Evaluating bike accessibility changes and transportation equity in Montgomery County, Maryland

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Abstract

The transportation system in the United States (US) is designed for driving, rather than any other form of transit. This has serious negative effects, contributing to high rates of traffic fatalities, population-level inactivity, and a large share of emissions associated with the climate crisis. These negative effects are inequitably distributed, affecting multiple marginalized groups at a greater rate than the general population. There is evidence that shifting the proportion of trips Americans take from private cars to other modes—like bicycling—can mitigate these harms. One strategy to encourage this mode shift is to build “all ages, all abilities” bicycle infrastructure. Montgomery County, Maryland adopted an ambitious Bicycle Master Plan in 2018; implementation of the plan would result in construction of nearly 1,000 miles of bicycle infrastructure. To determine how this network might increase the adoption of bicycling as transportation, we modeled bicycle accessibility in the county under current conditions and at each tier of implementation of the Bicycle Master Plan. And, to determine whether there is disparate impact on marginalized groups, we calculate the change in accessibility for neighborhoods at risk of high inequality—meeting a certain threshold for predefined sociodemographic variables—compared to the general population. Results indicate that high bike accessibility is currently not widespread. Additionally, there is evidence of slight inequities in accessibility: areas at risk of high inequality face lower levels of accessibility than the county as a whole. But, planned infrastructure will have its intended effect: as implementation progresses, accessibility in the urbanized area of the county as a whole is projected to increase dramatically, especially in the southern portion bordering the District of Columbia. Further results suggest that increasing accessibility in areas at risk of high inequality does not proceed in the quite the same pattern as the rest of the county; implementation of the Bicycle Master Plan results in a more inconsistent pace of change.

Introduction

The transportation system in the United States (US) is designed for driving. This is a problem because a system designed for driving results in most people driving most of the time: over 80 percent of all trips in the US are taken in automobiles (Federal Highway Administration, 2017). Driving has direct and indirect negative impacts on individuals and society most directly through traffic safety, public health, and climate disruption. Further, the negative impacts of driving are not equitably distributed across the population of the US. Often—due to a legacy of using transportation and urban planning policy as a tool of racial and economic segregation—these impacts affect marginalized or vulnerable groups (like African American/Black people, Latino groups, people living in poverty, the elderly, and young children) significantly more than the general population (Houston et al., 2004; Saffer et al., 2013, Anon, 2017).

Over 36,000 people in the US die in car crashes every year, and that number has been trending upward for a decade (National Highway Traffic Safety Administration, 2020). Annual fatalities have increased 8 percent since 2009, and, of these fatal crashes, 77 percent involved passenger vehicles, pickup trucks, SUVs, and minivans (National Highway Traffic Safety Administration, 2020). Only 50 percent of Americans meet the Center for Disease Control standards for weekly physical activity—leading to an increase in conditions including arthritis, asthma, cardiovascular disease, diabetes, cancer, and mental health issues—partly because driving has replaced more active ways of getting around (National Center for Health Statistics, 2018; Bhattacharya et al., 2019). Transportation also contributes the largest share (28 percent) of greenhouse gas emissions in the US, and 60 percent of those emissions come from passenger vehicles (US EPA, 2015; Popovich and Lu, 2019).

Shifting the proportion of trips Americans take from private cars to other modes—that are less dangerous, promote physical activity, and are less emissions-intensive—can mitigate these harms. There is evidence that increasing the use of bicycling and other active modes for transportation can help intervene in each of these crises: decreasing traffic deaths, increasing physical activity and its positive effect on health, and decreasing transportation related emissions (Pucher and Dijkstra, 2003; Mason et al., 2015). Bicycling works at the right scale: about 36 percent of vehicle trips in the US are under two miles, and nearly 60% are under five miles (Federal Highway Administration, 2017). Under the right conditions, this is a reasonable distance to travel by bike or e-bike (Pucher and Dijkstra, 2003). But, the conditions are key: the lack of bicycling-specific infrastructure often makes riding a bike for transportation unpleasant and unsafe due to various factors: from being forced to ride alongside stressful and dangerous vehicle traffic to circuitous, poorly maintained routes to various types of harassment (Pucher and Dijkstra, 2003).

One strategy to increase the share of trips by bicycle is by making places physically accessible by bike. Increasing bicycling adoption starts (but does not end) with building inclusive bicycling infrastructure (Pucher and Dijkstra, 2003; Bhattacharya et al., 2019). This is often termed “all ages, all abilities” or “8 to 80” infrastructure, meaning that it is designed to make people of all ages and bicycling abilities comfortable using it. The form of this infrastructure depends heavily on context, especially the speed and volume of vehicular traffic. When vehicular traffic is already low speed and low volume, no separation between bicyclists and traffic may be necessary for most bicyclists to feel comfortable; in these situations, a well-signed “neighborhood greenway” might qualify as reasonable infrastructure. If vehicular traffic is high speed and high volume, complete physical separation—like an off-street multi-use trail—may be necessary. A myriad of other forms exist—shared lanes (sharrows), painted bike lanes, protected bike lanes, buffered bike lanes, protected intersections, bike boxes—to handle the great variety of road conditions. The trick is matching the correct solution to the conditions; there is evidence that failing to make the right match can lead to worse safety outcomes than no intervention at all (Ferenchak and Marshall, 2019).

Montgomery County, Maryland has ambitious plans to expand their all ages, all abilities bicycle network. In 2018, Montgomery County approved the Bicycle Master Plan, a synthesis, update, and expansion of previous efforts to plan for bicycling in the county. The county created the plan explicitly as a strategy to help achieve its goal of reducing traffic fatalities in the county to zero by 2030 and achieving its climate action objectives. The plan has four goals:

1. “Increasing bicycling rates in Montgomery County;

2. Creating a highly-connected, convenient and low-stress bicycling network;
3. Providing equal access to low-stress bicycling for all members of the community;
4. Improving the safety of bicycling."

(Maryland-National Capital Park and Planning Commission, 2018)

Even advocates heralded the plan as ambitious, but the specific problem is that delivery of plan goals depends—as does any plan—on funding, resulting in unknown substantive gains in bicycle accessibility (Cranor, 2018). Because the projects that ultimately get built are a function of the available funding and many other constraints (e.g., political will) it is important to prioritize projects.

Modeling can help prioritize infrastructure projects that optimize public benefits within funding constraints. Brachman and Church (2019) demonstrated using an adapted minimum cost flow model to identify specific infrastructure improvement projects to decrease risk for pedestrians in a road network around a school, subject to funding constraints imposed by the federal Safe Routes To Schools program. Lowry et al. (2016) developed a model to prioritize planned bicycle infrastructure improvements by optimizing accessibility to multiple likely destinations. The Rails-to-Trails Conservancy built on this work to develop a bicycle accessibility analysis, equity analysis, and prioritization tool based on this methodology, and implemented it in Cleveland (Rails to Trails Conservancy, 2019, n.d.).

Modeling accessibility depends on being able to identify the road conditions under which most people are willing to ride a bike. In developing the Montgomery County Bicycle Master Plan, planners applied the Level of Traffic Stress (LTS) methodology to the county's road network (Maryland-National Capital Park and Planning Commission, 2018). LTS quantifies the willingness of any given person (not someone who identifies as a bicyclist) to ride a bike on a section of roadway, incorporating a wide variety of criteria, such as street width, prevailing traffic speed, and available bicycle facilities, among others (Furth et al., 2016). While other methods of measuring the quality of service for bicyclists on a transportation network exist, they are often both data intensive and can be unreliable in practice (Semler et al., 2017). In LTS, each segment of roadway is classified at a certain stress level—roughly corresponding to four well-known categories of bicyclists in the US—with the recognition that people will likely only choose to travel somewhere by bicycle if their route's LTS rating is at or below their comfort level (Dill and McNeil, 2016; Semler et al., 2017).

Table 1. Descriptions of each level of traffic stress rating, adapted from Maryland-National Capital Park and Planning Commission (2018).

Level of Traffic Stress Rating	**Description**
LTS 1	A level of traffic stress that would be tolerated by most children.
LTS 2	A level of traffic stress that would be tolerated by the mainstream adult population.

LTS 3	A level of traffic stress that would be tolerated by American bicyclists who were “enthused and confident” but preferred dedicated space for riding.
LTS 4	A level of traffic stress that would be tolerated only by those characterized as “strong and fearless” bicyclists.

Given the LTS data for Montgomery County’s road network, we can ask similar questions to Lowry et al. (2016), Brachman and Church (2019), and Rails to Trails Conservancy (2019) of Montgomery County as a whole: how do the infrastructure projects detailed in the Bicycle Master Plan change accessibility? How will implementation of the plan affect accessibility for groups harmed by past transportation planning policy? In this project we will:

- Model Montgomery County’s bike accessibility under current conditions and over four future scenarios (corresponding to progressive buildout of the Bike Master Plan) to measure the change in accessibility; and
- Compare bike accessibility across these scenarios in areas at risk of high inequality to accessibility in Montgomery County as whole.

The costs of a transportation system reliant on driving—to the climate, public health, and personal safety—are significant. Failing to make Montgomery County more bike accessible will have direct and indirect negative impacts on residents, disproportionately on those residents marginalized by conditions of societal inequality. Hundreds of people will die in preventable crashes each year, many more will suffer from health problems due to inactivity, and the costs of climate disruption will affect everyone. Decreasing the number of trips made in automobiles by increasing the safety, comfort, and convenience of bicycling is an evidence-based intervention that will help mitigate these costs. One of the ways to accomplish this is by building high quality all ages, all abilities bicycling infrastructure networks, as Montgomery County has planned to do. But, transportation infrastructure investment does not happen in a vacuum. The Bicycle Master Plan provides an opportunity to study how planned transportation projects will affect historically marginalized residents, and integrate those investigations into implementation in appropriate ways. To this end, we will conduct a network analysis on Montgomery County’s Level of Traffic Stress data to determine current and future bicycle accessibility in the county and investigate how accessibility might differ for communities at risk of high inequality.

Methodology

Study Area

The study area for this project is the urbanized area designated by the US Census Bureau within Montgomery County, Maryland. Montgomery County is located in the Washington, DC metropolitan area, north of and bordering the District of Columbia. The county has an estimated population over one million people—the most populous of any county in Maryland or DC—and is projected to grow to 1.2 million by 2050 (Montgomery Planning, 2020). It is racially and ethnically diverse, but segregated by race and income in parts of the county (Montgomery Planning, 2020). The urbanized portion of the county covers much of the southern half—immediately contiguous to DC—but tapers off towards the north end (Figure 1). This is because over the last 50 years the county has followed a “wedges and corridors” development pattern, where development has been focused in centers along major road (and now transit) corridors, leaving wedges of agricultural and natural preserve and lower density development (Montgomery Planning, 2020). The county will accommodate population growth by densifying the existing urbanized area, since most of the county’s land area (85%) is already development-constrained (Montgomery Planning, 2020).

