Cycling for Everyone: Incorporating Equity Principles into the Transportation Planning Process

Qiao Zhao

Department of Geography

McGill University

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ABSTRACT

Transportation is the linchpin that enables us to access goods and services, employment opportunities, and other social interactions. One form, bicycling, has witnessed a surge in popularity in recent decades as cities around the world recognize its multifaceted benefits, from environmental conservation to congestion mitigation. Particularly for disadvantaged populations, cycling emerges as an equitable solution, providing accessible and affordable transportation while also serving as a means for physical activity. As cities increasingly focus on promoting cycling, transportation equity becomes a central concern. Transportation equity ensures that all individuals, regardless of their socioeconomic or demographic backgrounds, have equal access to reliable and affordable transportation options. However, the allocation of cycling infrastructure has, in some cases, reflected broader societal inequalities. Affluent neighborhoods often receive more significant cycling infrastructure investments, whereas disadvantaged areas, which might benefit most from bicycling, are left behind. As cycling's popularity continues to rise, it is critical that policymakers and city planners must address these equity challenges to ensure cycling's benefits are universally accessible.

While it is essential to consider equity in transportation project planning and to implement equitable systems and infrastructure, it is rarely a primary objective and is often entirely lacking. This dissertation uses Montreal as a study area and examines travel behaviors' social disparities, investigates inequitable access to cycling infrastructure and destination accessibility, and proposes an inclusive approach to cycling planning with an equity focus. This dissertation seeks to answer three questions:

- What are the differences in travel behaviors among various sociodemographic groups?

- To what extent does access to cycling infrastructure and destination accessibility via bicycles vary among different population groups?
- How can areas be identified where new infrastructure should be prioritized for disadvantaged populations to promote transportation equity?

These research questions are addressed through interconnected empirical studies. By analyzing household travel surveys from 2003 and 2018, this dissertation first examines social disparities in travel behaviors, revealing that low-income individuals, children, and women have distinct travel patterns. These patterns feature shorter trip distances and a higher dependency on public transit and non-motorized modes. While these disparities, to varying degrees, have persisted over time, the reliance on non-motorized transportation among vulnerable populations underscores the need for enhanced urban planning promoting walkability and bikeability.

Analyzing Montreal’s bicycle network's expansion from 2006 to 2020, this dissertation seeks to understand the socio-spatial distribution of cycling infrastructure and how these investments affect access to essential urban opportunities across different population groups. The study adopts an innovative approach to destination accessibility measurement by integrating network connectivity. Results revealed persistent disparities, with moderately socioeconomically disadvantaged areas benefitting more from cycling investments and maintaining better network connectivity. While the most socioeconomically disadvantaged areas could access a higher number of destinations by bicycles, they often had to share routes with vehicular traffic due to a lack of connected cycling infrastructure.

Lastly, this dissertation introduces a replicable quantitative framework to aid planners in identifying and filling gaps in the bicycle network within budgetary constraints. It considers three distinct prioritization strategies: connectivity-focused, equity-based, and modal shift. Each strategy targets specific objectives: enhancing network connectivity, promoting social equity in infrastructure access, and encouraging a modal shift from cars to bicycles. By integrating quantitative and spatial data, this methodology offers insights on project prioritization, ensuring the systematic growth of bicycle networks.

In summary, this dissertation introduces a systematic framework for integrating transportation equity into future transportation policy and planning analysis, contributing to knowledge in three primary ways:

- Deepening the understanding of how travel behaviors of various socio-demographic groups differ and identifying who is most reliant on cycling as a mode of travel;
- Developing a planning support tool to assess cycling infrastructure allocation's equity impact on individuals' ability to reach urban destinations safely; and
- Introducing a quantitative framework to systematically prioritize cycling infrastructure investments to maximize benefits in network connectivity, social equity, and sustainability.

RESUME

Le transport est le pivot qui nous permet d'accéder à des biens et services, des opportunités d'emploi et d'autres interactions sociales. Une forme, le cyclisme, a connu une hausse de popularité ces dernières décennies, car les villes du monde entier reconnaissent ses multiples avantages, de la conservation de l'environnement à l'atténuation de la congestion. Le cyclisme est particulièrement pertinent pour les populations défavorisées, se présentant comme une solution équitable, offrant un moyen de transport accessible et abordable, tout en servant de moyen pour l'activité physique. Alors que les villes mettent de plus en plus l'accent sur la promotion du cyclisme, l'équité en matière de transport devient une préoccupation centrale. Celle-ci garantit que toutes les personnes, indépendamment de leurs antécédents socio-économiques ou démographiques, ont un accès égal à des options de transport fiables et abordables. Cependant, l'allocation de l'infrastructure cyclable a, dans certains cas, reflété les inégalités sociétales plus larges. Les quartiers aisés reçoivent souvent des investissements plus significatifs en infrastructure cyclable, tandis que les zones défavorisées, qui pourraient bénéficier le plus du cyclisme, sont laissées pour compte. Alors que la popularité du cyclisme continue de croître, il est crucial que les décideurs et les urbanistes abordent ces défis d'équité pour garantir que les avantages du cyclisme soient universellement accessibles.

Bien qu'il soit essentiel de considérer l'équité dans la planification des projets de transport et de mettre en œuvre des systèmes et des infrastructures équitables, cela est rarement un objectif principal et est souvent totalement absent. Cette thèse utilise Montréal comme zone d'étude et examine les disparités sociales dans les comportements de déplacement, enquête sur l'accès inéquitable à l'infrastructure cyclable et à l'accessibilité de la destination, et propose une approche

inclusive à la planification cyclable avec un accent sur l'équité. Cette thèse cherche à répondre à trois questions:

- Quelles sont les différences dans les comportements de déplacement entre divers groupes sociodémographiques?
- Dans quelle mesure l'accès à l'infrastructure cyclable et l'accessibilité de la destination varient-ils parmi les différents groupes de population?
- Comment peut-on identifier les zones où la nouvelle infrastructure doit être priorisée pour les populations défavorisées afin de promouvoir l'équité en matière de transport?

Ces questions de recherche sont abordées à travers des études empiriques interconnectées. En analysant les enquêtes de déplacement des ménages de 2003 et 2018, cette thèse examine d'abord les disparités sociales dans les comportements de déplacement, révélant que les individus à faible revenu, les enfants, et les femmes ont des motifs de déplacement distincts. Ces motifs mettent en évidence de plus courtes distances de trajet et une plus grande dépendance aux modes de transport non motorisés et en commun. Alors que ces disparités, à divers degrés, ont persisté dans le temps, la dépendance aux modes de transport non motorisés parmi les populations vulnérables souligne la nécessité d'une planification urbaine renforcée pour promouvoir la marchabilité et la cyclabilité.

En analysant l'expansion du réseau cyclable de Montréal de 2006 à 2020, cette thèse cherche à comprendre la distribution socio-spatiale de l'infrastructure cyclable et comment ces investissements affectent l'accès à des opportunités urbaines essentielles pour différents groupes de population. L'étude adopte une approche innovante pour mesurer l'accessibilité de la destination en intégrant la connectivité du réseau. Les résultats ont révélé des disparités persistantes, les zones de niveau socio-économique modéré bénéficiant davantage des investissements en cyclisme et maintenant une meilleure connectivité du réseau. Alors que les zones les plus défavorisées socio-économiquement pouvaient accéder à un plus grand nombre de destinations à vélo, elles devaient souvent partager des itinéraires avec le trafic automobile en raison d'un manque d'infrastructure cyclable connectée.

Enfin, cette thèse introduit un cadre quantitatif réplicable pour aider les planificateurs à identifier et combler les lacunes dans le réseau cyclable dans le cadre des contraintes budgétaires. Elle considère trois stratégies de priorisation distinctes : axée sur la connectivité, basée sur l'équité, et le changement modal. Chaque stratégie vise des objectifs spécifiques : améliorer la connectivité du réseau, promouvoir l'équité sociale dans l'accès à l'infrastructure, et encourager un changement modal de l'automobile vers le vélo. En intégrant des données quantitatives et spatiales, cette méthodologie offre des aperçus sur la priorisation des projets, garantissant la croissance systématique des réseaux cyclables.

En résumé, cette thèse introduit un cadre systématique pour intégrer l'équité en matière de transport dans les futures analyses de politiques et de planification des transports, contribuant au savoir de trois manières principales:

- Approfondir la compréhension de la manière dont les comportements de déplacement des différents groupes sociodémographiques diffèrent et identifier qui dépend le plus du cyclisme comme mode de déplacement;
- Développer un outil de soutien à la planification pour évaluer l'impact sur l'équité de l'allocation de l'infrastructure cyclable sur la capacité des individus à atteindre en toute sécurité des destinations urbaines;

- Introduire un cadre quantitatif pour prioriser systématiquement les investissements dans l'infrastructure cyclable afin de maximiser les bénéfices en matière de connectivité du réseau, d'équité sociale, et de durabilité.

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CONTRIBUTION TO ORIGINAL KNOWLEDGE

This dissertation delivers a comprehensive analysis of transportation equity, especially in the context of cycling planning and infrastructure. It not only uncovers the state of inequities in Montreal's transportation system but also proposes a framework for more inclusive cycling investments. The contributions of this dissertation to the existing body of knowledge include:

- Recognizing the important role of efficient transportation policies in benefiting all users, this dissertation offers a thorough examination of the evolution and nuances of travel behaviors across different sociodemographic groups. It not only reveals how travel behaviors vary based on factors such as income, age, and gender but also investigate whether these differences are diminishing or expanding over time. Such insights can lay the foundation for more sustainable and equitable transportation planning and policymaking.
- Another key contribution was the introduction of a novel tool to measure disparities in destination accessibility by bicycles among various socioeconomic groups. By accounting for traffic stress and comfort levels of the streets, we assessed not just whether the current cycling infrastructure connects cyclists to urban opportunities, but also if cyclists can access their daily needs safely and conveniently. Furthermore, our proposed metric, "bikeable neighborhood", which merges destination accessibility with network connectivity, helps identify areas that lack a connected bicycle network and where residents do not have easy access to urban destinations, thus signaling potential zones for enhancement.
- This research proposes a data-driven framework to prioritize future cycling investments. It considers various intervention strategies and aligns with specific goals and objectives,

keeping cyclists' routing preferences in mind. This framework aids not only in prioritizing new cycling investments but also provides insights into how network enhancements might affect both current and potential cyclists. Our prioritization approach highlights the value of systematically expanding the bicycle network, aiding cities in optimizing the returns from their cycling investments within budgetary limitations. Importantly, our methodology is not constrained by specific contextual considerations, so planners in other regions can replicate it using similar datasets.

AUTHOR CONTRIBUTIONS

This dissertation comprises three manuscripts that have been submitted to peer-reviewed journals. Details of author contributions are provided below:

Chapter 2 *"Social Disparities in Travel Behavior: A Study of Travel Behavior in Montreal (2003-2018)"* by Qiao Zhao, and Kevin Manaugh. Kevin Manaugh contributed to the conceptual design and provided comments and editing for the manuscript. Qiao Zhao conducted all the analyses and was the primary author.

Chapter 3 *"Do New Bike Lanes Lead to a More Equitable City? An Analysis of Cycling Infrastructure in Montreal"* by Qiao Zhao, and Kevin Manaugh. Kevin Manaugh contributed to the conceptual design and provided comments and editing for the manuscript. Qiao Zhao conducted all the analyses and was the primary author.

Chapter 4 *"Introducing a Framework for Cycling Investments Prioritization"* by Qiao Zhao, and Kevin Manaugh. Kevin Manaugh contributed to the conceptual design and provided comments and editing for the manuscript. Qiao Zhao conducted all the analyses and was the primary author.

PUBLICATION DETAILS

Chapter Two *"Social Disparities in Travel Behavior: A Study of Travel Behavior in Montreal (2003-2018)"* is currently under review at the journal Travel Behavior and Society.

Chapter Three *"Do New Bike Lanes Lead to a More Equitable City? An Analysis of Cycling Infrastructure in Montreal"* is currently undergoing peer review at the Journal of Transport Geography.

Chapter Four *"Introducing a Framework for Cycling Investments Prioritization"* is reprinted from Transportation Research Record, Volume 2677, Issue 7, Introducing a Framework for Cycling Investment Prioritization 265 – 277, copyright (2023), with permission from Sage.

CHAPTER ONE: INTRODUCTION AND LITERATURE REVIEW

1.1 Background and Motivations

Through much of the previous century, the automobile significantly overshadowed the bicycle as a mode of transportation. However, after intermittent and minor surges of interest, cycling has experienced a renaissance in recent times (Buehler & Pucher, 2021). Globally, cycling has not only become a recreational activity but also a symbol of sustainable urban living and a powerful tool to address critical socio-environmental challenges. Although the prevalence of cycling in the United States and Canada still lags behind many European countries, there is a clear upward trend in the number of people choosing cycling as a mode of transportation (Abdullah et al., 2020).

Cycling offers multiple benefits. On an individual level, integrating cycling into daily travel routines provides moderate-intensity physical activity, offering an array of health benefits, from reducing cardiovascular risks (Celis-Morales et al., 2017) to enhancing mental well-being (Mytton et al., 2016). On a macro level, cycling produces no in-use emissions and has low lifecycle greenhouse gas emissions (Teschke et al., 2012; Walsh et al., 2008). As a result, it is often seen by cities as an opportunity to improve air quality. The importance of cycling becomes even more pronounced for disadvantaged populations – those defined by racial background, indigeneity, disability, socio-economic status, and other intersecting identities. For communities historically marginalized or economically strained, access to reliable, affordable, and safe transportation can be transformative. Cycling, with its relatively low barriers to entry and maintenance costs, can provide a much-needed mobility solution. Furthermore, it offers a means of physical activity for individuals whose opportunities for recreation or fitness might be limited.

The presence of designated cycling infrastructure has been correlated with increased cycling adoption. Research has consistently shown that the presence of such infrastructure can significantly influence the decision to adopt cycling as a primary mode of transportation (Heesch et al., 2015; Mertens et al., 2016). However, as more cities embrace bicycling, a crucial issue emerges in the broader transportation landscape: transportation equity. This concept encompasses the idea that all individuals, regardless of their socioeconomic or demographic background, should have equal access to an affordable and reliable transportation system. While the evidence is mixed (Ferenchak & Marshall, 2021), advocates and scholars have suggested that cycling infrastructure investments tend to favor wealthier areas (League of American Bicyclists, 2013). While affluent neighborhoods see robust investments in cycling infrastructure, disadvantaged communities often lack such facilities. These disparities reinforce existing societal inequalities, preventing the populations that could benefit the most from cycling from accessing it.

The challenge that looms large is not only to recognize these disparities but also to methodically address them. Equity in transportation, especially in the realm of cycling, underscores the urgency to address these biases and build an inclusive framework. By employing a social equity lens, this dissertation aims to shed light on the travel behaviors of disadvantaged populations, explore discrepancies in cycling infrastructure access, and most importantly, propose a systematic framework for integrating transportation equity into future transportation policy and planning analysis. This dissertation is guided by three research questions:

- What are the differences in travel behaviors among various sociodemographic groups?
- To what extent does access to cycling infrastructure and destination accessibility via bicycles vary among different population groups?

- How can areas be identified where new infrastructure should be prioritized for disadvantaged populations to promote transportation equity?

In addressing these research questions, this dissertation provides quantitative evidence of social disparities in travel behaviors and potential discrepancies in access to cycling infrastructure in Montreal. It considers the implications of these disparities for planning practice and research, and suggests how planners might move towards a more equitable distribution of cycling infrastructure.

1.2 Thesis Outline

The remainder of this chapter presents the literature review conducted for this dissertation, identifying knowledge gaps in transportation equity and equity analysis. Chapter Two investigates the travel behaviors of various demographic groups in Montreal, drawing on household travel surveys from 2003 to 2018. It examines the evolution of travel behaviors over time and uses multilevel models to analyze the effects of sociodemographic variables on these behaviors. This analysis underscores the need for transpiration planning to cater to the diverse needs of all population segments and sets the stage for further examination of cycling infrastructure accessibility.

Chapter Three addresses the second research question by exploring the development of cycling infrastructure on the Island of Montreal between 2006 and 2020. It provides a detailed analysis in socio-spatial distribution of cycling infrastructure, seeking to elucidate how infrastructure investments affect cycling infrastructure access and bicycle destination accessibility among different socioeconomic groups. Additionally, this chapter introduces a “bikeable neighborhoods” metric that integrates destination accessibility and network connectivity, facilitating an assessment of whether the cycling infrastructure adequately enables safe access to key activities. It also quantifies the socioeconomic disparities among residents in the most and least bikeable neighborhoods, identifying areas where enhancements are needed.

Chapter Four proposes a framework to improve planning and investment in cycling equity. It employs accessible datasets and presents a quantitative model to prioritize cycling infrastructure projects, aiming to enhance accessibility to cycling infrastructure and urban opportunity access for transportation-disadvantaged neighborhoods. Beyond an equity-based strategy, this chapter also suggests additional interventions to encourage a modal shift and improve network connectivity. The proposed framework aids municipalities in strategically implementing new cycling infrastructure, aligned with specific policy goals, and is adaptable to other regions.

Finally, Chapters Five and Six synthesize the key findings of this dissertation, emphasizing its significance within the domain of transportation equity, and acknowledging the research limitations.

1.3 Literature Review

1.3.1 Transportation Equity

In the context of transportation, the concept of equity can be interpreted in a multitude of ways. Marsh and Schilling (1994) argue that equity in transportation implies that all groups should receive an equal share of the effects arising from facility location decisions. Their perspective primarily focuses on the output or results of decisions in transportation infrastructure placement. On the other hand, Litman (2002) incorporates not only the benefits from transport investments and services but also the transportation costs impose on other people, including crash risk, and exposure to air pollution. Litman (2002) further distinguishes the concept of transport equity into two categories: horizontal and vertical equity. Horizontal equity suggests an egalitarian approach where every individual or group, regardless of their socio-economic or demographic differences, should be treated equally. On the contrary, vertical equity, also known as social equity, aims to rectify existing disparities, such as income or access to resources, between different societal groups and consider how transportation systems serve disadvantaged and underserved groups. Nonetheless, transportation infrastructure distribution is influenced by various technical and political factors. The approach adopted by planners and policymakers in allocating limited resources inevitably favors specific groups, inadvertently marginalizing others. This implies an inherent challenge in ensuring equal access across all demographic groups. Furthermore, pursuing an even distribution of transportation infrastructure across a city potentially leads to deficiencies in efficiency and effectiveness metrics (Braun, 2018). In this dissertation, transportation infrastructure and services are considered equitable if they prioritize benefiting those population groups whose transport experiences are undermined by morally arbitrary traits beyond their control, as well as by the socio-economic conditions into which they are born.

The emergence of cycling as an affordable and alternative transportation mode has raised questions about the equity of cycling infrastructure (Lee et al., 2017). For example, Pucher and Renne (2005) discovered that older individuals, people with low income, and racialized groups exhibit lower levels of car ownership, instead demonstrating a greater reliance on public transit and active transportation when compared to the average population. In Canada, Hosford and Winters (2022) found a negative correlation between income level and car commuting. Instead, individuals with lower income were more likely to depend on alternative modes of transportation, such as walking, cycling, and public transit. However, this reliance on cycling has not been adequately addressed in infrastructure and policy development.

The discussion regarding equity in bicycle planning usually involves urban gentrification, which have led to the marginalization of deprived communities. Cycling infrastructure projects are frequently justified and promoted based on their anticipated contributions to economic growth. These projects are often seen as a tool for attracting and retaining young, modern, and independent individuals who from the “creative class” within thriving cities (Florida, 2002). However, while the argument for cycling infrastructure often incorporates broad and apparently inclusive ideas about livability and sustainability (Stehlin, 2015), it may imply that the primary beneficiaries are the more affluent users, and that these developments might stimulate economic benefits that could result in increased property values and decreased housing affordability. To date, some studies found that cycling infrastructure investments tend to concentrate in centrally located, socioeconomically privileged areas (Fuller & Winters, 2017; Hosford & Winters, 2022; Tucker & Manaugh, 2017). In contrast, marginalized neighborhoods characterized by low socioeconomic status and transportation poverty are often overlooked (Cunha & Silva, 2022). A similar trend was observed in a study conducted across 22 large U.S. cities which revealed that block groups with lower socioeconomic status, lower levels of education, and higher percentages of minority populations had less access to cycling infrastructure (Braun et al., 2019). This trend persisted even after controlling for demand-based factors such as urban form and cycling rate. Several authors have recently examined the integration of social equity objectives within transportation planning in North America and discovered that these aims were either missing or insufficiently converted into actionable strategies (Lee et al., 2017; Manaugh et al., 2015a). The neglect of equity considerations within bicycle planning and policy creation has resulted in an uneven distribution of cycling infrastructure investments and benefits (Grisé & El-Geneidy, 2018). Lucas et al. (2019) indicated that the absence of protected space for cycling in areas with high vehicle volumes and extensive street parking resulted in increased cycling-related collision and injury risk. This finding was further supported by Raifman and Choma (2022) who reported that in the U.S., the per-mile traveled fatality rate was disproportionately high for Black and Hispanic cyclists, exceeding that of white cyclists by over 1.5 times. However, variations do exist in the equity of access to cycling infrastructure among different urban areas. A longitudinal analysis by Houde et al. (2018) of the cycling network expansion in Montreal, Longueuil, and Laval from 1991 to 2016 revealed an improvement in spatial access for low-income individuals, recent immigrants, and seniors over the study period.

1.3.2 Equity Analysis

In the complex task of examining equity impacts within transportation systems, a critical step involves assessing the distribution of benefits across different geographical areas and/or demographic groups. Transportation equity is a pressing issue, particularly in the context of Canada's historically automobile-dominated economy. In the past, the emphasis on travel speed and time predominantly favored faster, more expensive modes of transportation, such as driving, over slower more affordable ones like walking, bicycling, and public transit. Discussions of equity primarily focused on the fairness of transportation funding and the degree to which different vehicles contributed their share of roadway costs. Little consideration was given to whether transportation systems catered to non-drivers, or how planning decisions influenced external costs like crash risk and pollution imposed on urban communities. Furthermore, the focus on increasing travel speed and reducing travel time often resulted in policies that were inequitable and ineffective (Martens, 2016; Van Wee, 2011). This issue is partly due to the fact that the monetary valuation of travel time savings, typically employed in conventional transport system appraisals such as cost-benefit analysis, implicitly favors transport projects that mainly benefit higher-income groups. These groups often make more trips than their lower-income counterparts, thereby accruing a higher proportion of benefits in aggregate cost-benefit analyses.

A promising approach to this problem shifts the focus from travel time to inequities in transportation accessibility. The primary benefit of transportation infrastructure is to enhance people's accessibility (Martens, 2012; Van Wee & Geurs, 2011), which is defined as a person's ability to access services within a given environment. Authors from both transportation planning practices (Manaugh et al., 2015a) and academic literature (Martens, 2012; Pereira et al., 2017) have contended that enhancing individuals' access to key destinations, such as employment, healthcare facilities, and educational services, should be central to understanding the benefits and equity of transportation. Accessibility to a minimum level is necessary for people to satisfy their daily needs and plays a crucial role in expanding people's freedom of choice. This, in turn, enables people to develop their capabilities and thrive. Equity in transportation, therefore, seeks to shift the focus from the traditional measure of travel time savings – which favors societal groups who travel more – to improvements in accessibility that cater to more vulnerable social groups (Martens & Di Ciommo, 2017). Given that accessibility offers one of the most comprehensive measures to examine the complex interactions between land use and transportation systems (Hansen, 1959), transportation researchers have devoted significant resources to developing methodologies for measuring accessibility in urban environments. Moreover, the concept of accessibility is now being employed in the evaluation of transportation plans in numerous major cities worldwide (Boisjoly & El-Geneidy, 2017; Manaugh & El-Geneidy, 2012) and in quantifying the benefits of urban plans for diverse socioeconomic groups (Foth et al., 2013; Martens, 2016).

In the context of transport, accessibility is often measured based on the effort, typically expressed in terms of time, required to reach key destinations (Albacete et al., 2017). Accessibility is largely dependent on various factors, including the transportation infrastructure, the land use patterns, and personal characteristics like age, income, and car ownership (Geurs & Van Wee, 2004). Given these components, accessibility is operationalized into two main categories: people-based measures and placed-based measures (Miller, 2018). People-based measures are directly related to the individual as they incorporate personal characteristics such as age, gender, and physical disabilities (Levinson & Krizek, 2005). On the other hand, place-based measures examine the spatial separation between locations where desired activities occur and key locations in individuals' lives, such as their homes or workplaces (Kwan & Weber, 2003). Therefore, these measures are most commonly used by policymakers to identify and quantify transportation service deprivation at the regional level (Dodson et al., 2007). The two most common metrics of place-based accessibility are cumulative opportunities and gravity-based measures. While cumulative opportunities capture the number of reachable destinations within a predefined travel time or distance from a specific location, gravity-based measures estimate a location's accessibility by assigning weights to opportunities available at all other locations based on a function of travel time or distance between them.

