

Exploring the Accessibility Gap: Quantifying Transport Disadvantage in the City of Toronto

by

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Author's declaration

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Abstract

Researchers and policymakers have become increasingly interested in understanding the intersection between transportation and equity. Many scholars argue that it is important to understand transportation through an equity lens insofar as transportation provides the basic capability of access, which is the freedom and ability for people to reach destinations that are important for participating in society. However, not all transportation systems provide everyone with comparable levels of access. Different groups and individuals may experience different socioeconomic constraints that inhibit their ability to use or afford different modes of travel. This combination of limited accessibility with different socioeconomic constraints that impede one's ability to travel is referred to as transport poverty, transport disadvantage, or transport-related social exclusion.

The purpose of this thesis is to help planners and policymakers identify, analyze, and understand existing accessibility conditions to non-work destinations and to measure the impacts of different interventions on accessibility for transport disadvantaged neighbourhoods. The City of Toronto is used as a case study. Overall, transport disadvantage in Toronto tends to be concentrated in the city's suburbs, namely in North York, Scarborough, and the northern parts of Etobicoke. The results suggest that improving transit service is the most effective intervention for increasing accessibility for transport disadvantaged zones and reducing the disparity in accessibility levels between zones with higher and lower transport disadvantage.

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List of abbreviations

ANM	Accessibility need measure
APA	Access profile analysis
API	Access profile indicator
DA	Dissemination area
GC	Generalized cost
GTFS	General transit feed specification
GTHA	Greater Toronto and Hamilton Area
NIA	Neighbourhood Improvement Area
OD	Origin destination (pair)
SNI	Socioeconomic need index
TAZ	Traffic analysis zone
TTC	Toronto Transit Commission
TTS	Transportation Tomorrow Survey
VOT	Value of time

1.0 Introduction

Cities and metropolitan regions are increasingly facing challenges associated with rapid urbanization—55% of the world’s population is urbanized and by 2050, it is expected that 68% of people will live in urban areas (United Nations, 2018). This shifting population trend puts tremendous pressure on society to provide the infrastructure and services needed to sustain rapidly growing urban populations. Experts across all sectors are grappling with how to manage urban centres, which is made more complex in an era of rapid technological, social, political, economic, and environmental change. One critical challenge is ensuring that no one is “left behind” as cities grow and develop. More specifically, questions have arisen as to how cities can be planned, designed, and their services operated such that everyone has the ability to participate in society and realize the quality of life that they desire.

Transportation is one avenue to address these questions—it has the potential to be an equalizer insofar as it provides people with access to different opportunities and networks that allow travelers to increase their quality of life and engage in society. Access is defined as the ease of reaching desired destinations, which is affected by different impedances to travel such as cost, the availability and spatial distribution of destinations, and the quality and level of transportation services (Bocarejo & Oviedo, 2012; Dalvi & Martin, 1976; Manaugh, Badami, & El-Geneidy, 2015; Social Exclusion Unit, 2003). Through comprehensive, affordable, and reliable transportation systems, people can access destinations (e.g. employment, education, health care, polling stations, places of worship) that help increase their quality of life and facilitate economic, social, and political participation in society.

However, not all transportation systems provide everyone with comparable levels of access. Existing public transit networks, for example, may provide unreliable or limited service

(limited in terms of time, frequency, and geographic distribution) in some neighbourhoods, which restricts people's ability to access important destinations. A lack of accessibility is further compounded for groups or individuals that experience different socioeconomic constraints, such as limited income, limited time availability, language barriers, or physical or cognitive disabilities, which inhibit their ability to use or afford different modes of travel. This combination of limited accessibility with different socioeconomic constraints that impede one's ability to travel is referred to as transport poverty, transport disadvantage, or transport-related social exclusion (Allen & Farber, 2019; Kamruzzaman, Yigitcanlar, Yang, & Mohamed, 2016; Ricci, Parkhurst, & Jain, 2016).

Since the 1990s, researchers and governments have become increasingly interested in identifying and understanding transport disadvantage and other related concepts (Beyazit, 2011). In 2003, the United Kingdom's Social Exclusion Unit (SEU) published a report on transportation and social exclusion that is often cited for reframing how transportation systems are evaluated (Beyazit, 2011; Lucas, 2012; Páez, Scott, & Morency, 2012; Ricci, Parkhurst, & Jain, 2016). Rather than focusing on the easily quantifiable, mobility- and operation-based measures of a transportation network, such as travel time, vehicle-kilometres traveled, and transit ridership, the report articulates the ability of a transportation system to promote social inclusion and equitable accessibility to opportunities (Social Exclusion Unit, 2003).

The SEU's report is a good example of how addressing transport disadvantage has become a key societal goal; indeed, a growing number of transportation agencies acknowledge accessibility or equity as an important consideration in their work (e.g. TransLink, 2008; Boston Metropolitan Planning Organization, 2015; Bay Area Rapid Transit, 2018; City of Seattle Department of Transportation, 2016; Metrolinx, 2018; Transport for London, 2016). By

approaching transportation planning through the lens of tackling transport disadvantage, transportation systems have the potential to foster equity and inclusivity in urban spaces to ensure that everyone is able to participate in society as cities grow.

Many studies seek to identify and measure transport disadvantage in a way that encapsulates many factors and to map out where transport disadvantage or accessibility gaps exist (e.g. Allen & Farber, 2019; Currie, 2010; Currie et al., 2009; El-Geneidy, et al., 2016; Liu & Zhu, 2004; Shay, et al., 2016). Fewer studies take their research further to investigate the efficacy of different economic, land use, or transportation service interventions that may address transport disadvantage. The bulk of accessibility research also focuses on access to employment destinations; fewer studies measure access to non-work destinations such as schools, clinics, grocery stores, social services, or community centres that are also important to one's quality of life (Grengs, 2015).

The purpose of this thesis is to fill these research gaps by helping planners and policymakers identify, analyze, and understand existing accessibility conditions to non-work destinations and to measure the impacts of different interventions on accessibility for transport disadvantaged neighbourhoods. More specifically, this research focuses on accessibility to five non-work destinations: post-secondary institutions, hospitals, recreation centres, public libraries, and centres with early childhood development programming. Furthermore, four types of interventions are modeled to study their impacts on accessibility: parking charges, reduced transit fare, transit service improvements, and land use changes.

The city of Toronto is used as a case study for this research to represent large, complex urban centres that are facing pressures from population growth and increasing socioeconomic disparity. Toronto currently has a population of 2.9 million people and is one of Canada's major

urban centres (City of Toronto, 2018d). The city is located in the Greater Toronto and Hamilton Area (GTHA), an urban region in southern Ontario that consists of 7.2 million people distributed across 30 municipalities (Metrolinx, 2018). By 2041, the GTHA's population is expected to increase to over 10 million and Toronto is predicted to receive 20% of that growth (City of Toronto, 2015; Metrolinx, 2018).

Toronto has some of the highest levels of income inequality in Canada (United Way Toronto and York Region, 2017). The proportion of low and very low-income neighbourhoods has overtaken the proportion of middle-income neighbourhoods over the last 45 years (Toronto Foundation, 2017; United Way Toronto and York Region, 2017). Toronto also has the highest prevalence of child poverty in the country with 26.3% of people under the age of 18 living in low-income households (Toronto Foundation, 2017). At the same time, Toronto has the second-highest share of households with an annual income greater than \$100,000 in the country at 10.5%.

The city is also faced with the challenge of providing adequate transit service to a rapidly growing and diversifying population. To date, accessibility in suburban areas where most low-income populations are located has been insufficient (Ades, Apparicio, & Séguin, 2012, 2016; Toronto Foundation, 2018). Allen and Farber (2019) estimate that 24% and 15% of the census dissemination areas in Toronto are at a high or very high risk of experiencing transport poverty, respectively.

Given the strains on Toronto's existing transportation system and the complex socioeconomic challenges associated with population growth and increasing urbanization, transportation and equity challenges in Toronto are undeniable. Further work is needed to help planners and policymakers understand how different interventions can address these challenges.

The remainder of this thesis: i) provides a literature review of social equity concepts in transportation planning and the different approaches used to measure accessibility and transport disadvantage; ii) outlines the methods used in this research to measure transport disadvantage and the impacts of different interventions on accessibility; iii) presents and discusses the results; and iv) summarizes the research contributions of this thesis and identify areas for future research.

2.0 Literature review

The purpose of this thesis is to help planners and policymakers identify, analyze, and understand existing accessibility conditions to non-work destinations and to measure the impacts of different interventions on accessibility for transport disadvantaged neighbourhoods. Before measuring accessibility and identifying transport disadvantage, it is first useful to understand the meaning of both concepts and why they are relevant to broader discussions on equity. This literature review begins by exploring the philosophical underpinnings of equity and other related concepts such as justice and fairness. It draws on existing research to explain why these concepts are important and how they are interpreted in a transportation context. Next, different methods of accessibility measurement are compared for their ability to operationalize equity in transportation research. Finally, this literature review presents synthesized findings from existing research that also seeks to measure accessibility and identify transport disadvantage in order to identify research gaps.

2.1 What is equity?

For centuries, society has grappled to define the meaning of equity, fairness, and justice.¹ Early philosophers provided theories on these concepts which have influenced our modern understanding and operationalization of them in policy and law (Beyazit, 2011). However, little work has been done to employ these philosophical theories of equity and justice in the transportation realm even though planners and researchers have become increasingly interested in their application to transportation policies and planning (Pereira, Schwanen, & Banister,

¹ The academic literature does not make strong distinctions between these terms and they are often used synonymously, as will be done for the remainder of this thesis (Blanchard, 1986; Pereira, Schwanen, & Banister, 2017).

2017). Understanding the philosophical underpinnings of equity and justice in transportation research is critical given that different interpretations of their meaning can “make it difficult to compare the findings from different studies and to obtain insights that could inform policy decisions” (Pereira, Schwanen, & Banister, 2017, p. 170).

Equity is broadly defined by Blanchard (1986) as the distribution of costs and benefits among citizens; however, “there is no consensus about what an equitable distribution of costs and benefits ought to be” (p. 29) or how costs and benefits are defined. Different studies refer to a variety of equity theories, each with their own interpretation of what constitutes a fair distribution of costs and benefits. Seven different theories of equity that are commonly identified in transportation literature are briefly discussed here: utilitarianism, libertarianism, intuitionism, egalitarianism, sufficientarianism, spheres of justice, and the capability approach.

2.1.1 Utilitarianism

Utilitarianism is grounded on the idea that the most equitable outcome is one that maximizes society’s collective “good” or utility (Lucas, van Wee, & Maat, 2016; Kymlicka, 2002). It takes on a consequentialist approach in that equity is defined by the *outcomes* of an action or policy; in this case, equity is realized when an outcome results in the greatest good for the most number of people. Cost-benefit analysis evaluation methods are based on a utilitarian theory of equity (Nahmias-Biran, Martens, & Shiftan, 2017). A new project or policy is deemed the best course of action if it produces the greatest ratio of benefits to costs.

