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High impact prioritization of bikeshare program investment to improve disadvantaged communities' access to jobs and essential services

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ABSTRACT

Bikeshare programs are increasingly popular in the United States and they offer an important alternative mode choice for many types of last-mile trips. Bikeshare systems have not captured high levels of ridership from disadvantaged populations, but there is some evidence that current bikeshare systems have specifically targeted certain populations to ensure sufficiently high demand for profitability. Far less attention has been paid to bikeshare programs' potential to provide greater access to jobs and essential services for disadvantaged communities. This paper uses two case study cities (Chicago and Philadelphia) to first, examine whether bikeshare systems have targeted specific populations, and to second, quantitatively assess the potential for bikeshare systems to provide greater accessibility for disadvantaged communities. Our results demonstrate that a well-designed bikeshare system can generate greater accessibility improvements for disadvantaged communities than the same system would produce for other populations. Using a newly developed spatial index that combines the potential for increased access to jobs and essential services, the level of bike infrastructure, and the disadvantaged population shares, we also find evidence that existing bikeshare systems have been specifically designed to target certain ridership. We find that locating stations in proximity to disadvantaged communities has the potential to increase household access (by bike and by bike-to-transit) to jobs and essential services and can close accessibility gaps between mobility constrained populations and critical services. The spatial index can be applied to identify potential locations to locate bikeshare stations (dock-based bikeshare systems) or rebalance bikes (dockless bikeshare systems) to address bikeshare equity issues.

1. Introduction

Bikeshare systems are a relatively recent mobility service offering access to a shared bicycle. Members typically pick up a bicycle at a bicycle-docking station and return the bicycle to any empty dock in proximity to their final destination. With the advent of successful bikeshare systems in Europe, a number of US cities, including Washington D.C., New York City, Chicago, and San Francisco, among others, have developed flourishing systems.

Most of the larger bikeshare systems are located in the U.S. west and the northeast and primarily operated by for-profit companies. For example, Motivate operates the bikeshare systems in San Francisco Bay Area (CA), Boston (MA), Chattanooga (TN), and Chicago (IL), while B-Cycle runs the bikeshare in Los Angeles (CA), Philadelphia (PA), Miami (FL); People took a record of 35 million bikeshare trips in 2017, 25% more than in 2016 (NACTO, 2018).

Bikeshare usage tends to be highly correlated with a variety of factors, including population density (Buck and Buehler, 2012; Krykewycz et al., 2010), income (Rixey, 2013), race (Rixey, 2013), education (Rixey, 2013), weather conditions (Li et al., 2015), and adjacency to bike lanes (Buck and Buehler, 2012). Among the aforementioned factors, it is worth noting that the proportion of the non-white population has a negative correlation with ridership (Rixey, 2013). To date, as a way of ensuring profitability, private bikeshare companies tend to target populations more likely to use their services: male, white, younger, employed, affluent, educated, and those more likely to already be engaged in cycling, independent of bikeshare (McNeil et al., 2017b; Ricci, 2015). For example, Washington DC's Capital Bikeshare (CaBi) demographics indicate the predominant users are white and of higher income (Buck, 2013). Only 19% of annual CaBi members are non-white and riders with an annual income of less than $50,000 make up only 24% of members (Buck, 2013).

The absence of bikeshare stations within walking distances is a barrier for users of the system (Bernatchez et al., 2015) and the siting of

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stations is the most critical feature of designing a system. A variety of methodologies have been applied in the literature demonstrating ways to optimize the placement of bikeshare stations (García-Palomares et al., 2012; Lin et al., 2013; Martinez et al., 2012; Romero et al., 2012). Most of these use objective functions with operational costs and/or service levels (measured by the availability rate and coverage of the respective origins and destinations) as inputs. In practice, bikeshare stations are usually placed in areas with high attraction rates (e.g. shopping centers, transit stations) and/or near sidewalks that are adjacent to bike lanes (Burden and Barth, 2009). Noted barriers to the siting of bikeshare stations include safety, weather, topography, membership registration process, and the unavailability of bike helmets (Fishman et al., 2012; Fishman et al., 2014).

The aforementioned barriers for general users are only a subset of the barriers faced by disadvantaged communities. First, there is a cultural divide that arises as many residents of disadvantaged communities mistakenly believe that bikeshare is a transport mode solely for high income, highly educated individuals and tourists (Bernatchez et al., 2015; Hoe, 2015; Stewart et al., 2013). The lack of financial resources such as credit cards, and additional costs such as membership fees also inhibit the active use of bikeshare systems in disadvantaged communities (Fishman et al., 2012). Furthermore, unsafe cycling environments near or adjacent to living areas can impede the popularity of bikeshare in disadvantaged areas. Of all of the barriers for disadvantaged communities, anxiety over safety issues stands out as most significant (Christie et al., 2011; Griffin et al., 2008; McNeil et al., 2017a).

Even when the barriers to cycling are low, there is little empirical data on the cycling behavior of residents in disadvantaged communities. We can draw a few conclusions based on correlations with certain types of trip making activity that have been studied. McDonald (2008) found that children from low-income and minority groups, particularly African-Americans and Hispanics, are potentially more likely to use active travel modes to attend school than whites or higher-income households when considering the combined effect of household income, vehicle access, distance between home and school, and residential density. Given this information, it is reasonable to conclude that there may be a strong likelihood for children in low-income and minority groups to use cycling as a primary mode to school. Additionally, McNeil et al. found that low-income African American residents are more likely to use bikeshare for recreation and/or exercise as opposed to utilitarian trips (McNeil et al., 2017b).

For bikeshare systems to prove useful to disadvantaged communities, the way in which they are designed must shift from operationalizing systems that target certain demographics to designing systems that target gaps in accessibility. In order to create high impact bikeshare systems in such communities, it is necessary to account for the complexities of how disadvantaged populations currently access jobs and essential services, while also acknowledging that the actual travel behavior forming the basis for these trips is constrained by factors that have not been well studied.

In this research, we present a new method for identifying how bikeshare systems might be spatially allocated to better serve low income and minority households. Using our new index, we test the hypothesis that existing bikeshare systems have been specifically designed to target certain ridership. We then go on to show that locating stations in proximity to disadvantaged communities has the potential to increase household access (by bike and by bike-to-transit) to jobs and essential services. We demonstrate that appropriately sited bikeshare facilities can close the accessibility gaps between mobility constrained populations and the critical services upon which they depend.

2. Methods and context

2.1. Case study cities

We recruited 16 experts from five different fields (bikeshare academics, a bikeshare company, metropolitan planning organizations (MPO), bike advocates, and local government) and asked them to rank 34 candidate cities across the available data in terms of usefulness for our study. Using their observations, we selected Chicago and Philadelphia for our analysis. These cities offer interesting similarities and contrasts in terms of size, location and funding.

In 2013, the Chicago Department of Transportation (CDOT) launched the Divvy bikeshare system (currently 581 stations), and contracted with Motivate to purchase, install, and operate the system (Motivate International, 2017a). Divvy acquired start-up federal funding from efforts aimed at promoting economic recovery, reducing traffic congestion and improving air quality. Funds were also provided from the City's Tax Increment Financing program. In July of 2015, Chicago also introduced the “Divvy for Everyone (D4E)” program, which provides affordable membership fees to qualifying residents (Motivate International, 2017b).

Indego, owned by the City of Philadelphia, was planned and managed by the Office of Transportation & Infrastructure Systems. A Philadelphia-based business that specializes in bikeshare launch (i.e., Bicycle Transit Systems) operates and maintains the bikes and the technology platform, which is provided by B-Cycle (City of Philadelphia, 2017). Indego started in 2015 and currently has 105 bikeshare stations, approximately one-sixth of the number of Chicago stations. Indego is in the early stages of development and Philadelphia made a concerted effort to learn from other bikeshare systems before launching (Scola, 2014). One of the critical aspects Indego considered prior to launch was the issue of social equity. Andrew Stober from the Mayor's Office of Transportation and Utilities in Philadelphia pointed out that areas outside of the business core are an important part of a new bikeshare system (Mcdonald, 2015; Scola, 2014). As a result, at the same time the program started, Indego implemented a reduced membership fee plan for low-income residents that includes a new cash payment option for its users (Hamilton, 2015; Indego Bikeshare System, 2017; People for Bikes, 2015; Wikipedia, 2017).

2.2. Identifying disadvantaged populations

We used the term “disadvantaged populations” to refer to people of color, low-income households, and transit-dependent households. We assembled demographic information (population, race, median household annual income, and household vehicle number data) for both Chicago and Philadelphia using the Census 2010 database. For the purposes of our analysis, we classified African-American, American Indian, Alaska Native, and Asian as minorities. We then calculated the percentages of minority populations for every block group in both Chicago and Philadelphia. The median household annual income and household vehicle number data were also assembled at the census block group level. We assumed that the ratio of household income and household vehicle ownership levels are approximately the same for every block within a block group.

Three criteria were used to designate block group disadvantaged populations: median household income, percentage of minority population, and the percentage of households owning 0–1 vehicles. We first identified those block groups with a median household income below \$25,000, the federal poverty definition for a household with four people (\$24,600) (U.S. Department of Health and Human Services, 2016). We set thresholds of low, moderate and high using the standard deviation and the percentage of minority population and percentage of households owning 0–1 vehicles within each block group. Our approach to setting threshold levels for percent population and number of vehicles is similar to the approach used by the North Central Texas Council of Governments (NCTCOG) in their “Bicycle Need Index” (Table 1) (Turner et al., 1997). Disadvantaged areas in Chicago are defined as a census block group with: a) a median household annual income below \$25,000; b) percent of minority populations over 60.9%; and c) percent of households owning or renting 0–1 vehicle over 77.9%

Table 1
Classification of disadvantaged populations.

Data	Level	Value	
Percentage of minority race[a]/households owning or renting 0–1 vehicle[b]	High Moderate Low	Percentage > mean + 0.5 × Sd[c] Mean − 0.5 × Sd ≤ percentage ≤ mean + 0.5 × Sd Percentage < mean − 0.5 × Sd	
Classification	Data	Chicago	Philadelphia
Disadvantaged	Income: below the poverty line	< $ 25,000 per year	
	Percentage 1[a]: high	> 60.9%	> 70.7%
	Percentage 2[b]: high	> 77.9%	> 84.9%
Other	Income Percentage 1 Percentage 2	Everything else	

[a] "Percentage of minority race" is abbreviated as "Percentage 1".
[b] "Percentage of households owning or renting 0-1 vehicle" is abbreviated as "Percentage 2".
[c] "Sd" stands for "standard deviation".

(Table 1). In Philadelphia, in a similar way, a disadvantaged area is a location with median household annual income below $25,000, percent of minority populations over 70.7% of, and percent of households owning or renting 0–1 vehicle above 84.9%.

2.3. Bicycle infrastructure

We relied on mapped bicycle infrastructure data from both the OpenStreetMap[1] and the local government data portals[2]. The bicycle paths in this research include exclusive restrictive paths, exclusive paths, and some paths tagged bicycle friendly in OpenStreetMap. Note that the bicycle path network is a subset of road networks; this means we restricted the cycling route options, which, in turn, causes an interesting finding in our accessibility analysis that we discuss later.

We calculated the total length of bicycle infrastructure (including designated bicycle routes, bicycle-pedestrian shared paths, and on-street bicycle paths) falling within each block group. Next, bike path density was calculated for every block group as the length of the bike path within the block group divided by the block group area. Using the bicycle infrastructure density, we organized block groups into high, moderate, and low levels using the same threshold approach discussed earlier. As noted earlier, areas with a high level of bike infrastructure will be considered as high potential locations for disadvantaged populations to safely cycle for recreation and/or exercise. Considering the importance of bicycle infrastructure for disadvantaged populations to make a bikeshare trip, we use the density of bicycle infrastructure to identify potential areas for bikeshare.

2.4. Accessibility analyses

Opportunities and travel time are two important components in any accessibility analysis. We use opportunities to refer to low-wage jobs (earning $3333/month or less[3]), grocery stores, hospitals, and schools. Jobs data were taken from the Longitudinal Employer-Household Dynamics (LEHD) database. We mapped essential services using the Google Map application program interface (API), which returns a large inventory of places (grocery stores, hospitals, and schools) within a specified search radius (Fig. 1, Fig. 2, and Fig. 3).

We measured the change in accessibility under two scenarios (Fig. 4). First, we assumed that the pedestrian system is used both alone and in conjunction with transit, and then we measured accessibility assuming access to bikeshare. In each scenario, the accessibility is calculated using the shortest time by comparing the two options. For the second scenario, we assumed that bikeshare is available in residential areas, transit stations, and destinations for services in our analysis areas. We also assumed that people are able to access the bikeshare system regardless of location or time. Thus, the walking time to get access to bikeshare stations is ignored in the second scenario. In this way, we can identify where bikeshare systems can produce the greatest benefits (accessibility improvements) when compared to the walk mode.

