GGRD30 Final Report

Toward Equitable Service Provision: A Catchment Area Analysis of The Bike Share Toronto System

by

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1 Introduction

In the past 20-30 years, cities around the world have increasingly taken an interest in expanding and promoting active mobility means and networks, such as providing dedicated or protected bike lanes, bike share programs, and active mobility networks (City of Toronto, n.d.-a). Bike Share Toronto is Toronto's official docked bike-sharing system, sponsored by Tangerine Bank since 2011 (Bike Share Toronto, n.d.; El-Assi et al., 2017). Bike-sharing not only inherits the benefits of cycling but also provides additional incentives such as convenience and financial savings for its users (Fishman, 2016). However, bike-sharing also faces challenges and barriers that may limit its accessibility and equity for diverse populations, especially due to its docked nature and the arising first and last-mile issues. With the golden exception of the Netherlands' extensive biking infrastructure, many cities' increasing interest in expanding active mobility networks has rarely extended beyond downtown districts (Annis, 2023; Fishman, 2016).

Toronto's ActiveTO program consists of a suite of major road closures or bike lane additions that contribute to the health and well-being of Torontonians by providing the space to be physically active. Sections in Scarborough include the 5 km Danforth Lane from Broadview to Dawes (City of Toronto, n.d.-a, n.d.-b, n.d.-c). Advocacy groups such as Cycle Toronto have developed campaigns such as Move365, intended to provide education for cyclists and cycling infrastructure advocates, including underserved areas such as Scarborough (Cycle Toronto, n.d.-a, n.d.-b: Hulchanski 2010). Vision Zero, a comprehensive action plan focused on reducing traffic-related fatalities and serious injuries on Toronto's streets (City of Toronto, n.d.-d), proposes methods such as expanding bicycle lanes as a measure to change the way more streets are used in dense areas for mobility and the creation of "complete streets" (Toronto City Council, 2019).

Within the academic realm, various studies have highlighted the socioeconomic implications of where bike-share stations tend to be placed within cities. Mohiuddin et al. (2023) point out that low-income users and people of colour are more likely to use bike-share frequently for various trip purposes compared to other groups. Sosa Lopez (2021) studied Mexico City's bike share program Ecobici and revealed that residents who would benefit most from the program were not explicitly targeted and remained isolated from the central urban network, staying in the peripheral low-income suburban districts despite historically relying on bicycles to reach workplaces. Studies such as Babagoli et al.'s (2019) paper underscore that NYC's Citi Bike stations tend to cluster and provide the most health benefits derived from cycling (WHO's Health Economic Assessment Tool) in high-income census tracts. These studies suggest that bike-sharing can be a powerful tool for deterring social exclusion through improved mobility for the residents when being properly operated. Therefore, to foster an inclusive and just society, it is important to consider service provision equity when developing and expanding bike-sharing systems.

This paper aims to examine the Bike Share Toronto system from an equity perspective. We focus on the station catchment areas and the population groups that reside within them, and we address the following two research questions (RQ):

RQ1. How equitable is the access to Bike Share Toronto for all Toronto residents, especially for population subgroups based on gender, income, or ethnicity?

RQ2. Which Bike Share Toronto service areas have higher or lower levels of equity, and where should the system expansion be prioritized to improve the service provision equity?

2 Literature Review

This section synthesizes existing research on the equity of Bike Share service provision, focusing on demographic inclusivity and the implications of station placement.

2.1 Equity in Bike Share Service Provision

Research has consistently shown that bike share systems tend to attract non-vulnerable demographics as their most consistent users (Buehler, 2012). However, recent studies indicate a positive response from vulnerable demographics when induced demand is created through equitable distribution of bike share stations. Caspi (2023) found that the introduction of e-bikes in disadvantaged areas of Philadelphia's Indego bike-share system led to an increase in regular usage. Conversely, Duran et al. (2021) argue that a focus on demand can undermine equitable distribution. Therefore, if ridership becomes the sole or primary metric for system expansion decisions, the equity of service provision may deteriorate over time.

2.2 Demographic Factors Influencing Bike Share Usage

Among various demographic factors, age has been considered to have a minimal impact on the likelihood of bike share usage and its relevance to equity concerns. Bachand-Marleau et al. (2012) reported age has a slight but significant negative effect on the probability of using Montreal's bike-share system, implying that elderly individuals are less inclined to use the service compared to their younger counterparts. Buehler (2012) also observed minor variations in the average age of casual versus annual users, with the most notable difference occurring between the age groups of 18-24 and 25-34. This suggests that there is no substantial age difference between regular long-term and short-term bike share riders. Although the elderly are considered a vulnerable demographic requiring prioritized mobility options, these findings suggest that cycling may not be the most suitable mode of transportation for them. Consequently, allocating resources to prioritize this group in the bike share system expansion may not be the most efficient use of funds with respect to equity concerns.

2.3 Bike Share Usage by Tourists vs. Residents

The distinction between temporary and regular users of bike-share systems is significant, particularly in the context of tourism. Buck et al. (2013) found that most short-term users in Washington, DC's Capital Bikeshare system utilized the service for tourism. Buning and Lulla (2021) highlighted that the spending habits of visitors were distinct enough to make them a more substantial revenue source than regular users. Acknowledging these variances among rider types, our analysis computes equity metrics separately using annual, casual, and total ridership at each station as weights.

3 Methods and Data

3.1 Data

We used four sources of data in this paper, as shown in Table 1 below. The ridership dataset encompasses a comprehensive record of all trips made throughout 2023, detailing the origin and destination stations for each journey. The Bike Share Toronto system's station data, sourced from the General Bikeshare Feed Specification (GBFS), offers up-to-the-minute information on station status. Owing to the absence of historical station data, we have employed real-time data retrieved on January 8th, 2024, as a proxy for the entire year of 2023. Additionally, road network data obtained from Geofabrik underpins our routing analysis. We integrated demographic insights from the 2021 Canadian Census to assess equity performance, accessed via the *cancensus* package (von Bergmann et al., 2021) in *R*.

