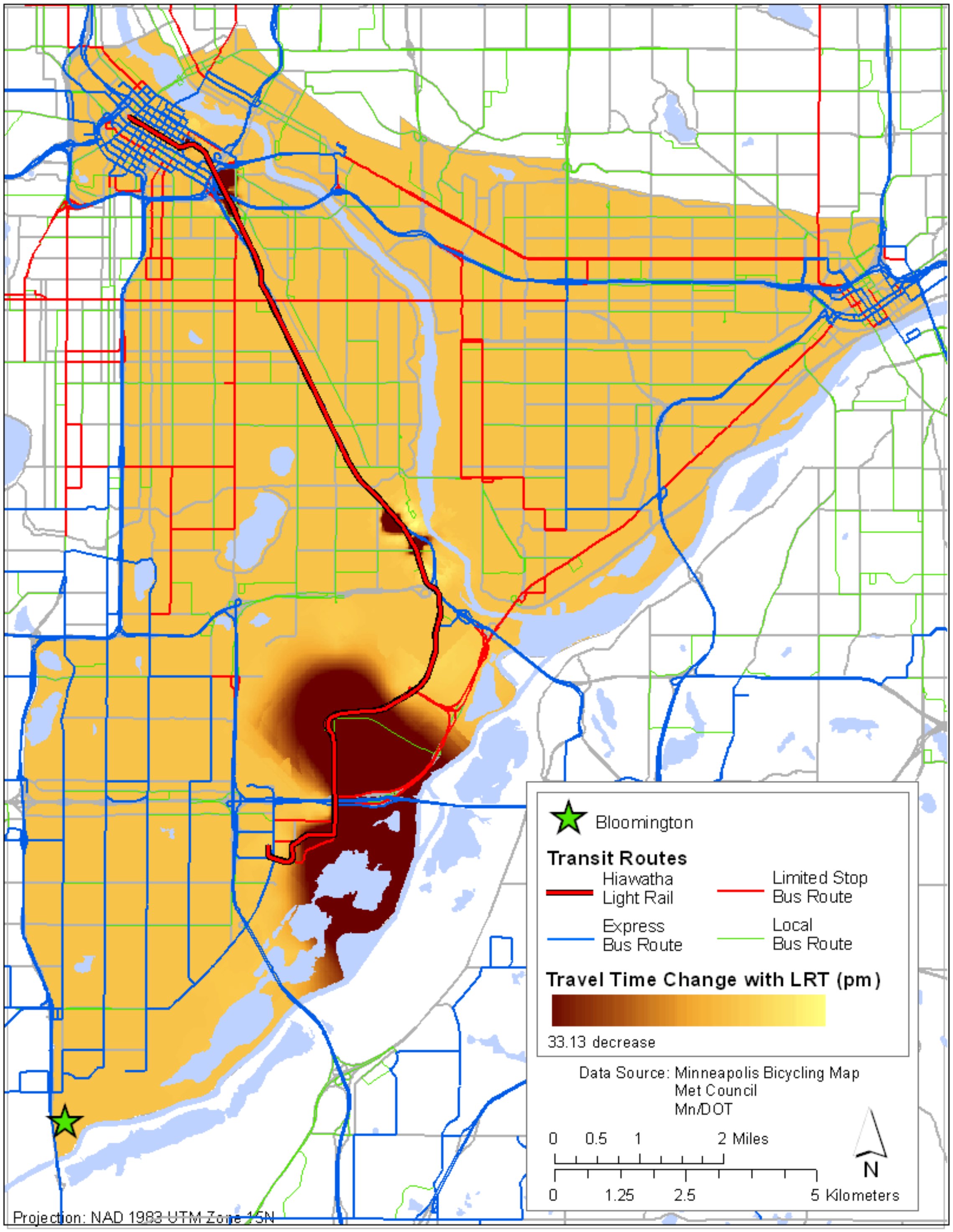

Figure 69. Change in transit travel time from Bloomington with LRT (pm)

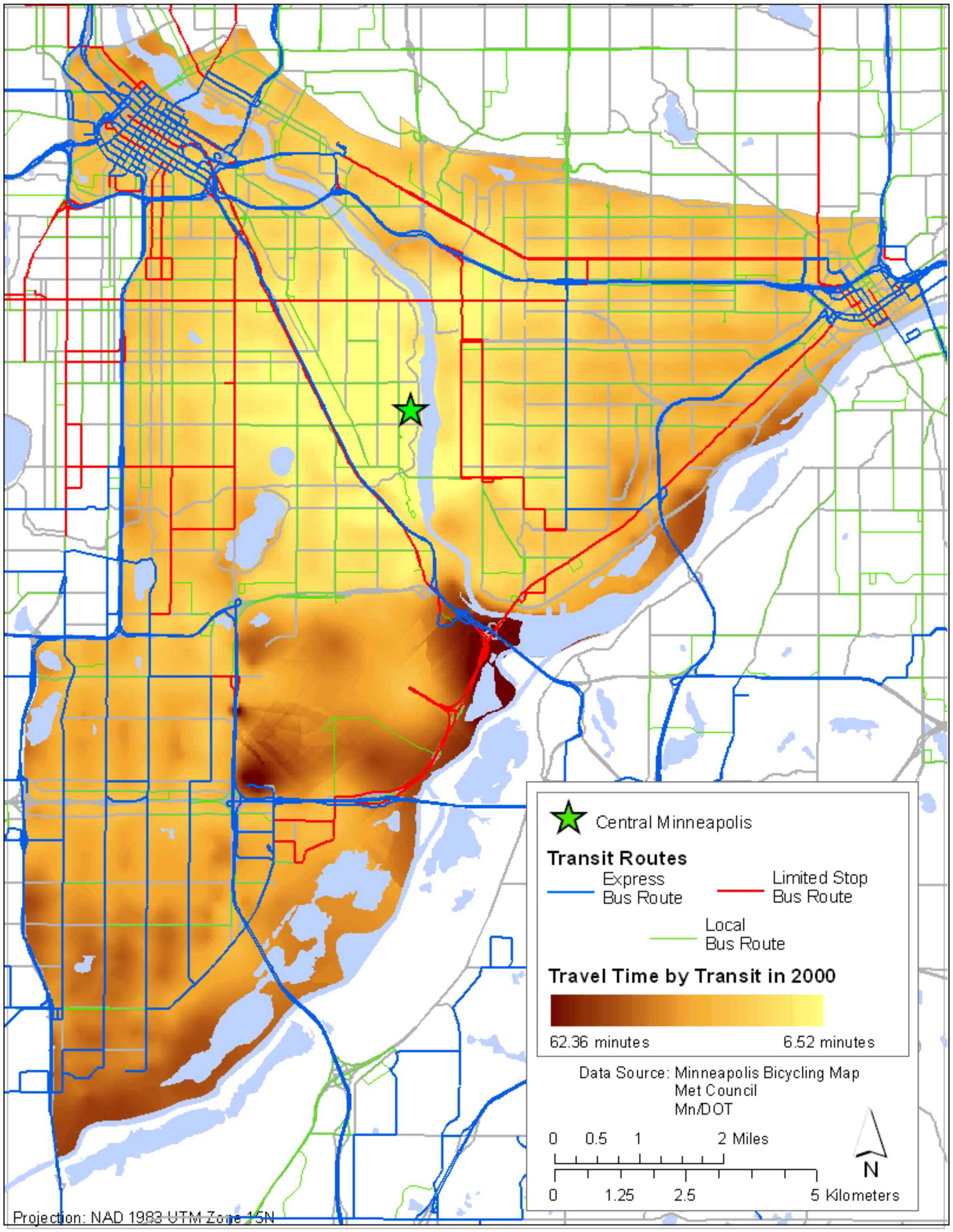

Figure 70. Transit travel time shed from central Minneapolis in 2000

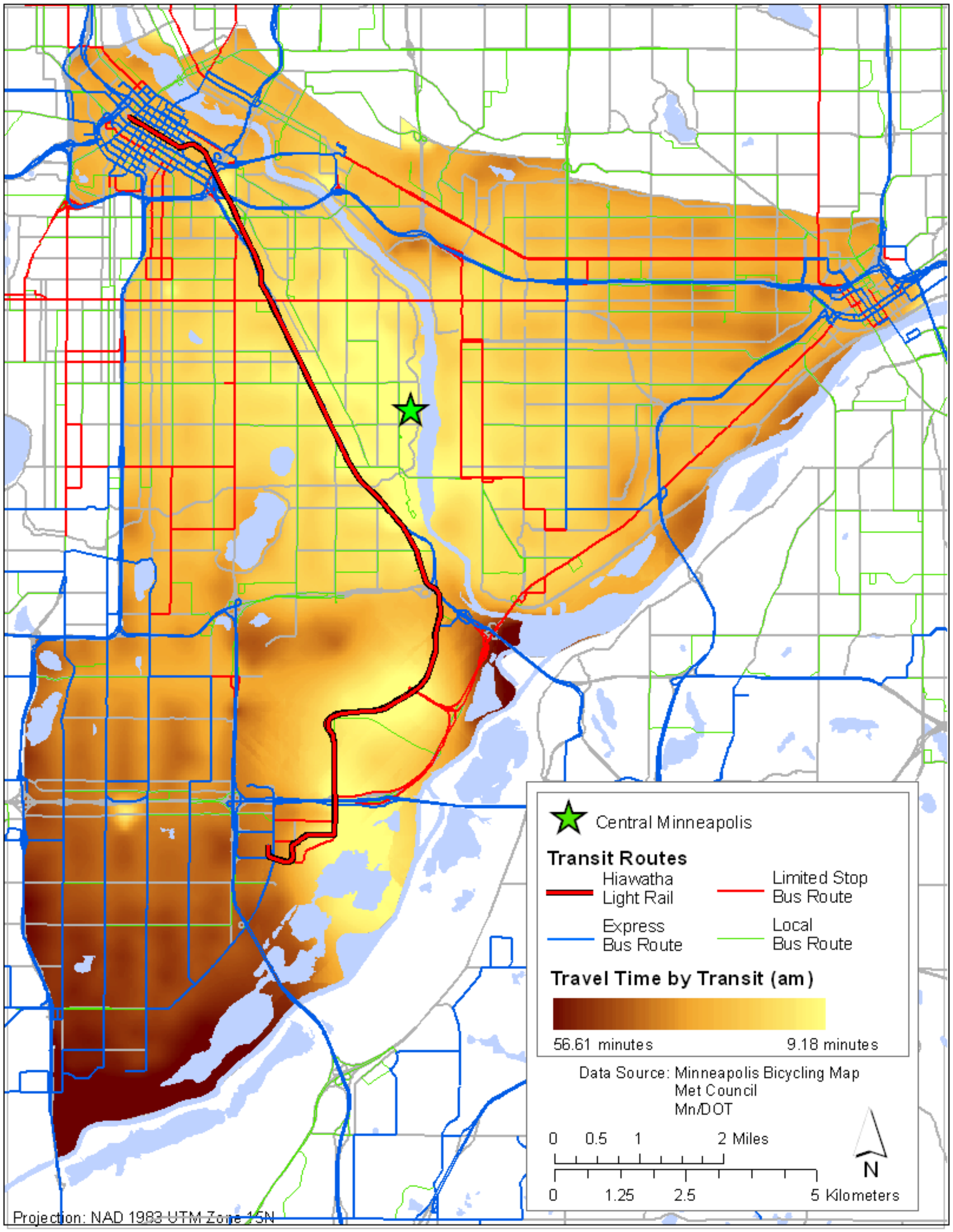

Figure 71. Transit travel time shed from central Minneapolis in 2005 (am)