One of the most cited flaws of utilitarianism is its lack of consideration for the distribution of utility across a population (Kymlicka, 2002; Nahmias-Biran, Martens, & Shiftan, 2017). It assumes that everyone’s individual interests and needs are the same, and therefore only the collective utility of a group is considered. This is problematic in situations where a project or

policy results in the greatest overall benefit to society, but the benefits accrue only to those who are already the most well off. In a transportation context, Pereira, Schwanen, and Banister (2017) explain that:

The utility derived from an activity is commonly measured by people's willingness to pay, and because benefits derived from transport projects have traditionally been evaluated in terms of the monetary value of travel time savings, an unintended consequence of utilitarian evaluations is that they implicitly prioritise accessibility gains to more profitable activities and people with higher incomes and hence higher values of time. (p. 179)

In other words, wealthier populations are considered to have higher values of time because they generate more income and are therefore willing (and able) to pay more for the time savings generated by a transportation project. In doing so, a utilitarian approach values the time savings of wealthier populations more than that of poorer populations.

Another limitation of a purely utilitarian approach to project or policy evaluation is that it does not recognize the unique barriers that different individuals face that may prevent transit use—for example, language barriers, limited income, or physical disabilities. By focusing purely on the utility derived from a project or policy, utilitarianism neglects the diverse needs of individuals and, in doing so, gives preference to those who are already the most advantaged (Beyazit, 2011).

2.1.2 Libertarianism

The core principle of libertarianism is that each person has the freedom to make their own choices without impedance from other individuals or groups on the condition that one's choices do not impede the same decision-making freedoms of others (Kymlicka, 2002).

Libertarians are strong proponents of free markets because they allocate resources according to

people's individual choices, which is the most equitable and efficient distribution method according to libertarianism.

Critics of libertarianism, however, point out that an individual's choices are not always made freely; rather, people's decisions are constrained by their individual circumstances, whether inherited or imposed by society (Kymlicka, 2002). Being poor, for example, limits one's purchasing power and therefore their ability to make choices in the market. In this way, the distribution of resources tends to gravitate towards those with higher purchasing power under free market conditions.

When it comes to providing transportation services in a purely free market, "private companies have no economic incentives to consider the special needs of minority groups such as people with disabilities, to provide public goods such as urban roads, and to provide transport services to distant and impoverished neighbourhoods where services are less profitable" (Pereira, Schwanen, & Banister, 2017, p. 180).

Libertarianism also does not provide a mechanism to account for the negative externalities that arise from individuals making decisions based on their own interests (Hausman & McPherson, 2006 as cited in Pereira, Schwanen, & Banister, 2017). If everyone chooses to make all their trips by driving, for example, this causes increased congestion and vehicular emissions. Libertarianism does not allow for governments to regulate the use of roads or other public goods to mitigate such negative externalities because it would infringe on individuals' decision-making freedoms.

2.1.3 Egalitarianism

Egalitarianism is based on Rawls' (1971) theory of justice, which is grounded on two principles. The first principle declares that everyone should have equal rights to basic liberties,

including freedom of speech and association. The second principle deals with the provision of primary goods, “which are various social conditions and all-purpose means that are necessary to enable citizens to pursue their life plans...; they include in broad categories income and wealth, opportunities, powers and prerogatives of authority, and the social bases of self-respect” (Pereira, Schwanen, & Banister, 2017, p. 174). Rawls asserts that justice is achieved when the distribution of primary goods results in the greatest benefit to those who are the least well-off (Lucas, van Wee, & Maat, 2016). In other words, actions or decisions need not result in the greatest net benefit—as suggested by utilitarianism—but should maximize the welfare of those who are the most disadvantaged. In this way, egalitarianism provides a useful lens to legitimize policies that aim to improve basic services for the most underserved populations, even if it negatively impacts aggregate levels of utility (Lucas, van Wee, & Maat, 2016).

Nahmias-Biran, Martens, and Shifan (2017), however, argue that egalitarianism is limited in providing direction for how primary goods should be distributed given that people derive varying levels of utility from different things. Consider a scenario where richer groups are taxed in order to finance transit services for the most disadvantaged. It is thought that taxing richer groups to finance those services will decrease the overall income of society since taxes disincentivize hard work. Although disadvantaged groups will benefit from transit services, there are potential ramifications to their personal income that arise from the overall decrease to society’s wealth (Nahmias-Biran, Martens, & Shifan, 2017). In this scenario, egalitarianism is unable to clarify whether transit services or income should be prioritized when distributing primary goods. Ultimately, different people have different needs, so it is difficult to determine which primary goods are more important than others (Beyazit, 2011).

2.1.4 Sufficiencyarianism

Sufficiencyarianism “assumes that everybody should be well off up to a certain minimum threshold, which is ‘sufficient’ for fulfilling their basic needs and to guarantee their continued wellbeing” (Lucas, van Wee, & Maat, 2016, p. 477). When someone has less than the minimum amount, society has an obligation to that individual to remedy their deficit of the good or service in question (Herlitz, 2018). One of the major difficulties of sufficiencyarianism is defining the minimum level of goods or services that is necessary to fulfill everyone’s basic needs when limited resources are available. In transportation, for example, there is a limit to the financial resources available to fund infrastructure to ensure that everyone has an acceptable level of transit service. In such situations where resources are scarce, sufficiencyarianism does not provide guidance on whether society should distribute available resources equally among those who have less than the minimum threshold, whether those with larger deficits should be prioritized, or whether resources should be distributed such that the most number of deficits are remedied (Herlitz, 2018).

2.1.5 Intuitionism

Unlike the other theories of equity presented here, intuitionism does not propose a singular idea of what equity is; rather, it suggests that equity is achieved in different ways depending on the moral dilemma at hand (Barry, 1965 and Miller, 1999 in Pereira, Schwanen, & Banister, 2017). Intuitionism calls for a context-dependent approach to decision making, whereby the distribution of costs and benefits will depend on a variety of considerations including “merit, basic needs, rights, formal equality, compensation, non-discrimination, or procedural fairness” (Pereira, Schwanen, & Banister, 2017, p. 174). Intuitionism suggests that equitable decisions are made based on moral judgements, which are self-evident and developed

through one's intuition. Although intuitionism recognizes that not all moral dilemmas are the same and that there is some level of subjectivity involved, it is unable to provide clarity on which theories or approaches are most effective in achieving equity in different situations (Kymlicka, 2002).

2.1.6 Spheres of justice

Spheres of justice is an approach proposed by Walzer (1983), which suggests that equity is achieved when the exchange and distribution of goods are conducted according to shared cultural values. Unlike libertarian thinkers, Walzer believes that the distribution of goods should not be dictated by market forces if those goods are attributed with distinct social meaning—that is, “if [their] social meaning differentiates [them] from regular commodities that are exchanged in the market place” (Nahmias-Biran, Martens, & Shiftan, 2017, p. 196). If a good has a distinct social meaning, its distribution should be conducted in what Walzer (1983) calls the ‘distributive sphere’, which has two conditions. First, a good should be distributed according to the social meaning that society has ascribed to that good. Second, a distributive sphere for a particular good should be independent of that for other goods so that the distribution of one good does not influence the distribution of others. The distribution of money and power, for example, which typically dominates the distribution of other goods in a free market, should not dictate the distribution of goods with distinct social meaning, such as education or health care (Nahmias-Biran, Martens, & Shiftan, 2017).

The major limitation of spheres of justice is similar to that of intuitionism. Walzer's theory does not specify the approach that should be used to distribute goods and services in an equitable manner, only that it should be based on socially-constructed values (Nahmias-Biran, Martens, & Shiftan, 2017). This makes it difficult to evaluate whether a decision or action is

equitable given that different people and societies value goods differently and have varying opinions on what it means to distribute something fairly.

2.1.7 Capability approach

The capability approach was developed by Amartya Sen in the 1980s largely as a response to the limitations of existing equity theories, namely utilitarianism and egalitarianism (Sen, 1980 in Beyazit, 2011). The capability approach changes the discourse on equity by shifting the focus away from the distribution of utility or goods towards the distribution of functionings and capabilities. “Functionings are states of being and doing, that is, activities that a person can undertake. A capability set represents a person’s opportunities to achieve functionings (Dagsvik, 2013)” (Nahmias-Biran, Martens, & Shiftan, 2017, p. 198). In other words, the capability approach is not concerned with the actual *outcomes or achievements* of one’s functionings or capabilities (e.g. wealth); rather, the capability approach values the *freedom and ability to achieve* different things, whatever they may be (Beyazit, 2011). Even if one does not take advantage of the capabilities made available to them, there is inherent value in the availability of opportunity and the freedom to choose one’s own life course (Sen, 2011 in Nahmias-Biran, Martens, & Shiftan, 2017).

Sen furthers the capability approach by calling for “basic capability equality”—that is, equality in the abilities of persons to do basic things, including the “ability to move..., the ability to meet one’s nutritional requirements, the wherewithal to be clothed and sheltered, [and] the power to participate in the social life of the community” (Sen, 1979, p. 218). Differences in capability levels above a certain threshold are not considered inequitable since everyone benefits from having a guaranteed minimum level of basic capabilities (Nahmias-Biran, Martens, & Shiftan, 2017). In this way, Pereira, Schwanen, and Banister (2017) explain that the capabilities

approach combines ideas from egalitarianism (by proposing some of kind of basic equality) and sufficientarianism (by requiring some minimum level of these basic equalities), which is the hybrid theory of equity proposed by Lucas, van Wee, and Maat (2016).

Like sufficientarianism, the biggest challenge with adopting the capabilities approach is defining the minimum level of basic capabilities that should be guaranteed to everyone (Pereira, Schwanen, & Banister, 2017). There is some level of values-driven decision making that is required to determine such minimum thresholds, which is challenging given competing perspectives on what is considered to be a sufficient level of capability necessary to achieve different functionings. Nonetheless, researchers agree that the capabilities approach is a useful theory to understand equity in a transportation context because fundamentally, transportation is a means to achieve different functionings—it provides people with the ability to access and engage in different opportunities (Beyazit, 2011; Nahmias-Biran, Martens, & Shiftan, 2017; Pereira, Schwanen, & Banister, 2017). Table 1 summarizes each of the equity theories discussed above. These theories are revisited at the end of this thesis to discuss how different transportation policies and interventions relate to equity.

Table 1: Summary of equity theories. Adapted from Pereira, Schwanen, & Banister (2017).

