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The Spatial Equity of Dockless Micromobility Sharing Systems in Calgary, Canada

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Abstract

Micromobility sharing systems, including bikes and e-scooters, are often promoted as solutions to urban transportation equity challenges. Dockless micromobility sharing systems however remain understudied due in part to their novelty. In particular, there has been limited research on the spatial equity of e-scooter sharing, which concerns whether systems are equally accessible across a city regardless of the relative advantage and disadvantage of urban areas.

This thesis reports on two related analyses of the spatial equity of e-scooter sharing in Calgary, Alberta, Canada using an open dataset of three months worth of trip data (July – September, 2019): a gravity model approach to analyzing the spatial equity of e-scooter trip flows, and an ANOVA and linear regression-based comparison of the spatial equity profiles of dockless bike and e-scooter sharing. The results show that both dockless bike and e-scooter sharing in Calgary are spatially inequitable, and that there are no significant spatial equity differences between the use of dockless bikes and e-scooters.

Keywords

Micromobility sharing, dockless bikes, e-scooters, spatial equity, Calgary, gravity model, ANOVA, linear regression

Summary for Lay Audience

Micromobility sharing systems, including bike sharing and e-scooter sharing, are being adopted at a rapid rate in cities all over the world. Micromobility sharing is often seen as a fun, convenient, and affordable way of moving around the city for both recreation and for commuting purposes This is advertised to be even more true for dockless micromobility sharing systems. Dockless systems seem to be even more convenient than docked systems because instead of picking up a bike or e-scooter from a station and trying to find a station to drop off the vehicle, users only have to find a vehicle to start riding, and at the end of a ride, the vehicle can be left almost anywhere the user desires. Dockless micromobility sharing could potentially benefit a city by providing more transportation options for citizens, better transportation connections to public transit systems like buses or trains, and fun recreational opportunities. But the question of whether everyone in the city has the same opportunity to access and use available micromobility sharing services has not yet been answered. For example, if a person lives in an area of the city that is historically seen as lower income or working class, are they able to find and use a public shared bike or e-scooter as easily as people living in more advantaged areas? This is part of the concept of spatial equity, and this research centers on investigating whether dockless micromobility sharing programs which include both dockless bikes and e-scooters are spatially equitable. This research used data from Calgary's shared mobilities program, which collected data on dockless bike and e-scooter trips made from July to September of 2019. The data was analyzed using statistical techniques that help determine how differences in the relative advantage or disadvantage of different areas within the city effect the use of dockless bikes and e-scooters in order to

understand whether the micromobility sharing program in Calgary was considered to be spatially equitable.

Co-Authorship Statement

This thesis was prepared in an integrated article format. The works included in this thesis was conducted by the author with the guidance and supervision of Dr. Agnieszka Leszczynski. My contributions to the articles include the formulation of research questions, data retrieval and formatting, analysis design and execution, and lead authorship of the papers. Dr. Leszczynski's contributions to the two articles includes providing research ideas, ideas for the methodologies and study design used, and co-authorship of the articles, including assistance with manuscript architecture, writing, revisions, and improvements. The introductory and conclusion chapters of this thesis are solely my contribution.

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Chapter 1

1 Introduction

1.1 Background

Micromobility sharing, which involves the shared use of lightweight, human-driven vehicles including bicycles, electric bikes, and electric scooters, have been increasing in popularity in Asia, Europe, and even more recently, in North America, with over 1,000 cities globally having adopted a micromobility sharing system to date (Gutman, 2016). A slew of micromobility sharing companies, such as Lime (Figure 1-1), Bird, JUMP, and ofo have also emerged as a result of the adoption of micromobility sharing, creating a whole industry revolving around providing micromobility sharing services in cities. With the sudden release and adoption of these new technology-mediated[1] transportation methods, micromobility sharing systems have been touted as a solution for many urban problems including but not limited to traffic congestion, climate change, city livability, and public transportation flexibility and convenience (Ricci, 2015).

[1] Vehicles that can be located and rented via a digital app. Features such as unlocking vehicles, paying for their use, and finding docks or other points to return vehicles to and terminate a trip.

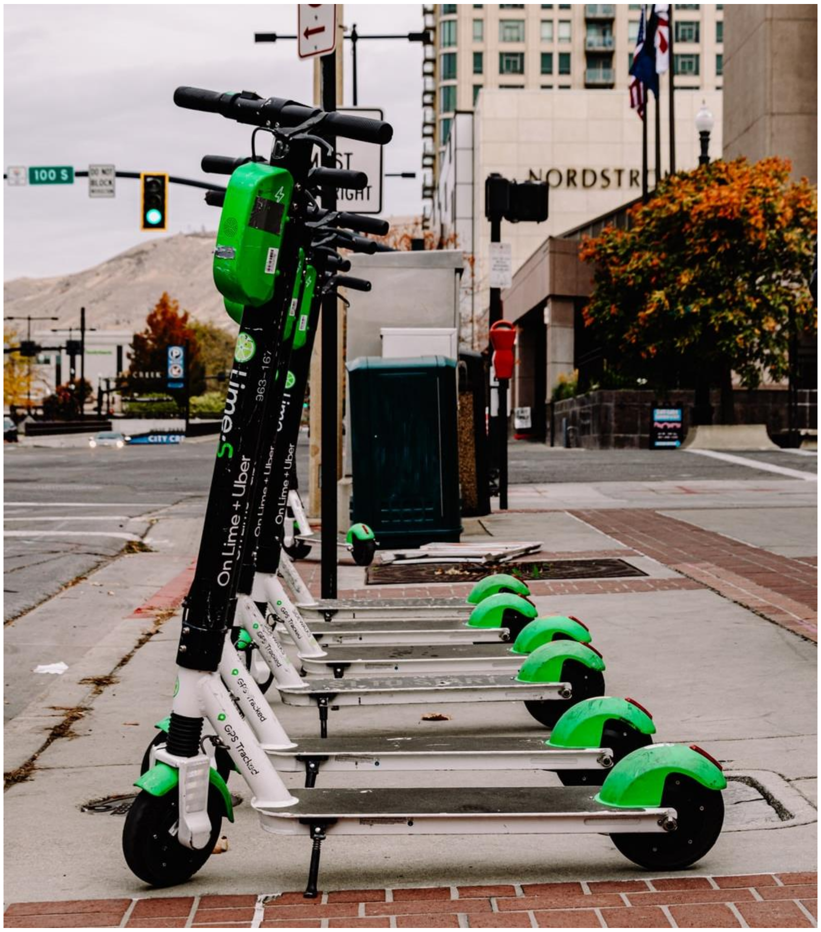

Figure 1-1. A nest of Lime dockless e-scooters in Salt Lake City, United States. E-scooters have often been advertised as a convenient and fun mode of urban transportation. *Source: Unsplash*[2]*, (Kayden, 2020*[3]*)*. Free for commercial use.

Despite the popularity of micromobility sharing systems, the impacts of these alternative transportations on cities and their populations have only recently begun to be studied. As more cities consider and implement micromobility sharing systems as a transportation option, further investigations into the impacts of these systems are required

[2] License: https://unsplash.com/license
[3] https://unsplash.com/photos/2kRjhPnX4QA

to ensure that micromobility sharing systems are a worthwhile investment for cities and citizens. This thesis specifically focuses on the concern of inequities in micromobility sharing systems and access to such services, as a contribution to the examination of micromobility sharing challenges that is of current relevance.

1.2 Research Motivations and Questions

Historically, micromobility sharing systems were developed as a utilitarian tool, with the idea originating from free-to-use White Bikes in the 1960s in Amsterdam (DeMaio, 2003). Since that time, bike sharing and the more recently developing e-scooter sharing systems have shifted away from a free micromobility sharing system, which was intended to improve transportation flexibility and accessibility for the community, and as a result has led to controversies surrounding the social impacts of modern micromobility sharing systems. For example, the demographics of bike share users show that users are often wealthier and disproportionately white (Fishman et al., 2013).

Inequities in micromobility sharing are also observed in the investments of cycling infrastructure which are also ridden on by micromobility vehicles. Areas with existing cycling infrastructure often receive continued support and maintenance, while areas with little to no infrastructure are disregarded as sites for micromobility sharing (García-Palomares et al., 2012), further exacerbating the socioeconomic inequalities in shared micromobility access and utilization. Although much of micromobility sharing research has focused on docked bike sharing due to its longer history, research on the newly emerging dockless bike and e-scooter sharing system has also suggested similar patterns of inequalities (Caspi et al., 2020).

But, as a result of the recentness of dockless e-scooter sharing systems, there has yet to be extensive research towards understanding e-scooter sharing, and even less that focuses on the spatial equity of these system. Similarly, lacking in the literature is research that features direct comparisons between bike and e-scooter sharing, especially in the contexts of equity. Further investigations and comparisons of micromobility sharing systems are essential for the understanding and future planning, utilization, and longevity of these systems.

This thesis aims to address and contribute to the understanding and research gaps in the study of micromobility sharing systems in regard to their spatial equity profiles. Specifically, this thesis poses and answers three main research questions:

1. What is the pattern of flows for dockless e-scooter usage in relation to socioeconomic profiles of origin and destination locations of micromobility trips?
2. What are the spatial equity profiles of dockless bike and dockless e-scooter sharing systems?
3. Do shared dockless bikes and dockless e-scooters differ in their patterns of usage in the context of spatial equity? Is one mode better in serving the community equitably than the other?

These questions are answered through the analysis of publicly available micromobility sharing data representing three months' worth of e-scooter and dockless bike trips collected between July 1st and September 30th, 2019 as part of the City of Calgary, Alberta's two-year Shared Micromobility Pilot Program (2018-2019).

1.3 Research Objectives

The overall objective of this thesis is to analyze the spatial equity of dockless e-scooter sharing, and compare it to the spatial equity of dockless bike sharing in a large metropolitan city (Calgary, Alberta) in order to contribute to newly emerging studies on contemporary micromobility sharing systems. As discussed above, there is a research gap in micromobility sharing research when looking at direct comparisons of different dockless micromobility sharing modes (dockless bikes and dockless e-scooters) as well as considerations of the spatial equity of these systems.

To satisfy these objectives, a combination of methods was used, including using a gravity model to estimate the effects of socioeconomic deprivation of origins and destinations of e-scooter trips, analysis of variance and Tukey's post hoc test to compare the spatial equity profiles of dockless bikes and e-scooters, and linear regression modelling to further analyze the patterns of the spatial equity of micromobility utilization.

1.4 Thesis Structure

This thesis is structured as a thesis by integrated articles, bookended by an introduction, literature review, and conclusion chapters. Chapter 2 contains a literature review of the current state of knowledge of micromobility sharing, with a focus on the spatial equity and accessibility of these systems. This chapter ends with an overview of the research gap that will be addressed in this thesis. Chapter 3 contains the first article, which aims to answer the research questions 1 and 2 by focusing on the spatial equity of e-scooter sharing in Calgary through an analysis of origin-destination flows of e-scooter trips within the city. This chapter uses the origin-destination flows to estimate a gravity model to analyze the influence of area-level deprivation as measured by the Pampalon Deprivation Index score on e-scooter utilization. Chapter 4 contains the second paper, which investigates both dockless bikes and e-scooter sharing. The second paper uses analysis of variance (ANOVA) and linear regression to compare differences in within-dockless micromobility mode spatial equity in answer to research questions 3 and 4. The final chapter of this thesis, Chapter 5, is the conclusion, which summarizes both research articles in response to the research questions, identifies how the research objectives of this have been met, discusses the limitations of the research, and identifies future directions for research.

1.5 Study Area

The study site of this research is the city of Calgary, Alberta, the fourth largest metropolitan city in Canada (Figure 1-2). In 2016, the city had a population of approximately 1.2 million people and a geographic size of 825 km^2 (Statistics Canada, 2018). The city prides itself on having the largest urban pathway and bikeway network in North America (The City of Calgary, n.d.), well suited for usage by micromobility vehicles such as shared bikes and e-scooters. Calgary was used as the focus of this research because it was the only city in Canada that, at the time of the commencement of this research, had a micromobility sharing system with publicly available trip data for analysis. A two-year Shared Mobility Pilot project (hereafter referred to as 'Pilot') was implemented in the city in the summer of 2018. The Pilot commenced with the introduction of a fleet of 500 shared dockless bicycles operated by the transportation company Lime (Krause, 2019). A year later in 2019, the Pilot added 1,500 shared dockless e-scooters with 1,000 scooters provided by Lime and 500 operated by the micromobility company Bird, alongside the 500 dockless bikes already in operation (The City of Calgary, 2019) for an initial trial period during that summer.

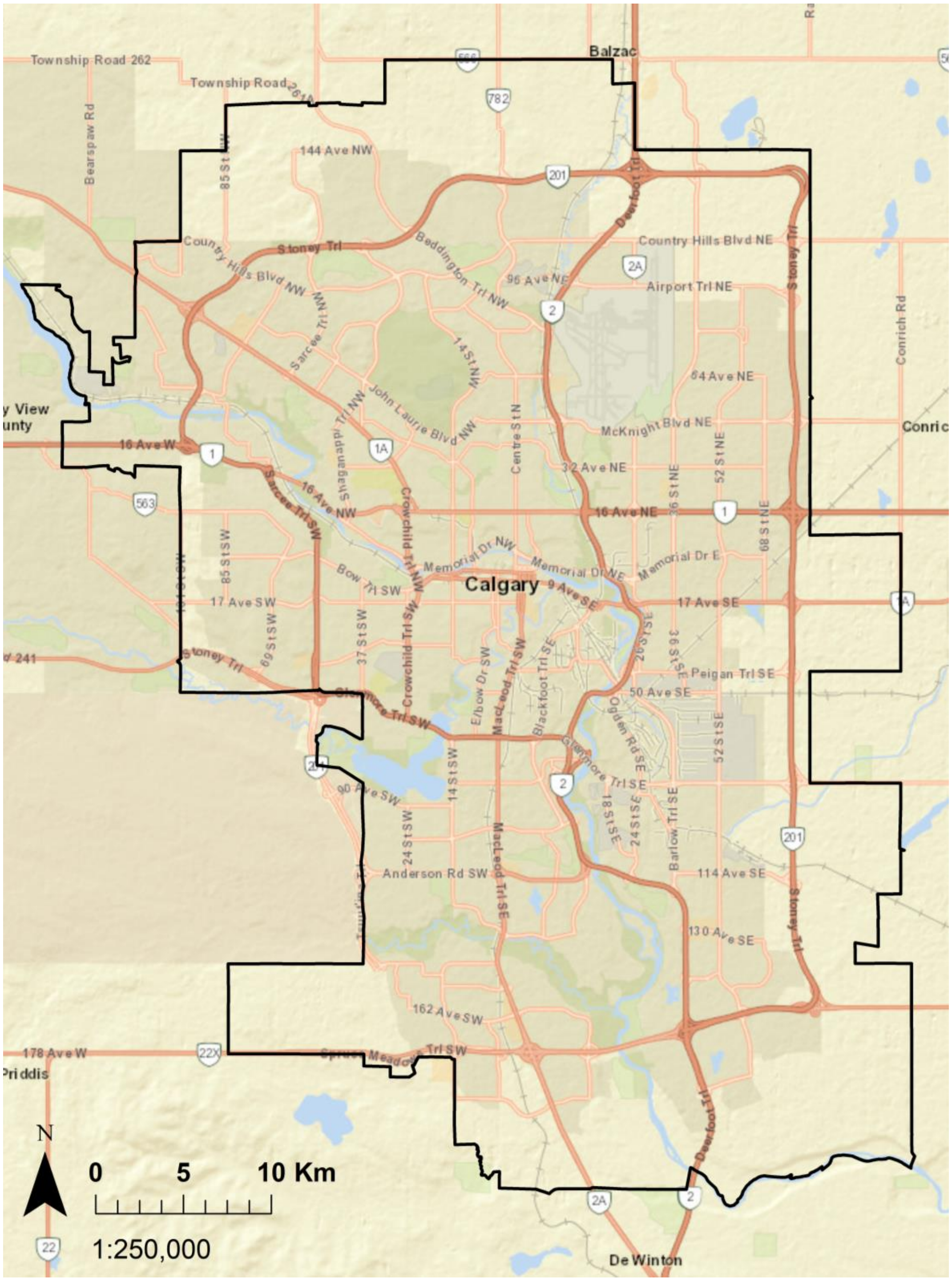

Figure 1-2. Map of the boundary of the City of Calgary. *Sources: Esri (basemap); The City of Calgary (city boundary[4])*

[4] https://data.calgary.ca/Base-Maps/City-Boundary/erra-cqp9

While other Canadian cities have also tested and implemented dockless micromobility sharing systems, this study focuses on Calgary's micromobility sharing system as it is the only Canadian city for which trip data for both scooter and bikes have been made available under an open data license. The inclusion of e-scooter and dockless bike share trips over the same geographic area (City of Calgary) within the same time period (three-month summer trial) provides a standardized spatio-temporal frame of reference for making a direct comparison of the spatial equity dimensions of shared dockless bikes versus e-scooters.