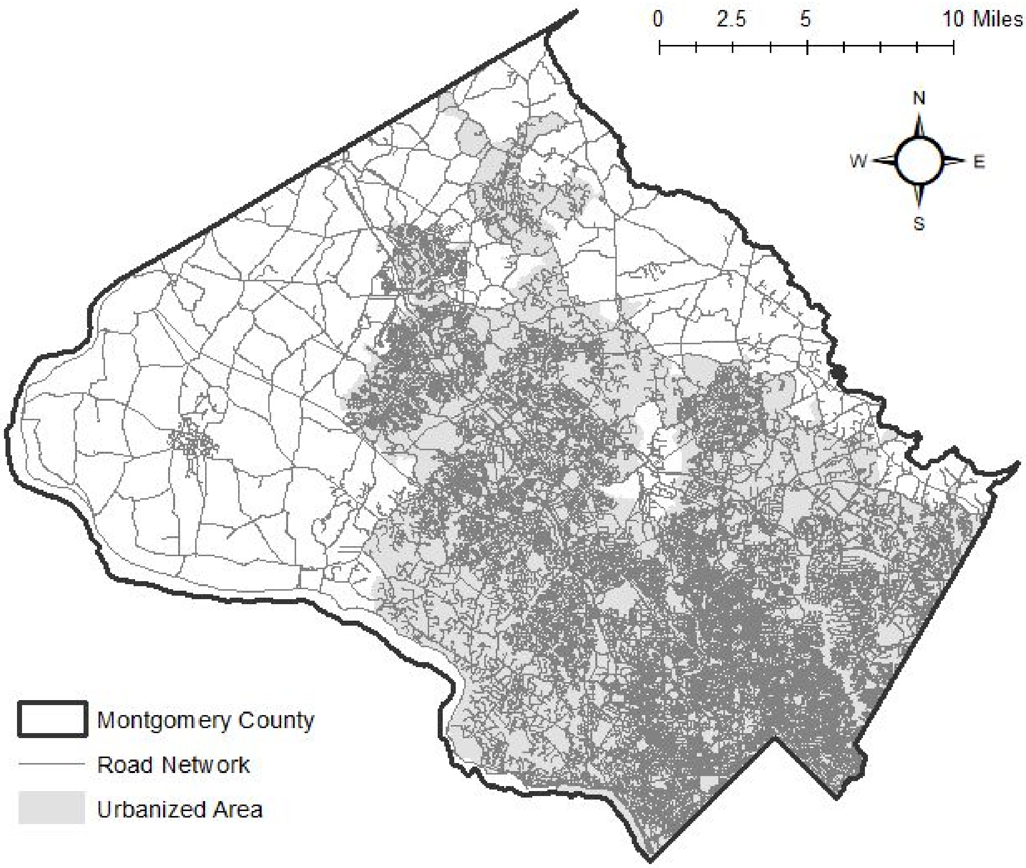

Figure 1. Map of Montgomery County, Maryland, showing the county’s urbanized area and road network. The road network is simplified for cartographic clarity.

Data Sources and Usage

Data for this project fits into three categories: contextual, core analysis, and equity analysis. Contextual data, like Maryland and Montgomery County jurisdictional boundaries and urbanized areas, are used to define the study area both for visualization and clipping other datasets to prepare for analysis (Table 2). Core analysis data, like the level of traffic stress network, planned bicycle infrastructure, residential parcels, transit stations, public high schools, and key destinations, are the necessary data for completing the Origin - Destination Cost Matrix network analysis problem at the center of this project (Table 2). Key destination data, along with transit stations and public high schools, will comprise the destination points for the OD Cost Matrix destination points; these locations represent places people might want to go to access goods (eg., groceries), services (eg., post office), or social/cultural amenities (eg., church). Equity analysis data, like census block level sociodemographic variables, are used to modify the core analysis for comparison between the full study area, and geographies at risk of inequality (Table 2).

Table 2. Details about the data used for this project, including type, source, and usage.

Data / Type	**Source**	**Usage**
Montgomery County Boundary *Vector, polygon*	DataMontgomery	Used to define the study area
Maryland State Boundary *Vector, polygon*	Maryland Open Data	Used to define the study area
Montgomery County Urbanized Area *Vector, polygon*	US Census	Used to define the study area
Community of Wheaton Boundary *Vector, polygon*	DataMontgomery	Used to subset data for testing
Planned Bicycle Infrastructure *Vector, line*	Montgomery Planning	Used to contextualize the study area and project
Level of Traffic Stress Network *Vector, line*	Montgomery Planning	Network dataset for OD Cost Matrix analysis
Residential Parcels *Vector, polygon*	Montgomery Planning	Origin points for OD Cost Matrix analysis
Transit Stations *Vector, point*	OpenMobilityData	Destinations points for the OD Cost Matrix analysis
Public High Schools *Vector, point*	Montgomery County Public Schools Open Data	Destination points for the OD Cost Matrix analysis
Key Destinations *Vector, point*	ESRI Business Analyst	Destination points for the OD Cost Matrix analysis
Sociodemographic Data (Block level) *Vector, polygon*	Census Reporter	Included for use in transportation equity analysis

Data Quality

Overall, the data quality of these sources is high (Table 3). Every dataset used for this project is collected either directly from government agencies specifically responsible for creating those data (for example, Montgomery Planning and the Level of Traffic Stress network) or are paid products (like the key destination data available through ESRI's Business Analyst extension) (Table 3). In some cases, data quality may be presumed lower because a significant amount of time has passed since an agency collected or updated a dataset, like the public high school location data, or are estimates, like the sociodemographic data (Table 3). The most important dataset in this analysis is the level of traffic stress network dataset. The level of traffic stress methodology attempts to model the felt risk of bicyclists. As a model of real qualitative conditions, it has inherent error. The measured LTS on a given segment may not reflect the actual level of traffic stress, or an individual's comfort bicycling under certain conditions. But, given the source of the data (Montgomery County Planning Department) and the uniform application of the methodology across the network, we can be confident in the data's consistency and place a fair amount of trust in its accuracy (Table 3).

Table 3. Details about the quality of the data used in this project, including the best known date for data collection or last update and evaluation of quality.

Data	Collected / Updated	Quality
Montgomery County Boundary	2/20/2019	Assumed high; provided by the county government Department of Technology Services
Maryland State Boundary	8/28/2016	Assumed high; provided by the state government Department of Information Technology
Montgomery County Urbanized Area	2010	Assumed high; provided by the US Census Bureau
Community of Wheaton Boundary	2/9/2018	Assumed high, created by DTS-GIS for Montgomery County government
Level of Traffic Stress Network	2018	High; Montgomery County planners carried out a modified level of traffic stress methodology to create these data
Planned Bicycle Infrastructure	2018	High; Montgomery County planners created these data as part of the Bicycle Master Plan
Residential Parcels	Unknown	Assumed high; data is hosted by the Montgomery County Planning Department
Sociodemographic Data (Block level)	2018	Assumed high; provided by the US Census Bureau, but the data is estimated
Transit Stations	2019	Assumed high; collected from the daily Generalized Transit Feed Specification provided by WMATA and RideOn
Public High Schools	9/25/2017	Assumed medium; provided by Montgomery County Public Schools,

		but three years old
Business Listings	10/21/2020	Assumed high; data comes from a paid ESRI product

Data Processing

We used ArcMap 10.7.1 and ArcGIS Pro 2.4 to complete all data pre-processing and ArcGIS Pro 2.4 to access the business listing data available from ESRI's Business Analyst extension.

Boundaries | To create the Maryland State Boundary, we used the Union tool to combine all of the Maryland counties, and then used the Select tool to create a new feature class with all counties except for the District of Columbia, which was included in the dataset. Then, we used the Dissolve tool to create the Maryland State Boundary. To create the Montgomery County Urbanized Area polygon, we used the Clip tool to create the polygon from a dataset that covered the whole Washington, DC region.

Level of Traffic Stress Network | Using the Network Dataset wizard, we created the Level of Traffic Stress (LTS) network using the default parameters. To create subsets of the LTS network for analysis, we selected segments with an LTS rating of less than or equal to two (≤ 2) for each scenario (Table 4), and exported the selected data as a new dataset. Using this subset, we created a new network dataset for each scenario repeating the methods above.

Origins | To create a dataset of residential parcels, we selected parcel features with a zoning code name that indicated residential use: apartments, commercial condominium, commercial/residential, residential, residential condominium, residential/commercial, or townhouse. From this subset of parcels, we further selected features where the land use category was equal to multi-family, single family attached, or single family detached. We exported the selected parcels to a new dataset, then used the Repair Geometry tool to delete any features with null geometry. Using the Clip tool, we cut the parcel dataset down to the boundaries of our study area, Montgomery County's urbanized area. To prepare this dataset for the OD Cost Matrix analysis, we used the Feature to Point tool to turn parcel polygons into points to be used as input for Network Analyst. This set of origins exceeded 240,000 points, and testing suggested that this exceeded available computing power. In order to reduce the size of the dataset but maintain the granularity of our analysis, we took a 25 percent subset of the parcel data (just over 60,000 features), and clipped the point dataset to this subset.

Key Destinations | The first dataset used to make up key destinations are business listings collected from ESRI's Business Analyst using the Generate Points From Business Listings tool, and clipped by the Montgomery County Boundary. To process Generalized Transit Feed Specification data for transit stops (WMATA and RideOn), we used the GTFS Stops to Features tool to create point datasets.

Sociodemographic Data | We isolated several sociodemographic variables for census block groups, following the Rails to Trails Conservancy (2019) methodology. These variables include percentage of population living below the poverty line, percentage unemployed, percentage without a high school degree, percentage of zero-car households, percentage of African American population, and percentage of Hispanic population. After isolating the relevant columns and calculating these variables, we created dummy variables for each: depending if a block group exceeds a certain threshold for that variable, the dummy variable value was one or zero (Table 6). We calculated a new attribute—the sum of the dummy variables—and selected only those block groups where the sum of dummy variables was greater than or equal to three, meaning that a given block group exceeded thresholds for at least three of the six variable indicators for inequality. These block group polygons made up our equity analysis study area.

General | For each dataset, we reprojected to the NAD_1983_StatePlane_Maryland_FIPS_1900_Feet projection, which is the projection of the Level of Traffic Stress network dataset. For datasets that extend beyond the borders of the Montgomery County urbanized area, we clipped data to the Urbanized Area dataset.

Analysis Methods

The methods described below were programmed into a standalone script using Python 3.8 (the script is available in Appendix III). The script replicates methods developed by Lowry et al. (2016) and used in several case studies by the Rails to Trails Conservancy (2019). Broadly, these methods include running multiple OD Cost Matrix network analyses iterated over multiple scenarios with information summarized back to the input data. A Lenovo Thinkpad laptop with an Intel(R) Core™ i7-3520M CPU @2.90GHz processor and 16.0GB of installed RAM was used to run the script. Running the script for the full study area analysis took 2 hours, 53 minutes, and 3 seconds, and 1 hour, 1 minute, and 32 seconds for the equity analysis study area.

Scenarios

To determine the change in bicycle accessibility if the Bicycle Master Plan (BMP) were implemented, we completed our analysis for five scenarios (Table 4). Each scenario corresponds to a level of buildout of the projects recommended by the BMP (Figure 2).

Table 4. Analysis scenarios corresponding to levels of buildout identified in the Montgomery County Bicycle Master Plan, with information about each level, including its contribution to overall implementation (Maryland-National Capital Park and Planning Commission, 2018). Tiers roughly correspond to the priority level of the projects they contain—earlier tiers will contain higher priority projects.