Equity Theory	Distribution of what?	Fairest distribution pattern	Key theoretical limitations
Utilitarianism	Utility, welfare	Maximum utility for the collective group/society	Does not consider individual needs and how utility is distribution across a population
Libertarianism	Basic liberties, specifically freedom of choice and decision making	According to people's individual choices	Does not account for the fact that individual choices are not always made freely Does not provide a mechanism to account for the negative externalities of individuals' choices
Egalitarianism	Basic liberties and primary goods	Maximizes benefit for the least well-off	Does not clarify how primary goods should be distributed given that individuals derive different levels of utility form different things
Sufficientarianism	Welfare, basic needs	Everyone has a minimum level of welfare that is considered to be 'sufficient' by society	Does not provide direction on how resources should be distributed when scarcity occurs (i.e. not enough resources to achieve a sufficient level of wellbeing for everyone)
Intuitionism	Varies depending on the moral dilemma at hand	Depends on context and based on one's moral judgement	Too subjective and therefore unable to clarify which distributive approach is most effective in achieve equity in different situations
Spheres of Justice	Goods with distinct social meaning	Based on socially-constructed values that are ascribed to the good in question	Too subjective and therefore unable to clarify which distributive approach is most effective in achieve equity in different situations
Capabilities Approach	Functionings and capabilities	Everyone has a guaranteed minimum level of basic capabilities	Does not define the minimum level of basic capability; some level of values-driven decision making is required to determine this

2.2 What is equity in a transportation context?

Many scholars argue that transportation is important because it provides the basic capability of access, which is the freedom and ability for people to reach destinations that are important for engaging in different opportunities or, as Sen (1980) refers to, functionings (e.g. Allen & Farber, 2019; Beyazit, 2011; Bocarejo & Oviedo, 2012; Currie, 2010; Lucas, 2011; Lucas, 2012; Neudorf, 2014; Pereira, Schwanen, & Banister, 2017). Unlike utility or primary goods, access is not an outcome, but a means to realizing an outcome. Access allows people to achieve different functionings, such as receiving medical care, attending school or work, or voting at a polling station during an election. Access is therefore a necessary capability for people to participate in society—without access, people are at risk of experiencing social exclusion or some form of deprivation, either economically, socially, politically, or otherwise (Kamruzzaman, Yigitcanlar, Yang, & Mohamed, 2016).

The concept of social exclusion is thought to originate in French literature during the 1970s where “the term was used to refer to individuals who ‘slipped’ through the social insurance system; the socially excluded were those who were administratively excluded by the state (Burchardt, Grand, & Piachaud, 1999; Burchardt, Grad, & Piachaud, 2002)” (Kamruzzaman et al., 2016, p. 3). In a transportation context, Kenyon, Lyons, & Rafferty (2002) describe transport-related social exclusion as “the process by which people are prevented from participating in the economic, political, and social life of the community because of reduced accessibility to opportunities, services, and social networks, due in whole or in part to insufficient mobility” (p. 210-211).

Based on this definition of transport-related social exclusion, it follows that equity is achieved when “there are no ‘exclusionary’ or discriminatory practices hindering individuals

from participating economically, socially, and politically in society” (Dempsey, Bramely, Power, & Brown, 2011, p. 292). Those who have limiting needs or abilities—either due to income, education level, social class, physical ability, or otherwise—should not be excluded from accessing opportunities insofar as participation is essential to achieving social inclusion (Farrington & Farrington, 2005; Gray, Shaw, & Farrington, 2006; Hine & Mitchell, 2003; Kamruzzaman, Yigitcanlar, Yang, & Mohamed, 2016; Yigitcanlar, Dodson, Gleeson, & Sipe, 2007). An equitable transportation system is therefore one that is inclusive, providing access to opportunity for all, regardless of physical mobility limitations; cognitive barriers that preclude or limit independent travel; income levels that reduce one’s travel choice set; language barriers that make it difficult for non-native speakers to navigate a transportation system; or other impedances that inhibit one’s ability to travel.

Accessibility is a measure of “how effectively travel effort is translated into destination access” (Neudorf, 2014, p. 2; also see Bocarejo & Oviedo, 2012; Dalvi & Martin, 1976; Manaugh, Badami, & El-Geneidy, 2015; Nahmias-Biran, Martens, & Shifan, 2017). It represents an individual’s or group’s potential to reach different opportunities by accounting for the level of travel effort required to overcome the impedances of reaching a destination, such as time, physical energy, and monetary costs (Bocarejo & Oviedo, 2012; Grengs, 2015; Hansen, 1959; Neudorf, 2014). In order to realize an equitable transportation system, the capability approach suggests that accessibility must be distributed in a way that guarantees everyone a minimum level of capability that is required to achieve different functionings (Pereira, Schwanen, & Banister, 2017). However, defining a minimum level of accessibility is difficult and has not been widely explored in the literature; further research is needed to gain a deeper

understanding of the relationship between accessibility and activity participation (Nahmias-Biran, Martens, & Shiftan, 2017).

Kamruzzaman et al. (2016) expands on this idea, noting that accessibility measures alone are unable to capture actual activity participation. Accessibility measures are limited in that they only “[evaluate] the performance of transport and/or land use systems that potentially facilitate participation in activities”; they do not examine “actual (or realized) activity-travel patterns of individuals” (p. 9). Sen (1980), however, argues that there is value in choice and the availability of opportunities. Even if one does not take advantage of the full range of accessibility available to them, they have the potential to realize that level of accessibility and the freedom to choose whether they act upon it. According to Sen’s capability approach, the ability and freedom to choose has value in and of itself.

Defining a minimum level of accessibility also depends on the way that accessibility is measured. The capability approach suggests that accessibility measures should account for individual characteristics that may impede mobility as well as characteristics of the transport and land-use system (Nahmias-Biran, Martens, & Shiftan, 2017). The following section will explore different methods for accessibility measurement and how they incorporate different factors that impact accessibility levels.

2.3 Accessibility measurement methods

Many studies have traditionally relied on anecdotal and qualitative evidence of expressed need to identify transport disadvantage; however, this is problematic for planners and policymakers because effective policy responses require “an objective and systematic approach to identifying gaps between services and social needs” (Currie, 2010, p. 31). Accessibility measures have become a common method to empirically and systematically evaluate equity and

inclusion in a transportation system because they reveal the extent to which a transportation system provides the ability for people to participate in society (Hine & Mitchell, 2003; Kenyon, Lyons, & Rafferty, 2002; Social Exclusion Unit, 2003). Different groups may experience disparate levels of accessibility because of where they live, financial constraints to be able to afford travel, limited time availability, or the spatial distribution of destinations, all of which affect an individual's potential to access opportunities and therefore participate in society. By comparing accessibility levels among different groups or areas, accessibility measures inform transportation planners which populations are underserved and where gaps in transportation service exist in order to develop solutions to resolve these disparities (Bocarejo & Oviedo, 2012; El-Geneidy, et al., 2016a; El-Geneidy, et al., 2016b; Mamun & Lownes, 2011).

Researchers have developed and refined different accessibility measurement tools with varying degrees of complexity and methodological rigour. Each attempt to capture all of the components that affect accessibility while maintaining the ease of its application and interpretability (Geurs & van Wee, 2004; Handy & Niemeier, 1997; Mamun & Lownes, 2011; Neudorf, 2014). Geurs and van Wee (2004) develop a set of criteria to evaluate the strengths and weakness of different methods. The first criterion is theoretical soundness, which is the ability of a measure to encapsulate all the different components which affect accessibility. As Pereira, Schwanen, and Banister (2017) note, accessibility measures should represent “a combination of personal abilities and the social, economic, and built environment, which is a more complex and multidimensional concept of accessibility than often used in transport studies (Tyler, 2006)” (p. 183). A theoretically-sound accessibility measure should be i) sensitive to land use changes (including the spatial distribution of destinations and competition for reaching these destinations), ii) sensitive to transportation system changes, iii) sensitive to the time constraints

of opportunities, and iv) incorporate individual characteristics (e.g. income, age, physical ability) that determine one's ability to reach opportunities (Geurs & van Wee, 2004).

Neudorf (2014) adds another element to Geurs and van Wee's (2004) theoretical soundness criterion, which is "the ability to distinguish between local and regional accessibility" (p. 11). This differentiates between destinations which require little travel effort (i.e. local) and those which require more effort (i.e. regional). This is an important consideration particularly when studying social equity since some populations may not be able to afford—in both monetary and time costs—the greater effort required to reach farther destinations.

Geurs and van Wee's (2004) second evaluation criterion is operationalization, which is the level of difficulty in using an accessibility measure in terms of data requirements, time, and expertise. Interpretability is the third criterion which evaluates how easy it is to understand the results of an accessibility measure. Although measurement tools should be methodologically rigorous, their complexity should not prevent planners and policymakers from interpreting their results. The final evaluation criterion is the ability for an accessibility measure to conduct social and economic comparisons—that is, to compare the social and economic impacts of accessibility conditions on different individuals/groups. Neudorf (2014) adds comparative analysis as another evaluation criterion to Geurs and van Wee (2004). This is similar to the social and economic comparisons criterion, but it recognizes the need for accessibility measures to be applied to comparisons more generally (e.g. between different locations, travel modes, etc.).

Geurs and van Wee (2004) assess different types of accessibility measures based on their evaluation criteria. They identify four types of accessibility measures: infrastructure-based, location-based, person-based, and utility-based measures. Infrastructure-based measures evaluate accessibility solely using transportation system characteristics, "such as travel times, congestion,

and operating speed on the road network” (Geurs & van Wee, 2004, p. 131). Research which studies transit accessibility often focuses on proximity to stops/stations and the frequency and range of transit services (e.g. Mamun & Lownes, 2011). Although these metrics are easy to conduct and interpret, they neglect the spatial distribution of destinations (i.e. land use), time considerations, and individual characteristics which severely limits the theoretical soundness of infrastructure-based measures (Geurs & van Wee, 2004; Neudorf, 2014).

Location-based measures usually analyze the time or distance required to travel between origins and destinations. A variety of location-based measures exist, including contour measures, potential measures, adapted potential measures, and balancing factor measures. Of these, contour and potential measures are the most commonly discussed in the literature and are usually referred to as cumulative opportunity measures and gravity-based measures, respectively (e.g. Boisjoly, Moreno-Monroy, & El-Geneidy, 2017; Chen, Yang, Kongsomsaksakul, & Lee, 2007; Handy & Niemeier, 1997; Neudorf, 2014). Cumulative opportunity models are often employed for their ease of operationalization and interpretation (Geurs & van Wee, 2004; Neudorf, 2014). They typically define a travel time or distance-based boundary around an origin and count the number of destinations that can be reached within that threshold (e.g. Boisjoly, Moreno-Monroy, & El-Geneidy, 2017; Moniruzzaman & Páez, 2012; Wang & Chen, 2015). The level of accessibility is therefore determined by the cumulative number of destinations that can be reached within that defined threshold. Although simple to use, cumulative opportunity models are criticized for their use of a binary, and sometimes arbitrarily defined, threshold (Neudorf, 2014).

