Examining spatial equity in accessibility to a public bicycle share program using a balanced floating catchment area approach

Elise Desjardins[*,1], Christopher D. Higgins[**,1], Antonio Paez[**,1]

[a]*School of Earth, Environment & Society, 1280 Main Street West, Hamilton, ON L8S4L8*
[b]*Department of Geography & Planning, 1265 Military Trail, Toronto, ON M1C1A4*

Abstract

Public bicycle share programs (PBSPs) are implemented to promote cycling as a convenient and sustainable mode of transportation. These systems can also play a role in addressing transportation needs and advancing transportation equity if they make cycling more accessible to lower income or disadvantaged populations. In Ontario, the City of Hamilton launched a public bicycle share program in 2015 that currently has over 900 operational bicycles and 130 docking stations. This system was expanded in 2018 by an equity initiative that added twelve docking stations with the explicit objective of increasing spatial equity in access. Since the cost of reaching a bicycle share station decreases the potential of accessing the program, the location of stations matters, and previous research found that Hamilton's public bicycle share program targeted well disadvantaged areas in the city. In this research, we revisit the case of Hamilton and investigate differentials in accessibility to bicycle share stations using a balanced floating catchment area (BFCA) accessibility approach. We compare accessibility with and without the equity stations to assess the effect of the initiative. We implement our analysis parting from micro zones to better reflect walking to a docking station, and conduct a sensitivity analysis at several walking time thresholds. We then reaggregate the estimated accessibility for further analysis using census data. The addition of equity stations increased the serviced population at every threshold examined, and although accessibility increased for the whole population, this increase was relatively modest especially for population in the bottom 20% of median household income.

[*]Corresponding Author
[**]Equal contribution
Email addresses: desjae@mcmaster.ca (Elise Desjardins), cd.higgins@utoronto.ca (Christopher D. Higgins), paezha@mcmaster.ca (Antonio Paez)

Introduction

The potential of public bicycle share programs (PBSPs) to increase cycling levels is but one of many reasons for implementing such programs in urban areas (Hosford et al., 2018, 2019). As a healthy, inexpensive, and convenient form of public transportation, shared bicycles can encourage individuals to take up cycling for short local trips or first and last mile trips to other public transportation instead of using personal vehicles. These systems can also play a role in addressing transportation needs and advancing transportation equity if they make cycling more accessible to lower income or disadvantaged populations. As these systems become increasingly common, their introduction has been accompanied by a flurry of research that investigates them from the perspective of spatial and transportation equity (e.g., Smith et al., 2015; Hosford and Winters, 2018; Hull Grasso et al., 2020; Mooney et al., 2019; Qian and Jaller, 2020; Qian et al., 2020). Indeed, although these programs are available to the general public and ought to be accessible to any individuals who wish to use them, research on PBSPs located in North American and European cities indicates that there are inequities in spatial accessibility in need of redress.

In this paper we investigate the case of the PBSP in the City of Hamilton, in Ontario, Canada. Hamilton Bike Share (previously also known as Social Bicycles, or SoBi) was launched in 2015 and currently has over 900 operational bicycles and 130 docking stations. An interesting feature of this system is that it was expanded by an equity initiative that introduced twelve docking stations in 2018 with the explicit objective of increasing spatial accessibility. Hamilton Bike Share was already studied by Hosford and Winters (2018) as part of a selection of PBSPs in Canada. These authors found that most of the cities in their research could benefit of greater efforts to expand service to areas with lower socio-economic populations - but Hamilton fared somewhat better than other cities in this respect. What distinguishes our research is the use of a balanced floating catchment area (BFCA) accessibility approach that accounts for the supply of stations and the potential demand from the population serviced. This requires a more disaggregated approach than the use of census geographies (q.v., Hosford and Winters, 2018), since many trips to a bike share station likely happen at a level lower than even the smallest census geography. For this reason, we implement our analysis parting from micro population zones to better reflect the friction of walking to a docking station. Further, we conduct a sensitivity analysis at several walking time thresholds. In terms of spatial equity, we compare accessibility with and without the equity stations to assess the effect of the initiative, before reaggregating the data for further analysis using median household income information from the census. We find that the addition of equity stations does increase the serviced population at every threshold examined. However, although accessibility increased for the whole population, this increase was relatively modest, especially for population in the bottom 20% of median household income. The analysis also identifies areas under-serviced within the core service area of the system.

This paper is an example of open and reproducible research that uses only open software for transportation and statistical analysis (Bivand, 2020; Lovelace, 2021). All data were obtained from publicly available sources and organized in the form a data package. Following best practices in spatial data science (Brunsdon and Comber, 2020), the code and data needed to reproduce (or modify/extend) the analysis are available for download.[1]

Literature Review

Public bicycle share programs have been implemented in over 800 cities worldwide and a great deal has been learned about their typical users (Fishman, 2016). In many cities, males use bike share more than females (**???**; Brey et al., 2017; Nickkar et al., 2019; Reilly, S. M. Wang, et al., 2020; Winters et al., 2019) as do younger age cohorts (Brey et al., 2017; Buck et al., 2013; Fuller et al., 2011). However, one study found that bike share users in Washington, DC were more likely to be female (Buck et al., 2013), which suggests that the gender gap among cyclists who use bike share is less disparate than the gap for personal bicycle use (Fishman, 2016). There is some evidence that bike share users are less likely to own a car (Buck et al., 2013; Reilly, Noyes, et al., 2020). However, the relationship between income or education and bike share use is less clear-cut. Stations in disadvantaged communities in Chicago have been found to generate most of the average annual trips (Qian and Jaller, 2020) and individuals from minority or lower socioeconomic status neighbourhoods in Minneapolis-St. Paul used the city's PBSP more (J. Wang and Lindsey, 2019a). Similar findings were reported in London (**???**). Being university educated was a significant correlate of bike share use in Montreal, Canada (Fuller et al., 2011). Perhaps not coincidentally, financial savings have been found to motivate those on a low income to use bike share (Fishman, 2016).

Many studies have found that geographic proximity to a bicycle share station is an important determinant of membership and use (Fishman, 2016; Fuller et al., 2011). This makes sense given that individuals are more likely to use services or programs that they can easily reach. Several studies have recently explored the equity of PBSPs by primarily examining who has access to bike share (e.g., differences by demographics or socioeconomic status) and where stations are located. It is important to note that equity can be achieved in two different ways: equal spatial distribution across a region (e.g., horizontal equity) or greater access for vulnerable or disadvantaged populations (e.g., vertical equity) (Chen et al., 2019). Both are of interest to researchers and transport planners since they are often linked in that advantage, or conversely disadvantage, has spatial patterns. Using a negative binomial regression model, Qian and Jaller (2020) estimated ridership in Chicago's PBSP among disadvantaged communities and found some disparities. While annual members in disadvantaged communities have a significantly lower share of trips compared to other areas in the city, they make longer trips. This suggests that they may be using PBSPs for utilitarian

[1]https://drive.google.com/drive/folders/1ZGRpSN2LxS2Fq2tLVJgfm1sI6I26vzZh?usp=sharing

trips (e.g., commuting), which points to the importance of ensuring equitable access (Qian and Jaller, 2020). Similar results were found in Philadelphia, where lower income areas generated fewer trips and it was suggested that efforts to increase equity within the program have not been as successful as intended (Caspi and Noland, 2019). In the case of Seattle, all neighbourhoods had some level of access to dockless bikes but those with higher incomes and more residents of higher education had more bikes (Mooney et al., 2019). Babagoli et al. (2019) also found that neighbourhoods in New York City with higher affluence had the greatest proportion of Citi Bike stations. Researchers have recommended targeted expansion of stations to areas that use bike share but have inequitable access (**???**).