1.6 Study Dataset

The dataset used in this thesis was downloaded from Calgary's Open Data portal under an open data license.[5] This dataset represents the aggregate of all shared dockless bike and dockless e-scooter trips between July 1st, 2019 and September 30th, 2019. During this period, dockless bikes (operated by the transportation company Lime) and dockless e-scooters (operated by transportation companies Lime and Bird) were available for commuters to use around the city. As part of the city's micromobility sharing project, trip data was collected and subsequently made available for public download. The dataset contains 482,021 records, representing 464,743 dockless e-scooter trips and 17,278 dockless bike trips with the locations of trip origin and destination points generalized to 30,000 m^2 hexagonal grids. Other information provided in the dataset includes the start

[5] https://www.calgary.ca/general/terms-of-use.html?redirect=/termsofuse

date, starting hour, trip distance, trip duration, and the coordinates of the centre point of the starting and ending hexagonal grids. Some more detailed information about the dataset is summarized in Table 1-1. Methods of data manipulation and analysis are explained in the context of the two articles within this thesis (Chapter 3 and Chapter 4).

Table 1-1. Descriptives and means of micromobility sharing data from Calgary's Shared Mobilities Pilot project for July 1st – September 30th, 2019 (± standard deviation)

Data	**Bikes**	**E-scooters**
Number of vehicles in service	500 (Lime)	1,000 (Lime) 500 (Bird)
Number of trips	17,278	464,743
Average trip distance	1712.52 m (± 1812.01 m)	1851.27 m (± 1893.34)
Average trip duration	704.71 s (± 721.16 s)	773.49811 s (± 812.43 s)
Average trip speed	9.48 km/s (± 4.57 km/s)	9.70 km/s (± 5.45 km/s)

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Chapter 2

2 Literature Review

2.1 Introduction

Since the mid-2010s, there has been a rapid rise in the popularity of shared transportation services in cities around the world, include micromobility sharing systems. ‘Micromobility’ generally refers to the use of small, lightweight vehicles intended for point-to-point shorter distance trips such as trips to and from transit stops (Yanocha & Allan, 2019). Examples of shared micromobility systems include bike sharing networks, which have existed as early as the 1960s (DeMaio, 2009), and the more recent addition of electrified scooter sharing services, also referred to as e-scooters. One of the main objectives of micromobility sharing systems, including bike and e-scooter sharing, is to provide alternative means of transportation, which improves the flexibility and accessibility of transportation services for the community (Ricci, 2015). Micromobility sharing systems are often used as a last-mile solution, being integrated with the location of public transportation hubs such as train stations and bus terminals to strengthen the utilization of shared transportation modes (Fishman et al., 2015). Micromobilities have been touted as extending many benefits for urban environments, including decreased traffic congestion (Hamilton & Wichman, 2018), reduced carbon emissions (Weiss et al., 2015), and increases in physical activity levels (Shaheen et al., 2010).

The belief that micromobility sharing services are convenient to access, highly connected to other transportation modes, and safe to use drives the popularity of these systems (Barnes, 2019; Mohiuddin, 2021; Santacreu et al., 2020). However, the research has shown that these gains are not only questionable (Médard de Chardon et al., 2017), but where present, they are spatially inequitable, favouring more socio-economically advantaged enclaves across international urban contexts (e.g., Hosford and Winters, 2018; Mooney et al., 2019; Stehlin, 2015; Winters et al., 2018; Su and Wang, 2019).

Transportation equity is understood as the fairness with which the impacts of accessible and affordable transportation is distributed to all members of a community (Shaheen et al., 2017). There are two dimensions of transportation equity: social equity, and spatial equity. Social equity measures equity in terms of the demographic characteristics of utilization of a mobility mode. Spatial equity, in the context of urban transportation, describes whether transportation services and all the components related to the successful and maximized use of those services, are equally distributed and accessible across all areas of urban space, regardless of differences in their relative socio-economic statuses. For micromobility sharing services, often the spatial relationship between the socioeconomic factors and indicators are analyzed in relation to the distribution of micromobility resources, whether that may be docking stations, availability of dockless bikes and e-scooters, and/or access to related urban transportation infrastructures such as cycling lanes (Babagoli et al., 2019; Médard de Chardon et al., 2017; Zhang et al., 2017; Bachand-Marleau et al., 2012). Investigations into the spatial equity of micromobility sharing systems are vitally important as more cities implement these services and require understanding of how to maximize their equitable adoption and use.

Although the popularity and rapid adoption of micromobility sharing seemingly occurred within the past decade, instances of micromobility sharing systems have existed for several decades. The early concept of micromobility sharing was developed in the 1960s, with Witte Fietsen, or White Bikes, in Amsterdam, Netherlands. White Bikes was a free bike sharing system where white-painted bikes were placed permanently unlocked throughout the city for the public to use free of charge. The White Bikes were intended to be both an accessible mode of public transportation, as well as a traffic solution in Amsterdam's consistently congested inner city. But, due to bikes being constantly stolen or damaged, the program failed soon after its launch (Shaheen, et al., 2010). These challenges were the catalyst to developing the next generation of micromobility sharing: the coin-deposit system.

In efforts to reduce thefts and damages to the free-to-use bikes, special bike racks were used to house the bikes for pick up and returns. Users were required to make a coin deposit at a designated bike station to unlock and use a bike. Once a trip was completed, users would return the bike to the station, and receive their returned deposit. City Bikes in Copenhagen, Denmark, was the first to utilize bike stations, but maintained the original utilization purposes of the shared bikes, as the system was funded by both non-profit groups and the government, which allowed for the bikes to be used for free (with a refundable deposit). Although this second iteration reduced bike thefts, the amount of thefts that occurred was still problematic enough that the system could not be appropriately sustained. This gave rise to the third generation of micromobility sharing systems, with technologically improved docking systems and bikes.

New GPS technology allowed bikes to be tracked, credit card payments could identify users, and mobile phones could be used to unlock bikes (DeMaio, 2009). Despite the new technology, the growth of the new bike sharing system was slow. It was not until

2005 with the launch of Velo’v, and subsequently Vélib in 2007 in Lyon and Paris respectively, that the third-generation systems gained traction. Bike sharing systems were also starting to be noticed outside of Europe, with third-generation bike sharing systems being implemented in Brazil, Chile, China, the U.S., and many other countries (DeMaio, 2009). From then on, bike sharing systems grew in popularity, with around 1,000 cities across the globe having a bike sharing system in 2016 (Gutman, 2016).

The history of micromobility sharing systems continue to develop today, with new technology, infrastructure, and policies leading to the current generation of micromobility sharing systems. Dockless bikes and even e-scooter sharing are rapidly emerging as well, with major U.S.-based bike and e-scooter sharing companies like Lime and Bird being established in 2017 (Aizpuru et al., 2019), and many others aiming to expand dockless micromobility sharing internationally.

Within the history of micromobility sharing, it is important to understand that the initial implementation of micromobility sharing was a means of creating more accessible public transportation that not only benefits individuals in the community with fewer transportation options, but it also proposes a solution to transportation challenges such as traffic congestion in major cities (in the case of White Bikes, traffic congestion in downtown Amsterdam). As is the theme with current modern micromobility sharing systems, micromobility sharing companies, vehicle vendors, and systems operators propose to improve a city’s accessibility in transportation choices for all members of the community (Médard de Chardon et al., 2017). But historically, micromobility sharing systems often fall short of accomplishing equitable transportation for all. Proponents of more recent dockless micromobility sharing system argue that dockless systems are more equitable that the previous docked versions as trips can be initiated and ended anywhere, unbound from the anchors of physical docking stations that users must retrieve and return the two-wheeled vehicle to (Qian et al., 2020). With the history of the development and purposes of micromobility sharing systems described, I next turn to look at the current state of micromobility sharing research, with a heavier focus on the social and spatial equity impacts of these services.

2.2 Challenges and Barriers of Micromobility Sharing Systems

With the increasing presence of micromobility sharing systems, including docked bikes, dockless bikes, and more recently, dockless e-scooters, potential riders have the choice of using an ever-increasing number of transportation modes. Users may opt for micromobility sharing over private bikes and e-scooters to not worry about thefts and storage space for private assets (Fuller et al., 2011). Micromobility sharing operators have also claimed that the systems offer numerous other benefits including health benefits and transportation flexibility. But evidence suggests that the benefits and services provided by micromobility sharing systems are disproportionately available in the more privileged areas of a city, and are often less accessible in more disadvantaged areas. In this section of the literature review, research will be presented on the usage patterns of micromobility sharing systems as they relate to spatial and social equity.

2.2.1 Social Equity Challenges of Micromobility Sharing

Transportation systems are considered to be socially equitable if the system benefits and favours socially and economically disadvantaged groups (Rawls, 1971).

Previous micromobility sharing equity research has found that the majority of micromobility sharing users are individuals who are wealthier, younger, male, white, have post-secondary education, and own a car (Fishman, 2016; Hosford et al., 2018; Ricci, 2015; Stehlin, 2019). Lower-income users were not as common compared to the number of users who are considered to be more socially privileged and have higher incomes. Cost, lack of access to payment options (such as mobile payment and credit cards), lack of mobile data plans and smart phones (which are often required to access micromobility sharing services), and lack of knowledge of the service are also common barriers that prevent disadvantaged users from using micromobility sharing services (McNeil et al., 2018).

The appeal and perceptions of micromobilities also influence the usage of these systems. Physical infrastructures used by micromobilities, such as cycling lanes, are perceived as being intended for certain kinds of users: those who are more educated, affluent, and Caucasian (Stehlin, 2019; Hoffmann 2016). Fitt and Curl (2020) found that e-scooters appeal to a broader demographic than bicycling, although most e-scooter sharing users are young, non-disabled, and male. Similarly, Hirsch et al.'s (2019) survey analysis showed that users of Seattle's dockless bike sharing system were disproportionately young, male, Caucasian, and are more likely to own or use a bike. These research show that users of micromobility sharing systems are often more likely to be privileged populations, revealing the disproportionate usage of the system based on the demographics of users. Although if micromobility sharing was made available in lower income areas, and more easily accessible, people in those areas report that they would use the systems more often than they currently do (Wang & Lindsey, 2019; Ogilvie & Goodman, 2012).

Social equity improvements can be made by offering higher fare discounts or equity programs that support lower income riders’ use of these systems, and research by McNeil et al. (2018) has shown that with such equity considerations, those who access micromobility sharing through these programs use the services as often other (more advantaged) members. While social equity considerations are important for micromobility sharing services, the focus of this thesis research is on the aspects of spatial equity, which is discussed further below.

2.2.2 Spatial Equity Challenges of Micromobility Sharing

Spatial equity, in the context of transportation services, is usually measured by assessing the distribution of the service relative to the socioeconomic characteristics of areas. To be considered spatially equitable, the physical components of micromobility services need to be equally distributed and accessible across a potential service area. But previous research has shown that often micromobility sharing systems are not spatially equitable, and inadequately serve disadvantaged urban enclaves.

Research on the spatial equity of micromobility sharing systems is reviewed in more detail in the integrated articles presented in Chapters 3 and 4, with specific attention given to the methods used by these studies and their findings. In contextualizing these more detailed engagements with these literatures, it is important to note that the utilization of micromobility sharing systems relies in part on having well maintained and easily accessible components for shared biking and scootering in place, such as docking stations and number of available vehicles. An important spatial equity consideration of docked bike sharing systems in particular are the locations of physical docking stations. Shared docked bikes can only be accessed and returned to stations, so the locations of the stations limit how far a user can travel on a shared bike since users must also return the bikes to a station or risk incurring additional charges and penalties. So, if a person's intended destination (such as the home) is located far from any bike docking stations, making bike sharing not a viable transportation mode, and leaving certain areas inaccessible to docked bike sharing.

For instance, an analysis of the BIXI bike sharing system in Montreal shows that residing close to a bike share docking station (i.e., within 250 m from home) increases the likelihood of its use (Fuller et al., 2011), and that stations are not built in lower income areas, reducing the chance of lower income communities accessing the service. Evidence does indicate that when bike sharing systems are sited in less affluent areas, lower income residents would be the highest population of bike sharing users (Ogilvie & Goodman, 2012). These results suggest that lower income communities do utilize micromobility sharing programs if they are accessible, but operators often do not serve these communities even when the need for micromobilities is greatest by the populations living in these areas.

Hosford and Winters' (2018) study on docked bike sharing systems in five different Canadian cities also suggests that bike docking stations are inequitable placed, centering closer to the downtown cores of the cities. Interestingly though, the study found that the publicly funded bike sharing systems had higher levels of spatial equity than the privately operated systems. These studies show that bike sharing systems, and possibly e-scooter sharing systems (since both are related in service operations and inequalities), can be addressed and improved with government and public interventions so long as equity considerations are being included as the forefront of improvements to be made to micromobility sharing systems.

Compared to docked bike sharing, dockless systems (both bikes and e-scooters) can improve on spatial equity due to their dockless nature, which allows users to ride bikes and e-scooters virtually anywhere in the city without having to find and anchor trips to physically located docking stations. Docked systems rely on physical docking stations to start and end trips, and previous research has shown that docking stations are often built and concentrated in more advantaged areas, forcing users to restrict rides to within and around these areas. Without docking stations, users of dockless systems would not have to end trips at docking stations (which may be restricted to certain areas), allowing users to end trips at any desired location, improving the convenience and accessibility of the service compared to their docked counterparts. Dockless e-scooters can be more cost effective than dockless bikes, since e-scooters are often cheaper than bikes, and as a result could provide services that are lower cost.

The lower cost of e-scooters could also benefit spatial equity by allowing operators to increase e-scooter fleet size, which would allow more users to find and access e-scooters compared to bike sharing systems (Qian et al., 2020; Zhu et al., 2020). Despite these claims, dockless micromobility sharing research, although more recent and limited, also suggests that dockless systems are as spatially inequitable as previously existing docked micromobility sharing systems (Couch & Smalley, 2019). An examination of the e-scooter sharing systems in Austin, Texas and Minneapolis, Minnesota by Bai and Jiao (2020) showed that e-scooter usage is most active within and around the downtown core and at the university campuses of both cities. These areas are often considered to be higher income, more privileged, and with more attractions that bring users to those areas. Overall, it has been observed in multiple contexts that e-scooter sharing, which has been more recently developed and popularized, still continue the patterns of spatial inequalities that plague micromobility sharing systems despite their objectives and promises.

2.3 Gaps in Micromobility Sharing Research

Previous studies on micromobility sharing systems have largely examined the impacts of docked bike sharing systems as those systems are the oldest form of the service, and are still being implemented in cities today (Eren & Uz, 2020; Ma et al., 2020). Limited research has also examined the impacts of dockless bike sharing in terms of the spatial usage and equity patterns (Han, 2020; Shen et al., 2018; Mooney et al., 2019). The more recently adopted e-scooter sharing systems have had research that focused on their health (Glenn et al., 2020; Trivedi et al., 2019; Puzio et al., 2020; Babagoli et al., 2019), environmental (Severengiz et al., 2020; Moreau et al., 2020), and policy (Bozzi & Aquilera, 2021; Riggs et al., 2021; Zhang & Guo, 2021) implications, but more research on the spatial equity impacts of e-scooter sharing is limited in the field (Caspi et al., 2020). Also sparse are research that compares different modes of micromobilities, particularly dockless bikes and e-scooters.