Table 1: Data Sources

Name	Description	Format	Source (URL)	Accessed Time
Bikeshare Ridership	Toronto bike-share trip data for the whole year 2023	CSV	City of Toronto Open Data	2024-01-20
Bikeshare Stations	Toronto bike-share station information	JSON	Toronto Parking Authority through GBFS	2024-01-08
Road Network	OpenStreetMap road network data for Ontario, Canada	PBF	OpenStreetMap through Geofabrik	2024-01-08
2021 Census	2021 Canadian Census data	*sf* data.frame	Statistics Canada through *cancensus* package (von Bergmann et al., 2021)	2024-02-05

3.2 Methods

3.2.1 Scope and Terminology

This paper aims to conduct a pure supply-side analysis. We will examine the equity of the service provision of Bike Share Toronto for all Toronto residents. The scope of this paper does not include the usage or demand of the bike share service by Toronto residents or tourists. We will only use the ridership data to weight the stations, assuming that a station with higher ridership has greater capacity and contributes more to the overall system service provision. We are not concerned with whether the residents within the station catchment areas use the service, as we only focus on the availability of the service to them. This idea resembles public service provision. We regard the bike share service as a cost-efficient transportation mode that can help vulnerable populations overcome transport poverty and the resulting social exclusion. Therefore, it is crucial for the service provider, especially Bike Share Toronto, which is owned by the Toronto Parking Authority and is not a profit-seeking private company, to take more social responsibility and promote an inclusive and just society. Thus, we are not doing any modern accessibility analysis, as we are not interested in whether the riders of Bike Share Toronto can easily reach places or opportunities. Instead, we examine the service provision equity through metrics calculated based on infrastructure or proximity to bike share stations.

In this paper, we will define equity as the absence of disproportionate over- or under-supply of the public service to any population group. We will only examine distributive justice, not procedural justice. We will not consider historical equity issues, such as whether historically underserved communities deserve oversupply now to compensate for their past deprivation. We will define vulnerable populations as population groups that self-identify as female, people of colour, or from self-reported low-income households. It is well-known that females and people of colour are underrepresented in multiple contexts, while low-income households lack mobility options, such as access to a private vehicle. Thus, we think it is reasonable to use these criteria to define the vulnerable population in our paper. Therefore, in this paper, we will examine whether the Toronto residents who live inside the catchment areas of Bike Share Toronto differ considerably from the overall Toronto residents in terms of their gender, ethnicity, and household income. If they are similar to each other in these three categories, we will conclude that Bike Share Toronto provides equitable services to all Toronto residents, as it does not disproportionately over- or under-supply any particular population group.

3.2.2 Spatial Analysis Methods

Our analytical processes were conducted using *R* and ArcGIS Pro. *R* was utilized for the entirety of our analyses, except for the mapping and suitability analysis pertinent to RQ2, which was executed in ArcGIS Pro. The workflow diagram, presented in Figure 1, delineates the sequence of our analytical procedures.