Gravity-based models measure accessibility by giving weight to different destinations according to level of effort required to reach that destination from an origin (Geurs & van Wee, 2004; Handy & Niemeier, 1997; Hansen, 1959). “Accessibility is positively related to the

number or magnitude of destinations and negatively related to the impedance associated with reaching them” (Neudorf, 2014, p. 17). A common approach to account for travel impedance is to use a decay function to represent decreasing willingness to travel as the time, distance, and/or cost of travel increases (e.g. Bocarejo & Oviedo, 2012; Foth, Manaugh, & El-Geneidy, 2013). Gravity models are methodologically stronger than cumulative opportunity models in terms of their theoretical soundness; they are able to account for the combined effects of land use and transportation system components, as well as some of the socioeconomic constraints of individuals (Geurs & van Wee, 2004).

One of the major flaws of gravity models is their inability to dynamically assess accessibility across a period of time (El-Geneidy, et al., 2016a; Neudorf, 2014). El-Geneidy et al. (2016a) overcome this by measuring and comparing accessibility at six different times of day in order to account for “daily fluctuations in service and job availability” (p. 541). Neudorf (2014) also notes that gravity-based measures are weak when it comes to comparative analysis. Grengs (2015) echoes this, arguing that “the gravity model presents a problem in making comparisons across social groups, and the problem stems from the differing use of travel modes among social groups” (p. 6). In order to meaningfully compare accessibility among different social groups using a gravity model, Grengs (2015) controls for the fact that some groups are dependent on certain modes—specifically public transit—while others are not.

Other categories of accessibility measures include person-based and utility-based measures, although these are less frequently used in the literature (Geurs & van Wee, 2004). Person-based approaches measure accessibility at the individual level—that is, they evaluate the number of activities that an individual can reach given their personal spatial and temporal constraints. Kwan (2010) argues that this improves the sensitivity of accessibility measurements

to individual variations, such as gender and ethnicity. This disaggregated approach improves the granularity of accessibility analyses which provides better detail of individual differences in accessibility and therefore is a more accurate representation of transportation equity gaps (Geurs & van Wee, 2004). The trade off, however, is that disaggregation increases measurement complexity.

Finally, utility-based measures evaluate accessibility according to the economic benefit that someone gains from reaching a destination using a particular mode relative to other destinations/mode choice (Bocarejo & Oviedo, 2012; Geurs & van Wee, 2004; Handy & Niemeier, 1997). Chen et al. (2007) use a utility-based approach to measure changes to accessibility—in terms of travel time, cost, and behavioural responses from travelers—as a result of disruptions to the transportation network (e.g. traffic accidents or natural disasters). In general, though, it is rare to find utility-based approaches in the literature given the difficulty in operationalizing and interpreting them (Neudorf, 2014).

2.3.1 Access Profile Analysis (APA): A new approach to accessibility measurement

Cumulative opportunity models and gravity models have historically dominated accessibility research (Geurs & van Wee, 2004). In 2014, Neudorf developed a new accessibility measurement method called Access Profile Analysis (APA) building off of Black & Conroy's (1977) work in an attempt to overcome some of the limitations of these mainstream accessibility measurement approaches. "The basic analytic goal of APA is to measure the ease of reaching destinations using various travel modes" (Neudorf, 2014, p. 25). It measures accessibility across a spectrum of travel effort by determining the cumulative number of destinations that can be reached from an origin using different modes at varying levels of generalized cost. The generalized cost (GC) is a measure of the travel effort required to reach a destination—

specifically, the linear sum of a trip's out-of-pocket expenses and its associated time costs expressed as a monetary value. In essence, APA uses the cumulative opportunity model approach, but it determines the number of reachable destinations across a continuum of travel effort rather than only within single, discrete thresholds (see Figure 1). This approach overcomes the arbitrarily defined thresholds used in cumulative opportunity models; the method can also be applied to multiple modes and time periods, allowing easy comparisons of accessibility under different scenarios.

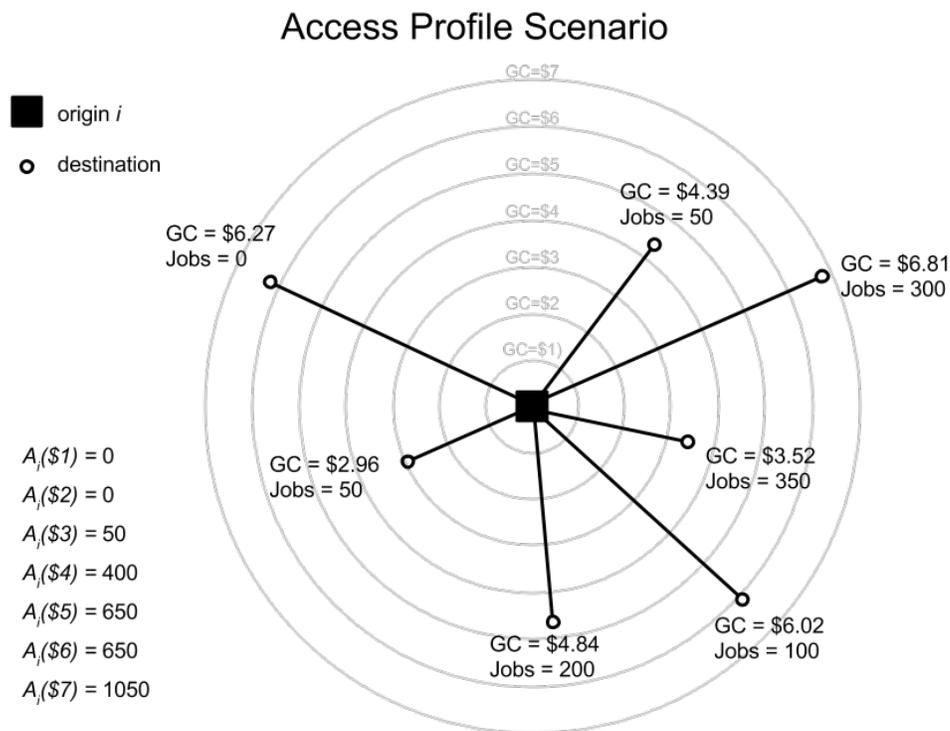


Figure 1: Example of an access profile scenario. From Neudorf (2014).

Access Profile Illustration

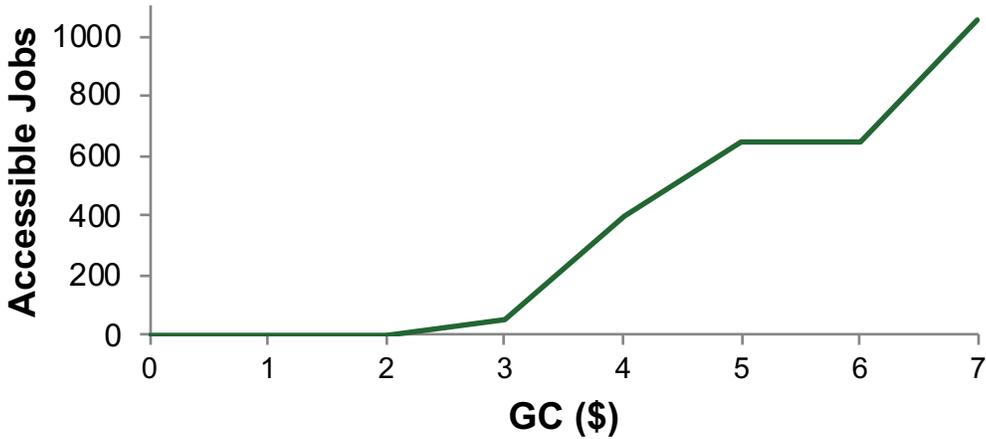


Figure 2: Example of an access profile illustration. From Neudorf (2014).

Because the number of reachable destinations is determined across a spectrum of travel effort, APA allows for a graphical representation of accessibility, or what Neudorf (2014) calls an access profile (see Figure 2). The cumulative number of reachable destinations is graphed as a function of *GC* and can be compared among different modes to determine which mode provides the best accessibility at different *GC* intervals. The area under the access profile curve is divided by the total graph area to generate an overall accessibility indicator, referred to as the Access Profile Indicator (*API*) (Neudorf, 2014; see Figure 3). A maximum *API* value can also be calculated to indicate the maximum level of accessibility that is possible when all modes are considered. This is done by combining the access profile curves of each mode to generate a new curve—the maximum access profile curve—that indicates the highest number of reachable destinations at different *GC* levels (see Figure 3). The area under the maximum access profile curve divided by the total graph area gives the maximum *API* value. A more technical discussion of how the APA method is used is provided in section 3.0.

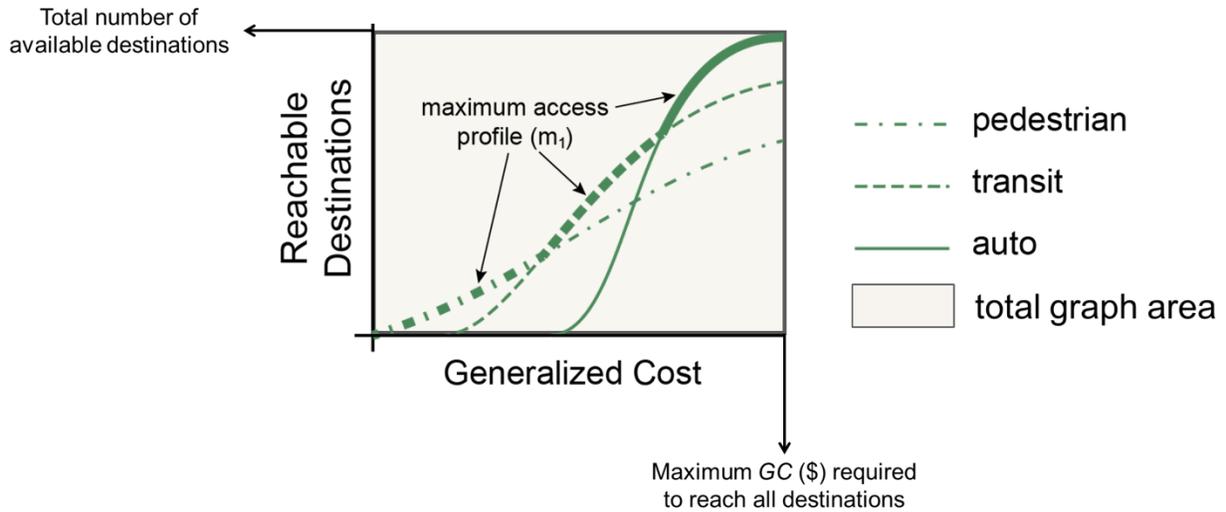


Figure 3: Example of a maximum access profile. Adapted from Neudorf (2014).