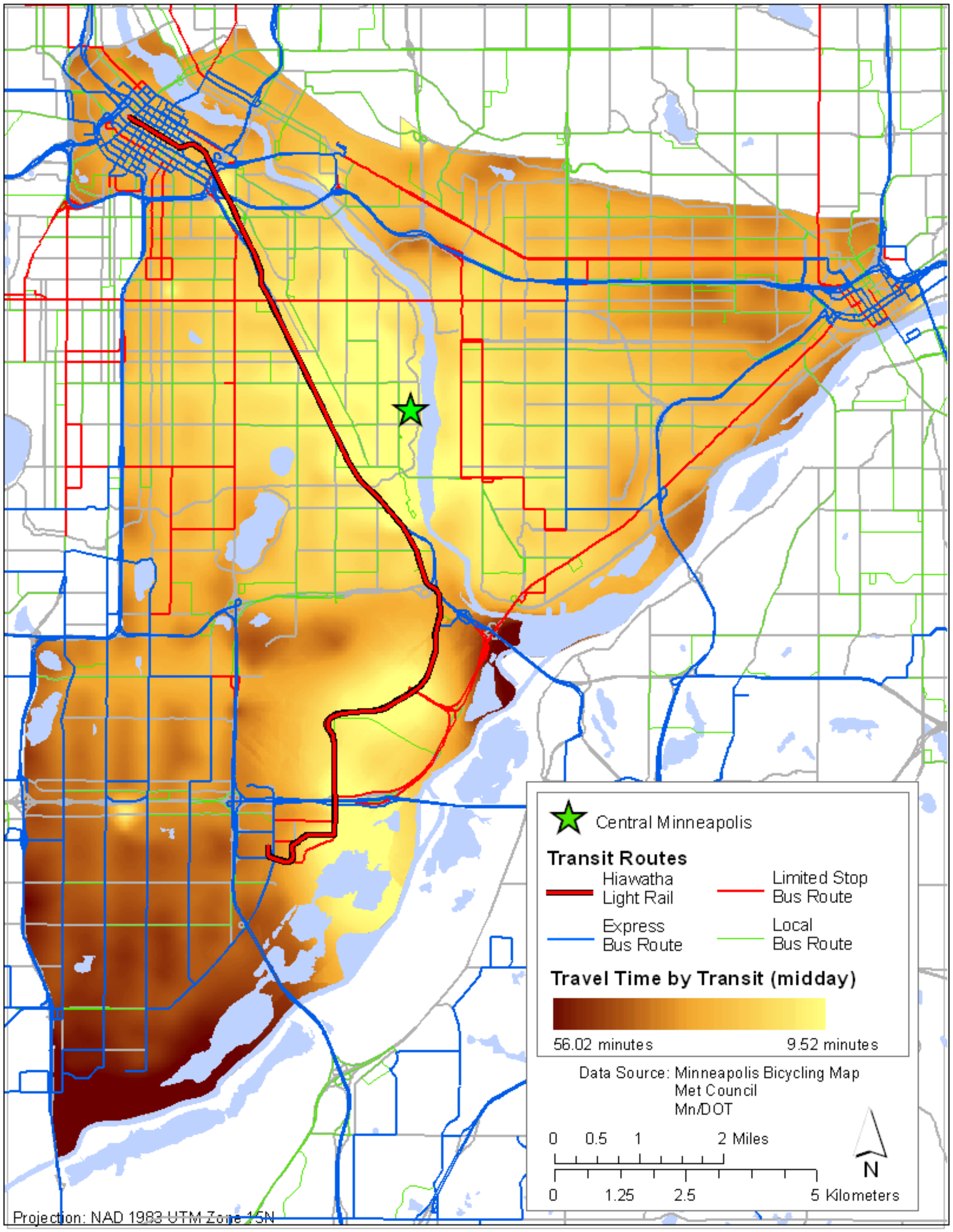

Figure 72. Transit travel time shed from central Minneapolis in 2005 (midday)

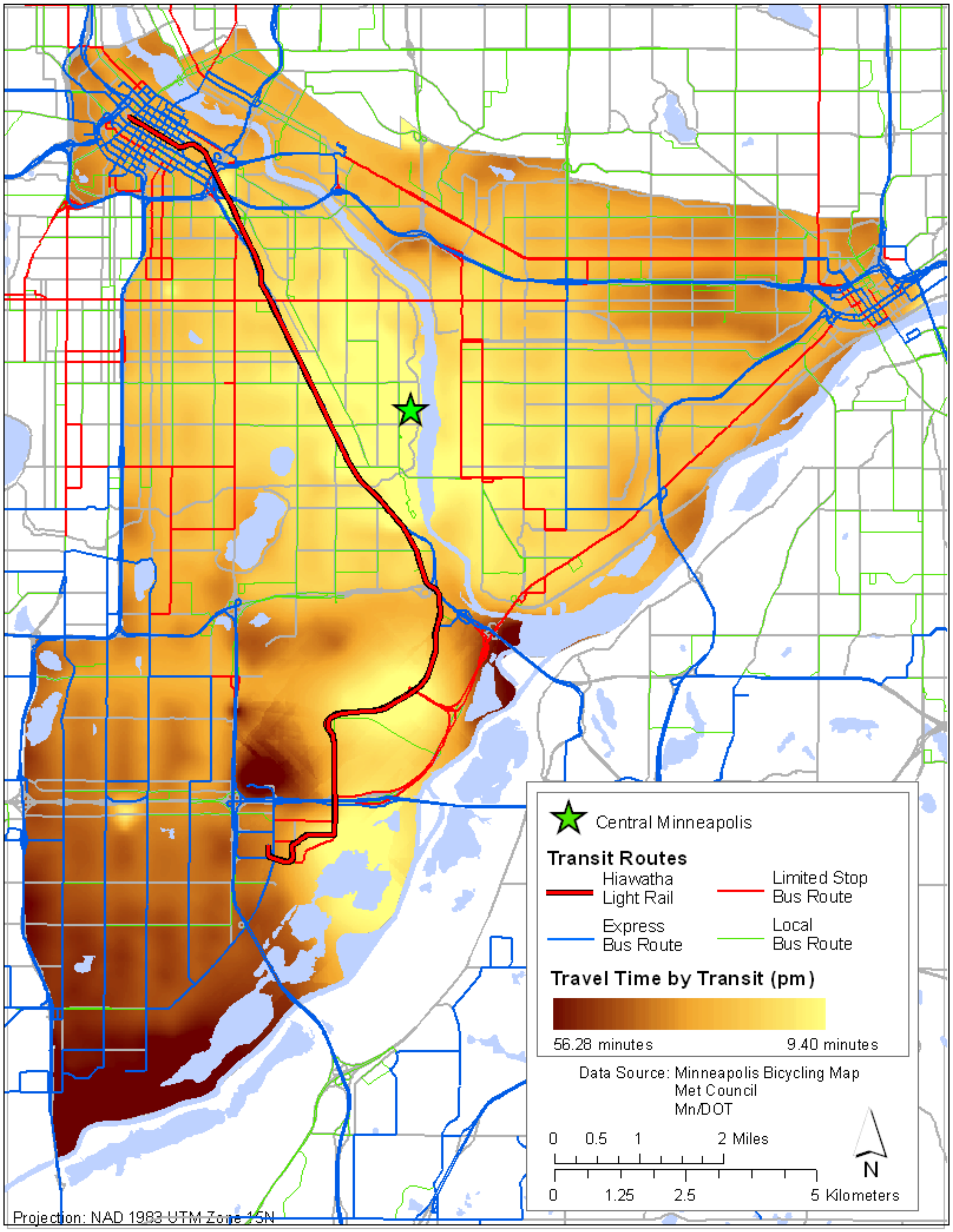

Figure 73. Transit travel time shed from central Minneapolis in 2005 (pm)