On the whole, existing studies highlight the need for bicycle share systems to be more highly accessible for diverse populations in order to increase use beyond the "typical" users. This has been the focus of recent research (see, among others, Auchincloss et al., 2020; Hull Grasso et al., 2020; MacArthur et al., 2020). Offering more people the option of using sustainable and active transportation, particularly those who have lower socioeconomic status and might benefit the most, is a worthy policy goal for cities with PBSPs. Several cities have launched specific programs to address barriers to bike share or to expand service to more deprived areas: London, United Kingdom (**???**); Philadelphia, Pennsylvania (Caspi and Noland, 2019), and Hamilton, Ontario (Hosford and Winters, 2018). Findings to date suggest that horizontal equity can be easier to achieve than vertical equity. However, exploring transportation equity by investigating where bicycle share stations are located, often using neighbourhoods or census tracts as the geographical unit of analysis, can ignore or miss the benefits that may be derived from adjacent zones. Meaning that, stations may be lacking in certain neighbourhoods but there may be stations accessible within a reasonable walking time. This is where geographical accessibility becomes an important consideration.

Accessibility has been applied in both a positive and normative way to inform transportation planning (Páez et al., 2012), but its utility to this field has evolved over the past century and has increasingly become linked with recent interest in prioritizing local proximity and modes that are suitable for local trips like walking and cycling (Levine, 2020). As a measure of the ease of reaching potential destinations spread spatially in a given area, accessibility is relevant to PBSPs because it can identify current inequities in the provision of infrastructure, as well as guide interventions that increase access for groups that are under-serviced or address gaps in transportation options. It also addresses some of the challenges of other performance measures such as level of service within a transportation network by measuring person-based indicators and exploring differences in use between population groups (Páez et al., 2012).

Beyond the utility derived from using shared bikes to destinations of value, an important aspect of accessibility associated with PBSPs is the distance an individual must travel to reach a bicycle share station (Kabra et al., 2020; J. Wang and Lindsey, 2019b). Since the time or distance needed to reach a bicycle share station decreases the potential of accessing the program and ultimately their use of the program, the location and size (e.g., maximum number of bicycle racks available) of stations matters. Indeed, distance to bicycle share stations is associated with use (Fuller et al., 2011; J. Wang and Lindsey, 2019b) and can be a barrier to using PBSPs (Fishman et al., 2014). Kabra et al. (2020) found that the majority of bike share usage in Paris comes from areas within 300 metres of stations, which amounts to 2-4 minutes walking by an able-bodied adult. Furthermore, similar to other public amenities affected by crowding, like health care services (e.g., Pereira, Carlos Kauê Vieira Braga, et al., 2021), the utility of stations is limited by the number of bicycles that they can hold. The program may not necessarily be improved if stations are easy to reach but offer only a small number of bicycles. Likewise, more people may not opt to use the program if the supply of bicycles available at the nearest station is insufficient to meet demand. The location and size of stations is important to increase the utility of this public transportation option for more people, thus achieving vertical equity. Accessibility analyses for PBSPs constitute a positive and evaluation-based approach that also has the potential to inform equity efforts. For instance, Wang and Lindsey (2019b) investigated whether new or relocated bicycle share stations increased accessibility and use, which offered important insights to improve the performance of the program.

Several approaches have been commonly used for measuring place-based accessibility, including cumulative opportunities, gravity, and utility-based measures (Handy and Niemeier, 1997). Geurs and Van Wee (2004) and Paez et al. (2012) provide recent overviews of various formulations and applications of accessibility in transportation research. The common gravity-based approach for example involves weighting destination opportunities, such as the quantity of bicycle share stations, by the time required to reach them from an origin using an impedance function (Handy and Niemeier, 1997; Kwan, 1998). However, while such measures are suitable for capturing the potential for reaching destinations from a given location, they do not take demand or congestion effects into account.

In contrast, floating catchment area (FCA) methods incorporate information on capacity and demand in calculating accessibility. FCA measures have been widely employed in healthcare accessibility research and are typically calculated across two steps. In the first, a ratio of supply to demand at service locations is calculated, such as the number of beds at a hospital divided by the number of people within the catchment area of the hospital, weighted by the distance involved in reaching the facility. Next, these service level ratios are allocated back to the population centres and summarized as a measure of congested accessibility. Thus, this model does a good job of considering potential crowding or competition for services. While there have been many methodological innovations in FCA methods (for example, **???**; **???**; **???**; **???**; **???**), a recent improvement to this approach was achieved through a simple and intuitive balancing of the impedance that addressed the effects of demand and service inflation found in previous FCA approaches (see Paez et al., 2019).

When measuring accessibility, researchers have taken different approaches when it comes to aggregation of data, either by using the individual or household as the smallest unit of analysis or larger spatial zones. Previous research on bike share equity has typically used a meso- or macro-level approach with aggregate data from entire neighbourhoods or census tracts (Babagoli et al., 2019; Mooney et al., 2019; Qian and Jaller, 2020; J. Wang and Lindsey, 2019a), although there are recent exceptions (Chen et al., 2019; Chen and Li, 2021). This is also true for studies examining correlates of bike share demand (J. Wang and Lindsey, 2019b). Handy and Niemeier (1997) note that using disaggregated data in accessibility analyses provides a more accurate estimate for individuals, which is useful for addressing vertical inequities in PBSP usage.

Using the balanced floating catchment area method (Paez et al., 2019), a novel approach that has not been used yet in cycling research, with disaggregate population-level data, in this paper we examine accessibility to a public bicycle share program in Hamilton, Ontario. We (1) conduct a sensitivity analysis by measuring accessibility and level of service to bike share stations at different walking time thresholds to reach a station: 3 minutes, 5 minutes, 10 minutes, and 15 minutes; (2) explore the contribution of specific stations that were added to Hamilton's PBSP to reducing both horizontal and vertical inequities; and (3) examine whether disparities in accessibility exist according to median household income of dissemination areas within the core service area.

Case Study

Original System

The focus of this study is the city of Hamilton, located in Ontario, Canada. The city launched a public bicycle share program in March 2015 with 115 stations and 750 bicycles (Hamilton, 2015). Before June 2020, the program was known as Social Bicycles or SoBi Hamilton but is now called Hamilton Bike Share. Stations are spaced between 300 and 600 metres apart (Scott et al., 2021). The core service area spans 40 sq.km of the city although it was planned to be 20 sq.km (**???**), and roughly 138,000 people are within 30 minutes walking of a bike share station [see Figure 1]. This represents roughly one fifth of the total population of the Hamilton Census Metropolitan Area according to the 2016 Canadian Census. The City of Hamilton undertook a large public engagement campaign to validate the locations of bicycle share stations that had been selected and to crowdsource potential locations for additional locations (**???**). Most of the suggested locations were in the east end of the core service area that lack stations or in neighbourhoods not serviced by the PBSP. The program was enthusiastically welcomed in the city in 2015 - within three weeks of launching, 10,000 trips had been made (Hamilton, 2015), however inadequate coverage given the size of the Hamilton Bike Share's service area was identified as a problem early on, and transportation planners noted that the small size (i.e., supply of bicycle racks) and low quantity of stations would lead to challenges in balancing the system (**???**). Based on public feedback, 13 stations were added to the original system.