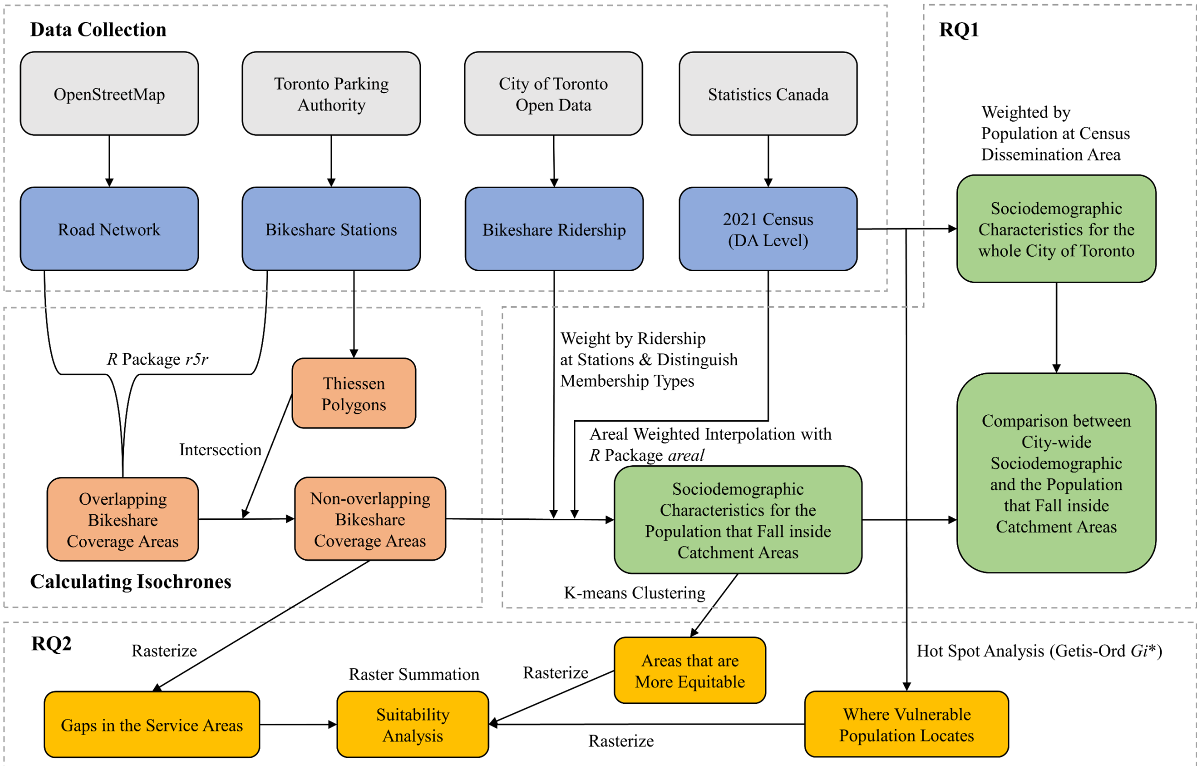

Figure 1: Workflow Diagram

3.2.2.1 Catchment Area Analysis

To measure the coverage area of each bike share station, we calculated the 15-minute walking distance network buffers around them, using the *r5r* package in *R* (Pereira et al., 2021). This package uses an R5-specific extension to the RAPTOR routing algorithm (Conway et al., 2017) to estimate the travel times from each trip origin to all the nodes in the OpenStreetMap road network. It then computed the concave hull (Gombin et al., 2020) of all the reachable nodes from each origin to obtain the network buffers, assuming a walking speed of 5 km/h. However, many bike share stations are located close to each other, especially in downtown Toronto, resulting in overlapping network buffers. To avoid this, we created Voronoi polygons (Okabe et al., 2009) based on Euclidean distance for each station and intersected them with the network buffers to get the non-overlapping coverage areas for each bike share station. This method delineates non-overlapping coverage areas, operating under the assumption that residents within multiple catchment areas will opt for the nearest station based on Euclidean distance rather than network distance. This assumption is particularly valid in downtown Toronto, where the complex road network likely leads residents to choose the closest visible station, typically simply determined by straight-line distance.

3.2.2.2 Areal Weighted Interpolation

To construct metrics quantifying the equity of service provision, we calculated eight socio-demographic variables: the percentages of Females, Indigenous people, White people, Chinese people, Black people, Latino people, people with household total income below $40,000, and people with household total income above $100,000 in 2020 for each census dissemination area (DA) in the City of Toronto. We used the *areal* package in *R* (Prener & Revord, 2019) to reshape the census data into the non-overlapping coverage areas, using the areal weighted interpolation method. This method assumes that the population within each census DA is homogeneous or spatially uniformly distributed. The method involves four steps:

- Intersecting the non-overlapping coverage areas with the census DAs.
- Calculating an areal weight for each intersected feature, as shown in Equation 1.

$$W_i = \frac{A_i}{\sum_i A_{ik}} \tag{1}$$

Where

W_i = areal weight for intersected feature i

A_i = area of intersected feature i

$\sum_i A_{ik}$ = total areas of intersected features within target feature k

- Estimating the share of the population value that occupies the intersected feature, as shown in Equation 2.

$$E_i = V_j \times W_i \tag{2}$$

Where

E_i = estimated value for intersected feature i

W_i = areal weight for intersected feature i

V_j = population value for source feature j

- Summarizing the data based on the target identification number, as shown in Equation 3.

$$G_k = \sum_i E_{ik} \tag{3}$$

Where

G_k = sum of all estimated values for target feature k

E_{ik} = estimated values from intersected features in i within target feature k

We then calculated the Toronto Bike Share system-wide socio-demographics as a weighted average based on ridership at each station, as shown in Equation 4.

$$x_{ac} = \frac{\sum_b n_{bc} \times x_{ab}}{\sum_b n_b} \tag{4}$$

Where

x_{ac} = estimated value for socio-demographic variable a of the whole bike share system for rider type c (c takes values of all riders, casual riders, or annual riders)

n_{bc} = ridership count of rider type c at bike share station b

x_{ab} = estimated value for socio-demographic variable a at bike share station b

Similarly, we calculated the Toronto city-wide socio-demographics as a weighted average based on the population count at each census DA. We used the city-wide average values as a baseline or benchmark to compare with the bike share system-wide metrics. If Bike Share Toronto is serving all Toronto residents equitably, we would expect the system-wide metrics to be similar to the city-wide metrics, indicating that no population subgroup in Toronto is underserved.

3.2.2.3 Cluster Analysis and Hotspot Analysis

In addition to the aggregated system level comparison, to get a more detailed picture of the bike share system service provision, we applied the Multivariate Clustering Geoprocessing tool (K-means Clustering) to the eight socio-demographic variables of the bike share stations in order to group them into 5 clusters based on their attribute similarities. Based on Figure 2, the K-means Cluster Analysis showed that cluster 3 captures the catchment areas that are the least equitable in the whole bike share system, as they oversupply White people and high-income residents while undersupplying people of colour compared to other clusters. We then converted cluster 3 (as not equitable catchments) and the other four clusters (as equitable catchments) into two sets of rasters in preparation for the Suitability Analysis.