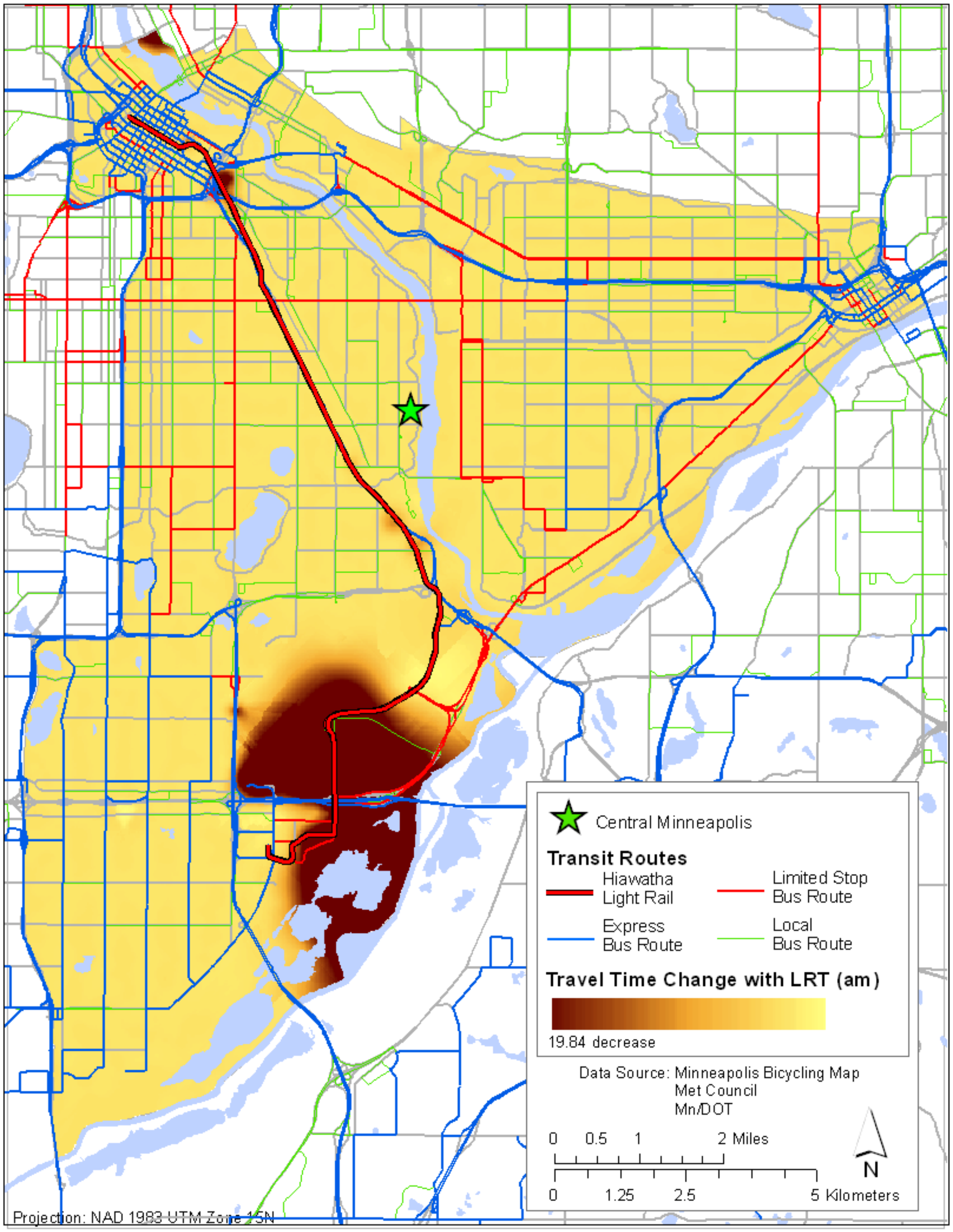

Figure 74. Change in transit travel time from central Minneapolis with LRT (am)

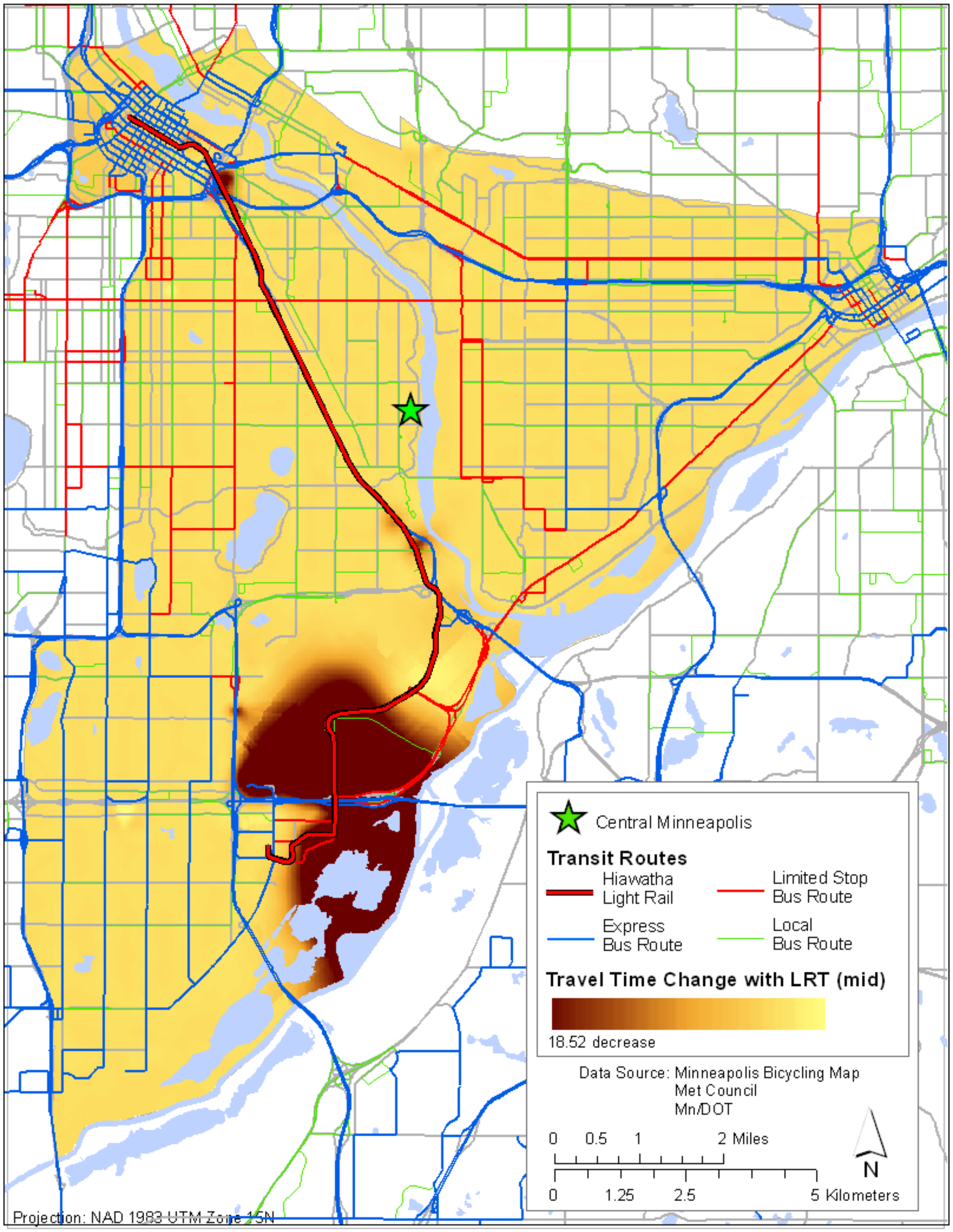

Figure 75. Change in transit travel time from central Minneapolis with LRT (midday)

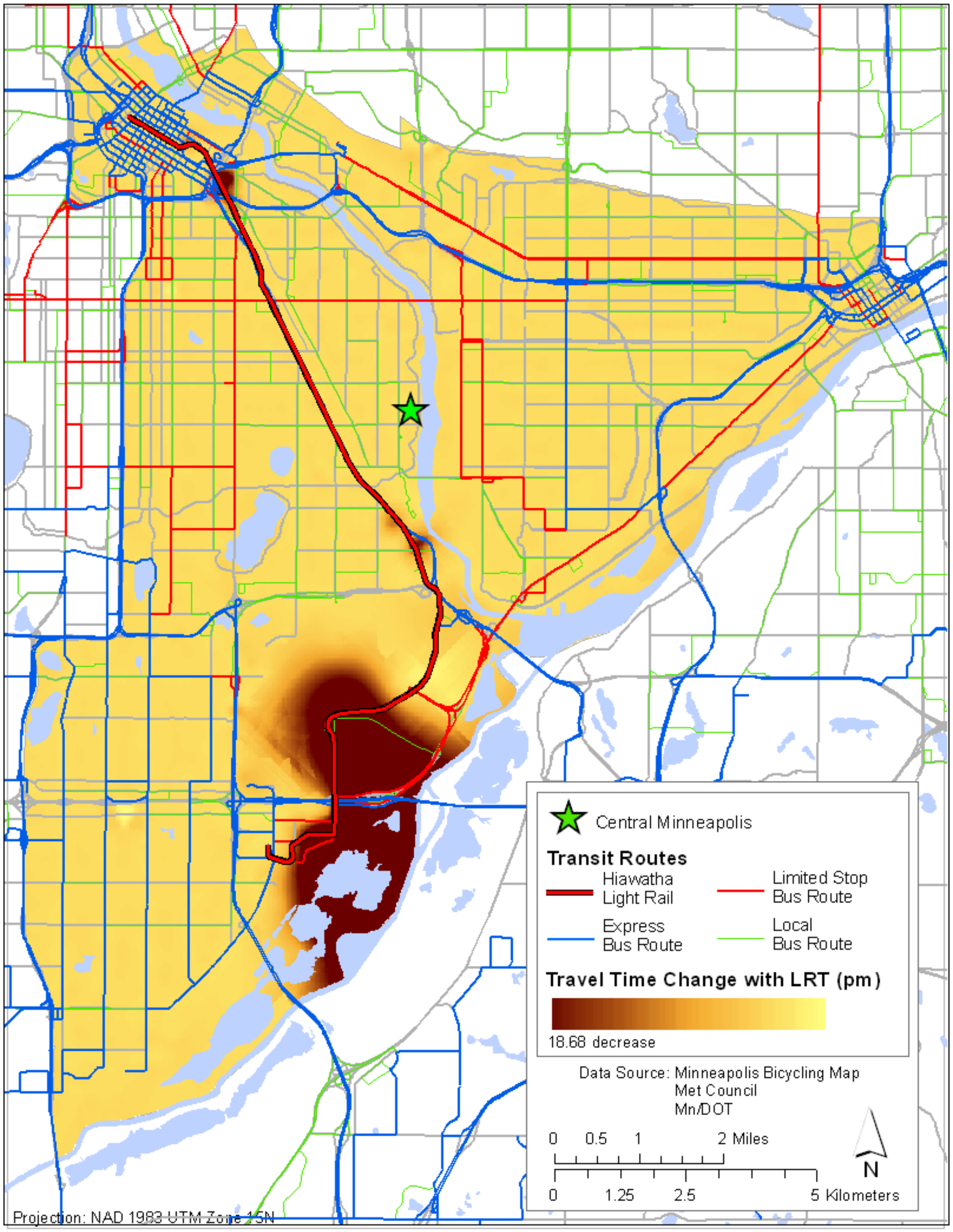

Figure 76. Change in transit travel time from central Minneapolis with LRT (pm)