Scenario	Level of Buildout	Description	Miles/Percent of Buildout
1	Tier 0 (existing conditions)	The road network with Level of Traffic Stress conditions as they existed in 2018, when the Bicycle Master Plan was approved and adopted.	N/A
2	Tier 1	The road network with predicted Level of Traffic Stress conditions after the buildout of programmed projects (already completely or partially funded)	93 miles / 24.6%

		and Tier 1 projects (high demand projects and those located in and around priority areas).	
3	Tier 2	The road network with predicted Level of Traffic Stress conditions after the buildout of Tier 2 projects (remaining projects in the priority areas).	91 miles / 24.1%
4	Tier 3	The road network with predicted Level of Traffic Stress conditions after the buildout of Tier 3 projects (remaining neighborhood greenway projects, high demand projects outside of priority areas, and high demand recreational projects).	115 miles / 30.5%
5	Tier 4 (Full Buildout)	The road network with predicted Level of Traffic Stress conditions after the buildout of Tier 4 projects (recreational routes and any remaining transportation project identified by the plan).	78 miles / 20.6%

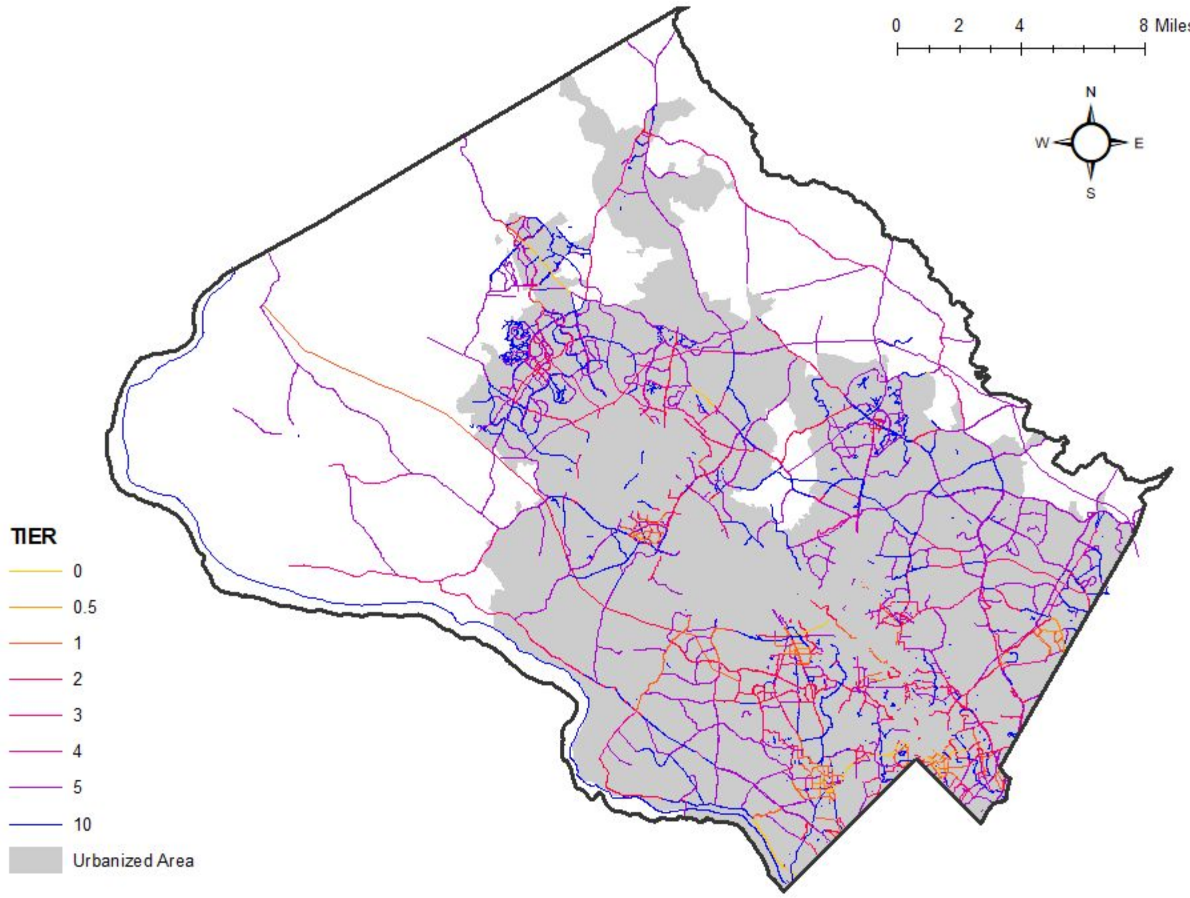

Figure 2. Map of the existing and planned bicycle infrastructure projects in the Bicycle Master Plan, categorized by tier. For the purposes of this project, Tier 0.5 is rolled into Tier 1, Tier 5 is rolled into Tier 4, and Tier 10 is existing infrastructure.

Modeling Bicycle Accessibility

In this project, bicycle accessibility is defined as the ability to travel from a given origin point to a variety of destinations necessary for everyday life on a low-stress bicycling network in two miles or less. A low stress bicycling network is the network of roads and trails with a Level of Traffic Stress (LTS) rating of two or below (Table 1).

Origin-Destination Cost Matrix

Testing the ability to travel between origins and destinations on a network under certain conditions sets up a classic Origin-Destination Cost Matrix network analysis problem. For this study, points representing residential parcels were set as origins and points representing business listings from ESRI's Business Analyst, transit stations, and public high schools were set as destinations. To determine the baseline number of destinations reachable within two miles of an origin point, we solved an OD Cost Matrix problem using the full road network, regardless of the LTS rating; we used this baseline to compare against each of the other scenarios. For each line feature representing the route between an origin and destination, we selected a subset where the length of the route was less than or equal to two miles. We used the Frequency tool to count the number of destinations reached by each origin point, then joined the resulting table back to the origin points in the OD Cost Matrix network analysis layer. We used the Spatial Join tool to join the origin points to the parcel polygon data, adding the number of destinations reachable on the network in under two miles as a new attribute. For each scenario, we created a subset of the network dataset, only including segments of the network with an LTS of two or below. Then, we repeated the OD Cost Matrix analysis using the subsetted network dataset for each scenario, and again summarized the number of destinations reachable in under two miles to each origin point as a new attribute. To model the accessibility of residential parcels in each scenario, we divided the number of destinations reachable from each parcel on the subsetted network (LTS ≤ 2) by the number reachable on the full road network, and added this value to each origin point as a new attribute, the accessibility rating (A).

$$\text{Accessibility Rating (A)} = \frac{\text{\# destinations reachable within 2 miles on low stress network (LTS} \leq 2)}{\text{\# destinations reachable within 2 miles on full network}}$$

With each origin point now containing an accessibility rating (A) on a low stress network under each scenario, we developed summary statistics of bike accessibility for each scenario. For ease of interpreting the accessibility rating (A), we reclassified values into five plain-language categories of accessibility: Very Poor, Poor, Average, Good, and Excellent (Table 5).

Table 5. Reclassification of Accessibility Rating (A) to categories of accessibility.

Accessibility Rating (A)	**Destinations Reachable from Parcel**	**Accessibility Category**
0.00 - 0.20 or NULL	0% to 20%	Very Poor
0.21 - 0.40	21% to 40%	Poor
0.41 - 0.60	41% to 60%	Average
0.61 - 0.80	61% to 80%	Good
0.81 - 1.00	81% to 100%	Excellent

Analyzing Transportation Equity

Rails to Trails Conservancy (2019) identified six factors that might contribute to high neighborhood inequality: the percentage of population living below the poverty line, percentage unemployed, percentage without a high school degree, percentage of zero-car households, percentage of African-American population, and percentage of Hispanic population. Through pre-processing, we identified the census block groups in Montgomery County where at least three of these variables rose above certain thresholds defined by Rails to Trails Conservancy in previous research. (Table 6)

Table 6. Socioeconomic and demographic variables used to identify possible census block groups experiencing high inequality.	
Variable (percent of population)	**Threshold**
Living below the poverty line	> 30%
Unemployed	> 30%
No high school degree	> 20%
Zero-car households	< 60%
African-American or Black population	> 75%
Hispanic or Latino population	> 30%

To evaluate bicycle accessibility in the equity analysis study area identified, we used the Clip tool to subset the origin point dataset to the boundaries of these census block groups. From these origin points—representing residential parcels in areas at risk for high inequality—we repeated the O-D Cost Matrix analysis for each of the five scenarios (Table 4). We developed summary statistics for each of these scenarios, and compared the abundance of each accessibility category to that of the entire county.

Results

Results for the full urbanized area in Montgomery County suggest significant, steady gains in bicycle accessibility as the Bicycle Master Plan is built out (Figure 3). Under existing conditions (Tier 0), 78.9 percent of parcels have either Very Poor or Poor levels of accessibility, which steadily decreases through Tier 1 (70.7 percent), Tier 2 (58.4 percent), Tier 3 (48.8 percent), and Tier 4 (42.1 percent) (Figure 3). This shift is paralleled by a significant increase in the number of parcels with Good or Excellent levels of accessibility: from 4.6 percent under existing conditions (Tier 0), nearly doubling through Tier 1 (9.2 percent), Tier 2 (17.6 percent) and Tier 3 (30.2 percent), and slower growth in Tier 4 (38.8 percent) (Figure 3). The number of parcels categorized as Average stays relatively even, from 16.5 percent at its lowest in Tier 0 to 24.0 percent at its highest in Tier 2, a range of 7.5 percent (Figure 3). Looking at a map of accessibility across the study area for Tier 0 and Tier 4, this transformation is clearly visible (Figure 4). (Maps of the full study area for each scenario are in Appendix I, Figures I-1 through I-5.)

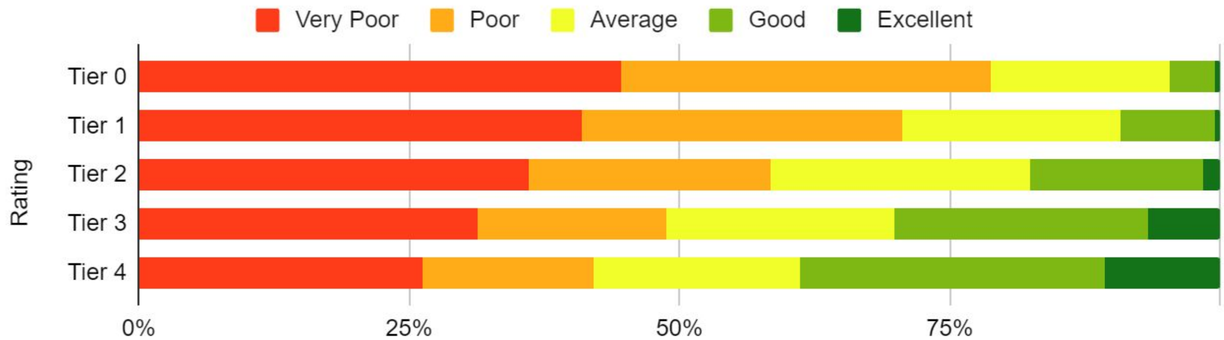

Figure 3. Percent of parcels in the full study area in each accessibility category in each scenario (n = 60,710).