We calculated travel times assuming typical walking and bicycling speeds (walk speed of three miles per hour and bike speed at ten miles per hour (Salon and Handy, 2014)). Travel times for public transit network in each of the cities are calculated using data in the General Transit Feed Specification (GTFS) format, which is created by local transit providers. The GTFS data provide spatially and temporally explicit information on transit routes, stops, and schedules and can be incorporated into a GIS framework, making it reasonably straightforward to determine access via travel along the transportation network. Note that we restrict the travel time by transit by the schedule of transit services. Thus, a person may not have access to an opportunity if there is no transit service available at the time they want to start a trip and walking to another block group is not allowed (within the specified time allocation). This feature will cause some block groups with zero accessibility in scenario 1 and infinite accessibility improvements (scenario1 vs scenario 2). It is important to also note that the trip purposes of bikeshare users vary (Buck et al., 2013; McNeil et al., 2017a). Job commute is reported to be the main purpose followed by shopping/recreation, school, medical care, and other purposes (McNeil et al., 2017a). In Eq. 1, we assigned different weight factors to different opportunities based on the percentages of trip purpose from survey results by (McNeil et al., 2017a).

We measured accessibility in the standard way using Hansen's formula (Liu and Zhu, 2004),

$$A_i = \sum_{j=1}^{N} O_j e^{-\beta t_{ij}} \tag{1}$$

where A_i is the accessibility of block group i, O_j is the opportunities (jobs, transit stations, grocery stores, hospitals, and schools) available at block group j, and N is the total number of blocks that block group i has access to within a specific time threshold; β is an empirically-derived dispersion parameter (Fotheringham, 1981) and t_{ij} is the travel time between block group i and block group j. We divided block groups

[1] This database contains all the road information for a selected area (https://mapzen.com/data/metro-extracts/). In the database, there are a tag for a single path. For example, a path may be tagged with "pedestrian way".
[2] Chicago government data portal (https://data.cityofchicago.org/Transportation/Bike-Routes/3w5d-sru8) and Philadelphia open data resource (https://www.opendataphilly.org/dataset/bike-network).
[3] This job data is from LEHD. This database divides jobs by income per month. There are three categories: 1) $1250/month or less; 2) $1250/month to $3333/month; 3) greater than $3333/month. This work chose the first two categories and defined them as low-income jobs.

Fig. 1. Distribution of grocery stores in Chicago and Philadelphia.

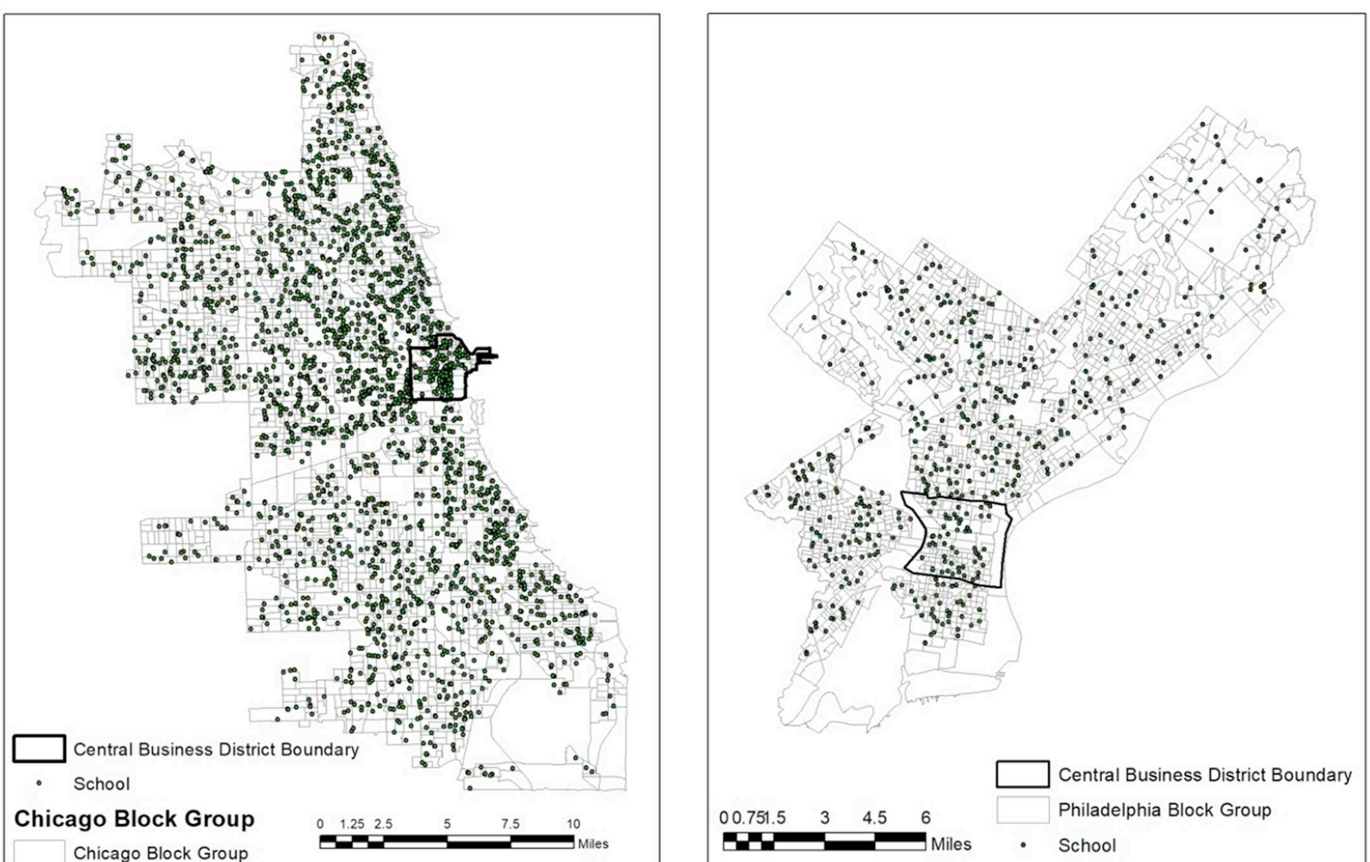

Fig. 2. Distribution of schools in Chicago and Philadelphia.

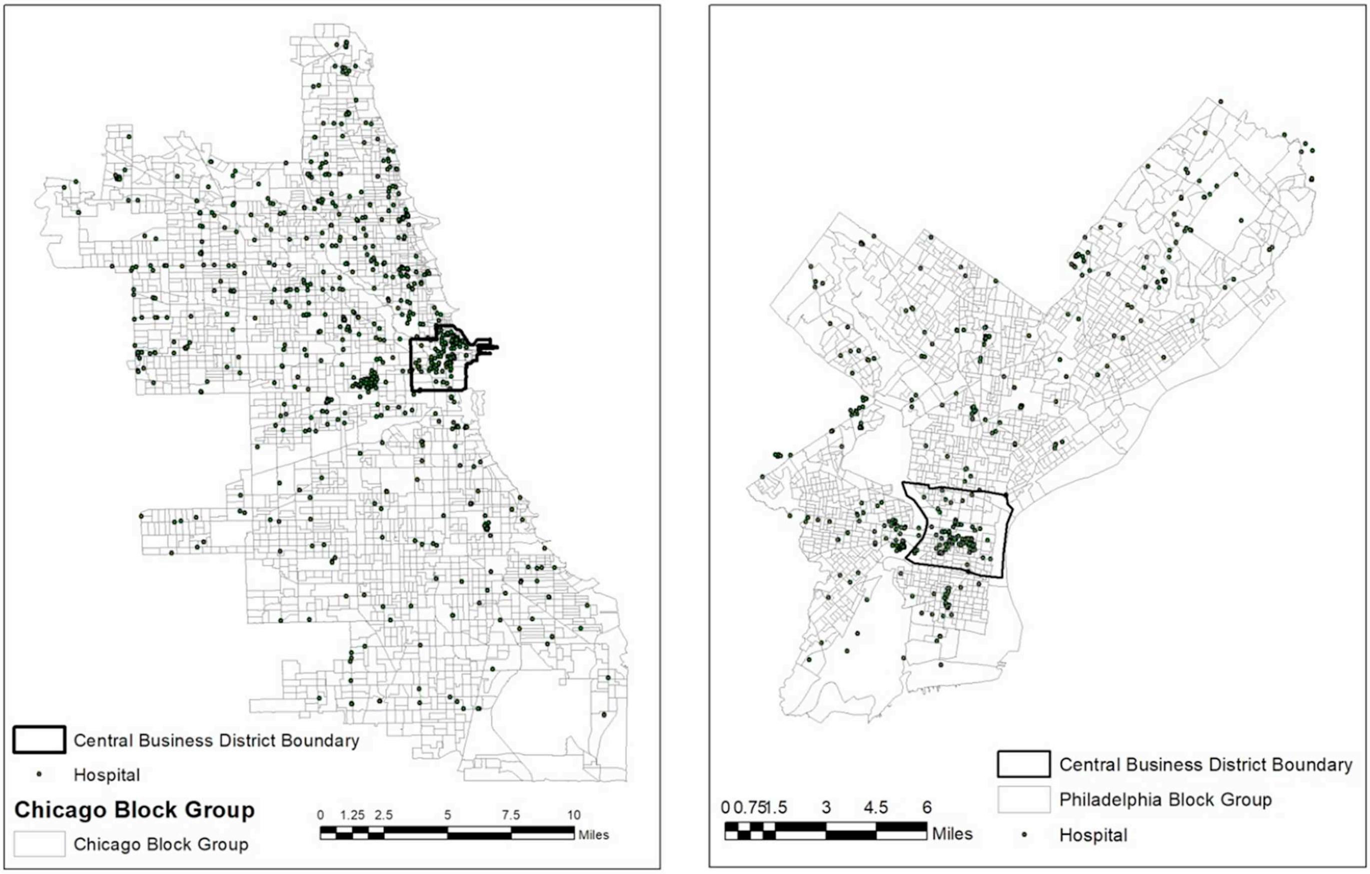

Fig. 3. Distribution of hospitals in Chicago and Philadelphia.

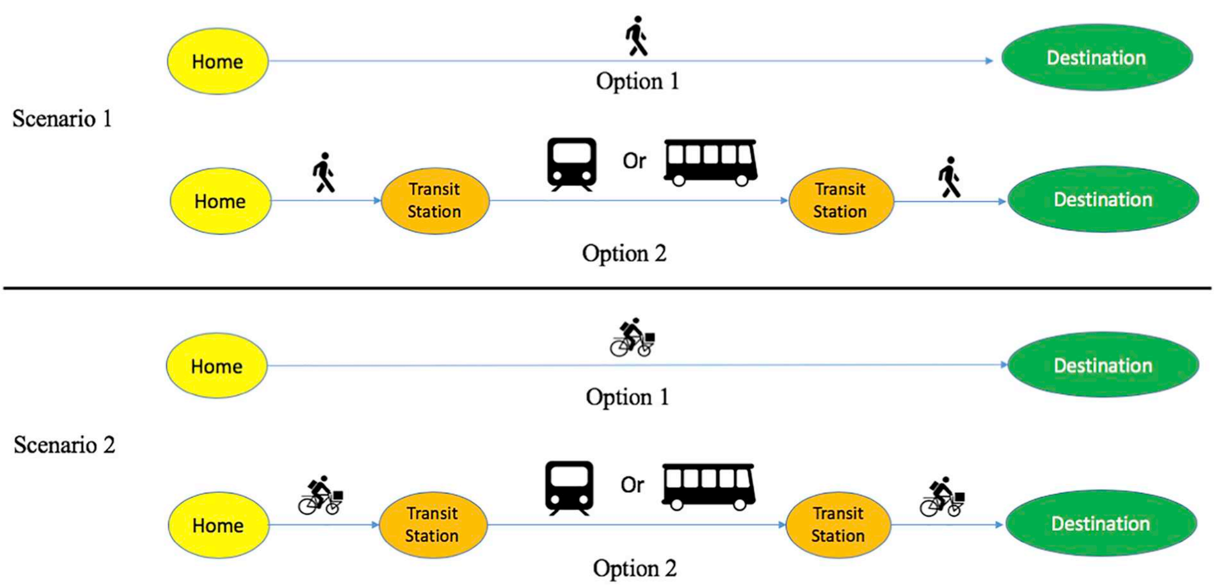

Fig. 4. Traffic mode choices in two scenarios.

into high, moderate, and low levels based on accessibility improvements using the same threshold approach discussed earlier.

2.5. Identifying priority areas

We developed a new index to identify locations where bikeshare stations have a high potential to increase accessibility for disadvantaged communities. We classified each census block group into four different categories based on the quantiles of the levels of served populations, levels of bike infrastructure, and level of accessibility improvement (Table 2). "Very high priority for bikeshare stations" refers to locations below each threshold established for disadvantaged populations, high level of bike infrastructure quality, and high potential for increased job and essential services access via bikeshare. "High priority for bikeshare stations" covers areas that have disadvantaged populations, have a high or moderate level of bike infrastructure, and provide

Table 2
Categories classification based on quantiles of three measures.