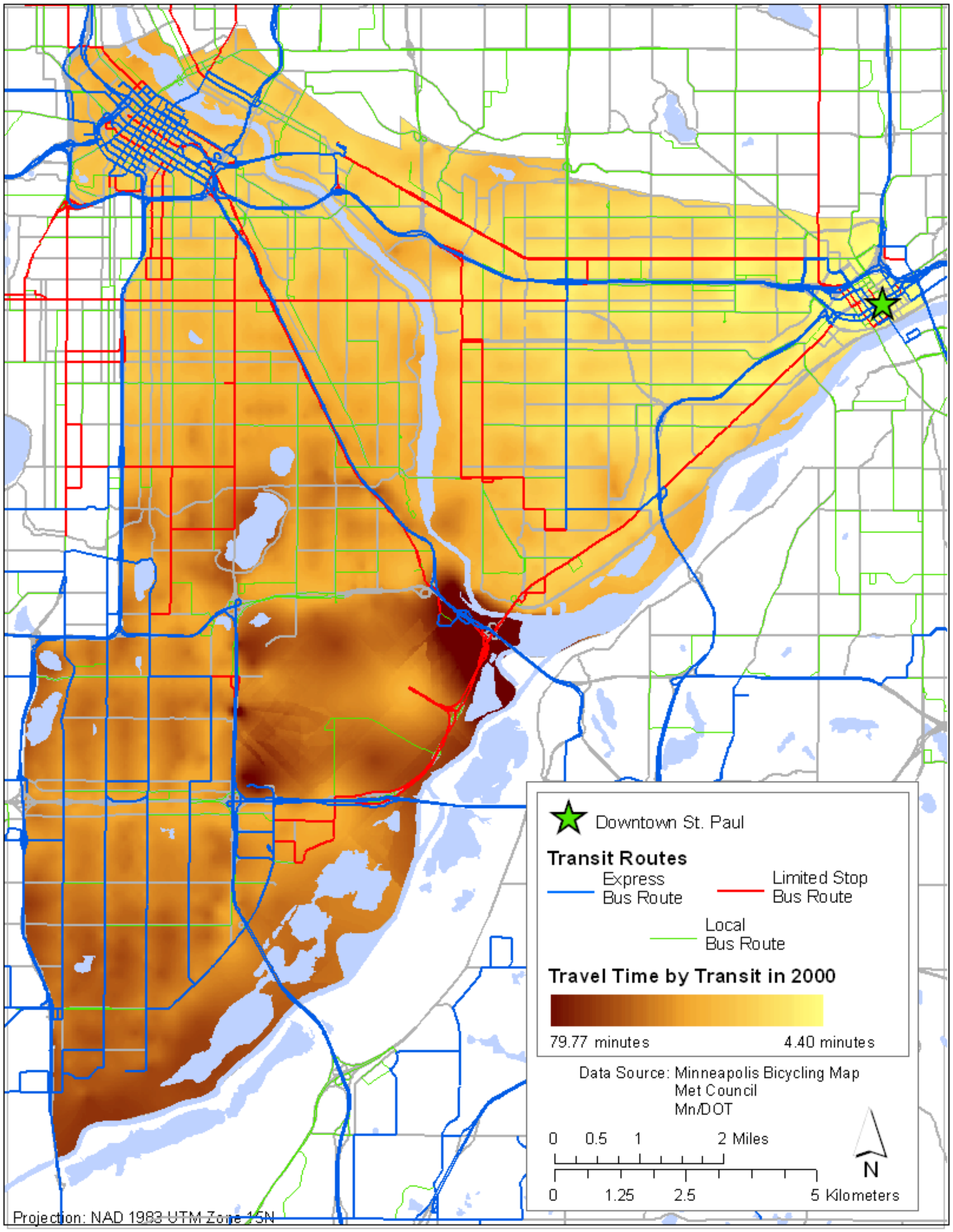

Figure 77. Transit travel shed from downtown St. Paul in 2000

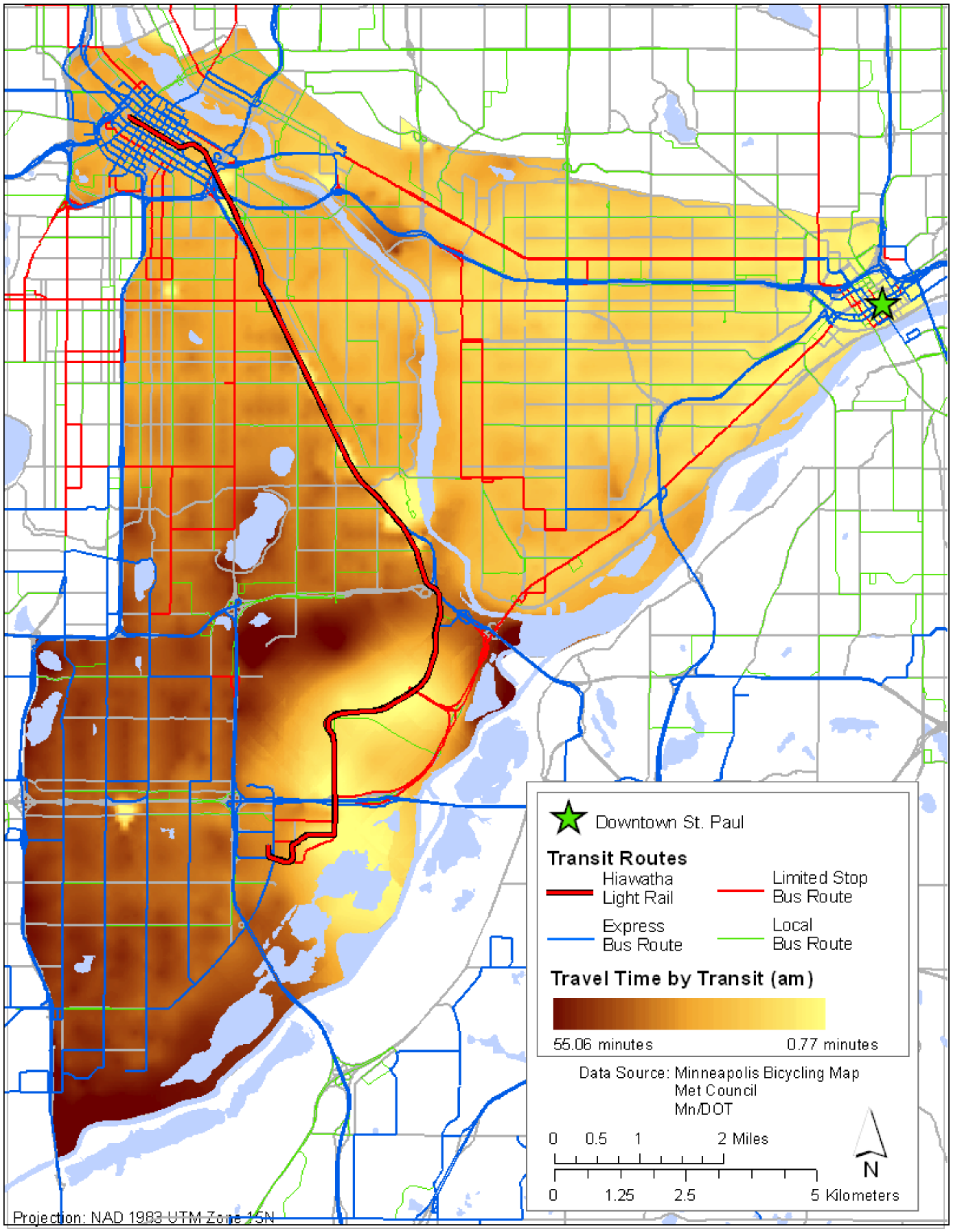

Figure 78. Transit travel shed from downtown St. Paul in 2005 (am)

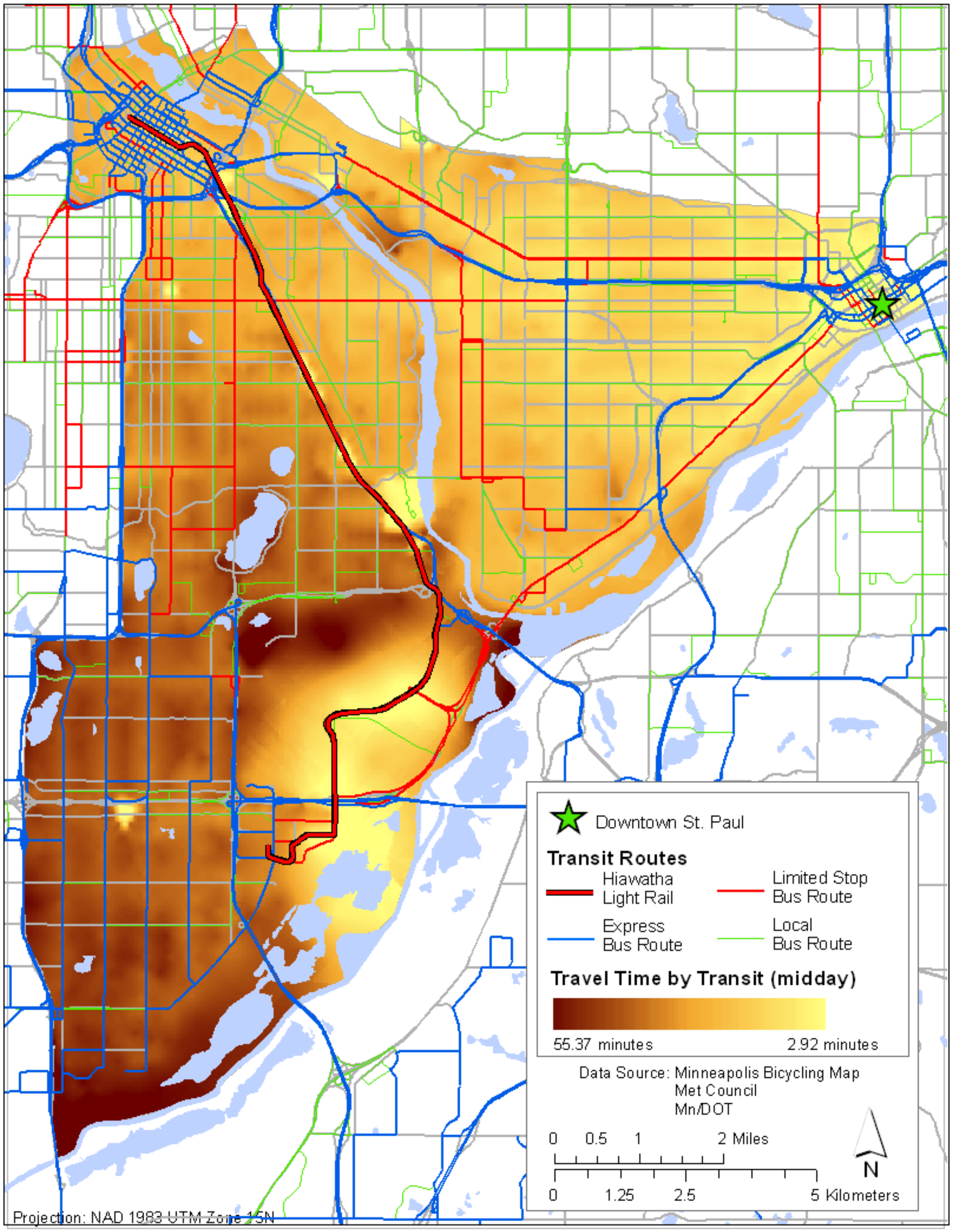

Figure 79. Transit travel shed from downtown St. Paul in 2005 (midday)