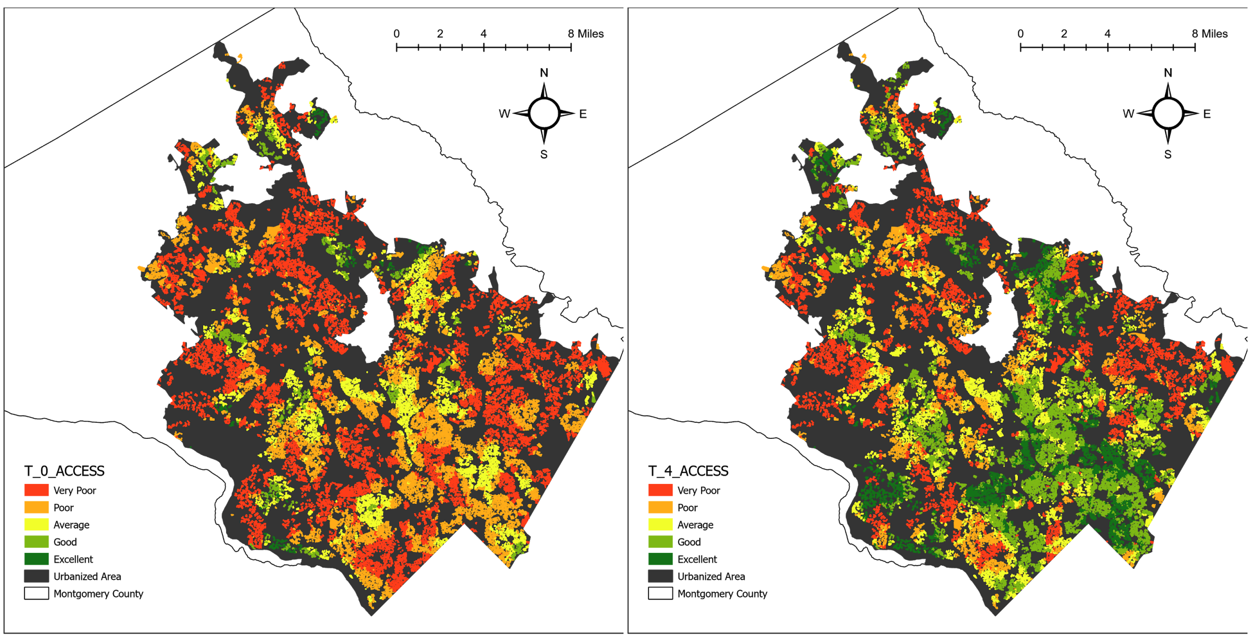

Figure 4. Location of parcels, visualized by accessibility category, in the full study area. The map on the left shows Tier 0 (existing conditions) and the map on the right shows Tier 4 (full buildout).

Results of the equity analysis—census block groups within the study region at risk of high inequality—broadly mirror the results of the full Montgomery County urbanized area, with some differences (Figure 5). Under existing conditions (Tier 0), 88.3 percent of parcels have either Very Poor or Poor levels of accessibility, which is about 10% higher than the full study region. This steadily decreases through Tier 1 (70.5 percent), Tier 2 (53.7 percent), Tier 3 (47.2 percent), and Tier 4 (27.7 percent) (Figure 5). In contrast to the full study area, the shift in the number of parcels with Good or Excellent levels of accessibility happens both more slowly but, ultimately, to a greater extent. For the first three scenarios (Tiers 0 - 2) the percentage of parcels exhibiting Good or Excellent accessibility stays under 10 percent, before rapidly growing in Tier 3 (21.1 percent) and especially Tier 4 (50.6 percent) (Figure 5). The number of parcels categorized as Average changes more than in the full study area, ranging from 11.7 percent at its lowest in Tier 0 to 38.3 percent at its highest in Tier 2 (Figure 5), a range of 26.6 percent.

Looking at a map of accessibility across the study area for Tier 0 and Tier 4, this transformation is clearly visible (Figure 6). (Maps of the equity analysis study area for each scenario are in Appendix II, Figures II-1 through II-5.)

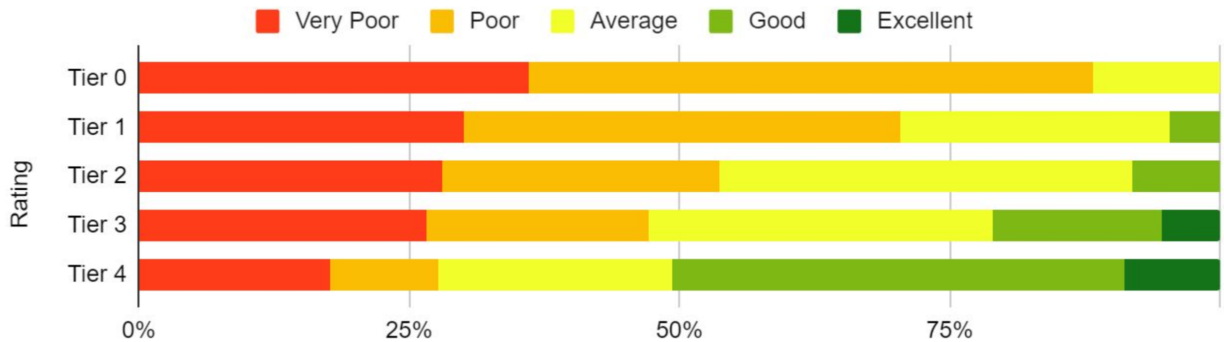

Figure 5. Percent of parcels in the equity analysis study area in each accessibility category in each scenario (n = 16,867).

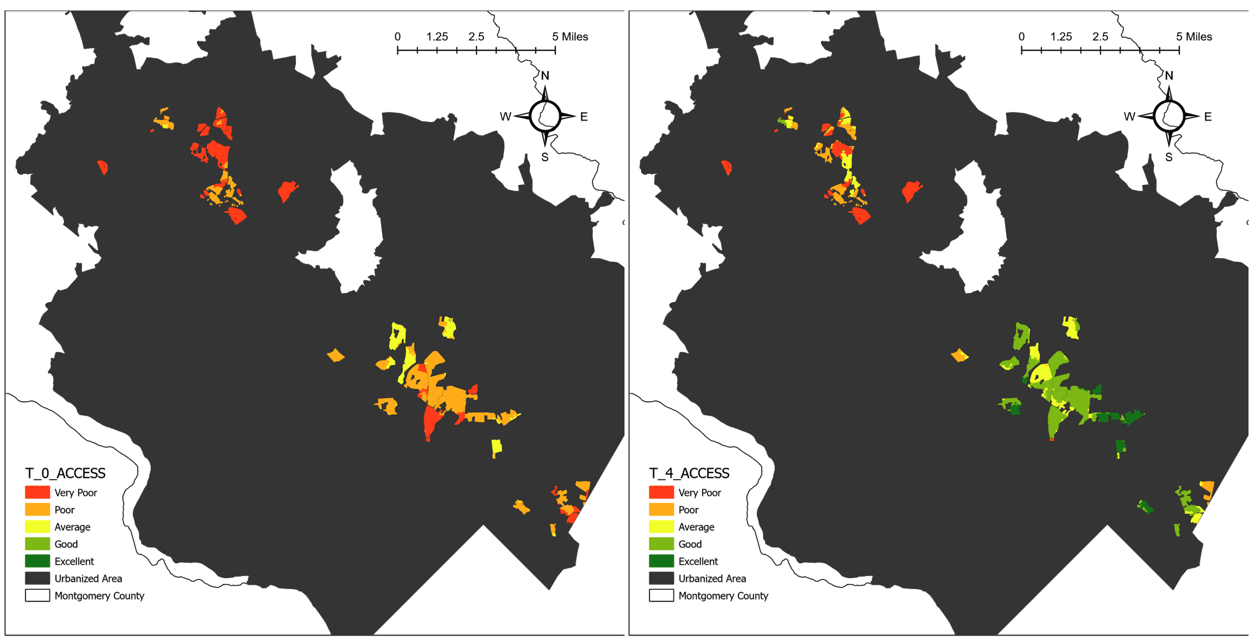

Figure 6. Location of parcels, visualized by accessibility category, in the equity analysis study area. The map on the left shows Tier 0 (existing conditions) and the map on the right shows Tier 4 (full buildout).

Across tiers, the equity analysis study area has consistently fewer parcels categorized as Very Poor than the full study area. While the equity analysis study area starts with a higher percentage of parcels categorized as Poor accessibility in Tier 0 (+17.9 percent), this steadily decreases in each tier, to the point where, in Tier 4 it has 5.9 percent fewer than the full study area. The equity analysis study area starts with a lower percentage of parcels categorized as Average accessibility than the full study area (-4.9 percent), progressively increases to a much higher percentage than the full study area through Tier 2 (+14.3 percent), and then decreases again to just 2.5 percent more. The percentage of parcels categorized as Good accessibility is lower in the equity analysis study area than the full study area, decreasing from Tier 0 (-4.2 percent) to Tier 3 (-7.8 percent), but then jumps up in Tier 4 to 13.5 percent more Good accessibility parcels than the full study area. In each successive tier, the relative percentages of parcels categorized as Excellent do not differ much between the two study areas, though the equity analysis study area consistently has slightly lower levels; that disparity grows slightly through implementation (Figure 7).

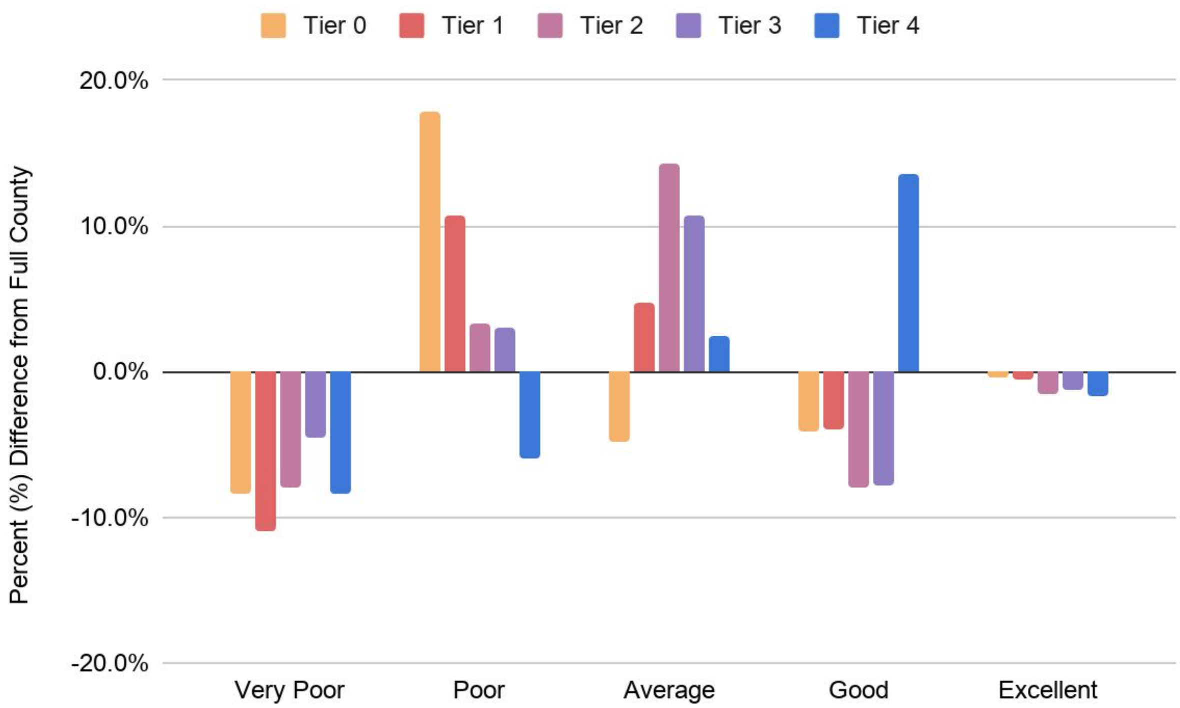

Figure 7. Difference between the equity analysis study area and the full study area in each accessibility category, across each tier.

Discussion

This study modeled bike accessibility in Montgomery County's urbanized area (full study area) across five scenarios corresponding to existing conditions and the buildout of the Montgomery County Bicycle Master Plan (BMP). Additionally, we compared bicycle accessibility in each scenario across the full study area to accessibility in sub-areas of the county identified as being at risk of high inequality (equity analysis study area).