Much existing research has centered on destination accessibility for bicycles, often focusing on access to a single specific type of destination. For instance, Arranz-López et al. (2019) evaluated walking and cycling accessibilities to retail facilities using gravity-based models and established minimum accessibility requirements and identified accessibility thresholds for different population groups. Hosford et al. (2022) utilized the cumulative opportunity measure to compute the number of grocery stores reachable within a 15-minute walking or cycling distance. Recently, the accessibility of a wide range of destinations by bicycle has emerged as a critical issue in urban and transport planning. For example, Iacono et al. (2010) calibrated the distance-decay model and measured non-motorized accessibility to five types of destinations: employment, shopping, school, restaurant, and recreation. Similarly, Saghapour et al. (2016) developed a

Cycling Accessibility Index (CAI) to quantify cycling accessibility to four types of trip purposes, including education centers, health and care facilities, community services, and retail and recreation centers.

Much of the existing research has used methods similar to those employed for motorized vehicle travel to measure cycling accessibility. However, unlike car-based or transit-based accessibility, where the primary level of service indicator is typically time and/or distance, cycling accessibility is significantly influenced by both land use and other level of service dimensions such as comfort level of cycling infrastructure, and connectivity and directness of bicycle network. Cyclists, unlike transit riders and drivers who typically exhibit a high degree of comfort in their respective modes of transportation, may experience varying degrees of discomfort when navigating different streets. The research mentioned above generally considers only the time component of the travel and does not account for cyclists' preferences on route infrastructure. Several recent studies have sought to measure cycling accessibility by taking into account traffic stress and comfort levels on the street network. For example, Sisson et al. (2006) determined bikeability to elementary schools by considering factors such as traffic volume, proposed speed limit, and surface conditions. McNeil (2011) assigned an "effective length" to each road link where greater comfort resulted in shorter, effective lengths and developed the "20-min neighborhood" concept to examine the bicycle accessibility to destinations including schools, transit, and retail stores. Similarly, Furth et al. (2018) classified road segments according to the level of traffic stress and quantified employment accessibility by bicycle.

1.3.3 Bicycle Network Design

Decisions to develop or not build particular types of transportation infrastructure in specific locations can affect community cohesion, alter exposure to air pollution, and impact road safety risks. Despite the extensive policy guidelines on the physical design of bicycle facilities (CROW, 2007; Sustrans, 2014), the literature on prioritizing and locating cycling infrastructure investments appears to be limited. Efforts in this area primarily utilized origin-destination data to formulate an optimization framework for urban bicycle network planning. Larsen et al. (2013) devised a grid-cell model to identify priority areas within a region for cycling infrastructure investments. Their model, based on origin-destination and stated preference surveys, took into account both existing bicycle trips and potential short car trips amenable to cycling, also incorporating bicycle-vehicle collision data. Guerreiro et al. (2018) developed a method using Geographic Information System (GIS) to objectively determine optimal locations for new bikeways. They used data mining of disaggregated origin-destination data, factoring in both real and potential users. Instead of identifying bike lanes between origins and destinations, Zuo and Wei (2019) introduced a systematic and quantitative approach for locating new cycling infrastructure, relying on a multicriteria analysis technique with the aim of improving bicycling connectivity and bicycle-transit connections.

The traditional travel surveys often fail to capture detailed and comprehensive information about people's travel routes or facility preferences. Consequently, there is a growing body of literature on bicycle planning that employs crowdsourced data to improve the understanding of urban dynamics and influence planning. Using large-scale bike-sharing trajectory data within a greedy network expansion framework, Bao et al. (2017) generated bicycle network constructure plan for Shanghai, China, incorporating a flexible objective function to balance the coverage of existing bike users and the length of their trajectories. Inspired by percolation theory, Olmos et al. (2020) suggested a data-driven strategy for prioritizing new facilities by integrating smartphone-based bicycle GPS data with origin-destination matrices extracted from mobile phone data. They outlined potential bicycle trips and identified a well-connected bicycle network covering the entire city, composed of links with the highest potential demand flows.

In recent years, bicycle network design research has leveraged network science to measure the statistical and dynamical properties of bicycle networks and devise optimal strategies for bicycle network growth. An innovative study by Szell et al. (2021) considered the structural complexity of bicycle networks and proposed growth strategies to optimize quality metrics such as cohesion, spatial coverage, Points of Interest (POI) coverage, resilience, directness, and local and global efficiency. Finally, Akbarzadeh et al. (2018) created a weighted network based on the number of taxi trips. They identified seven different network clusters using a modularity maximization method and proposed the bicycle routes that minimized the total travel distance in the network as priority corridors for new bikeways. Nonetheless, rather than constructing a connected network, their focus was on linking nodes in each sub-network to minimize travel time and total length of proposed bikeways, ultimately aiming to enhance directness.

In summary, the decisions regarding the location of new bikeways are often made in practice using less rigorous methodologies. Research on optimizing the planning of bicycle network is still emerging. Cyclists, as opposed to motorized road users, consider a wider array of factors when selecting bicycle routes, including time, distances, and comfort (Winters et al., 2011). However, many studies have not considered factors other than distance and travel time when identifying key priority bike travel corridors. Moreover, it is noteworthy that all the literature mentioned above has primarily aimed to prioritize cycling investments to enhance bicycle connectivity and increase the number of bicycle users. However, as far as the author's knowledge goes, none of the existing literature has prioritized cycling infrastructure development specifically for equity-deserving groups with the aim of advancing social equity. This gap in the literature underscores the need for more inclusive planning approaches that consider the unique needs and challenges of these underserved communities, thereby fostering more equitable access to cycling infrastructure.

CHAPTER TWO: SOCIAL DISPARITIES IN TRAVEL BEHAVIOR: A STUDY OF TRAVEL BEHAVIOR IN MONTREAL (2003-2018)

Abstract

This study investigates the variations in travel behaviors among diverse sociodemographic groups in Montreal, Canada, using data from household travel surveys from 2003 to 2018. It highlights persistent disparities in travel behaviors, especially among low-income households, children, and women, when compared to their counterparts. Specifically, people from low-income households make shorter trips and are more dependent on public transportation and non-motorized travel. While there is a declining trend in distance-based disparity for these individuals, their dependency on public transport remains steady. Children generally travel shorter distances and mainly depend on walking, cycling, and parent/caregiver driving. Women consistently travel shorter distances than men and are more likely to use public transit, although their use of such modes has declined over time. Regression models further demonstrate a positive correlation between car ownership with trip distance, while household size negatively impacts it. Additionally, our multilevel regression analysis aligns with the descriptive results, indicating that people with low-income, children, and women are more likely to use non-motorized modes and public transportation. The persistence of social disparities in travel behaviors underscores the need for equitable considerations in transportation planning and the potential benefits for policy makers to tailor transport solutions specific to the needs of different socio-demographic groups.

Keywords: Mobility, Travel behavior, Socioeconomic disparity, Equity

2.1 Introduction

Mobility refers to the movement of people, objects, and information, including not only the social mobility of individuals and groups but also their physical mobility, commonly referred to as travel behavior (Kaufmann et al., 2004). Over the past few decades, travel behavior in Canada has undergone significant transformations (Khan et al., 2016). Despite the country's heavy reliance on automobiles for mobility, demographic, economic, and technological changes are impacting how mobility is achieved (Litman, 2005). Concurrently, under public pressure to address issues such as traffic congestion, greenhouse gas emissions, financial deficits, and high levels of physical inactivity, governments and organizations across Canada have invested in cycling facilities to promote more sustainable travel behaviors among Canadians (Pucher & Buehler, 2006).

However, Canada, like many other countries, is experiencing growing socioeconomic inequality. Travel needs, conditions, and behaviors vary among different groups. In particular, socially disadvantaged groups, women, and seniors may exhibit distinct travel patterns compared to their counterparts due to constraints such as distance, personal resources, and division of household labor (Hanson, 2010). Furthermore, advocates and scholars argue that transportation planners often overlook the differences in travel behaviors, leading to unequal provision of transportation services in urban areas (Martens, 2016). For example, transit policies often prioritize expanding commuter-oriented express bus and rail service to attract wealthier suburban commuters, while devoting less attention and resources to improving transit services for transit-dependent individuals, who are generally poorer and include a disproportionate number of minority passengers (Garrett & Taylor, 1999). This limits their access to jobs, healthcare, and other services.

To develop and implement efficient transport policies that benefit all users, address the substantial demand for transit services and active transportation facilities from predominately low-income and minority residents, and provide a sustainable and equitable transport system, differences in travel behaviors must be considered in transport planning and policymaking processes. Consequently, this study aims to investigate variations in travel behavior among different population groups in Montreal by analyzing data from household travel surveys conducted between 2003 and 2018. Specifically, this study seeks to answer the following research questions: 1) How does travel behavior vary by sociodemographic characteristics? 2) Are differences in travel behaviors shrinking or growing over time? 3) How do variables such as income, age, and gender influence trip distance and mode choice?

2.2 Literature Review

Travel behavior refers to the ways in which people move through time and space, the reasons for such movement, and the various circumstances that surround physical mobility (Van Acker et al., 2010). Trip frequency, trip duration, and mode of transportation are among the most commonly studied aspects in travel behavior studies. Trip frequency measures the number of trips an individual makes within a given time period, while trip duration focuses on the time it takes to travel from one point to another or through several points in a single trip. Previous research has identified various socioeconomic factors that affect travel behavior, resulting in different travel patterns among different socioeconomic groups. For instance, low-income individuals tend to make fewer and shorter trips than comparable people from households making more money (Allen & Farber, 2020; Paez et al., 2009; Pucher & Renne, 2003; Roorda et al., 2010). Similarly, gender differences also delineate travel patterns, with women tending to make more trips, cover shorter distances in individual trips, and work closer to home, relative to men (Hanson & Hanson, 1980; Li et al., 2004; Rosenbloom, 2004). However, recent evidence suggests that the differences in travel behavior between genders are converging, as more women enter the workforce, pursue higher education, and advance in their respective fields (Ng & Acker, 2018). Origin-destination (O-D) surveys in the Quebec Metropolitan Area revealed that gaps between work trip distances of men and women decreased between 1991 and 2001 (Theriault et al., 2006). Similarly, Crane (2007) measured commute trends for the metropolitan United States from 1985 through 2005 and pointed out that commuting distances were converging slowly for men and women.

Travel mode choice refers to the decision-making process of choosing between various transport alternatives (De Witte et al., 2013). Socioeconomic status plays a critical role in differences in mode choice. These differences occur along the dimensions of gender, age, income, and vehicle ownership. While there is no real consensus in the literature on impacts of gender and age on mode choice (Cirillo & Axhausen, 2006; Hosford & Winters, 2022; Martin et al., 2016; Pucher & Renne, 2003), studies confirm that income has a positive relationship with car use and an inverse relationship with public transit use (Hensher & Rose, 2007; Hosford & Winters, 2022; Pucher & Renne, 2003). Furthermore, vehicle ownership is highly correlated with mode choice, as households that cannot afford a car are more likely to use public transportation or other modes of travel.

The relationship between built environment characteristics, which characterize the spatial environment in which mode choice takes place, and mode choice has been widely investigated. Neighborhood design and the way land is developed and used can affect mode choice. In particular, high densities and land-use mixtures at both origin and destination locations lower the probability of driving and increase the likelihood of taking public transit (Camagni et al., 2002; Cervero, 2002; Limtanakool et al., 2006). Furthermore, proximity to infrastructure has been shown to impact mode choice. Studies indicate that the availability of a public transit stop increases transit use (Kenworthy & Laube, 1996; Limtanakool et al., 2006), while Kenworthy and Laube (1996) mention that car use increases significantly with increasing road density.

2.3 Methodology

2.3.1 Study Context

Greater Montreal is the second-largest metropolitan area in Canada, with approximately 4.3 million residents in 2021 (Statistics Canada, 2022). Central to the fabric of the region is the Société de transport de Montréal (STM), which operates an extensive network of buses and metro lines throughout the Island of Montreal (**Figure 2.1**). Complementing STM's services, Exo operates commuter rail and metropolitan bus services to enhance connectivity between the downtown core and outlying suburban areas. In addition, several local transit agencies, such as Société de transport de Laval (STL) and Réseau de transport de Longueuil (RTL), cater to the transit needs of their respective municipalities.

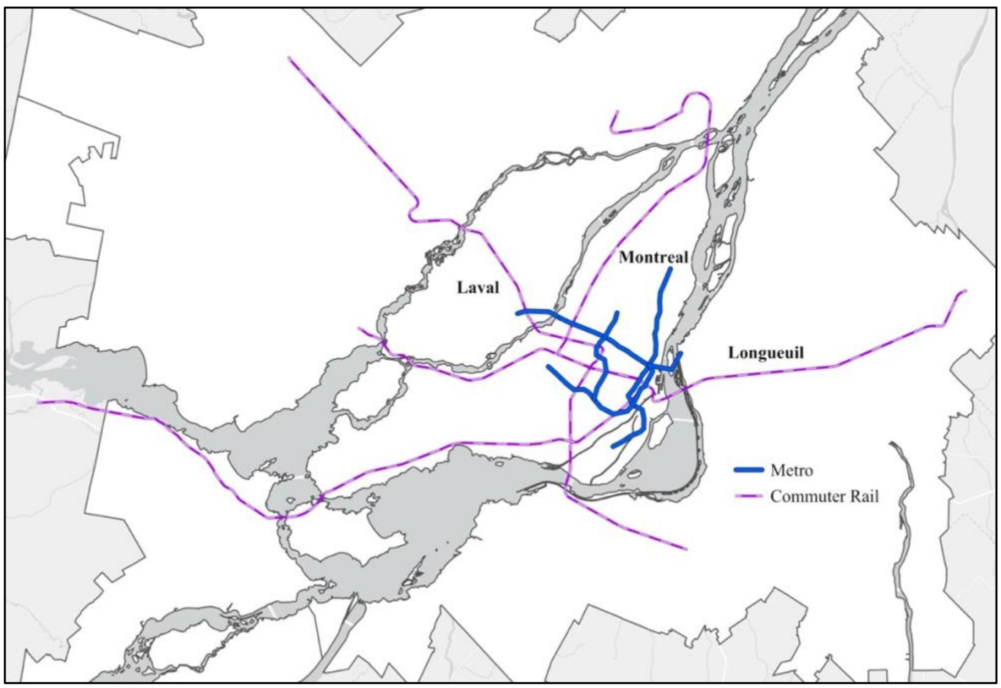

Figure 2.1: Metro lines and commuter rails in Montreal metropolitan area

2.3.2 Data Sources

The study sample is comprised of individuals aged four or older. Data on individuals' travel behavior, sociodemographic characteristics, and trip attributes were obtained from the Origin-

Destination (O-D) Survey. The survey was conducted in the years 2003, 2008, 2013, and 2018, and included 56,959, 66,124, 78,731, and 73,421 households respectively (**Table 2.1**), reported each year by samples of approximately 5% of region residents. The O-D Survey is a regionally representative travel diary survey administered by the ARTM through telephone interviews within the Montreal metropolitan area. This survey captures information on each movement made by all members of a sampled household, tracing their journey from origin to destination on the previous weekday. The survey includes data on household characteristics (such as size, income, and number of vehicles), individual characteristics (including age, gender, driving license ownership, and employment status), and travel information (covering origin, destination, trip purpose, and mode of transportation). The primary objective of the O-D survey is to acquire a comprehensive understanding of all trips undertaken by residents within the region, spanning all transportation modes, with the purpose of evaluating the urban travel needs of the population. To better represent Montreal's population, the producing agency assigned unique weights to households, individuals, and trips, respectively.

Over the survey years, the sampled territory has undergone changes and has extended beyond the boundary of the metropolitan area. For consistency, our analysis focused exclusively on households that had trips limited to O-D pairs within the Montreal metropolitan area. To obtain a more comprehensive understanding of travel behavior, we concentrated on home-based trips which were associated with specific activities. This approach was chosen because non-home-based trips are often closely linked to their respective home-based origin trips within a chain of connected trips that start and end at home (Bowman et al., 1999). Consequently, the mode of the initial trip in a home-based trip chain exerts a strong influence on the modes of subsequent trips. Therefore, our mode choice models examined trips that originate at home. In each year's survey, the final sample contained 136,554, 148,349, 179,462, and 161,426 respectively, which accounted approximately 42% of the total trips reported in the survey (**Table 2.1**).

Table 2.1: Household count and trip count across four surveys

	Households	Trips	Home-based Trips (% Trips)
2003	56,959	329,353	136,554 (41.5%)
2008	66,124	354,915	148,349 (41.8%)
2013	78,731	452,978	179,462 (42.1%)
2018	73,421	393,826	161,426 (41.0%)

To enable more effective comparisons of travel behaviors across various population groups, we classified both income and age variables into distinct categories. The income variable was categorized into three groups: low, middle, and high income. In order to account for inflation and shifts in the distribution of households towards higher income levels, the income categorization for the years 2013 and 2018 differed from that of 2003 and 2008 (**Table 2.2**). This approach ensured a more accurate representation of income groups for each time period. Following the guidelines provided by Statistics Canada (Statistics Canada, 2017), the age variable was divided into four groups: children (0-14 years), youth (15-24 years), adults (25-64 years), and seniors (65 years and over).

Table 2.2: Income groups in different surveys

Income Group	2003 & 2008	2013 & 2018
Low	$0 - $39,999	$0 - $59,999
Middle	$40,000 - $79,999	$60,000 - $119,999
High	Above $80,000	Above $120,000

2.3.3 Analysis

The findings presented in this paper are derived through a combination of descriptive analysis and statistical methods. All analyses utilized appropriate weights at the individual and trip levels, which were generated by the data producer. Descriptive analysis was performed to explore travel behaviors among the different sociodemographic groups, taking into account variations in trip distance and mode of transportation. Trip distances between origins and destinations were estimated using the R package igraph (Csardi & Nepusz, 2006). The road network utilized for routing was obtained from the Montreal Open Data Portal in January 2023, and as such, it may reflect alterations not present when the surveys were conducted. Although historical road network data were inaccessible, the network in the study area had already been well-established during the O-D surveys, which suggests that differences in road distances are likely to be relatively insignificant. Statistical measures were built to shed light on the impact of sociodemographic factors on travel behaviors. A multilevel linear model was developed to estimate how sociodemographic variables relate to trip distances, while a multilevel multinomial logistic regression model was employed to predict mode choices. These models included a year-level random intercept and utilized nearly the same set of explanatory variables. The primary explanatory variables were the demographic and economic characteristics of individuals and households, including household income, number of automobiles owned, number of people in the household, age, gender, and ownership of driver's license. Additionally, we considered trip purpose as well as built environment attributes at the Census Tract level, such as population density and road density in residential areas.

2.4 Results

2.4.1 Descriptive Analysis

Despite a lack of statistical verification, the descriptive statistics of the sociodemographic indicators that influence travel behavior reveal a nuanced picture of personal travel in Montreal. The data indicates that Montreal residents heavily rely on automobiles for their travel needs (**Figure 2.2**). In 2018, 66% of all trips, irrespective of purpose, were made by car, either as a driver or as a passenger, while another 17.4% of individuals used public transit, including buses, metro, and trains. School bus and active transportation, including walking and cycling, accounted for the remaining 16.6% of trips. Over time, discretionary trips, such as shopping, eating, medical appointments, and other personal business, consistently cover shorter distances compared to utilitarian trips. Between 2003 and 2018, trip distances of utilitarian trips increased by 16.4% over this period, while those of discretionary trips rose by half that rate (8.3%).

Figure 2.2: Modal split by trip purpose

Automobiles are the predominant mode of choice not only for utilitarian trips but also for discretionary trips in Montreal. The reliance on automobiles for utilitarian trips has been decreasing, while their share has been increasing in discretionary trips between 2003 and 2018. In contrast, public transit has been serving a rising percentage of utilitarian trips over the years, rising from 21.7% in 2003 to 24.5% in 2018. Among public transit options, buses and metro services are more prevalent for utilitarian trips, while train transit is primarily used for utilitarian purposes. Active transportation shows minor differences in mode share by trip purpose. Walking is predominantly used for discretionary trips, while bicycling is used much more for utilitarian purposes, probably due to the longer distances involved in such trips. Additionally, bicycle use for utilitarian trips has been on the rise over the study period, growing from 1.3% to 1.8%.

Mode choice is influenced by car ownership. As seen in **Table 2.3**, an increase in the availability of automobiles in a household results in a higher tendency to use a car and a lower inclination towards using public transit or active transportation. People without access to automobiles heavily depend on public transit or active transportation as their main mode of transportation. Note that we have observed a low driving rate among households without cars across surveys. This can be attributed to the availability of transportation alternatives, such as car-sharing services and car rentals, which allow these households to access private vehicles. Additionally, even the ownership of a single car greatly transforms mode choice. In 2018, car usage ranged from 8.9% of trips made by households with no car to 62.6% of trips made by households with one car. The use of public transit was 53.5% of trips made by households with no car and 19.4% of trips made by households with one car, while trips made via active transportation were 36.6% and 15.3% of all trips, respectively. Subsequent increase in car ownership has comparatively limited additional impacts on modal split, though they still result in further decreases in the usage of public transit and active transportation. It is worth noting that there are substantial variations in the modal split of different types of transit. While the modal split of bus and metro services decreases with increased car ownership, households owning two are more cars are more likely to utilize commuter trains. These patterns are observable in all survey years and broadly align with expectations. Between 2003 and 2018, car use has fallen for all car ownership groups while use of public transit has risen significantly for households with one car and households with two or two more cars.

Income is the primary factor that influences car ownership, which, in turn, serves as the principal determinant of modal choice. Cars are the primary mode of transportation for all income groups, with a growing trend of car use among people with low-income between 2003 and 2018 (**Table 2.4**). The majority of car trips are taken as drivers, and less than 20% reported as passengers across all surveys. Although household income is generally found in the literature to show a positive relationship with automobile dependency, the increase in income is not necessarily associated with an increase in automobile dependency in Montreal. The only increase in car use can be seen between low- and middle-income groups, with little to no change in car mode share with subsequent increases in household income. The low-income group consistently has the largest transit use. Different types of public transit show varying usage patterns across different income groups. For example, in 2018, the low-income group was 1.5 times as likely as the high-income group to take the bus (7.9% vs. 5.4%). On the contrary, the high-income group was four times more likely than the low-income group to take commuter rail (0.3% vs. 1.3%). In between these two extremes, the usage of metro services was more evenly distributed across the income groups. The modal split of metro falls from 4.8% among low-income individuals to 4.1% among the middle class, followed by an increase to 4.3% among the wealthy. It is worth noting that low-income individuals make a higher percentage of trips by transit with multiple modes compared to the middle- and high-income groups.