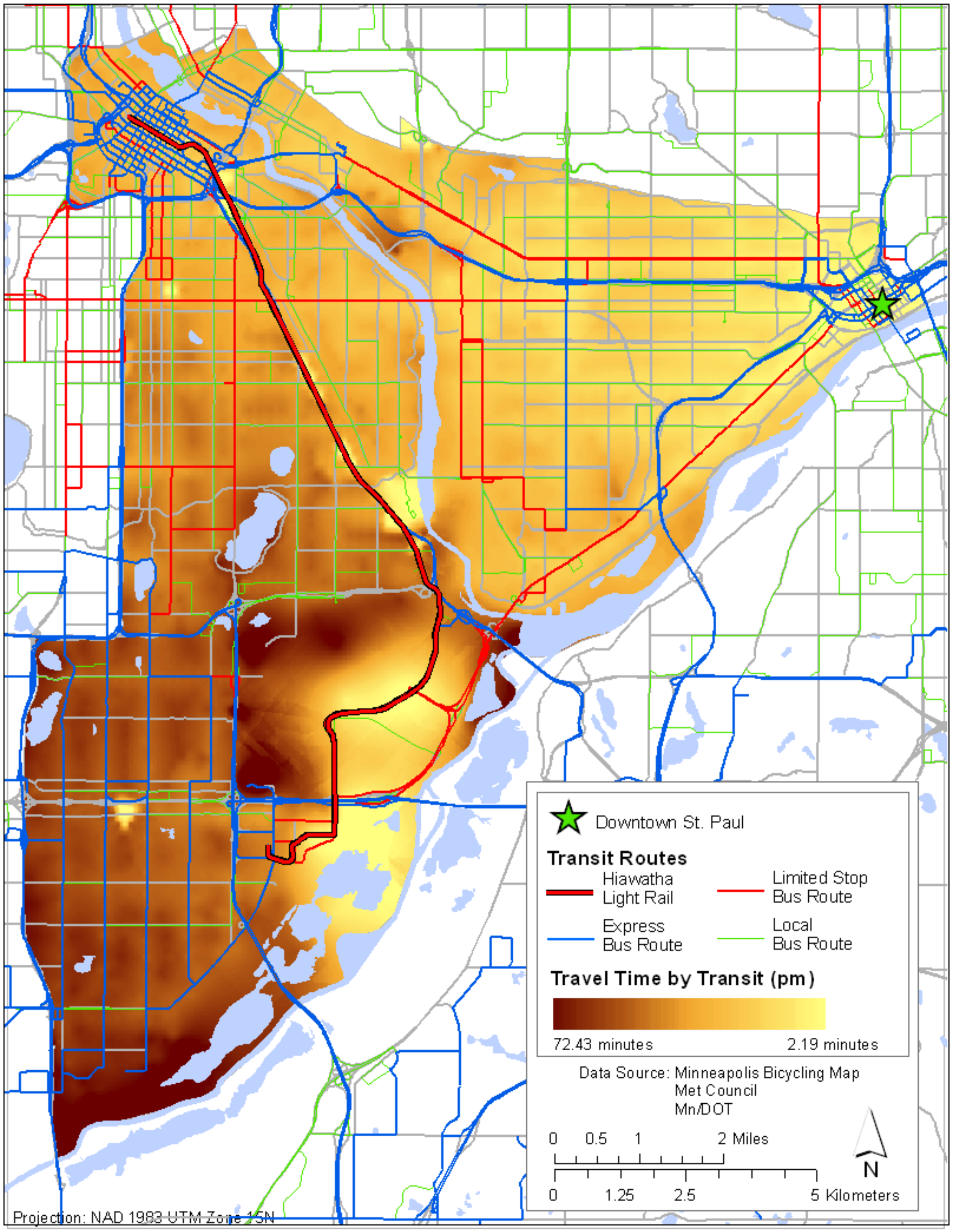

Figure 80. Transit travel shed from downtown St. Paul in 2005 (pm)

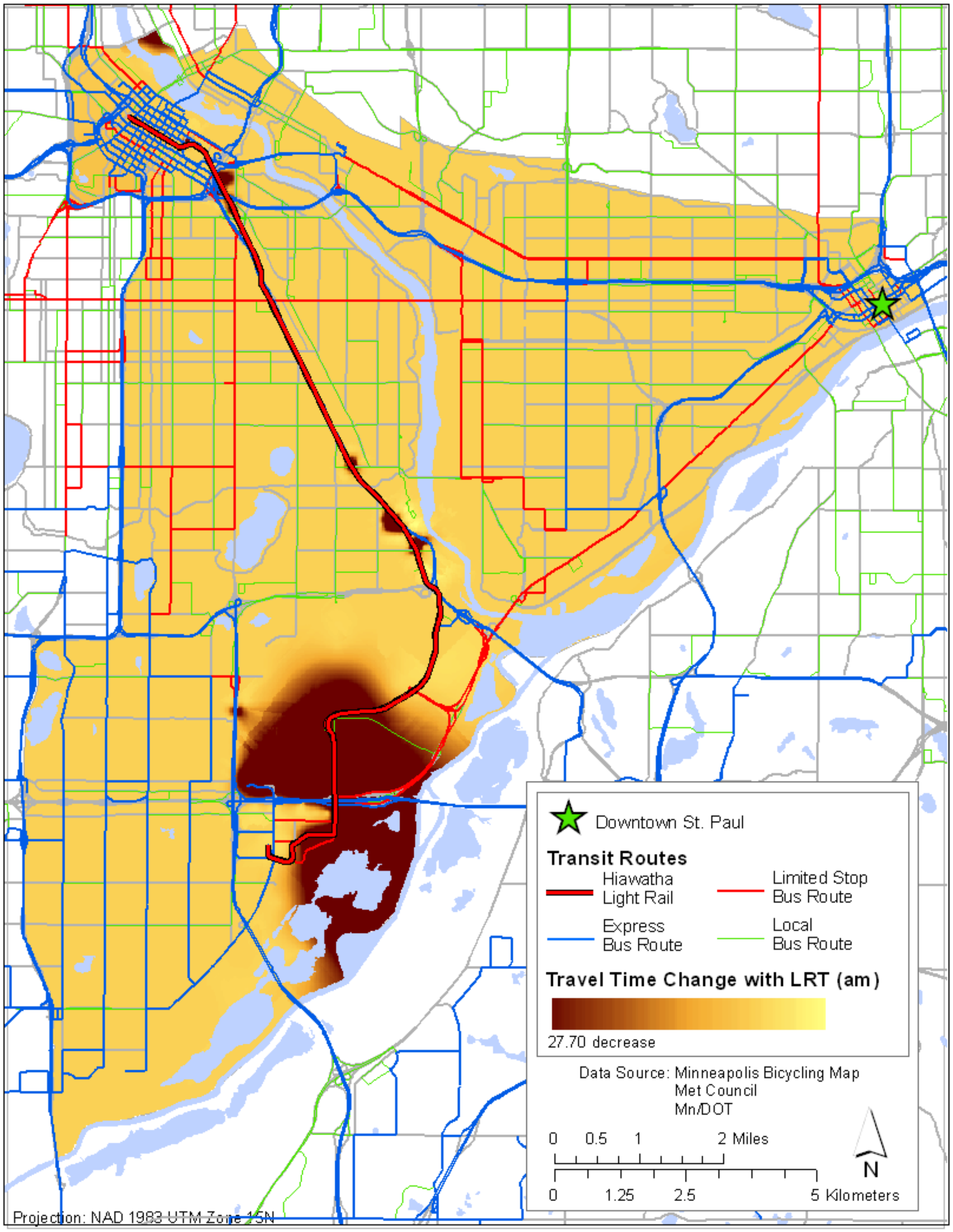

Figure 81. Change in transit travel time from downtown St. Paul with LRT (am)

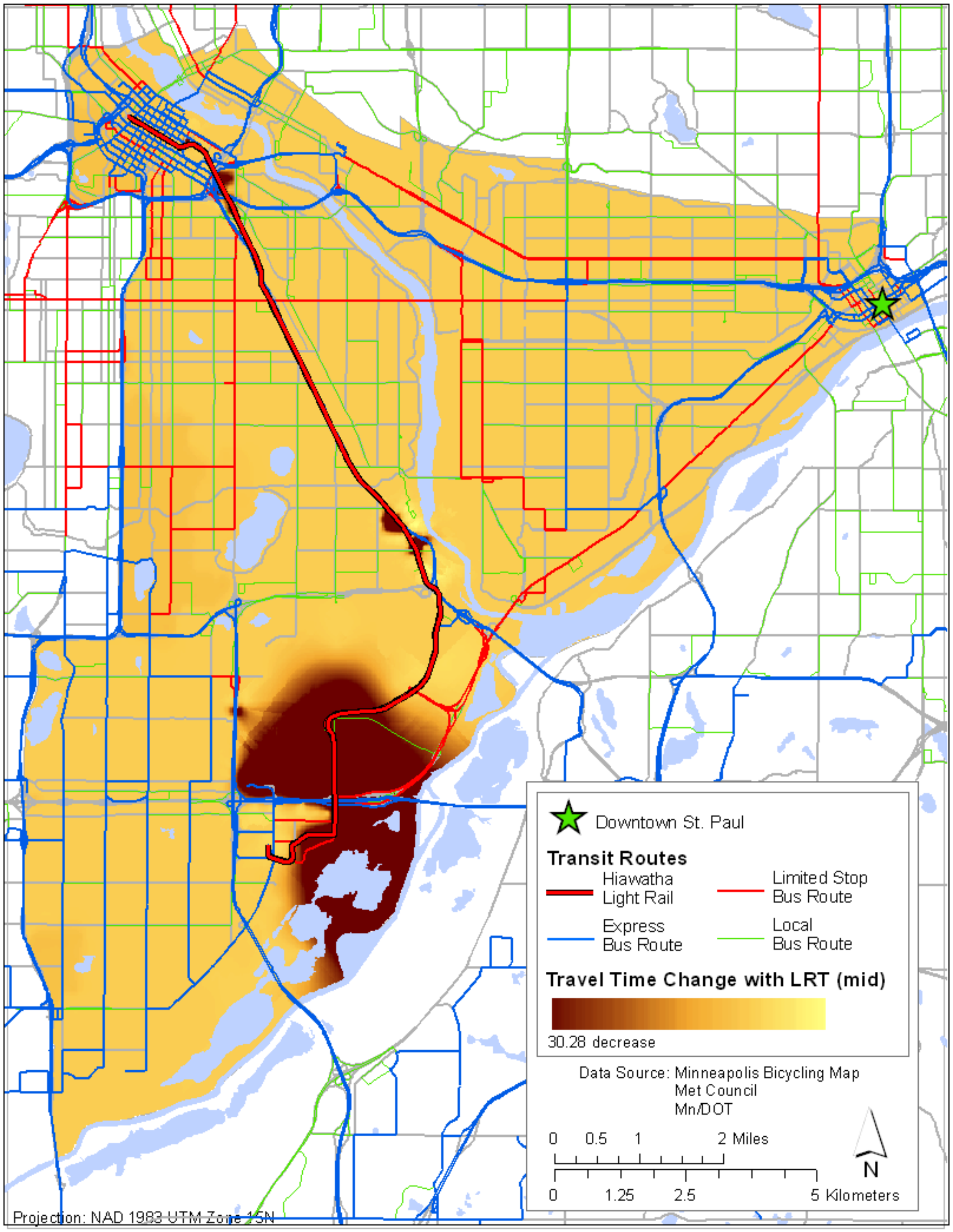

Figure 82. Change in transit travel time from downtown St. Paul with LRT (midday)