Our results indicate that over the full study area, reasonable bike accessibility under existing conditions is rare (Figure 3). This means that, for the average resident, destinations within two miles that could be accessed by driving could typically not be accessed by bicycle. But, accessibility steadily increases through each tier of buildout of the BMP (Figure 3). Much of this improvement occurs near the southern border of the county, adjacent to the District of Columbia

(DC) (Figure 4). This area—the inner ring suburbs or “inside the beltway”—is typically the most densely populated part of the county, meaning that, should the increases in bicycle accessibility revealed by our analysis materialize, they could disproportionately increase the number of trips being taken by bike.

Our results also indicate that the growth of bike accessibility in the equity analysis study area proceeds differently than in the full study area: generally more slowly, but ultimately more drastically (Figure 5). Throughout most of the implementation, bicycle accessibility improvements are small, with many parcels moving up just one level of accessibility, while in the full study area the shift is from low to high accessibility (Figure 5). That is, until the final phase of BMP buildout, where the percentage of parcels categorized as Good in the equity analysis study area leaps from 16 percent to 42 percent, closing the gap between the two. Increase in accessibility in the equity analysis study area proceeds in a similar spatial pattern as the full study area: areas closer to DC are subject to more stark increases in accessibility than areas further north in the county.

Given our results, we can be optimistic about the impact that implementation of the BMP might have on bike accessibility in Montgomery County overall. A shift from just over 4 percent to nearly 40 percent of residential parcels with Good or Excellent bike accessibility rating is an enormous improvement. But, in absolute terms, over half of the urbanized area in the county would remain inaccessible by bike after full implementation of the BMP. It is notable—and telling—that a plan praised so highly by advocates is only the first step in the direction of making bicycling a viable transportation mode in Montgomery County. The BMP will make progress, but our results show that more efforts will be necessary to increase even just the physical bicycle accessibility enabled by infrastructure.

Our results also provide fruitful ground for discussion of how the BMP affects transportation equity. What are the costs, benefits, or unintended consequences of an inconsistent pace of BMP implementation in areas of the county that are at high risk for inequality compared to a consistent growth of bicycle accessibility throughout the rest of the county? Residents in these areas of the county are already likely to be subject to greater traffic-related health and safety risks and lack of mobility than the county at large. A slower pace of implementation means delaying relief from these material harms and increasing transportation inequality in the short term. Transportation inequality perpetuates other types of inequality: for instance, economic opportunity can be heavily impacted by the number and types of jobs that a person has access to for a reasonable amount of time, money, and effort in getting there. But, beyond direct costs to the residents, pursuing this strategy might have unintended consequences: in neighborhoods that remain inaccessible for bicycling and subject to the harms above, inequality could seed perceptions around bicycling as exclusionary and mistrust in the planning process. Implementation of the BMP is a complex process that the county government does not even have total control over (Maryland-National Capital Park and Planning Commission, 2018). But, planners should use our results as a foundation to make strategic changes that prioritize these areas for investment.

Our analysis attempts to model bike accessibility now and in the future, but we recognize that this method presents many limitations. First and foremost, the analysis of accessibility is based solely on the availability of bicycle network infrastructure, and it is well known that infrastructure is not the only factor that affects bicycle accessibility. Many factors besides safety from vehicular traffic affect a person's decision to take a trip by bike: cultural perceptions, vulnerability to harassment and discriminatory policing, workplace amenities, availability of bikes, bike parking, openness to change, and more. While infrastructure might be one of the more quantifiable, it cannot alone predict how accessible a given trip will feel to a given person. Second, these results could change drastically based on future development patterns. If Montgomery County pursues dense, infill, mixed use development throughout the urbanized area, our results could be under-estimates of increasing bicycle accessibility over time. More key destinations like businesses, churches, amenities, and transit stops built near where people already live might skew the accessibility calculation (A) towards higher bicycle accessibility, even if the planned infrastructure does not change. Finally, these results could even change based on the magnitude of adoption of bicycling in the county: it is a truism of bicycling that there is safety in numbers. If bicycling is adopted quickly and to a great extent, it could make more of the county feel accessible by bike, even without changes in infrastructure. This is not out of the realm of possibility: there is evidence that the COVID-19 crisis has both increased the number of people bicycling and pushed some away from traveling by public transit and towards bicycling (Fuller et al., 2020; Teixeira and Lopes, 2020).

Change is difficult for any community, and it is especially important to discover its possible effects on residents—as well as their perceptions of it—in areas that are already at risk for high inequality. This analysis uncovers the possibility of disparate impact in the implementation of the BMP, but the line of research should not end there. What changes need to be made to the BMP and to its implementation that prioritize investment in communities at risk for high inequality and mitigate the transportation-associated harms their residents disproportionately bear? There is also more to be learned about how our results affect actual residents: our results could be weighted by population and the demographics of areas that differ in accessibility can be further explored. As the BMP is implemented, it would also be useful to know how well accessibility, as defined in this analysis, correlates with bicyclist behavior. Are the rates of bicycle trips higher in areas rated as Good or Excellent accessibility in our analysis? And, tying back to the traffic safety, public health, and climate benefits discussed earlier, are there fewer crashes that result in death or serious injury in these areas? How does accessibility correlate with health outcomes? Are there lower rates of air pollution in more bike accessible areas of the county? And, recent events provide new perspectives: how will the "bike boom" created by the COVID-19 crisis change travel behavior? Perhaps the implementation of the BMP should be reevaluated to accommodate these shifts, especially in areas at high risk for inequality, where the rate of transit use is higher than the general population.

Conclusion

Using network analysis, this study identified how planned bicycle infrastructure detailed in Montgomery County's Bicycle Master Plan might change bicycle accessibility in the county's urbanized area as a whole, and investigated how changes in accessibility might differ specifically in areas of the county at risk of high inequality. Results indicate that high bike accessibility is currently not widespread, though slightly better in the county as a whole than it is in areas at risk of high inequality. But, planned infrastructure will have its intended effect: as implementation progresses, accessibility in the urbanized area of the county as a whole is projected to increase dramatically, especially in the southern portion bordering the District of Columbia. Further results suggest that increasing accessibility in areas at risk of high inequality does not proceed in the quite the same pattern as the rest of the county. Implementation of the Bicycle Master Plan results in a more inconsistent pace of change, though the gap in accessibility is ultimately closed by the end of implementation. With further study, this knowledge could help identify ways in which implementation may need to change to ensure that transportation infrastructure investment happens equitably in the county. Future research should focus on identifying how individual projects in and around the areas at risk for high inequality might affect accessibility and consider reprioritizing high impact projects. If the Bicycle Master Plan is implemented, changes in bike accessibility suggested by our results will be truly transformative for Montgomery County: they will result in a safer, healthier county that is making necessary strides towards reducing transportation emissions, a model for suburban counties across the country. Further study can ensure that these benefits are specifically delivered to residents who need them most.

Appendix I

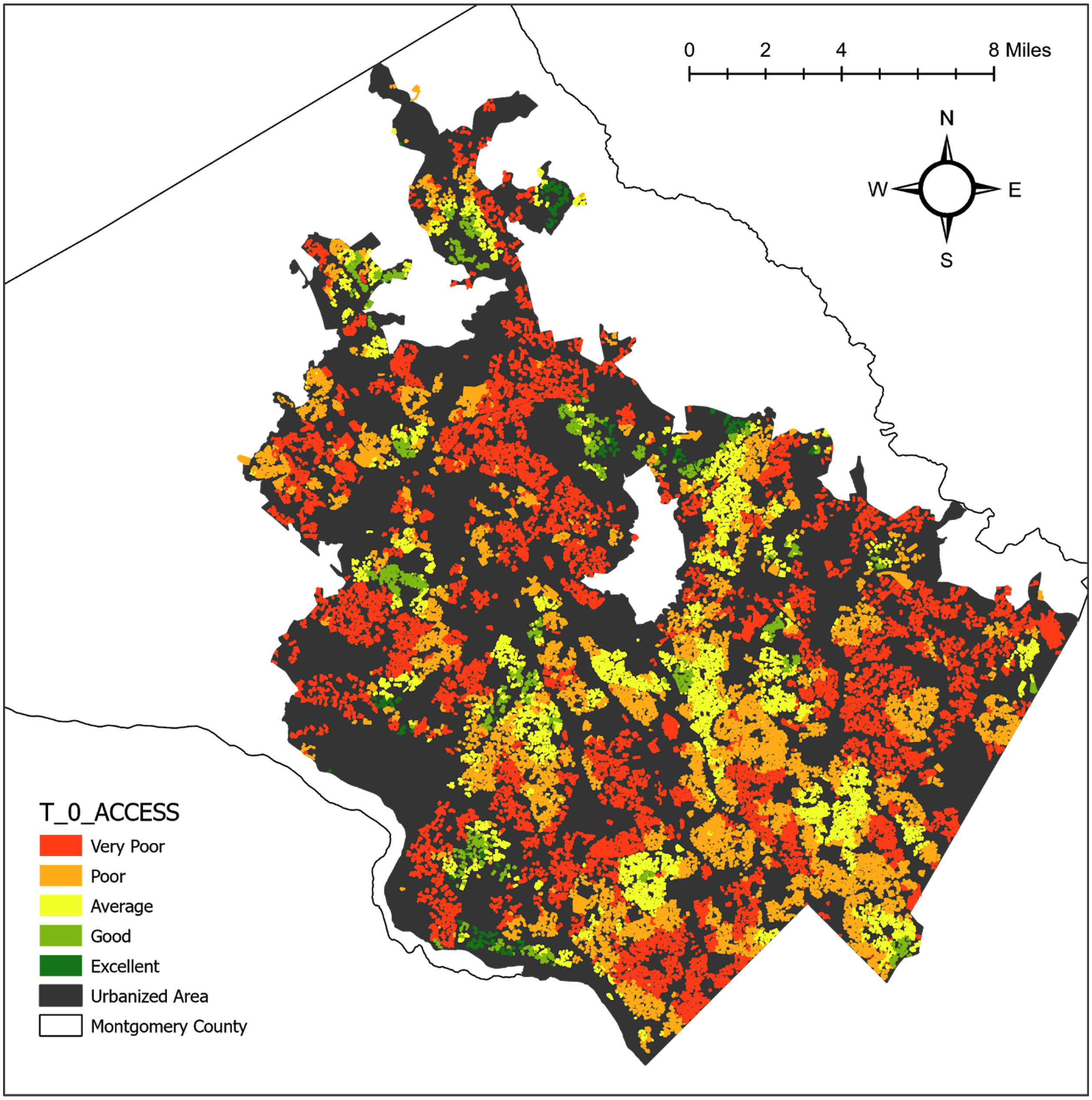

Figure I-1. Location of parcels, visualized by accessibility category, in the full study area in Tier 0.