Table 2.3: Modal split by car ownership

	2003			2008		
	0	1	2 or more	0	1	2 or more
Modal Split						
Car	**10.2%**	**67.4%**	**79.1%**	**10.2%**	**62.6%**	**76.3%**
Driving	2.7%	51.9%	65.5%	3.3%	48.6%	63.8%
Passenger	7.4%	15.5%	13.5%	6.9%	13.9%	12.5%
Public Transit	**53.9%**	**15.8%**	**7.4%**	**52.8%**	**19.1%**	**9.3%**
Bus	23.8%	5.9%	3.0%	21.9%	6.6%	3.3%
Metro	12.3%	3.4%	1.0%	13.8%	4.7%	1.7%
Train	0.1%	0.5%	0.6%	0.2%	0.7%	0.8%
Multi-modal Transit	17.8%	6.0%	2.7%	16.8%	7.2%	3.4%
School Bus	**2.0%**	**4.0%**	**6.8%**	**1.4%**	**3.7%**	**7.5%**
Active Transportation	**33.9%**	**12.8%**	**6.7%**	**35.6%**	**14.5%**	**6.9%**
Biking	3.4%	1.2%	0.7%	4.5%	1.6%	0.7%
Walking	30.6%	11.6%	6.0%	31.1%	12.9%	6.2%
Trip Distance (km)	**4.52**	**7.15**	**9.98**	**4.66**	**7.47**	**10.87**

	2013			2018		
	0	1	2 or more	0	1	2 or more
Modal Split						
Car	**8.6%**	**63.3%**	**77.9%**	**8.9%**	**62.6%**	**77.3%**
Driving	2.9%	49.7%	65.2%	3.5%	49.9%	64.9%
Passenger	5.7%	13.5%	12.7%	5.4%	12.7%	12.4%
Public Transit	**53.0%**	**19.0%**	**9.6%**	**53.5%**	**19.4%**	**10.3%**
Bus	21.8%	6.6%	3.6%	20.0%	6.1%	3.4%
Metro	14.5%	4.8%	1.7%	16.2%	5.6%	1.8%
Train	0.2%	0.7%	0.9%	0.1%	0.7%	1.1%
Multi-modal Transit	16.6%	6.9%	3.5%	17.1%	7.1%	4.0%
School Bus	**0.9%**	**2.8%**	**6.0%**	**1.0%**	**2.7%**	**6.0%**
Active Transportation	**37.4%**	**14.9%**	**6.4%**	**36.6%**	**15.3%**	**6.4%**
Biking	6.0%	2.2%	0.7%	5.3%	2.1%	0.6%
Walking	31.5%	12.7%	5.7%	31.3%	13.2%	5.8%
Trip Distance (km)	**4.67**	**7.10**	**10.64**	**4.87**	**7.47**	**11.15**

Table 2.4: Modal split by income

	2003			2008		
	Low	Middle	High	Low	Middle	High
Modal Split						
Car	**54.9%**	**71.1%**	**71.1%**	**52.1%**	**67.0%**	**67.6%**
Driving	42.6%	57.3%	56.5%	41.0%	54.8%	54.4%
Passenger	12.3%	13.8%	14.6%	11.1%	12.2%	13.2%
Public Transit	**22.8%**	**12.8%**	**14.2%**	**23.9%**	**15.7%**	**16.1%**
Bus	9.9%	4.8%	5.7%	10.2%	5.3%	5.6%
Metro	4.9%	2.6%	2.7%	5.4%	3.8%	3.8%
Train	0.2%	0.5%	0.8%	0.2%	0.6%	1.0%
Multi-modal Transit	7.9%	4.9%	5.0%	8.1%	5.9%	5.7%
School Bus	**3.9%**	**6.0%**	**5.2%**	**4.1%**	**5.7%**	**5.8%**
Active Transportation	**18.4%**	**10.1%**	**9.4%**	**19.9%**	**11.6%**	**10.5%**
Biking	1.7%	1.2%	0.8%	2.1%	1.6%	1.2%
Walking	16.7%	8.9%	8.6%	17.8%	10.0%	9.3%
Trip Distance (km)	**6.44**	**8.87**	**8.97**	**6.54**	**9.23**	**9.66**

	2013			2018		
	Low	Middle	High	Low	Middle	High
Modal Split						
Car	**60.7%**	**70.0%**	**69.4%**	**60.4%**	**68.8%**	**67.7%**
Driving	49.2%	57.4%	56.2%	49.1%	56.9%	55.4%
Passenger	11.4%	12.6%	13.2%	11.3%	11.8%	12.3%
Public Transit	**19.9%**	**14.4%**	**16.0%**	**20.2%**	**15.4%**	**17.1%**
Bus	8.2%	4.7%	5.8%	7.9%	4.6%	5.4%
Metro	4.5%	3.6%	3.7%	4.8%	4.1%	4.3%
Train	0.3%	0.8%	1.2%	0.3%	0.8%	1.3%
Multi-modal Transit	6.9%	5.3%	5.4%	7.1%	5.8%	6.0%
School Bus	**3.5%**	**5.3%**	**4.4%**	**3.4%**	**5.0%**	**4.6%**
Active Transportation	**15.9%**	**10.3%**	**10.1%**	**16.0%**	**10.8%**	**10.6%**
Biking	1.9%	1.8%	1.3%	1.7%	1.5%	1.4%
Walking	14.0%	8.5%	8.7%	14.3%	9.3%	9.2%
Trip Distance (km)	**7.26**	**9.68**	**9.52**	**7.54**	**9.87**	**9.90**

Active transportation accounts for the smallest proportion among various modes across different income groups and over time. Despite declining usage of active transportation among low-income individuals and increasing usage among the middle class and the wealthy between 2003 and 2018, people with low-income still rely far more on active transportation than the other two income groups. Walking declines sharply with increasing income across all surveys, decreasing from 14.3% of all trips among low-income group to around 9% among all other income groups in 2018. Bicycle use, on the contrary, decreases to a lesser extent with increasing income. For example, bicycle use drops from 1.7% of trips among the low-income group to 1.4% of trips among the high-income group in 2018. Average trip distances tend to increase with increased income. The average trip distance increased from 6.44 km for low-income groups to 8.97 km for the high-income group in 2003. Moreover, average trip distances for all income groups increased steadily between 2003 and 2018, but those of the high-income group rose by a smaller percentage than those of the low-income group (10.4% vs. 17.1%). Over the years, the distance-based disparity between low-income and high-income households is getting smaller.

The reliance on automobiles varies among different age groups (**Table 2.5**), with adults and seniors exhibiting a greater reliance on cars compared to children and youth. The largest increase in car use can be consistently observed between the youth and adults categories, likely due to ownerships of car and driver's license. Interestingly, seniors make over half of their car trips as drivers across all surveys, highlighting the importance of the convenience, comfort, and privacy that cars provide to seniors. This, however, raises concerns about the risks associated with driving for seniors with declining vision, hearing, and reflexes, posing a potential danger to both themselves and others. Car use has increased among children and seniors and decreased among youth and adults since 2003.

Table 2.5: Modal split by age

	2003				2008			
	Children	Youth	Adults	Seniors	Children	Youth	Adults	Seniors
Modal Split								
Car	**34.0%**	**43.0%**	**77.7%**	**73.4%**	**32.9%**	**41.8%**	**74.1%**	**73.0%**
Driving	0.2%	28.9%	69.5%	54.8%	0.3%	29.2%	66.8%	55.6%
Passenger	33.9%	14.1%	8.2%	18.6%	32.6%	12.6%	7.3%	17.4%
Public Transit	**7.6%**	**36.7%**	**14.2%**	**12.9%**	**8.3%**	**37.7%**	**16.2%**	**12.0%**
Bus	5.5%	16.0%	4.6%	7.7%	5.9%	15.1%	4.7%	7.3%
Metro	0.7%	6.7%	3.4%	1.7%	0.8%	7.7%	4.5%	1.7%
Train	0.1%	0.5%	0.7%	0.1%	0.2%	0.7%	0.9%	0.1%
Multi-modal Transit	1.4%	13.5%	5.5%	3.3%	1.4%	14.2%	6.1%	3.0%
School Bus	**28.9%**	**6.8%**	**0.0%**	**0.0%**	**31.3%**	**8.1%**	**0.0%**	**0.0%**
Active Transportation	**29.4%**	**13.5%**	**8.1%**	**13.7%**	**27.5%**	**12.3%**	**9.6%**	**14.9%**
Biking	1.5%	1.9%	1.1%	0.3%	1.5%	1.9%	1.5%	0.7%
Walking	27.9%	11.6%	7.0%	13.3%	26.0%	10.5%	8.1%	14.2%
Trip Distance (km)	**3.55**	**8.47**	**9.52**	**5.60**	**4.20**	**9.57**	**10.17**	**5.86**

	2013				2018			
	Children	Youth	Adults	Seniors	Children	Youth	Adults	Seniors
Modal Split								
Car	**38.9%**	**43.7%**	**75.0%**	**79.1%**	**39.1%**	**41.9%**	**73.5%**	**79.7%**
Driving	0.2%	31.0%	68.5%	62.8%	0.2%	30.2%	67.6%	64.9%
Passenger	38.7%	12.7%	6.5%	16.2%	38.9%	11.7%	5.8%	14.8%
Public Transit	**8.0%**	**36.7%**	**15.3%**	**9.6%**	**6.8%**	**39.8%**	**16.7%**	**9.2%**
Bus	6.0%	15.2%	4.4%	5.5%	4.7%	15.5%	4.4%	4.5%
Metro	0.7%	7.0%	4.3%	1.6%	0.9%	8.1%	4.9%	2.0%
Train	0.1%	0.8%	1.0%	0.2%	0.1%	0.9%	1.2%	0.1%
Multi-modal Transit	1.2%	13.7%	5.6%	2.3%	1.1%	15.2%	6.3%	2.6%
School Bus	**27.2%**	**7.6%**	**0.0%**	**0.0%**	**27.9%**	**7.4%**	**0.0%**	**0.0%**
Active Transportation	**26.0%**	**12.0%**	**9.7%**	**11.3%**	**26.2%**	**11.0%**	**9.8%**	**11.1%**
Biking	1.4%	2.1%	1.9%	0.6%	1.4%	1.8%	1.7%	0.7%
Walking	24.6%	9.9%	7.8%	10.7%	24.8%	9.2%	8.1%	10.4%
Trip Distance (km)	**3.80**	**9.91**	**9.96**	**6.38**	**3.97**	**10.75**	**10.50**	**6.91**

Public transit usage patterns show significant differences among age groups. Youth make over 35% of their trips by public transit, the highest percentage compared to any other age group across surveys. Between 2003 and 2018, an increase in transit use can be observed among adults, rising from 14.2% to 16.7%, while the increase in transit use by youth is even greater, growing from 36.7% to 39.8%. Moreover, train usage is highest among youth and adults. In 2018, youth and adults are over eight times as likely as seniors and children to use trains, reflecting the radial design of the commuter rail system in Montreal, which primarily serves peak-hour commuting trips between suburban areas and downtown. This type of trip is not typically required by children and seniors.

In terms of active transportation, children are more likely to make active transportation trips. While children make more than 25% of their trips by walking across all surveys, walking accounts for only around 10% of the trips of the other three age groups. Furthermore, seniors have the least mode share in bicycle usage, while bicycle modal share has increased for adults and seniors over the years. Seniors and children make significantly shorter trips than youth and adults. However, the average trip distance for all age groups increases steadily over the study period. Trips made by youth have lengthened by 26.9%, while those of children, adults, and seniors grew by 11.8%, 10.3%, and 23.4%, respectively.

Over the study period from 2003 to 2018, travel behavior has become increasingly similar between men and women. While average trip distances for both genders have increased, women's distances have lengthened at a faster pace than men's (16.2% vs. 11.3%). Women consistently exhibit shorter travel distances than men, but the gap has slightly decreased from 1.6 kilometers in 2003 to 1.4 kilometers in 2018. In terms of mode choice, both genders display a high reliance on cars, with approximately 65% of their trips being made by car (**Figure 2.3**). However, men tend to drive alone more often, while women tend to engage more in "serve passenger" trips, where they escort other household members. Although the proportion of public transit trips taken by women has been consistently higher than that of men, the gap has been gradually narrowing over the years. Specifically, women tend to take more trips by bus and metro, while men are more likely to use trains. When it comes to active transportation, major disparities exist between men and women, with men being significantly more likely to cycle than women. For instance, in 2018, men are two times as likely as women to cycle (2.1% vs. 1.0%).

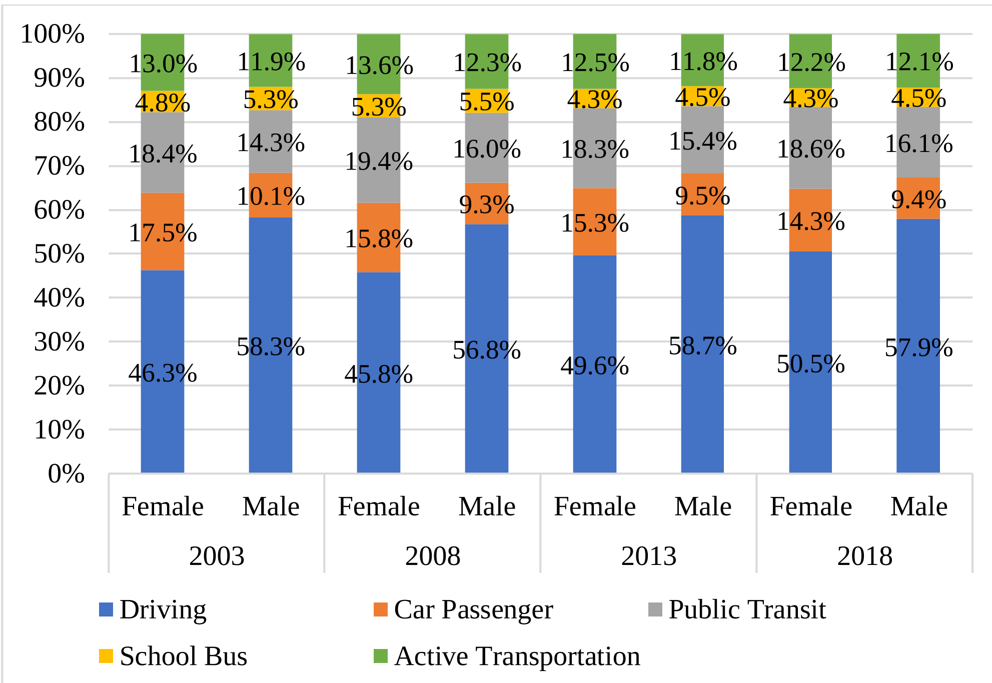

Figure 2.3: Modal split by gender

2.4.2 Regression Results

We applied linear regression models to surveys from different years to estimate the relationship between sociodemographic variables and trip distances (**Table 2.6**). Our findings reveal that car ownership is positively associated with trip distance, suggesting that individuals with more cars tend to travel longer distances than those with fewer cars. In contrast, household size is negatively associated with trip distance. Individuals in larger households generally travel shorter distances, possibly due to the need to coordinate schedules and travel plans to accommodate everyone's preferences. Conversely, those living alone or in smaller households may have a greater need or desire to make trips, either for social interaction or to complete necessary tasks when no one else in the household is available to make the trip. Additionally, trip purpose is negatively associated to trip distance, indicating that trips for leisure or other non-utility purposes tend to be shorter than trips for utility purposes.

In relation to sociodemographic variables, the coefficients for the age variable indicate that adults tend to travel longer distances compared to their counterparts. Individuals from low-income households and women are more likely to make shorter trips than their counterparts. Concerning built environment variables, both population density and road density in residential areas are negatively related to trip distance. These results suggest that individuals living in densely populated or well-connected areas tend to travel shorter distances. Furthermore, the estimated random intercepts for different years indicate variations in travel distances. In particular, travel distances in 2003 were shorter on average compared to the overall average, while in 20018, they were longer on average, consistent with previous descriptive analysis findings.

Results from the multilevel multinomial logistic model are shown in Table 2.7. The coefficients of a multinomial logit model represent the log odds of choosing each transportation mode (i.e., active transportation, public transit, and school bus) compared to the reference group (car). A positive log odd indicates the variable increases the odds of choosing the corresponding mode of transportation, while a negative log odds suggests a decreasing effect.

Table 2.6: Estimates from multilevel linear model for travel distance (in meters)

	Coefficient
Fixed Effect	
Intercept	14490***
# Vehicles in Household	1264***
# People in Household	-381***
Age (Base: Adults)	
Children	-7794***
Youth	-1348***
Senior	-848.8***
Household Income (Base: Not Low-income)	-739.6***
Gender (Base: Male)	-1179***
Trip Purpose (Base: Utility)	-5509***
Population Density (1,000 people/sq.km)	-431.1***
Road Density in Residential Area (km/sq.km)	-2.7***
Random Intercept	
2003	-357.8
2008	41.6
2013	29
2018	287.2

*p<0.1; **p<0.05; ***p<0.01

As expected, having more vehicles in a household is significantly negatively associated with the odds of choosing active transportation or public transit over using a car. Conversely, residents of larger households exhibit a higher propensity to use active transportation or public transit over cars. Regarding personal characteristics, the coefficient for the age variable suggests that, compared to adults, children are significantly more inclined to choose active transportation, yet less likely to use public transit. Conversely, youth show a higher probability of selecting both active transportation and public transit over cars. Individuals from lower-income households are approximately 11.3% more likely to choose active transportation over a car compared to those from higher-income households. Females are more likely than males to choose active transportation or public transit.

Concerning trip characteristics, utility trips, perhaps due to their time efficiency, tend to involve cars more frequently. With respect to urban form, living in densely populated areas boosts the likelihood of choosing active transportation or public transit. Specifically, an increase of 1000 people per sq.km is associated with a significant 12.3% rise in the odds of using active transportation and a 10% rise in the odds of opting for public transit over cars.

Table 2.7: Estimates from multilevel multinomial logit model for mode choice

	Active Transportation	Public Transit
Intercept	-1.733^{***}	-0.426^{***}
# Vehicles in Household	-1.147^{***}	-1.292^{***}
# People in Household	0.163^{***}	0.171^{***}
Age (Base: Adults)		
Children	1.893^{***}	-0.282^{***}
Youth	1.512^{***}	1.960^{***}
Senior	-0.024	0.107^{***}
Household Income (Base: Not Low-income)	0.107^{***}	0.007
Gender (Base: Male)	0.166^{***}	0.366^{***}
Trip Purpose (Base: Utility)	-0.154^{***}	-1.776^{***}
Population Density (1,000 people/sq.km)	0.116^{***}	0.094^{***}
Road Density in Residential Area (km/sq.km)	0.001^{***}	0.001^{***}

$^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$

2.5 Discussion and Conclusions

In this study, we investigated the variations in travel behavior associated with sociodemographic characteristics by analyzing O-D survey collected over several years in the

Montreal metropolitan area. The results provide further evidence to support the findings of earlier studies, indicating that people from low-income households, children, and women exhibit significant disparities in their travel behavior compared to their counterparts. A temporal analysis of the O-D data reveals that these differences have persisted, with some differences increasing and others remaining stable or decreasing.

People from low-income households, on average, make shorter trips and have a higher dependency on public transportation than those from higher-income households. Over time, the disparity in trip distances for people with low-income has decreased, while their reliance on public transit remains constant. Children also tend to travel shorter distances, and their mode choices are largely influenced by their dependence on adults for transportation, resulting in a greater dependency on walking, cycling, or being driven by parents or caregivers. The data indicates a minor increase in the disparity in trip distances for children, possibility due to suburbanization and the increasing distance between residential areas and schools. Women consistently exhibit shorter travel distances than men and are more likely to use public transportation for their trips. The disparity in trip distances for women has slightly diminished over the years, potentially attributable to changing societal roles and the increasing participation of women in the workforce. Conversely, the data reveals a decline in the use of public transportation and non-motorized modes by women over time, emphasizing the need for transportation policies that address women's unique travel patterns and responsibilities.

The regression results reveal that car ownership exhibited a positive relationship with trip distance, whereas household size demonstrated a negative association with trip distance. People from low-income households, children, and women were found to be more likely to undertake shorter trips compared to their counterparts. Furthermore, the regression analysis confirms the findings from descriptive analysis, indicating that people with low-income, children, and women are more likely to utilize public transportation.

In summary, social disparities in travel behaviors persist and have evolved over the years. Disadvantaged populations, especially those with low incomes, rely on active transportation and public transit for access to and participation in daily activities, including securing and maintaining employment. Nevertheless, numerous transit agencies across Canada, including Montreal, have had to reduce service due to operational funding shortages (Société de Transport de Montréal, 2023). Service cuts disproportionately impact lower-income neighborhoods compared to higher-income areas. Declining revenues and increasing costs could further exacerbate social disparities in travel behaviors. To ensure the continued access to transit for people with low-income, transit operators and funding agencies should prioritize maintaining and enhancing transit services in neighborhoods with a higher concentration of low-income households. Moreover, walking plays a critical role in providing access to daily necessities, particularly for the poor and children. Walking is not only an affordable option for accessing essential services such as schools, healthcare facilities, and grocery stores without incurring additional expenses, but it is also a viable mode of transportation in inner-city neighborhoods where many low-income households reside. However, walking has often been neglected in the urban planning agendas of most cities, this significant discrepancy between planning, investment, and travel needs results in disadvantaged populations facing greater barriers to walkability. To improve walking conditions for disadvantaged populations, it is essential for government agencies to focus more on enhancing the safety, convenience, and feasibility of walking in urban environments. It should be noted that Montreal is currently making investments in active transport including sidewalk enlargements and improvements and pedestrianized streets as well as continued expansion of the cycling network.

Overall, this paper has sought to investigate the differences in travel behavior between sociodemographic groups and whether these differences diminish or exacerbate over the years. While travel behavior is strongly interconnected with individuals' well-being and societal participation, travel behavior alone does not reveal whether these differences stem from individuals' voluntary choices or external contextual constraints (Pereira & Karner, 2021). One potential venue for future investigation is to delve into the underlying reasons for discrepancies in travel behaviors among different sociodemographic groups. Nonetheless, the presence of social disparities in travel behaviors in this study highlights the importance of equity considerations in the realm of transportation planning. Policy makers could potentially take advantage of the differences in travel distances and mode choices by different sociodemographic groups to deliver specially crafted transport solutions.

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Link between Chapters

In our exploration of travel behavior variations based on sociodemographic characteristics, one observation stands out: the reliance on bicycling among disadvantaged populations. The previous chapter revealed that, certain groups, notably those from low-income households and households without access to a car, have shown a consistent higher reliance on bicycling for their daily commutes and essential travel compared to their counterparts. Given the challenges these groups face, from economic constrains to limited access to transportation services, bicycling has emerged as a cost-effective and flexible mode of transportation.

However, the reliance on bicycling raises an essential question about equitable access to cycling infrastructure. How can bicycling become an inclusive mode of transportation, especially for those who depend on it for daily mobility?

This leads us to transition from these behavioral observations to the focus of our next chapter: the equity of cycling infrastructure access in Montreal. Key questions we aim to address include:

- How does cycling infrastructure accessibility vary among sociodemographic groups?
- Does the current cycling infrastructure allow disadvantaged populations to meet their daily needs safely and conveniently?
- As Montreal expands its bicycle network, is this development prioritizing areas inhabited by disadvantaged groups, given their higher reliance on bicycling?

The subsequent chapter seeks to provide insights into potential discrepancies in cycling infrastructure access. As we delve into this exploration, our goal remains to understand how cycling investments can best serve those who stand to benefit the most.

CHAPTER THREE: DO NEW BIKE LANES LEAD TO A MORE EQUITABLE CITY? AN ANALYSIS OF CYCLING INFRASTRUCTURE IN MONTREAL

Abstract

This research examines the expansion of the bicycle network on the Island of Montreal from 2006 to 2020 to identify differences in cycling infrastructure access and destination accessibility via bicycles among different socioeconomic groups. Our findings indicate a disproportionate distribution of cycling infrastructure. Notably, areas with moderate socioeconomic status benefited significantly from cycling infrastructure investments, while the most disadvantaged areas had the lowest level of cycling infrastructure in 2020. In 2006, residents in socioeconomically disadvantaged areas generally had better access to destinations using bicycles compared to residents in other areas. However, the majority of these destinations were accessible using only 25% or less of the cycling infrastructure on potential routes, forcing users to share the road with motor vehicles. Over the 14 years, even though infrastructure development improved network connectivity for these residents, areas with a moderate socioeconomic status retained better regional connectivity. A composite measure, defining "bikeable neighborhoods" based on destination accessibility and network connectivity, revealed that socioeconomically disadvantaged areas generally offered higher levels of destination accessibility but less continuous cycling infrastructure in 2006. This trend persisted over the 14 years, while there are still considerable portions of Dissemination Areas (DAs) with high socioeconomic disadvantage that were considered as the least bikeable areas, particularly concerning healthcare accessibility. These findings stress the need to integrate equity considerations into transportation and infrastructure planning and suggest potential biases in transport policies that warrant further investigation.

Keywords: Cycling, Equity, Accessibility, Connectivity, Cycling Network Expansion

3.1 Introduction

Investments in cycling can produce multiple environmental and societal benefits – reducing air pollution, addressing health disparities, improving mental health, and encouraging active and healthy behavior (Dunn et al., 1999; Gordon-Larsen et al., 2005; Reynolds et al., 2010). Studies have shown that the availability of cycling infrastructure significantly contributes to the promotion of cycling, by enhancing its safety and attracting non-cyclists to adopt cycling (Hong et al., 2020; Hull & O'Holleran, 2014; Pucher & Buehler, 2016; Teschke et al., 2012). As a result, many cities in North America have dedicated large investments toward the development of cycling infrastructure and implemented governance frameworks to facilitate planning and construction of cycling infrastructure in a systematic and cohesive manner (Pucher & Buehler, 2017).

However, the design of transportation systems and the allocation of limited resources inevitably favor specific population groups or neighborhoods at the expense of others (Litman, 2022; Pereira & Karner, 2021). Recent evidence suggests that bicycle facilities have not been equitably distributed across communities with varying socio-demographic composition (League of American Bicyclists, 2013). While some communities have benefited from cycling infrastructure investments, disadvantaged communities with greater social and economic needs have been physically isolated, limiting their mobility. This poor access to bicycle network can restrict their access to employment, educational, and healthcare opportunities, thereby perpetuating existing social and economic inequities (Giles-Corti et al., 2016).