There has been limited research that directly compares the two dockless micromobility modes, but few of these studies compare the spatial equity dimensions of both systems. As e-scooter sharing becomes more incorporated into urban transportation frameworks, it is important to know if there are within-mode equity differences between different dockless micromobilities. This knowledge is important for urban planners, policy makers, and micromobility operators because as more cities adopt micromobility sharing systems, there needs to be information provided to stakeholders of the equity concerns of micromobility sharing systems, especially when there are some areas in the city that may not be utilizing these services. As a result, the relevant stakeholders can be informed of where to place more shared vehicles (i.e., bikes and e-scooters) in order to maximize the utilization of the system for the most amount of people, especially those who have been deprived of micromobility sharing options.

Pilot programs that test the feasibility and uptake of micromobility sharing systems are commonly implemented for a brief period in a city, with spatial equity rarely considered in the pilot testing phase (Palm et al., 2020). Yet the results of pilot programs inform decisions about how to proceed with a system such as whether the system stays permanent and what the service area of operations will be. Spatial equity analysis information of the pilot programs can help inform the decision making about how and where to expand its service to ensure that it is spatially equitable in future proceedings of the program (such as in the next stages of the program, or as it is made a permanent service). This can ensure that historically disadvantaged areas are not re-disadvantaged by being precluded from enjoying the potential benefits of new transportation innovations, such as dockless bike and e-scooter sharing systems.

E-scooters require concerted analysis because they are advertised as a contemporary transportation mode with a uniqueness that calls community users and tourists alike to ride not only for commuting purposes as with shared bikes, but also for casual and recreational activities. E-scooters are lighter and therefore more easily distributed into new and/or targeted areas. The purposes of e-scooter sharing trips may be different from bikes, and may show different usage patterns. Similarly, with dockless systems being a more recently developed than docked systems, more research is required to identify whether the proposed benefits of dockless systems are in fact manifesting or whether dockless systems continue to show similar patterns of spatial inequity. Also absent in micromobility sharing research is an abundance of research in the Canadian context, which is distinct from the American context with fewer large cities. Dockless micromobilities have also been more recently adopted in Canada compared to elsewhere in the world such as the U.S., China, and Europe.

The rest of this thesis follows into two article-based analyses that addresses these research gaps in micromobility sharing research. Chapter 3 presents an analysis of the spatial equity of e-scooter sharing in Calgary, a field that is currently limited in research in part due to the recentness of e-scooter sharing systems. Chapter 4 presents a comparison of the spatial equity of dockless bikes and e-scooters in Calgary. Previous research has compared dockless e-scooters and docked bike sharing systems (Younes et al., 2020; McKenzie, 2020), but currently, there is limited research that directly compares dockless bikes and e-scooter sharing systems within a common spatial framework, such as that of the same city.

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Chapter 3

3 E-Scooter Spatial Equity: An Analysis of Dockless Scooter Sharing in Calgary

3.1 Introduction

Since the mid-2010s, there has been a rapid rise in the popularity of micromobility sharing systems in cities around the world. ‘Micromobility’ refers to the use of small, lightweight vehicles intended for point-to-point short distance trips such as those to and from transit hubs (Yanocha & Allan, 2019). Most recently, there has been a proliferation in dockless micromobility sharing, which includes dockless bikes and electrified or ‘e’-scooters. Because dockless systems do not rely on fixed stations, such as shared bicycle docks, to anchor micromobility vehicles to predetermined trip origin and terminus locations, they have been touted as having the potential to “bridge the existing transportation divide” in micromobility sharing between advantaged and disadvantaged social groups, as well as between socioeconomically affluent and deprived neighbourhoods (Kim et al., 2019: p263). Dockless systems specifically do not require expensive expansion of infrastructure (e.g., siting more bike racks) to be made more equitable (McCarty Carino, 2018). Funds saved from building docking infrastructure may be used towards putting more shared vehicles into circulation, stepping up redistribution efforts to ensure that all areas of a city are equally served by the system, or by reducing the costs of ridership (McCarty Carino, 2018). Yet how well these potential equity gains are realized for e-scooter sharing systems remains understudies.

This paper presents the findings of a spatial equity analysis of electrified scooter sharing in Calgary, Alberta, the fourth largest city in Canada. In the context of micromobility sharing systems, spatial equity refers to the equitable spatial access to and distribution of the service and its components—such as docking infrastructure and shared vehicles—across a city's areas irrespective of differences in the relative advantage and disadvantage between them (Hosford & Winters, 2018). Using a publicly available open dataset representing three months' worth of e-scooter trip data collected as part of the City of Calgary's two-year Shared Mobility Pilot Project (2018–2019), this study reports on the spatial equity of e-scooter utilization. This analysis of utilization takes into account the relative socioeconomic characteristics, or deprivation, of the locations from which e-scooter trips originate and in which they end, improving upon previous studies of micromobility sharing which have foregrounded access to vehicles at trip origins (as proxied by docking station or dockless system rebalancing locations) as a sole determinant of spatial equity. To account for both trip origin and terminus locations in assessing the spatial equity profile of e-scooter sharing, this study uses a gravity model approach to analytically identify patterns of e-scooter trip flows based on differences in deprivation profiles of the origin and destination locations of individual trips taken between July–September 2019, the three-month period for which data is available. If e-scooter sharing in Calgary during July–September 2019 was spatially equitable, then the model will indicate that differences in area-level deprivation at trip origin and destination location had no influence on e-scooter trip volume during the three months of data capture.

This paper begins with a review of the literature on micromobility sharing systems, with a focus on the methods used in a number of key studies. This leads into a discussion on the gravity model and its use in micromobility research, followed by a presentation and discussion of the analytical findings.

3.2 Literature Review

3.2.1 E-scooters, Micromobility Sharing, and Spatial Equity

Scooter sharing—which involves the public shared use of a fleet of dockless electric scooters—initially gained momentum in 2017 with the emergence of two major scooter sharing companies, Lime and Bird (Kolodny, 2017). Since then, over 100 cities worldwide have adopted a scooter sharing system and over 10 million scooter trips have been taken to 2018 (Hawkins, 2018). Despite the recent emergence of e-scooter sharing, it remains an understudied mode of urban transportation. The limited research to date has overwhelmingly focused on e-scooter injury and public health impacts (e.g., Aizpuru et al., 2019; Badeau et al., 2019; Mitchell et al., 2019; Basky, 2020; Siman-Tov et al., 2016; Trivedi et al., 2019), and to a lesser extent regulatory, environmental, and urban governance concerns (e.g., Anderson-Hall et al., 2019; Gössling, 2020; Hollingsworth et al., 2019; Johnston et al., 2020; Moreau et al., 2020; Severengiz et al., 2020; Weiss et al., 2015). Where the spatial dimensions of e-scooter sharing have been examined, preliminary spatiotemporal analyses of e-scooter data have examined the spatial extent of e-scooter service areas, and identified temporal patterns of use (e.g., McKenzie, 2019; Younes et al., 2020). However, what has not yet been substantially attended to are the spatial equity dimensions of e-scooter sharing.

Spatial equity may be understood as an indicator of whether micromobility infrastructures and assets are equitably distributed between neighbourhoods characterized by different levels of privilege, as measured by their socioeconomic statuses in urban spatial hierarchies. Spatial equity is often determined based on the spatial relationship between the deprivation profile of urban enclaves and the distribution of mobility assets across a sharing network (Babagoli et al., 2019; Médard de Chardon et al., 2017; Zhang et al., 2017; Bachand-Marleau et al., 2012). Spatial equity provides an indication of differences in where mobility resources and infrastructures may be accessed, which often has a circumscribing effect on utilization demographics (often referred to as social equity).

The equity profile of a micromobility network is key to understanding whether increases in personal transportation options, flexibility, and efficiency represented by the addition of micromobilities as another transportation option in cities are equally accessible by all members of an urban community irrespective of whether they live (McNeil et al., 2018; Howland et al., 2017; Johnston et al., 2020). However, analytical research has only very recently begun to assess whether dockless micromobility systems' potentials for equalizing spatial inequalities in alternative modes of urban transportation are being realized in cities. These studies have emphasized dockless bike sharing over scooter sharing due largely to the comparative recentness of e-scooters. Mooney et al. (2019) for instance analyzed the spatial equity of dockless bike sharing in Seattle, WA. In their study, bike share usage measures, such as the number of bikes available and the average number of days a bike went unused, were reported at the neighbourhood level. Through analyzing the locations to which bikes were rebalanced (or redistributed) by system operators, the researchers found that areas with higher dockless bike availability were characterized by higher socioeconomic factors, including higher median incomes, and more college-educated residents.

In a direct comparison of dockless and docked micromobility sharing systems, Lazarus et al.'s (2020) investigation of the JUMP dockless bike pilot program in San Francisco found that dockless bikes had a far wider service area compared to GoBike, San Francisco's docked bike sharing system. Whereas docked bike share usage was concentrated in the central business districts, dockless bike share usage was observed to be more spread out, with more trip origins and destinations observed in neighbourhoods surrounding the central business districts (CBDs). This suggests that dockless bike sharing can serve the demand for transportation options outside of CBDs more so than docked counterparts, potentially improving the equity of spatial access to micromobility sharing.

Research attentions have more recently begun to engage the implications of e-scooters as a more novel, distinct mode of dockless micromobility. An important analysis of the spatial dimensions of shared e-scooter use by Arnell (2019) focused on scooter sharing in Nashville, Tennessee; San Diego, California; and Portland, Oregon. Using multivariate spatial regression analysis, Arnell (2019) found that fewer trips were initiated in more marginalized communities in Nashville and Portland. Furthermore, the study found that e-scooters were rebalanced (moved from one location to another by systems operators) to areas with high employment density and CBDs. While the study makes no definitive claims as to the spatial equity profile of e-scooter sharing in the three cities, the results suggest that scooter sharing programs emphasize serving areas characterized by high densities of population and employment opportunities over and above providing alternative transportation modes to all communities both within and outside the central business districts.

In addition to studies deploying surveys to assess social inequities in e-scooter sharing, which emphasize barriers to micromobility sharing access experienced by marginalized communities and demographics over spatial concerns (e.g., Sanders et al. 2020), a further source of e-scooter equity research comes from investigative reports on such services, often produced by organizations that are commissioned to research mobility services by policy makers and government officials. One such report by Fedorowicz et al. (2020) focused on new mobility equity in mid-sized American cities. New mobilities in this context refers to on-demand forms of transportation such as car sharing, ride sharing, bike sharing, and e-scooter sharing, although this report focuses mainly on addressing equity concerns of e-scooters. Data from this report came from interviews with transportation and equity representatives from various planning organizations and reviewing the transportation plans in 10 different medium-sized cities across the US. Study participants acknowledged that existing barriers, such as infrastructure gaps and inadequate funding, limit new mobility technologies' equity potentials. They identified that beyond equity in new mobility sharing simply being a question of access, historically underinvested-in urban neighbourhoods are less likely to have the pre-existing infrastructure, namely cycling infrastructure such as bikeways, necessary to support utilization of new mobilities (Fedorowicz et al. 2020).

These findings are consistent with the previous research that suggests micromobility sharing disproportionately serves city centers (e.g., Médard de Chardon, 2019; Stehlin, 2015; Qian et al., 2020; Matthew et al., 2019), despite the need for them to service the urban fabric as a whole. These micromobility research studies also showcase different methods of analyzing micromobility data to assess dimensions of the spatial equity of these systems, including spatial multivariate analysis (Arnell, 2019), negative binomial modelling (Bai & Jiao, 2020), surveys (Sanders et al., 2020), and qualitative interviews (Fedorowicz et al., 2020). This study, however, departs from these methodological antecedents and instead operationalizes a spatial gravity model approach to measuring spatial equity sharing in Calgary. The gravity model is an appropriate tool for analyzing origin-destination flows of transportation modes such as e-scooters, and for establishing relationships between these flows and additional factors such as distance and socioeconomic indicators.

3.2.2 Gravity Model in Transportation Research

The gravity model is a statistical approach that provides an analysis of spatial flows by calculating the probability of the interaction of flows between origin and destination points in space (Kincses & Tóth, 2014). The interaction is based on the inverse distance between the points, where points that are closer together have higher probability of interaction than points that are further apart. Although other conceptualizations of distance can be used in the gravity model instead of distance decay (as described in papers such as Brun et al., 2005; Mikkonen and Luoma, 1999; and Wilson, 1971), for the purposes of this research, the classical approach of the gravity model (using distance decay) will be used for the subsequent gravity model analysis.

The gravity model approach was originally described in 1885 (Ravenstein, 1885), although contemporary uses of the model in social sciences is based on the demographic gravitation equation, an adaptation of Newton's law of gravity as described by Stewart (1948) via the formula:

$$F_{12} = G \cdot \frac{N_1 N_2}{d^2{}_{12}} \qquad \mathbf{1}$$

Where F_{12} is the demographic force and is left to be defined based on the research, G is a constant of proportionality and is left for future determination, N_1 is the demographic size of group 1, N_2 is the demographic size of group 2, and d_{12} is the distance between group 1 and 2.

Stewart's (1948) demographic gravity equation serves as the basis for understanding of gravity model approaches across domains of application in the social sciences. The most frequently encountered use of this technique has its origins in the domain of international trade between countries, where the gravity model posits that the trade flows between two countries can be modeled and predicted by using the economic masses of two countries and the spatial distance between them (Rodrigue et al., 2013), similar to Newton's law of gravity. The basis for the gravity mode of international trade can be described as (Isard, 1954):

$$F_{ij} = G \cdot \frac{M_i M_j}{D_{ij}} \qquad \mathbf{2}$$

The equation surmises that the relationship between the trade flows of two countries (F_{ij}) is directly proportional to the economic sizes of both countries (M_i and M_j) and inversely proportional to the distance (D_{ij}) between those countries, as well as proportional to a constant of proportionality (G) which in the case of trade relations can represent overall factors that influence global trades such as trade treaties and global gross domestic product, and can be adapted to what the model is analyzing. For example, if global trades are restricted due to circumstances beyond country-specific influences, the constant in the trade flows gravity equation can represent such restrictions, depending on the specific goals of the gravity model. The gravity model can be used identify the influence of factors on a response, such as the influence of GDP on trade flows. It can also be adapted to predict flows and interactions between two subjects, for instance, the trade flows between countries, human migration patterns, and the volume of traffic flows. This is the basis of the gravity model, and various applications and modifications have been made to this model for specific analyses.

A different approach of visualizing the gravity model is in the logarithmic form (shown as Equation 3), where both sides of the equation are logged. This form of the equation is beneficial for analysis because it allows for a simple linear regression to be run on the logged terms, and it is the basis for the gravity model analysis run in this study. The formula can be described as (Shepherd et al., 2019):

$$log\, X_{ij} = c + b_2\, log\, GDP_i + b_2\, log\, GDP_j + b_3\, log\tau_{ij} + e_{ij} \tag{3a}$$

$$log\tau_{ij} = log\left(distance_{ij}\right) \tag{3b}$$

Where X_{ij} represents the trade flows between country *i* and country *j*, GDP is the gross domestic product of country *i* and country *j*, τ_{ij} represents the trade costs between the two countries, distance is the geographical distance between countries *i* and *j* (which is a proxy for trade costs between countries), and e_{ij} is a random error. The regression constant is represented by *c*, and *b* represents coefficients that need to be estimated (also known as the estimated coefficients).