APA improves upon existing accessibility measures in a number of ways, most notably in its ability to visualize and interpret accessibility at varying levels of travel effort. Although gravity and cumulative opportunity models can calculate overall accessibility levels, APA is able to produce access profiles that illustrate a more nuanced story about accessibility than a single accessibility score. The point along the x-axis where the access profile curve begins represents the “barrier to entry”, or the minimum level of travel effort (in time and money) that is required for a particular mode to reach any destination (Neudorf, 2014). In urban areas where destinations are more densely distributed, pedestrian travel typically has the lowest barrier to entry since walking is free; the only associated cost with walking is the time it takes to reach a destination. This is why pedestrian travel tends to be the most competitive travel mode (i.e. provides the best accessibility) at lower *GC* levels—more destinations can be reached by walking at a lower cost than other modes when destinations are close to an origin. The barrier to entry for transit and auto travel is not free. Travelers must pay a transit fare in order to access any destinations by bus, streetcar, or subway, or pay the fixed costs associated with car ownership in order to reach any

destinations by auto. Because car ownership has the most expensive barrier to entry of all the modes, the access profile curve for auto travel begins at a much higher *GC* level on the x-axis.

The slope of an access profile represents the “relative accessibility gain for a unit increase of *GC*” (Neudorf, 2014, p. 49). A steeper slope indicates that a higher level of accessibility is gained for each additional unit of *GC*. Of all the inputs to the *GC* calculation, travel time is the most variable factor due to the difference in travel speed between the different modes, making time the primary determinant of the access profile slope (Neudorf, 2014). Faster travel speeds mean that more destinations can be reached per unit of *GC*, resulting in a steeper access profile curve. Auto travel is generally faster than taking transit or walking and typically will produce the steepest slope. Walking, however, is the slowest and will have the shallowest access profile curve. It is also important to note that the density of destinations will also impact the slope of an access profile (Neudorf, 2014). A higher concentration of destinations will result in a steeper access profile since more locations can be reached per unit of *GC* compared to a lower density area.

One of the major limitations of the APA method is its sensitivity to the *GC* calculation (Neudorf, 2014). Including or excluding different variables in the *GC* calculation can result in very different accessibility outcomes. For auto travel, for example, incorporating the fixed costs of car ownership into the *GC* calculation may reduce accessibility by car to be lower than accessibility by transit. When car ownership costs are not considered, however, auto travel may provide higher accessibility than transit. APA also does not consider the fact that trips can be taken using multiple modes—for example, someone may take transit to a particular subway station and then get picked up by a friend driving a car to reach their final destination. Similarly, it is difficult for APA to capture the pedestrian elements of all trips, unless the access and egress

segments of a trip are directly accounted for in the time costs of the *GC* calculation. Calculating the *GC* of driving trips, for example, may not account for the time needed to walk from a parking spot to the final destination. In this way, access profile curves are not able to capture the complexity of combining multiple modes and the impact it has to accessibility levels.

APA also does not account for household or personal incomes. This is problematic because although auto travel may provide the highest accessibility at certain *GC* levels, it does not preclude someone from not being able to afford or have access to a vehicle. Similarly, some people may not be able to take transit—even though they live in an area that offers high accessibility by transit—because of physical abilities. APA also does not capture the time constraints of destinations (Neudorf, 2014). Temporal factors such as jobs shifts and congestion during peak hours are not reflected in accessibility levels, but this could be resolved by developing and comparing access profile curves at different time periods.

2.4 Findings from existing transport disadvantage and accessibility research

A significant portion of existing accessibility research focuses on accessibility levels for groups that have historically been disadvantaged (e.g. women, low-income groups, and recent immigrants) (Walks, 2015). Some studies suggest that socioeconomically disadvantaged populations do not always experience lower levels of accessibility compared to other groups. In Melbourne, Australia, for example, Delbosc and Currie (2011) conclude that low-income groups and youth benefit more from greater transit supply in the inner city than the general population. In the Greater Toronto Area (GTA), El-Geneidy et al. (2016a) find that the most socially disadvantaged areas in the region experience equitable accessibility by transit. They find that the most socially disadvantaged areas have significantly better accessibility to low-wage jobs between 5:00 am and 6:00 am, 6:00 am and 7:00 am, and 12:00 pm to 5:00 am. Similarly, Foth,

Managuh, and El-Geneidy (2013) find that socially disadvantaged populations in Toronto experience high accessibility to jobs compared to non-disadvantaged groups despite their migration to the suburbs (i.e. away from central, high-density neighbourhoods) between 1996 and 2006.

Other research, however, reveals that disadvantaged groups do experience greater transport disadvantage. Farber, et al. (2018), for example, find that Syrian refugees in the Durham Region, a regional municipality adjacent to the City of Toronto, experience lower perceived levels of accessibility than the general population, which has negatively affected activity participation. Some research suggests that a lack of car access is the main barrier to accessibility for immigrant and minority populations (Parks, 2004; Patacchini & Zenou, 2005). Páez et al. (2013) explore accessibility levels for single parents in Toronto and find that, overall, they experience lower levels of accessibility to employment.

In a country-wide study, Allen and Farber (2019) investigate the extent of transport poverty in eight major cities in Canada. Similar to El-Geneidy et al. (2016a) and Foth, Managuh, and El-Geneidy (2013), Allen and Farber (2019) find that residents with low socioeconomic status generally experience better levels of accessibility by transit. However, they emphasize that there is still a considerable portion of Canadians with low socioeconomic status that live in neighbourhoods with poor transit accessibility. They estimate that “40% of all low-income residents in [the study areas] are at risk of transport poverty, 5% of the overall population, and nearly one million people in total” (p. 219). Residents that experience transport poverty tend to be located away from major transit corridors, either in high-density, low-income neighbourhoods with many high-rise towers, or in low-density, low-income suburban neighbourhoods (Allen & Farber, 2019).

The majority of existing accessibility research focuses on access to employment opportunities as an “indicator for evaluating the performance and social outcomes of a city's transport network (Shen, 1998; El-Geneidy and Levinson, 2006; Bania et al., 2008)” (Allen & Farber, 2019, p. 215). Fewer studies explore accessibility to non-work destinations, which is problematic given that some groups experience lower accessibility to specific destination types. Grengs (2015), for example, finds that vulnerable social groups in Detroit, Michigan—specifically, low-income households, African Americans, and Hispanics—have lower accessibility to supermarkets and shopping venues compared to more privileged populations.

Other accessibility research has focused on quantifying changes to accessibility as a result of different interventions such as new infrastructure, economic incentives, and regulatory tools. As Currie (2010) suggests, identifying ways to improve accessibility is an important next step in research once accessibility gaps have been identified. Bocarejo and Oviedo (2012) model three different interventions in Bogota, Colombia. They find that redistributive fare policies have a bigger impact on improving accessibility compared to transit network expansions such as adding a new BRT line. Similarly, Neudorf (2014) uses APA to model different accessibility interventions in the Kitchener-Waterloo (Ontario) area, including increased density, improved bus service, and implementation of a gas tax. He finds that increased job density and adding express bus routes improves accessibility especially along major corridors.

2.5 Research Gaps

Many studies seek to identify and measure transport disadvantage in a way that encapsulates many factors and to map out where transport disadvantage or accessibility gaps exist (e.g. Allen & Farber, 2019; Currie, 2010; El-Geneidy, et al., 2016a; ; El-Geneidy et al., 2016b; Liu & Zhu, 2004; Shay, et al., 2016). Researchers have also made policy

recommendations to improve accessibility where transport disadvantage exists, such as investing in public transit, intensifying and diversifying land use, and subsidizing ride-sharing services (Allen & Farber, 2019); however, less research has been done to quantitatively evaluate the extent to which such economic, land use, or transportation service interventions address transport disadvantage.

The majority of existing accessibility research also focuses on accessibility to employment (Allen & Farber, 2019); less attention is given to non-work destinations such as schools, hospitals, social service agencies, and grocery stores, that are also essential to achieving social inclusion (Grengs, 2015). By default, this has limited the research to focus on accessibility during peak commuting hours rather than understanding accessibility at varying times of day.

Furthermore, many studies only account for travel time in their accessibility measure (e.g. El-Geneidy et al., 2016a; Foth, Managuh, and El-Geneidy, 2013; Grengs, 2015). Many other barriers to accessibility exist beyond travel time, such as the cost of travel, spatial distribution of destinations, and the safety and reliability of a transportation system (Pereira, Schwanen, & Banister, 2017; Social Exclusion Unit, 2003), which are not often incorporated into accessibility measures.

The purpose of this thesis is to fill the research gaps identified above by helping planners and policymakers identify, analyze, and understand existing accessibility conditions to non-work destinations and to measure the impacts of different interventions on accessibility for transport disadvantaged neighbourhoods. The next section will explain the methods used to measure accessibility, identify transport disadvantage, and quantitatively assess the impact of different economic, land-use, and transit network interventions on accessibility using Toronto as a case study.

3.0 Methods

The purpose of this research is to help planners and policymakers identify, analyze, and understand existing accessibility conditions to non-work destinations and to measure the impacts of different interventions on accessibility for transport disadvantaged neighbourhoods. Toronto is used as a case study to measure the level of accessibility to five types of non-work destinations: post-secondary institutions, hospitals, recreation centres, public libraries, and centres with early childhood development programming. As will be discussed later, these destinations were selected for their importance in increasing one's quality of life and ability to participate in society. The access profile analysis (APA) method (Neudorf, 2014) is used to: i) measure the level of accessibility to these destinations by walking, driving, and taking transit, and ii) quantitatively and spatially assess the impacts of different interventions on accessibility for transport disadvantaged areas. The interventions applied in this research—parking charges, reduced transit fare, transit service improvements, and land use changes—have been discussed in the literature and by policymakers as possible ways to influence accessibility levels. Transport disadvantaged areas are identified by combining the accessibility measure from the APA method with a socioeconomic need index (*SNI*) that captures some of the socioeconomic constraints that impede one's ability to travel. The following sections provide more detailed explanations of the research methods.