Equity Initiative

In 2017, Hamilton Bike Share Inc., the non-profit organization that operates the program, initiated an equity program, Everyone Rides Initiative (ERI), with the objective of reducing barriers that may prevent individuals from accessing bike share in Hamilton. Additional bicycles and stations were added to the program which expanded it to more disadvantaged areas in the core service area [see Figure 2]. The program also offers subsidized memberships to individuals who identify as low income, and complements these initiatives with cycle skills education. A comparable program can be found in Philadelphia (see Caspi and Noland, 2019).

Current System

As of June 2020, Hamilton Bike Share has 900 bikes, 130 stations [see Figure 2], and over 26,000 active memberships (Hamilton, 2015). The core service area remains 40 sq.km. The PBSP has 13 stations that were added as part of the ERI initiative; we refer to these as "equity stations" throughout the paper while all other stations are "conventional stations". In total, 117 stations are "conventional" and 13 are "equity".

Membership

Hamilton Bike Share conducted one membership survey in 2018 (Civicplan, 2017) and the findings from 420 members are broadly in line with the trends that were discussed above (see Fishman, 2016 for a recent review of the literature). The majority of respondents live within the core service area and the gender split is expected: 57% of respondents are male and 41% are female. The majority of respondents, both male and female, are between 25 and 34 years of age, but the percentage of male respondents is higher in the subsequent age groups. Respondents use bike share for commuting (40% of trips) or errands and meetings (24% of trips) and nearly 50% of trips have an average length of 11 to 20 minutes. As a result of having a bike share membership, 49% of respondents report that they use their private vehicle less often or much less often but 48% report that their private vehicle use has remained about the same. This suggests that Hamilton Bike Share has been useful for certain kinds of trips but not all, meaning that some trips continue to require a private vehicle.

Relevant Research

Our analysis builds upon a previous and recent study (Hosford and Winters, 2018), which found that areas in Hamilton with less advantage are better served by the city's PBSP compared to other Canadian cities [i.e., Toronto, Vancouver, Montreal, and Ottawa-Gatineau] where areas that are less deprived have greater access. Hosford and Winters (2018) acknowledge that "Hamilton stands out in that the lower income neighborhoods are located near the city center and wealthier neighborhoods are in the surrounding suburban areas". Therefore, the core service area for the PBSP in Hamilton by default covers some of the less advantaged areas in the city. However, there is also a great deal of variation

Figure 1: The core service area of Hamilton Bike Share is outlined in black. Hamilton Census Metropolitan Area (CMA) is shown in grey.

in income in the city center because of the local university and increasing gentrification. Hosford and Winters (2018) took a macro-level and system-wide approach in their analysis by using dissemination areas *across* the city as the unit of analysis. They did not focus specifically on the core service area and did not differentiate between conventional and equity stations.

Methods

Floating Catchment Area

Floating catchment area (FCA) methods are an approach commonly used in the healthcare accessibility literature. This approach is more appropriate and informative than calculating provider-to-population ratios (PPR) that simply divide the level of supply of a service (e.g., the number of bicycle racks at a station) by the population who have access to the service (Paez et al., 2019). In particular, the Two-Step Floating Catchment Area (2SFCA) method (**???**; **???**) produces flexible catchment areas instead of using rigid boundaries like PPR. This provides more useful information because it does not assume that people are limited to service within pre-defined boundaries (Paez et al., 2019). This is an important property that supports our rationale for applying this method to measure accessibility to Hamilton Bike Share. The City of Hamilton has positioned stations between 300 and 600 metres apart, but anticipates that hubs will service those living within a 250 metre buffer from the station (**???**). The latter constitutes a normative statement: people ought to be able to access a

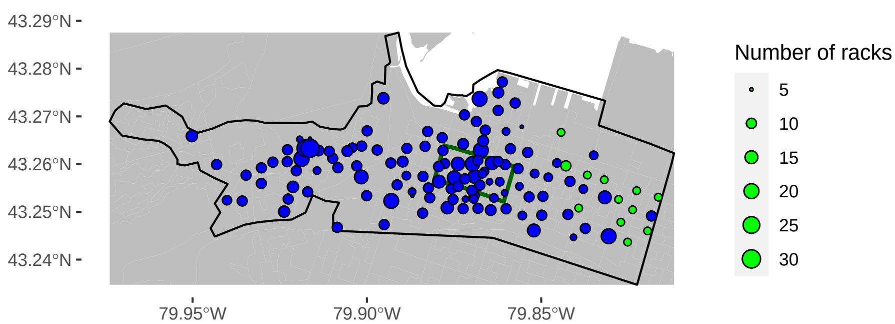

Figure 2: The spatial distribution of bike share stations in Hamilton, Ontario. The service area of Hamilton Bike Share is outlined in black and the city's downtown core is outlined in dark green. Hamilton CMA is shown in grey.

station in less than 600 metres if they live in the core service area, with usage coming from 250 metres around. However, it is not known how far people are actually willing to travel to reach a station. It would be reasonable to assume that people are willing to walk beyond this threshold to access other stations if the ones nearest them have no supply of bicycles.

More recently, the *balanced* floating catchment area (FCA) approach was developed to address issues with demand and supply inflation that result from the overlapping catchment areas produced by earlier FCA methods (Paez et al., 2019). Briefly, overlapping catchment areas lead to inflation of population totals and deflation of service levels across a study area and generates inaccurate or misleading accessibility estimates. In contrast, Paez et al. (2019) adjust the impedance weights so that both supply and demand are proportionally allocated. The results is a FCA method that balances the population and level of service by eliminating the over-counting of population and level of service that leads to distortions in demand and supply. Other benefits of this adjusted method include consideration of competition which can occur when catchment areas overlap, as well as the preservation of population and level of service. Balanced floating catchment area methods have been used to explore accessibility to health care providers (Paez et al., 2019) and COVID-19 health care services (Pereira, Carlos Kauê Vieira Braga, et al., 2021), but have not yet been used in the cycling literature to explore issues of accessibility.

The first step in the floating catchment area method is to allocate the population to be serviced by each Hamilton Bike Share station:

$$P_j = \sum_{i=1}^{n} P_i w_{ij}$$

As seen in the equation above, the population allocated to station j is the weighted sum of the population in the region; a spatial weight w_{ij} represents the friction that the population at i faces when reaching station j, and is usually given by a distance-decay function, so that each station is assumed to service only a segment of the population within a limited geographical range.