The estimated coefficients reflect the relationship between the independent variable and the dependent variable(s) depending on the magnitude and direction (i.e., positive or negative sign) of the relationship between them (Shepherd, et al., 2019). The regression constant is the value of the response (for example, trade flows between two countries) when the independent variables are 0. The model applies a logarithmic function to the variables in order to allow the results of the model to be interpreted as a rate of change, i.e., a one unit change in the independent variable can represent a percentage change or a measured value change in the dependent variable based on the estimated coefficient depending on the parameters set for the generation of the model (Shepherd et al., 2019). For example, a one percent increase in a country's GDP can lead to a percentage change in the trade volumes between a pair of countries. The estimated coefficient values and strength of the model are determined from the dataset that is used to develop and calculate the model.

Gravity modelling has two main purposes. It may be used to establish the strength of relationships between independent and dependent values through the estimated coefficients calculated for the model. It may also be used to generate an equation—or model— that can be used to predict the values of dependent variables when applied to new data. For instance, if a model was created from the data of trade flows between European countries in 2015 to analyze the relationship between country GDP and trade flows, and the model was shown to be strong (predicted the trade flows within a desired range of accuracy), then the same model could be used to predict the trade flows between European and non-European countries based on their GDPs.

Beyond the domain of trade, the gravity model has been applied to other types of bilateral flows including migration, foreign investment, traffic, and, most importantly for this study, transportation. In the context of transportation, the dependent variable being investigated is usually the transportation flows between two areas, and researchers often look at variables that can influence the volume of transportation flows, such as the number of points of interest at the origin and destination locations, and the distance between the origin and destination locations. Depending on the motivations of the research, other possible influences (e.g., land use types, road network connectivity, or average income) may be included in the model to provide a better understanding and prediction of transportation flows between areas. This also shows how the premise of the gravity model can be applied to numerous applications involving interactions between two locations.

In a particularly relevant transportation study involving mobility-as-a-service (MaaS), which includes peer-to-peer ride sharing, car share, and micromobility sharing services, He and Chow (2021) analyzed the origin-destination patterns of shared vehicle trips in Chicago. Citing privacy concerns, MaaS operators often publish very limited or highly generalized data. Using data for trips taken in a number of MaaS modes including shared-ride vehicles, micromobilities, and public transit, He and Chow (2021) used a gravity model to predict single-modal trips by estimating the origins and destinations of MaaS trips to provide a better indication of MaaS travel patterns city-wide. The resulting model accurately predicts origin-destination patterns of these MaaS services, and suggests that the model can be used to help inform future transportation planning.

The gravity model has also been applied to specific micromobility sharing systems such as bike sharing. Zhang et al. (2018) aimed to produce a gravity model to predict shared bike distribution patterns using data from the bicycle sharing system in the City of Ningbo in East China. Their gravity model described the attraction between origins and destination zones, reflected as the volume of shared bike trips between shared bike docking stations. It assumes that the number of trips between any two locations is proportional to the total number of trips produced at the origin location and the number of attractions at the destination location, and inversely proportional to the impedance of travel between zones, such as distance and traffic volumes. Using these factors and data from the city’s bike sharing system, the researchers produced and tested a gravity model that accurately reflects the relationship between the number of trips between two stations. Predicted origin-destination matrix values produced by the gravity model were tested against real bike sharing trip data in the city, and the model was shown to be accurate in predicting trip volumes between bike docking stations. This study utilized the gravity model to produce a formula that predicts docked bike sharing distribution, which can be used by governments and bike sharing operators to identify areas that may require more bikes and bike stations to keep up with demands.

Another example of the gravity model being used for micromobilities comes from a study in Shenzhen, China by Li et al. (2021), who produced a gravity model to infer the purposes of dockless shared bike trips. Data for this study came from multiple datasets characterizing origin and destination locations including points of interest (POIs) of destination locations, and real-time bike trip data from five different bike sharing operators (Mobike, ofo, Bluegogo, Ubike, and Xiaoming Bike). The researchers used the gravity model to infer nine types of trip purposes: home, work, transfers to other transportation modes, dining, shopping, recreation, schooling, life services such as banking and post office, and medical. Further comparing the impacts of different factors on dockless bike share trips, Li et al (2021) found that shorter distance bike trips were more likely to be used to connect users directly from homes to workplaces rather than connecting them to transit hubs for commutes in the suburbs. The models generated from this study can help to predict and inform demand for bikesharing services as well as to optimize connectivity between different transportation modes.

Notwithstanding these studies demonstrating the utility of the gravity model for studying bike sharing, the gravity model has not similarly been applied in studies of e-scooter sharing. Compared to shared bikes, e-scooters have different patterns of use. Scooters are intended for shorter trips compared to shared bikes (McKenzie, 2020; Yanocha & Allan, 2019), and enjoy an appeal of uniqueness that attracts both community users and tourists to ride scooters for recreation and commuting purposes (Espinoza et al., 2019; McCarty Carino, 2018). Scooter sharing also requires analytic evaluation to determine whether the spatial inequities that characterize other modes of micromobility sharing similarly apply to e-scooters, or whether scooter sharing demonstrates a more spatially equitable mode of transportation compared to other emergent short-hop modes of transportation.

To close this research gap, this study employs the gravity model to assess the spatial equity of e-scooter sharing in Calgary, Alberta, Canada between July-September

2019. Rather than using this approach to predict future flows, it instead uses the model for its sensitivity to influences of various factors—here, areal deprivation as a measure of relative socio-spatial advantage and disadvantage at trip origin and terminus locations—on the volume of flows of e-scooter trips taken during this three-month period of data availability. Using the gravity model, e-scooter sharing in Calgary during the period of data availability will be determined to have been equitable if the estimated coefficients show was that there was no significant impact of differences in area-level deprivation at trip origin and destination locations on e-scooter trip flow patterns.

3.3 Data, Methods, and Analytic Rationale

3.3.1 Study Area and Context of Micromobility Sharing

Calgary is the largest city by population in the province of Alberta, and is the 4th largest city in Canada. It is home to 1.2 million within a roughly 825 km^2 area (Statistics Canada, 2018). The city features the largest bicycling path network in North America, which is also well suited for shared e-scooters (The City of Calgary, n.d.a). On July 16, 2018, Calgary implemented a two-year Shared Mobility Pilot Project (hereafter referred to as 'Pilot') that started with a fleet of dockless shared bicycles provided by the commercial operator Lime (The City of Calgary, 2019). Fifteen hundred (1,500) shared electric scooters were added to the Pilot in July 2019. Calgary's scooter share services are currently owned and operated by two commercial operators: Lime (dockless bikes and scooters) and Bird (dockless scooters) (Krause, 2019; Lo, 2019). Calgary is currently the only Canadian city that has publicly released trip data for both shared bikes and scooters under an open data license.

3.3.2 Dataset and Data Processing

Trip data was accessed online from Calgary's Open Data portal (Calgary Open Data, 2019). The original dataset represents 482,021 shared dockless scooter and bike trips taken between July 1st, 2019 and September 30th, 2019 (The City of Calgary, 2019). The published dataset excludes trips lasting less than 30 seconds or 100 meters, as well as trips where the geospatial data quality made it unsuitable for analysis (The City of Calgary, 2019). The start and end location of each trip is provided in the dataset, generalized to 30,000 m^2 (0.03 km^2) hexagonal bins (hexbins) that tile the city. The latitude and longitude coordinates for the start and end points of the trips represent the centroid of the corresponding hexbin. Other information in the dataset includes the trip start date, day of the week for the trip start, start hour, trip duration in seconds, and trip distance in meters.

Post data retrieval, further filtering was carried out in advance of analysis conducted as part of this study. This included removing bike trips and excluding scooter trips over two hours in duration, as it is likely that these trips are not genuine trips due to e-scooters' limited battery life, which permits trips of up to two hours on a single charge (Marshall, 2018; McKenzie, 2019). Trips starting or ending outside of the City of Calgary boundary were also excluded in order to contain the analysis within the bounds of the city. E-scooter trips were also filtered based average trip speed, determined by using the recorded trip distance (meters) and the recorded trip duration (seconds). The City of Calgary has upper speed limits of 20 km/h for the shared e-scooters physically in place within the e-scooter programming (Potkins, 2019), so any e-scooter trips with an average speed higher than 20 km/h are likely not genuine trips or have inaccurate data unfit for analysis. Trips that originated or were terminated in dissemination areas with no calculated Pampalon Deprivation Index score (detailed further) were also excluded from the analysis. Similarly, for the purposes of the gravity mode (detailed further), trips with a calculated distance of 0 (i.e., e-scooter trips that start and end in the same hexbin) were also excluded from analysis. As trips beginning and ending within the same hexbin have a maximum linear distance of 214.9m (the long diagonal of a 30,000m^2 hexbin), or approximately one-tenth of the average e-scooter trip distance reported in other studies (McKenzie 2019), it is rationale to assume that these do not represent legitimate e-scooter trips. It is instead more likely that trips beginning and ending in the same hexbin may represent either erroneous data, or abandoned trips (where a rider may have initiated a trip but changed their mind about riding the scooter, and terminated it in the location of origin).

3.3.3 Measuring Deprivation

This analysis uses the material component of the Canada-specific Pampalon Deprivation Index (PDI; Pampalon et al., 2012) as a proxy indicator of the relative socioeconomic advantage and disadvantage of areas in the City of Calgary. The PDI is an area-based measure of material deprivation in Canada determined by a principal component analysis of Canadian census variables (Pampalon et al., 2012), and is calculated for Dissemination Areas (DAs), the smallest unit of census geography for which census data are disseminated (Statistics Canada, 2015). Three socioeconomic indicators inform the calculation of a quintile score representing the level of deprivation for each DA ranging from the least deprived (PDI = 1) to the most deprived (PDI = 5) (Institut National de Santé Publique du Québec, 2016): 1) the proportion of persons without a high school diploma; 2) average personal income; and 3) the employment-population ratio (Pampalon et al., 2012). The area-level PDI scores for 2016 (most recent Canadian census for which data has been published) were downloaded from the Institut National de Santé Publique du Québec website[6] and spatially joined to DA census geometries downloaded from the Statistics Canada Dissemination Area Boundary Files online catalogue[7]. This yielded a spatial data layer of DAs (clipped to the City of Calgary) populated with a PDI score attribute. Figure 3-1 shows the City of Calgary mapped by its DA-level geography of deprivation.

[6] https://www.inspq.qc.ca/en/expertise/information-management-and-analysis/deprivation-index/deprivation-index-canada-2016

[7] https://www150.statcan.gc.ca/n1/en/catalogue/92-169-X

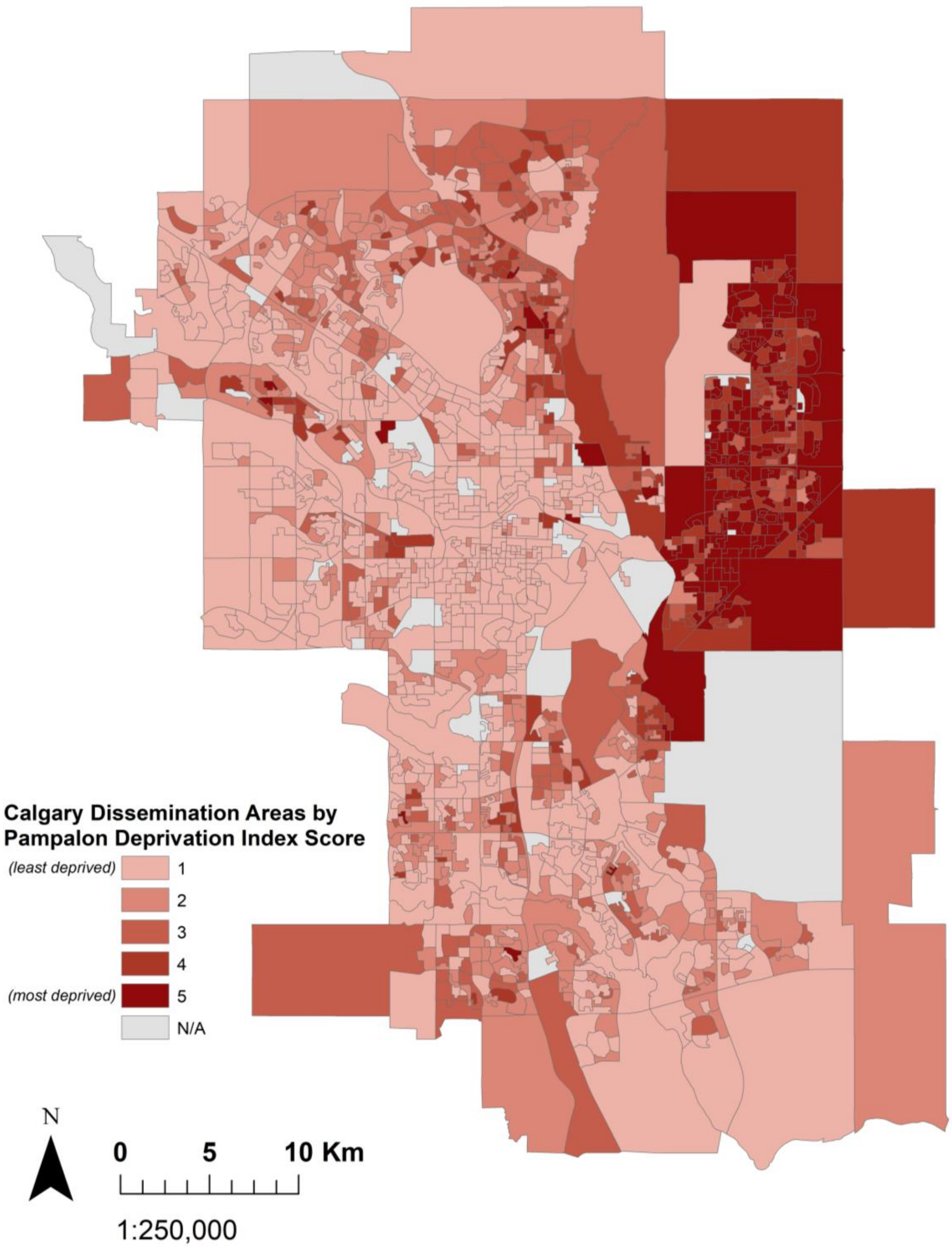

Figure 3-1. Calgary Dissemination Areas (DAs), colour-coded by their Pampalon Deprivation Index score (PDI). A PDI score of 1 represents membership in the least deprived (most advantaged) quintile while a PDI score of 5 represents membership in the most deprived (least advantaged) quintile. This represents the distribution of PDI scores across the city of Calgary.

3.3.4 Analysis

To determine the deprivation score for trip origin and end locations for e-scooter trips taken during the three months of July-September 2019, the Pampalon Deprivation Index (PDI) scores for each DA were spatially joined to the hexbin centroid point locations approximating trip origins and terminuses. Hexbin centroids were considered to have the same deprivation score as the DA that the point spatially intersected with. This associated the deprivation quintiles with start and end locations for all trips. Each hexbin in the dataset has an associated grid ID, so this ID was used to generate an origin-destination table consisting of each unique origin and destination pair (i.e. each unique trip, which are generalized to 30,000 m^2 hexbins), the deprivation quintile classification of the originating hexbin, the deprivation quintile classification of the terminating hexbin, the Euclidian distance between each unique pair's hexbin centroid in meters, and the number of trips made between each pair of hexbins.