3.1 Study area

Toronto is used as a case study for this research to represent large, complex urban centres that are grappling with pressures from population growth and increasing socioeconomic disparity. Toronto is one of Canada's major cities, making up 8% of the country's population and attracting 18% of the country's recent immigrants (City of Toronto, 2018e). Since 2009, the

Toronto region’s GDP as grown by an annual average of 2.4% compared to the country-wide average at 1.8% (City of Toronto, 2018e). As of 2017, Toronto has a population of 2.9 million people distributed across 630 square kilometres (City of Toronto, 2018d). The city is located in the Greater Toronto and Hamilton Area (GTHA), an urban region in southern Ontario that consists of 7.2 million people distributed across 30 municipalities (see Figure 4). By 2041, the GTHA’s population is expected to increase to over 10 million and the City of Toronto is predicted to receive 20% of that growth (City of Toronto, 2015; Metrolinx, 2018).



Figure 4: Map of the Greater Toronto and Hamilton Area (GTHA) (Statistics Canada, 2019a).

In a recent report, the United Way Toronto and York Region (2017) found that Toronto has the highest income inequality in Canada. Income inequality in Toronto has increased by 68%, more than any other municipality in the GTHA. The city's middle class has been shrinking over the last 45 years as the percentage of low and very low-income neighbourhoods have overtaken the proportion of middle-income groups (Toronto Foundation, 2017; United Way Toronto and York Region, 2017). Toronto also has the highest prevalence of child poverty in Canada—26.3% of people under the age of 18 live in low-income households. At the same time, Toronto has the second-highest share of households with an annual income greater than \$100,000 in the country at 10.5%, second only to Calgary at 16.3% (Toronto Foundation, 2017).

The Toronto Transit Commission (TTC) is Toronto's public transport agency. At the time of writing, the TTC's transit network consists of 4 subway lines, 11 streetcar routes, and more than 140 bus routes (Toronto Transit Commission, 2018a). There are also several new transit infrastructure projects underway, either in construction or in planning and development, including the Toronto-York Spadina Subway Extension, Scarborough Subway Extension Project, Eglinton Crosstown LRT, Finch West LRT, Sheppard East LRT, and the Downtown Relief Line (Toronto Transit Commission, 2018b).

As more people live and work in Toronto, the city must meet increasing demands for transit service from a diversifying population. Poverty in Toronto has also been suburbanizing in recent years, making it challenging to provide transit service to lower-income households that live further away from the city's core (Ades, Apparicio, & Séguin, 2012, 2016; Toronto Foundation, 2018). Allen and Farber (2019) estimate that 24% and 15% of the census dissemination areas in Toronto are at a high or very high risk of experiencing transport poverty, respectively.

Given the strains on Toronto’s existing transportation system and the city’s complex and changing socioeconomic landscape, Toronto is an interesting case study for this research.

Findings from this thesis can be used to inform planners and policymakers in other cities that face similar transportation and socioeconomic challenges to address transport disadvantage.

3.2 Measuring accessibility using access profile analysis (APA)

Access profile analysis is a method used to measure accessibility—that is, the ease of reaching desired destinations—using different travel modes (Neudorf, 2014)². APA measures accessibility by determining the cumulative number of destinations that can be reached from an origin using a specific mode across a spectrum of generalized cost (*GC*). The *GC* represents the impedances to travel, which include both monetary and time costs. In this thesis, APA is used to measure accessibility to post-secondary institutions, hospitals, recreation centres, public libraries, and centres with early childhood development programming in Toronto by walking, driving, and taking transit. APA is also used here to model different interventions, including parking charges, reduced transit fare, transit service improvements, and land use changes, to evaluate their impact on accessibility in transport disadvantages areas. The following sections provide more detail on how APA is used in this research.

3.2.1 Defining origins and destinations

In order to calculate accessibility using APA, it is first necessary to define the origins and destinations of interest (Neudorf, 2014). In this research, trip origins are defined as the centroid of each traffic analysis zone in the Transportation Tomorrow Survey (TTS). The TTS is a “comprehensive travel survey conducted in the Greater Golden Horseshoe,” which is a region in southern Ontario that includes the city of Toronto (Data Management Group, 2014).

² See section 2.3.1 for a discussion on the methodological advantages and limitations of the APA method.

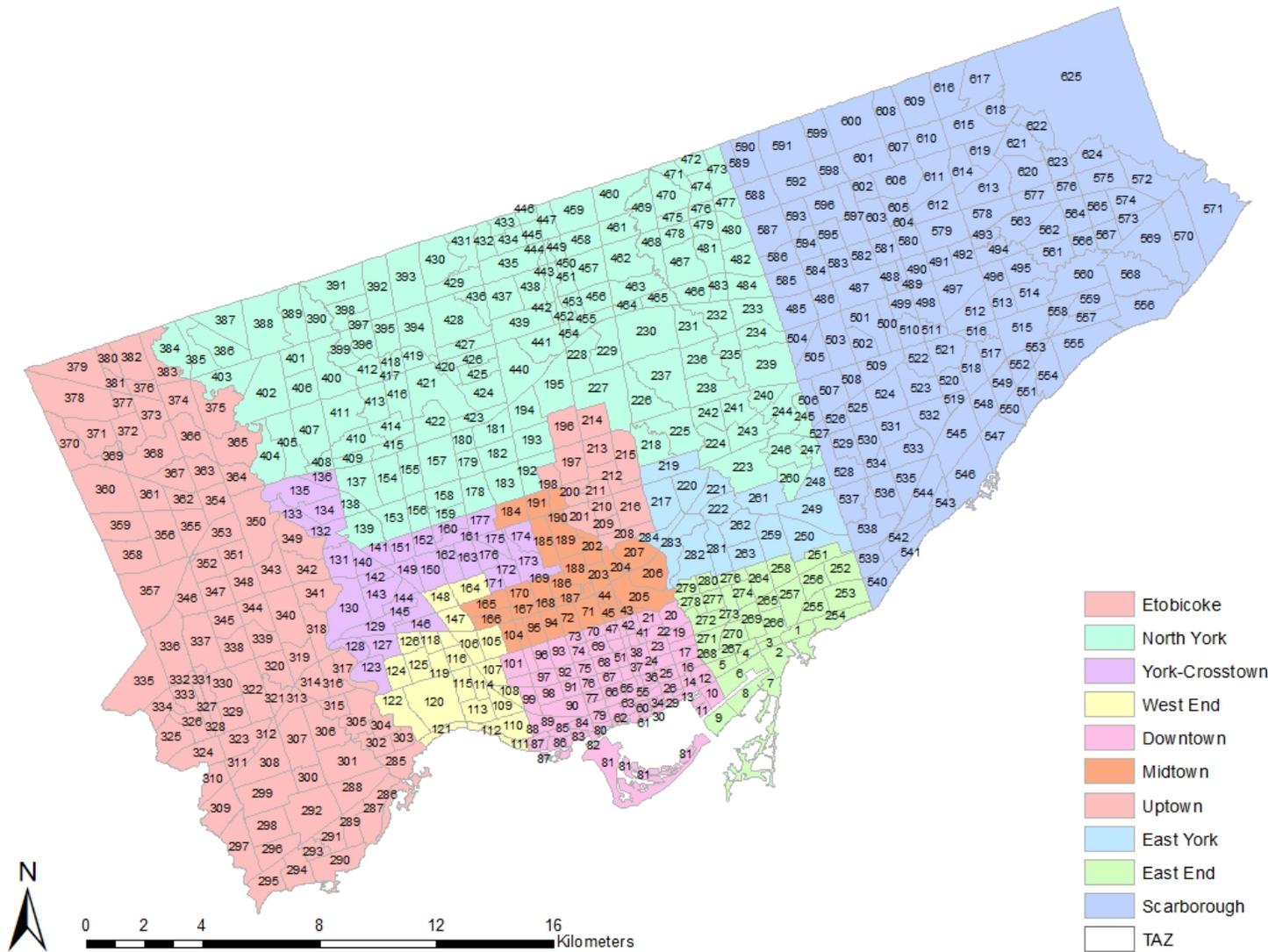


Figure 5: Traffic analysis zones (TAZs) in Toronto and their corresponding neighbourhood districts (Data Management Group, 2006).

The most recent TTS divides Toronto into 625 traffic analysis zones (TAZs) (Rose, 2018; see Figure 5). The centroid of each TAZ was determined using the ‘Calculate Geometry’ field in ArcMap. Each centroid is meant to represent the average location from which a trip originates in a TAZ. TAZ 81, which is the Toronto Islands, was removed from the analysis since it is only accessible by boat, a mode that is not included in this research. Furthermore, the Toronto Islands are primarily a tourist attraction and were not considered vital to studying transport disadvantage. As such, 624 origins are included in the analysis.

Destinations are defined as the locations of post-secondary institutions, hospitals, recreation centres (specifically, municipally owned and operated facilities for physical activity and community meeting spaces), public libraries, and Ontario Early Years Centres (centres with early childhood development programming) in Toronto. A total of 449 destinations were included in this research and were coded using the x and y coordinates for each destination location (see Table 2; maps showing the spatial distribution of destinations are provided in the Appendix).

The destinations used in this thesis were selected as examples of non-work destinations that play an important role in increasing one’s quality of life and ability to participate in society (Grengs, 2015). Post-secondary institutions, for example, provide higher-level education that help people gain the skills, knowledge, and networks that are useful for career development and advancement. Colleges and universities also provide people with a sense of community through the connections they provide to peers, teachers, and mentors. Access to hospitals is crucial for receiving urgent and specialized medical care and other medical services that walk-in clinics do not provide. Chemotherapy and lab testing, for instance, are often conducted in hospitals. Recreation centres provide facilities—such as gymnasiums, swimming pools, weight rooms, and

ice rinks—and programing for children and adults to be active and maintain a healthy lifestyle. They also provide community meeting spaces for groups to gather and host events (e.g. community workshops and board meetings for non-for-profit groups). Public libraries not only offer access to information and opportunities for self-learning, but they also provide free space for people to study, meet, and work. Community events and programs are often hosted at libraries as well, such as computer literacy training, ESL and newcomer programs, book clubs, and art exhibits, which provide opportunities for people to learn and engage with others. Ontario Early Years Centres offer free early childhood development programming for parents and caregivers of children up to six years old (Ministry of Education, 2019). Parents and caregivers can receive professional advice on early childhood development, learn about other available family services, and connect with other families with young children. This is an especially useful resource for low-income families or new immigrants that may not be familiar with or cannot afford other local childhood development services.

The destinations used in this research were also selected because of the ease of collecting their spatial data through open data sources. Other non-work destinations that could be included in future research include grocery stores, walk-in clinics, places of worship, and public green space. Ultimately, the destinations used in this thesis serve as representative examples of non-work destinations that provide opportunities for people to increase their quality of life and participate in their community. Table 2 identifies the number of locations included in the analysis for each destination category with a total of 449 destination locations. With 624 origins and 449 destinations, this research analyzes 280,176 OD pairs.

Table 2: Destination categories.