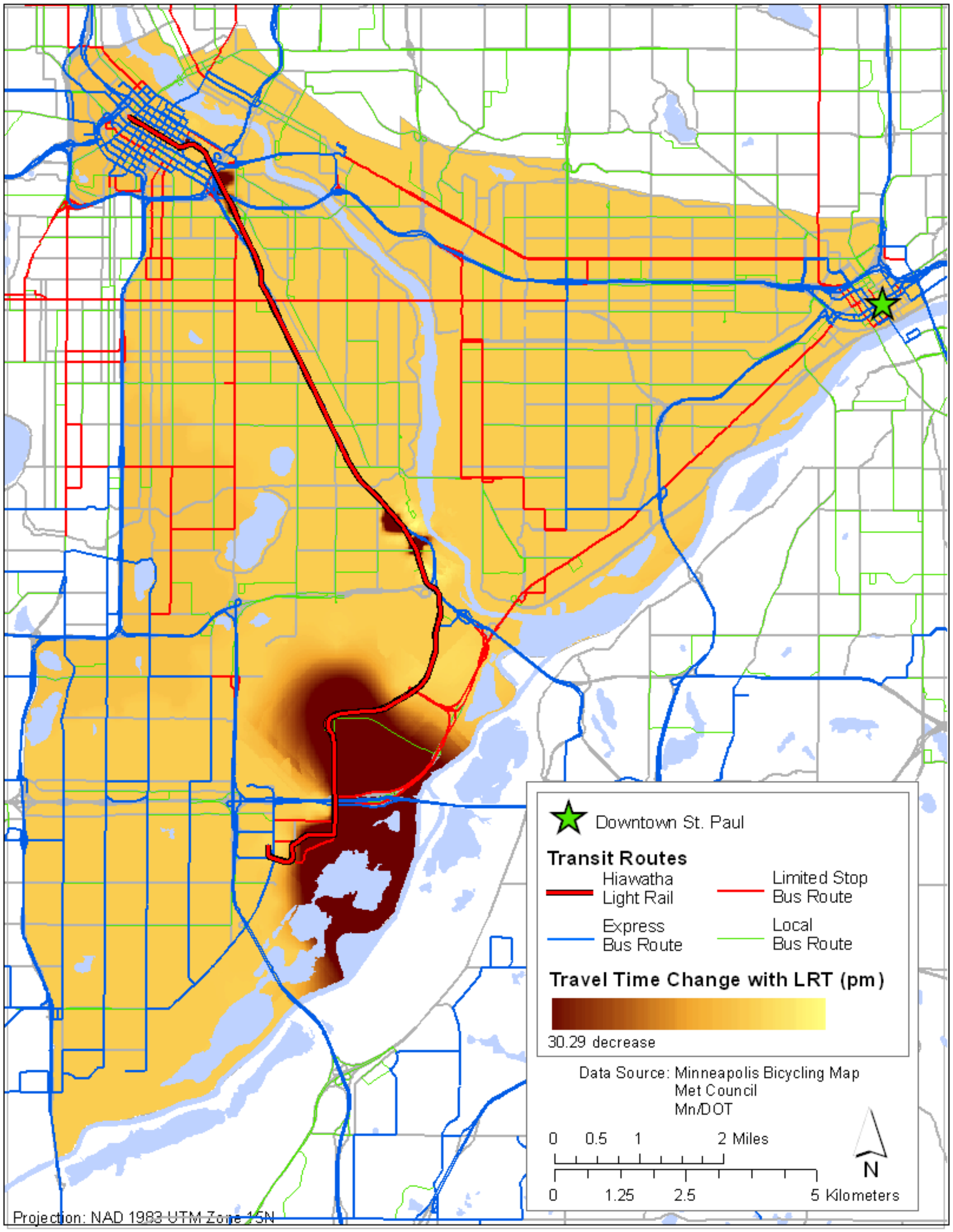

Figure 83. Change in transit travel time from downtown St. Paul with LRT (pm)