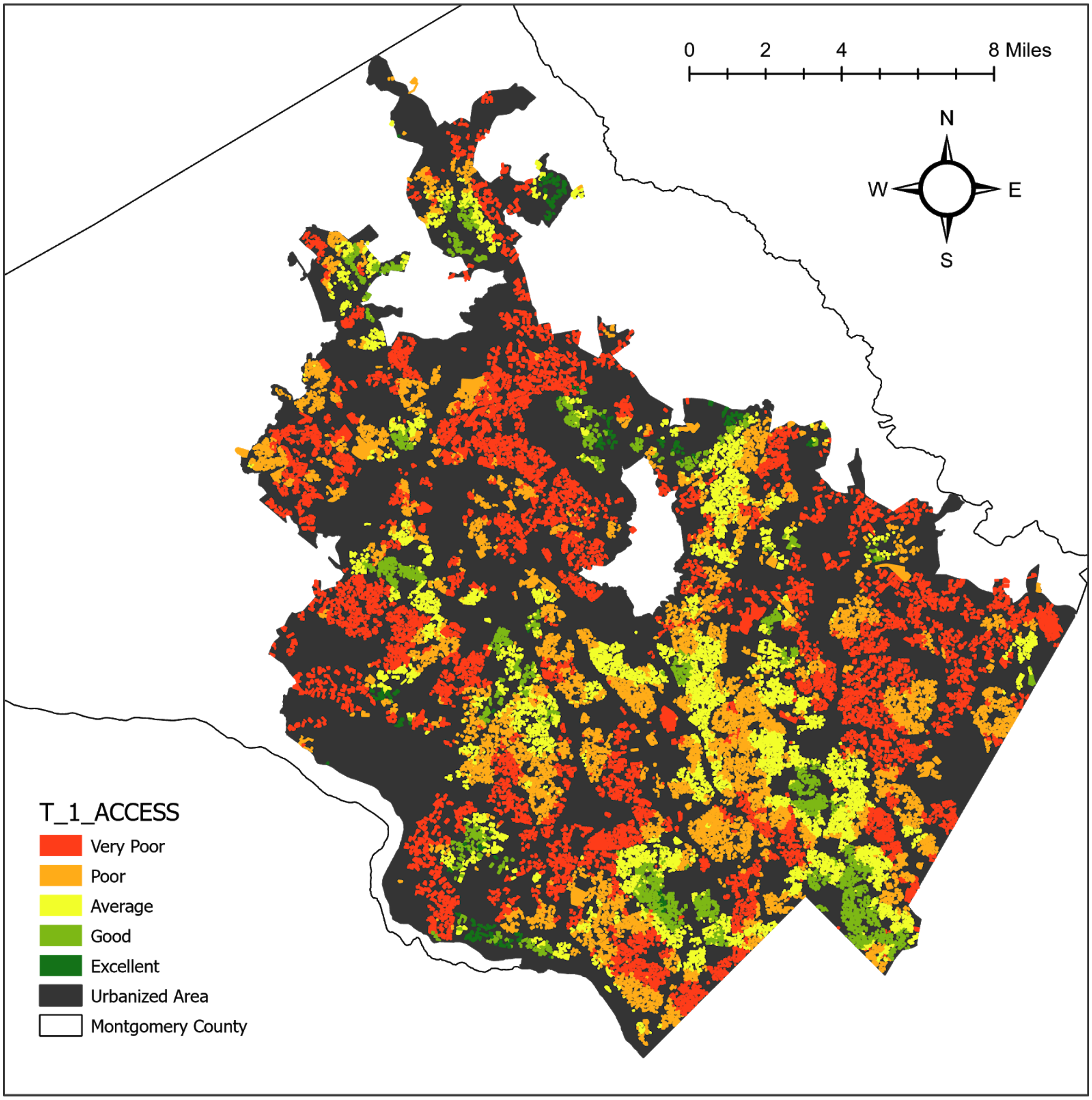

Figure I-2. Location of parcels, visualized by accessibility category, in the full study area in Tier 1.

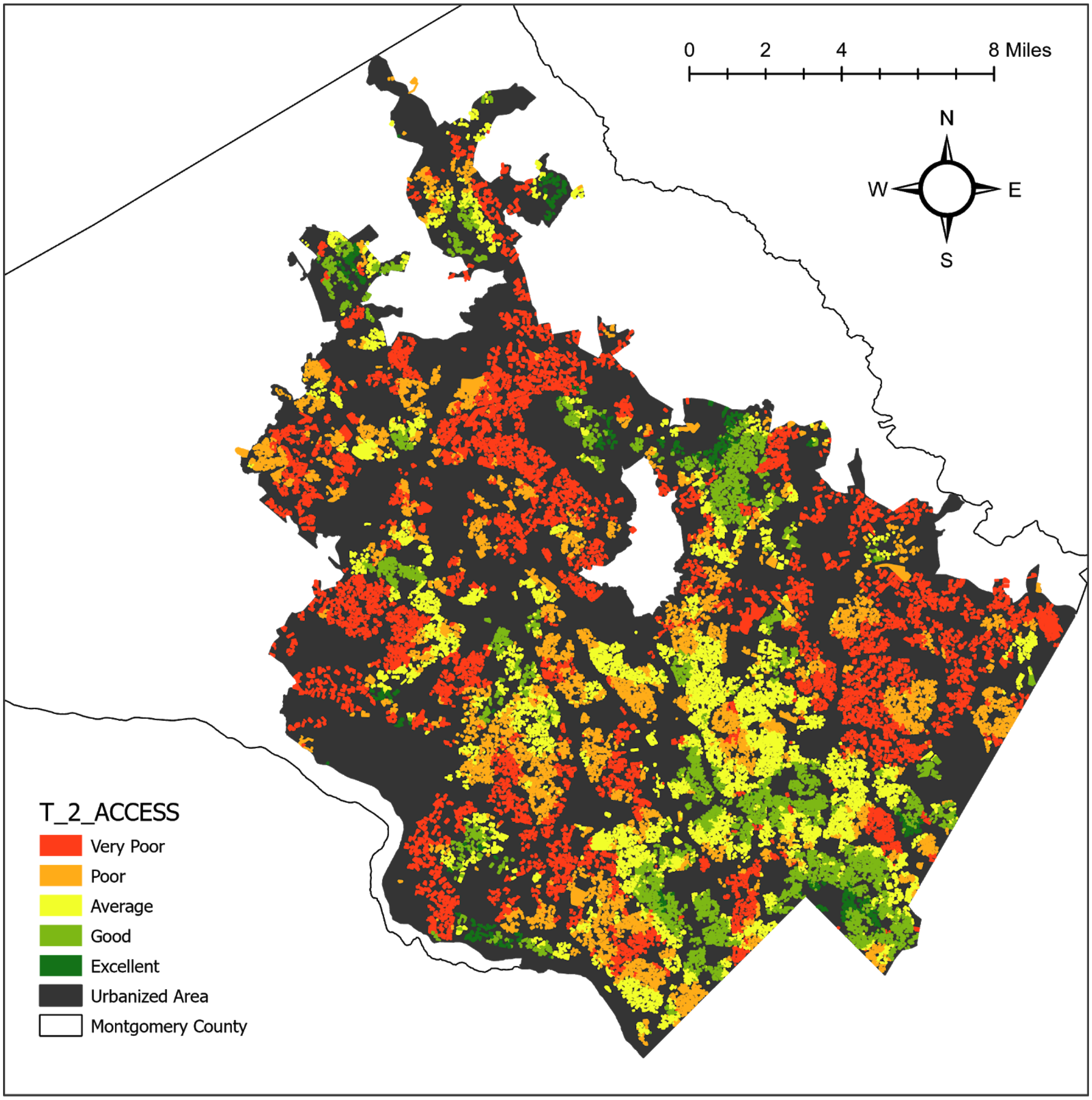

Figure I-3. Location of parcels, visualized by accessibility category, in the full study area in Tier 2.

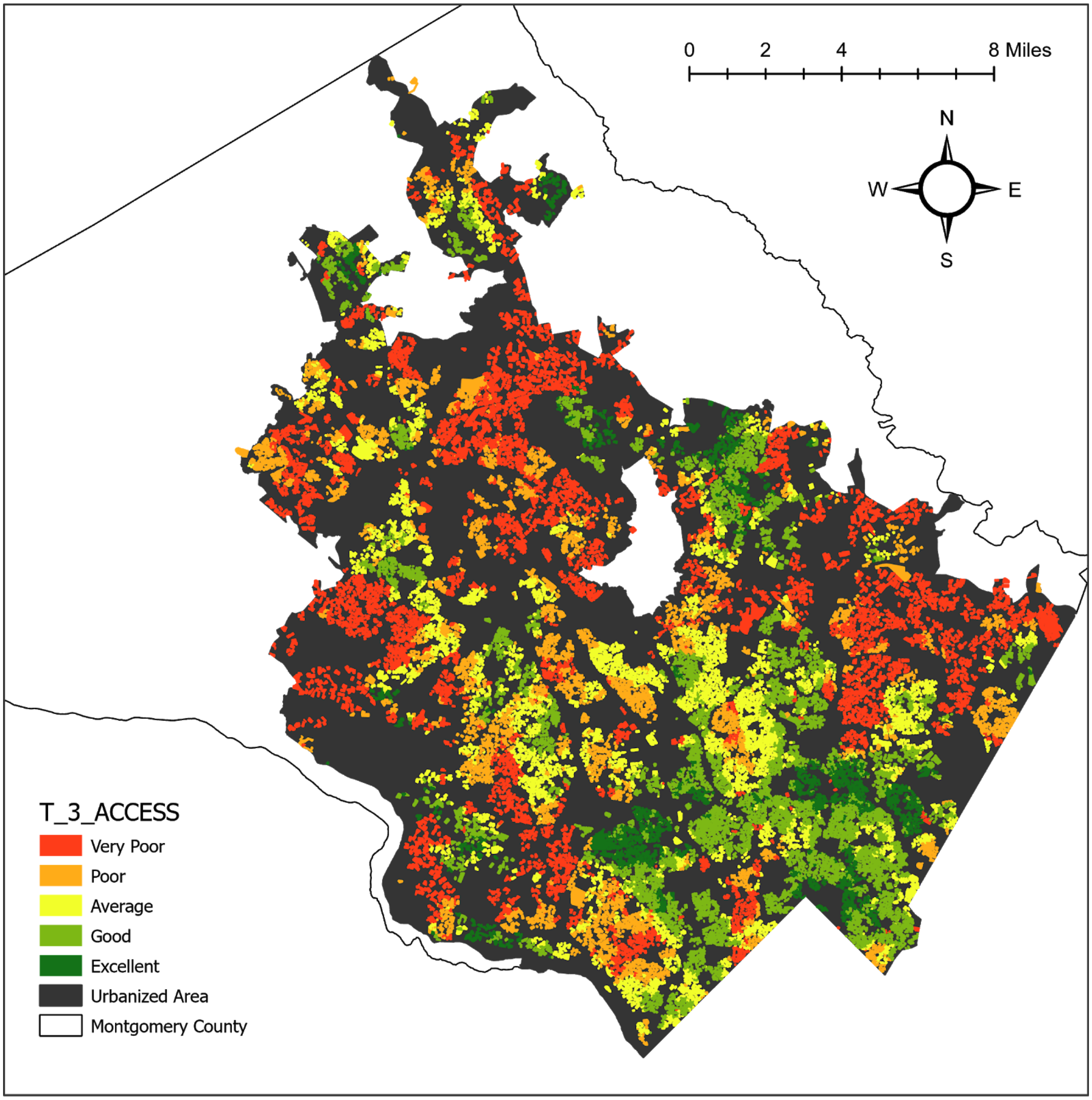

Figure I-4. Location of parcels, visualized by accessibility category, in the full study area in Tier 3.