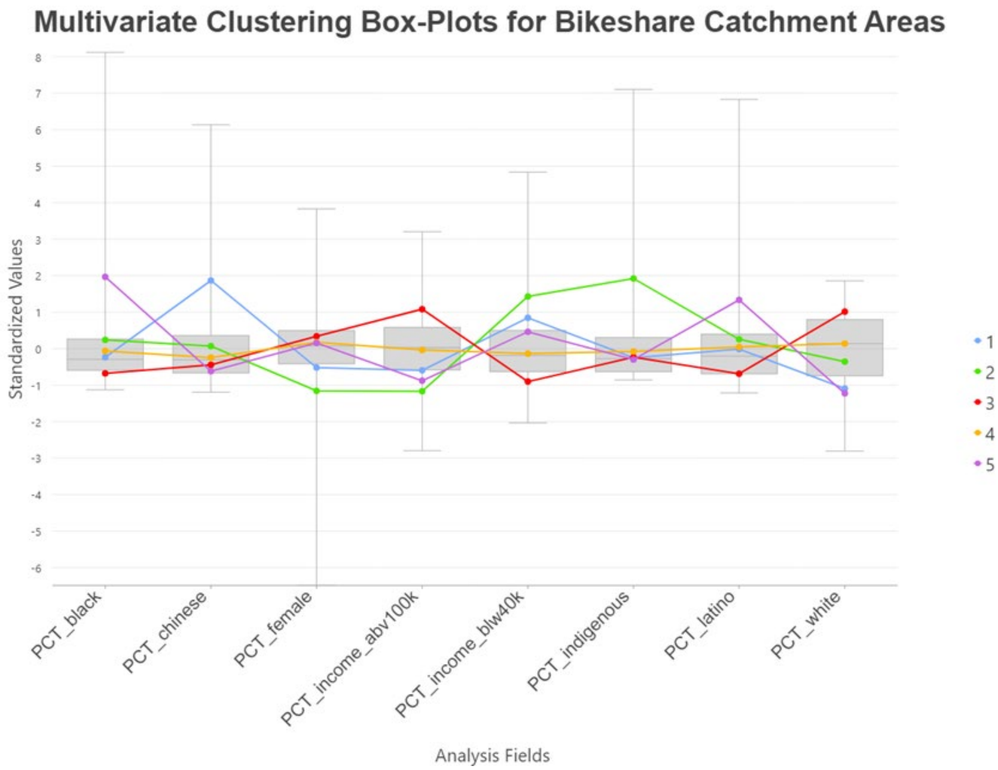

Figure 2: Multivariate Box-Plots for K-means Clustering Analysis

To identify the census DAs that have high or low values of the socio-demographic variables, compared to the surrounding areas, we utilized Hot Spot Analysis (Getis-Ord Gi^*) in ArcGIS Pro. The Gi^* statistics is defined as Equation (5) below (Getis & Ord, 1992).

$$Gi^* = \frac{\sum_j w_{ij} \times x_j}{\sum_j x_j} \tag{5}$$

Where

w_{ij} = spatial weight between census DAs i and j

x_j = socio-demographic variables value at census DA j

$$w_{ij} = \left[1 - \left(\frac{d_{ij}}{\alpha_i}\right)^2\right]^2 \tag{6}$$

$$\sum_j w_{ij} = 1 \tag{7}$$

Where

d_{ij} = the Euclidean distance between the centroids of census DAs i and j

α_i = bandwidth which is based on the longest distance between census DA i and its neighbours

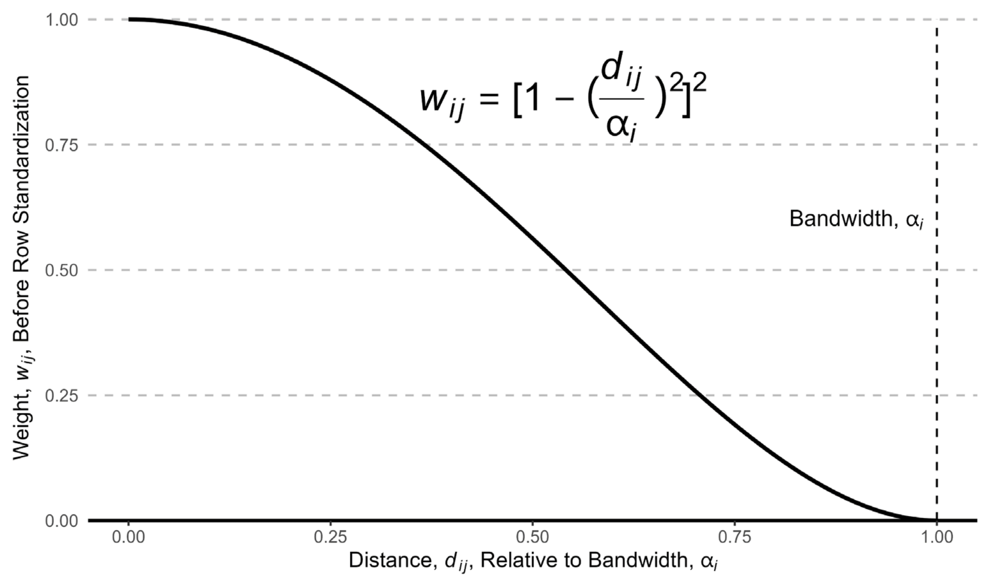

Figure 3: Bisquare Kernel Function

To conceptualize the spatial weight matrix for hotspot analysis, we used Neighborhood Explorer, a new tool introduced in ArcGIS Pro 3.2, to help construct a spatial weight matrix that describes the connectivity between each pair of census DAs. After trial and error, we found that preimplemented spatial weight matrix options, such as rook and queen contiguity or inverse distance, could not capture the spatial relationships between the census DAs due to the variability of sizes of DAs. As a result, we turned to the manual option to set the Neighbourhood Conceptualization to 40-nearest-neighbours and use the Bisquare Kernel Function (Esri, n.d.) to assign weights to neighbours. The Bisquare Kernel Function can be expressed mathematically as Equation (6). Figure 3 above visualizes the pre-row-standardized weights assigned by the Bisquare Kernel Function. This weighting scheme imposes a weaker penalty for neighbours that are further away from the specific census DA than the inverse distance, while being a stronger penalty than the Gaussian Kernel Function. To ensure that each census DA has the same summed values of weights from neighbours, we also row standardized the weight matrix, so the spatial weight matrix also satisfies the property shown in Equation (7).