The social equity and inclusion objectives have been increasingly integrated into active transportation plans at both provincial and municipal levels across Canada (Government of Canada, 2017). A thorough understanding of the exiting distribution of bicycle facilities across various population segments and the impact of cycling infrastructure investments on the accessibility of disadvantaged communities to urban opportunities is vital for incorporating equity considerations into bicycle planning. It is crucial that the provision of cycling infrastructure does not show favoritism towards specific socioeconomic groups and that investment decisions are guided by empirical, equity-focused policies and programs. Considering this, we examine the expansion of the bicycle network on the Island of Montreal from 2006 to 2020 to understand the evolution in socio-spatial distribution of accessibility to cycling infrastructure over time. We further probe into the effects of cycling investments on people's access to key activities to understand how the benefits of such investments vary across different population groups. The paper first reviews existing research on bicycle equity and accessibility, followed by a description of our data and methodologies. Subsequent sections present our results and conclude with a discussion of policy implications.

3.2 Literature Review

The principle of transportation equity aims to provide equal access to urban opportunities by providing equitable levels of access to an affordable and reliable transportation system for all people (Litman, 1999; Sandt et al., 2016). Recent research on transport equity has employed a social equity lens to investigate the social and spatial distribution of transport facilities, requiring clear definitions of the socio-economic groups that are of interest. In transportation discussions, equity-deserving groups have been defined as racialized people, Indigenous peoples, LGBTQ2S+ people, people with disabilities, people living in poverty or experiencing homelessness, newcomers and immigrants, women and people with diverse gender identities, children and youth, and seniors (Linovski et al., 2021). As these groups exhibit different needs and anticipations for transport facilities, analyzing transport equity proves to be a complicated task (Manaugh & El-Geneidy, 2011).

The emergence of cycling as a cost-effective alternative to traditional transportation mode has raised questions about the equity of cycling infrastructure, in terms of use, access, and associated benefits (Lee et al., 2017). For example, people who are older, lower income, and racialized, have lower levels of car ownership and higher rates of public transit and active transportation use than the average population (Pucher & Renne, 2005). In Canada, people with lower income were less likely to commute to work by car, and more commonly relied on walking, cycling, and public transportation (Hosford & Winters, 2022). Additionally, failure to incorporate equity concerns into bicycle planning and policies has resulted in disparities in cycling infrastructure investments and their intended benefits (Grisé & El-Geneidy, 2018). Some studies found that cycling investments are more frequent in central, privileged areas with more socioeconomic advantage (Fuller & Winters, 2017; Hosford & Winters, 2022; Tucker & Manaugh, 2017), while marginalized neighborhoods with low socioeconomic status and transport poverty remained excluded (Cunha & Silva, 2022). Research conducted in 22 large U.S. cities found that block groups with lower socioeconomic status, lower levels of education, and a higher percentage of minority populations had lower access to cycling infrastructure and this trend persisted even after accounting for demand-based factors such as urban form and cycling rate (Braun et al., 2019). Due to the absence of protected space for cycling, people who live in areas with higher vehicle volumes and higher levels of street parking experienced higher risks of being involved in a cycling collision or an injury crash (Lucas et al., 2019). In the U.S., the fatality rate per-mile traveled was more than 1.5 times higher for Black and Hispanic cyclists than for white cyclists (Raifman & Choma, 2022). However, there is a variation in the equity of access to cycling infrastructure among different cities. For example, Houde et al. (2018) evaluated expansion of cycling network in

Montreal, Longueuil, and Laval from 1991 to 2016 and found that spatial access for people with low incomes, recent immigrants, and seniors had improved over 25 years.

Accessibility has been placed at the center of understanding transportation equity since the primary goal of transportation policies and initiatives is to improve people's accessibility to key destinations. In a transportation context, accessibility indicates people's overall ability to reach certain destinations and illustrates how much effort, often quantified as time or money, is required from a given location (Martens, 2012; Morris et al., 1979). This involves elements related to transport infrastructure and services, land use system, and personal characteristics such as age, race, income, and car ownership. Given the critical role of accessibility in evaluating both current and future transport scenarios, transportation researchers have dedicated significant resources to develop methodologies for measuring accessibility in urban environments. Moreover, the concept of accessibility is now being utilized in the assessment of transportation plans in numerous major cities globally (Boisjoly & El-Geneidy, 2017; Manaugh & El-Geneidy, 2012), and in calculating the benefits of urban plans for diverse socioeconomic groups (Foth et al., 2013; Martens, 2016).

Three types of metrics of accessibility to destinations can be distinguished in the literature: 1) Cumulative opportunities, which count the number of reachable destinations within a predefined travel time or distance; 2) Gravity-based measures, which estimate the accessibility of a location by assigning weights to opportunities available at all other locations based on a function of travel time or distance between them; and 3) Utility-based models, which are particularly apt for individual accessibility as they incorporate individual preferences. Most existing studies on destination accessibility by bicycles focus on access to a single specific type of destination. For instance, Arranz-López et al. (2019) evaluated walking and cycling accessibilities to retail facilities using gravity-based models. They also established minimum accessibility requirements and identified accessibility thresholds from different population groups. Hosford et al. (2022) utilized the cumulative opportunity measure to compute the number of grocery stores reachable within a 15-minute walking or cycling distance. Recently, the accessibility of a broad range of destinations by bicycle has emerged as an important issue in urban and transport planning. For example, Iacono et al. (2010) calibrated the distance-decay model and measured non-motorized accessibility to five types of destinations: employment, shopping, school, restaurant, and recreation. Similarly, Saghapour et al. (2016) developed a Cycling Accessibility Index (CAI) to quantify cycling accessibility to four types of trip purposes including education centers, health and care facilities, community services, and retail and recreation centers.

Much of the existing research has measured cycling accessibility using methods similar to those used for motorized vehicle travel. However, unlike car-based accessibility and transit-based accessibility, which mainly depend on the travel impedance to reach destinations, cycling accessibility is influenced significantly by characteristics of the cycling infrastructure. Cyclists, unlike transit riders and drivers who typically exhibit a high degree of comfort in their respective modes of transportation, may experience varying degrees of discomfort when navigating through different streets. For instance, while some roads are legally designated for cyclists, many cyclists may be disinclined to use them due to discomfort and feelings of unsafety when traveling alongside automobiles, thereby significantly impacting accessibility. The research mentioned above usually considers only the time component of the travel and does not account for cyclists' preferences on route infrastructure. Several recent studies have sought to measure cycling accessibility by taking into account traffic stress and comfort levels on the street network. For example, Sisson et al. (2006) determined the bikeability to elementary schools by considering factors such as traffic volume, proposed speed limit, and surface conditions. Similarly, Furth et al. (2018) classified road segments according to the level of traffic stress and quantified employment accessibility by bicycle.

3.3 Methodology

3.3.1 Data Collection

We chose the Island of Montreal as our study area, which comprises the City of Montreal and 15 other municipalities, with a total population of 2,004,265 people (Statistics Canada, 2022). Montreal serves as a valuable case study for bicycling due to its highly developed cycling network, a robust bike-sharing system, and comparatively high levels of bicycle commuting in comparison to other Canadian cities. Moreover, Montreal has implemented a variety of policies and initiatives aimed at promoting cycling and enhancing cycling equity (Doran et al., 2021). This study incorporates three types of data: the road and cycling networks, destination locations, and sociodemographic data. The cycling network in 2006 was reconstructed based on previous research (Houde et al., 2018). The cycling network in 2020, as well as the road networks excluding roads where cycling is prohibited (e.g., highways) in 2006 and 2020, were obtained from Montreal Open Data Portal. We merged the road and cycling networks to create bikeable networks for each year, and reclassified cycling facilities into three categories based on safety and user comfort levels: high-comfort bikeways, medium-comfort bikeways, and low-comfort bikeways. High-comfort bikeways provide a comfortable riding experience for the majority of cyclists, including children. They either physically separate cyclists from motor vehicle traffic or guide them along off-street paths that are separate from roads, such as cycle tracks and bike paths. Medium-comfort bikeways offer a lower to moderate level of stress and involve cyclists sharing lanes with pedestrians. This category includes road types like multi-use paths. Low-comfort bikeways consist of painted bike lanes and shared bike lanes. These facilities generate high traffic stress and are uncomfortable for most cyclists. Cyclists either travel along exclusive lanes next to busy roads or share lanes with motor vehicles, or they use an exclusive cycling zone located between a vehicular travel lane and on-street parking.

The location data for urban opportunities in 2006 and 2020 were obtained from the Enhanced Points of Interest (EPOI) databases provided by DMTI Spatial. These datasets contain information on over one million Canadian points of interests, including the name, address, and codes for Standard Industrial Classification (SIC) and North American Industry Classification (NAICS). For our study, we focused on three types of urban opportunities that represent essential destinations for cyclists: groceries, pharmacies, and healthcare facilities. Groceries and pharmacies were chosen as they represent everyday shopping opportunities (Tucker & Manaugh, 2017), while healthcare facilities were selected due to their provision of essential medical services. We extracted the data for these selected destinations from the EPOI databases based on their SIC codes.

Regarding sociodemographic characteristics, we obtained the data from the Statistics Canada population censuses of 2006 (Statistics Canada, 2007) and 2016 (Statistics Canada, 2017). Since the 2021 census data was not available at the time of our research, we used 2016 census data as a proxy for sociodemographic information in 2020. Dissemination areas (DAs) were used as the geographic unit of analysis as they provide the most disaggregated level of standard geography for which census data is publicly available.

3.3.2 Socioeconomic Status (SES) Measurement

We developed an index to measure Socioeconomic Status (SES) at DA level. This SES index considered four variables sourced from Canadian census data: median household income, low-income cut-offs (LICO), unemployment rate, and proportion of recent immigrants. Each of the four variables was standardized to a z-score, which measures a DA’s standing in terms of each variable compared to the overall mean for all DAs. The standardized z-scores for the four variables were then summed for each DA to generate a composite SES score. Finally, we rescaled the SES scores to a 1 to 10 scale, with a higher SES score implying a greater level of socioeconomic disadvantage.

3.3.3 Accessibility Calculation

Accessibility to cycling infrastructure was measured using length of infrastructure over land area. Within each DA, we calculated total length of cycling network and normalized by land area to account for differences in the size of DAs. As cycling infrastructure often forms the boundaries of DAs, we buffered DAs by 10 m of boundaries to include all infrastructure.

Destination accessibility by bicycle was calculated based on a cumulative opportunities measure. We calculated the shortest cycling distance from the centroid of each DA to each urban destination based on the bikeable network. However, cyclists often do not strictly follow the shortest possible route, instead preferring to use dedicated cycling infrastructure that separates them from motor traffic, even if it involves a slightly longer travel distance (Nawrath et al., 2019; Skov-Petersen et al., 2018). Therefore, we assigned a weight to each road segment in the bikeable network based on its comfort level classification (**Table 3.1**), with lower-stress routes given a lower weight, and calculated weighted shortest route (**Figure 3.1**).

$$WL = \sum_{i=1}^{n} x_i w_i \tag{1}$$

where *WL* is the weighted length of a potential route, x_i is the length of road segment *i*. Based on existing studies, we set a 25% diversion threshold, implying that cyclists are willing to detour up to 25% from the shortest route to benefit from cycling infrastructure (Broach et al., 2012; Mekuria et al., 2012; Winters et al., 2010). In other words, we assume that a reasonable weighted shortest route that prioritizes less stress road segments should not be more than 25% longer than the shortest route.

Table 3.1: Weighting of different types of road segments

Route Type	Weight
Cycle Track	0.5
Bike Path	0.5
Multi-use Path	0.8
Painted Bike Lane	1
Shared Bike Lane	1
Bikeable Road	5

Figure 3.1: Potential routes between centroid of DA and closest healthcare facility

The “15-Minute City” (Moreno et al., 2021) served as a guiding version for calculating destination accessibility by bicycles. This framework aims to create cities that are more livable, with a focus on providing equal access to opportunities for underserved areas and disadvantaged populations. This goal is to ensure individuals with different needs and abilities can fulfill their daily requirements within a 15-minute bicycle ride from their homes. Therefore, we measured destination accessibility for each DA based on a 15-minute cycling time as a threshold, with an average cycling speed of 16 km/h (Espada & Luk, 2011). For each dissemination area, we calculated the number of each type of destination reachable within this 15-minute cycling time, considering the 25% diversion threshold.

Additionally, to assess the extent to which the cycling infrastructure enables access to key activities safely, we integrated network connectivity into our accessibility measure. The network connectivity was calculated as the proportion of the chosen route (the weighted shortest route if it is within 25% longer than the shortest route, otherwise the shortest route) that is on designated bikeways. We calculated the connectivity for each route from each DA to every urban destination and then derived an average connectivity score for each DA. This score, weighted by the route distances for all origin-destination pairs involving the DA, serves as an aggregate estimate of the extent to which cyclists can make use of designated cycling infrastructure when travelling from each DA. Therefore, in addition to calculating the total number of reachable destinations within a 15-minute cycling distance, we also calculated the percentage of total destinations that can be reached by considering different levels of network connectivity, using thresholds of 25% and 50%.

3.3.4 Estimation of Cycling Infrastructure Benefits Disparities

To comprehensively assess the differential impacts of cycling infrastructure investments across diverse population groups, we classified DAs based on their bikeability, which we defined by combining both the destination accessibility by bicycle and network connectivity metrics. We divided DAs into terciles based on destination accessibility and set connectivity thresholds of 25% and 50%. Therefore, DAs with the highest levels of destination accessibility and connectivity score above 50% were classified as most bikeable, offering residents substantial access to daily needs and over half of their trips on bikeways. Conversely, DAs with the lowest levels of destination accessibility and connectivity scores below 25% were designated as least bikeable. Residents in these areas face restricted access to daily necessities and can use bikeways for less than a quarter of their potential routes, often contending with high traffic stress. Finally, with this classification of DAs, we estimated the number of the most and least socioeconomically disadvantaged populations residing in the most and least bikeable neighborhoods respectively.

3.4 Results

3.4.1 Expansion of Bicycle Network

In 2020, the Island of Montreal contains close to 970 kms of bike lanes. The high-comfort bikeways make up 10% of the cycling facilities across the Montreal agglomeration, with the medium-comfort bikeways composing an additional 31% of the bicycle network. The low-comfort bikeways comprise the remaining 59% of the bicycle network. This reflects the fact that a very small fraction of the current bicycle network is comfortable for cyclists of all skill levels. Over half of bike lanes can benefit from improvements to become more comfortable and safer. Doing this can, in turn, discourage vehicle encroachment in bike lanes and encourage more people to ride bicycles for utilitarian purpose, especially those who are interested in cycling, but who only cycle occasionally due to their safety concerns about sharing roadways with motor vehicles.

The Island of Montreal has more than doubled the size of its bicycle network from 2006 to 2020. These developments have strengthened cycling by providing a more comprehensive network of cycling facilities. The evolution emphasized development of low-comfort bikeways (**Figure 3.2**). Painted bike lanes, which are considered uncomfortable for most people, comprise 46% of the new cycling infrastructure in the region. Multi-use paths have expanded to more than 300 km and are classified as medium-comfort bikeways due to the mixing of pedestrians and cyclists. Physically separated bike lanes spanned close to 100 km, up from 28 km in 2006. In terms of spatial development of bicycle network, the extension mainly happened in central boroughs, but as commuting and housing patterns changed and rural commuting became more common, the development took place in suburban town centers. The connectivity of the overall bicycle network in the region has been improved over the past 14 years. Connections between boroughs and between municipalities were constructed to link various activity destinations, and several bicycle corridors were built to connect green spaces and outdoor destinations. However, high-comfort bikeways in the region are too fragmented to connect home and urban opportunities, contributing barriers to existing and potential cyclists. The bicycle network in the boroughs along the western edge of the island is less continuous than the overall bicycle network, giving rise to safety concerns as residents in these neighborhoods are exposed to motor vehicle traffic.

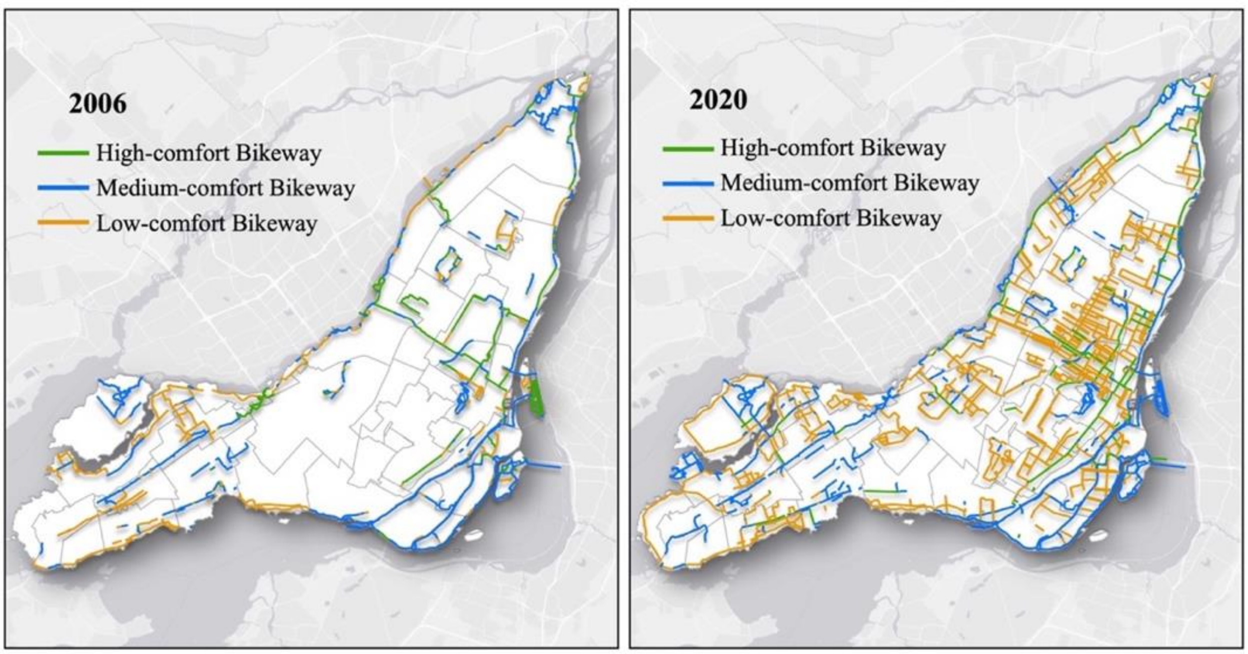

Figure 3.2: Expansion of bicycle network

3.4.2 Distribution of Socioeconomic Disadvantaged Populations

Figure 3.3 shows the spatial distribution of the socioeconomic status deciles in the region for both years. The darkest blue indicates the most socioeconomically disadvantaged DAs. Certain DAs are excluded from the analysis due to unreported data in the census. In 2006, the most socioeconomically disadvantaged DAs were mainly located in the south of Montréal-Nord (district

11), the north and southeast of Villeray-Saint-Michel-Parc-Extension (district 27), the southeast of Ville-Marie (district 4), and throughout most of Côte-des-Neiges-Notre-Dame-de-Grâce (district 23). The distribution of least socioeconomically disadvantaged DAs showed concentrations in the western part of the Island of Montreal. For 2020, the extremes in socioeconomic disadvantage still showed some distinct spatial patterns. For example, concentrations of low socioeconomic disadvantage remain in the western part of the island. Villeray-Saint-Michel-Parc-Extension (district 27), Ville-Marie (district 4), and Côte-des-Neiges-Notre-Dame-de-Grâce (district 23) continued to show greater socioeconomic disadvantage. The south of Montréal-Nord and the south of Mercier-Hochelaga-Maisonneuve maintained their status within the high socioeconomically disadvantaged categories.

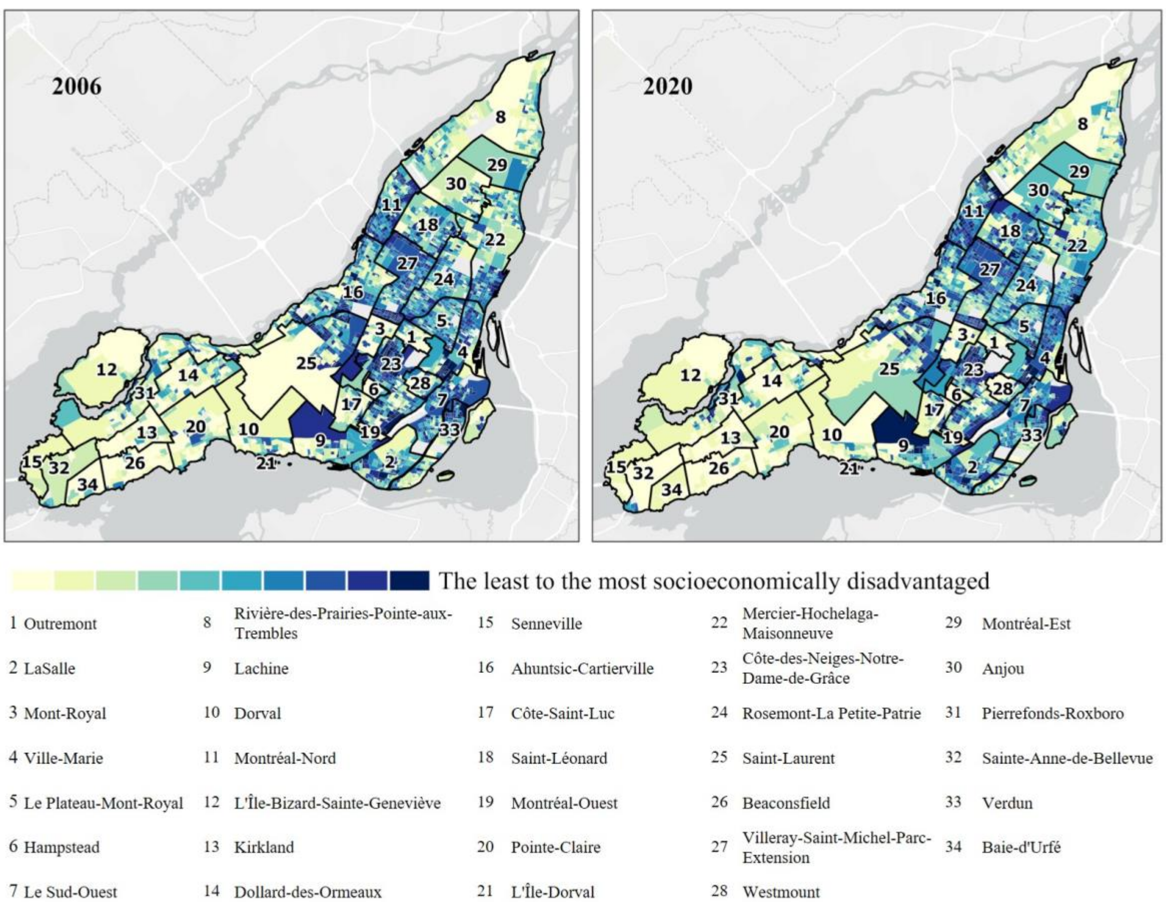

Figure 3.3: Spatial distribution of the socioeconomic status deciles on the island of Montreal

3.4.3 Access to Cycling Infrastructure

In 2006, 29% of DAs (n=911) had access to bikeways, corresponding to 30% of total population (n = 561,896) on the Island of Montreal. Only 15% of DAs (n = 48) in the most socioeconomically disadvantaged decile had access to cycling infrastructure, equating approximately 16% of residents (n = 33,136) living in these DAs. By 2020, The proportion of DAs with access to cycling infrastructure had increased significantly to 71%. The most socioeconomically disadvantaged decile also saw a substantial improvement, with 58% of DAs (n = 184) in the last decile having access to cycling infrastructure, affecting around 58% of residents (n = 122,248) living in these areas.

Figure 3.4 displays the variation in normalized bikeway lengths based on socioeconomic status. In 2006, the first three deciles of DAs, characterized by relatively low levels of socioeconomic disadvantage, enjoyed better access to bicycle network than all other decile groups. This indicates that the provision of cycling infrastructure was not equitably distributed across socioeconomic groups. Between 2006 and 2020, every decile group experienced an improvement in accessibility to cycling infrastructure due to the expansion of bicycle network on the island. However, the investment in cycling infrastructure improved accessibility significantly more for the middle decile groups. Interestingly, the third to fifth deciles experienced a higher level of accessibility to bicycle network in 2020. Conversely, the ninth and tenth deciles, representing the most socioeconomically disadvantaged DAs, had the lowest level of cycling infrastructure access. This suggests that bicycle facilities were more likely be located in areas where are relatively wealthier, had fewer immigrants and a higher employment rate.