Next, the supply at each station (i.e., the maximum number of bicycle racks) is divided by its estimated service population within the established catchment area; this gives the level of service of station j in bicycle racks per person:

$$L_j = \frac{S_j}{P_j} = \frac{S_j}{\sum_{i=1}^{n} P_i w_{ij}}$$

Finally, the accessibility of population cell i is calculated as the weighted sum of the level of service of all stations that can be reached from there according to the spatial weights:

$$A_i = \sum_{j=1}^{J} L_j w_{ji} = \sum_{j=1}^{J} \frac{S_j w_{ji}}{\sum_{i=1}^{n} P_i w_{ij}}$$

The balanced approach of Paez et al. (2019) replaces the spatial weights with normalized versions as follows:

$$w_{ij}^{i} = \frac{w_{ij}}{\sum_{j=1}^{J} w_{ji}}$$

and:

$$w_{ij}^{j} = \frac{w_{ij}}{\sum_{j=1}^{J} w_{ji}}$$

These weights satisfy the following properties:

$$\sum_{j=1}^{J} w_{ji}^{i} = 1$$

and:

$$\sum_{i=1}^{n} w_{ji}^{j} = 1$$

With these weights accessibility can be calculated without risk of demand or supply inflation:

$$A_i = \sum_{j=1}^{J} \frac{S_j w_{ij}^{j}}{\sum_{i=1}^{n} P_i w_{ij}^{i}}$$

By allocating the population and level of service proportionally, this method preserves the values of the population and level of service and provides a regional provider-to-population ratio since:

$$\sum_{i=1}^{n} A_i = \sum_{j=1}^{J} L_j = \frac{\sum_{j=1}^{J} S_j}{\sum_{i=1}^{n} P_i}$$

In fact, since the proportional allocation procedure means that any proportion of the population allocated to a station is never allocated to other stations, and conversely any level of service allocated to a population is never re-allocated elsewhere, this property is replicated for any level of aggregation. For this paper, we employ a hybrid location-based and person-based approach to calculating accessibility using disaggregate population data. In their review of accessibility measures, Geurs and van Wee (2004) highlight the need for greater inclusion of individual spatio-temporal constraints but acknowledge the challenges of acquiring and analyzing person-based data. This comes after Kwan's (1998) work to show that space-time measures are better able of capturing interpersonal differences, especially the effect of space-time constraints on individual behaviour, and are more helpful for unraveling gender/ethnic differences. Applying the balanced floating catchment area approach allows us to examine accessibility by stratifying according to median household income, which would constitute the individual component of the accessibility measure (Geurs and van Wee, 2004). However, conducting a further sensitivity analysis to measure accessibility at different distance thresholds would help to consider potential spatio-temporal constraints. Different people may be willing to travel different distances to access a public bicycle share station.

Table 1: Landscape features extracted from the Hamilton Bike Share core service area before population is interpolated.

Feature	Description
Hamilton Bike Share Stations	The location of stations and the number of racks available at each station.
Golf Courses	The location of City and privately owned golf courses.
Parks	The location of parks and other green spaces.
Designated Large Employment Areas	The location of large business parks and industrial lands.
Municipal Parking Lots	The location of municipal car parks.
Cemeteries	The location of cemeteries.
Environmentally Sensitive Areas	The location of either land or water areas containing natural features or significant ecological functions.
Streets	The street network in Hamilton, including road classification for highways.
Educational Institutions	The location of all educational institutions and schools.
Places of Worship	The location of buildings used for religious congregations.
Municipal Service Centres	The location of all municipal service centres, including City Hall.
Recreation and Community Centres	The location of all recreation and community centres.
Arenas	The location of all indoor arenas.
Emergency Stations	The location of all Emergency Management Services (EMS) Ambulance stations.
Fire Stations	The location of all fire stations.
Police Stations	The location of all police stations.
Railways	The railway network in Hamilton.
Hospitals	The location of all hospitals.

Pycnophylactic Interpolation

To obtain population at sub-census geography levels (at the micro scale) we use pycnophylactic interpolation (Tobler, 1979). We obtained population data from the 2016 Census of Canada for dissemination areas (DAs, the smallest publicly available census geography in Canada). This zonal values of the population were interpolated to smaller polygons 50 by 50 metres in size. Pycnophilactic interpolation involves smoothing out the population from each dissemination area while preserving total volume [see Figure 3]. When interpolating the population at this high level of resolution it is important to ensure that population numbers were not allocated to areas where people do not live in Hamilton (e.g., to parks, large institutional buildings, etc.) To do so, we retrieved shapefiles for various geographic features [see Table 1] from Open Hamilton. Next, we removed these features from the PBSP core service area and used pycnophylactic interpolation to disaggregate and reallocate population within the remaining area [see Figure 4].

Travel Time Matrix

To calculate walking times from the centroid of our micro population cells we extracted OpenStreetMap data for Hamilton Bike Share's service area from BBBike, an online cycle route planner that interfaces with OpenStreetMap. OpenStreetMap data provides the networks for calculate walking times from each population cell to nearby bike share stations, using a maximum walking distance of 10 km and walking time of 30 minutes as thresholds. A travel time matrix was created with the origins as the coordinates of the population cells

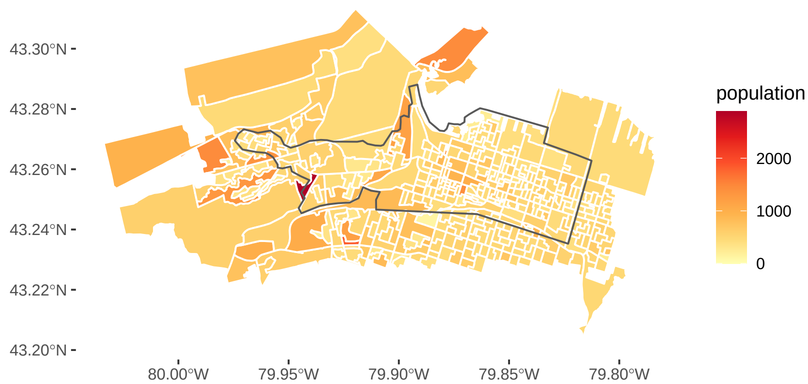

Figure 3: Population in all dissemination areas (outlined in white) that are inside or touch the bounding box of the Hamilton Bike Share core service area (outlined in black).

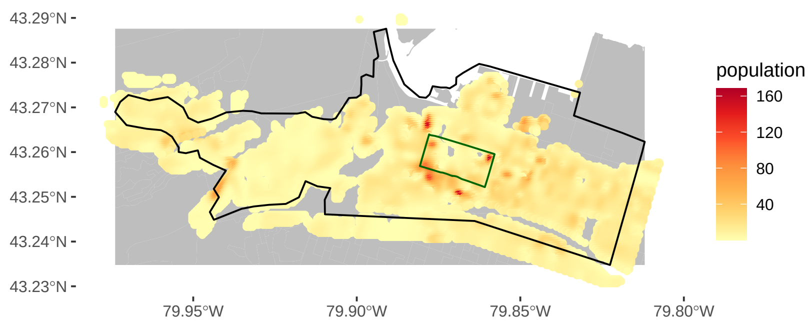

Figure 4: Interpolated population in the Hamilton Bike Share core service area (outlined in black) and within 30 minutes of walking to the core service area (outlined in blue). Each micro population cell is 50-by-50 m in size. The downtown area is outlined in dark green.

and the destinations as the coordinates of the bike share stations within the maximum threshold. This process provides a more realistic measure of the friction of reaching bike share stations by taking infrastructure into account of travel times, rather than using the Euclidean distance from population cell to station. Routing and travel time calculations were completed using the `R` package `r5r`, used for rapid realistic routing operations (Pereira, Saraiva, et al., 2021).

Data

All data for this research were accessed from publicly available Census of Canada sources, from OpenStreetMaps, and from Open Hamilton[2], a public online repository of data curated by the City of Hamilton.

Results

Accessibility by Distance Thresholds

Consensus regarding the distance that individuals are willing to walk to access a PBSP station is lacking, but the literature on walking behaviour was consulted to determine the thresholds for the sensitivity analysis. Previous studies have found that living within 250 metres (Fuller et al., 2011) and 300 metres (Kabra et al., 2020) is correlated with bike share use, while other research has found that walking trips are less than 600 metres and rarely more than 1200 metres (Millward et al., 2013) or a median distance of 650 metres (Larsen et al., 2010). In Hamilton, Hamilton Bike Share will depict a map at some stations to show the user the locations of the other nearest stations within a five minute walk, which suggests that this is an average distance that people are expected to walk.