Destination Category	Number of Locations	Source of Location Information
Hospitals	33	York Region (2017)
Libraries	100	Toronto Public Library (2018)
Post-Secondary Institutions	26	City of Toronto (2018a)
Early Years Centres	142	City of Toronto (2018c)
Recreation Centres	148	City of Toronto (2018b)
Total	449	

3.2.2 Calculating the generalized cost (*GC*) of travel between origins and destinations

Once trip origins and destinations have been defined, the next step in APA is to calculate the generalized cost (*GC*) of travel between each origin and destination (OD) pair using different modes (Neudorf, 2014). The *GC* accounts for both the monetary and time costs of travel using the general formula shown in Equation 1.

Equation 1: Basic formulation for generalized cost (*GC*).

$$GC_{ij}^M = (VOT \cdot t_{ij}^M) + MC_{ij}^M$$

Where:

GC_{ij}^M = generalized cost of travel between origin *i* and destination *j* using mode *M*

VOT = value of time

t_{ij}^M = travel time between origin *i* and destination *j* using mode *M*

MC_{ij}^M = monetary cost of traveling between origin *i* and destination *j* using mode *M*

The value of time (*VOT*) used in this research is \$13 per hour. Small (2012) suggests that the *VOT* for commuting is often estimated as half of the gross wage rate. From 2014 to 2019, the hourly wage in Ontario ranged from approximately \$24 to \$27 (Statistics Canada, 2019b), which suggests a *VOT* between \$12 and \$13.50. A study prepared by Steer Davies Gleave (2016) for the GTHA region estimates a *VOT* of \$14.63. Based on these estimates, a *VOT* of \$13 per hour is used for this study. The travel time (t_{ij}^M) and monetary costs (MC_{ij}^M) vary depending on the mode.

The following sections provide the specific *GC* equations for auto, transit, and pedestrian modes and explain how travel time and monetary costs were determined.

3.2.2.1 Generalized cost of auto travel

The *GC* of travelling between an origin and a destination by driving (GC_{ij}^{auto}) is calculated using Equation 2. The monetary cost of driving includes both variable (C_{var}) and fixed (C_{fixed}) costs, which are based on the Canadian Automobile Association's (2013) estimates of operating and owning a compact vehicle that has a mileage of 18,000km per year. The variable cost is estimated at 14.53 cents per kilometre, which includes the cost of fuel, maintenance, and tires. The average annual fixed cost is estimated at \$6,482.16 per year, which includes the cost of insurance, license and registration, depreciation, and car loans. To determine the average fixed cost per trip, \$6,482.16 was divided by 702.5, which is the average number of trips taken per person per year in Toronto according to the 2016 TTS (Data Management Group, 2016a; Data Management Group, 2016b)³. The fixed cost of driving is therefore \$9.23 per trip.

Equation 2: Formulation for the generalized cost of auto travel (GC_{ij}^{auto}).

$$GC_{ij}^{auto} = \left(VOT \cdot t_{ij}^{auto} \cdot \frac{1 \text{ hour}}{60 \text{ min}} \right) + (C_{var}^{auto} \cdot d_{ij}^{auto}) + C_{fixed}^{auto}$$

Where:

$$VOT = \$13/\text{hour}$$

$$t_{ij}^{auto} = \text{time [minutes] to travel by car between origin } i \text{ and destination } j$$

$$C_{var}^{auto} = \text{variable cost of car travel} = \$0.1453/\text{km}$$

$$d_{ij}^{auto} = \text{distance [km] between origin } i \text{ and destination } j$$

$$C_{fixed}^{auto} = \text{fixed cost of car travel per trip} = \$9.23$$

³ The 2016 TTS reports that 5,141,775 trips are made per day in Toronto and that there are 2,671,492 people living in the city. 5,141,775 trips per day divided by 2,671,492 people multiplied by 365 days per year gives 702.5 trips made per person each year.

The travel times (t_{ij}^{auto}) and distances (d_{ij}^{auto}) for auto trips were collected at the TAZ level from the University of Toronto Transportation Research Institute (2018a; 2018b). Travel times are based on AM peak period travel, defined as 6AM to 9AM. They do not incorporate a perceived congestion factor but do account for slower auto travel resulting from more cars on the road during the AM peak period. Travel distances were generated using the shortest path between TAZs using Toronto's road network. Auto travel times and distances between each OD pair were only available at the TAZ level—that is, between the centroid of an origin zone and the centroid of a destination zone. As such, GC_{ij}^{auto} was calculated between TAZ centroids rather than from the origin zone's centroid to the exact location of the destination (as done when calculating the GC for transit and pedestrian trips). Although using the destination zone's centroid is not as accurate as using the exact destination location when determining auto trip times and distances, there is no systematic bias for or against auto travel since the methods for determining trip time and distance are consistent for each OD pair.

Deciding whether to include fixed costs when calculating GC_{ij}^{auto} is debateable since car owners may perceive the fixed costs of owning a vehicle as sunk costs—the purchase of a vehicle and its associated costs have already been incurred and cannot be recovered. As such, they may not consider the cost of insurance, depreciation, and registration when deciding whether to make a trip by car or selecting another mode of travel. For the purpose of this research, however, the fixed costs of auto travel are included in order to capture all of the costs associated with driving (Neudorf, 2014). This is particularly important when considering low-income groups since fixed auto costs may be a barrier to car ownership, which ultimately affects a person's level of accessibility.

Parking charges are not included in the baseline GC_{ij}^{auto} calculation; rather, parking charges are incorporated separately as an accessibility intervention in section 3.5. This was done to isolate the impacts of parking charges on accessibility from travel time and auto ownership and operating costs. Unlike the fixed costs of auto travel, parking charges are not a sunk cost since they have not yet been incurred before a trip is made. For example, a traveller can choose to avoid a car trip if they believe the parking charges at their destination point are too high.

3.2.2.2 Generalized cost of transit travel

The GC of making a trip by transit was determined using Equation 3. The monetary cost of transit travel is the cost of transit fare. In Toronto, the TTC's single adult cash fare is \$3 (Toronto Transit Commission, 2018c); however, many riders use special concessions, such as a monthly Metro pass or a student or senior pass, which reduces their fare. In order to account for these different fare schemes and to capture the cost to the average transit user, the average transit fare was used in Equation 3. The average transit fare was calculated by dividing the TTC's 2016 passenger revenue (\$1,126,453,000) by the number of annual passenger trips (538,100,000) (Toronto Transit Commission, 2016), resulting in an average fare of \$2.09.

Equation 3: Formulation for the generalized cost of transit travel ($GC_{ij}^{transit}$).

$$GC_{ij}^{transit} = \left(VOT \cdot t_{ij}^{transit} \cdot \frac{1 \text{ hour}}{60 \text{ min}} \right) + \text{fare}$$

Where:

$$VOT = \$13/\text{hour}$$

$$t_{ij}^{transit} = \text{time [minutes] to travel by transit between origin } i \text{ and destination } j$$

$$\text{fare} = \$2.09$$

Transit travel times ($t_{ij}^{transit}$) were generated in ArcMap using the *Add GTFS to a Network Dataset* tool (Morang, 2018) based on the TTC's 2017 transit schedule for Wednesdays at 7AM. This time was chosen to represent peak hours during a given weekday when transit

service tends to be the most frequent. Since the resulting accessibility levels are based on travel times during peak service hours, they should reflect the highest possible level of accessibility based on existing transit service.

Transit trip times were generated starting from an origin zone’s centroid and ending at the exact location of a destination. The duration of a trip includes the access time, wait time, in-vehicle time, transfer time, and egress time. As such, the *GC* of transit trips includes the necessary pedestrian elements needed to complete a trip (e.g. the access time to walk from an origin zone’s centroid to the transit station/stop, and the egress time to walk from the transit station/stop to the final destination). The General Transit Feed Specification (GTFS) data and the sidewalk network used in the ArcMap tool were gathered from the (City of Toronto, 2017a) (City of Toronto, 2017b).

3.2.2.3 Generalized cost of pedestrian travel

The *GC* of pedestrian travel was calculated using Equation 4. Since walking is free, there are no monetary costs associated with pedestrian travel. The only cost of pedestrian trips is the time it takes to walk between an origin and destination.

Equation 4: Formulation for the generalized cost of pedestrian travel (GC_{ij}^{ped}).

$$GC_{ij}^{ped} = VOT \cdot t_{ij}^{ped} \cdot \frac{1 \text{ hour}}{60 \text{ min}}$$

Where:

$$VOT = \$13/\text{hour}$$

$$t_{ij}^{ped} = \text{time [minutes] to travel by walking between origin } i \text{ and destination } j$$

Walking times (t_{ij}^{ped}) were generated using an OD cost matrix with the Network Analyst extension in ArcMap. Like transit trips, pedestrian trip times were generated from the origin zone’s centroid to the exact location of the destination with the assumption that people walk at a

pace of 5 km/hour.⁴ The pedestrian network used in the Network Analyst was taken from the City of Toronto's (2017b) Sidewalk Inventory (see Appendix for a list of sidewalk types included in the analysis).

3.2.3 Calculating the access profile indicator (*API*)

Once the *GC* between each OD pair is calculated using each mode, an access profile indicator (*API*) for each origin zone can be determined (Neudorf, 2014). The *API* is the measure of accessibility that indicates the cumulative number of destinations that can be reached from an origin using a specific mode at varying levels of *GC* as a proportion of the total number of destinations that can be reached at all *GC* intervals. The general equation to calculate the *API* is:

Equation 5: Calculating the access profile indicator (API).

$$API_i^M = \frac{\sum_{GC=1}^{GC^{max}} \text{number of reachable destinations}_i^M}{GC^{max} \cdot \text{number of destinations}}$$

Where:

$$API_i^M = \text{access profile indicator for origin } i \text{ using mode } M$$

Equation 5 essentially calculates the area under the access profile curve as a proportion of the entire graph area (see Figure 6). If a mode were to provide perfect accessibility, then the access profile curve would be a horizontal line that intersects the y-axis at the total number of available destinations. In other words, every destination can be accessed at every *GC* interval. The area under the access profile curve would therefore be equal to the graph area, resulting in an *API* of 1.

The term in the denominator of Equation 5 labeled GC^{max} is equal to the maximum *GC* required to reach all destinations when all modes are considered. Pedestrian travel resulted in the

⁴ Walking speeds in the literature vary, ranging from 3.28 km/hour to 5.47 km/hour (Currie, 2004; Knoblauch, Pietrucha, & Nitzburg, 1996; Krizek, Horning, & El-Geneidy, 2012). 5 km/hour was used in this thesis as an approximate average of the walking speeds used in existing research.

highest GC between an OD pair at \$129, and therefore a GC^{max} of \$129 was used in Equation 5 when calculating API_i^M . The same GC^{max} is used for each mode in order to directly compare the API_i^M values for transit, auto, and pedestrian trips.