Category	Disadvantaged areas		Level of bike infrastructure			Potential for increased Job and essential service access		
	Yes	No	High	Moderate	Low	High	Moderate	Low
A	✓		✓			✓		
B	✓			✓		✓		
	✓		✓				✓	
	✓			✓			✓	
		✓	✓			✓		
C		✓		✓		✓		
		✓	✓				✓	
		✓		✓			✓	
D	✓				✓	✓		
	✓				✓		✓	
		✓			✓	✓		
		✓			✓		✓	

Note:
A: Very high priority for bikeshare stations.
B: High priority for bikeshare stations.
C: Intermediate priority for bikeshare stations.
D: High priority bikeshare and bike infrastructure combined need area.

Table 3
Number of block groups and population in different levels of served populations.

Classification	Chicago	Philadelphia		
	Block group	Population	Block group	Population
Disadvantaged	207 (9.0%)	222,887 (7.8%)	163 (12.2%)	158,103 (10.2%)
Others	2082 (91.0%)	2,646,668 (92.2%)	1173 (87.8%)	1,393,670 (89.8%)
Total	2289[a]	2,869,555[b]	1336	1,551,773

[a] Note: The unit is a block group.
[b] The unit is one person.

Table 4
Sensitivity analysis for disadvantaged population classification.

Classification	Threshold	Chicago	Philadelphia
1	Income: < \$25,000 P1[a]: > M[c] + Sd[c] P2[b]: > M + Sd	BG[c]: 128 (5.6%) Pop[c]: 131,900 (4.6%)	BG: 66 (4.9%) Pop: 60,898 (3.9%)
2	Income: < \$25,000 P1: > M + 0.75 × Sd P2: > M + 0.75 × Sd	BG: 179 (7.82%) Pop: 190,782 (6.6%)	BG: 116 (8.7%) Pop: 111,893 (7.2%)
3	Income: < \$25,000 P1: > M + 0.5 × Sd P2: > M + 0.5 × Sd	BG:207 (9.0%) Pop: 222,887 (7.8%)	BG: 163 (12.2%) Pop: 158,103(10.2%)
4	Income: < \$25,000 P1: > M + 0.25 × Sd P2: > M + 0.25 × Sd	BG: 236 (10.3%) Pop: 252,301 (8.8%)	BG: 191 (14.3%) Pop: 185,413 (11.9%)
5	Income: < \$25,000 P1: > M P2: > M	BG: 263 (11.5%) Pop: 280,268 (9.8%)	BG: 224 (16.8%) Pop: 223,158 (14.4%)

[a] "Percentage of minority race" is abbreviated as "P 1".
[b] "Percentage of households owning or renting 0-1 vehicle" is abbreviated as "P 2".
[c] "M", "Sd", "BG", "pop" stand for "mean", "standard deviation", "block group", "population", respectively.

a high or moderate potential to increase accessibility. "Intermediate priority for bikeshare stations" is a location with other populations that have a high or moderate level of bike infrastructure or potential to increase accessibility. The last category, "high priority bikeshare and bike infrastructure combined need areas," reflects locations having disadvantaged or other populations, a low bike infrastructure quality, and a moderate to high potential for increased job and essential service access via bikeshare.

3. Results

3.1. Disadvantaged populations

In both Chicago and Philadelphia, block groups with a median household annual income of less than \$25,000 are largely, but not completely coincident with block groups having minority population percentages > 50% (Fig. 14 and Fig. 15 in Appendix). Additionally, households tend to have fewer vehicles as we move toward the central city areas (Fig. 16 in Appendix). Philadelphia has slightly more block groups (12.2%) and also a larger population (10.2%) falling into the disadvantaged category compared to Chicago (9.0% of block groups and 7.8% of total population) (Table 3). There were not any block groups identified as disadvantaged within the central business district (CBD) of Chicago. Two block groups within the Philadelphia CBD are classified as low income, people of color, and limited accessibility areas (Fig. 17 in Appendix).

Since we arbitrarily assign thresholds for minority race and household vehicle ownership, we also conducted a sensitivity analysis with four different thresholds for classification (Table 4). Our initially assigned thresholds are represented in Class 3. Smaller thresholds obviously result in greater numbers of block groups or population segments as disadvantaged (Table 4). The number increase of disadvantaged population or block groups also becomes smaller when the thresholds become bigger (see below, classifications 1 to 5). The reason is that the income threshold stays fixed (below \$25,000 per year). Based on the proportion of disadvantaged population and block groups, we determined that our initial thresholds were reasonable (Class 3). If we observe the spatial distributions of disadvantaged block groups under different classifications (Fig. 5), the number of disadvantaged areas expand, but still concentrate in specific areas (in the

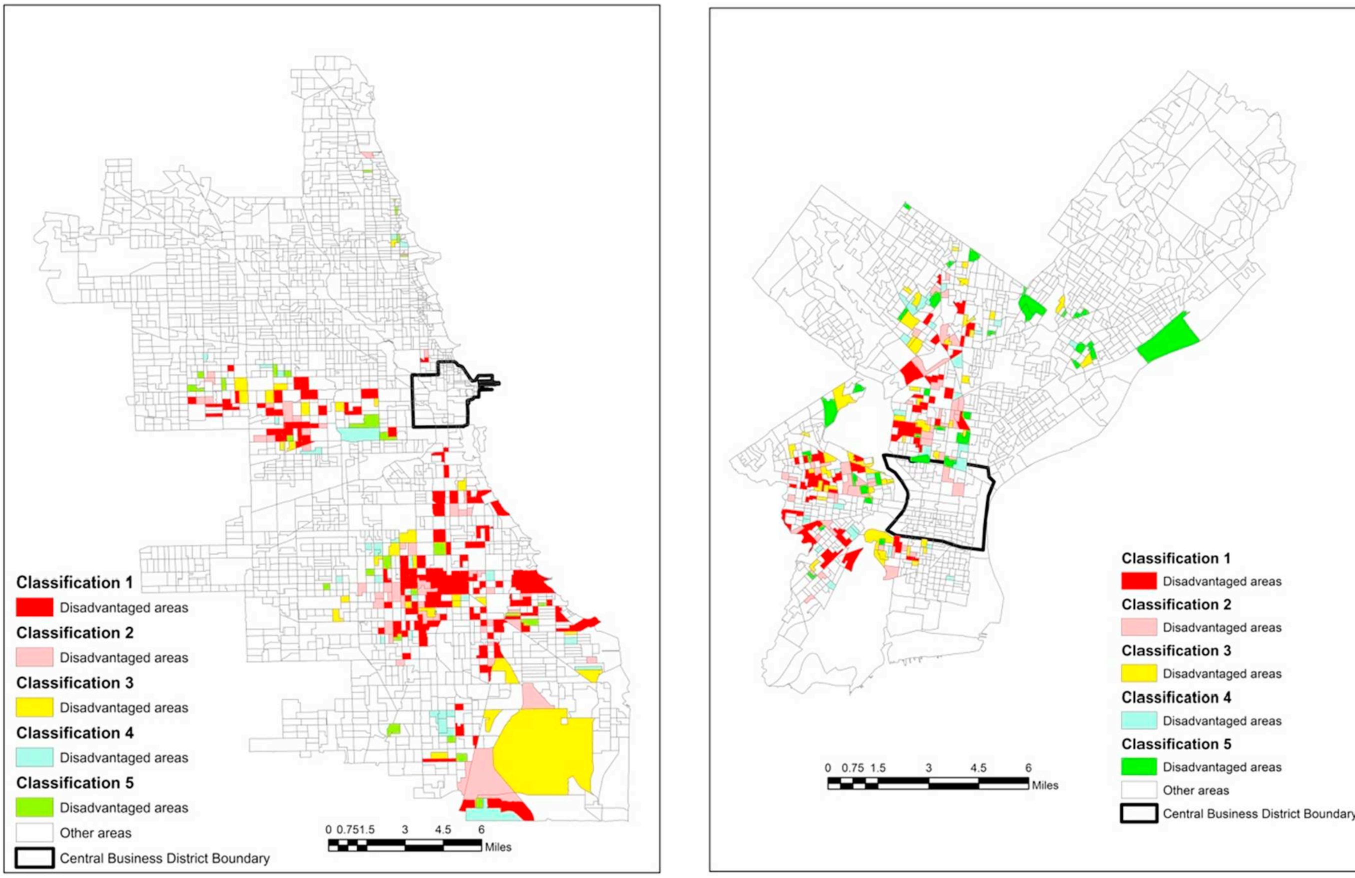

Fig. 5. Distribution of disadvantaged block groups under different classification.

Table 5
Statistics for bicycle path density within block groups.

Quantile		Chicago	Philadelphia
25%		0[a]	0
50%		15	12
75%		33	32
Maximum		215	220
Mean		22.3	22.8
Standard deviation		28.0	32.1
Threshold	High	> 36.3	> 38.8
	Moderate	8.3≤ and ≤36.3	6.7≤ and ≤38.8
	Low	< 8.3	< 6.7

[a] Note: The unit is meter per 10,000 square meters.

west and south of Chicago or in the west and north of Philadelphia).

3.2. Bicycle infrastructure

The quantiles for bicycle path densities across all block groups are shown in Table 5. We divided block groups into different levels of bicycle infrastructure using the same threshold process used to identify disadvantaged communities (Table 5). Philadelphia has fewer block groups (22.7% in Chicago vs. 19.2% in Philadelphia) and less population (23.6% in Chicago vs. 18.7% in Philadelphia) identified as having a high level of bicycle infrastructure (Table 6). From the ArcGIS map (Fig. 18 in the Appendix), the areas with the highest bicycle infrastructure density tend to be almost exclusively in the CBD areas. As might be expected, we find limited bicycle path coverage in sub-urban areas (Fig. 18 and Fig. 19 in Appendix).

The relationship between the level of served population and the availability of bicycle infrastructure (as expressed by the density of biking facilities) is shown in Table 7 and Table 8. In general, greater population and larger numbers of block groups in disadvantaged communities have a low level of bicycle infrastructure compared to other areas in both Chicago and Philadelphia. However, there are still some disadvantaged block groups (2.0% in Chicago and 3.1% in Philadelphia) located in areas with sufficient bicycle infrastructure. Most of these areas are adjacent to parks where there are numerous bike paths for exercise and recreation. In Philadelphia, this pattern is even more obvious. (Fig. 17 and Fig. 19 in Appendix). Here, most of the disadvantaged communities in the west of the central business boundary in Philadelphia are located in areas with high levels of bicycle infrastructure. If we consider just the proportion of block group, 25.4% (3.1% out of 12.2%) in disadvantaged areas have high-levels of bicycle infrastructure, while only 18.3% (16.1% out of 87.8%) of block groups in other areas taking Philadelphia as an example.

3.3. Accessibility improvement

When calculating the accessibility values, the choices of β and the maximum travel time in Eq. 1 are important. We also conducted sensitivity analyses for both β and the maximum travel time (Fig. 6). As reflected in Eq. 1, the absolute value of accessibility of scenario 1 or 2 becomes greater with the increase of the maximum travel time and drops with the increase of β, which are also shown in Fig. 6. The average accessibility improvement is significantly greater when the maximum travel time is smaller. This makes sense because access to some opportunities in scenario 2 can be achieved within a constrained time compared to no opportunities in scenario 1. We set the value of β equal to 0.5 based on our sensitivity analysis and related distance decay parameter research (Qian, 2018) and set the maximum travel time

Table 6
Number of block groups and populations at different levels of bicycle infrastructure.

Level of bicycle infrastructure	Chicago	Philadelphia		
	Block group	Population	Block group	Population
High	520 (22.7%)	676,942 (23.6%)	256 (19.2%)	290,386 (18.7%)
Moderate	852 (37.3%)	1,101,726 (38.4%)	525 (39.3%)	636,828 (41.1%)
Low	917 (40.0%)	1,090,887 (38.0%)	555 (41.5%)	624,559 (40.2%)
Total	2289	2,869,555	1336	1,551,773

Table 7
Distribution of block groups.

Level of bicycle infrastructure	Area type			
	Disadvantaged areas		Other areas	
	Chicago	Philadelphia	Chicago	Philadelphia
High	46 (2.0%)	41 (3.1%)	474 (20.8%)	215 (16.1%)
Moderate	77 (3.4%)	53 (4.0%)	775 (33.8%)	472 (35.3%)
Low	84 (3.6%)	69 (5.1%)	833 (36.4%)	486 (36.4%)
Total	207 (9.0%)	163 (12.2%)	2082 (91.0%)	1173 (87.8)

Table 8
Distribution of populations.