In preparation for the suitability analysis, we executed the Hot Spot Analysis in ArcGIS Pro, focusing on six socio-demographic variables: the percentages of Females, Indigenous people, Chinese people, Black people, Latino people, and people with household total income below $40,000 in 2020 for each census DA in the City of Toronto. We identified hot spots with a confidence level exceeding 90% and converted them into raster format, with cell values equal to the original socio-demographic variables, which are percentages within a 0 to 100 range. These raster layers were then aligned for the upcoming raster summation.

3.2.2.4 Suitability Analysis

We created an approximate 1-kilometre buffer zone raster around the equitable catchment areas identified by cluster analysis, as illustrated in Figure 4. This buffer zone raster layer outlines the areas adjacent to equitable station catchments, deemed more suitable for system expansion due to their connectivity to the existing network.

We conducted a suitability analysis using the seven aforementioned raster layers. We computed a weighted sum of these layers to ascertain the most suitable areas for the expansion of the Bike Share Toronto system. The weights for the socio-demographic hotspot layers were set as the inverse of their respective means, $w_i = \frac{1}{\mu_i}$. The buffer layer was assigned a weight of 1.2 to balance the importance of proximity to existing stations against the need to serve underserved populations. While the choice of 1.2 is somewhat arbitrary, it suggests that proximity to existing equitable catchment areas is valued at 1.2 times of serving an underserved population group's hotspot with cell values at the mean level. Subsequently, we applied the Clip function to remove the vector catchment areas of existing stations, resulting in a weighted suitability map for the system's expansion. Areas with higher values are identified as more favourable for system expansion.

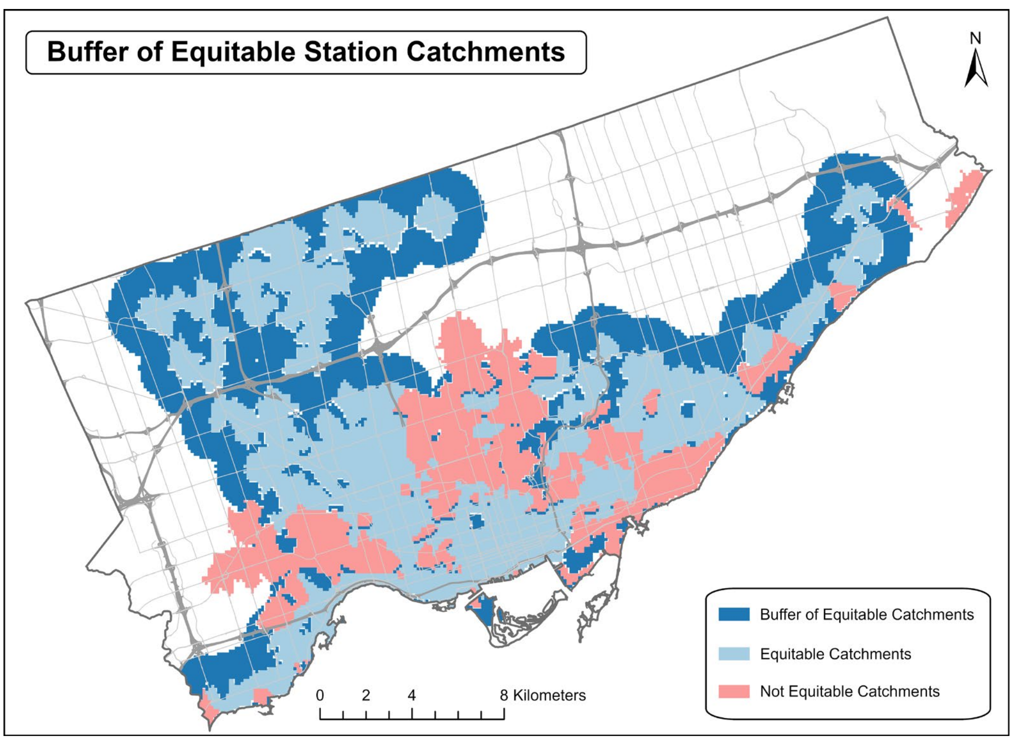

Figure 4: Buffer of Equitable Station Catchments

4 Discussion

The catchment area analysis results are depicted in Figure 5, illustrating the non-overlapping catchment areas for each Bike Share Toronto station and their corresponding total ridership in 2023. The ridership is quantified by the aggregate number of trips originating or concluding at each station. A clear pattern emerges from the data: the majority of bike-share usage is concentrated in the downtown core, with a discernible decline in ridership correlating with increased distance from this central hub. Notably, stations situated in the northern and eastern extremities of the network exhibit the least amount of usage, underscoring a considerable disparity in ridership across the system.