The gravity model requires that all non-dummy variables have values above 0 in order to be calculated. Non-dummy variables are those that do not take a binary value of only 0 or 1 to indicate one of only two possible outcomes of a categorical variable such as being inside or outside of a spatial boundary. As explained in the data processing section above, trips that were shown to start and end in the same hexbin were calculated to have a trip distance of 0. Although there are possible reasons for trips beginning and ending within the same hexbin, due to the dataset being generalized to 30,000m^2 hexbins, there was no way to confidently disseminate further information about trips starting and ending within the same hexbin. However, it is rational to exclude these trips on the basis that it is unlikely that these data represent trips actually taken. Round trips that return to the origin location would likely be reported as two separate trips since the service charges users based on increments of time. If a user takes an e-scooter for a round trip (e.g., from home to work or school), users will likely end the trip at the destination rather than leave the e-scooter on to not incur additional fees while undertaking business at the destination. Furthermore, it is unlikely for trips to be contained within a single hexbin (never crossing into neighbouring hexbins) as any such trips would represent travel over a maximum linear distance of 214.9m (the long diagonal of a 30,000m^2 hexbin i.e., from the centroid to a corner of a hexagon/hexbin), or approximately one half of the average e-scooter trip distance reported in other studies (McKenzie 2019). In this latter scenario, it is rational to assume that these trips may represent either erroneous data, or abandoned trips (where a rider may have initiated a trip but changed their mind and terminated the trip at or very near to the trip's origin location within the same hexbin). Since 'flows' cannot be captured starting and ending at the same point (because there is no calculated distance for those trips, and thus no transportation flow), these data points had to be removed to execute the processing of the gravity model.

After filtering the data with the parameters described, a total of 122,743 trips were removed from the dataset, for a final dataset of 359,278 e-scooter trips to be analyzed. Once these additional trips were removed from the dataset, trip origin and destination locations were first used to populate an Origin-Destination (O-D) matrix based on the PDI scores of the origin and terminating hexbins. This was used to describe the raw volume of trips between areas based on deprivation score. Next, to analyze the effects of PDI score on the distribution of e-scooter trips, the O-D matrix formatted data was used to calculate a gravity model to determine the effects of the deprivation profiles of origins and destination points on the flows of e-scooter trips. Using the identified matrix of 89,289 unique O-D pairs (which includes data for the PDI scores of the trip origin and terminus hexbins, the distance between the two hexbin centroids, and the volume of trips made between the hexbin pairs), a log-linearized gravity model was calculated using the open-source software *R* to analyze the O-D pairs dataset, generating output expressed in terms of the percent change in the dependent variable resulting from changes in the independent variable.

For the model, e-scooter trips between origin and destination points were defined as the dependent variable, while distance, trip origin PDI score (Origin PDI) and trip terminus PDI score (Terminus PDI) were included as independent variables in the model. The model for this analysis can be described by the equation:

$$log\, X_{od} = b_1\, PDI_o + b_2\, PDI_d + b_3\, log\tau_{od} + e_{od} \qquad \textbf{4}$$

Where X_{od} represents the volume of e-scooter flows between the origin and destination, PDI_o is the PDI score of the origin location, PDI_d is the PDI score of the destination location, τ_{od} is the distance between the two locations, b represents the estimated coefficients for the three terms of the model, and e_{od} is the random error term. The PDI score terms are not logged because PDI score is not a continuous variable, unlike distance, so it is instead modelled as a percent change of the number of e-scooter trip flows for each increase in PDI score.

The gravity model used the O-D matrix data to formulate a model that analyzes the number of scooter trips between origin and destination locations based on the impact of the trip distance, starting location PDI score (Origin PDI), and ending location PDI score (Terminus PDI). For the purposes of this analysis on spatial equity patterns in e-scooter sharing in Calgary, the results of the model that are of significance is how changes in the PDI score of the origin and terminus location of e-scooter trips impact the volume of trips. In this case, if e-scooter sharing in Calgary is spatially equitable, then increases in deprivation score (from less to more deprived) for the origin and terminus locations would not have a significant impact on the volume of trips between locations. This result would be reflected in the gravity model coefficients for the explanatory variables of Origin PDI and Terminus PDI being identified as non-significant.

3.4 Results and Discussion

3.4.1 Spatial Equity of E-Scooter Utilization: Summary Findings

Of 359,278 scooter trips taken within the City of Calgary during the data collection period, there was a total of 89,289 unique pairs of trip origin and destination locations (e-scooter trip origin and destination point locations are summarized to 30,000 m^2 hexbins). For descriptive and analytical purposes, these pairs were used to populate an O-D matrix organized by the PDI scores of the origin and destination locations of trips. A summary of O-D pairings by trip origin and terminus PDI score is provided in Table 3-1. The majority of trips taken flowed between the most socioeconomically advantaged areas in the city. As per Table 3-1, 90.91% of all trips originated and were terminated in hexbins in the two least deprived quintiles (hexbins with a PDI score of 1 or 2). By contrast, only 0.95% of all e-scooter trips taken began and ended in DAs within the two most deprived quintiles (PDI score of 4 or 5; Table 3-1). Moreover, 3.52% of trips originating in DAs within the two most deprived quintiles were terminated in DAs within the two least deprived quintiles. While 3.52% represents a small share of trips, it is still 3.7 times more trips than those that began and ended in the two least deprived quintiles (0.95% of trips, Table 3-1), meaning that trips originating in areas of highest deprivation were more than twice as likely to be terminated in areas of lowest deprivation than to be terminated in comparatively deprived DAs. This shows that rather than being equitably utilized across all areas regardless of deprivation score, the e-scooter trip volume was concentrated within the most advantages (least deprived) areas of the city during the three-month Pilot period.

Moving beyond the level of summary description, a gravity model was computed to statistically test for the influence of PDI score of individual trip origin and terminus locations on the volume of e-scooter trip flows.

Table 3-1. Summarized Origin-Destination Matrix of the Pampalon Deprivation Index score (PDI) of each scooter trip's origin and terminus Dissemination Area (DA) for all trips taken within the City of Calgary during the Shared Mobility Pilot Project (July 1st – September 30th, 2019).

PDI of trip origin DA[a]	**PDI of trip terminus DA[a]** 1	2	3	4	5	**Total trips by PDI of origin DA**
1	294,528 trips *(81.98% of all trips)*	15,398 *(4.29)*	1,924 *(0.54)*	10,214 *(2.84)*	1,055 *(0.29)*	323,126 *(89.94)*
2	15,359 *(4.27)*	1,347 *(0.37)*	236 *(0.07)*	427 *(0.12)*	73 *(0.02)*	17,443 *(4.85)*
3	1,626 *(0.45)*	253 *(0.07)*	392 *(0.11)*	119 *(0.03)*	34 *(0.01)*	2,424 *(0.67)*
4	11,223 *(3.12)*	530 *(0.15)*	202 *(0.06)*	2,561 *(0.71)*	281 *(0.08)*	14,797 *(4.12)*
5	821 *(0.23)*	64 *(0.02)*	27 *(0.01)*	196 *(0.05)*	388 *(0.11)*	1,496 *(0.42)*
Total trips by PDI of terminus DA	323,564 *(90.06)*	17,593 *(4.90)*	2,781 *(0.77)*	13,517 *(3.76)*	1,831 *(0.51)*	359,278[b] *(all trips)*

[a] A Pampalon Deprivation Index (PDI) score of 1 indicates the quintile of lowest deprivation, whereas a PDI score of 5 indicates the quintile of the highest deprivation

[b] Number of e-scooter trips originating and/or terminating in dissemination areas with no calculated Pampalon deprivation index score = 52,219 trips. Number of e-scooter trips originating and terminating in the same hex bin = 32,557 trips.

3.4.2 Spatial Gravity Model

The model output is provided in Table 3-2. The component of the model output that was of most significance were the estimated coefficients, which are the values that represent the strength and direction of the relationship between independent and dependent variables. The model necessarily accounts for distance irrespective of application domain. In this analysis, the model showed that distance was inversely proportional to e-scooter trip flow volume between July and September of 2019. This means that as the distance between a trip origin and terminus location increased, the volume of e-scooter trips decreased. Specifically, a 1% increase in trip distance was significantly associated with a 0.373% decrease in the number of e-scooter trips generated between two locations ($t = 71.12$, $p < 0.001$). This pattern is expected, as the theory of gravity as well as assumptions of distance decay suggest that there is less interaction and influence of two places as the distance increases between two locations (Pun-Cheung, 2017). This is also a function of the e-scooter vehicle itself, which as described is intended for short-distance trips in part due to the vehicle charging requirements and standard battery depletion rates each minute of usage (McKenzie, 2019; Moreau et al., 2020).

Table 3-2. Gravity model analysis results for number of shared e-scooter trips

	E-scooter trip volume gravity model		
Variable	Estimated coefficient	t-value	sig
Distance[a]	-0.382	-71.24	<0.001
Origin PDI[b]	-0.054	-14.68	<0.001
Terminus PDI[b]	-0.061	-17.04	<0.001

Multiple R-squared = 0.097
Adjusted R-squared = 0.097

[a] Distance is modelled as log(distance) to provide a more accurate estimate of the impact of the change in rate of distance on a percent change in trip frequency. As a result, the results of the effects of distance are reported as a percent change rate of growth.

[b] Origin PDI and Terminus PDI are not continuous variables, unlike distance, so these factors cannot be modelled as a percent change rate of growth, and is instead reported by a percent change of the number of e-scooter trips with an increase in one PDI score.

In this study however, I was interested not in how distance influenced e-scooter trip volumes but rather in whether the area-level deprivation of the locations in which trips began and ended significantly impacted e-scooter trip flows. The results of the model showed that PDI score did significantly influence e-scooter trip volumes in Calgary at both trip origin and terminus locations between July–September 2019. At e-scooter trip locations of origin, PDI score was negatively associated with e-scooter sharing trip flows. Specifically, each one-level increase in PDI score from one quintile to the next most deprived quintile (e.g., from quintile 2 to 3, moving from more to less advantaged) was significantly associated with a 5.4% decrease in e-scooter trips ($t = -14.68$, $p < 0.001$; Table 3-2). Similarly, for terminus locations of e-scooter trips, a single-quintile increase in PDI score was significantly associated with a 6.1% decrease in e-scooter trip volume ($t = -17.04$, $p < 0.001$; Table 3-2). Both the trip origin and terminus location PDI scores were shown to have statistically significant coefficients, indicating that in this model, the deprivation profiles of origin and terminus locations of e-scooter trips had a significant impact on the volume and patterns of observed e-scooter sharing trips taken during the three months of the Shared Mobility Pilot for which data were made available. This indicates that e-scooter sharing in Calgary was not spatially equitable, with areas characterized by higher levels of deprivation (lower advantage) associated with lower volumes of e-scooter sharing trips taken during the three months of the Shared Mobility Pilot Program for which data were available. Had e-scooter sharing been relatively spatially equitable, the results of the model would have shown no statistically significant effect of the PDI score on e-scooter sharing trip volumes.

We see this reflected in the summary data as well. As per Table 3-1, there was a marked decrease in the number of e-scooter trips the more deprived the starting and ending locations became, especially when comparing the total number of trips originating (323,126 total trips) and terminating (323,564 total trips) in the least deprived areas (PDI score = 1), to the total number of trips originating (1,496 total trips) and terminating (1,831 total trips) in the most deprived areas (PDI score = 5).

One matter of note in the resulting gravity model is the R-squared value. The R-squared value suggests that the model explains approximately 9.7% of the observed variation in the data. This means that there are other variables that could also account for the differences in trip volumes between different areas. Although the R-squared value was seemingly low, models often have difficulties producing a high level of fit in the social sciences due to the complex nature of social phenomenon, especially since this analysis tested for the impact of only one factor (PDI score) on e-scooter trip patterns. However, as the purpose of this study was to analyze e-scooter utilization patterns in regard to spatial equity rather than to determine the factors that may explain these inequitable patterns, other variables were not included in this specific analysis. Further research is required to analyze other possible factors that impact the patterns of e-scooter trip flows. Previous research has found that factors such as the centrality of the city (i.e., where the downtown/areas of high economic activities are), and locations of transit hubs (such as bus stops and train stations) also explain patterns of e-scooter trip flows. Future research on micromobility sharing in Calgary could consider these factors, as well finding as identifying and testing for other additional factors that could explain patterns of e-scooter usage in the city.

3.5 Conclusion

This study evaluated the spatial equity of e-scooter sharing utilization in Calgary, Canada by analyzing e-scooter trip data collected over three months as part of a Shared Mobility Pilot Project (July 1st – September 30th, 2019). In analyzing spatial equity through the geographies of e-scooter utilization, which takes into account the deprivation profiles of both trip origin and terminus locations, this study improves upon previous methodologies which rely solely on trip origins—determined solely by dock or rebalancing locations—as an analytic entry-point, without considering where trips end. This study is also one of the first to analyze available open data on scooter sharing trips in Canada, as scooter sharing is only a recently available service and trip data availability has been limited.

Based on a spatial gravity model approach, the results of the model indicate that e-scooter utilization in Calgary was spatially inequitable during the three months period, with e-scooter trip volume decreasing with increases in area-level deprivation of both trip origin and destination locations. This parallels and confirms findings of spatial inequity identified within earlier studies of both docked and dockless micromobility sharing systems, and dispels conjectures about the potentials for dockless scooter sharing to redress some of the spatial inequalities in pre-existing micromobility sharing services such as docked and dockless bike sharing (see also Médard de Chardon, 2019). As per Federowicz et al (2020), initial planning decisions about the introduction of new mobilities within a city tend to be made in advance of a firm decision about whether or not any such newly introduced mobility modes will a permanent staple of a city's mix of transportation options. The result if that often, plans to address equity often occur after a testing/piloting phase of the program has occurred (Federowicz et al 2020).

The findings of this research may be beneficial to scooter sharing operators and urban planners by informing a greater understanding of where their systems may be spatially inequitable, and to remedy the inequities in those areas. Scooter sharing stakeholders, such as service operators, urban and transportation planners, and policy makers require data to inform an understanding of the utilization patterns of e-scooter sharing across individual systems. Without knowledge of where there is a lack of e-scooter sharing utilization, the systems would be unable to be improved on.

This study also established the utility of the gravity model as a tool for evaluating spatial equity in order to improve delivery of micromobility sharing services by identifying where there are equity gaps that need to be addressed, and to maximize utilization of this micromobility mode by all inhabitants of a city irrespective of where within a city they may live. Future research could use and adapt the methods used in this analysis to increase an understanding of the spatial equity profiles of not only e-scooter sharing systems, but other micromobility and transportation modes as well.

3.6 References

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Chapter 4

4 Spatial Equity of Dockless Bike and E-Scooter Sharing Systems in Calgary, Alberta, Canada

4.1 Introduction

Micromobility sharing systems, including shared bikes and e-scooters, have been adopted by many cities as an alternative mode of short-range urban transportation (Fishman, 2016). Dockless micromobilities, which do not rely on physical stations for accessing vehicles, grant greater flexibility in travel compared to their docked counterparts, whose fixed station locations restrict the distances over which vehicles may be utilized across a service area (Aizpuru et al., 2019; Siman-Tov et al., 2017). Because they forgo the need to originate and terminate trips at fixed station locations, dockless micromobilities have been identified as having the potential to close some of the spatial equity gaps that previous analyses have identified to be characteristic of docked bike sharing systems (Chen et al., 2019; Clewlow et al., 2018; McCarty Carino, 2018; Mooney et al., 2019; Qian et al., 2020).

Spatial equity is a measure of how well a transportation system equally serves all potential users in a service area, irrespective of differences in the socioeconomic characteristics of the neighbourhoods in which those users live (Chen, van Lierop, & Ettema, 2020). As more cities start piloting micromobility sharing programs as approaches to facilitating more sustainable, healthy modes of transportation that either ease or do not further contribute to surface road congestion (Stehlin, 2015), spatial equity is an important axis to consider in the planning and evaluation of these systems to ensure that their actual and potential benefits are evenly distributed such that they may be equally shared by urban denizens, works, and visitors alike. Yet to date, there has been little research that has evaluated which mode of shared dockless micromobility—bikes or e-scooters—expresses superior potentials for spatially equitable short-hop transportation in cities. While previous studies have explored the spatial equity dimensions and uptake of dockless bikes specifically (Chen, van Lierop, & Ettema, 2020; Shen, Zhang, & Zhao, 2018), and limited work has investigated e-scooter micromobilities (Basky, 2020; Eccarius & Lu, 2020; Matthew et al., 2019), direct spatial equity comparisons of dockless bikes and e-scooter sharing systems within the same city remain largely outstanding.