Level of bicycle infrastructure	Area type			
	Disadvantaged areas	Other areas		
	Chicago	Philadelphia	Chicago	Philadelphia
High	51,808 (1.8%)	40,080 (2.6%)	625,134 (21.8%)	250,306 (16.1%)
Moderate	85,374 (3.0%)	51,054 (3.3%)	1,016,352 (35.4%)	585,774 (37.7%)
Low	85,705 (3.0%)	66,969 (4.3%)	1,005,182 (35.0%)	557,590 (35.9%)
Total	222,887 (7.8%)	158,103 (10.2%)	2,646,668 (92.2%)	1,393,670 (89.8%)

equal to 10 min to avoid unrealistic accessibility improvements.

After setting β and the maximum travel time, we can examine the accessibility values for disadvantaged areas and other areas in detail. Histograms of the calculated accessibility values for each scenario for both disadvantaged areas and other areas (Fig. 7) indicate that some areas show no accessibility improvement. This is the result of limited bicycle infrastructure in these areas. That is, for areas with limited bicycle paths, negative accessibility improvements (-100%) can be observed.

The histograms of accessibility values for scenario 1 and 2 suggest that disadvantage areas tend to have smaller absolute accessibilities compared with other areas, especially in Chicago. However, when comparing the accessibility improvements, block groups in disadvantaged areas experience greater accessibility improvements. To compare the distributions of accessibility improvements in two types of areas, we applied the Kolmogorov-Smirnov test, which is a general nonparametric method for comparing two samples (Massey Jr, 1951). The K-S test suggests that the distribution of accessibility improvements in disadvantaged areas is approximately equivalent to other areas (Chicago: $D = 0.069$ and p-value = .31; Philadelphia: $D = 0.075$ and p-value = .40). Even though these two distributions are similar based on the K-S test, we still can observe increased number of block groups in disadvantaged areas with improved accessibility in the tail of the distribution.

Fig. 8 and Fig. 9 show the absolute value of accessibilities for each scenario and accessibility improvements (scenario 1 vs scenario 2) in Chicago and Philadelphia. There are two completely different patterns that emerge between absolute value of accessibility and accessibility improvement. As might be expected, there are specific areas with low accessibility in either scenario 1 or 2, for example, the west and south of Chicago (the most left picture in Fig. 8). In scenario 1 and 2, there are even some block groups with zero accessibility. As mentioned earlier, these result from limited transit service within the maximum travel time or insufficient bicycle paths. Many of the zero accessibility block groups are located in disadvantaged areas where there is not frequent transit service and the cycling environment is unsafe. However, the block groups with high levels of improvements are much more evenly distributed throughout Chicago and Philadelphia (the most right picture in Fig. 8 and Fig. 9), which is totally different from the spatial distribution of block groups with absolute high accessibility in scenario 1 or 2. In Philadelphia, there are large areas with negative accessibility improvements. Using Google Map, it's clear that these areas are mainly within an airport and ports along the Delaware River in Philadelphia. Fig. 10 shows the distribution of block groups at different levels of accessibility improvements under the aforementioned classification framework.

3.4. Priority areas for bikeshare stations in disadvantaged communities

Recall from Table 2 that we had four categories of priority areas. In this study, categories A and B refer to areas in which we are mostly concerned with equitable access to bikeshare systems. In Chicago 3.9% (0.7% + 3.2%) of all block groups are captured by the A and B categories; these block groups should be considered high priority areas for the expansion of bikeshare systems (Table 9). Approximately 5.6% (1.5% + 4.1%) of the block groups in Philadelphia are identified as

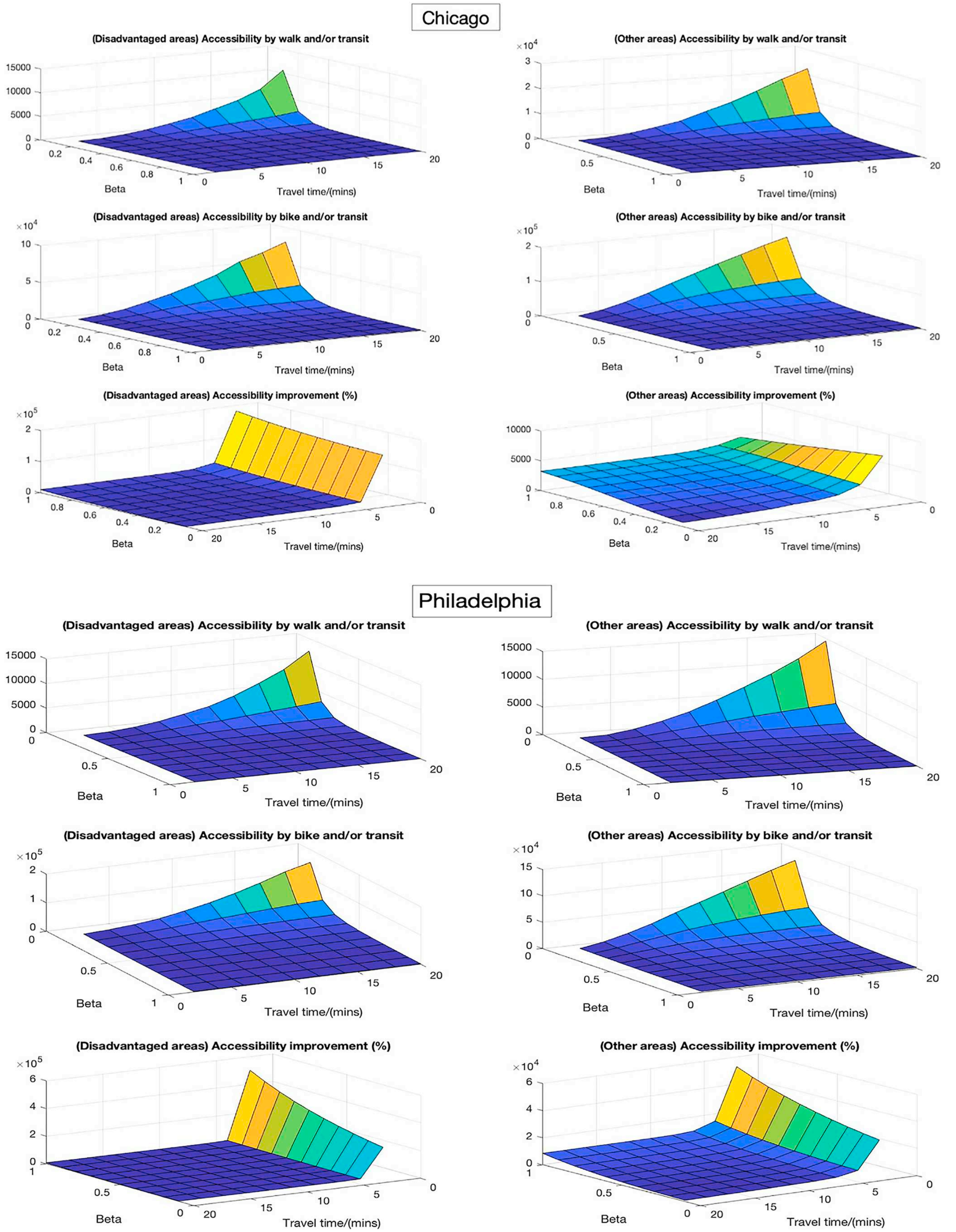

Fig. 6. Sensitivity analyses for average accessibility improvement for different groups.

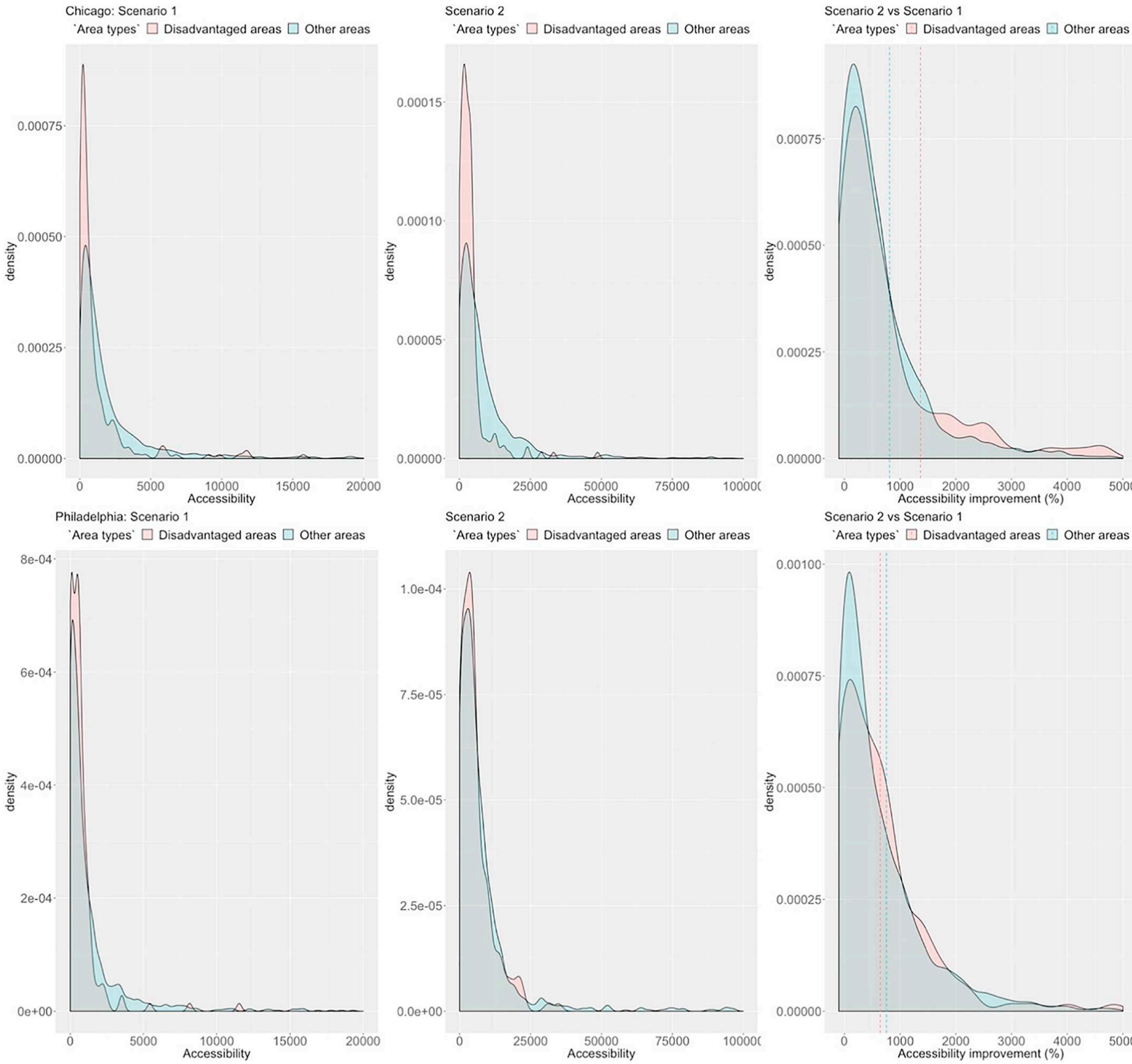

Fig. 7. Histogram of accessibility (two scenarios) and improvements in Chicago and Philadelphia.

high priority areas for bikeshare stations. In both Chicago and Philadelphia, nearly one third of them (38.5% for Chicago and 37.9% for Philadelphia) are labeled with intermediate priority for bikeshare stations. Almost a quarter of block groups (23.1% for Chicago and 24.9% for Philadelphia) are categorized as high priority areas for bikeshare and bike infrastructure. These results clearly indicate that there are sufficient numbers of areas of demand to support targeted bikeshare systems.

3.5. Current bikeshare station locations

We also compared the current bikeshare stations to those block group categories we classified. As shown in Table 10, both Chicago (0.3%) and Philadelphia (1.0%) have a small number of stations sited in disadvantaged areas that provide very high accessibility improvements. For category B, Chicago has only 3.3% of stations in this group, while Philadelphia has 2.9% of stations. Comparing percentages of current bikeshare stations located in areas identified as high priority for bikeshare systems (category A and category B), Philadelphia performs better than Chicago but Philadelphia also has a much smaller system than Chicago. This suggests that Indego's stated intention to design a bikeshare system with equitable access has been to some degree accomplished. There is another interesting finding; in Chicago, the proportion of bikeshare stations in category D (high priority bikeshare and bike infrastructure combined need areas) is nearly three times greater than in Philadelphia. This may be the result of differences in the spatial distribution of bicycle infrastructure and disadvantaged populations. Note that category D includes some disadvantage block groups with limited bike paths. In Chicago, there are a certain number of bikeshare stations in the south and west where a high overlap between disadvantaged population and areas with insufficient bicycle paths occurs (Fig. 11).