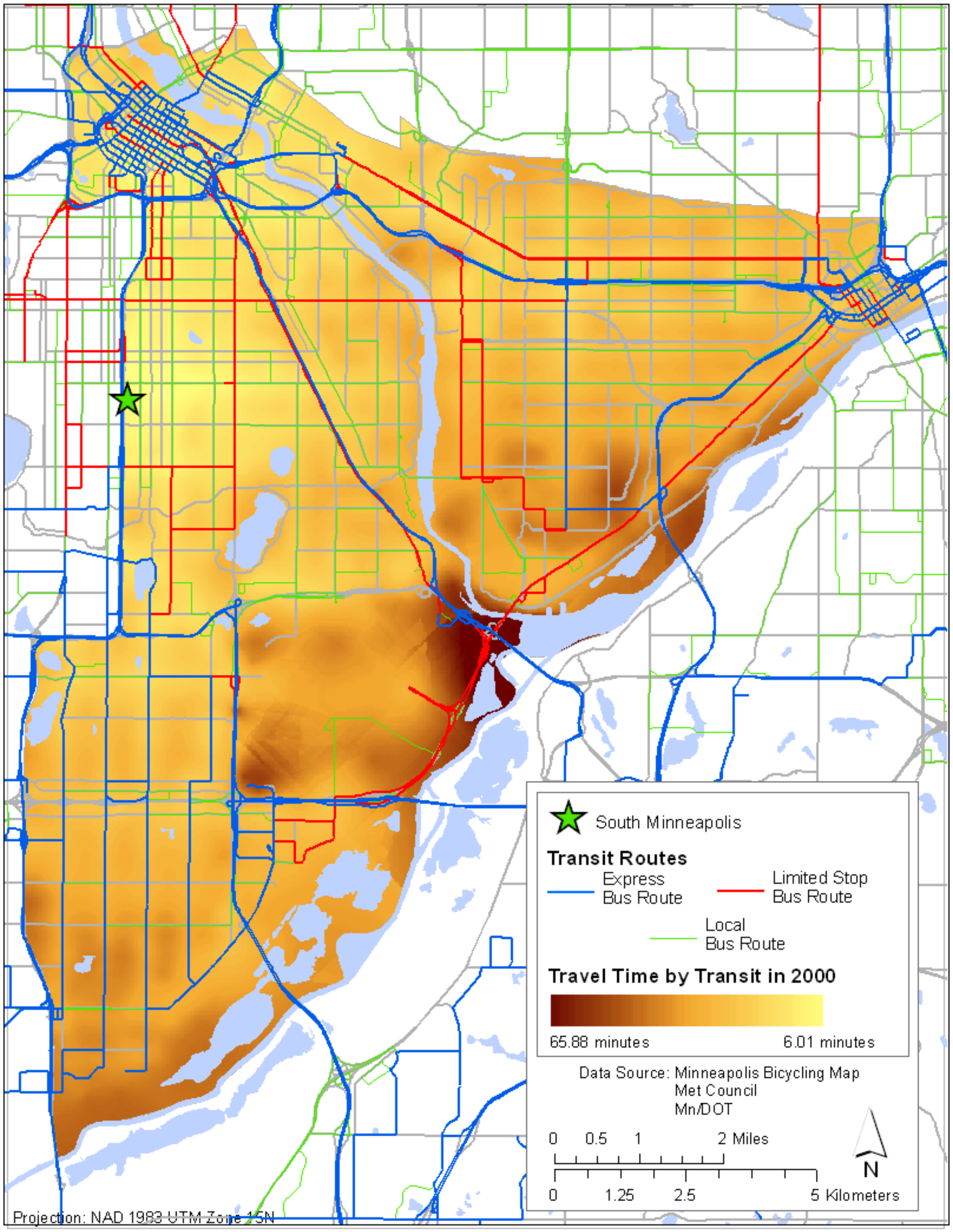

Figure 84. Transit travel shed from south Minneapolis in 2000

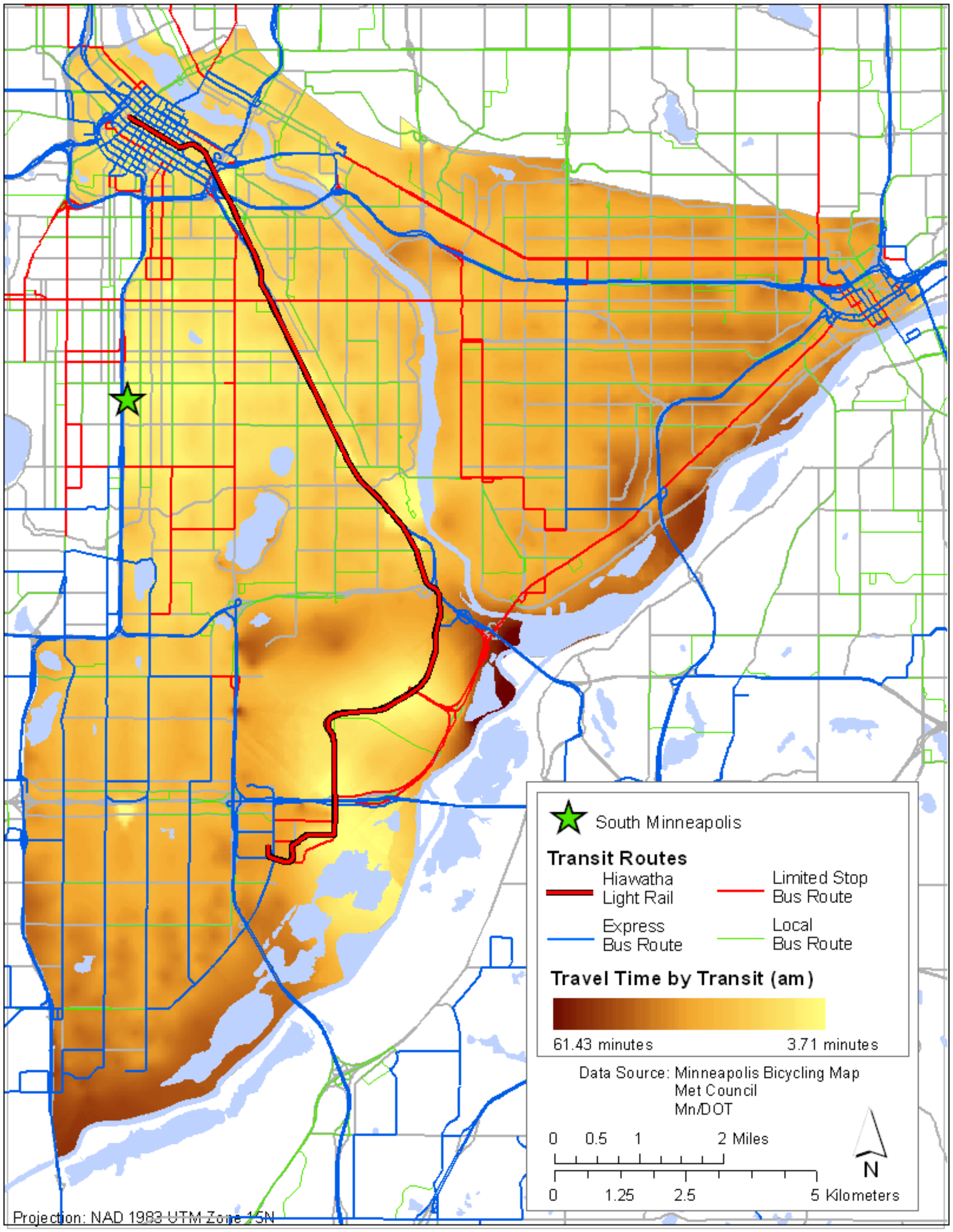

Figure 85. Transit travel shed from south Minneapolis in 2005 (am)

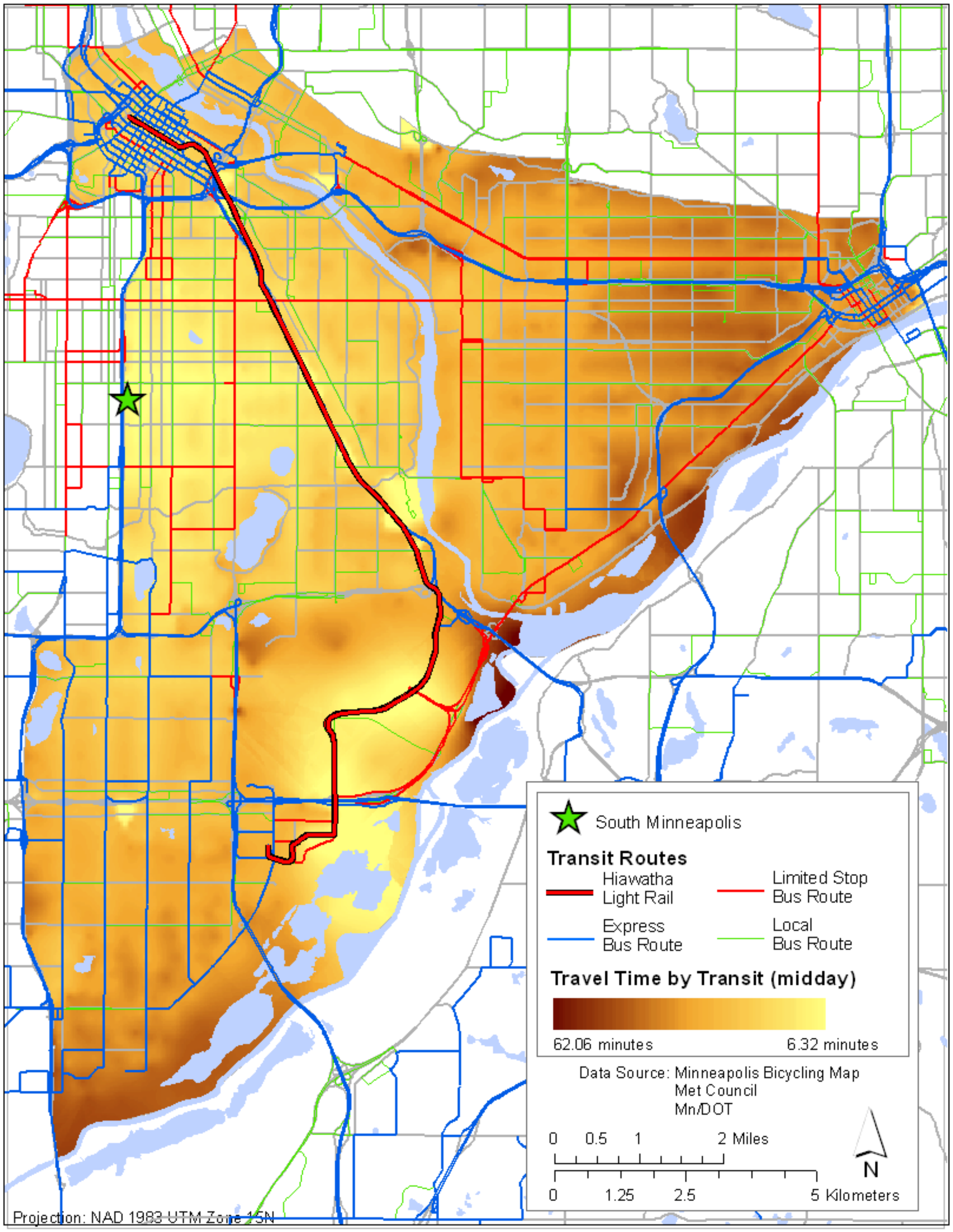

Figure 86. Transit travel shed from south Minneapolis in 2005 (midday)

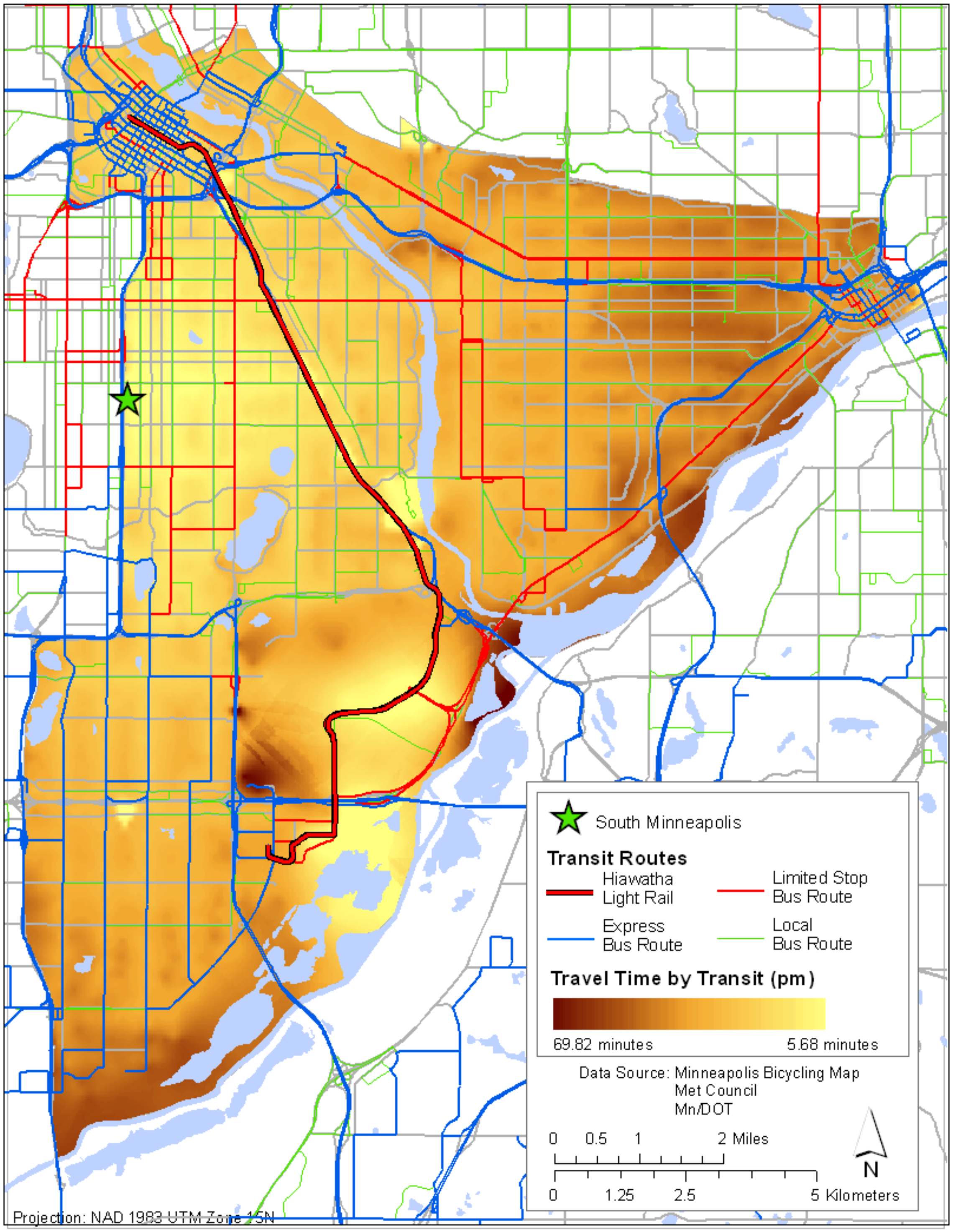

Figure 87. Transit travel shed from south Minneapolis in 2005 (pm)