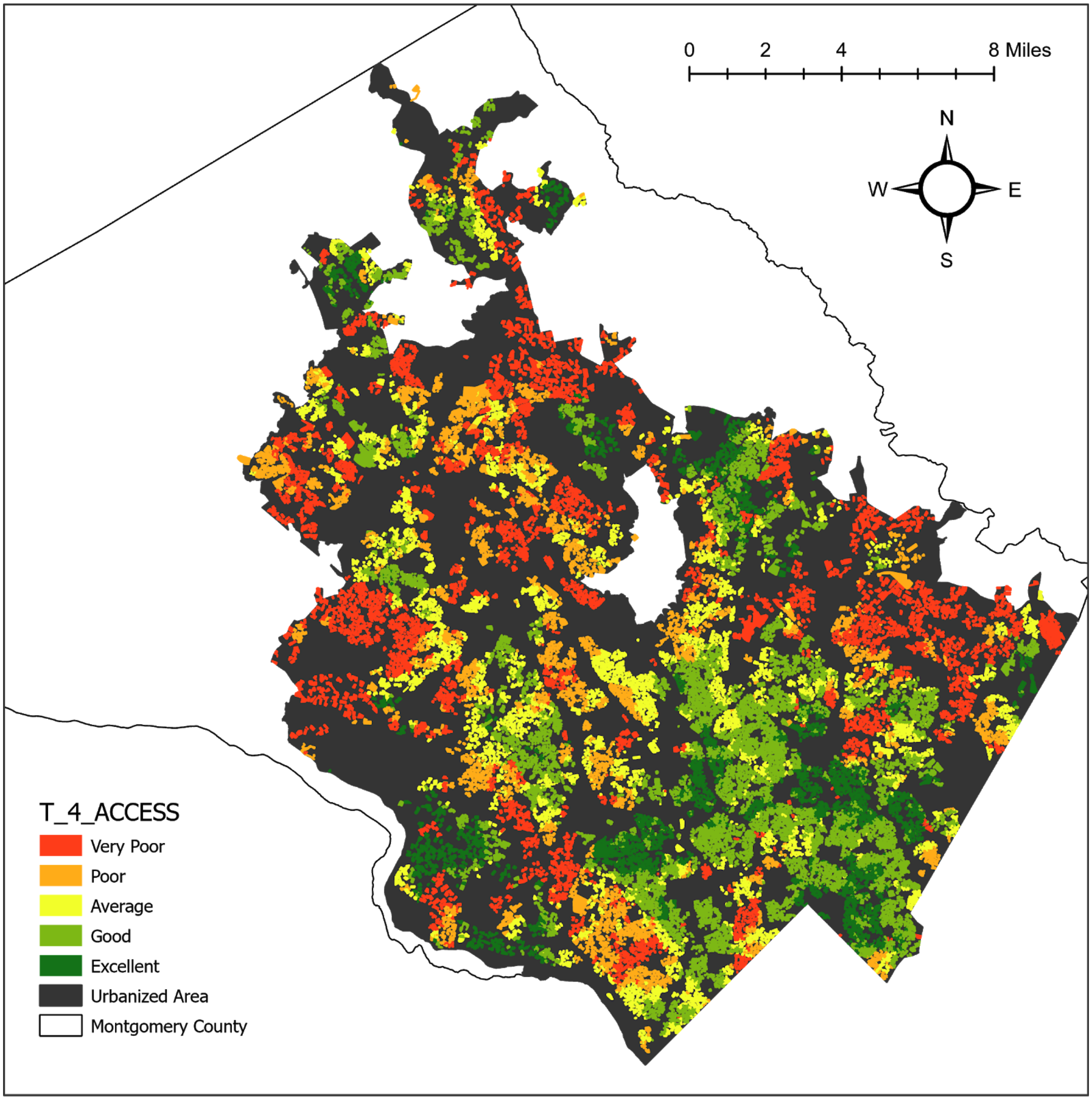

Figure I-5. Location of parcels, visualized by accessibility category, in the full study area in Tier 4.

Appendix II

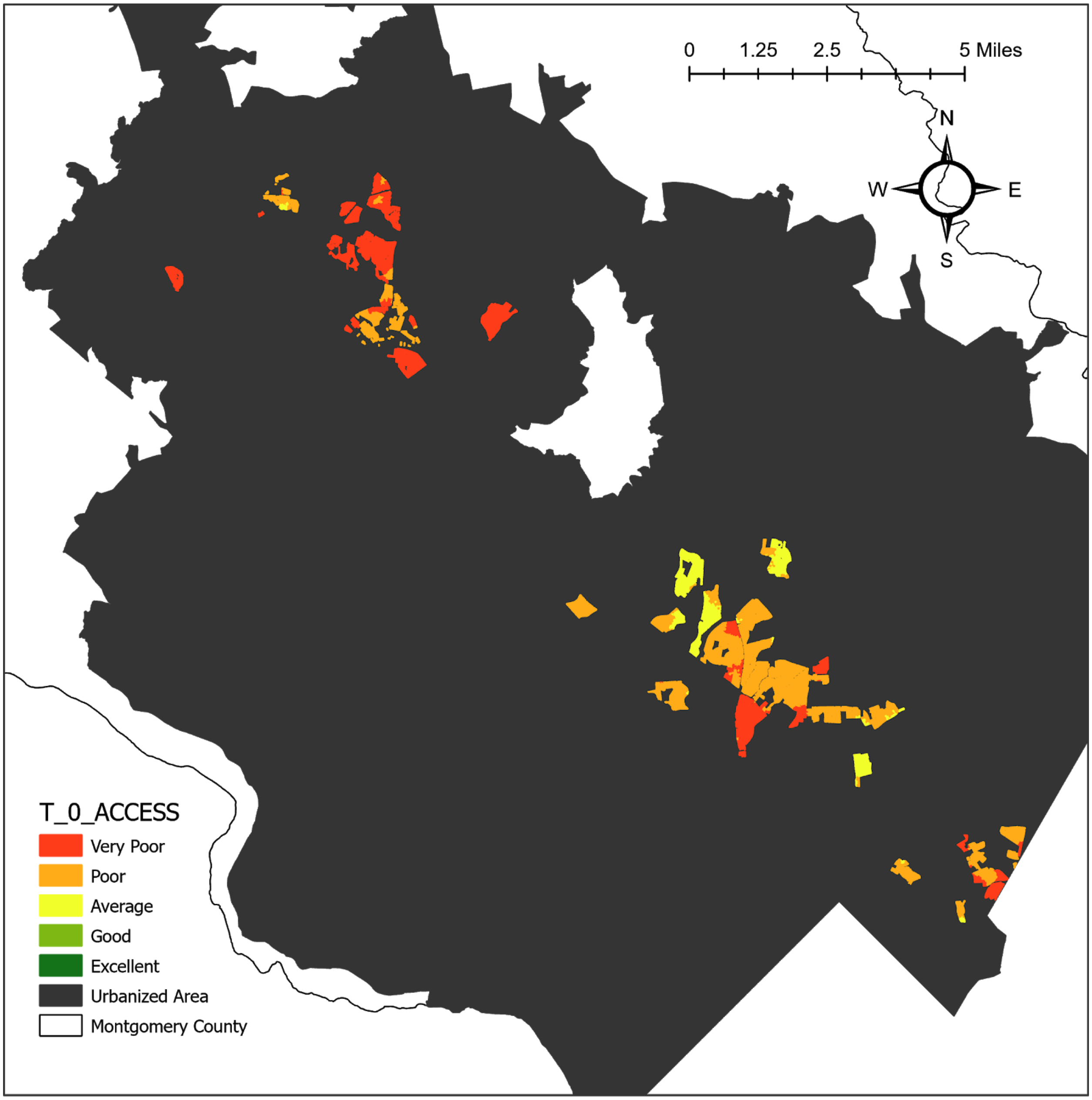

Figure II-1. Location of parcels, visualized by accessibility category, in the equity analysis study area in Tier 0.

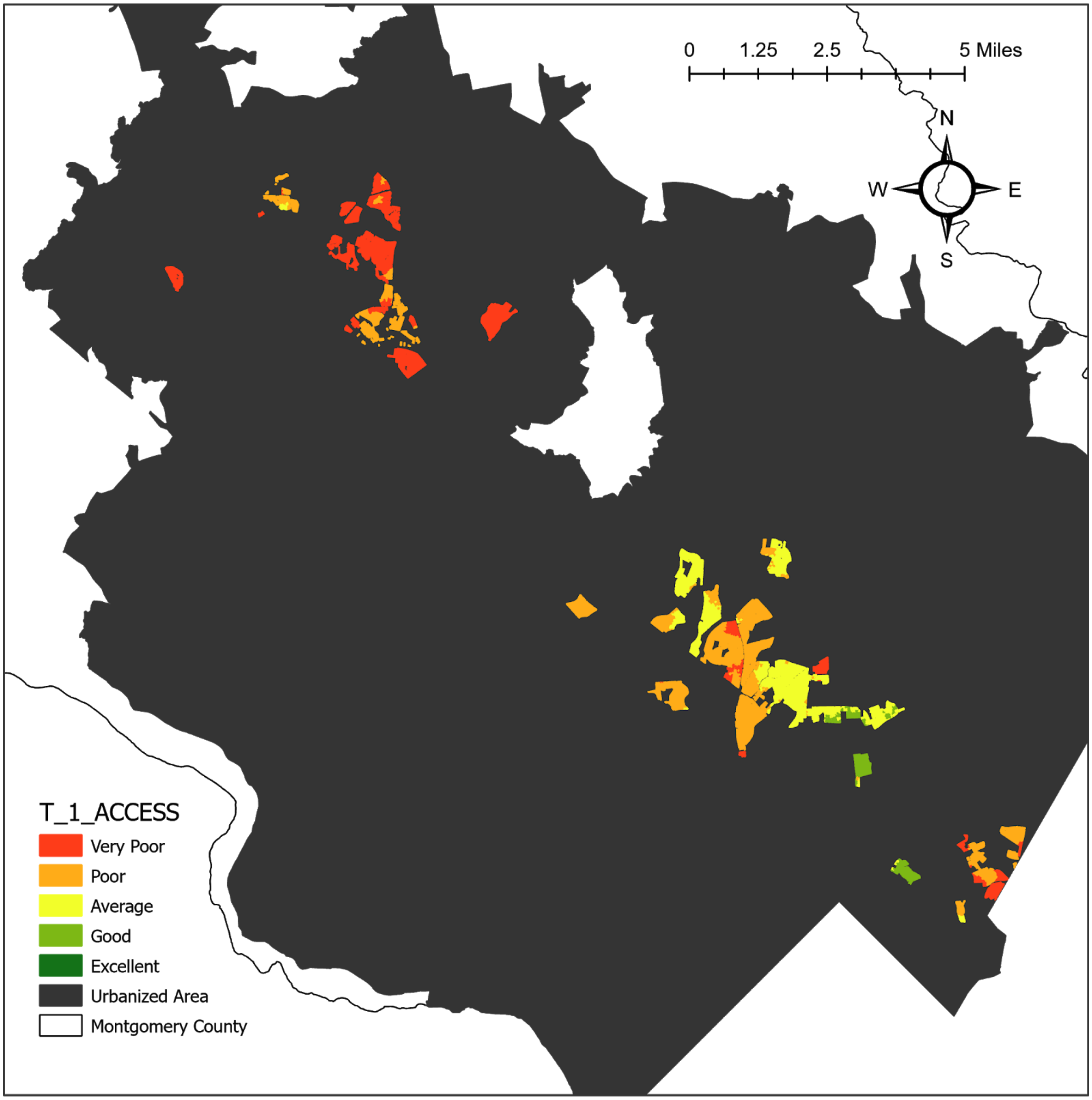

Figure II-2. Location of parcels, visualized by accessibility category, in the equity analysis study area in Tier 1.