In the present case, we found that congested accessibility calculated using the balanced FCA approach increases with a threshold between two and four minutes, but is then maximized at 5 minutes. Accessibility decreases substantially after eight minutes, which is intuitive given that demand on a limited supply increases as more people can reach each bike share station.

For this reason, we experiment with various walking thresholds by conducting a sensitivity analysis to calculate accessibility at different walking times from population cell to bicycle share station: 3 minutes, 5 minutes, 10 minutes, and 15 minutes. We categorize these thresholds as minimum, average, maximum, and extreme, respectively. At each threshold, we compare accessibility between the current system and the original system to examine the contribution of the additional equity stations.

Minimum Threshold

With a walking distance of three minutes, we find that there are 25.2 bicycle racks per person in the original system. The addition of equity stations increases

[2]https://open.hamilton.ca/

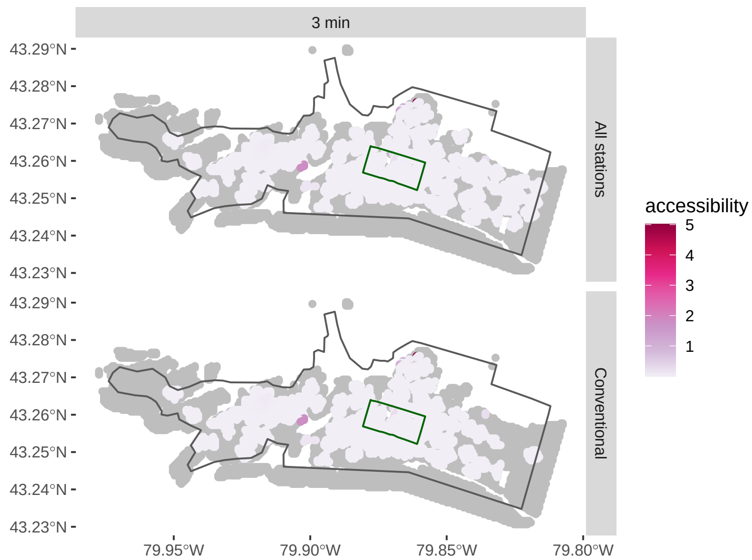

Figure 5: Accessibility at 3 minutes walk (minimum threshold) compared between current system with equity stations and the original system without equity stations.

this ratio slightly to 25.4 bicycles per person. Figure 5 presents a comparison of accessibility between the systems for the population cells. Accessibility is fairly uniform overall, with the exception of two small areas where accessibility is slightly higher.

Average Threshold

With a walking distance of five minutes, we find that there are 68.6 bicycle racks per person in the original system. With the addition of equity stations, there are now 68.8 bicycles per person. Figure 6 presents a comparison of accessibility between the systems. Again, accessibility is fairly uniform, with the exception of one very small area. At this threshold, there are more bicycle racks per person than at the minimum threshold. This occurs because fewer stations can be reached when the travel time is 3 minutes or less.

Maximum Threshold

With a walking distance of ten minutes, we find that there are 3.61 bicycle racks per person in the original system. With the addition of equity stations, there are now 3.74 bicycles per person. Figure 7 presents a comparison of accessibility between the systems. We begin to see differences in accessibility across the service area, with users near the university and its adjacent neighbourhoods, as well as neighbourhoods north of the downtown area (outlined in green), having slightly higher accessibility. While the differences are modest, they are more apparent at this threshold than at shorter walking distances.

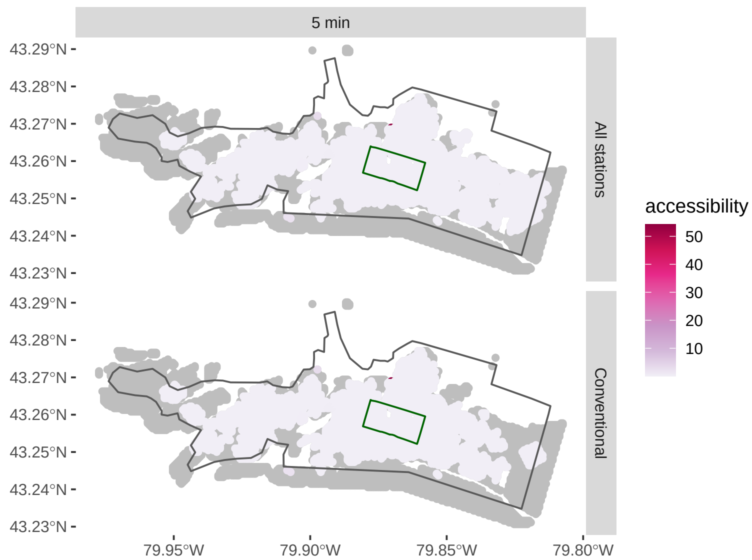

Figure 6: Accessibility at 5 minutes walk (average threshold) compared between current system with equity stations and the original system without equity stations.

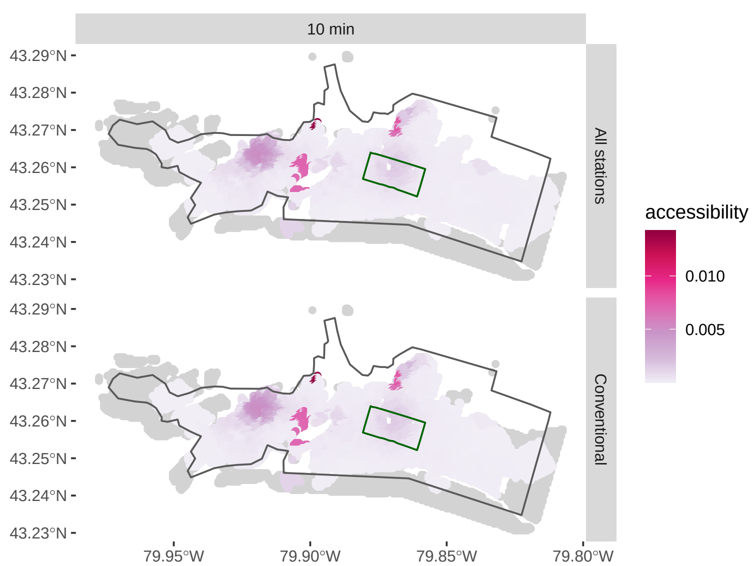

Figure 7: Accessibility at 10 minutes walk (maximum threshold) compared between current system with equity stations and the original system without equity stations.

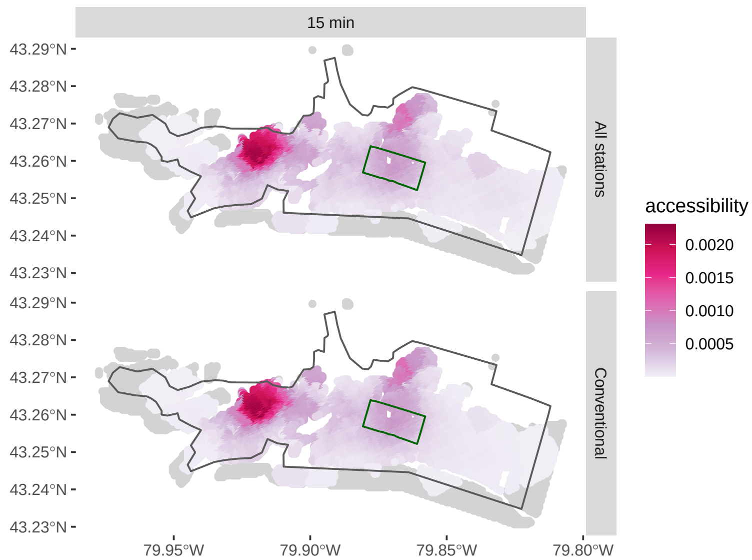

Figure 8: Accessibility at 15 minutes walk (extreme threshold) compared between current system with equity stations and the original system without equity stations.