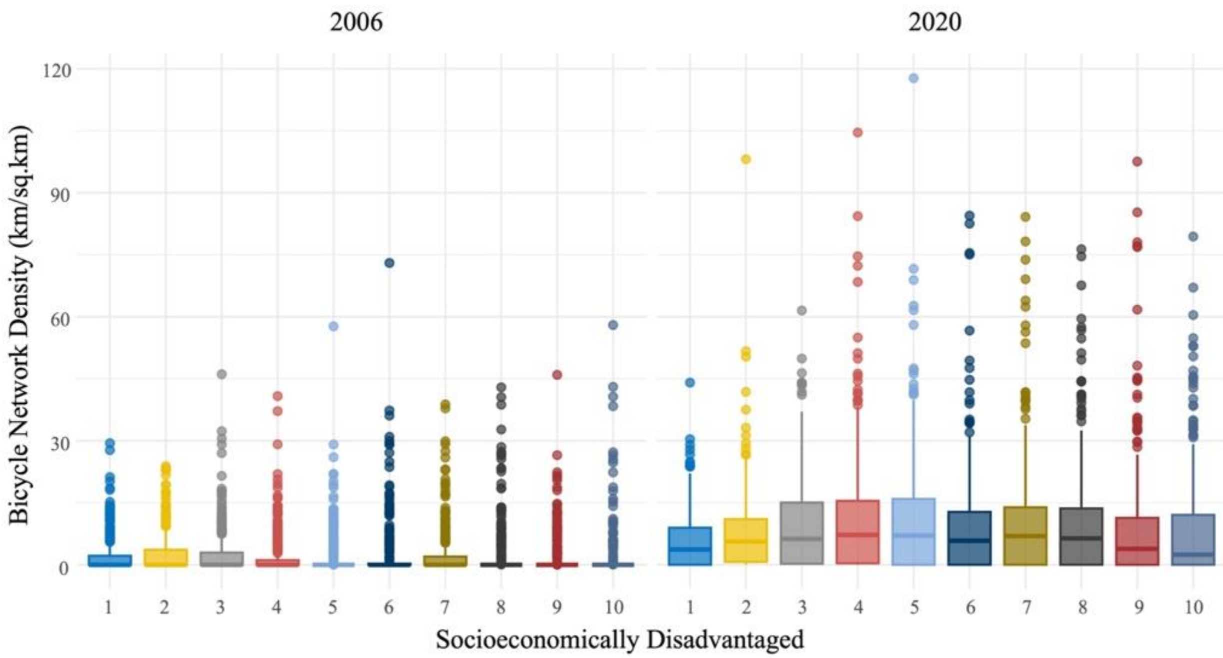

Figure 3.4: Bicycle network density by socioeconomic status deciles (1 is least disadvantaged, 10 is most)

3.4.4 Access to Urban Destinations via Bicycle

In 2006, the average accessibility by bicycle to grocery stores, healthcare facilities, and pharmacies in the region was 205, 15, and 42, respectively. We see that the lower deciles (1-3), representing DAs with lower socioeconomic disadvantages, generally exhibited less accessibility to these key destinations (**Table 3.2**). Conversely, the fifth to tenth deciles exceeded the average accessibility to all destination types. Overall, this implies that individuals living in socioeconomically disadvantaged DAs have better access to activities by bicycles compared to residents in other areas. Specifically, accessibility to grocery stores tended to increase with increasing socioeconomic disadvantage. With respect to healthcare facility accessibility, there was a consistent increase from decile 1 to decile 5, after which accessibility remained relatively stable up to decile 10. Pharmacy accessibility increased as socioeconomic disadvantage increased, but for deciles 7 to 10, there was a slight decline in accessibility. Despite this, these deciles still maintained significantly higher levels of pharmacy accessibility compared to DAs with lower socioeconomic disadvantages.

Table 3.2: Accessibility by bicycles by decile showing destinations reachable on less than 25% and more than 50% dedicated cycling facilities

	Grocery						**Healthcare Facility**					
	2006			**2020**			**2006**			**2020**		
	Total	Less than 25%	More than 50%	Total	Less than 25%	More than 50%	Total	Less than 25%	More than 50%	Total	Less than 25%	More than 50%
Decile 1 (Least socioeconomically disadvantaged decile)	98	83%	8%	91	55%	32%	9	84%	9%	9	59%	27%
2	137	77%	14%	100	51%	36%	12	80%	13%	8	50%	37%
3	167	74%	16%	178	41%	47%	13	74%	17%	15	39%	50%
4	204	74%	18%	217	40%	47%	16	76%	17%	16	39%	49%
5	238	72%	18%	218	42%	47%	18	74%	16%	16	39%	49%
6	234	74%	17%	232	43%	46%	18	75%	15%	19	39%	49%
7	263	74%	17%	253	41%	47%	18	73%	16%	21	38%	51%
8	253	76%	15%	240	46%	43%	18	77%	14%	19	38%	50%
9	243	79%	12%	213	53%	34%	18	80%	11%	18	47%	41%
Decile 10 (Most socioeconomically disadvantaged decile)	222	82%	10%	213	51%	37%	17	85%	8%	22	43%	41%
Average	**206**	**76%**	**15%**	**195**	**46%**	**43%**	**15**	**80%**	**13%**	**16**	**44%**	**50%**

	Pharmacy					
	2006			**2020**		
	Total	Less than 25%	More than 50%	Total	Less than 25%	More than 50%
Decile 1 (Least socioeconomically disadvantaged decile)	23	79%	13%	28	56%	32%
2	29	76%	16%	28	52%	36%
3	34	73%	18%	45	43%	45%
4	41	72%	19%	52	44%	44%
5	47	72%	19%	52	45%	45%
6	47	73%	18%	56	45%	44%
7	52	72%	18%	61	43%	46%
8	50	76%	17%	58	46%	43%
9	49	79%	13%	54	53%	35%
Decile 10 (Most socioeconomically disadvantaged decile)	48	83%	10%	57	48%	40%
Average	**42**	**76%**	**17%**	**49**	**47%**	**43%**

However, when considering network connectivity, which is measured as the proportion of routes on bikeways, the distribution of accessibility across socioeconomic deciles differs. For example, in 2006, the percentage of reachable destinations using 25% or less of bikeways for all types of destinations decreased from the least socioeconomic disadvantage to the moderate level of socioeconomic disadvantage, and then increased for the most socioeconomic disadvantage. Conversely, the percentage of reachable destinations using more than 50% of bikeways exhibited the opposite trend, increasing and then decreasing. This indicates that while residents in disadvantaged DAs can generally reach more destinations within a 15-minute cycling distance, they often have to share their trips with motor vehicle traffic instead of using dedicated cycling infrastructure due to the lack of connected bicycle networks in those areas.

In 2020, the average bicycle accessibility to grocery stores, healthcare facilities, and pharmacies in the study area was 195, 16, and 49. While DAs with moderate and high levels of socioeconomic disadvantages still maintained above-average access to all types of key opportunities, accessibility to grocery stores from the most socioeconomically disadvantaged DAs (decile 8-10) decreased, while for healthcare facilities and pharmacies, it increased. When considering different levels of connectivity, a significantly larger number of key destinations could be reached using more than 50% of bikeways on potential routes in 2020. Nonetheless, the percentages of reachable destinations using less than 25% bikeways and more than 50% of bikeways across the deciles still followed the same patterns as in 2006. Bicycle networks in DAs with a moderate level of socioeconomic status remained more connected to the rest of the region.

To provide a fair assessment of each DA's evolving destination accessibility, we calculated standardized accessibility to each destination type in 2006 and 2020. This allows us to evaluate how each DA's destination accessibility compares to the regional average and assess the even distribution of cycling infrastructure over time. **Figure 3.5** displays the standardized accessibility for all destination types by decile. Grouping standardized accessibility by decile allows us to compare the cycling investment benefits for one decile to the rest. A clear divide in accessibility to all destination types between less socioeconomically disadvantaged and more socioeconomically disadvantaged deciles is apparent. In both years, the least socioeconomically disadvantaged DAs (deciles 1-3) had relatively low levels of destination accessibility. Specifically, in 2006, the accessibility to grocery stores exhibited a pattern of initial increase followed by a subsequent decrease from decile 4 and decile 10. Decile 7 (moderately socioeconomically disadvantaged DAs) stands out as having the highest average standardized accessibility among the deciles. A similar pattern was observed in accessibility to pharmacies with decile 7 having the highest levels of standardized accessibility relative to the rest of the region, while accessibility to healthcare facilities remained relatively stable from decile 5 to decile 10. In 2020, accessibility to all destination types exhibited similar patterns as in 2006. Decile 10 saw an improvement in accessibility to grocery stores and pharmacies, while decile 9 did not benefit from the expansion of the bicycle network in terms of destination accessibility.

To further assess vertical equity, we established a definition for "bikeable neighborhoods" based on a composite measure of destination accessibility and network connectivity. We then estimated the number and percentage of individuals in each decile living in the least and most bikeable neighborhoods. This approach allows us to highlight how residents in the study area might be underserved by the bicycle network in various ways.

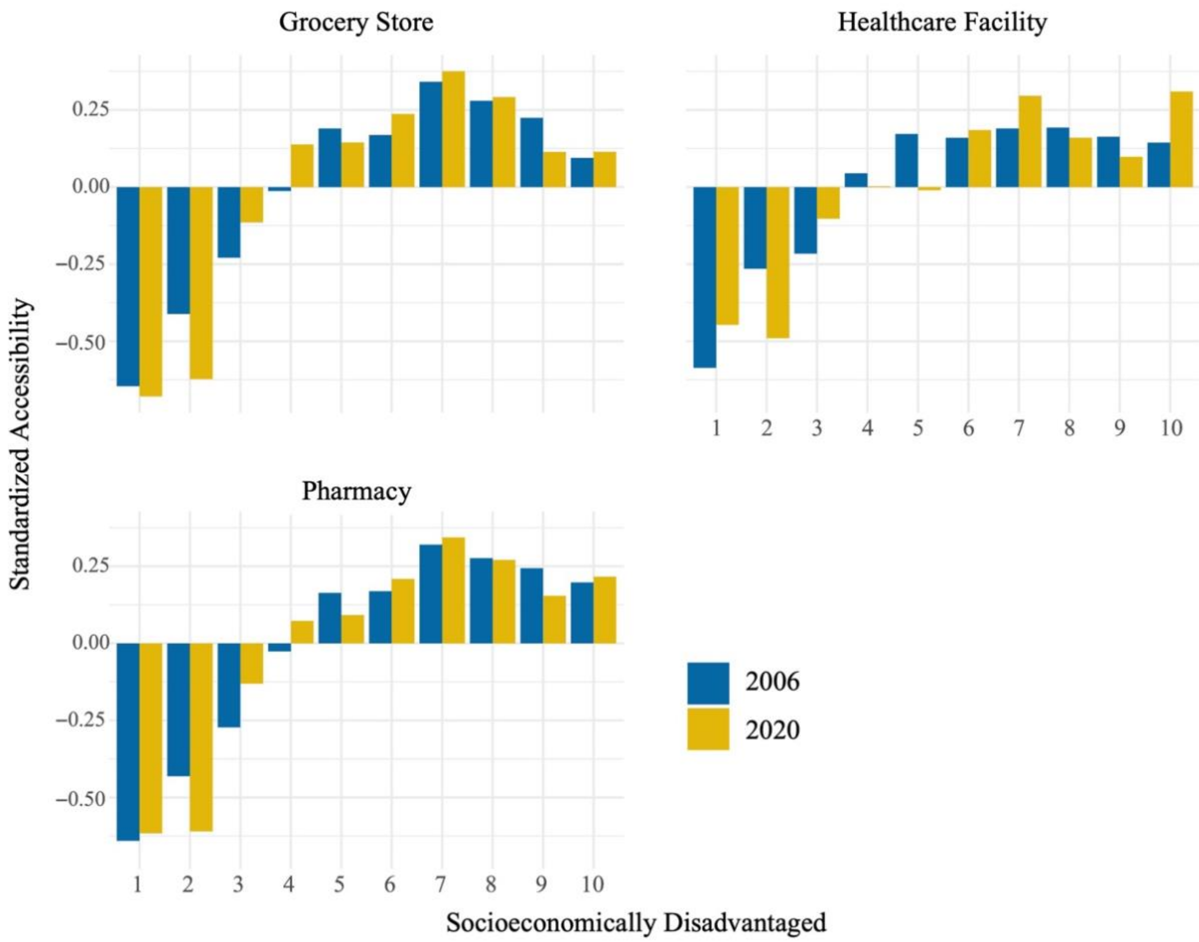

Figure 3.5: Standardized accessibility by decile (1 is least disadvantaged, 10 is most)

In 2006, DAs with low socioeconomic disadvantage (deciles 1-4) were consistently overrepresented in least bikeable neighborhoods (**Table 3.3**). This indicates that areas with low socioeconomic disadvantage generally offer limited levels of destination accessibility and less continuous cycling infrastructure. Residents living in these areas can only utilize less than 25% of the cycling infrastructure on potential routes to reach their daily needs. Conversely, less than 20% of individuals living in more socioeconomically disadvantaged DAs (deciles 7-10) were identified as having the lowest levels of accessibility to grocery stores and pharmacies and the lowest levels of connectivity. However, there were still 21% of the population from decile 9 and 26% of the population from decile 10 living in the least bikeable neighborhoods in terms of healthcare accessibility. Overall, only 1% of residents in the study area lived in the most bikeable neighborhoods. Importantly, the most socioeconomically disadvantaged deciles (deciles 9-10) were consistently underrepresented in the most bikeable neighborhoods.

Due to the ongoing development of the network of cycling infrastructure over the past 14 years, a greater number of people now live in the most bikeable neighborhoods (**Table 3.3**). In 2020, approximately 300,000 residents lived in the most bikeable neighborhoods for all types of destinations, representing around 16% of study population. The population living in deciles 1and 2 were still consistently overrepresented in the least bikeable neighborhoods. Conversely, more socioeconomically disadvantaged DAs offered better accessibility and connectivity to key destinations.

Table 3.3: Distribution of population groups in the least and most bikeable neighborhoods

2006	Grocery		Healthcare Facility		Pharmacy	
	Least Bikeable	Most Bikeable	Least Bikeable	Most Bikeable	Least Bikeable	Most Bikeable
Total Population	**505,343 28%**	**12,740 1%**	**406,617 22%**	**28,666 2%**	**381,059 21%**	**9,336 1%**
Decile 1 (Least socioeconomically disadvantaged decile)	101,082 55%	556 0%	49,800 27%	556 0%	70,608 39%	556 0%
2	83,529 46%	723 0%	46,802 26%	1,693 1%	60,406 34%	723 0%
3	75,228 42%	0 0%	439,14 25%	4,519 3%	52,763 29%	0 0%
4	53,170 30%	3,915 2%	38,003 22%	6,100 3%	39,770 23%	2,875 2%
5	35,503 20%	994 1%	35,110 20%	4,176 2%	27,561 16%	429 0%
6	39,517 22%	2,363 1%	37,563 21%	2,726 2%	31,614 17%	1,816 1%
7	31,000 17%	2,072 1%	29,540 16%	5,374 3%	21,466 12%	2,072 1%
8	25,738 14%	2,117 1%	32,518 18%	2,608 1%	198,53 11%	865 0%
9	27,802 15%	0 0%	40,226 21%	0 0%	30,489 16%	0 0%
Decile 10 (Most socioeconomically disadvantaged decile)	32,774 16%	0 0%	53,141 26%	914 0%	26,529 13%	0 0%

2020	Grocery		Healthcare Facility		Pharmacy	
	Least Bikeable	Most Bikeable	Least Bikeable	Most Bikeable	Least Bikeable	Most Bikeable
Total Population	**226,502 12%**	**352,424 18%**	**234,196 12%**	**298,348 15%**	**238,523 12%**	**306,265 16%**
Decile 1 (Least socioeconomically disadvantaged decile)	47,622 26%	5,870 3%	31,038 17%	7,297 4%	44,878 24%	6,098 3%
2	36,729 19%	9,711 5%	31,888 17%	7,165 4%	34,224 18%	5,100 3%
3	27,649 14%	42,050 21%	27,330 14%	36,392 18%	27,445 14%	30,885 16%
4	26,049 14%	42,240 23%	11,117 6%	27,782 15%	25,202 14%	33,861 18%
5	20,755 11%	44,871 24%	21,224 11%	29,649 16%	20,879 11%	36,580 20%
6	17,370 9%	51,096 27%	20,721 11%	45,630 24%	20,271 11%	45,456 24%
7	10,667 6%	53,812 29%	18,509 10%	42,407 23%	13,667 7%	46,132 25%
8	13,621 7%	44,643 23%	18,849 10%	42,673 22%	17,545 9%	41,012 21%
9	13,379 7%	25,362 12%	23,171 11%	27,073 13%	17,680 9%	26,183 13%
Decile 10 (Most socioeconomically disadvantaged decile)	12,661 6%	32,769 16%	30,349 15%	32,280 15%	16,732 8%	34,958 17%

3.5 Discussion

Many studies on transport equity have examined disparities in access destinations among different population groups, focusing on transit-based and car-based accessibility. However, little research has explored how destination accessibility by bicycles is distributed across society. This paper aims to address this gap by identifying differences in accessibility to bicycle network and destinations via bicycles among distinct socioeconomic groups over the years.

Between 2006 and 2020, the bicycle network on Island of Montreal grew from 434 to 970 kms of bikeways. However, the majority of new bikeways were classified as low-comfort bikeways, which are considered uncomfortable for most people, and were concentrated in central areas. High-comfort bikeways were fragmented in this region, creating barriers for existing and potential cyclists. To promote cycling as a transportation mode for people of all ages and abilities, municipalities should prioritize the development of continuous and connected high-quality cycling facilities.

The analyses conducted in this study revealed disparities in accessibility to the bicycle network. In terms of vertical equity, which involves providing for groups with the greatest potential to benefit from cycling infrastructure, Montreal did not prioritize higher levels of accessibility to cycling infrastructure for the most socioeconomically disadvantaged groups relative to the other socioeconomic groups in the region. In 2006, areas with lower levels of socioeconomic disadvantage had better access to cycling infrastructure, while only a small percentage of the most disadvantaged areas had access to cycling infrastructure. By 2020, there was a significant increase in the proportion of DAs with access to cycling infrastructure, including notable improvements in the most disadvantaged areas. However, disparities remained, with moderately disadvantaged areas being better served than their counterparts.

Regarding destination accessibility, the results showed that in 2006, individuals in socioeconomically disadvantaged areas generally had better access to destinations using bicycles compared to residents in other areas. This can be attributed to the spatial distribution of socioeconomic deciles, with disadvantaged areas being closer to major activity centers, while advantaged areas were located on the outskirts of the island. However, when considering network connectivity, disparities in destination accessibility across socioeconomic deciles emerged. Residents in disadvantaged areas could generally reach more destinations within a 15-minute cycling distance, but they could only access most of these destinations using 25% or less of bikeways. The lack of connected cycling infrastructure in these areas forced residents to share their trips with motor vehicle traffic. Over the 14-year period, although the development of the cycling infrastructure allowed residents in disadvantaged neighborhoods to access more destination using more than 50% of the bikeways, areas with a moderate level of socioeconomic status remained more connected to the rest of the region.

The examination of standardized destination accessibility further highlighted inequities in destination accessibility. Decile 7, representing moderately disadvantaged areas, consistently showed the highest average standardized accessibility. The patterns in accessibility to different types of destinations remained consistent over time, but it is important to note some deciles did not benefit from the expansion of the bicycle network. For example, standardized accessibility to all types of destinations decreased over the years for decile 9.

The typology of DAs provided additional insight into variations in accessibility and connectivity across population groups. In 2006, DAs with lower levels of socioeconomic disadvantage were overrepresented in the least bikeable neighborhoods, indicating lower levels of accessibility and network connectivity. Over the 14 years, areas with lower socioeconomic disadvantage continued to be overrepresented in the least bikeable neighborhoods, while more socioeconomically disadvantaged areas offered better accessibility and connectivity to key destinations. However, there were still considerable portions of DAs with high socioeconomic disadvantage that coincided with the least bikeable areas, particularly concerning healthcare accessibility.

3.6 Conclusions

This study focuses on examining variations in accessibility among different socioeconomic groups and how they have changed over time. We propose an innovative approach to measure destination accessibility for bicycles, considering parameters related to road safety that are tailored to the constraints faced by disadvantaged cyclists. Additionally, this analysis provides an important framework for assessing the equity effects of fully implemented or proposed cycling networks, creating an evidence base to promote equitable bicycle planning practices.

Our analyses confirm the presence of inequities in accessibility on the Island of Montreal. While disadvantaged groups generally experience higher levels of accessibility to the bicycle network and destinations compared to more advantaged groups, areas with moderate socioeconomic disadvantage received greater investments over the 14-year period and consistently demonstrated the highest levels of accessibility to the bicycle network and destination accessibility by bicycles. These findings highlight the importance of incorporating equity considerations into transportation plans that guide infrastructure investments and may warrant further investigation into potential bias within transport policies.

It is important to note several limitations of our analyses. First, like any destination accessibility index, the measure we have developed provides only a rough estimate of a person's actual experienced accessibility. Specifically, cumulative accessibility measure assigns equal value to both nearby and distant opportunities encountered within a predefined travel time threshold. This may not reflect the actual preferences and behaviors of individuals, who often value more distant destinations less. Secondly, the equity analyses rely on comparisons of group averages, which inherently conceal variations in accessibility within groups. Further research could incorporate distance decay functions into accessibility measurements for different types of destinations to better capture the decreasing likelihood of reaching destinations as the distance increases.

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Link between Chapters

In examining the cycling infrastructure access across various socioeconomic groups over the years, we have discovered significant observations that emphasize the need for a reevaluation and redirection of Montreal's cycling infrastructure policies. Our findings indicate inequity in cycling infrastructure access: while the overall accessibility to cycling infrastructure improved markedly by 2020, disparities remain. Montreal did not prioritize its most socioeconomically disadvantaged citizens, even though they stand to benefit the most from these facilities.

The distribution of accessibility is revealing. Socioeconomically disadvantaged areas often enjoy better destination accessibility via bicycles, but they lack a connected cycling infrastructure. These insights highlight a challenge: without a connected bicycle network, residents of these areas frequently find themselves sharing routes with motor vehicles. This not only poses safety risks but also undermines the potential for a sustainable shift away from car travel.

As we turn our attention to the subsequent chapter, we narrow our focus on actionable strategies to address these disparities. Building on our findings here, the next chapter introduces a quantitative framework designed to prioritize future cycling investment projects, specifically aims at enhancing accessibility for disadvantaged communities. This new approach will not only consider the principles of transportation equity but will also advocate for interventions that emphasize network connectivity and encourage a modal shift towards cycling. In doing so, it will aid in reducing emissions and promoting a more sustainable urban environment.

CHAPTER FOUR: INTRODUCING A FRAMEWORK FOR CYCLING INVESTMENT PRIORITIZATION

Abstract

Concerns over urban congestion, air pollution, and health disparities have encouraged many cities to expand their bicycle networks to foster a cycling culture. Given limited budgets, choosing a set of road segments for investments in cycling infrastructure to achieve a city's ambitious goals is still a challenge. This study introduces a quantitative framework for prioritizing future bicycle improvement projects for implementation within budgetary constraints using different intervention strategies with regard to specific goals and objectives. The "connectivity-focused" prioritization strategy aims to consolidate bicycle networks and improve network connectivity. The "equity-based" strategy grows the bicycle networks and favors cycling equity goals; it prioritizes cycling projects that improve bicycle accessibility to urban opportunities for disadvantaged populations and mitigates disparities in access to bicycle facilities. The "modal shift" strategy seeks to build a bicycle network which would appeal to prospective bicycle commuters and thereby reduce vehicle kilometers traveled (VKT) and greenhouse gas (GHG) emissions. The results highlight the importance of growing bicycle networks in a systematic way and show that this framework is useful for guiding the implementation of new bicycle facilities with specific policy priorities.

Keywords: Bicycle Facility, Cycling Investments Prioritization, Network Connectivity, Equity, Modal Shift

4.1 Introduction

The potential of cycling to combat congestion, diminish air pollution, address health disparities, and improve mental health has received increasing attention from scholars and policy makers (Teschke et al., 2012). Although, in principle, road networks for motor vehicles are sufficient to connect the origins and destinations of cyclists, there is an agreement that building a complete network with bicycle-specific facilities is essential for cities seeking to provide a safe and comfortable experience that most cyclists prefer over sharing spaces with motorized vehicles (Pucher & Buehler, 2006). Cycling infrastructure, therefore, provides the backbone for cities' bicycle plans, either for recreational or utility cycling, and decisions on where to build new bikeways are usually taken as part of strategic plans. Planners are faced with the problem of prioritizing and choosing a set of road segments for investment in cycling infrastructure within a limited budget.