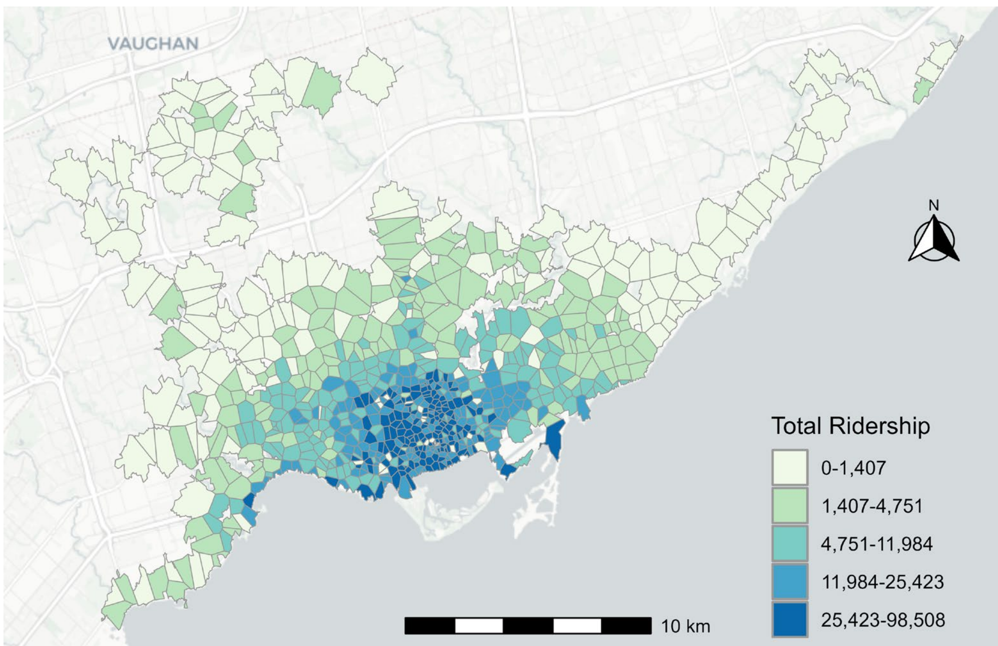

Figure 5: Non-overlapping Catchment Area Map

Figure 6 presents the system-wide equity performance results. It employs three colours to represent the weighted average results based on different ridership counts at each station: annual, casual, and total ridership—the latter being the sum of the first two. The disparities among these three metrics are minimal for all socio-demographic variables, as annual riders constitute only about 6.27% of the total trips in 2023. The left panel quantifies the disparity between the system-wide average and the city-wide average for various population subgroups. Values above the city-wide average indicate a relative oversupply of Bike Share services, whereas values below suggest an undersupply. The analysis reveals a considerable oversupply to White, Chinese, and Low-income residents. Given that low-income groups are often deemed vulnerable and deserving of equitable service provision, this oversupply aligns with the goals of social justice and service equity. Conversely, the data indicates a notable undersupply to Female and Black residents, signalling systemic inequities within the service provision. The right panel reveals that within the entire catchment area of the Bike Share Toronto system, over 50% of residents are White, and approximately 40% have a total annual household income in 2020 exceeding $100,000. Although some vulnerable subgroups receive an excess of services, the overall distribution within the Bike Share Toronto system exhibits substantial inequities.

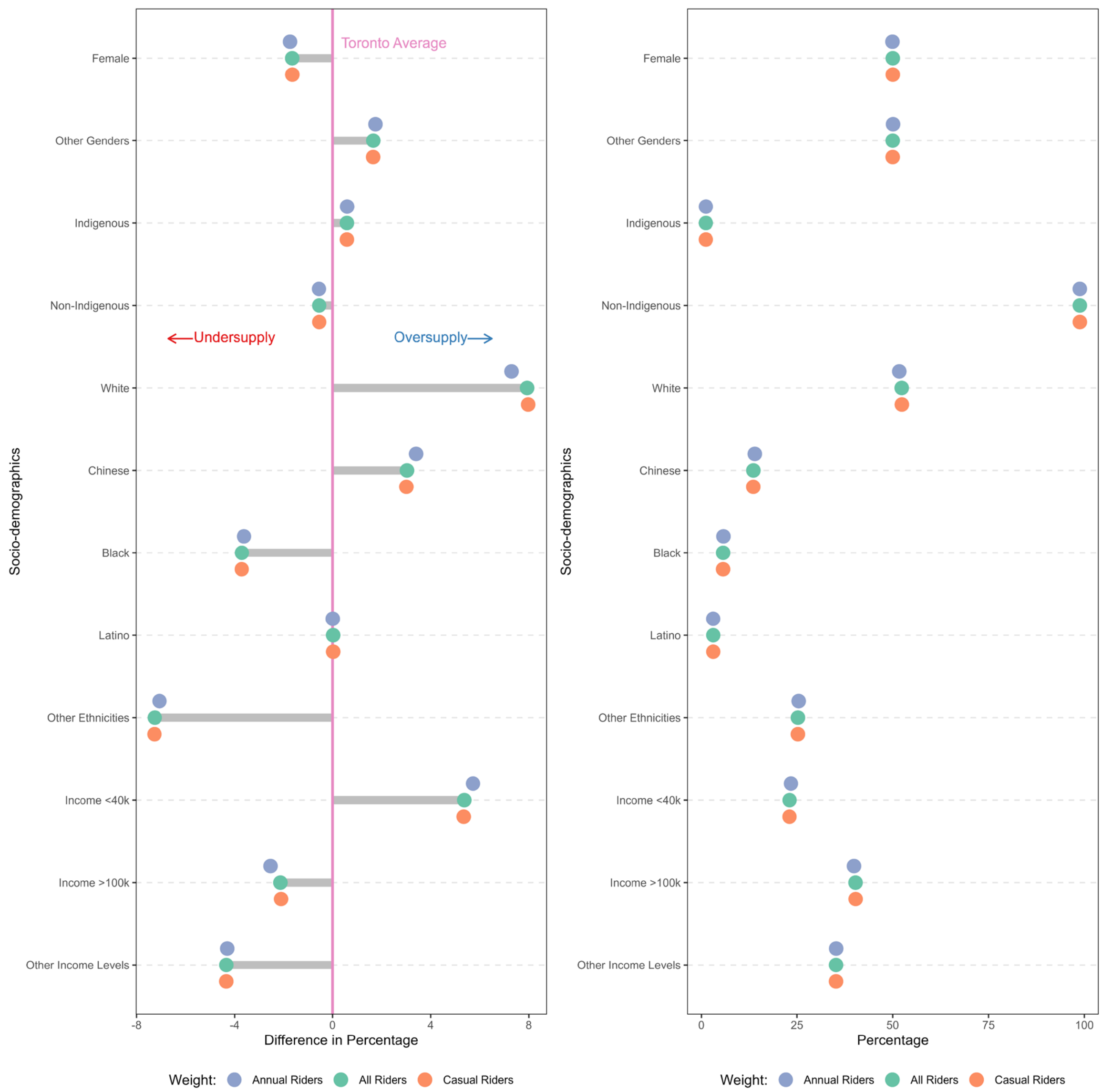

Figure 6: System-wide Service Provision Equity Performance

Based on hotspot analysis results shown in Figure 7 below, in Toronto, the low-income population is primarily concentrated in the downtown area, with additional pockets throughout the city. The Black community is chiefly found in the northwest and northeast, while the Chinese community is largely situated in North York and North Scarborough, with a presence in downtown as well. The Indigenous population mainly resides in the southern part of the city and surrounding downtown areas. The Latino community is concentrated in the western part of the city, and the female population is dispersed predominantly across the Midtown and York regions.