Extreme Threshold

With a walking distance of fifteen minutes, we find that there are 2.44 bicycle racks per person in the original system. With the addition of equity stations, there are now 2.55 bicycles per person. Figure 8 presents a comparison of accessibility between the systems. Users near the university and the neighbourhoods north of the downtown area (outlined in green) have the highest accessibility, followed by those who live in the city's downtown area. Accessibility in the east end of the core service area remains low.

Accessibility by Median Household Income

One of the unique properties of the balanced floating catchment area method is that data can be reaggregated while preserving the total population in the service area and the supply at each station. This avoids demand and supply inflation, and also enables us to present findings in a way that is easier and more intuitive to interpret. Therefore, we reaggregate population and accessibility from the smallest 50 by 50 metres population cells to the median household income for each dissemination area. We divide income by quintiles: bottom 20%, second 20%, third 20%, fourth 20%, and top 20%.

Panels 1 [9], 2 [10], 3 [11], and 4 [12] depict bivariate choropleth maps with the combined spatial distribution of accessibility and median household income at different thresholds. Our analysis demonstrates that the extreme threshold of fifteen minutes allows the most people to access a station. We find that stations added to Hamilton's public bicycle share program to increase equity for

Figure 9: Bivariate map of accessibility and income (threshold: 3 min): without equity stations (top panel) and with equity stations (bottom panel)

disadvantaged neighbourhoods achieved their goal by increasing access, albeit only modestly [see Table 2]. By implementing equity stations in more areas with lower median total income in Hamilton, the PBSP has achieved greater horizontal equity by extending the spatial distribution of bicycles across the city. This is particularly evident at the minimum and average thresholds of three and five minutes, respectively, where the equity stations fill a number of gaps in program coverage. The largest gains were made for dissemination areas in the second 20%, where an additional 3,073 and 5,395 people could reach a bicycle share station within three and five minutes walk, respectively, after the addition of the equity station.

However, we found that dissemination areas with the lowest median household income do not have much greater access to the program [see Table **??**]. Income disparities still persist, however only at certain thresholds. With and without equity stations, people in the top 20% of income have the highest level of access at a threshold of ten and fifteen minutes. Although dissemination areas in the second 20% have the highest level of access by a significant amount at lower distance thresholds, the bottom 20%, who may benefit the most from Hamilton Bike Share's equity initiatives, have the lowest access at three minutes threshold and the second lowest access at all other thresholds.

Figure 10: Bivariate map of accessibility and income (threshold: 5 min): without equity stations (top panel) and with equity stations (bottom panel)

Figure 11: Bivariate map of accessibility and income (threshold: 10 min): without equity stations (top panel) and with equity stations (bottom panel)

Figure 12: Bivariate map of accessibility and income (threshold: 15 min): without equity stations (top panel) and equity stations (bottom panel)

Table 2: Accessibility and population serviced by income quintile and between systems (with and without equity stations).

	Without Equity Stations		With Equity Stations		Difference	
Income Quintile	Accessibility	Population	Accessibility	Population	Accessibility	Population
Threshold - 3 minutes						
Bottom 20%	2.377	22359	2.424	22798	0.047	439
Second 20%	12.203	9347	12.281	12420	0.078	3073
Third 20%	3.093	7745	3.156	9455	0.063	1710
Fourth 20%	4.119	1673	4.119	1673	0.000	0
Top 20%	3.757	2151	3.784	2416	0.027	265
Threshold - 5 minutes						
Bottom 20%	1.302	35477	1.357	35803	0.055	326
Second 20%	56.048	17513	56.137	22908	0.089	5395
Third 20%	4.259	15117	4.291	18309	0.032	3192
Fourth 20%	1.094	2867	1.095	3116	0.001	249
Top 20%	6.256	4074	6.264	4540	0.008	466
Threshold - 10 minutes						
Bottom 20%	0.604	41824	0.622	41981	0.018	157
Second 20%	0.862	27546	0.929	30503	0.067	2957
Third 20%	0.776	22394	0.802	25128	0.026	2734
Fourth 20%	0.225	4544	0.227	4989	0.002	445
Top 20%	1.346	7989	1.348	9078	0.002	1089
Threshold - 15 minutes						
Bottom 20%	0.536	42208	0.557	42327	0.021	119
Second 20%	0.555	30507	0.614	31069	0.059	562
Third 20%	0.554	26108	0.581	26660	0.027	552
Fourth 20%	0.093	6312	0.096	7435	0.003	1123
Top 20%	0.808	10209	0.811	11089	0.003	880

Note:

[a] With equity stations = Hamilton Bike Share current system (118 conventional stations, 12 equity stations)
[b] Without equity stations = Hamilton Bike Share original system (118 conventional stations, no equity stations)

Discussion

Using disaggregate data, we examined spatial equity and accessibility to Hamilton Bike Share, with a particular focus on assessing the contribution of the program's equity stations. Our balanced floating catchment area approach, combined with pycnophylactic interpolation, enabled us to measure accessibility on a micro sale. This differentiates our analysis from similar papers exploring equity in PBSPs that use larger geographical units of analysis or that focus on station location instead of level of service. In this way, our paper has made contributions in a positive way by applying an intuitive and useful approach to measure accessibility to a PBSP, and in a normative way by serving to inform future investments in cycle infrastructure for Hamilton Bike Share.

The sensitivity analysis revealed that accessibility to Hamilton Bike Share stations is maximized at five minutes and decreases significantly by eight minutes [see Table 2]. This reflects the normative guide, advertised on some bicycle share stations in Hamilton, that people can access other stations within a five minute walk if the station of origin has no bicycles. We find that over 118,000 people can access a bicycle share station within a 15 minute walk, which represents roughly 85% of the total population in the core service area [see Table 2]. At a minimum threshold of three minutes, too few stations can be accessed which leads to lower levels of accessibility. However, accessibility is at its lowest after eight minutes whereby congestion occurs due to increased potential demand. The City of Hamilton has recognized from the launch of the PBSP that significantly more stations and bicycles are needed to service the area (**???**). With a service area of 40 sq.km, Hamilton should have between 380 and 440 stations, instead of 130, and 1,500 bicycles instead of 900 (**???**). Reduced capacity within the system leads to gaps in coverage in some areas of the city "with some areas not having the recommended station density of 300m between stations or 10 stations per square km" (**???**). This study illustrates the consequences of an imbalanced system whereby levels of accessibility are not equitable across income groups and become very low when congestion occurs.