The Island of Montreal is chosen as a case study since it has been making efforts to expand its bicycle network. From 2006 to 2021, the Island of Montreal has more than doubled the size of its bicycle network. Connections between boroughs and between municipalities were constructed to link various activity destinations, and several bicycle corridors have been built to connect green spaces and outdoor destinations. The recently released Quebec active transportation action plan pledged to invest in cycling infrastructure to close the gaps in the current network, reduce car dependency, connect communities, and address the needs and safety of people regardless of age, ability, or background (Direction des Communications, 2018). Montreal also promised to add an extra 840 km of bike paths and published the future bike network map (Service de l'urbanisme et de la Mobilité, 2019) which guides the expansion of the bicycle network on the island. In this context, this paper aims to present a practical framework that planners can use to prioritize bicycle facility projects for implementation within budgetary constraints and assess the impacts of infrastructure interventions. This framework integrates readily available quantitative and spatial data sources, determines priorities of bicycle projects, and yields a proposed network in an easily interpretable format suitable for decision makers and the public. While we evaluate our methodology within the context of Montreal, the focus of this study is not to produce a locally specific model for a particular city, but to introduce a replicable framework that could be used to optimize cycling investments in any other city by using similar data sets.

This paper first reviews the literature related to identification of transportation-disadvantaged populations and the models and algorithms used for optimal planning of a bicycle network. The methodology section then introduces the data sources and explains the prioritization strategies related to specific goals and objectives. We then present proposed bicycle networks from prioritization strategies and their potential benefits. The final section provides a discussion and conclusions on the implications for practice relevant to the case of Montreal, and cities more generally, as well as limitations and possible refinements.

4.2 Literature Review

4.2.1 Transportation-Disadvantaged Populations

Access to transport services represents a critical factor in determining quality of life by enabling participation in essential activities central to a healthy and happy lifestyle. Transportation disadvantage (TD) has been defined as "a situation where people experience a shortage of transport options, which restricts their mobility and hence their access to goods, services and relationships" (Stanley, 2004, p. 14). Transportation-disadvantaged populations may, therefore, face chronic problems, not limited specifically to transportation services, such as poor health or lack access to jobs and other social opportunities (Currie et al., 2009).

While TD is increasingly receiving attention from researchers and planners, it remains a concept that is difficult to measure, given that it is a complex and multidimensional construct resulting from the interaction between environmental, socioeconomic, and demographic variables (Currie & Delbosc, 2011). Much work uses proxy indicators of socioeconomic status (SES), which are presumed to incline people toward TD, to identify disadvantaged populations (Foth et al., 2013; Manaugh & El-Geneidy, 2012; Stanley, 2011). Common variables include car ownership, household income, minorities, immigrants, elderly, and children. Since socio-demographics alone do not make people transportation disadvantaged, several studies combine area mobility measures (e.g., distance to public transport services) with social indicators to identify transportation-disadvantaged areas (Casas, 2007; Church et al., 2000).

4.2.2 Bicycle Network Planning

While a considerable number of policy guidelines have been written on the physical design of bicycle facilities (CROW, 2007; Sustrans, 2014), the literature on questions of cycling investment prioritization is relatively scarce. Efforts in that direction are primarily based on origin–destination (O-D) data to develop an optimization framework for urban bicycle network planning purposes. Larsen et al. (2013) developed a grid-cell model for identifying priority areas within a region for investing in cycling infrastructure based on an O-D survey, a stated preference survey, and bicycle-vehicle collision data. Guerreiro et al. (2018) developed a method based on a geographic information system (GIS) to objectively determine the optimum location of new bikeways based on data mining of disaggregated O-D data, considering current and potential users. Instead of identifying bike lanes between origins and destinations, Zuo and Wei (2019) introduced systematic and quantitative analytics for locating new bike infrastructure, based on a multicriteria analysis technique, aiming to improve bicycling connectivity and bicycle–transit connection.

Given that traditional travel surveys do not capture accurate and comprehensive information about people’s routes or facility preferences, there is a growing body of literature on bicycle planning that uses crowdsourced data to support evidence-based transportation planning and inform decision making. Using large-scale bike-sharing trajectory data, along with a greedy network expansion framework, Bao et al. (2017) developed bike lane construction plans for the city of Shanghai in China. They introduced a flexible beneficial score function to tune the benefit between the number of covered users and the length of bike trips. Inspired by percolation theory, Olmos et al. (2020) proposed a data science approach to prioritize new facilities by integrating biking trajectories with O-D data extracted from mobile phone data. They defined the potential demand for cycling and prioritized streets with the highest potential bike flows.

In recent years, studies on bicycle network design have taken advantage of network science to measure the statistical and dynamical properties of bicycle networks and develop optimal strategies for bicycle network growth. One recent study by Szell et al. (2021) took into account the structural complexity of bicycle networks and introduced growth strategies to optimize quality metrics including cohesion, spatial coverage, POI coverage, resilience, directness, and local and global efficiency. Finally, Akbarzadeh et al. (2018) abstracted a weighted network based on the number of taxi trips. They detected seven different network clusters using a modularity maximization method and proposed bicycle routes that minimized the total travel distance in the network as priority corridors along which to build new bikeways. However, instead of building a connected network, they focused on connecting nodes in each sub-network to minimize travel time and the total length of proposed bikeways and, finally, to improve the directness.

In summary, decisions on where to build new bikeways are, in practice, currently made with less rigorous methods. Research optimizing planning of cycling networks is still emerging. Compared with motorized road users, cyclists consider a broader range of factors for selecting bicycle routes such as travel, distance, and comfort (Winters et al., 2011). However, many studies have yet to account for factors other than distance and travel time when determining the key bike travel corridors. By taking inspiration from previous studies and expanding on their limitations, this work will: 1) plan bicycle facilities considering the network as a whole; 2) propose bikeways in a manner that takes into account cyclists' routing preferences; and 3) provide a variety of growth strategies with different prioritizations.

4.3 Methodology

4.3.1 Data Sources

This study uses multiple data sets to develop and demonstrate the capabilities of our approach for the prioritization of new bike lanes.

1. *Sociodemographic data:* The sociodemographic characteristics of the population in the dissemination area (DA) level are obtained from the Canadian Census of 2016 (Statistics Canada, 2016a). The Island of Montreal contains 3,202 DAs, which are the smallest standard geography at which census data are publicly available; they contain a population of between 400 and 700 people (Statistics Canada, 2017).
2. *Locations of transit stops:* Transit data for 2021 provided by the Société de Transport de Montreal (STM) contain the locations of bus stops and metro stations on the Island of Montreal. This data set is used to identify neighborhoods that have poor access to transit services.
3. *Commuting data:* The commuting data are provided by Statistics Canada (Statistics Canada, 2016b). This data set contains information on mode-specific commuting behavior at the census tract (CT) level and indicates the number of commuting trips between home and work locations, for the entirety of the employed labor force aged 15 and older having a usual place of work on the Island of Montreal.
4. *Locations of urban opportunities:* Point locations of urban opportunities are derived from the Enhanced Points of Interest (EPOI) data set of 2019 (DMTI Spatial Inc., 2019) provided

by DMTI Spatial, which includes over 1 million business and recreational points of interests across Canada. We select four types of urban opportunities to represent destinations that are relevant for cyclists: groceries, pharmacies, health care facilities, and elementary and secondary schools. Groceries and pharmacies are selected because they were identified as “everyday shopping opportunities” (Tucker & Manaugh, 2017). Health care facilities are selected because they provide necessary medical services. Elementary and secondary schools are selected because they provide early childhood education which is an essential element in future success.

5. *Existing and proposed bicycle networks:* The current state of the bicycle network is obtained from the Montreal Open Data Portal. For analytical purposes, we reclassify cycling facilities into three categories based on the level of safety and user comfort: high-comfort bikeways, medium-comfort bikeways, and low-comfort bikeways. High-comfort bikeways are places where most cyclists will feel comfortable riding, including children. Cyclists are either physically separated from motor vehicle traffic or travel along an off-street path located away from a road. Route types include cycle track and bike path. Medium-comfort bikeways are low to medium stress routes, offering cyclists a shared lane where they interact with pedestrians. Multi-use paths fit within this category. Low-comfort bikeways include painted bike lanes and shared bike lanes. These facilities present high traffic stress and are uncomfortable for most cyclists. Cyclists either travel along an exclusive lane beside a busy road, a shared lane with motor vehicles, or in an exclusive cycling zone between a vehicular travel lane and on-street parking. The proposed bicycle network is constructed in ArcGIS based on the 2019 Montreal Bicycle Network Plan (Service de l'urbanisme et de la Mobilité, 2019), which identifies potential road segments

for new bikeways. Given the data limitations, all the projected bicycle facilities are categorized as low-comfort bikeways.

6. *Road networks:* The road network comes from the Montreal Open Data Portal. We exclude roads where cycling is prohibited (e.g., highways) and integrate road and cycling networks to build a bikeable network.

4.3.2 Connecting Network Components

Bicycle networks can be abstracted as graphs which consist of a set of vertices connected by a set of edges: edges represent bicycle-specific facilities; vertices represent intersections and endpoints of bicycle facilities; flows represent the bicycle trips on networks. Bicycle networks are generally not fully connected and are split into several network components, where no connection exists between nodes in different disconnected components. The number of network components can be used to measure how well connected a network is. Typically, as a network grows, the fragmented components are gradually connected, and the largest connected component will expand until it contains all the nodes in the network. The network components in the bicycle network on the Island of Montreal are identified using R package igraph (Csardi & Nepusz, 2006). For the components identified, we calculate the total points of interest (POIs) that can be reached within 500 m from nodes as POI coverage.

Prioritization Strategy 1: Improving Connectivity of Bicycle Network

This prioritization strategy aims to consolidate the bicycle network and improve connectivity. By creating connections between network components, this growth strategy will deliver a fully connected bicycle network, allowing cyclists to rely on the bicycle network to get to their destinations. The following steps are suggested:

1. rank the network components according to their POI coverage;

2. identify the two components that cover the most POIs;
3. calculate the shortest path between two components using the proposed bicycle network and add it into the existing bicycle network; and
4. repeat steps 2 and 3 until only one component exists or the budget constraint is met.

4.3.3 Identifying Transportation-Disadvantaged Neighborhoods

Transportation disadvantage at the DA level is measured using six common socioeconomic variables from the literature and one mobility-related variable:

- median household income;
- low-income cut-offs (LICO);
- low-income measure (LIM);
- proportion of recent immigrants;
- proportion of population without certificate, diploma or degree;
- unemployment rate; and
- number of public transport services (e.g., bus routes and metro lines) within 500 m from centroids of DAs.

Each variable is standardized using Z-scores and summed unweighted to create the disadvantage index. Lower values signify low accessibility to public transit and high socioeconomic need and, therefore, higher levels of transportation disadvantage. The DAs are then categorized into quantiles according to their index score, with quintile 1 (Q1) representing the most transportation-disadvantaged neighborhood and quintile 5 (Q5), the least. The identified transportation-disadvantaged DAs are predominantly characterized by immigrant households with low incomes, low educational achievement, and poor accessibility to public transit.

4.3.4 Estimating Potential Cycling Demand

Potential cycling demand is defined as the number of one-way bicycle trips between origins and destinations. Based on the bikeable network, we compute cycling routes for each O-D pair of the potential demand using the R package stplanr (Lovelace & Ellison, 2018). To consider the level of traffic stress for cyclists, we assign a weight w_i to each road segment according to their comfort level classification (**Table 4.1**) and calculate weighted shortest routes (**Figure 4.1**).

$$WL = \sum_{i=1}^{n} x_i w_i$$

where *WL* is the weighted length of a potential route and x_i is the length of road segment *i*. Based on existing studies, a 25% diversion threshold was selected to model cyclists' willingness to divert from the shortest path to use bicycle facilities (Broach et al., 2012; Mekuria et al., 2012; Winters et al., 2010). A reasonable weighted shortest route that prioritizes less stressful road segments should not be more than 25% longer than the shortest route. Therefore, the shortest cycling route without considering traffic stress will only be selected when the length of the weighted shortest route exceeds a 25% detour criterion. Overall, weighting the road segments and assigning lower weights to roads with existing cycling infrastructure allows us to account for the route preferences of cyclists and determine the shortest paths that favors a bike path over the vehicular road segments.

Table 4.1: Weighting of different types of road segments

Route type	**Weight**
Cycle track	0.5
Bike path	0.5
Multi-use path	0.8
Painted bike lane	1
Shared bike lane	1
Bikeable road	5

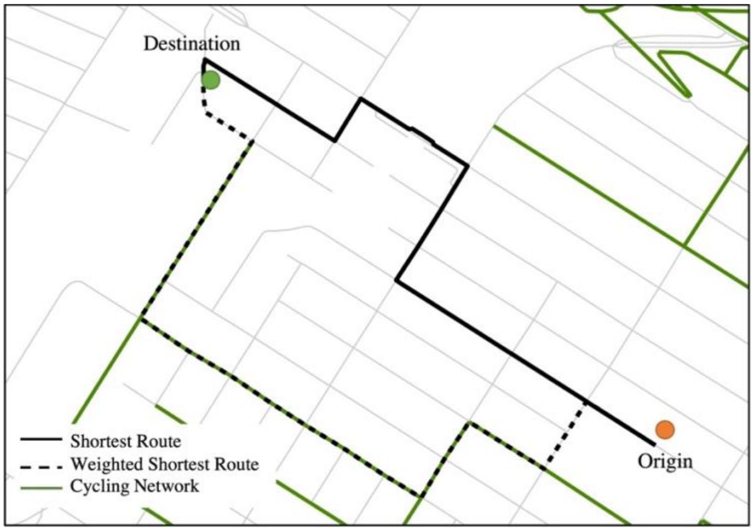

Figure 4.1: Potential routes between origin-destination (O-D) pair

4.3.5 Growing Bicycle Networks

After assigning the potential cycling demand onto the bikeable network, we estimate the cumulative cycling potential at the road segment level by calculating the number of overlapping shortest routes. The proposed bikeway with the highest cumulative cycling demand will be prioritized. By doing so, we focus our attention on the routes that are most likely to serve the greatest number of cyclists, and ensure that new facilities serve places with high cycling demand. Considering the multiple priorities of the City of Montreal in expanding the bicycle network, we develop two prioritization strategies to allow us to compare a solution that focuses on accessibility to one that focuses on GHG emissions.

Prioritization Strategy 2: Enhancing Accessibility for Transportation-Disadvantaged Population

The second prioritization strategy set out to improve bicycle accessibility to urban opportunities for disadvantaged populations and mitigate disparities in access to bicycle facilities. Thus, the bicycle projects that connect key destinations with transportation-disadvantaged DAs (Q1) will be prioritized. The following procedures are suggested:

1. identify transportation-disadvantaged DAs;

2. calculate potential cycling demand between transportation-disadvantaged DAs and selected urban destinations;
3. identify cycling routes that consist of the proposed bikeways with the highest cycling potential and add them to the existing bicycle network; and
4. repeat step 3 until all cycling demand is satisfied or the budget constraint is met.

Prioritization Strategy 3: Reducing GHG Emissions from Transportation Sector

This prioritization strategy intends to prioritize the potential for substituting short car trips by cycling and reducing vehicle kilometers traveled (VKT) as well as GHG emissions. The network is consolidated by adding connections which concentrate modeled commuter rider flows described as follows:

1. identify car trips of less than 5 km as cyclable trips based on commuting data;
2. calculate potential cycling demand between CTs and assume that commuters would substitute cycling for car trips that are less than 5 km;
3. identify cycling routes that consist of proposed bikeways with the highest number of cyclable trips and add them to the existing bicycle network; and
4. repeat step 3 until all cycling demand is satisfied or the budget constraint is met.

4.4 Results

4.4.1 "Connectivity-Focused" Prioritization Strategy

4.4.1.1 Connectivity of Existing Bicycle Network

The existing bicycle network on the Island of Montreal contains close to 970 km of bike lanes, consisting of 17,534 nodes and 17,594 edges. The network is made up of 213 network components, and the largest connected component spans 53% of the existing network. Under the "connectivity-focused" growth scenario, the connectivity of the bicycle network is measured using the gamma (γ) index developed by Garrison and Marble (33). The γ index calculates the degree of connectivity as the ratio between the actual number of edges in the network and the maximum possible number of edges. Because bicycle networks are almost always planar where no edges cross each other, the potential number of edges is calculated as $3(v\text{-}2)$. Consequently, the degree of connectivity (γ) of existing bicycle network is 0.33, meaning that 33% of the network in the region is connected.

Besides measuring the connectivity from the perspective of graph theory, we estimate POI coverage to investigate whether the existing network of bicycle facilities can get cyclists to their potential destinations. For this, we created a buffer of 50 m from each link in the existing network. POI point data were then spatially joined to the buffers to obtain the number of urban opportunities accessible to the bicycle network. Currently, the bicycle network covers 29% (n = 910) of opportunities; 74% (n = 674) of them are accessible by cyclists using continuous cycling routes.

4.4.1.2 Priority Bicycle Network

The "connectivity-based" intervention strategy seeks to give priority to cycling projects that connect the existing network with places of interest and, therefore, maximize connectivity of the bicycle network. As a result, this strategy yields a well-connected network that ensures people cycle to destinations without leaving dedicated bike lanes and using sidewalks or roads with a high volume of traffic. The expanded bicycle network is presented in **Figure 4.2**. The existing facilities are shown in gray, while all recommended routes are shown in different shades of blue representing the investment priority. As can be observed, bikeways that close "gaps" between network components in the existing bicycle facilities are prioritized. Cycling projects with high priority are primarily located in non-central areas of Montreal which can be explained by the connectivity of the cycling network, while bicycle facilities on the periphery are more fragmented and less continuous than those that lie centrally within the city.

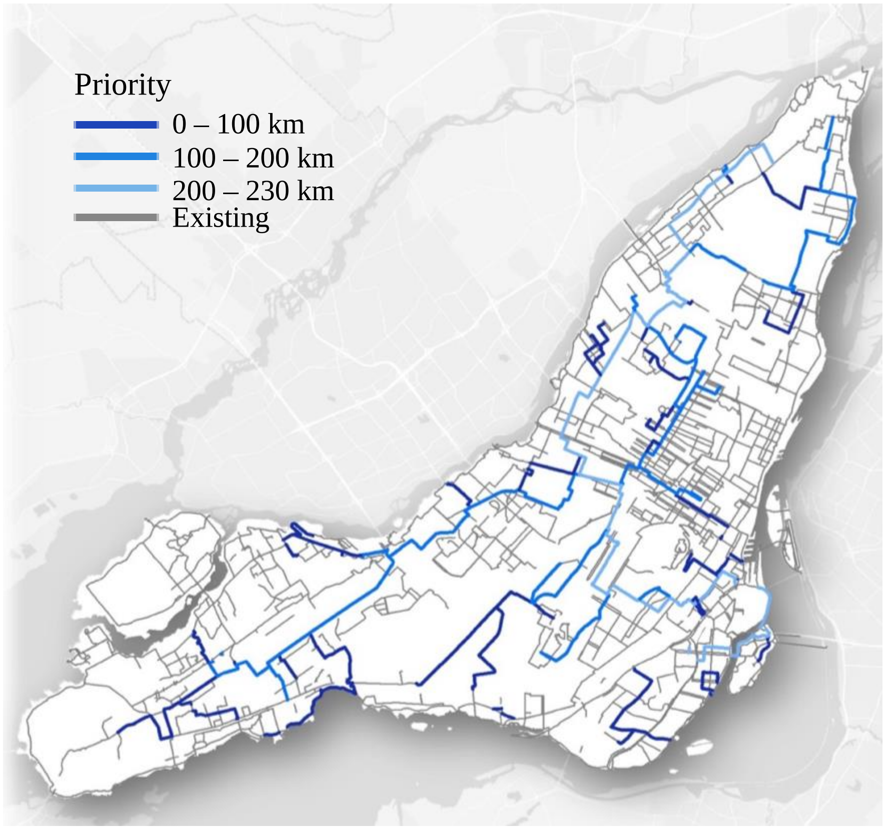

Figure 4.2: Priority bicycle network

4.4.1.3 Potential Benefits

The potential benefits of a “connectivity-based” intervention strategy are shown in **Figure 4.3**. We can see that the number of components is reduced with newly added infrastructure. The expanded bicycle network consists of 19,417 nodes and 19,708 edges, featuring 128 network components. Cyclists will have access to 1,161 destinations using the proposed infrastructure. The addition of 230 km of dedicated bike lanes under this intervention strategy also more than doubles the size of the largest connected component, which will contain 1,118 km of bikeways and cover 1,150 POIs.

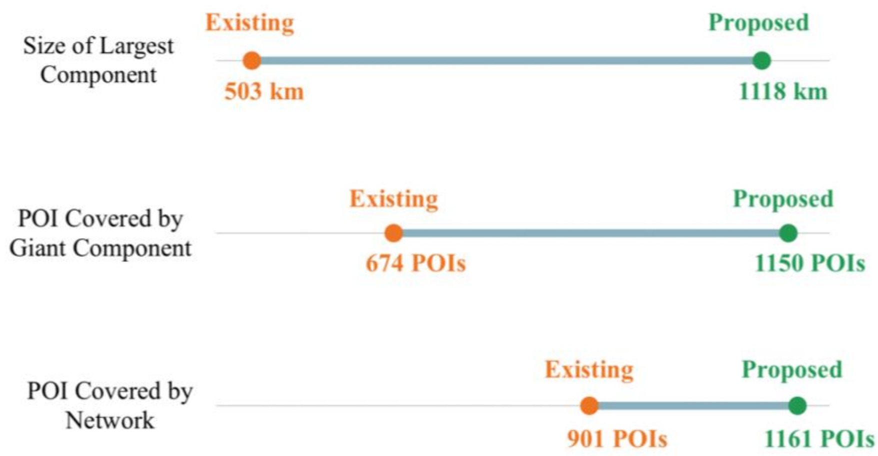

Figure 4.3: Potential benefits of "connectivity-based" strategy

4.4.2 "Equity-Based" Prioritization Strategy

4.4.2.1 Transportation-Disadvantaged DAs

As discussed above, transportation-disadvantaged areas are identified based on a composite measure of socioeconomic and mobility-related variables to help planners prioritize areas where populations suffer from a lack of access to public transit which limits their ability to participate in essential activities. In 2021, around 25% of Montreal's population lived in DAs with high socioeconomic need and low public transit accessibility. The spatial pattern of the transportation-disadvantaged areas is presented in **Figure 4.4**. Most DAs with the highest levels of transport disadvantage tend to be concentrated in suburbs, particularly in the eastern part of Montreal Island, including the boroughs of Montreal-North and Villeray–Saint-Michel–Parc-Extension, and southwest of downtown Montreal, such as Le Sud-Ouest. This is not surprising given that these areas already experience high levels of socioeconomic need since they have documented reputations as being the poorest and most racially diverse neighborhoods in Montreal. Also, they are not well served by public transit. All these factors result in great transportation disadvantage in these DAs.