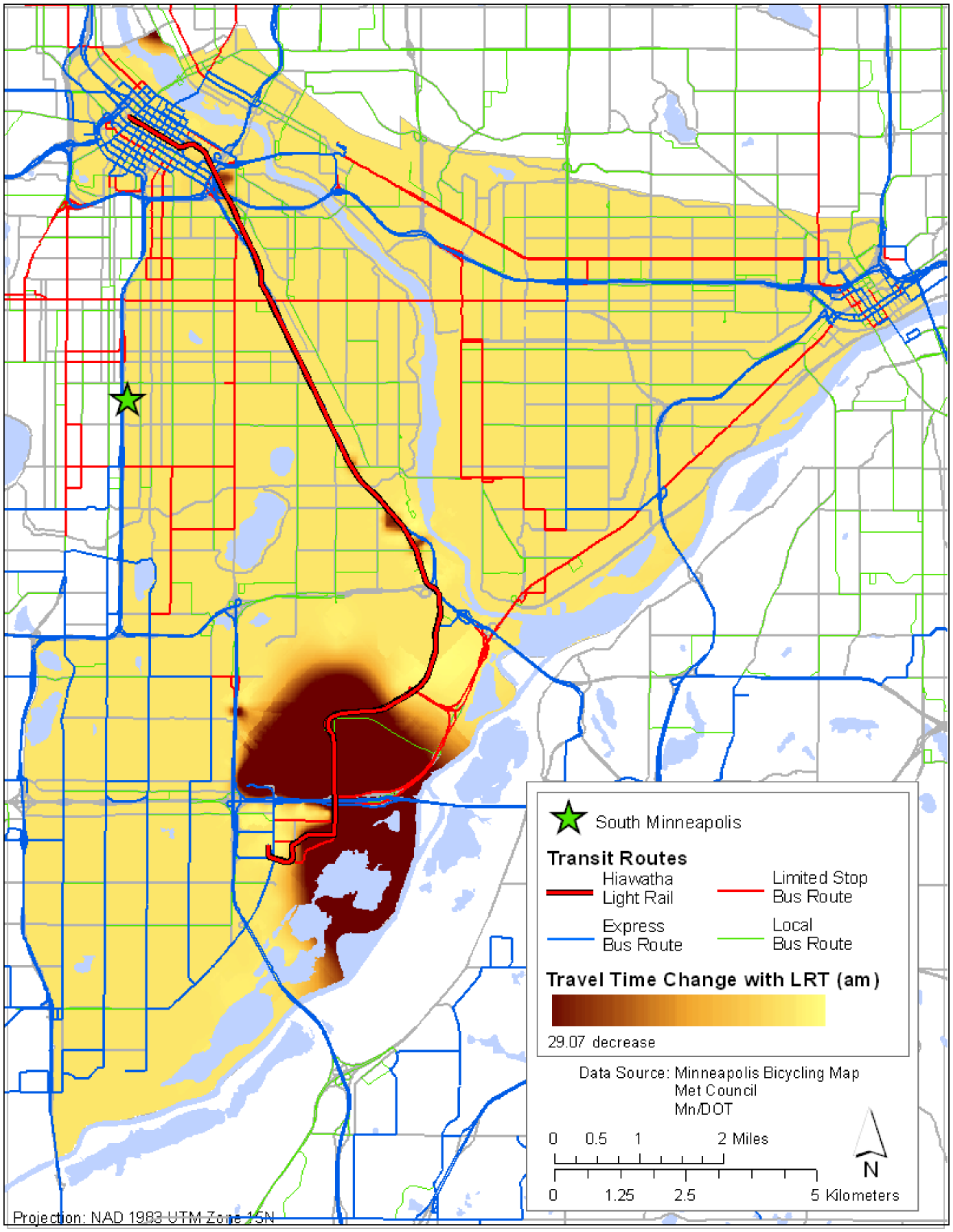

Figure 88. Change in transit travel time from south Minneapolis with LRT (am)

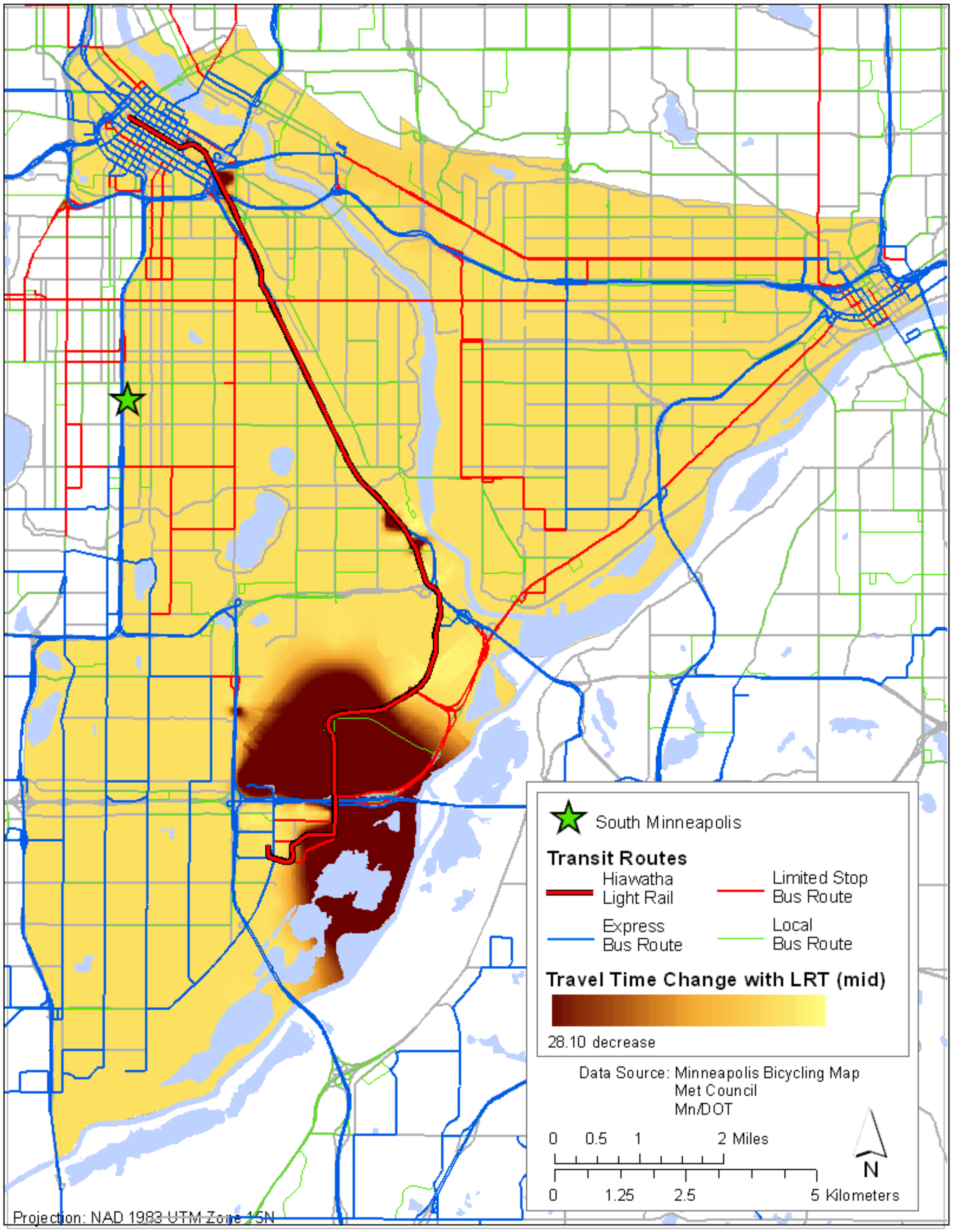

Figure 89. Change in transit travel time from south Minneapolis with LRT (midday)

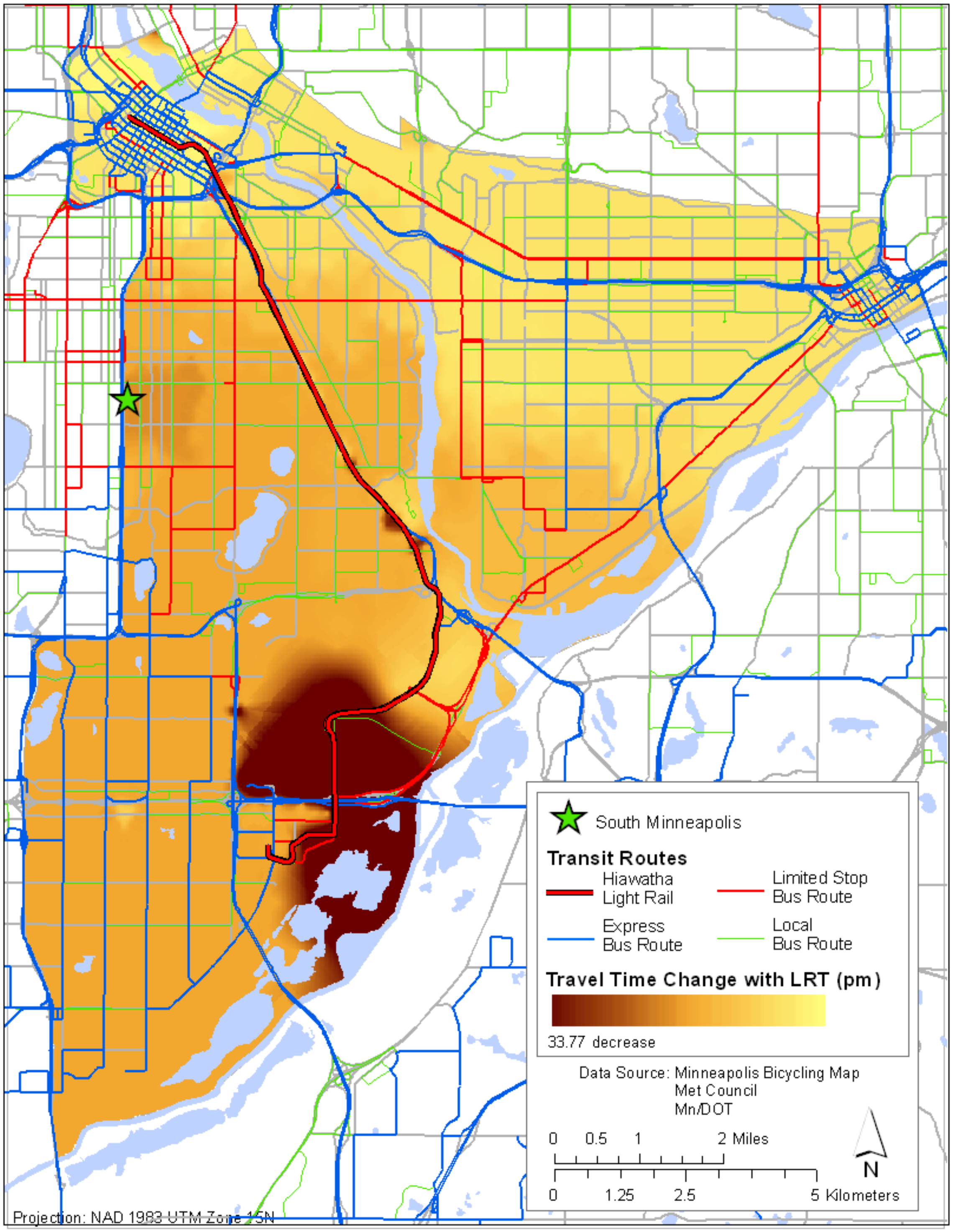

Figure 90. Change in transit travel time from south Minneapolis with LRT (pm)