We found that equity stations achieved their goal of increasing horizontal equity in Hamilton's core service area. Panels 1[9], 2 [10], 3 [11], and 4 [12] demonstrate how gaps in service were filled by these additional stations. In this respect, there are some commonalities between the expansions of Hamilton Bike Share and that of Citi Bike in New York. Babgoli et al. (2019) found a slight but not statistically significant increase in the proportion of neighbourhoods with the highest levels of poverty with stations after the Citi Bike expansion in 2015. Although the Citi Bike expansion was not specifically driven by a desire to reduce inequities in access, 16% of neighbourhoods with the most poverty had stations compared to 12% before. With the addition of equity stations, there were large gains in accessibility for the second 20% at the average threshold, over 5,000 more people, but much smaller gains for the bottom 20% with only 326 more people.

Vertical inequities, however, continue to persist despite the addition of equity stations. While the addition of equity stations modestly increases accessibility for all income groups at all thresholds, they did not increase accessibility significantly for any single income group. Most importantly, individuals in the bottom 20% median household income quintile have the second lowest level of access to Hamilton Bike Share at most thresholds (average, maximum, and extreme). At the minimum threshold, the bottom 20% have the lowest level of access. While previous research found that neighbourhoods with more disadvantage are better serviced by Hamilton Bike Share, the authors used the Pampalon Deprivation Index to determine the level of disadvantage for dissemination areas *across* the city not just within the core service area (Hosford and Winters, 2018). Instead, we use median household income for each dissemination area *within* the core service area. We conclude that Hamilton's PBSP, while by default located in areas with more deprivation compared to other cities, has disparities in accessibility between income groups. With equity stations, many areas with low median household income in the east end of the service area continue to have low accessibility. At higher thresholds of 10 and 15 minutes, the top 20% have the highest level of access to Hamilton Bike Share. This aligns with other studies from Tampa (Chen et al., 2019) and Seattle (Mooney et al., 2019), which have found disparities in station location or access to bicycles between levels of income and education.

Based on our analysis, we identified specific areas that have both low accessibility and low median household income which would benefit from an increased supply of public bicycles. These empirical findings provide support to the City of Hamilton's efforts to increase equity and balance the system, and confirm that additional stations and bicycles are needed to improve access not only for the bottom 20% but for all income groups. Panels 1[9], 2 [10], 3 [11], and 4 [12] highlight potential locations for new equity stations.

Study Limitations

This paper did not examine or compare ridership data between conventional and equity stations. Therefore, further research is needed to determine whether the addition of equity stations encouraged more cycling for low-income individuals living near them. Other studies have specifically looked at differences in trip type, frequency, or length among users from disadvantaged neighbourhoods (Caspi and Noland, 2019; Qian and Jaller, 2020; J. Wang and Lindsey, 2019a), but our analysis is limited by the lack of publicly available route or user data to conduct similar analyses for Hamilton Bike Share.

Conclusion

The addition of specific equity stations to the public bicycle share program in Hamilton, Ontario had the net effect of increasing accessibility and reducing both horizontal and vertical inequities. In particular, accessibility improved the most for those in the second 20% median household income at all thresholds, but the gains were only modest for all income groups. Dissemination areas with the bottom 20% had the lowest accessibility at three minutes, and second lowest levels of accessibility at five, ten, and fifteen minutes. Congestion effects were observed at higher thresholds, with accessibility decreasing significantly once the catchment area is increased to 10 minutes walking.

Wang and Lindsey (2019b) have noted that there is a lack of research that examines how bike share users' behaviour changes as a result of program changes to station locations or improvements in accessibility. As such, a logical next step to this research is to examine whether Hamilton Bike Share's equity stations increased ridership or resulted in new memberships in areas that were previously under-served. An examination of the types of trips undertaken by residents in these areas would also be informative, such as the study undertaken by Caspi and Norland (2019) after bike share stations were implemented in low-income Philadelphia neighbourhoods. The bulk of cycling facilities that have been built in Hamilton to date located in the core service area near the conventional stations. It would be worthwhile to explore the route choice of bike share trips departing or ending at the equity stations and to identify factors that specifically influence trips from these stations, which would extend existing studies conducted by Scott and colleagues (Lu et al., 2018; Scott and Ciuro, 2019; Scott et al., 2021). This paper, combined with additional studies such as those conceptualized above, would serve as a valuable case study for Hamilton and other cities with PBSPs who wish to evaluate and address spatial inequities in accessibility and transportation options in urban areas.

References

Auchincloss, A.H., Michael, Y.L., Fuller, D., Li, S., Niamatullah, S., Fillmore, C.E., Setubal, C., Bettigole, C., 2020. Design and baseline description of a cohort of bikeshare users in the city of Philadelphia. Journal of Transport & Health 16, 100836. doi:10.1016/j.jth.2020.100836

Babagoli, M.A., Kaufman, T.K., Noyes, P., Sheffield, P.E., 2019. Exploring the health and spatial equity implications of the New York City Bike share system. Journal of Transport & Health 13, 200–209. doi:10.1016/j.jth.2019.04.003

Bivand, R.S., 2020. Progress in the r ecosystem for representing and handling spatial data. Journal of Geographical Systems 1–32. doi:10.1007/s10109-020-00336-0

Brey, R., Castillo-Manzano, J.I., Castro-Nuño, M., 2017. "I want to ride my bicycle": Delimiting cyclist typologies. Applied Economics Letters 24, 549–552. doi:10.1080/13504851.2016.1210760

Brunsdon, C., Comber, A., 2020. Opening practice: Supporting reproducibility and critical spatial data science. Journal of Geographical Systems 1–20. doi:10.1007/s10109-020-00334-2

Buck, D., Buehler, R., Happ, P., Rawls, B., Chung, P., Borecki, N., 2013. Are Bikeshare Users Different from Regular Cyclists?: A First Look at Short-Term Users, Annual Members, and Area Cyclists in the Washington, D.C., Region. Transportation Research Record 2387, 112–119. doi:10.3141/2387-13

Caspi, O., Noland, R.B., 2019. Bikesharing in Philadelphia: Do lower-income areas generate trips? Travel Behaviour and Society 16, 143–152. doi:10.1016/j.tbs.2019.05.004

Chen, Z., Guo, Y., Stuart, A.L., Zhang, Y., Li, X., 2019. Exploring the equity performance of bike-sharing systems with disaggregated data: A story of southern Tampa. Transportation Research Part A: Policy and Practice 130, 529–545. doi:10.1016/j.tra.2019.09.048

Chen, Z., Li, X., 2021. Unobserved heterogeneity in transportation equity analysis: Evidence from a bike-sharing system in southern Tampa. Journal of Transport Geography 91, 102956. doi:10.1016/j.jtrangeo.2021.102956

Civicplan, 2017. SoBi Hamilton Membership Survey. Civicplan | Planning Engagement Research.

Fishman, E., 2016. Bikeshare: A Review of Recent Literature. Transport Reviews 36, 92–113. doi:10.1080/01441647.2015.1033036

Fishman, E., Washington, S., Haworth, N., Mazzei, A., 2014. Barriers to bikesharing: An analysis from Melbourne and Brisbane. Journal of Transport Geography 41, 325–337. doi:10.1016/j.jtrangeo.2014.08.005

Fuller, D., Gauvin, L., Kestens, Y., Daniel, M., Fournier, M., Morency, P., Drouin, L., 2011. Use of a New Public Bicycle Share Program in Montreal, Canada. American Journal of Preventive Medicine 41, 80–83. doi:10.1016/j.amepre.2011.03.002

Geurs, K.T., van Wee, B., 2004. Accessibility evaluation of land-use and transport strategies: Review and research directions. Journal of Transport Geography 12, 127–140. doi:10.1016/j.jtrangeo.2003.10.005

Hamilton, C. of, 2015. Hamilton Bike Share.