This paper reports on an analysis comparing the spatial equity profiles of dockless bike and e-scooter sharing systems in Calgary, Alberta, Canada. Using publicly available data on scooter sharing and bike sharing trips collected as part of a three-month micromobility pilot program (July 1st – September 30th, 2019), this study compares the volume of shared e-scooter and dockless bike trip terminus locations (where trips end) by the Pampalon Deprivation Index (PDI) quintile scores (from 1 to 5, with one being the least deprived and 5 being the most deprived) calculated for the sub-neighborhood scale Dissemination Area (DA) geographies in which those trips ended (Pampalon et al., 2012). Specifically, this paper aims to investigate whether there is any difference in the spatial equity profile of dockless bikes and e-scooters in Calgary, Alberta, Canada. Micromobility sharing in Calgary was considered to be equally spatially equitable across both dockless modes if the number of dockless bike and e-scooter trip terminus locations—normalized by population and the number of vehicles in service—were evenly spatially distributed across DA-based quintiles of deprivation. For the purposes of this study, dockless bikes and e-scooters was considered to be equally spatially in/equitable if both systems show the same pattern of distribution of across deprivation profiles (i.e., trips in both modes are similarly un/evenly spatially distributed across deprivation profiles).

The null hypothesis is that if the utilization of both dockless modes is equally spatially equitable, there will be no significant effect of the PDI quintile score on the total number of normalized micromobility trip terminuses across DAs in the City of Calgary despite differences in deprivation scores of the areas (DAs) in which those trips ended. In other words, dockless bike and e-scooter trips taken during the three-month Pilot will have ended equally in highly deprived DAs as they would have in less deprived DAs in proportion to the populations of these areas. This would indicate that during the Pilot period, both dockless modes were being utilized equitably, and equally so. Also, if bike sharing and e-scooter sharing in Calgary were equal in their spatial equity profiles, then there will be no difference in the patterns of utilization (proxied by trip ends) between the two dockless micromobility modes.

To assess and analytically compare the spatial equity dimensions of dockless bike and e-scooter utilization during the three-month pilot program period, ANOVA and linear regression analyses were used to analyze the relationship and effects of areal deprivation score on the distribution of micromobility trip ends. The results of this analysis indicate the spatial equity profiles of both bike sharing and e-scooter sharing services are relatively similar in that both dockless bike and e-scooter sharing systems are comparatively spatially inequitable. This study is amongst the first to directly compare the equity profiles of dockless bikes and e-scooters within the same city, allowing for direct comparison of within dockless mode differences in the same spatial context.

4.2 Micromobility Research and Spatial Equity Analyses

Docked micromobilities have historically been the dominant form of micromobility sharing. Accordingly, research on micromobilities has emphasized the impacts of docked bike sharing systems. Many of the analyses on micromobility sharing systems stem from the methods initialized by docked bike sharing research, including analyses that focus on the spatial equity and utilization of such systems. Spatial equity, in terms of micromobility sharing, is considered as the equitable distribution of services (in this case, micromobility sharing services and access to bikes/scooters) across different spatial areas, regardless of socioeconomic factors and resource opportunities (Johnston et al., 2020). With the static nature of bike sharing systems oriented around fixed station locations, an overarching method of analyzing the spatial equity of docked bike sharing systems has been to consider the distribution of bike sharing stations across urban geographies stratified by differences in income, racialized/ethnic minoritized composition of neighbourhoods, and deprivation profiles.

One example is Babagoli et al.'s (2019) investigation of the health and spatial equity impacts of New York City's docked bike sharing system, Citi Bike. The researchers compared the spatial distribution of docking stations at the start of the Citi Bike program in 2013 to the distribution after the first expansion in 2015 in relation to neighbourhood poverty levels. Neighbourhood poverty level was calculated for each census tract as the proportion of residents with incomes below the Federal Poverty Level

(FPL) using the American Community Survey 5-Year Estimate for 2009–2013. Health factors for each census tract were also measured using the Health Economic Assessment Tool (HEAT), a measure of reduced mortality and the related economic benefits due to walking or cycling. Upon mapping and joining the bike station locations to census tracts, Babagoli et al. (2019) found that bike stations were disproportionately located in wealthier neighbourhoods, and the disparity in access remained the same after the system's expansion. While spatial equity did not improve with the expansion of the system, the economic value of reduced mortality (based on the HEAT) did improve over time with an increase in the number of users. This suggests that not only are micromobility sharing services inaccessible in more deprived NYC neighbourhoods, but also that the other touted benefits of micromobility sharing—such as health benefits—are likewise not realized equally for all populations in a city, and may further exacerbate socioeconomic divides in transportation access.

In a separate analysis of the spatial equity of docked bike sharing in five Canadian cities (Montreal, Toronto, Hamilton, Ottawa, and Vancouver), Hosford and Winters (2018) compared the deprivation geography of the service area for bike sharing systems in all five cities using the Pampalon Deprivation Index, a Canadian-based measure of socioeconomic status calculated using census data which classified sub-neighbourhood scale dissemination areas (DAs) into quintiles from 1 (least deprived) to 5 (most deprived). In their study, the bike share service area for each city was identified as the area within the perimeter comprised of DAs that were fully or partially enveloped by a 500 m buffer of a bicycle docking station. With the service area of each system defined by the DAs classified according to their quintile of deprivation, bike sharing systems were considered to be equitable if the DAs contained within each city's service area reflected an even distribution of PDI quintile scores. Their results showed that the bike sharing systems in most of the cities disproportionately served the least deprived, with the exception of Hamilton, Ontario, where the system privileged the most deprived areas (see also Bradshaw and Kitchin, 2021).

With technological advancements, micromobility sharing systems have started to move beyond docked systems and have started testing and adopting the dockless model, in which micromobility vehicles such as bicycles and e-scooters do not need to be retrieved from stations at fixed locations. Many theories and approaches to analyzing the spatial equity of dockless micromobility sharing systems are adapted from the analysis of docked systems but modified to fit their dockless nature. Based my review of key literatures, I found that studies that use spatial methods as an approach to analyzing dockless micromobility emphasize either dynamics of utilization or spatial equity, even where usage is analyzed in relation to socioeconomic factors.

One approach to analyzing spatial utilization may be found in Caspi et al.'s (2020) study of dockless e-scooter sharing in Austin, Texas. Their study focused on how e-scooters were being used within the city center, where most e-scooter trips are concentrated. Using open data on e-scooter trips for over a six-month period (August 15th, 2018 to February 28th, 2019), the researchers superimposed a grid of 200 m squared cells over trip point locations covering the city of Austin. The cells were populated with data such as the aggregate number of e-scooter trip starts and ends (point locations), land use and street network data, socioeconomic factors such as median annual income, and information about presence/absence of bicycle infrastructure (also used by e-scooters). The authors then used Geographically Weighted Regression (GWR) to evaluate the relationship between the number of trips and the explanatory variables (such as land use and socioeconomic factors) by providing a unique regression coefficient for each grid cell. Their findings showed that e-scooters were most likely to be used in the downtown districts of the city and in areas with higher employment rates and existing cycling infrastructure, such as bike lanes. Importantly, their study found that e-scooters were used throughout the city regardless of the socioeconomic characteristics of Austin's neighbourhoods, suggesting that dockless e-scooters can potentially minimize the gaps of public transportation inequities.

Another study on the usage of dockless bike sharing was conducted by Shen et al. (2018) in Singapore, with the purpose of identifying the impact of dockless bike fleet size on usage. The researchers sourced real-time bike share data, including the unique bicycle ID and real-time idle GPS location for each bike for a short-term period from April 26 to May 4, 2017 from one of the largest bike share operators in Singapore. The spatial distribution of the average number of available (idle) bikes was mapped in 300 m by 300 m cells exhausting the island state. The researchers also identified factors that can influence bike usage, namely the built environment, public transportation, bicycling infrastructure, and weather conditions aggregated to each cell. To determine the impacting factors of dockless bike usage, the researchers constructed a spatially weighted spatial lag model considering all the aforementioned elements. Their results showed that the number of bicycles (i.e., fleet size) had a positive correlation with the usage of dockless bike sharing. Built environment factors, such as longer bike paths and accessible bike racks were also associated with higher bike share usage. Overall, Shen et al. (2018)

found that dockless bike sharing had the potential to constitute an affordable and accessible mode of transportation, especially where more vehicle assets are available for use. Yet while the researchers maintain that providing this alternative mode of transportation can improve transportation equity for all members of the community, investment in built environment factors such as bicycling infrastructure (e.g., bike lanes) is also required in order to maximize bike sharing adoption.

In addition to studies analyzing dockless micromobility utilization, researchers are also developing spatial methods to analyze the spatial equity dimensions of dockless micromobility sharing systems as the prominent focus of the research. Many of these analyses often evaluate the system's service area, with a focus on the socioeconomic profiles of the area. For example, Mooney et al. (2019) analyzed the spatial equity of access to dockless bike sharing in Seattle, Washington. Using data from the American Community Survey for socioeconomic characteristics such as income, age, and educational attainment, dockless bike trip data and rebalancing activities were spatially associated with 93 different neighbourhoods. Using the joined data, the researchers compared differences in spatial access based on rebalancing locations as a proxy for dockless vehicle availability. The driving principle of their study was that an equitable dockless bike sharing system would be characterized by rebalancing (redistribution) of bicycles in proportion to the probability of a bike being ridden, independent of neighbourhood characteristics, and that the system would not fail to service less advantaged neighbourhoods (i.e., bikes would be equally available in more advantaged and less advantaged enclaves). To measure the equity of dockless bike sharing in Seattle, Mooney et al. (2019) derived a ratio of available bikes per day per resident/employee in each neighbourhood. The results of their analysis suggested that dockless bikes were available throughout the city (serving all neighbourhoods), although there was a higher availability of vehicles in neighbourhoods considered to be wealthier and more privileged (areas with more community resources overall). While these results of disproportionate availability and access align with previous studies of social equity in micromobility sharing studies, the researchers highlight the promise of improvements to spatial equity associated with dockless systems over docked bike sharing systems.

Finally, an important group of dockless micromobility sharing equity studies are those that offer comparative analyses of the spatial equity profiles of docked versus dockless systems. Such analyses are vital because dockless systems are often touted as being potentially more spatially equitable than docked systems due to ‘freedom from the station’ (Mooney et al., 2019) of fixed docking locations which can limit how far a bike or scooter can be used (as users would have to find a docking station to return the vehicle). Similar to previous micromobility sharing research, current notable comparative analyses may be categories as those studies which compare the usage patterns docked and dockless systems, and those which compare the deprivation profiles of their service areas. For instance, McKenzie (2019) conducted a spatiotemporal comparative analysis of the usage patterns of dockless e-scooter sharing and docked bike sharing systems in Washington, D.C. This study collected real-time Lime scooter (dockless e-scooter) data and Capital Bike Share (docked bike share) data for a time period spanning June 13 to October 23, 2018. To compare utilization across the two modes (docked bike sharing and dockless e-scooters), McKenzie (2019) constructed a Voronoi polygon tessellation for D.C. based on the point locations of the docking stations for bike sharing. The basis for creating Voronoi polygon tessellations was that a user looking for a docked bike would navigate to the closest docking station. Creating the tessellation polygons also allowed the dockless scooter trip starting and ending locations to be aggregated to the same polygons, so that docked bikes and dockless scooters can be spatially compared at the same resolution. The results of the analysis showed that the spatial usage of docked bikes and dockless scooters are considerably different: bike sharing was found to be used for commuting purposes, whereas dockless scooters were more often used for recreational and leisure purposes in Washington, D.C. Furthermore, the areas with the least number of scooter and bike sharing trips were areas characterized by low income and majority African American residential composition. While the focus of McKenzie's (2019) study is the spatial usage of the two systems, a related study by Clewlow et al. (2018) identified that dockless bike and e-scooter sharing in Washington, D.C. did not improve upon the spatial inequities of the docked Capital Bike Share system, with vehicles across both docked and dockless modes being unevenly distributed across their service areas.

Elsewhere, a spatial equity comparison of micromobility sharing systems was conducted by Qian et al. (2020), who compared the equity of service between dockless and dock-based bike sharing systems in San Francisco between January and March 2019. The study analyzed differences in accessibility to docked and dockless bike sharing services for disadvantaged populations in the city, defined as Communities of Concern (CoC). Census tracts were identified as CoCs based the proportion of the population over a certain threshold level for eight disadvantage factors (majority ethnic/racial minority residents; low income; limited English proficiency; zero-vehicle household; high proportion of seniors 75 years and over, persons with disability, and single-parent families; and severely rent-burdened household) in the 2012–2016 American Community Survey data. The two systems were compared on the basis of the number of CoCs within each system's service area. For docked bike sharing, a 400 m buffer around each docking station was used to help define the service area. A census tract was considered to be part of the service area if the docking station buffer contained a majority of the census tract. For the dockless system, a census tract was considered to be included in the service area if any part of the tract fell within the San Francisco Municipal Transportation Agency's predetermined restricted service area for dockless bikes. Based on a t-test analysis, Qian et al. (2020) found that the dockless bike sharing system in San Francisco covered a wider area and a larger population of CoCs than the dock-based system. Dockless bikes were also more available in CoCs than docked bikes (dockless bikes outnumbering docked counterparts at ~2:1), and the study suggested that if docked systems increased the spread of docking stations around the city, the docked services may also reach the same levels of bicycle availability as their dockless equivalents.

While there have been comparisons of docked and dockless modes within the same urban context, to date no study has examined differences between the spatial equity potential potentials between different dockless modes (i.e., dockless bikes and dockless scooters). This study analyzes the spatial equity of dockless bike sharing and e-scooter utilization within the same city (Calgary, Alberta, Canada), which much like McKenzie (2019) and Qian et al.'s (2020) studies, provides a consistent spatial frame of reference where the contours of deprivation geographies and urban inequalities are held constant, allowing for meaningful and direct comparisons of spatial equity profiles for different micromobilities within the dockless mode. This study also analytically combines a focus on utilization and spatial equity together, rather than analyzing them separately as in previous studies.

4.3 Methods and Analysis

4.3.1 Study Area

This study analyzed the spatial equity of dockless micromobility utilization in Calgary, Alberta, the fourth largest metropolitan area in Canada. In 2016, the city had a population of approximately 1.2 million people within its 825 square kilometre area (Statistics Canada, 2018a). The city prides itself on having the largest urban pathway and bikeway network in North America (The City of Calgary, n.d.a), which is well suited for the use of micromobility sharing services. A two-year Shared Mobility Pilot project (referred to as the ‘Pilot’) was implemented in the city in the summer of 2018. The Pilot commenced with the introduction of a fleet of 500 shared dockless bicycles operated by the transportation company Lime (Krause, 2019). A year later in 2019, the Pilot added 1,500 shared dockless e-scooters, with 1,000 scooters provided by Lime and 500 operated by the micromobility company Bird, alongside the 500 dockless bikes already in operation (The City of Calgary, 2019) for an initial trial period during that summer. While other Canadian cities have also tested and implemented dockless micromobility sharing systems, this study focusses on Calgary’s micromobility sharing system as it is the only Canadian city for which trip data for both scooter and bikes have been made available under an open data license. The inclusion of e-scooter and dockless bike share trips over the same geographic area (City of Calgary) within the same time period (three-month summer trial) provides a standardized spatio-temporal frame of reference for making a direct comparison of the spatial equity dimensions of dockless bikes versus e-scooters.

4.3.2 Micromobility Data and Data Processing

For the Pilot, data for a trial period covering 92 operating days inclusive of July 1 to September 30, 2019 was published under and open data license through the City of Calgary's Open Data Portal. This dataset represents dockless bike and scooter trips made using vehicles operated by the companies Lime and Bird, and includes the origin and terminus locations of each trip generalized to 30,000 m^2 hexagonal bins (hexbins), with the location points corresponding to the centroid of the hexbin. Additional information contained in the dataset includes the trip start date and day of the week, start hour, trip duration in seconds, and trip distance in metres. Prior to publication, the curators of the dataset removed trips lasting less than 30 seconds or 100 metres, and trips with poor geospatial data quality. The resulting downloadable dataset contains a total of 482,021 trips recorded, comprised of 464,743 (96.42%) scooter trips and 17,278 (3.58%) bike trips.