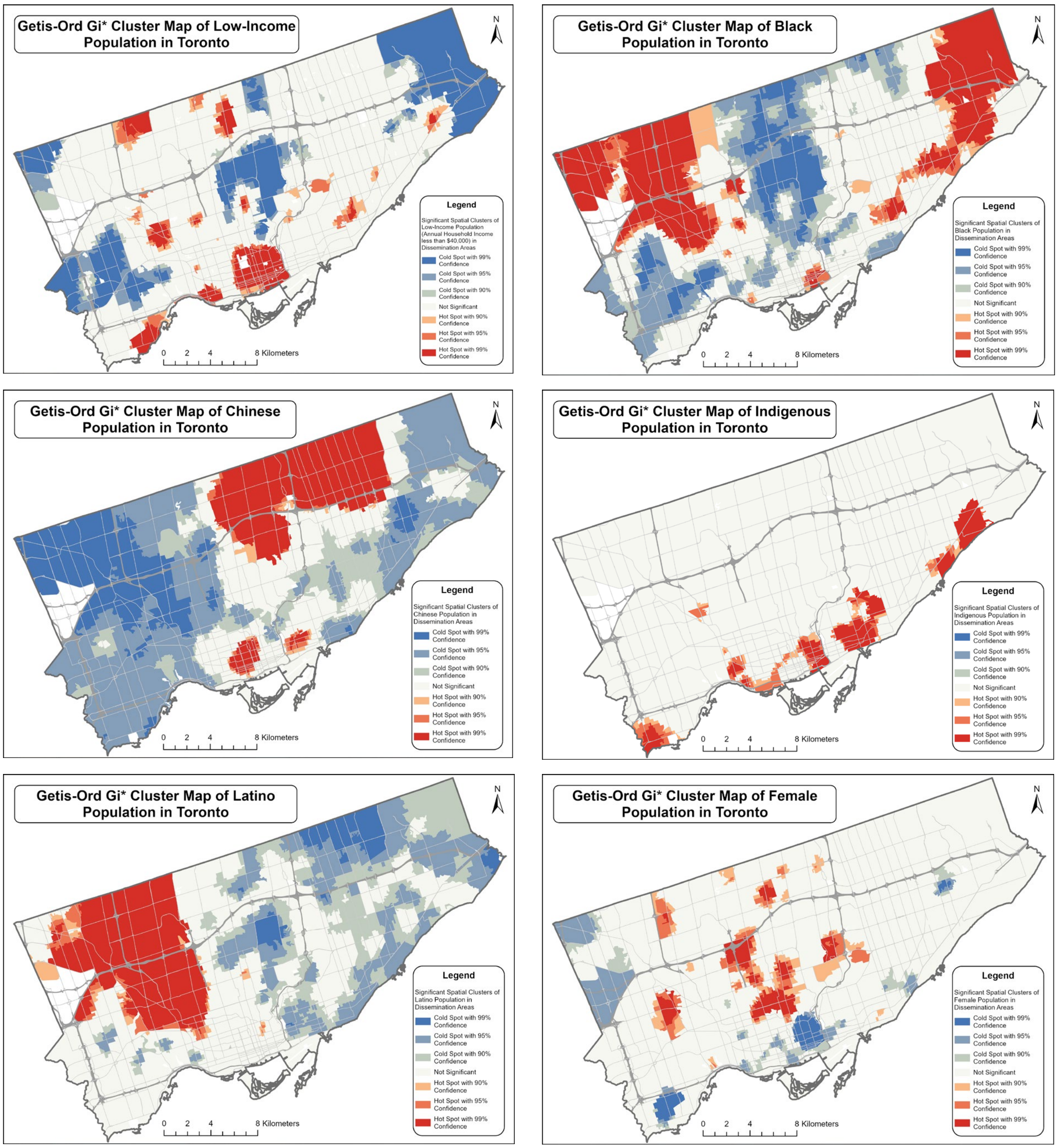

Figure 7: Hotspot Analysis Maps

Figure 8 below delineates the results of the suitability analysis for the potential expansion of the Bike Share Toronto system. The crossed-out regions in grey represent areas currently serviced by existing stations. Zones depicted in dark blue signify higher suitability values, marking them as prime candidates for system expansion with respect to enhancing equity performance. The areas that stand out with the highest suitability scores are Scarborough's West Hill, North York, Yorkdale, and predominantly the Jane and Finch area.