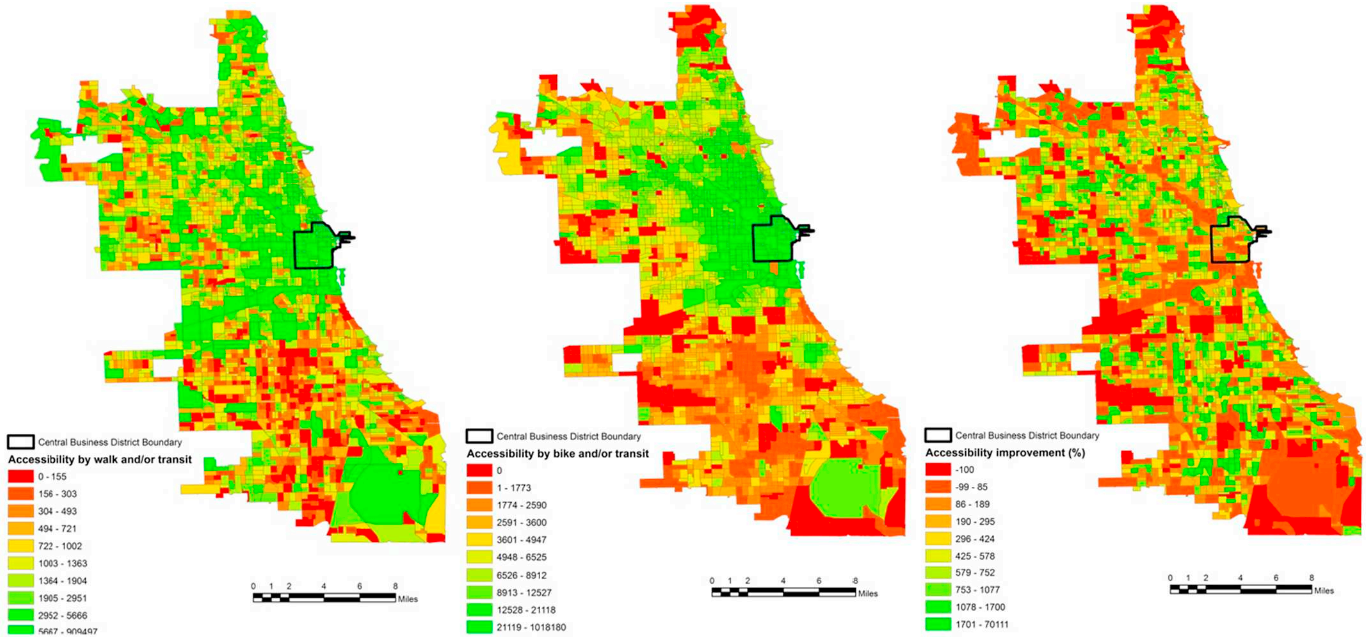

Fig. 8. Spatial distribution of accessibility (two scenarios) and improvements in Chicago.

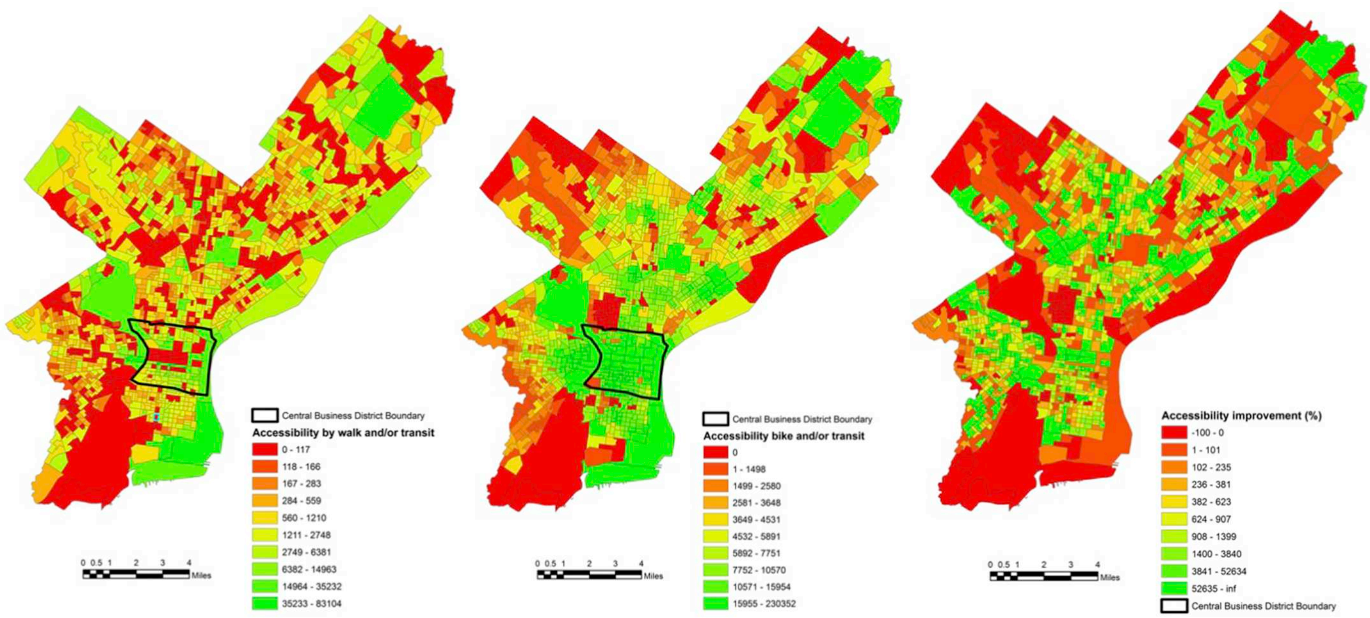

Fig. 9. Spatial distribution of accessibility (two scenarios) and improvements in Philadelphia.

4. Discussion

4.1. The current bikeshare station siting

We have quantitatively demonstrated that bikeshare stations in both Philadelphia and Chicago tend to be located in areas with more affluent and white populations. This is consistent with findings from McNeil et al. (2017a)'s qualitative investigation and from Ursaki and Aultman-Hall (2016)'s demographic information analysis using bikeshare stations' buffer areas. Additionally, the overall number of bikeshare stations in every block group tends to be higher in those block groups having a higher percentage of white population (Fig. 12). Having limited bikeshare stations in disadvantaged areas affects the bikeshare usage there. Taking Chicago as an example (Fig. 13), most of the bikeshare stations with high numbers of annual origination or destination trips are located in areas with greater white population. Many bikeshare system programs claim to have taken equity into consideration for station siting (Howland et al., 2017; Shaheen et al., 2014), but, as with bikeshare operators, have lacked a quantitative method or index for confirming the allocation of stations is equitable (Howland et al., 2017). While guidelines for implementing bikeshare systems are available (National Association of City Transportation Officials, 2014), they tend to suggest, somewhat simplistically, locations with heavy pedestrian or visitor flow or adjacent to safe bicycle infrastructure. They also tend to provide guidance on physical bikeshare station siting types and design principles such as how to fit a bikeshare station into a

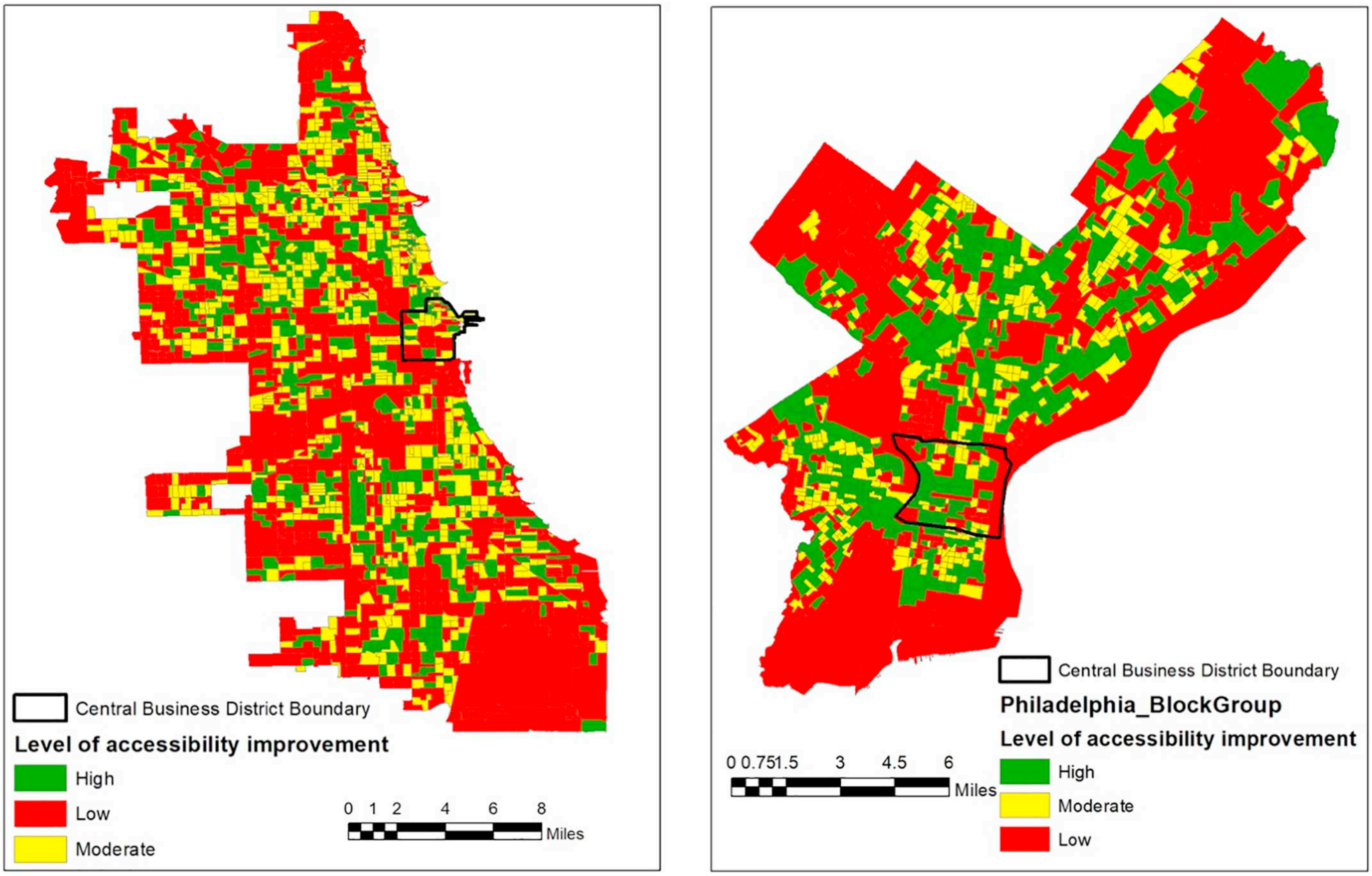

Fig. 10. Distribution of block groups at different levels of accessibility improvements.

Table 9
Distribution of block groups in four categories in Chicago and Philadelphia.

Category	Chicago	Philadelphia
A	16 (0.7%)	20 (1.5%)
B	73 (3.2%)	55 (4.1%)
C	881 (38.5%)	507 (37.9%)
D	528 (23.1%)	332 (24.9%)
Others	791 (34.5%)	422 (31.6%)
Total number of block groups	2289	1336

Note:
A: Very high priority for bikeshare stations.
B: High priority for bikeshare stations.
C: Intermediate priority for bikeshare stations.
D: High priority bikeshare and bike infrastructure combined need areas.

Table 10
Distribution of bikeshare stations in four different categories in Chicago and Philadelphia.

Category	Chicago	Philadelphia
A	2(0.3%)	1 (1.0%)
B	19 (3.3%)	3 (2.9%)
C	253 (43.6%)	51 (48.5%)
D	68 (11.7%)	4 (3.8%)
Others	239 (41.1%)	46 (43.8%)
Total number	581	105

A: Very high priority for bikeshare stations.
B: High priority for bikeshare stations.
C: Intermediate priority for bikeshare stations.
D: High priority bikeshare and bike infrastructure combined need areas.

street parking lot. When compared with the physical design of a station, we would argue that siting a bikeshare station at a location where residents actually need it is more important. The index we developed shows that not enough bikeshare stations are placed in disadvantaged areas in Chicago and Philadelphia, despite the substantial benefits bikeshare would bring to these communities.