Data cleaning was performed in advance of the spatial equity analysis. Scooter trips that were recorded to be over two hours (7,200 seconds) in duration were excluded from analysis due to the scooter's battery life limitations that only allows for a maximum trip duration of 2 hours on a single charge (McKenzie, 2019). As a result, scooter trips over two hours in length were not likely to constitute genuine trips or may have included a stop, such that the trip would not have been continuous. Trips that originated or were terminated outside of the City of Calgary limits were also excluded from the analysis in order to contain the data within the city boundary and dissemination areas, circumscribing the analysis to the Calgary city limits. Similarly, trips that originated or were terminated in dissemination areas with no calculated deprivation index score (detailed below) were excluded from analysis as well. Finally, trips were also filtered based on the average speed of the trip. The City of Calgary limits e-scooter speeds to up to 20 km/h via limitations on the physical assets themselves (Potkins, 2019), so any scooter trips with an average speed greater than 20km/h (calculated using the recoded distance and duration of each trip) are either inaccurately recorded or are not indicative of a genuine trip and were excluded. For bike sharing trips, Lime bikes (which were the only bikes available for the bike sharing service in Calgary) similarly have an upper speed limit of 15 mph, or approximately 24 km/h, so bike trips with an average speed of over 24 km/h were also excluded from analysis. After subsequent data cleaning, a total of 406,895 trips remained, comprised of 391,843 (96.30% of all micromobility trips) e-scooter and 15,052 (3.70% of all micromobility trip) bike trips.

4.3.3 Socioeconomic Measures

Following Hosford and Winters (2018) approach, this study uses the Pampalon Deprivation Index (PDI) as a proxy for the contours of Calgary’s urban geography of socio-economic inequality, an essential data point for making within-city comparisons of differences in the spatial equity dimensions of micromobility sharing between dockless bikes and e-scooters. The PDI is an area-based measure of material deprivation for Canada calculated at the sub-neighbourhood scale of Dissemination Areas (DAs), a unit of Canadian Census geography finer than the Census Tract. The material component of the PDI provides an indication of relative socioeconomic advantage and disadvantage for each DA in Canada (Pampalon et al., 2012). The PDI score is calculated using three socioeconomic indicators from Canadian census data with known relations to material deprivation:

1. The proportion of people without a high school diploma
2. Average personal income
3. The employment-population ratio

The PDI uses a quintile scoring system for the deprivation level of each DA ranging from least deprived (PDI score = 1) to most deprived (PDI score = 5) (Institut National de Santé Publique du Québec, 2016). A dataset of the PDI scores was downloaded from the Institut National de Santé Publique du Québec website (Institut National de Santé Publique du Québec, 2016). The dataset includes a table of PDI scores for each DA in Canada. A separate spatial dataset of the DAs across Canada was downloaded from the Statistics Canada open data portal (Statistics Canada, 2016). The attributes of the PDI scores were joined to the DA dataset using the unique DA number identifier. This allowed for the PDI quintile score of each DA to subsequently be associated with micromobility trips with further analysis.

In this study, the material component of the PDI was used as opposed to the social component because micromobility sharing usage has historically been more associated with material deprivation including income and employment rates, rather than social deprivation factors such as marital status and family arrangements (Stehlin, 2015).

4.3.4 Data Normalization

This analysis combines the two datasets used for this study: 1) the trip data, including trip origin and terminus locations; and 2) the DAs mapped with associated PDI quintile scores. The point locations of all e-scooter and bike trip terminuses were mapped (with points representing the hexbin centroid that contains the start or end of the trip) and spatially joined to the DA in which any one trip ended. The number of trip terminuses were then summarized in each DA with an associated PDI score. The total number of bike and scooter trip terminus locations were summed to the level of the DA, the trip counts for each mode were then normalized by the population of the DA. This was calculated by dividing the total number of scooter and bike trip ends separately for each DA by its population (based on the 2016 census data). The normalized value was then multiplied by 1,000 for the purposes of visual clarity and reporting of values, rather than maintaining the small decimal values after the normalizing processes. Normalizing the values by population was important because while Canadian dissemination areas are defined as small, relatively stable geographic unit with a targeted population count of between 400 to 700 each (Statistics Canada, 2018b), the range of Calgary dissemination areas were much wider, with some DAs comprising of populations over 10,000. As a result of the varying DA populations, it was appropriate to adjust the total trip values by population to accurately reduce the impacts of differences in population when comparing utilization patterns between different deprivation quintiles.

After being normalized by DA population, the micromobility trips were also normalized by the number of bikes or e-scooters available during the Pilot. Throughout the Pilot’s 3-month period, there were 1,500 e-scooters and 500 bikes deployed for use. To account for the disproportionate number of in-service vehicles between the two different transportation modes, total numbers of trips taken in either mode were also normalized by the number of available vehicles (i.e., the total number of e-scooter trips were divided by 1,500, and the total number of bike trips were divided by 500 for each DA). The resulting values to be analyzed were the number of micromobility trip ends per vehicle per 1,000 persons in each DA that has an associated PDI score.

4.3.5 Analysis and Rationale

To determine whether there was a significant difference in the normalized volume of bike and e-scooter trips taken during the period of the Pilot between different deprivation areas, a one-way analysis of variance (ANOVA) at $\alpha = 0.05$ was run to compare the mean number of trip ends[8] per vehicle per 1,000 persons for the two micromobility sharing modes. The ANOVA test was used to determine if there are statistically significant differences between the means of two or more groups (Fisher, 1919). In this case, I wanted to determine whether there was a significant difference in the number of normalized trip ends between different PDI categories for both bikes and e-scooters. Tukey’s honestly significant difference test was subsequently run post hoc to identify any PDI quintiles with significant differences in the volume of trip ends for bikes

[8] Trips are counted by the number of trip ends, as end point locations indicate trips actually taken.

and e-scooters, as well as to identify any utilization patterns differences between the two micromobility modes.

This study also ran a linear regression[9] in SPSS to further analyze the effects of PDI score on micromobility sharing utilization. Linear regression models are used to determine whether the strength of the relationship between the independent (in this instance, PDI score) and dependent variables (in this instance, normalized bike and e-scooter trip ends) are statistically significant, and also helps to determine how much the dependent variables changes with a change in the independent variable (i.e. how many more or less bike and e-scooter trips occurs with each change in PDI score) through the unstandardized beta coefficient (Freedman, 2009). The linear regression analysis also determines the strength of the model through the R squared value, which explains how much of the variance in the dependent variable is explained by the independent.

The use of trip terminus locations as proxies for dockless micromobility utilization moves beyond previous analytical studies privileging asset rebalancing locations that prefigure vehicle availability as a basis for evaluating the spatial equity profile of a dockless system. Rebalancing locations, or locations to which dockless vehicles are periodically redistributed, reflect the spatial preferences of micromobility system operators (locations where operators intend for riders to initiate travel from). Rebalancing effectively circumscribes the potential locations from which riders may

[9] Linear regression was used because as opposed to other regression analyses because it was suitable to answer the question with the dataset available. Other analyses used in previous micromobility sharing works required additional data that was not available for this project.

choose to originate trips, and may not reflect the spatial needs of riders in that they may not correspond to the locations from which riders would themselves choose or like to originate travel from. Furthermore, while vehicles may be rebalanced to specific locations, this does not mean that they are necessarily used by the urban denizens who live, learn, work, and/or leisure in these vicinities; indeed, assets may sit idle (unused) for extended periods of time before being rebalanced to subsequent locations where they may have a greater likelihood of being used. While some studies use dockless vehicle idle time as an inverse proxy of utilization (see e.g., Mooney et al., 2019), it is unclear whether the end of an idle period for any one vehicle marks a trip initiated by a rider or the vehicle being collected for purposes of further redistribution (rebalancing) to alternate locations where demand and/or utilization rates may be higher. By contrast, dockless micromobility trip destinations (where trips end) provide spatial information about trips actually taken. As such, trip terminus locations provide a more direct proxy of the utilization equity profile of a shared micromobility system for the reason that destination locations impart information about the spatial intentions and needs of riders (locations where micromobility users need and choose to travel to), which are independent of usage circumscriptions imposed by operators' spatial preferences as proxied by rebalancing locations.

4.4 Results

4.4.1 ANOVA and Tukey's Results

On the basis of the ANOVA, the results show that there is a significant difference between the number of both normalized bike ($F(4,1540) = 13.679$, $p < .001$, Table 4-1) and e-scooter ($F(4,1540) = 6.351$, $p < .001$; Table 4-1) trips ending in DAs classified as being within different quintiles of deprivation, indicating that area-level deprivation did have an impact on the utilization of dockless bikes and e-scooters in Calgary during the three-month period of the Pilot.

Table 4-1. ANOVA of normalized dockless micromobility trip volume by vehicle type during Calgary's Shared Mobility Pilot (July 1st – September 30th, 2019).

	One-Way ANOVA		
	F-value	Degrees of freedom	p-value
E-scooter	6.351	1540	.000
Bike	13.679	1540	.000

Tukey's honestly significant difference post hoc test (described in Table 4-2) revealed that the least deprived areas of the city (categorized as PDI score of 1) had a significantly higher volume of normalized e-scooter trips ending in them compared to areas with PDI quintile scores of 2 (.453 ± .116, $p = .001$), 3 (.513 ± .134, $p = .001$), 4 (.462 ± .150, $p = .018$) and 5 (.518 ± .134, $p = .001$) (Table 4-2). Similar results were also found for dockless bikes (Table 4-2), where higher volume of bike trip ends was found in areas (DAs) with a PDI quintile score of 1 compared to 2 (.048 ± .008, $p < .001$), 3 (.055 ± .009, $p < .001$), 4 (.051 ± .011, $p < .001$), and 5 (.056 ± .009, $p < .001$). While the least deprived (i.e., most advantaged) areas of Calgary were significantly different from the more deprived areas, the categories that were more deprived (i.e., PDI scores of 2, 3, 4, and 5) were not significantly different from each other for both e-scooters and bikes. The results of the Tukey's test reveal that for both micromobility modes, a disproportionate majority of trips ended in the least deprived areas of Calgary during the period of the micromobility Pilot, while DAs further down the deprivation spectrum (from the second least deprived through to the most deprived quintiles; PDI scores 2–5) were underrepresented as dockless micromobility trip destinations.

The results of this analysis support rejection of the null hypothesis, and inform two significant findings: first, micromobility sharing utilization in Calgary during the Pilot was spatially inequitable, with utilization (proxied by trip end locations) of both modes shifted more towards the least deprived, more privileged areas of the city; and second, there were no significant differences between the spatial equity profiles of dockless bikes and e-scooters. In other words, not only was the utilization of both bikes and e-scooters spatially inequitable in the favouring of the most advantaged areas of the city as destinations for micromobility travel, but both modes were inequitable in the same way (with utilization dropping off from the second-least deprived quintile).

Table 4-2. Tukey's HSD for E-scooters and bikes

(I) PDI	(J) DI	E-scooter Mean Difference I-J *(Std. Error)*	Sig.	Bike Mean Difference I-J *(Std. Error)*	Sig.
1	2	0.453* *(0.116)*	.001	0.048* *(0.008)*	.000
	3	0.513* *(0.134)*	.001	0.055* *(0.009)*	.000
	4	0.462* *(0.150)*	.018	0.051* *(0.011)*	.000
	5	0.518* *(0.134)*	.001	0.056* *(0.009)*	.000
2	1	-0.453* *(0.116)*	.001	-0.048* *(0.008)*	.000
	3	0.059 *(0.152)*	.995	0.007 *(0.011)*	.964
	4	0.008 *(0.166)*	1.000	0.003 *(0.012)*	.999
	5	0.065 *(0.152)*	.993	0.009 *(0.011)*	.923
3	1	-0.513* *(0.134)*	.001	-0.055* *(0.009)*	.000
	2	-0.059 *(0.152)*	.995	-0.007 *(0.011)*	.964
	4	-0.051 *(0.179)*	.999	-0.004 *(0.013)*	.998
	5	0.006 *(0.166)*	1.000	0.002 *(0.012)*	1.000
4	1	-0.462* *(0.150)*	.018	-0.051* *(0.011)*	.000
	2	-0.008 *(0.166)*	1.000	-0.003 *(0.012)*	.999
	3	0.051 *(0.179)*	.999	0.004 *(0.013)*	.998
	5	0.057 *(0.179)*	.998	0.005 *(0.013)*	.992
5	1	-0.518* *(0.134)*	.001	-0.056* *(0.009)*	.000
	2	-0.065 *(0.152)*	.993	-0.009 *(0.011)*	.923
	3	-0.006 *(0.166)*	1.000	-0.002 *(0.012)*	1.000
	4	-0.056 *(0.179)*	.998	-0.005 *(0.013)*	.992

Based on observed means.
* The mean difference is significant at the .05 level

4.4.2 Linear Regression Analysis Results

The findings from the linear regression model of the effects of PDI score on the mean number of trip ends showed that there was a significant difference between the mean number of both normalized e-scooter and bike trips ending in DAs classified as being within different quintiles of deprivation, indicating that area-level deprivation did have an impact on the utilization of dockless bikes and e-scooters in Calgary during the three-month period of the Pilot. In particular, based on the unstandardized coefficient of the linear regression model (Table 4-3), each increase in deprivation quintile score (i.e., increasing from least to most deprived quintiles) was associated with a decrease of 0.138 trips per 1,000 persons per vehicle in circulation for dockless e-scooters ($t = -4.146$, $p < .001$), and a decrease of 0.015 trips per 1,000 persons per vehicle in circulation for dockless bikes ($t = -6.171$, $p < .001$). These results suggests that both dockless micromobility modes were inequitable in utilization since higher deprivation areas was associated with a decrease in micromobility usage.

Table 4-3. Micromobility sharing ends per 1,000 persons per vehicle in operation: Linear regression analysis results

	Linear Regression					
	E-scooter			**Bike**		
	Unstandardized coefficient	t	Sig	Unstandardized coefficient	t	Sig
PDI	-0.138	-4.146	.000	-0.015	-6.171	.000
R Squared = .011 Adjusted R Squared = .010				R Squared = .024 Adjusted R Squared = .023		

Note that the adjusted R squared value of the first linear regression analysis for bikes and e-scooters was relatively low (R^2 = .023 for bikes; R^2 = .010 for e-scooters). These values indicated that about 2.3% of the variance of bike trip ends, and about 1.0% of the variance of e-scooter trip ends was explained by the differences in PDI score. This suggests that PDI score does not entirely explain the distribution and variance of the number of trip ends per 1,000 persons per vehicle during the Pilot, nor does the PDI score accurately predict the volume of trip ends across different areas of the city. This indicates that other factors beyond DA-level material deprivation accounts for the majority of the variance in the distribution of normalized micromobility trip ends across the City of Calgary.

4.5 Discussion

The results of this analysis support rejection of the null hypothesis and informs two significant findings. First, micromobility sharing utilization in Calgary during the Pilot was spatially inequitable, with utilization (proxied by trip end locations) concentrated in the least deprived, more privileged areas of the city, and declined when moving to more deprived areas of the city. Second, there were no differences between the spatial equity profiles of dockless bikes and e-scooters, in that both modes were similarly inequitable by virtue of favouring the most advantaged areas as destinations for micromobility travel, and with utilization declining in more deprived areas. Overall, this study found that micromobility sharing in Calgary was disproportionate in their usage during the Pilot period, and favoured more privileged areas of the city, as opposed to providing equitable services across different areas based on populations. E-scooters, while having the potential to alleviate the disparities in micromobility sharing, in this case maintained the historically ingrained inequities of these systems as with older bike sharing modes. The results from this analysis can help to inform service providers and micromobility transportation policies to strive towards more equitable services for all members of the community.