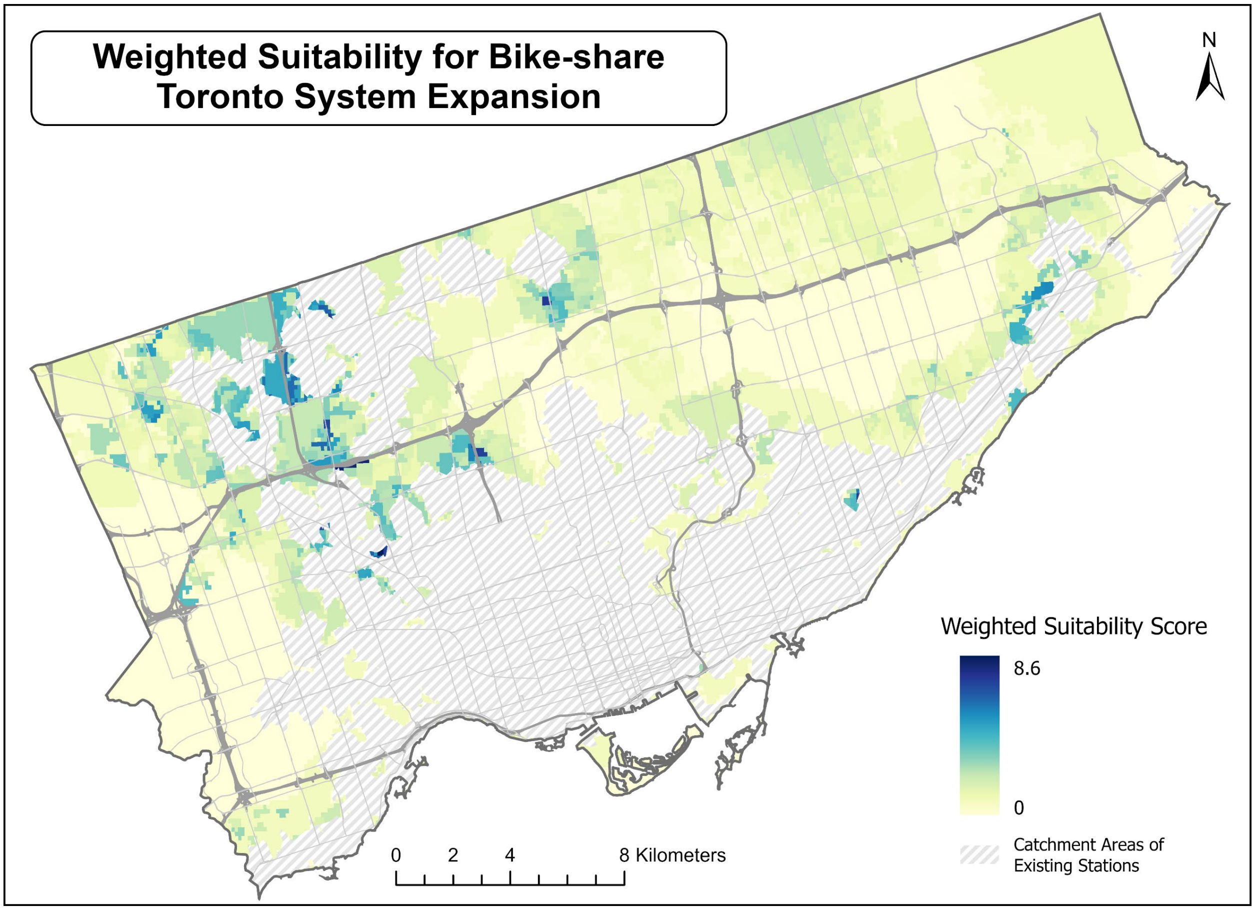

Figure 8: System Expansion Priority Zone Map

5 Conclusion

Our analysis of the Bike Share Toronto system, through an equity-focused lens, has revealed considerable disparities in service provision. Employing catchment area analysis, based on Figure 6, we discovered disparities in service provision: an oversupply to White, Chinese, and low-income populations contrasted with an undersupply to Black and female demographics. These findings indicate sizable opportunities for enhancing the system's equitable distribution of services.

In pursuit of this goal, we conducted a suitability analysis to identify areas that would benefit most from network expansion, thereby promoting equitable access throughout the city. Based on Figure 8, the areas with the highest suitability scores for expansion, based on equity performance, are Scarborough's West Hill, North York, Yorkdale, and predominantly the Jane and Finch area. These areas represent strategic opportunities for Bike Share Toronto to enhance service coverage and accessibility, particularly for underserved communities.

To promote transportation justice, we recommend prioritizing system expansion in areas with high suitability levels. Key considerations involve household income level, ethnicity, and gender representation. We call for the implementation of targeted outreach initiatives designed to enhance awareness and bolster usage among underrepresented demographics. Engaging in partnerships with community organizations, educational institutions, and local authorities is crucial to dismantle obstacles impeding the utilization of bike-share services. For instance, we suggest the exploration of economic incentives such as subsidized rates and introductory free trial periods, specifically tailored for low-income households and marginalized communities.

While our study provides valuable insights into the Bike Share Toronto system, it is important to acknowledge certain constraints that may affect the robustness of our findings. The absence of historical data for bike share stations necessitated reliance on real-time station data as of January 8, 2024. Consequently, discrepancies may exist between trip records and current station operations, including potential closures or relocations of stations active in 2023. This limitation could lead to inaccuracies in the calculated weights for these stations and the overall system catchment area.

Furthermore, the delineation of non-overlapping catchment areas relied on Euclidean distance measurements. The routing package *r5r* lacks native support for generating non-overlapping catchment areas based on network distance, which introduces a degree of imprecision. This approach, while offering a general perspective, does not account for actual travel distances along the road network, which may result in misrepresentations in the spatial distribution of catchment areas, particularly for stations in close proximity.

Future research should aim to incorporate historical station data to refine the accuracy of catchment areas. Additionally, advancements in routing algorithms could enable more precise modelling of non-overlapping catchment areas, accounting for the complexities of urban travel. Additionally, conducting surveys among riders to assess potential equity concerns would provide a better understanding of the demand side of bike-sharing services. By addressing these limitations, subsequent studies can build upon our findings to further the development of an equitable and inclusive Bike Share system.

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