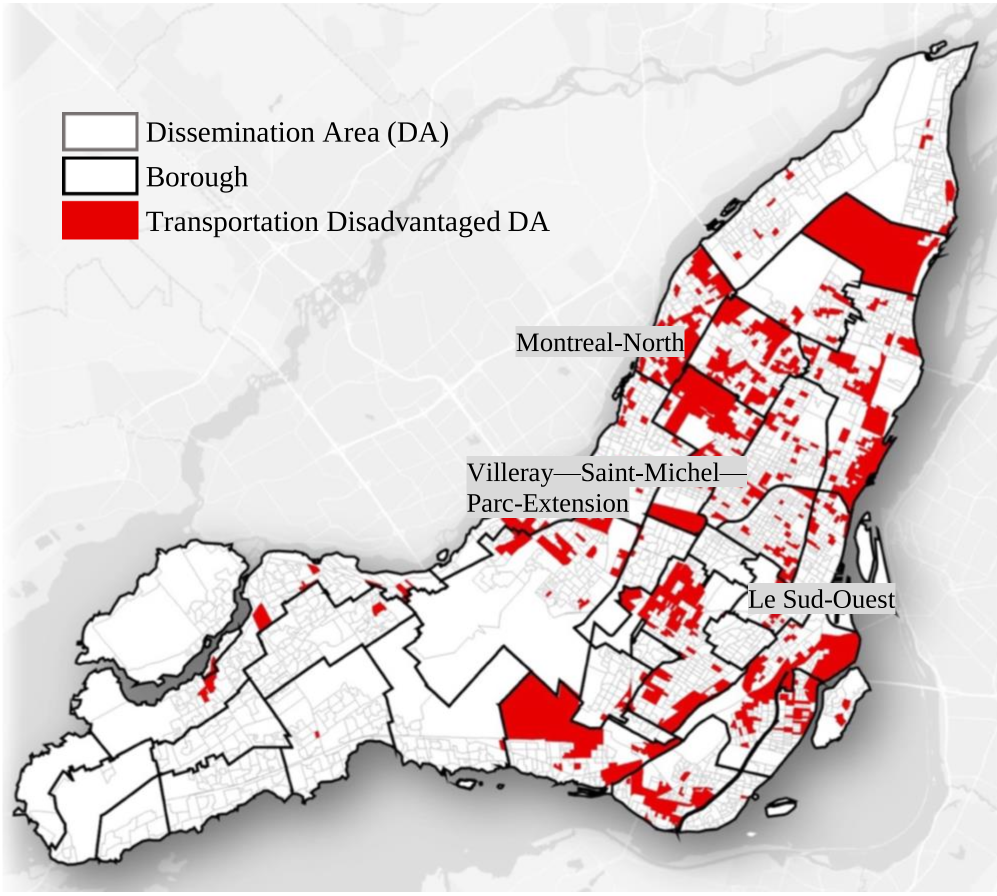

Figure 4.4: Identified transportation-disadvantaged dissemination areas

4.4.2.2 Priority Bicycle Network

The "equity-based" intervention strategy focuses on cycling investment for neighborhoods that experience high levels of socioeconomic need and transportation disadvantage, and prioritizes route developments with high predicted volumes of disadvantaged cyclists. This strategy would, therefore, deliver a network that serves the most disadvantaged residents and assist them in traveling to major education, health, retail, and recreation destinations. As we can see, prioritized bike lanes are spaced closely together in identified transportation-disadvantaged neighborhoods, including the Hochelaga-Maisonneuve neighborhood and the boroughs of Montreal-North and Villeray–Saint-Michel–Parc-Extension, to ensure their residents have access to a bicycle route within a short cycling distance (**Figure 4.5**). Several bicycle corridors are prioritized to link disadvantaged areas to various activity destinations, such as borough of Le Plateau-Mont-Royal.

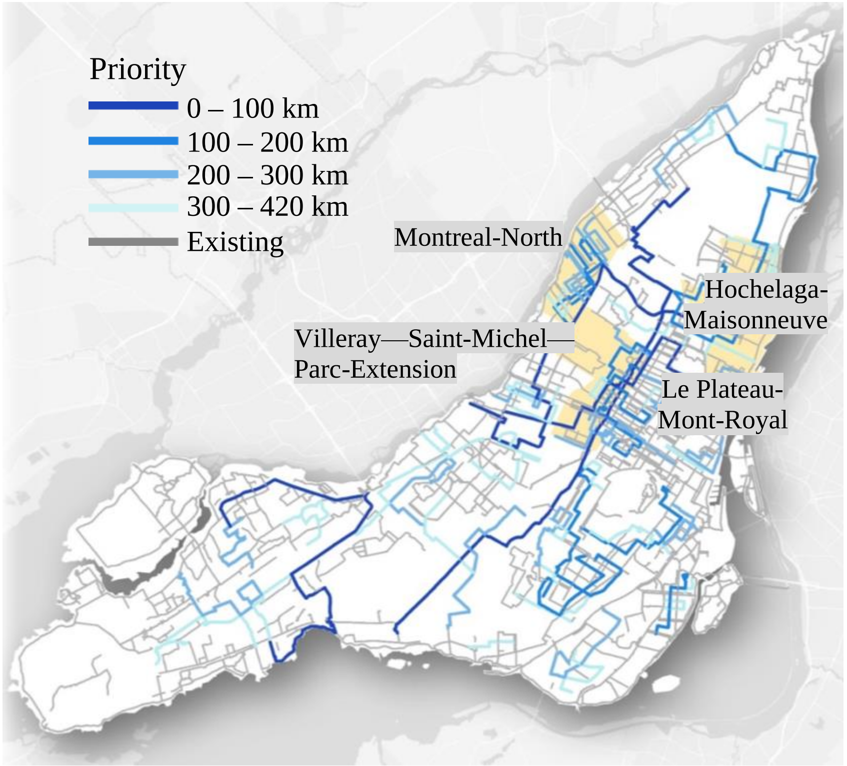

Figure 4.5: Priority bicycle network

4.4.2.3 Potential Benefits

We first examine the improvements in accessibility to the bicycle network to measure equitable outcomes of this intervention strategy. **Figure 4.6** shows the changes in accessibility of the bicycle network, which are measured as the density of the bicycle network (left y axis) and the proportion of people that have access to the bicycle network (right y axis). We can see that, residents living in transportation-disadvantaged areas experience, on average, greater levels of accessibility to the existing bicycle network relative to the region's average, implying that bicycle investments were directed to populations dependent on cycling, and bicycle plans took into account the needs of disadvantaged neighborhoods. In this equity-based scenario, all neighborhoods are gaining in accessibility to dedicated bike lanes given the expansion of the bicycle network, but the prioritized cycling investments improve accessibility more for transportation-disadvantaged neighborhoods than for the general population. With the prioritized infrastructure, accessibility for the disadvantaged population improves by 24% to 82%, while accessibility for the general population improves only marginally to 32%. This is expected because this intervention strategy focuses on prioritizing bicycle investments in light of the equity perspective to better serve disadvantaged residents. Also, from a vertical equity standpoint, disadvantaged neighborhoods are arguably the most important to prioritize in giving increased accessibility.

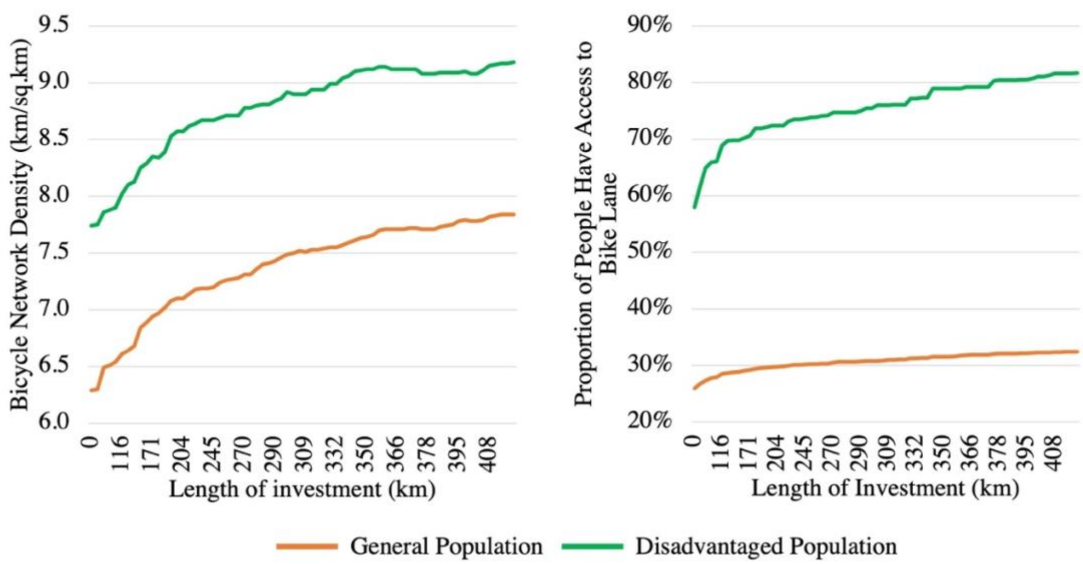

Figure 4.6: Changes in accessibility to bicycle network

The proximity of the cycling network is not the only factor in understanding the potential benefit of this "equity-based" strategy. We also estimated the improvement in connectivity of bicycle facilities between centroids of identified transportation-disadvantaged DAs and urban destinations of cyclists. Under this scenario, network connectivity is quantified as the proportion of the route traveled on bicycle facilities. In this manner, we will be able to measure the degree to which each destination category is connected with origins using the proposed bicycle network, and whether residents of disadvantaged areas can access key destinations without leaving the proposed bicycle network and entering mixed traffic.

Figure 4.7 displays the current state of the network connectivity and the potential improvement that the proposed facilities will bring. The baseline level of connectivity for five types of destinations is quantified using the current bicycle network. We can see that pharmacies and grocery stores are poorly connected with origins by the existing bicycle network. While residents of disadvantaged neighborhoods can access their nearby pharmacy and grocery store using a path consisting of 20% of bicycle facilities, they travel a higher proportion of their trips on bikeways to the closest parks, on average 40%. This may be explained by the differences among quantities of pharmacies, grocery stores, and parks. On the other hand, the result reflects disadvantaged residents being unable to travel safely and comfortably from their homes to destinations using the current bicycle network. The additions of bicycle facilities under this proposed plan increases network connectivity levels, but the benefits of these improvements differ across destination categories. Particularly the increase in connectivity to health care facilities is large, yet the increase in connectivity to grocery store is smaller.

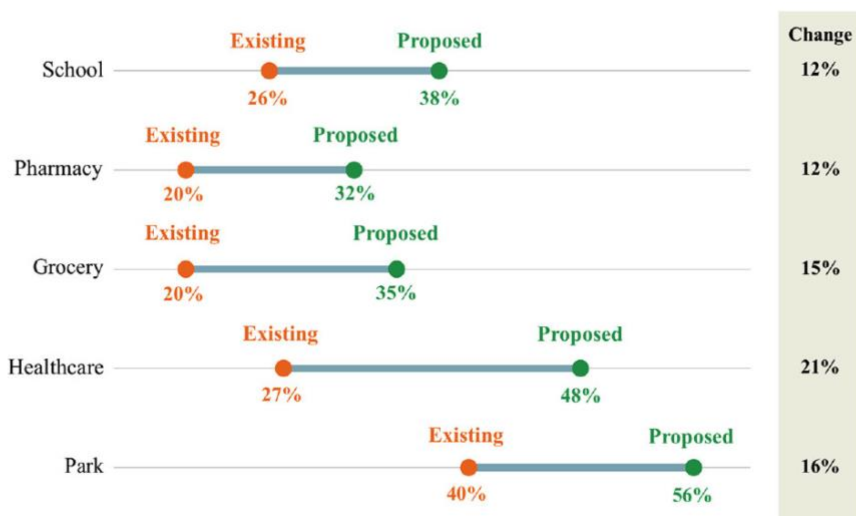

Figure 4.7: Improvement in proportion of route on facilities

The final step in assessing the potential benefits of the infrastructure enhancements is to calculate the percentage of disadvantage suffered by residents under the set of combinations in travel distance and portion of route on facilities for each of the destination category. As shown in **Figure 4.8**, rows represent increased trip distances, while columns represent a greater proportion of route traveled along bikeways. The individual plots depict the percentage of the disadvantaged populations for each destination type under the specified thresholds. Currently, for trips of less than 2 km, more than 20% of the disadvantaged population could include over 50% of their rides on dedicated bike lanes to reach school, pharmacy, and grocery store, while less than 10% of disadvantaged residents could access all five destination types using a route consisting of more than 75% bikeways. After the prioritized infrastructure is added, more than a quarter of the disadvantaged population will be able to reach urban opportunities within 2 km by traveling over 50% of their trips on bicycle facilities.

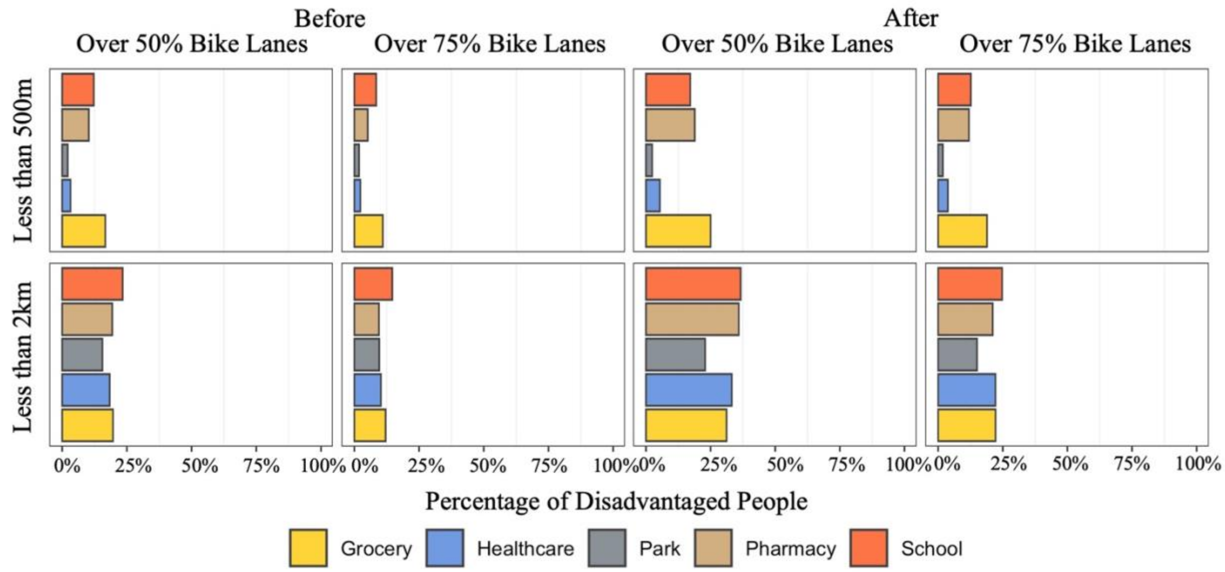

Figure 4.8: Potential benefit of "equity-based" strategy

4.4.3 "Modal Shift" Prioritizations Strategy

4.4.3.1 Commuting in Montreal

The first step in identifying car trips that could be reasonably cycled is to explore commuting patterns. We categorized CTs between suburbs and urban areas using the Urban Core Index (UCI) (34). UCI was calculated as the sum of normalized values of three variables: (1) the percentage of dwellings built before 1946; (2) the percentage of non-single-family homes; and (3) the modal share of public transit and active transportation in a CT. Each variable was standardized (Z-score), weighted equally, and summed together to create the UCI. Urban areas were CTs with a UCI score of 1 or above. Based on the classification of urban and suburban CTs, we divided commuting flows into four main categories to describe commuting activity on Montreal Island: (1) traditional commute, in which commuters travel from suburbs to urban areas; (2) reverse commute, in which commuters travel from urban areas to suburbs; (3) inter-urban commute, in which commuters travel between urban areas; and (4) inter-suburban commute, in which commuters travel between suburbs.

The Island of Montreal showed strong urban dominance. Urban CTs account for the majority of employment destinations with 92% of commutes. Historically, traditional commuting from suburbs to urban areas was dominant in Canada. However, the inter-urban commuting share outnumbered the share of workers who have a traditional commute in the region (**Figure 4.9.a**). With regard to the distribution by modes of commuting, commuters of Montreal Island were heavily dependent on public transit. In 2015, 43% of commuters used public transit, including bus, subway, light rail, and ferry, while another 45% of workers commuted to work using an automobile, either driving alone or carpooling. Active transportation, including walking and cycling, made up a small proportion of all commute trips at a rate of 12%. The modes of commuting differ according to the types of commuting flows. The greatest tendency to drive was found in inter-suburban flows at 78%, while the rate of commuters who rely on nonmotorized transportation was notably high in commuting from urban CT to urban CT where there tend to be more dedicated bike lanes. The spatial distribution of share of car trips by origin is shown in **Figure 4.9.b**. Montreal's urban areas (i.e., downtown and surrounding CTs) have systematic concentrations of relatively low driving rates. In other parts of the Island of Montreal, driving rates are relatively high. However, we find that 29% of car trips were shorter than 5 km, suggesting a strong potential for mitigating car dependency and reducing GHG emissions.

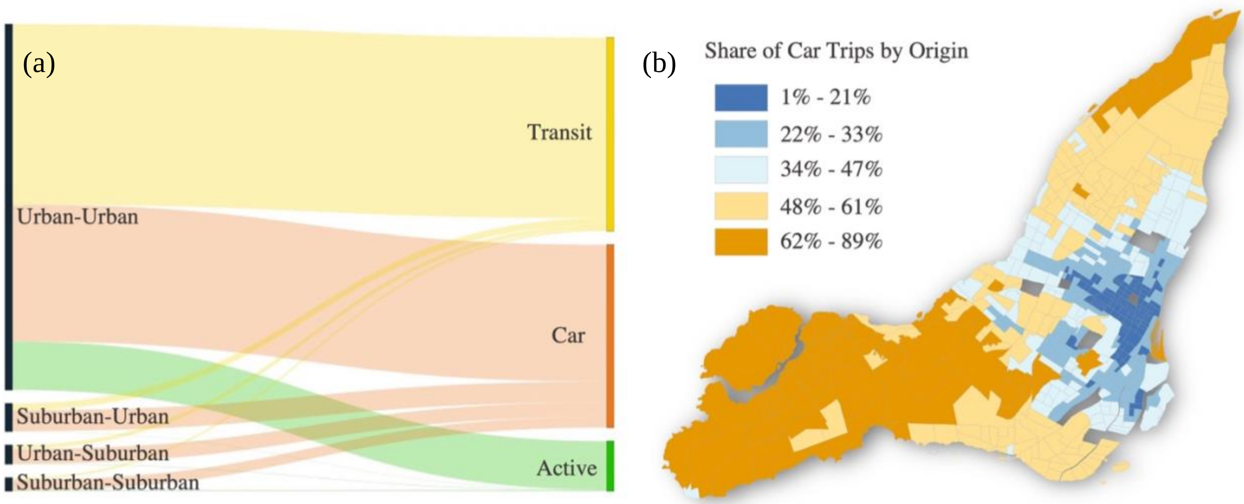

Figure 4.9: Commuting in Montreal: (a) inter-urban commuting share; and (b) the spatial distribution of share of car trips by origin

4.4.3.2 Priority Bicycle Network

The "mode shift" strategy prioritizes bicycle facilities where there are high future volumes of people cycling to work to make cycling a viable option for commuters. This strategy would create a bicycle network that connects homes to workplaces and support short commuting trips, enabling a modal shift from car driving to cycling. **Figure 4.10** indicates that bikeways are mainly suggested in central regions of the Island of Montreal where jobs are concentrated, but route developments which connect areas with a high proportion of commutes by car (e.g., West Island) to main employment are prioritized to facilitate further growth in the cycling rate.

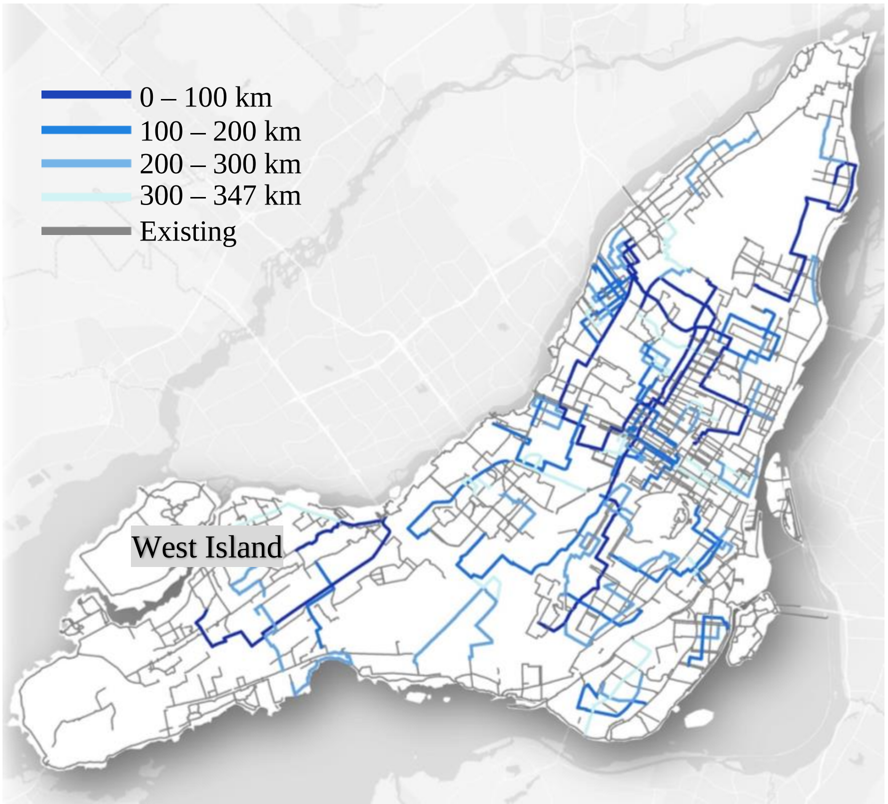

Figure 4.10: Priority bicycle network

4.4.3.3 Potential Benefits

Figure 4.11 demonstrates the power of the "modal shift" intervention strategy by showing the change in potential for savings in GHG emissions from replacing short car trips with cycling. Given the lack of data on car details (e.g., vehicle age, fuel type, vehicle size) and vehicle speed, the CO_2 emissions were estimated based on the distance traveled for each car trip. The calculations applied in this study were based on the suggestions by Brand et al. (2014) that the average CO_2 emissions savings by cycling compared with 100 km of car driving is 19 kg. As can be observed, the number of potential cyclable trips and the reduction in VKT are gradually increased as more infrastructure is added. With an investment of 347 km of bicycle facilities, potentially 14%

(n = 48,890) of car trips would be cycled, and such a move would shift approximately 143,090 VKT in short car trips and thereby reduce GHG emissions by 27,187 kg every day.

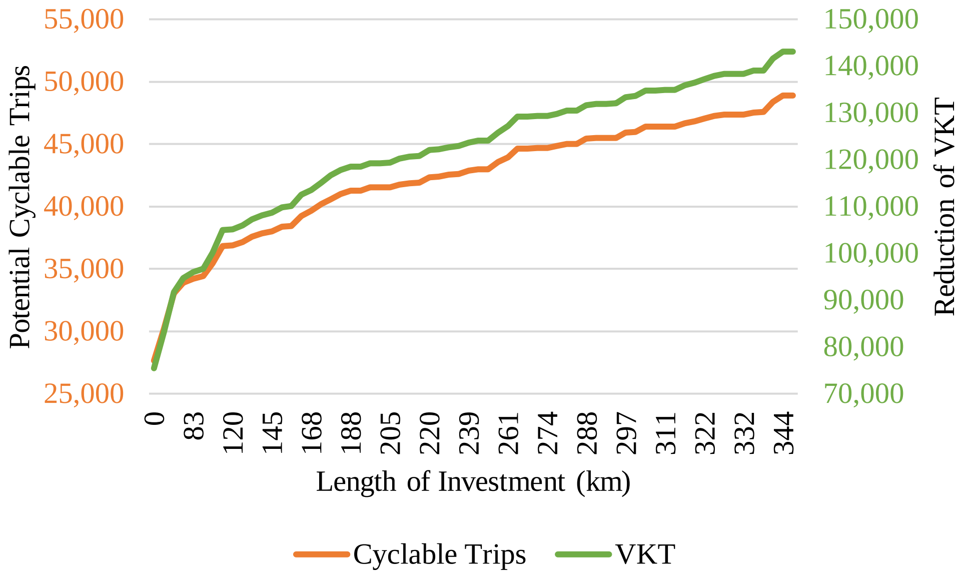

Figure 4.11: Potential of GHG emissions

4.5 Discussion and Conclusions

With the growing consensus on the benefits of cycling, cities are expanding bicycle networks to foster a cycling culture. This paper set out to formulate a framework that supports the planning of bicycle facilities. Although this is not the first study tackling the problem of planning a bicycle network, the paper is unique in introducing quantitative methods for prioritizing future bicycle improvements, which have been proposed in Montreal Bicycle Network Plan, using different intervention strategies about specific goals and objectives.

The "connectivity-focused" prioritization strategy considered the connectivity objective and sought to establish a well-connected bicycle network by employing a network-theoretical methodology. We prioritized cycling projects that connect fragmented network components to increase the size of the largest component and maximize coverage of important destinations. The "equity-based" intervention strategy grew the bicycle network favoring cycling equity goals. To improve accessibility to bicycle networks and urban opportunities for those neighborhoods that are currently socially isolated and experience a shortage of transit services, we first identified transportation-disadvantaged DAs by using a composite index comprised of six socioeconomic indicators plus one mobility-related indicator. Project priorities were then decided based on a project's ability to connect identified disadvantaged neighborhoods to destinations via connected dedicated bike lanes. The "modal shift" strategy focused on commuting trips, which aligns with the sustainability goals of Montreal, being to promote cycling as an alternative to driving and thereby to increase cycling ridership and reduce carbon emissions. We prioritized cycling projects which concentrated several possible overlapping short car trips of less than 5 km to build a bicycle network that would appeal to prospective bicycle commuters.