4.2. Policy insights for elimination of access barriers and potential accessibility improvement for disadvantaged communities (dock-base or dockless systems)

The index developed in this study can prioritize high bikeshare investment area to eliminate access barrier and indicate potential accessibility improvement for disadvantaged populations. The granularity for our analyses is census block group. There are two reasons to conduct spatial analyses at this level. First, on average, there is usually at least one bikeshare station in a census block group, making it easy to use the block group as a planning unit when a bikeshare system considers expanding. Secondly, the presence of bikeshare stations within walking distance is just one of many barriers residents of disadvantaged communities face. In our analysis, the average area of block groups is 263,140 (Chicago)/272,869 (Philadelphia) square meters, which is approximately a 500-m long square. If a disadvantaged block group has a bikeshare station, the average walking distance for residents in this block group to get access to the station is within a reasonable 400-m range (Cohen, 2016). In this way, our scale appropriate index can

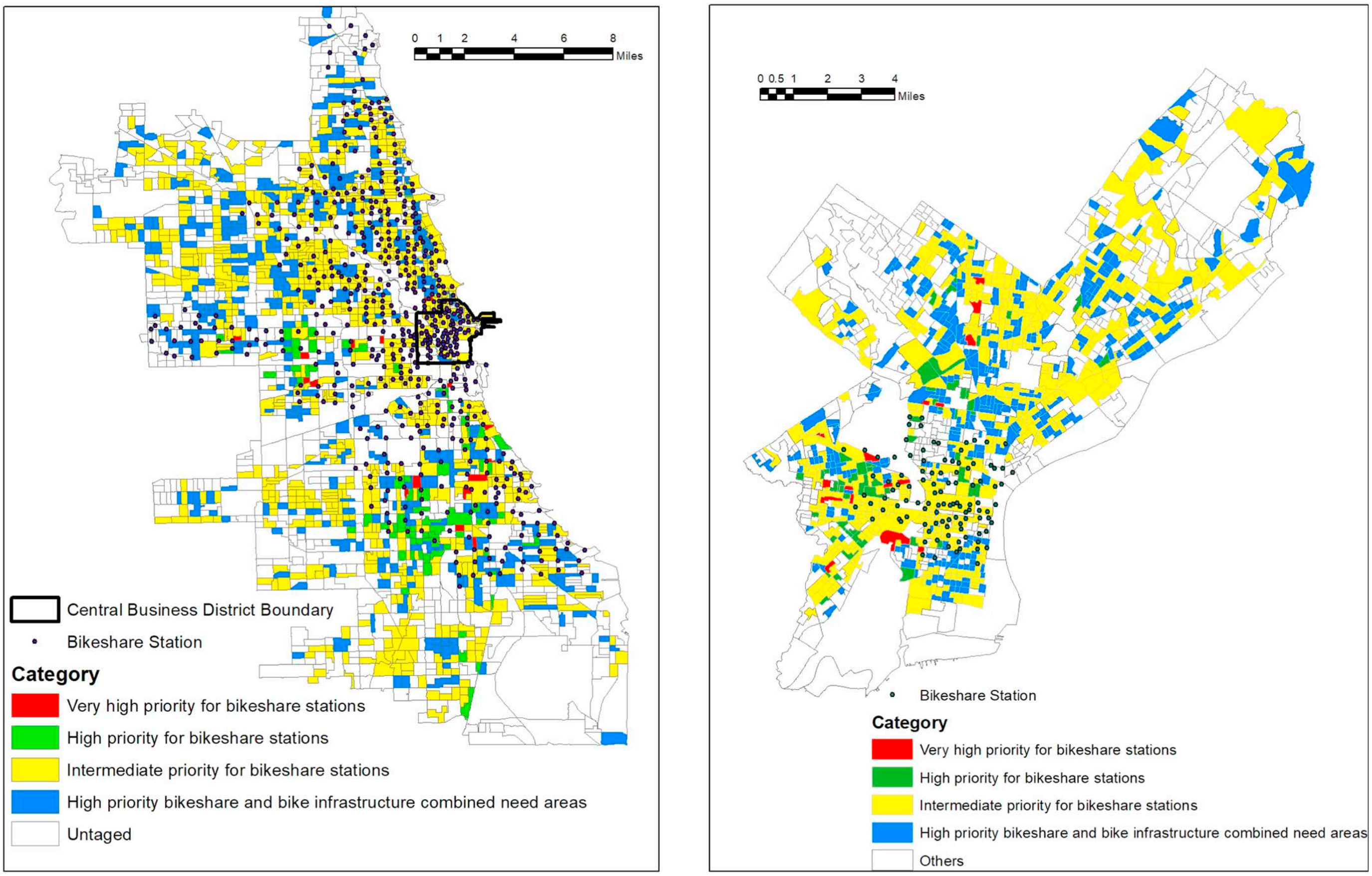

Fig. 11. Map of current bikeshare stations and block group classifications in Chicago and Philadelphia.

identify the priority areas for bikeshare stations and help to eliminate access barriers for disadvantaged populations. Our index also identifies areas that need more bike paths, which could suggest how to allocate fund resource to improve bicycle infrastructure.

4.3. Lessons from two case study cities

As mentioned in section 2.1, the two bikeshare systems in Chicago and Philadelphia are owned by the cities and operated by two for-profit companies (Motivate and B-Cycle, respectively). Both systems have tried to include more disadvantaged areas into their service areas offering, for example, discounted membership for low-income households. This manifests as an agreement between bikeshare operators and local cities. Municipalities could reduce taxes on those bikeshare operation companies or develop metrics to measure bikeshare equity to incentivize companies to offer greater coverage in disadvantaged neighborhoods.

Finally, even though the two bikeshare systems we studied are similar in addressing bikeshare equity issues, there is still a difference in how they developed their operational strategies. As noted by other research (Buck, 2013; Howland et al., 2017), the extension of a large bikeshare system will increase the potential to cover greater numbers of disadvantaged areas. However, as our study implies, a smaller bikeshare system still early in its development (like Indego in Philadelphia) can also make a significant reduction in access barriers for disadvantaged communities. Chicago has a 581-station system compared to the 105-station system in Philadelphia. Both Chicago and Philadelphia have made efforts to guarantee equitable access, but the Philadelphia is a good example of proactively attempting to eliminate access barriers for disadvantaged communities. Taking disadvantaged communities into early consideration and developing a clear metric to represent different kinds of populations are critical factors to making bikeshare systems more equitable. In the early stages of planning, Philadelphia reflected on how to implement their system. To eliminate the access barrier for disadvantaged communities, 20 out of the first 60 bikeshare stations were planned to be located in low-income communities with the remaining 40 to be located in the greater Center City and University City (Hahn, 2014). Moreover, Indego in Philadelphia reconsidered all the barriers (payment systems, membership models, and perceptions about bikeshare) for low-income members. Our research quantitatively shows that access barriers for use of bikeshare can be overcome, to some extent, by carefully considering each factor in the early stages of designing a bikeshare system.

4.4. Limitations and future research directions

It is important to emphasize there are limitations to this study. For one, in our accessibility analysis we assumed two scenarios, walk-to-transit and bike-to-transit, to focus on benefits of bikeshare systems. However, in reality bicycles are not usually the primary transport mode. If more information about traffic demand and transport mode split in disadvantaged areas were available, we could have precisely estimated the number of bike trips and created a more nuanced model for accurate estimation of accessibility improvement by bikeshare systems. Second, the travel times are averaged across entire block groups, and therefore only offer an approximate travel time between every block group pair. Third, in the accessibility analysis, other important travel elements such as travel cost of access could be included since cost is also an essential factor of concern for disadvantaged population. Finally, dockless bikeshare systems have become increasingly this is just very interesting

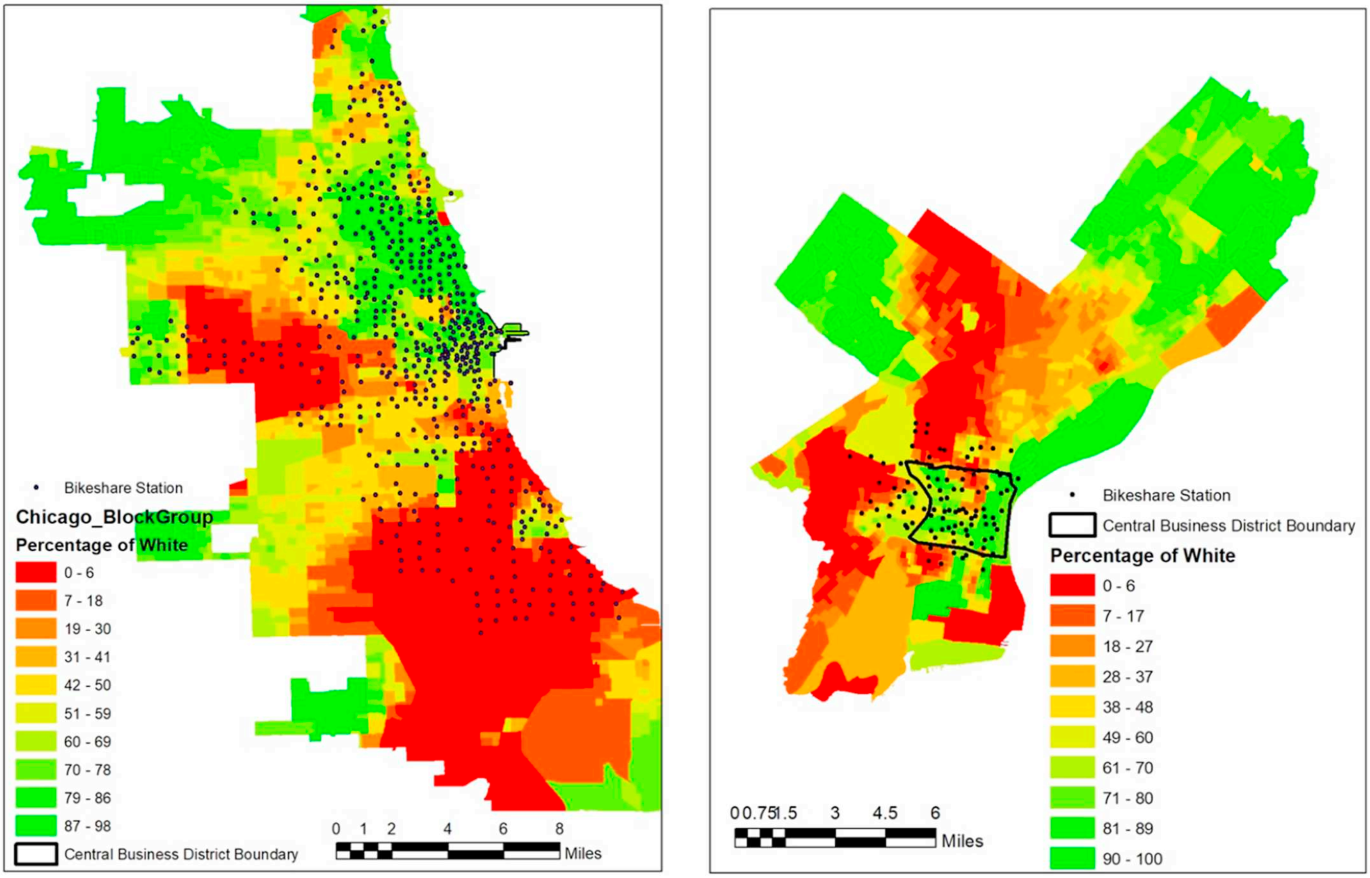

Fig. 12. Distribution of bikeshare stations and white population in Chicago and Philadelphia.

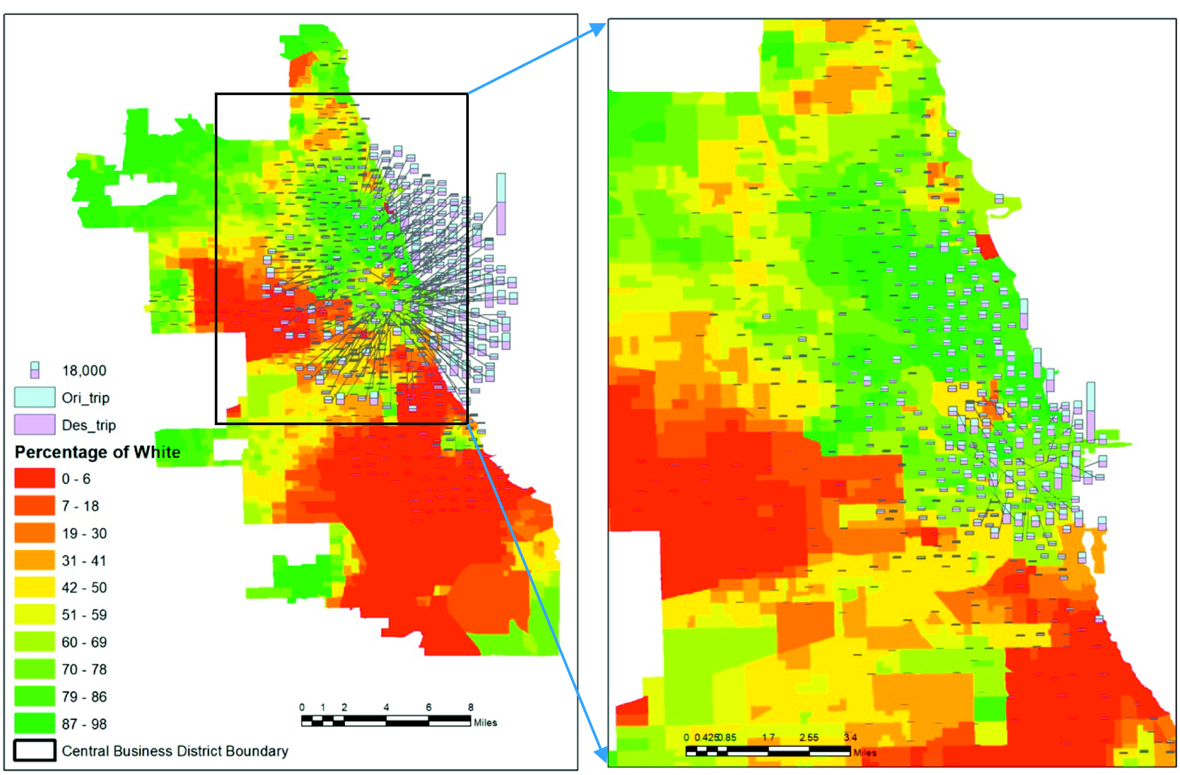

Fig. 13. Number of annual origination ("ori_trip") and annual destination ("des_trip") trips for every station in Chicago.

prevalent. Our study does not include dockless systems because this new system has no physical bikeshare station and its system data are not available. The dockless systems may be more efficient to cover disadvantaged areas since a physical station is not necessary to expand their service areas. However, more studies are needed to compare the expense to dynamically relocate bikes to cover more areas (dockless) and the financial support to open new bikeshare stations (dock-based). Despite these limitations, this study contributes by providing a better understanding of how prioritized investments in bikeshare can improve essential accessibility for disadvantaged communities.