Handy, S.L., Niemeier, D.A., 1997. Measuring Accessibility: An Exploration of Issues and Alternatives. Environment and Planning A: Economy and Space 29, 1175–1194. doi:10.1068/a291175

Hosford, K., Fuller, D., Lear, S.A., Teschke, K., Gauvin, L., Brauer, M., Winters, M., 2018. Evaluation of the impact of a public bicycle share program on population bicycling in Vancouver, BC. Preventive Medicine Reports 12, 176–181. doi:10.1016/j.pmedr.2018.09.014

Hosford, K., Winters, M., 2018. Who Are Public Bicycle Share Programs Serving? An Evaluation of the Equity of Spatial Access to Bicycle Share Service Areas in Canadian Cities. Transportation Research Record 2672, 42–50. doi:10.1177/0361198118783107

Hosford, K., Winters, M., Gauvin, L., Camden, A., Dubé, A.-S., Friedman, S.M., Fuller, D., 2019. Evaluating the impact of implementing public bicycle share programs on cycling: The International Bikeshare Impacts on Cycling and Collisions Study (IBICCS). International Journal of Behavioral Nutrition and Physical Activity 16, 107. doi:10.1186/s12966-019-0871-9

Hull Grasso, S., Barnes, P., Chavis, C., 2020. Bike Share Equity for Underrepresented Groups: Analyzing Barriers to System Usage in Baltimore, Maryland. Sustainability 12, 7600. doi:10.3390/su12187600

Kabra, A., Belavina, E., Girotra, K., 2020. Bike-Share Systems: Accessibility and Availability. Management Science 66, 3803–3824. doi:10.1287/mnsc.2019.3407

Kwan, M.-P., 1998. Space-Time and Integral Measures of Individual Accessibility: A Comparative Analysis Using a Point-based Framework. Geographical

Analysis 30, 191–216. doi:10.1111/j.1538-4632.1998.tb00396.x

Larsen, J., El-Geneidy, A., Yasmin, F., 2010. Beyond the Quarter Mile: Re-examining Travel Distances by Active Transportation. Canadian Journal of Urban Research 19, 70–88.

Levine, J., 2020. A century of evolution of the accessibility concept. Transportation Research Part D: Transport and Environment 83, 102309. doi:10.1016/j.trd.2020.102309

Lovelace, R., 2021. Open source tools for geographic analysis in transport planning. Journal of Geographical Systems 1–32. doi:doi.org/10.1007/s10109-020-00342-2

Lu, W., Scott, D.M., Dalumpines, R., 2018. Understanding bike share cyclist route choice using GPS data: Comparing dominant routes and shortest paths. Journal of Transport Geography 71, 172–181. doi:10.1016/j.jtrangeo.2018.07.012

MacArthur, J., McNeil, N., Cummings, A., Broach, J., 2020. Adaptive Bike Share: Expanding Bike Share to People with Disabilities and Older Adults. Transportation Research Record 2674, 556–565. doi:10.1177/0361198120925079

Millward, H., Spinney, J., Scott, D., 2013. Active-transport walking behavior: Destinations, durations, distances. Journal of Transport Geography 28, 101–110. doi:10.1016/j.jtrangeo.2012.11.012

Mooney, S.J., Hosford, K., Howe, B., Yan, A., Winters, M., Bassok, A., Hirsch, J.A., 2019. Freedom from the station: Spatial equity in access to dockless bike share. Journal of Transport Geography 74, 91–96. doi:10.1016/j.jtrangeo.2018.11.009

Nickkar, A., Banerjee, S., Chavis, C., Bhuyan, I.A., Barnes, P., 2019. A spatial-temporal gender and land use analysis of bikeshare ridership: The case study of Baltimore City. City, Culture and Society 18, 100291. doi:10.1016/j.ccs.2019.100291

Paez, A., Higgins, C.D., Vivona, S.F., 2019. Demand and level of service inflation in Floating Catchment Area (FCA) methods. PLoS ONE 14. doi:10.1371/journal.pone.0218773

Páez, A., Scott, D.M., Morency, C., 2012. Measuring accessibility: Positive and normative implementations of various accessibility indicators. Journal of Transport Geography, Special Section on Accessibility and Socio-Economic Activities: Methodological and Empirical Aspects 25, 141–153. doi:10.1016/j.jtrangeo.2012.03.016

Pereira, R.H.M., Braga, C.K.V., Servo, L.M., Serra, B., Amaral, P., Gouveia, N., Paez, A., 2021. Geographic access to COVID-19 healthcare in Brazil using a balanced float catchment area approach. Social Science & Medicine 273, 113773. doi:10.1016/j.socscimed.2021.113773

Pereira, R.H.M., Saraiva, M., Herszenhut, D., Braga, C.K.V., Conway, M.W., 2021. R5r: Rapid realistic routing on multimodal transport networks with r^5 in r. Findings. doi:10.32866/001c.21262

Qian, X., Jaller, M., 2020. Bikesharing, equity, and disadvantaged communities: A case study in Chicago. Transportation Research Part A: Policy and Practice 140, 354–371. doi:10.1016/j.tra.2020.07.004

Qian, X., Jaller, M., Niemeier, D., 2020. Enhancing equitable service level: Which can address better, dockless or dock-based Bikeshare systems? Journal of Transport Geography 86, 102784. doi:10.1016/j.jtrangeo.2020.102784

Reilly, K.H., Noyes, P., Crossa, A., 2020. From non-cyclists to frequent cyclists: Factors associated with frequent bike share use in New York City.

Journal of Transport & Health 16, 100790. doi:10.1016/j.jth.2019.100790

Reilly, K.H., Wang, S.M., Crossa, A., 2020. Gender disparities in New York City bike share usage. International Journal of Sustainable Transportation 0, 1–9. doi:10.1080/15568318.2020.1861393

Scott, D.M., Ciuro, C., 2019. What factors influence bike share ridership? An investigation of Hamilton, Ontario's bike share hubs. Travel Behaviour and Society 16, 50–58. doi:10.1016/j.tbs.2019.04.003

Scott, D.M., Lu, W., Brown, M.J., 2021. Route choice of bike share users: Leveraging GPS data to derive choice sets. Journal of Transport Geography 90, 102903. doi:10.1016/j.jtrangeo.2020.102903

Smith, C.S., Oh, J.-S., Lei, C., 2015. Exploring the equity dimensions of us bicycle sharing systems. Western Michigan University. Transportation Research Center for Livable . . . .

Tobler, W.R., 1979. Smooth Pycnophylactic Interpolation for Geographical Regions. Journal of the American Statistical Association 74, 519–530. doi:10.1080/01621459.1979.10481647

Wang, J., Lindsey, G., 2019a. Neighborhood socio-demographic characteristics and bike share member patterns of use. Journal of Transport Geography 79, 102475. doi:10.1016/j.jtrangeo.2019.102475

Wang, J., Lindsey, G., 2019b. Do new bike share stations increase member use: A quasi-experimental study. Transportation Research Part A: Policy and Practice 121, 1–11. doi:10.1016/j.tra.2019.01.004

Winters, M., Hosford, K., Javaheri, S., 2019. Who are the "super-users" of public bike share? An analysis of public bike share members in Vancouver, BC. Preventive Medicine Reports 15, 100946. doi:10.1016/j.pmedr.2019.100946