After determining priorities for future investment, we modeled the impacts of proposed bicycle projects beyond added kilometers. The results suggested that the "connectivity-focused" scenario would increase the size of the largest connected component from 503 km to 1,118 km. Cyclists would access 1,150 important destinations using connected cycling routes. It is important to note, however, that bicycle projects proposed by Montreal Bicycle Network Plan cannot connect all fragmented components. The "equity-based" scenario demonstrated that the expanded network would improve accessibility to bicycle facilities for transportation-disadvantaged neighborhoods from 58% to 82%. Residents living in those areas would be able to access a majority of destinations using a path consisting of more than 35% bicycle facilities. The findings from "modal shift" scenario showed an increase in potential cyclable trips and reductions in VKT and GHG emissions.

Overall, by applying this methodology to the bicycle network on the Montreal Island, the results proved that this framework is not only useful for guiding the implementation of new bicycle facilities with specific policy priorities but could also provide insights on how the improvements in the network impact both existing and potential cyclists. In addition, the output of project prioritization highlighted the importance of growing the bicycle network in a systematic way and could help cities maximize the benefits of cycling investment within budget constraints. Lastly, this approach does not involve context-specific considerations. Planners and engineers elsewhere can, therefore, easily replicate this methodology using similar data sets.

This study is not without limitations. A major problem to have evolved in this study is that of defining transportation-disadvantaged neighborhoods based on census data. The aggregate approach falsely assumed that the attributes of areas reflect those of the residents living in the areas and therefore may miss transportation-disadvantaged individuals in other neighborhoods. In addition, when deciding about prioritization of bike path section investments, it is important to take into consideration intersections where the majority of bicycle–vehicle conflicts occur (Korve & Niemeier, 2002). This could help in measuring the quality of proposed facilities to prioritize investments that reduce the risk of conflicts and increase safety for cyclists. Modeling cycling potential also presents its own unique challenges. We assumed all of the commuters with potentially cyclable trips would switch to bicycle, without knowing whether or not the trip is cyclable for them. Since the propensity to cycle to work is determined by multiple factors, trip and traveler characteristics, as well as the environmental and social characteristics, the potential cycling demand may be overestimated. We anticipate that a future stream of work should include disaggreagated data to enhance our abilitiy to explore who lives in certain neighborhoods. Moreover, using detailed travel survey data would allow for a more accurate determination as to where there is high potential for cycling.

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CHAPTER FIVE: DISCUSSION

5.1 Overview

The interconnected studies previously conducted in this dissertation offer a detailed analysis of three transport-related inequities crucial to people's well-being: observed daily travel behavior, access to cycling infrastructure, and destination accessibility by bicycles. Together, these studies present a quantitative framework for bicycle network planning with an emphasis on equity.

5.2 Key Findings

5.2.1 Social Disparities in Travel Behavior

The first study aims to deepen our understanding of travel behavior by examining disparities in travel patterns among different sociodemographic groups and how these differences change over time. In the Montreal metropolitan area, the reliance on public transportation by low-income households has been emphasized. Although transit usage among these households has been a minor decline over time, the usage of buses and metro remain higher than that of their high-income counterparts. Train usage has increased among high-income households, consistently surpassing the rates of low-income groups. Furthermore, individuals from low-income households generally travel shorter distances, a trend that has remained consistent over time. This could stem from the lack of available or affordable transport options. While high-income households often have more access to personal vehicles and can easily bear the expenses of public or alternative transportation, low-income groups face transportation barriers. This limits their ability to travel considerable distances to access employment, education, or healthcare services. It is noteworthy that recent transit subsidy policies in Montreal have invested significantly developing commuter-oriented rail lines that predominantly serve a wealthier, less transit-dependent population, while simultaneously reducing public transit services in central area, which predominantly house lower-income residents more dependent on buses and metro. Considering decision-makers often do not have clear definitions and measures of equity when deciding on transportation services expansion or reduction (Manaugh et al., 2015b), such inequitable resource distribution can further exacerbate disparities in travel behaviors, reinforcing socioeconomic divides (Garrett & Taylor, 1999). As Montreal makes strides in its transportation infrastructure, it is vital to keep these disparities at the forefront. Failing to consider needs of disadvantaged groups in policy design could risk deepening divides and alienating its residents.

Results reveal that seniors have become increasingly reliant on private automobiles to meet their travel needs. This reflects the trend of "increased automobility" in senior travel behavior observed in other regions (Newbold et al., 2005; Rosenbloom, 2001). In 2018, a higher proportion of seniors in Montreal were drivers compared to 2003, and their trip lengths have been increasing over time. The current preference for automobiles may largely depend on the accessibility and effectiveness of public transportation or other alternative modes of transportation. Lacking these options, it becomes challenging for seniors to give up driving, leading to a further rise in private car dependence. The consequences are not limited to environmental effects but also encompass increased accident and fatality risks due to illness-related functional impairments affecting the driving capabilities of seniors. Recent evidence emphasizes the significance of public transit in facilitating driving cessation (Hensher, 2007). Therefore, offering more reliable and accessible transportation alternatives is essential for seniors to reduce their reliance on driving while maintaining their lifestyle.

Walking is often the most overlooked mode of transportation. Our findings indicate that walking accounts for 14.3% of trips made by people with low-income and 24.8% of trips by children. However, neighborhoods with low socioeconomic status face increased health risks due to inadequate pedestrian infrastructure. Community elements, such as streets, housing, parks, and amenities are not always designed to prioritize pedestrian safety in these neighborhoods (Janzen et al., 2018; Rothman et al., 2019). These risks are further exacerbated for specific vulnerable groups, such as children. Moreover, a recent review of pedestrian safety plans in Canadian cities revealed a significant absence of engagement strategies and policies that address the needs of low-income group (Battista & Manaugh, 2019). Given the vital role of walking in our urban transportation system, it is essential for government agencies to place a greater emphasis on enhancing the safety, convenience, and feasibility of walking in urban settings. While Montreal is actively investing in the expansion and enhancement of sidewalks and pedestrianized streets, it is essential for the planning process to embed social equity as its core, particularly when addressing pedestrian safety. Specifically, the planning framework should prioritize equity, focusing on targeted improvements and fostering partnerships with neighborhoods and populations that rely on safe walking conditions.

5.2.2 Differences in Access to Cycling Infrastructure and Bicycle Destination Accessibility

While bicycling, with its affordability and eco-friendly nature, offers a transportation solution for disadvantaged populations, the lack of access to safe and dedicated cycling infrastructure can form barriers. The second study investigates how cycling infrastructure access is distributed across socioeconomic groups and whether the expansion of bicycle network results in a more equitably distributed cycling infrastructure. From 2006 to 2020, Montreal has seen considerable growth in its bicycle network, yet this expansion hasn't been without challenges. The prevalence of low-comfort bikeways could discourage potential cyclists, particularly those who are novices or have safety concerns. Interestingly, in contrast to findings from other global studies

(Braun et al., 2018; Tucker & Manaugh, 2017), Montreal's most socioeconomically disadvantaged populations enjoy better access to cycling infrastructure than their less disadvantaged counterparts. Many of Montreal's initial bikeways emerged in disadvantaged neighborhoods, taking advantage of spaces left vacant after industrial decline. A prime example is the Lachine Canal bike path, which repurposed former industrial zones, historically populated by underprivileged, working-class individuals, into cycling corridors. The late 1970s saw the emergence of cyclist advocacy groups, whose activism paved the way for a prominent north-south bikeway. Nevertheless, our study identified that the most socioeconomically disadvantaged areas often lacked connected cycling infrastructure, forcing residents to share roads with motor vehicles, while moderately disadvantaged areas consistently enjoyed superior access to connected cycling networks over time. Several reasons account for this. Firstly, the expansion of cycling network likely touched areas housing populations with varied socioeconomic statuses. Secondly, this could point to potential planning biases favoring residents with moderate socioeconomic disadvantages and potential sociodemographic shifts, like gentrification. As observed in U.S. contexts (Flanagan et al., 2016; Stehlin, 2015), bike lanes in multiple U.S. cities are framed as economic development tools. Given that gentrification is a gradual process that can result in advantage pockets within traditionally disadvantaged neighborhoods, areas undergoing gentrification that receive cycling infrastructure investments might still exhibit high socioeconomic disadvantages.

Furthermore, the disparities observed in this analysis might be rooted in institutional challenges within the planning and advocacy processes that influence public decisions about cycling investments. Primarily, social equity goals have not been comprehensively integrated into the transportation planning documents which guide infrastructure investments. For instance, Manaugh et al. (2015b) analyzed transportation plans across 18 major North American metropolitan areas. While they found regular mentions of social equity goals, there was often a lack of specific objectives, strategies, and actionable measures conducive to tangible implementation. This gap may arise from an absence of comprehensive guidelines for conducting equity analysis. This trend is notably prominent in active transpiration plans. Lee et al. (2017) identified considerable variations in how 13 major US cities understand, incorporate, and prioritize equity within their pedestrian and bicycle master plans. Such variations underscore the idea that active transportation strategies have not been consistently aligned with social equity goals, potentially leading to inequitable infrastructure investments. Specially, in the recent published 2023-2027 bicycle vision (Ville de Montréal, 2022), the City of Montreal emphasizes territorial equity. Instead of exploring who stands to benefit more or less from a transportation project – essentially the aim of this dissertation – territorial equity mainly examines the spatial allocation of transportation resources. However, such a focus on territorial equity is inadequate in transportation contexts. While emphasizing territorial equity might broaden the reach of the cycling network, it could inadvertently favor specific demographics, leaving behind those populations that heavily depend on bicycling for their essential needs.

5.2.3 Framework for Prioritizing Cycling Investment

The creation of a framework for prioritizing cycling investments marks a step towards equitable infrastructure development. The proposed approach goes beyond a mere focus on equity, it also emphasizes network connectivity and potential modal shifts. Three distinct prioritization strategies were introduced: connectivity-focused, equity-based, and modal shift. Each targets specific objectives, whether bridging existing gaps in the bicycle network, focusing on socioeconomically disadvantaged areas with limited transit services, or promoting a shift from car usage to bicycling to mitigate greenhouse gas emissions. This methodological approach, devoid of context-specific considerations, holds the promise of replication in diverse urban settings. Planners across different cities, faced with unique challenges and demographics, can adapt and implement this framework to derive optimal returns from cycling investments.

It is important to note that the bicycle network in Montreal remains fragmented. The results found that the proposed bicycle network by the Montreal Bicycle Network Plan does not yet connect all network components. This implies that the existing gaps in the network remain unaddressed, forcing cyclists in these fragmented areas to leave the dedicated bicycle facilities and share the road with motor vehicles. While a number of cycling projects are currently underway, Montreal needs to clearly identify and address the gaps in the existing network, connecting it to surrounding communities. Furthermore, irrespective of the primary planning objective, priority should be given to new cycling investment projects that strive to connect with the existing network.

Overall, the outcomes of proposed bicycle projects across different scenarios emphasize the usefulness of leveraging data-driven models to connect cycling infrastructure and optimize the bicycle network, ensuring efficient and economical growth of sustainable transport links. For successful expansion of bicycle networks, it is essential to grow bicycle network systematically, emphasizing the need for strategic planning over arbitrary developments. By focusing on a city-wide scale rather than the traditional "random growth-like" strategy based on local, stepwise enhancements, benefits of cycling investments can be maximized within budget constraints.

5.3 Policy Implications

The findings of this dissertation hold significant implications for policy. First, the observed socioeconomic disparities in travel behavior may stem from the issue of procedural inequity, wherein not all population groups have their transportation demands equally considered during the planning process (Bullard, 2003; Pereira et al., 2017). Often, people with low-income are underrepresented in planning process (Golub, 2016), and some immigrants encounter barriers in participating in decision-making processes due to a lack of voting rights (Government of Canada, 2022). Moreover, transportation planning institutions are predominantly influenced by white, middle to upper-class individuals, potentially leading to a planning process that lacks diverse perspectives and, consequently, equitable transportation system. To counteract this, it is important that planners engage in meaningful dialogue with these communities about their needs and preferences. Lubitow et al. (2016) argue that a top-down approach is insufficient to reflect the interests of all residents. Hence, actively involving community members in the planning process could lead to policies that are more attuned to the specific needs of a community. Furthermore, for effective feedback collection from disadvantaged neighborhoods, governments are suggested to implement strategies such as hosting virtual meetings, offering direct consultancy to these communities, and adopting inclusive hiring practices so planners reflect the demographics of the communities they serve.

Second, walking is crucial for children, especially since they have limited transportation options unlike adults, relying on walkable environments to navigate the city. However, the research findings indicate a decline in children's walking over the study period. This decline can be attributed to a complex interplay of various factors, including the lack of proximity and connectivity to local destinations, the absence of proper walking infrastructure, unfavorable social norms, and parental safety concerns (Giles-Corti et al., 2009; Larouche, 2018; Riazi & Faulkner, 2018). Therefore, increasing the levels of walking among children requires a multifaceted approach, which should encompass environmental modifications that support children's walking, such as the provision of adequate walking infrastructure and the implementation of traffic calming measures on streets. It should also involve policies aimed at directly or indirectly alleviating parental safety concerns and interventions to address the social and individual barriers to walking. While Montreal has allocated funds to enhance walking conditions, including widening sidewalks and creating pedestrian-friendly streets to promote walking, the issue of equity must be taken into account. It is important to note that walking rates among minority and low-income children are two to three times higher than those among their white counterparts, but they also experience higher pedestrian injury rates (McDonald, 2008). This raises concerns about potential conflicts between increasing walking rates, with a focus on children who typically do not use walking as their primary mode of transportation to reach destinations and are more likely to be white and suburban, and improving safety for areas where walking rate are already high, predominantly in urban areas with significant low-income and minority populations. Therefore, improving walking conditions for minority and low-income children might not significantly increase walking rates. However, the government should still consider the socioeconomic status of different areas when planning walking condition improvements and providing additional assistance to disadvantaged areas in the planning process.

Third, disparities in bicycle destination accessibility and the fragmented cycling infrastructure in socioeconomically disadvantaged areas illustrate that an emphasis on rapid outcomes, such as an immediate increase in cycling usage, for sustained funding and support can maintain or even exacerbate existing disparities. Focusing on areas with already high usage fails to consider communities facing systemic barriers, such as disconnected cycling infrastructure. These communities might not immediately demonstrate high cycling usage, making it difficult to secure funding tied to short-term success indicators. To address this issue, policymakers must advocate for a more comprehensive interpretation of success that extends beyond immediate outcomes. Emphasis should be places on equity, accessibility, and connectivity within cycling initiatives, even if they do not deliver instantaneously high usage figures.

5.4 Research Limitations

While the presented studies provided insightful results, they were not without limitations. In our examination of social disparities in travel behavior, a major concern is the limited temporary coverage of a single-day travel diary. This limited perspective may overlook the variety and nuances associated with travel behavior that might become evident over extended periods and make it challenge to calculate trip frequency accurately – an essential measure commonly assessed in travel behavior research. Moreover, a reliance on self-reported travel diaries can introduce recall bias. Participants may unintentionally exclude certain trips or inaccurately recall routes or modes of transportation. This potential for human error can lead to data inconsistencies. Some demographic groups, such as elderly, low-income, minority, and people with limited educational attainment, may be underrepresented in travel survey data, as these populations may face significant barriers to complete surveys, like language proficiency, time constraints, and privacy concerns (Tourangeau, 2014). A limited response from these disadvantaged populations could result in an inaccurate representation of their transportation behaviors and needs.

Additionally, while quantitative data enabled us to describe travel behavior disparities among diverse sociodemographic groups, it does not fully clarify whether these disparities emerge from individual preferences or from external constraints beyond an individual's control. Even though travel patterns are closely tied to an individuals' well-being and societal participation, data on travel behavior alone can't determine if shorter travel distances are a result of limited transportation options or residential self-selection. This limitation points to the importance of integrating qualitative data into our analysis. Qualitative insights can offer a deeper understanding of the travel experiences, perceptions, and challenges faced by disadvantaged groups, allowing for a more comprehensive exploration of the root causes behind these disparities (Clifton & Handy, 2003).

In our assessment of disparities in cycling infrastructure access and destination accessibility via bicycles, a key limitation of this work is the reliance on area-level socioeconomic data as a proxy for individual socioeconomic status. This approach can potentially neglect individuals who, although living in areas characterized by low socioeconomic disadvantage, face challenges in accessing cycling infrastructure. Moreover, area-based measures suffer from the modifiable areal unit problem, leading to greater homogeneity in smaller areas and consequently a higher probability of detecting disparities. Further, the equity analysis predominantly centered on comparisons of group averages. While this offers a broad understanding of disparities between socioeconomic groups, it may inadvertently conceal the nuances and variations in accessibility experienced within these groups. By focusing on between-group comparisons, we might mask significant intra-group disparities, resulting in an oversimplified view of accessibility and its associated equity implications.

Furthermore, the equity analysis focuses on the distribution of accessibility across various socioeconomic groups, emphasizing disparities between these groups. An essential consideration is that higher accessibility for a particular group does not necessarily translate to adequate access. By merely identifying which groups have better or worse access, we might neglect assessing whether this "better" access meets an adequate level of accessibility that allows people to address basic needs with dignity and lead a meaningful life (Pereira & Karner, 2021). This viewpoint pushes beyond relative disparities, urging us to define a baseline of acceptable level of accessibility.

In the proposed framework for cycling investment prioritization, the primary limitation of my research lies in the methodology employed to estimate cycling demand based on OD pairs. By adopting this approach, we did not account for the specific routes potential cyclists might choose in real-world scenarios. While we have assumed that all cyclists would invariably opt for the shortest route, we did factor in a detour ratio to represent a cyclist's willingness to use bicycle facilities. However, this could still lead to an overestimation of cycling demand. Moreover, when considering a modal shift prioritization strategy, the research assumes that all commuters, given potentially cyclable trips, would transition to using a bicycle. This oversimplification does not consider the factors determining the feasibility of such a shift. For instance, is the trip cyclable for them in terms of distance, topography, or personal physical constraints? The propensity to cycling, especially for commuting trips, is influenced by various factors including trip attributes, traveler characteristics, environmental conditions, and broader social contexts. By not dissecting these elements further, we potentially run the risk of overestimating the cycling demand. Therefore, for a more nuanced estimation, it might be beneficial to delve deeper into disaggregated data that could reflect a cyclist's preferences concerning route infrastructure and built environment characteristics. We also anticipate that complementing this method with additional traffic flow and movement data, such as trips recorded using GPS or mobile devices – potentially sourced from municipalities and transportation agencies – could further enhance the growth strategies.

Furthermore, our analysis prioritizes road segment for future cycling investments in bikeable network without considering the impact of intersections. This is concerning, especially when intersections are recognized hotspots for bicycle-vehicle conflicts (Korve & Niemeier, 2002). Considering attributes of intersections in the process of prioritization cycling investments would be helpful for measuring the quality of prosed facilities to prioritize investments that reduce potential risks of conflicts and ensure safe cycling. Last but not least, while employing data-driven strategies to prioritizing cycling investments offers a promising direction, our current method shouldn't be viewed as the final solution in cycling infrastructure development. Rather, it should be seen as an initial step, offering prioritized candidates that warrant further exploration and evaluation. While data-driven methods provide invaluable insights and direction, establishing a comprehensive bicycle network requires a collaborative approach. Further research could enhance this quantitative framework by integrating qualitative data obtained through engaging transportation planners, cycling advocates, community leaders, and importantly, community members, about the challenges faced in planning for a more equitable distribution of cycling infrastructure. The combined expertise and input of these individuals are vital for developing bicycle networks that are not only efficient but also align with the needs of cyclists.

CHAPTER SIX: CONCLUSION

Ensuring an equitable distribution of the benefits of transportation systems should be a top priority for planners and policymakers. Throughout the three interconnected studies, a cohesive narrative emerges that emphasizes the interrelation of equity, accessibility, and bicycle planning. Each study paints a segment of the broader portrait of Montreal's current transportation landscape, highlighting opportunities for improvement.

The first objective was to understand variances in travel behaviors among various sociodemographic groups. This was accomplished by analyzing O-D surveys collected over serval years in the Montreal metropolitan area, using a combination of descriptive analysis and statistical methods outlined in Chapter Two. The results indicate significant disparities in travel behavior among people from low-income households, children, and women compared to their counterparts. A temporal analysis of the O-D data from 2003 to 2018 reveals that these differences have persisted. The disparity in trip distances for people with low-income has decreased, while their reliance on public transit remains constant. Children tend to travel shorter distances and primarily rely on walking, cycling, or being driven by parents or caregivers.

The examination of travel behaviors serves as the foundation, shedding light on the variances in travel behaviors and mobility among various sociodemographic groups. It is complemented by the second objective, focused on exploring the accessibility of cycling infrastructure among population groups with different socioeconomic statuses. Throughout the assessment, depicted in Chapter Three, substantial disparities in accessibility to cycling infrastructure and destination accessibility were unearthed, especially in socioeconomically disadvantaged neighborhoods. From a vertical equity perspective, Montreal did not prioritize higher levels of accessibility to cycling infrastructure for the most socioeconomically disadvantaged groups relative to the other socioeconomic groups in the region. Furthermore, while residents in disadvantaged areas could generally reach more destinations within a 15-minute cycling distance, but when considering network connectivity, they could only access most of these destinations using 25% or less of bikeways. The absence of connected cycling infrastructure in these areas compelled residents to share their trips with motor vehicle traffic. Over 14 years of bicycle network expansion, network connectivity in most socioeconomically disadvantaged neighborhoods still lags behind areas with a moderate level of socioeconomic status. The typology of DAs further confirms that considerable portions of DAs with high socioeconomic disadvantage still coincided with the least bikeable areas, particularly concerning healthcare accessibility.

The third objective focused on developing a methodological framework to prioritize cycling infrastructure in areas. This objective was fulfilled in Chapter Four by introducing data-driven prioritization strategies for prioritizing future bicycle improvement projects using different intervention strategies. This quantitative framework serves as a pragmatic guide for urban planners and policy makers, aiming to improve network connectivity, enhance destination accessibility by bicycles for disadvantaged populations, mitigate disparities in access to cycling infrastructure, and encourage a modal shift from short car trips to bicycling to reduce vehicle kilometers traveled (VKT) and greenhouse gas (GHG) emissions.

The findings from this dissertation highlight four primary directions for achieving a sustainable and equitable transportation system. First, planners and policymakers need to understand the varied travel behaviors across different sociodemographic groups to provide tailored transport solutions. Given that disadvantaged groups often rely heavily on public transportation, it is essential to prioritize transit services in areas with a significant number of low-income households. Additionally, with an increasing trend of automobility among seniors, enhancing the accessibility and efficiency of public transit, including expanding routes to areas with a large senior population and incorporating features like low-floor buses which can address the unique mobility needs of seniors, to encourage seniors to opt for sustainable transportation.

Second, the observed decline in children's walking highlights the need for an integrated approach to transportation planning that prioritizes walkable environments for children. Investments, such as those made by Montreal to improve pedestrian infrastructure, are a step in the right direction. However, policies must extend beyond infrastructure to address broader concerns, including social equity. Significantly, improving walking conditions for minority and low-income children is imperative. While enhancing conditions may not drastically increase walking rates among these groups, it is essential for policies to be inclusive and responsive to the socioeconomic status of different neighborhoods, ensuring equitable access to safe walking conditions for all children.

Third, there is a clear disparity where the most socioeconomically disadvantaged groups, although having greater access to destinations, face challenges due to fragmented bicycle network. In comparison, areas with moderate disadvantages often have better accessibility. This calls for a reassessment of the metrics used by policymakers to prioritize investments. While many active transportation plans emphasize social equity, making decisions based on short-term metrics can worsen existing inequities. Regions with established cycling infrastructure will show rapid outcomes. However, underserved areas might struggle to showcase such immediate benefits due to challenges like inadequate infrastructure or safety concerns. To foster an equitable cycling environment, investments might be necessary, even if they do not yield quick results. Policymakers should recognize values of equity, accessibility, and inclusivity, understanding the long-term public health impacts and the importance of prioritizing social equity in cycling investments.

Lastly, the estimated benefits from investment prioritization strategies emphasize the need for a systematic framework for bicycle network growth. By focusing on a city-wide scale and integrating the existing network, instead of the “random growth-like” strategy, cycling investments can achieve the greatest value within budgetary limits. It is also important to integrate qualitative feedback from planners, cycling advocates, and the community on challenges faced, especially concerning equitable distribution of cycling infrastructure. These insights would enhance the quantitative findings of this dissertation.

In summary, the examination of travel behaviors, the identification of disparities in cycling infrastructure, and the introduction of a prioritization framework collectively provide a robust foundation for advancing transportation equity. They underscore the necessity of adopting an equity-focused approach in transportation initiatives, especially in the context of cycling planning and infrastructure. This approach should not only acknowledge the current state of the transportation landscape but also aspire towards a more inclusive future.

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