While deprivation score is important in identifying patterns of utilization across different areas, other factors should also be considered alongside deprivation score, such as centrality, which was explored in this study. These findings are similar to results found in previous studies, which have suggested that micromobility sharing systems are often utilized disproportionately in the most advantaged/least deprived enclaves of a city (see e.g., Hosford & Winters, 2018; Qian et al., 2020).

4.6 Conclusion

This study investigated the spatial equity of dockless micromobility sharing systems, specifically bikes and e-scooters, in Calgary, Alberta, Canada by analyzing bike and e-scooter sharing data collected as part of the city's three-month Shared Mobility Pilot Project (July 1st – September 30th, 2019). To my knowledge, this is one of the first analyses of spatial equity for both dockless bikes and e-scooters within the same city, providing a comparable geographic context of the two systems.

The findings show an overall inequity in micromobility utilization in Calgary in that most trip ends are disproportionately located in the least deprived areas of the city, and declined in more deprived areas of the city. When comparing the spatial equity profiles of bikes compared to e-scooters, the results found that both systems showed the same patterns of inequity. This study helps to facilitate future research in micromobility sharing, as future research can explore the potential inequalities of the systems through surveys which helps to accurately identify deprivation profiles of users, as well as providing a novel method of micromobility sharing analysis that can be expanded upon in future investigations.

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Chapter 5

5 Conclusions

5.1 Key Findings

The results from the analyses presented in Chapters 3 and 4 of this thesis indicated that micromobility sharing in Calgary, Alberta, Canada was spatially inequitable during the three months of the city's Shared Mobility Pilot Program for which data was made available (i.e., between July–September, 2019). Both e-scooters and dockless shared bikes were found to have been utilized in more privileged, less deprived areas of the city. E-scooter sharing during this period was determined to be spatially inequitable, since significantly more e-scooters were found to be utilized in the least deprived areas of the city, and declined in utilization towards more deprived areas. In the comparison of dockless bike and e-scooter sharing utilization, both systems were shown to be spatially inequitable in the same way i.e., significantly more utilized in the least deprived areas.

Overall, the research in this thesis provides the following answers to the research questions presented in Chapter 1:

1. The pattern of flows for dockless e-scooter sharing usage suggested that e-scooter sharing was mostly utilized in areas considered to be more privileged and least deprived both for the trip origin and destination locations.

2. The spatial equity profiles of dockless bike and dockless e-scooter sharing systems show that the systems were almost exclusively used in the least

deprived areas of the city. Micromobility sharing usage was shown to decline with areas of increasing deprivation.

3. Shared dockless bikes and dockless e-scooters showed the same patterns of usage in the context of spatial equity i.e., both modes of micromobility sharing were spatially inequitable in their utilization and served least deprived, more advantaged areas disproportionately more often than the areas of higher deprivation.

To satisfy the research objectives introduced in this thesis and to answer the research questions, two analyses of micromobility sharing in Calgary were conducted to analyze the spatial equity of e-scooter sharing and to compare it to dockless bike sharing in Calgary. In both analyses, spatial equity was measured using the Pampalon Deprivation Index (PDI), which is an area-based measure of deprivation. The quintile score of the PDI was used to relate micromobility trip origins and destinations to a deprivation profile. As reported in Chapter 3, a gravity model was used to analyze the strength of the influence of deprivation scores on e-scooter trip volumes at trip origin and destination locations. The results show that a one-quintile increase in the trip origin location deprivation score (from less to more deprived, e.g., from PDI score of 2 to 3) was associated with a 5.4% decrease in e-scooter trip volumes, and a similar increase in the destination location deprivation score was associated with a 6.1% decrease in e-scooter trip volumes. Overall, the gravity model produced from this analysis showed that higher deprivation areas were less likely to have e-scooter trips going to and from them, and that there was a significant negative association between deprivation score and e-scooter trip volumes. If e-scooter sharing had been spatially equitable, then the gravity model would show that PDI score does not significantly influence the volume of e-scooter trips between origins and destinations.

Next, in Chapter 4, the spatial equity dimensions of both dockless bike and dockless e-scooter sharing in Calgary were analyzed and compared to each other. The number of normalized bike and e-scooter trips were analyzed using a one-way ANOVA to determine whether there was a significant difference between the number of normalized trip ends between bikes and e-scooter for each PDI quintile. Tukey's honestly significant difference test was used to identify significant differences in the pairs of PDI quintiles. Furthermore, a linear regression was also used to determine the strength of the relationship between PDI score and normalized bike and e-scooter trip ends. The results of this analysis indicated that both dockless micromobility sharing systems were spatially inequitable. There was a significant difference in the volume of trips between DAs of different deprivation scores, most notably for the least deprived areas (PDI score of 1) compared to the more deprived areas. Both bikes and e-scooters showed higher trip volumes in the least deprived areas, with the more deprived areas having no significant difference in the number of trips between each other. The ANOVA and linear regression analyses of dockless micromobility sharing systems in Calgary thus show that they were spatially inequitable in utilization, and that bikes and e-scooters were both inequitable in the same way, with more trips taken in both modes contained in the least deprived areas of the city.

5.2 Caveats and Limitations

There are several study limitations and caveats that must be considered when interpreting the results of the analyses reported in this thesis. A caveat applies to the Pampalon Deprivation Index that was used to categorize dissemination areas based on socioeconomic factors that represent quintile-divided measure of deprivation, focusing on the most and least deprived areas of the city. The study uses the deprivation profiles of each trip's origin and terminus locations, but this does not necessarily mean that riders are representative of the area as not all individuals starting their scooter rides in more socially deprived areas have low socioeconomic status and vice versa.

A limitation of the analyses is associated with the dataset itself. Unlike some other studies, the dataset used in this analysis did not contain information such as rebalancing (when operators move vehicles to new locations themselves) or real-time information on bike/e-scooter availability and idle times after conclusion of the pilot. Rebalancing information about where operators move dockless bikes and e-scooters to and from (especially at the start of the day, when operators arrange the original locations for bikes and e-scooters) could be used to identify which areas are prioritized for service by systems operators. Rebalancing information would provide an indication of the motivations influence the service geographies: whether assets are rebalanced to be available across all areas, or whether they are moved exclusively to areas of high demand. Real time data on bike availability and idle times can also help identify whether vehicles are available in areas but are left unused or whether vehicles are absent in certain areas. Without data on real time availability, it was not possible to assess whether bikes and e-scooters were available in all areas, but were not used and that would instead suggest that the system does not underserve areas, which brings into question whether the program is desired and used equally across differently deprived versus advantaged areas of the city.

I would like to note that the micromobility sharing project in Calgary did provide real time bike and scooter availability information[10] categorized by operators in JavaScript Object Notation (JSON) format, but since this thesis was produced after the pilot period (July 1st – September 30th), the micromobility sharing service was retired and as a result, no real time data could be scraped from the website. A suggestion for future research would be to collect real time trip data if possible while the micromobility sharing service is in operations to solidify and better understand micromobility sharing utilization patterns and equity. However, the analyses conducted in this research showed that regardless of real-time vehicle availability data, the utilization of dockless micromobilities in Calgary was nevertheless spatially inequitable.

This thesis also does not identify the factors or variables that explain the observed patterns of spatial inequity of micromobility. The objective of this research was to identify whether utilization was spatially equitable, but not to identify reasons for these inequalities. Other factors that could influence the spatial equity of the system could be the effects of centrality, where most micromobility sharing trips (as well as other services) are focused on serving the economic and cultural center of the city, often the

[10] https://data.calgary.ca/Transportation-Transit/Calgary-Bike-and-Scooter-Share/bwkw-h2bc

downtown cores. Depending on the socioeconomic profile of the downtown core, the spatial equity of the system could be different. For instance, in Hosford and Winter's (2018) research on the docked bike sharing systems in five different Canadian cities, they found that the service for all cities were centered within and around their downtown cores. But, the bike sharing service of Hamilton, Ontario was considered to be more spatially equitable that the other four cities because the downtown core of Hamilton was associated with the more deprived areas of the city, whereas the downtown cores of the other cities were associated with more advantaged areas of the city. In the City of Calgary, the downtown core is considered to be a more advantaged area, i.e., the majority of the DAs comprising the area of the downtown core has a PDI score of 1. It has also been heavily invested in to support downtown development and attractiveness[11], with over $200 million being invested into the city's Greater Downtown Plan (The City of Calgary, n.d.). The downtown of Calgary was also highly concentrated with micromobility sharing trips, which also could factor into the utilization of micromobility sharing systems, although different factors aside from the PDI score were not investigated in this thesis.

Another limitation of this research is the predictive and explanatory value of the models produced in this thesis. The gravity model in Chapter 3 showed an R^2 value of about 0.09 and the linear regression in Chapter 4 showed an R^2 value of about 0.01 for e-scooters and 0.02 for bikes. These low R^2 values suggested that there are other factors

[11] https://www.calgary.ca/pda/pd/downtown-strategy/downtown-strategy.html

beyond PDI score that explain the patterns of micromobility sharing usage, such as centrality as described above, land use types, number of points of interest in different areas, proximity to transit hubs, and availability of cycling infrastructures. These factors could improve the models' explanatory and predictive value of micromobility sharing usage, but they were not included because they expand the scope of the research beyond considerations of spatial equity that were the focus of the study's objectives. As a result, the models in this research are limited in their predictive usage, and are unlikely able to accurately predict micromobility trip flows between hexbins or dissemination areas.

Finally, this study does not investigate the motivations for using, or not using, Calgary's micromobility sharing service, which will have affected patterns of utilization. Other non-spatial factors may be additional barriers to accessing the service, such as the pricing scheme, available payment methods, road network quality, preference to other transportation methods, and personal perceptions of shared bikes and e-scooters. It is possible that some areas may have had fewer shared micromobility trips because the majority of people in those areas had little to no desire to use a shared bike or shared e-scooter for these or other reasons.

5.3 Contributions

The works presented in this thesis contributes to the overall understanding of micromobility sharing, providing contexts for both bike sharing and the recently adopted e-scooter sharing systems. Chapter 3 provides a dedicated analysis on the spatial equity of dockless e-scooter sharing, which is still a new field in micromobility research due to the novelty of the system. Chapter 4 contributes a direct comparison of spatial equity within dockless micromobility sharing modes, filling the research gap of comparisons of micromobility sharing modes in the micromobility sharing field, and especially within the limited research on dockless micromobility sharing modes. The comparisons were also made in the same city, which provides a constant spatial frame of reference for appropriate comparisons to be made. The overall major findings in both Chapters 3 and 4 was that the dockless micromobility sharing services was spatially inequitable which was consistent with related previous research, and supports the ongoing discussion about the inequalities of micromobility sharing systems. While micromobility sharing systems, especially dockless e-scooters, tout to be better serving of the community than previous docked systems, this research suggests that newer dockless micromobility modes—specifically, e-scooter systems—are as inequitable as previous systems. More work and considerations need to be made to address the equity concerns of dockless micromobility sharing inequalities in order to allow all members of the community to experience and receive the benefits provided by these transportation modes regardless of the relative advantage or disadvantage of the areas in which they live, work, go to school, and leisure and recreate.

The results from this thesis can also help to inform policy makers, micromobility sharing operators, and transportation planners to adapt micromobility sharing into a more equitable and accessible service for the city. The dataset used to support this research came from Calgary's Shared Mobilities Pilot Project, which piloted dockless bike and e-scooter sharing systems in the city operated by third party companies. Pilot projects such as Calgary's provides a valuable short-term applied test of the perceptions and impacts of the systems, and ultimately informs whether the system remains operational in the city and identifies the potential changes in their operations and policies that need to be made as systems are made permanent and/or expanded. For instance, the City of Calgary surveyed opinions and provided reports on the Pilot to identify areas of concern and potential changes to the system's operation (Sedor & Carswell, 2019). The report analyzed on the usage of the system, focusing exclusively on the communities within the city's downtown, and also addressed concerns about the usage of the service on streets and sidewalks. But, the Pilot report did not explicitly analyze, measure, or address the equity impacts of the system, which is unsurprising given that most micromobility sharing pilot projects rarely consider the spatial equity impacts of the system (Palm et al., 2020).

The results of this thesis can help to inform relevant stakeholders of the main spatial equity concerns with micromobility sharing systems: that the systems tend to be used most heavily in areas of higher socio-economic advantage, while being underutilized within and between the most deprived (less advantaged) areas, as was the case with dockless micromobility sharing in Calgary. This knowledge can be used to help identify areas in a city that may require more considerations in the access to micromobility sharing services, and recommendations can be made to place more e-scooters and bikes in those areas. Awareness of the services may also be lacking, so advertising and promoting the service, or providing cheaper pricing schemes to identified underutilized areas may also improve the utilization and social equity of the service. The methods used in this thesis identify easily implementable approaches (both the gravity model and linear regression analysis) to measure the spatial equity impacts at critical stages of decision making, such as during or after the pilot project to help improve the service for all areas within a community, especially for people living in more deprived areas that may greatly benefit from access to micromobility sharing.

5.4 Future Research

As mentioned in the Introduction, micromobility sharing research is a burgeoning field of research as more and more cities implement micromobility sharing systems as part of the expanding world of lightweight accessible and connected transportation options. While this thesis provides an analysis and understanding of the spatial equity of utilization of micromobility sharing in Calgary, Alberta, future research could expand on the works presented here. As mentioned in the limitations, this research does not provide explanations for the patterns of spatial inequalities. Future research would be needed to identify the variables that influence and explain these patterns to further understand the reasons for the observed spatially inequitable patterns of micromobility usage in Calgary. Factors such as centrality, land use types, and proximity to public transit points such as train stations and bus stops could be potential factors that influence utilization and can be investigated in future research.

Regarding micromobility sharing in Calgary specifically, Lime, which provided the city’s only bike sharing service, removed their bike sharing services from the city after 2019 (Pike, 2020), so future research on micromobility sharing in Calgary could investigate whether the removal of the bike sharing service impacted the spatial equity of the service. The same methods used in this thesis could be used again to compare differences in the spatial equity of e-scooter utilization before and after the removal of dockless bike sharing from available micromobility options in the city. Without dockless bike sharing, does the spatial equity of e-scooter sharing in Calgary improve, decline, or remain the same? This could also lead into future research on cities with multiple dockless micromobility modes. For instance, does having multiple modes improve the spatial equity of the systems due to increased number of options and available vehicles to rent, or is it more beneficial for a city to focus their investments on one type of system to maximize its spatial equity considerations? As more cities invest in micromobility sharing systems, more research to determine which system is best suited to the spatial equity needs of the city given their specific environments and contexts, especially in cities with multiple micromobility sharing systems. It is possible that some systems are not as sustainable as others, such as bike sharing in Calgary, so it may be better for the city to maximize the usage of systems that are more sustainable, and increase the spatial equity of the system for the community by increasing the number of available vehicles, or reducing the cost of the service.

5.5 References

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Appendices

Appendix A: Descriptions of each variable collected from the City of Calgary's Shared Mobility Pilot project for each micromobility trip that is relevant to this analysis (Calgary Open Data, 2019).

Data	Description
Vehicle type	Type of vehicle used for trip (e.g., scooter, bicycle)
Start date	Date the trip was started
Start hour	Hour the trip was started in 24-hour clock (e.g., 13 is 1:00 pm-1:59 pm, 17 is 5:00 pm-5:59 pm)
Start day	Day of the week the trip started
Start day of week	Day of the week the trip started, prefixed for sorting (e.g., 0 is Sunday, 1 is Monday, etc.)
Trip distance	Distance of the trip, in metres
Trip duration	Duration of the trip, in seconds
Starting grid ID	Unique identifier of the grid in which the trip started
Ending grid ID	Unique identifier of the grid in which the trip ended
Startx	Longitude of the centrepoint of the start grid
Starty	Latitude of the centrepoint of the start grid
Startpoint	Centrepoint of the start grid
Endx	Longitude of the centrepoint of the end grid
Endy	Latitude of the centrepoint of the end grid
Endpoint	Centrepoint of the end grid

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