5. Conclusions

Bikeshare programs can play an important role in sustainable transportation systems by offering a viable mode choice for many types of last mile trips. However, recent bikeshare systems tend to target more affluent and white-dominated areas. To address this problem, this paper conducts an accessibility analysis before and after bikeshare is available. Based on our quantitative analysis, bikeshare systems can produce substantial accessibility improvements for disadvantaged communities. Average accessibility improvements for disadvantaged communities can be greater than those experienced in other areas. Furthermore, our research presents a new index that identifies bikeshare station locations providing high potential accessibility improvement to jobs and essential services for disadvantaged communities. By comparing these potential locations with current dock-based bikeshare station siting, our research clearly demonstrates that most of the current bikeshare stations in Chicago and Philadelphia are not located in high priority areas for bikeshare stations if we consider disadvantaged populations. Through these two study cities, we learn that a bikeshare system in its early stages can proactively attempt to eliminate access barriers for disadvantaged communities with consideration of equitable accessibility.

Conflict of interest

None.

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Appendix

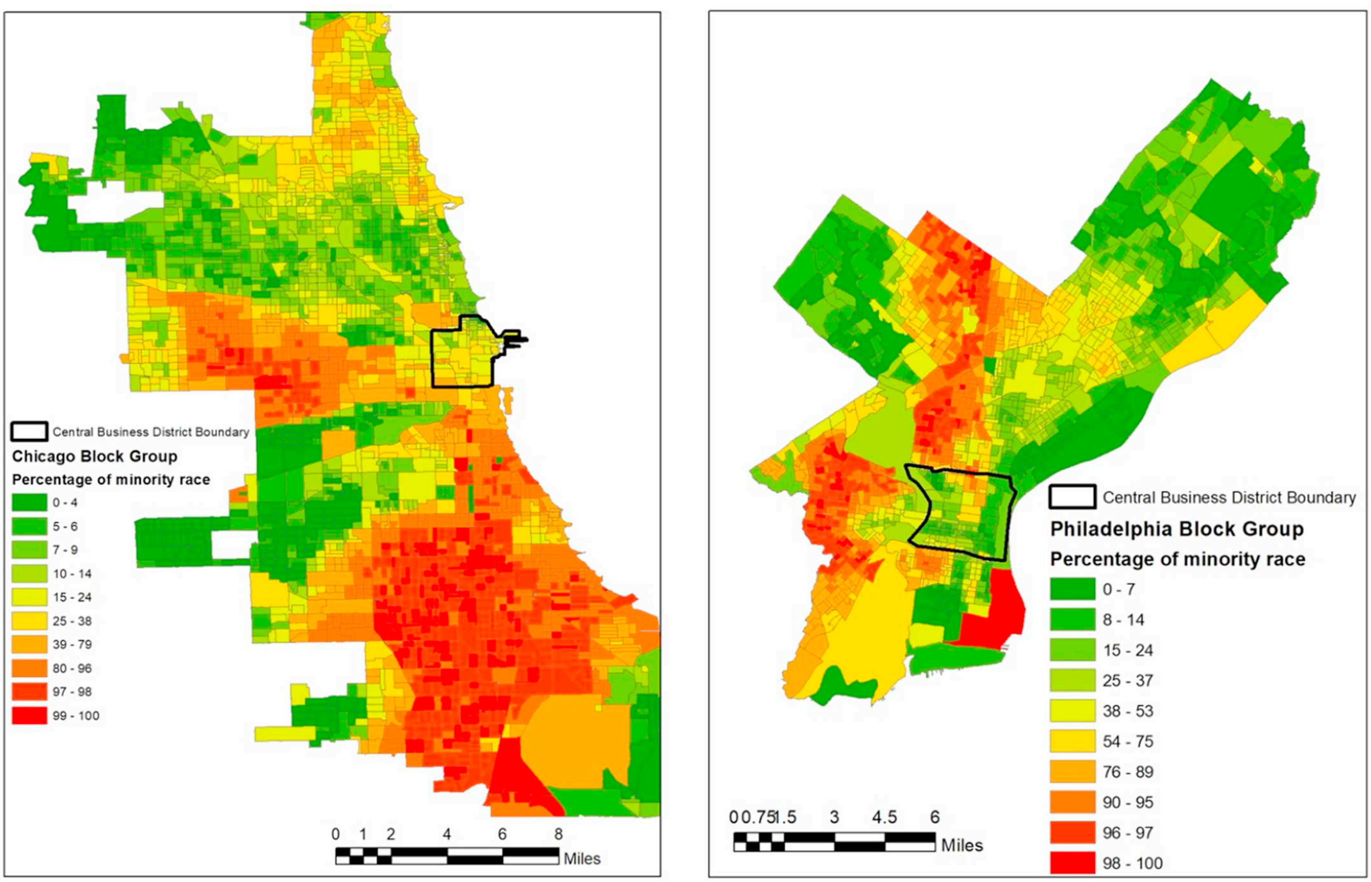


Fig. 14. Percentage of minority population.

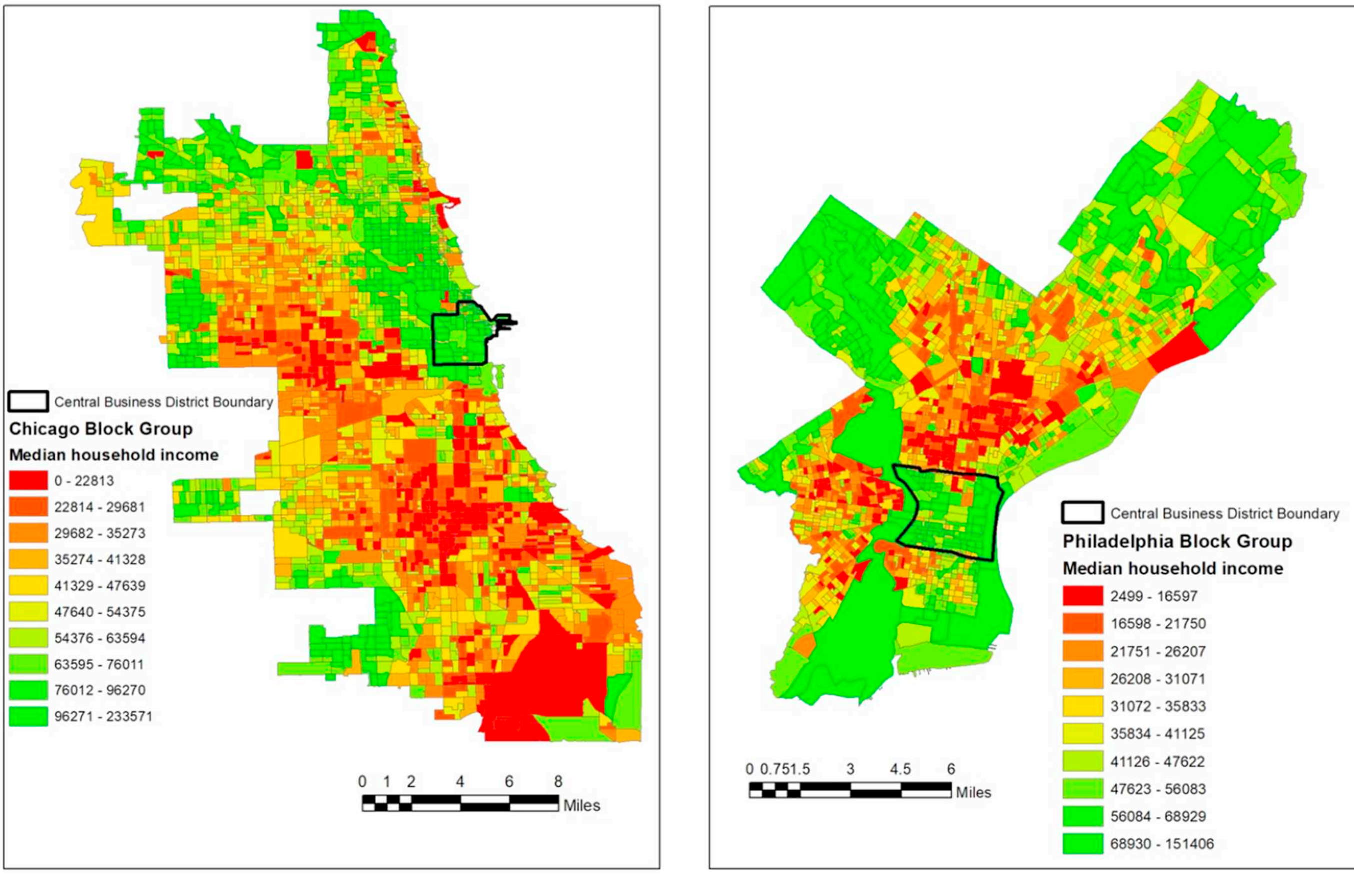


Fig. 15. Median household income.

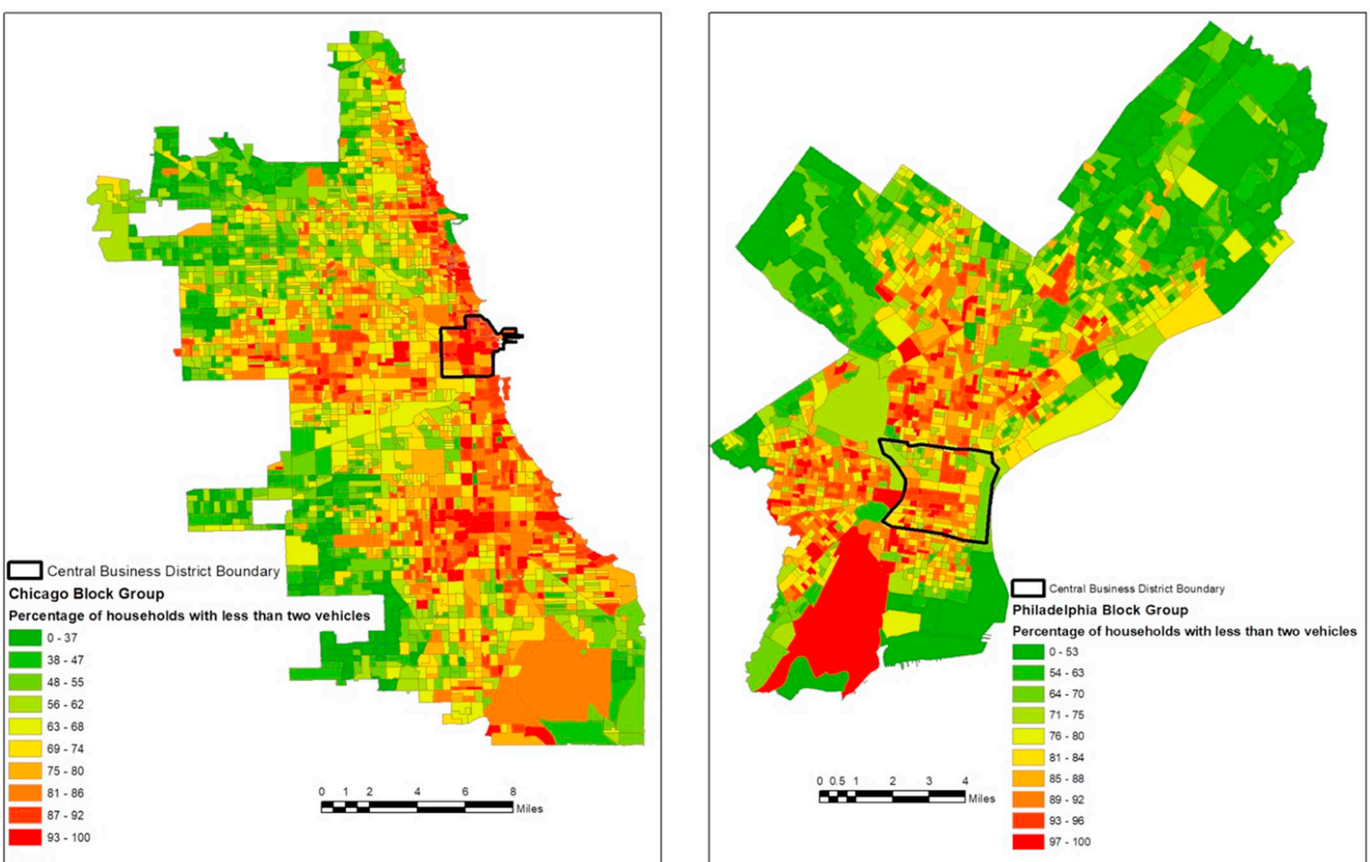


Fig. 16. Percentage of households with less than two vehicles.