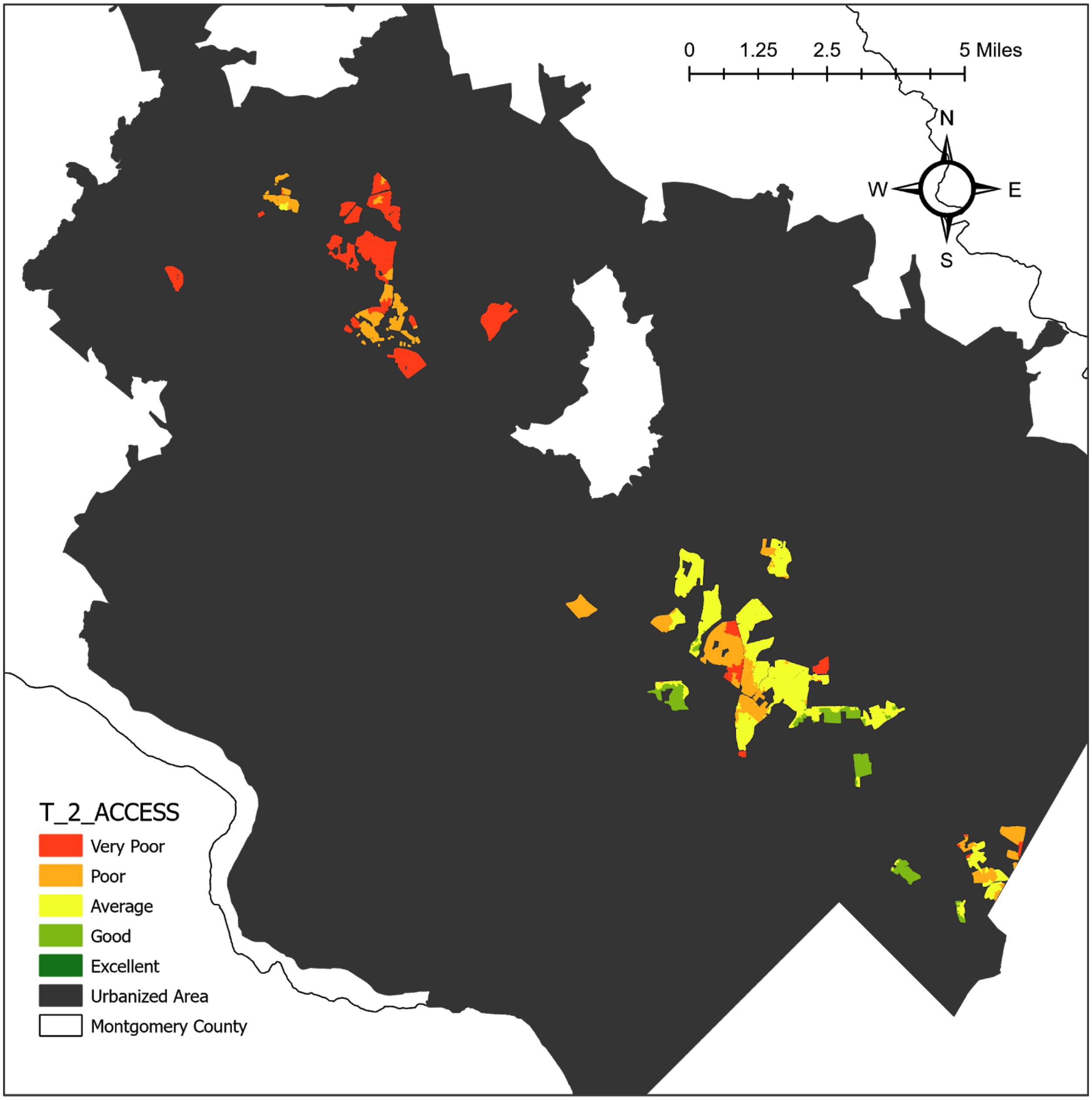

Figure II-3. Location of parcels, visualized by accessibility category, in the equity analysis study area in Tier 2.

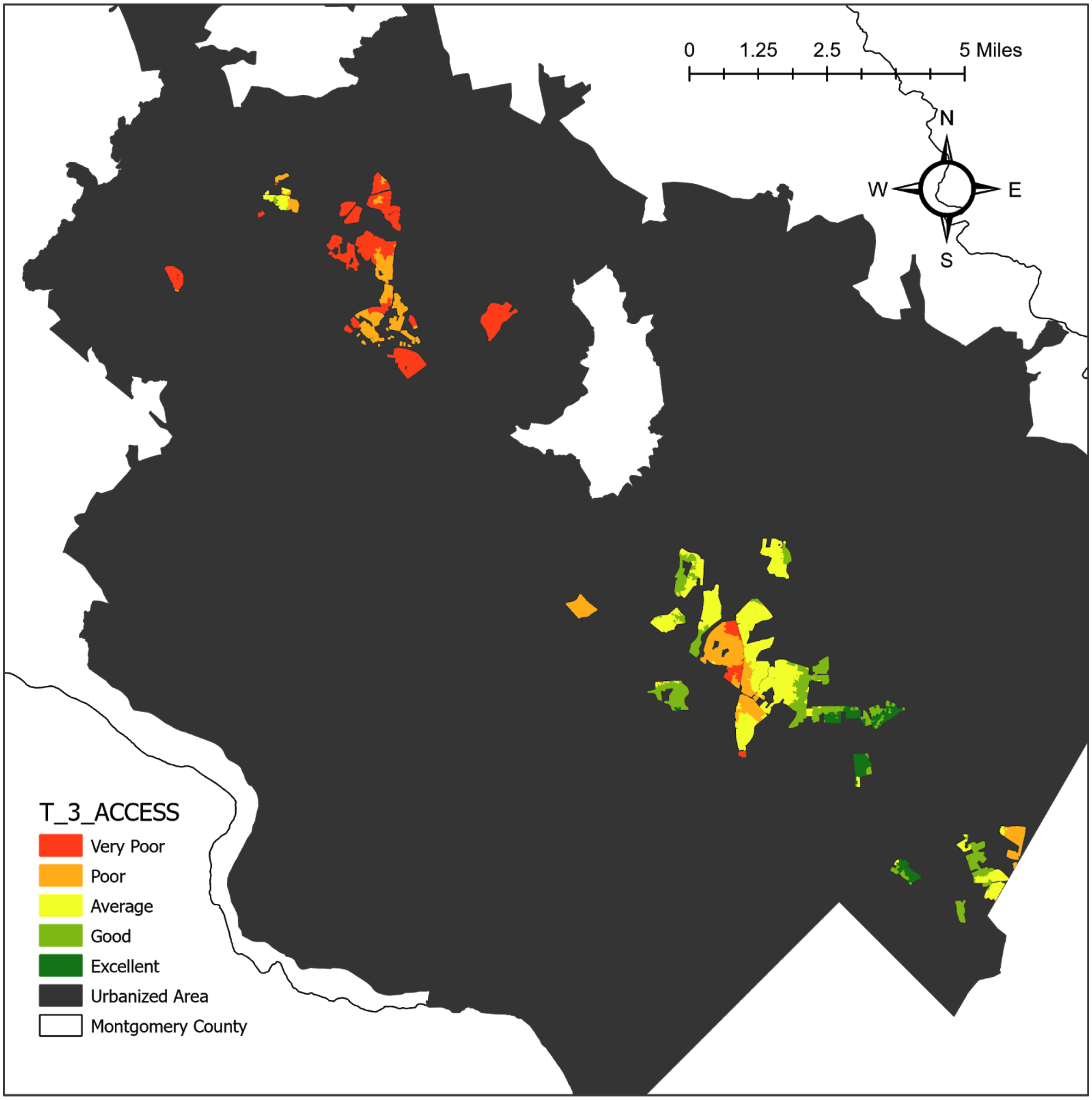

Figure II-4. Location of parcels, visualized by accessibility category, in the equity analysis study area in Tier 3.

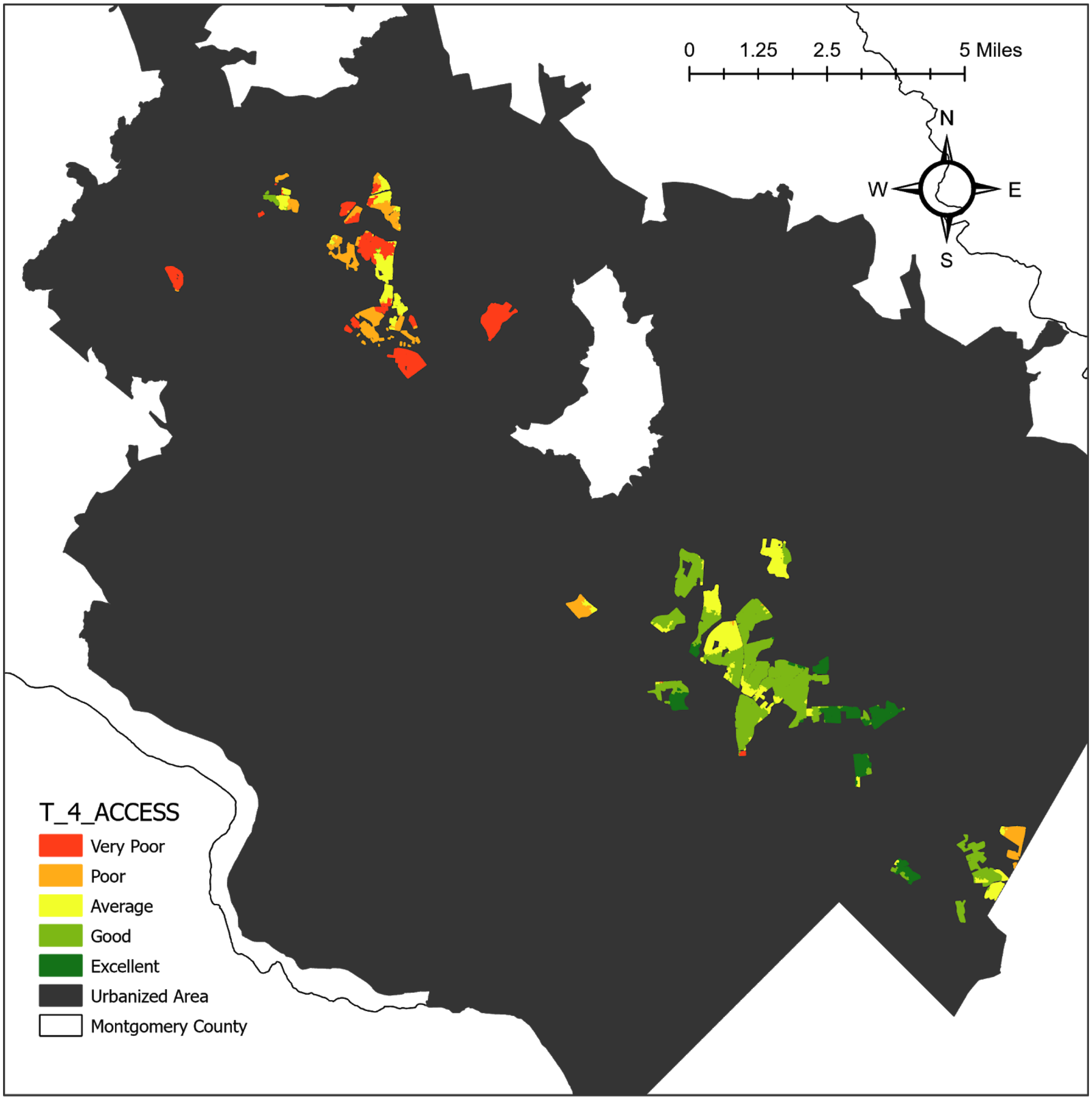

Figure II-5. Location of parcels, visualized by accessibility category, in the equity analysis study area in Tier 4.

Appendix III

The Python 3.8 script created to carry out the analysis is available in a Github repository. The URL is: https://github.com/cyrchi/bike-accessibility-capstone/blob/main/accessibility_analysis.py.

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