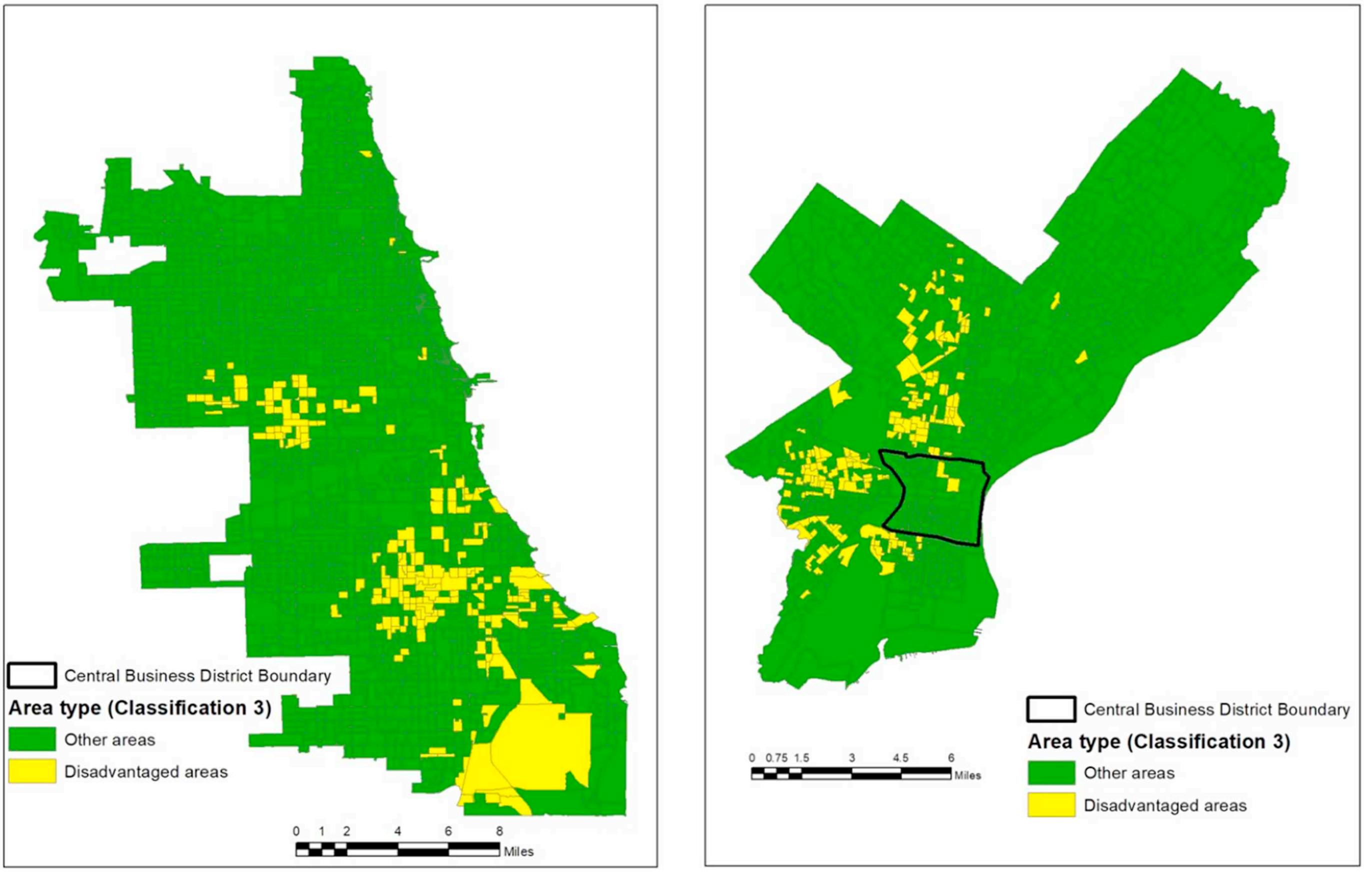


Fig. 17. Distribution of disadvantaged areas.

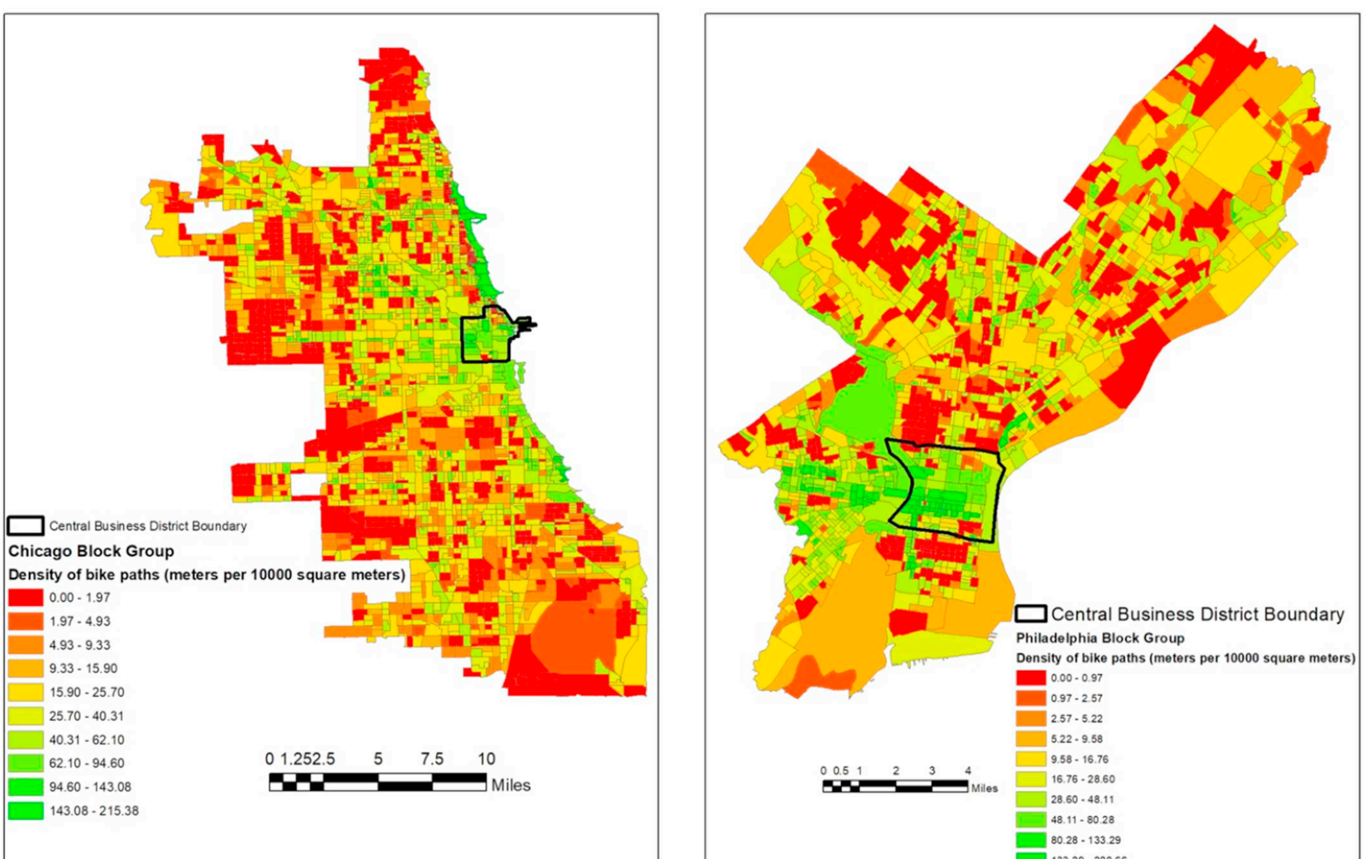
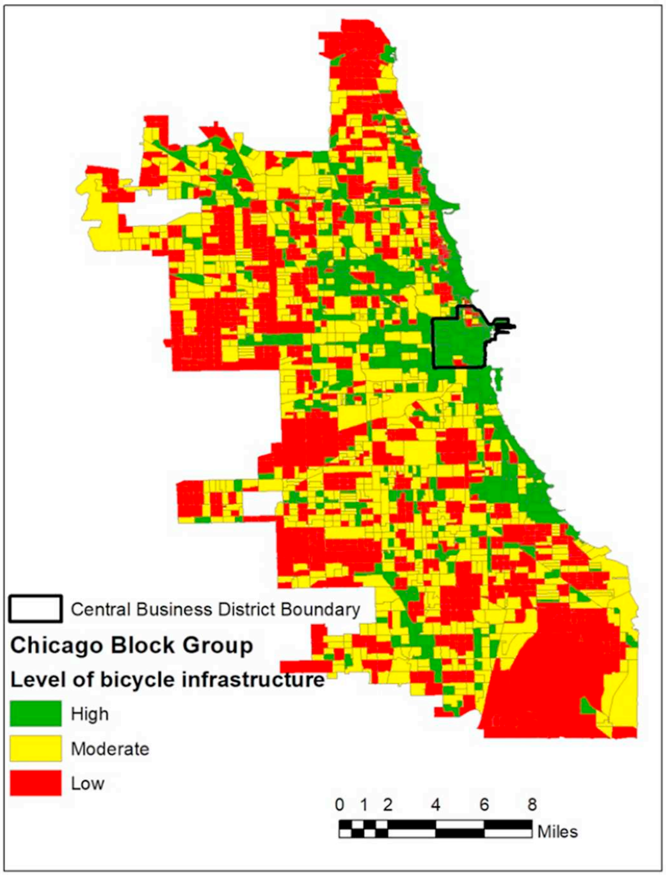


Fig. 18. Density of bike path.



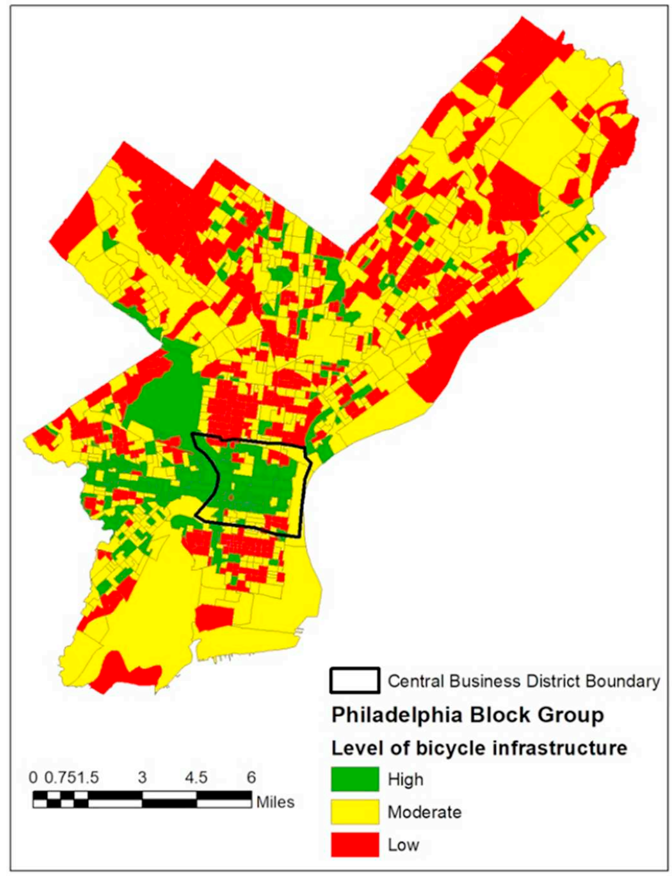


Fig. 19. Distribution of block groups at different levels of bicycle infrastructure.

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