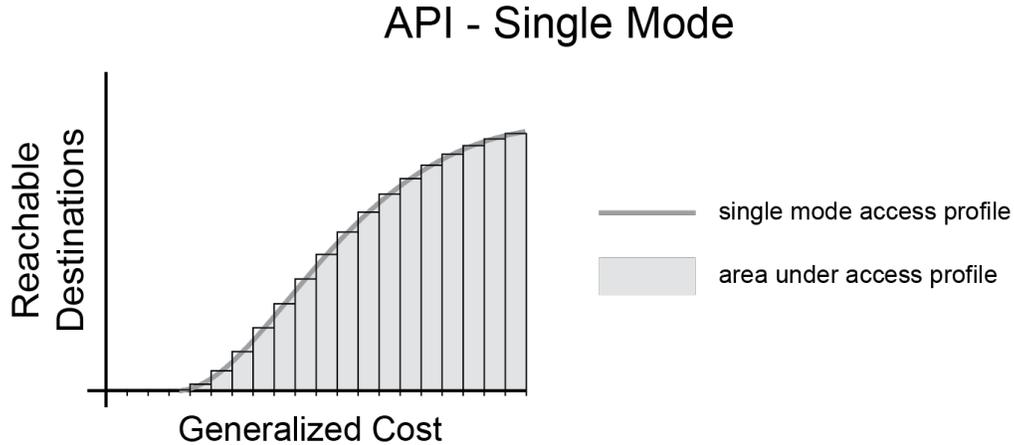


Figure 6: Calculating API_i^M using the area under the access profile. From Neudorf (2014).

A maximum API , referred to as API_i^{max} , can also be calculated, which indicates the maximum level of accessibility from origin i when every mode is considered (Neudorf, 2014). In this case, the numerator in Equation 5 is the sum of the maximum number of reachable destinations at each GC level from origin i when transit, auto, and pedestrian modes are considered. For example, if five destinations can be reached from TAZ 1 at a GC of \$5 by walking, versus 20 destinations using transit and 30 destinations using auto, then the API_i^{max} calculation uses 30 destinations at that GC . This process is repeated for each origin at every GC interval. The sum of the maximum number of accessible destinations across all GC intervals estimates the area under the maximum access profile curve (see Figure 7). This is divided by the total graph area to calculate API_i^{max} . An average API_i^{max} can be determined by averaging the maximum number of destinations reachable from each origin at every GC interval.

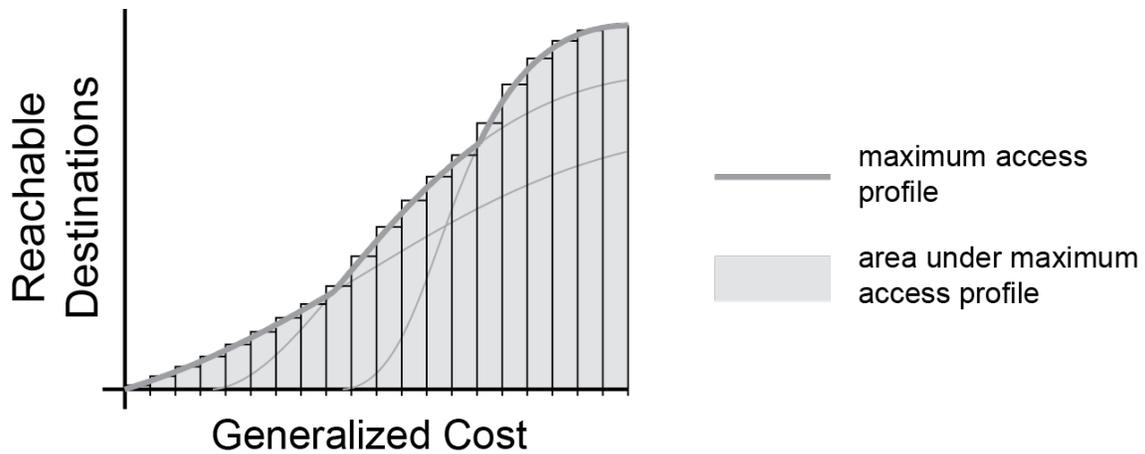


Figure 7: Calculating API_i^{max} using the area under the maximum access profile. From Neudorf (2014).

3.3 Developing a socioeconomic need index (SNI)

One of the outcomes of this research is to measure the impacts of different interventions on accessibility for transport disadvantaged areas. To do this, transport disadvantaged areas must first be identified. Recall that transport disadvantage is the combination of limited accessibility to destinations with different socioeconomic constraints that impede one’s ability to travel (Allen & Farber, 2019; Kamruzzaman, Yigitcanlar, Yang, & Mohamed, 2016; Ricci, Parkhurst, & Jain, 2016). As discussed in the previous section, accessibility to destinations is measured using the access profile indicator (*API*). Socioeconomic constraints are represented in this research through a socioeconomic need index, *SNI*, which incorporates four variables that quantify some of the factors that contribute to social and economic disadvantage at the TAZ level.

The four variables used in the *SNI* are based on those used in Foth, Manaugh, and El-Geneidy (2013) and were selected for their applicability to Toronto’s socioeconomic context: average household income⁵, unemployment rate, recent immigration rate, and the percentage of

⁵ Note that Foth, Manaugh, and El-Geneidy (2013) use median household income at the census tract level. Because the analysis in this research is at the TAZ level, it was necessary to use average household income due to data availability.

households spending 30% or more of their income on shelter costs. As discussed in section 3.1, Toronto has the highest income inequality in Canada (United Way Toronto and York Region, 2017), making income an important criteria when considering the economic constraints of households in the city. Unemployment rate is included in the SNI because it is a commonly used variable in Canada to measure economic well-being (Statistics Canada, 2016; Toronto Foundation, 2017). The City of Toronto, for example, designates neighbourhoods with higher unemployment rates, among other criteria, as Neighbourhood Improvement Areas (NIA), which are priority areas for investment to address different socioeconomic challenges (City of Toronto, 2014).

The rate of recent immigration is particularly relevant to the transportation context in Ontario, where newcomers are more reliant on public transit than their native-born counterparts (Amar & Teelucksingh, 2015; Mercado, Paez, Farber, Roorda, & Morency, 2012). Furthermore, immigrants that are ethnic minorities tend to face racism that impedes their ability to reliably and comfortably take transit (Rusu, 2018). There are reported instances where newcomers—particularly women and those with limited English proficiency—experience discriminatory behaviour from transit operators (e.g. blaming newcomers for fare evasion, refusing to stop for people of colour, and not offering to help minority women with strollers board the bus) (Khosla, 2003). The percentage of household spending on shelter costs is also an important indicator of socioeconomic disadvantage in Toronto where a lack of housing affordability is increasingly problematic (Haines & Aird, 2018). Furthermore, “when households spend more than 30 per cent of their gross income on housing, it can result in greater financial strain, meaning fewer resources at their disposal to spend on other necessary goods such as food, clothing and transportation” (Toronto Foundation, 2017, p. 38).

Table 3 shows how each *SNI* variable is calculated using data from the 2016 Canadian census. Census data were retrieved from Computing in the Humanities and Social Sciences (2015) at the census dissemination area level. A Pearson correlation test was conducted between each of the four *SNI* variables to determine the extent to which each variable is related to the others (see Appendix for a matrix with the correlation coefficients). If a correlation coefficient between two variables is high, it suggests that both variables serve a similar purpose in identifying socioeconomic need and that one variable can be removed from the *SNI* to avoid redundancy (Salzman, 2003). A correlation coefficient can range between 0 and 1 and determining the acceptable level of redundancy within this range is a subjective decision (Salzman, 2003). The absolute values of the correlation coefficients between each *SNI* variable range from 0.20 to 0.46. For the purpose of this thesis, a correlation less than 0.5 was considered low enough to indicate that each *SNI* variable serves a relatively unique purpose in the identifying socioeconomic need. As such, all four variables were included in the final *SNI*.

Table 3: SNI variables and the census data used to calculate each variable.

SNI variable	Census data and SNI variable calculation
Average household income	= Average after-tax income of households
Unemployment rate	= $\frac{\text{Number of unemployed people in labour force}}{\text{Total number of people in labour force}} \cdot 100\%$
Immigration rate	= $\frac{\text{Number of immigrants arriving between 2011 and 2016}}{\text{Total number of immigrants}} \cdot 100\%$
Percentage of households spending more than 30% of income on shelter costs	= $\frac{\text{Number of owner and tenant households that spend more than 30% of income on shelter costs}}{\text{Total number of owner and tenant households}} \cdot 100\%$

Because accessibility is calculated at the TAZ-level in this research, it is necessary to measure socioeconomic need at the same spatial unit in order to combine the two measures when identifying transport disadvantage. Since the census data used to develop the *SNI* are provided at the dissemination area (DA) level, they were translated to the TAZ-level before calculating each *SNI* variable as shown in Table 3. To do this, DAs and TAZs were intersected in ArcMap to determine the proportion of each DA area within a TAZ. This proportion was multiplied by each census data input (with the exception of average after-tax income). For example, if 50% of a DA occurs in a TAZ, then the number of unemployed people within that DA is multiplied by 0.5 to calculate the number of unemployed people from that DA that occur in that TAZ. Summing the number of unemployed people from all of the DAs that occur in a TAZ results in the total number of unemployed people in that TAZ. Equation 6 (adapted from Neudorf, 2014) explains this process in mathematical terms. This approach assumes that the unemployed population in a DA is evenly distributed. The data translation process from the DA-level to the TAZ-level was repeated for each census data input (again, with the exception of average after-tax income) in order to calculate each *SNI* variable at the TAZ-level.

Equation 6: Converting DA-level census data to the TAZ level using the number of unemployed people as an example.

$$Unemployed\ population_{TAZ} = \sum_{DA=1}^n \frac{Area_{TAZ} \cap Area_{DA}}{Area_{DA}} \cdot Unemployed\ population_{DA}$$

Calculating the average household income at the TAZ-level required a different process. First, the total income for each DA was determined by multiplying the total number of households in a DA by the average after-tax household income in the same DA. Next, the total income of each TAZ was calculated using the same intersect method as shown in Equation 6. The total number of households was also translated from the DA-level to the TAZ-level using

the same intersect approach. The average household income for each TAZ was then calculated by dividing the total income in each TAZ by the total number of households in the same TAZ.

After calculating the four *SNI* variable for each TAZ, each variable was normalized into a z-score. A z-score is a measure of how far above or below a raw score is from the population average based on units of standard deviation. For example, a z-score for unemployment rate would indicate how many standard deviations above or below the unemployment rate is in a particular TAZ from the average unemployment rate in Toronto. Z-scores are used to transform each *SNI* variable, which has different units, into “pure, dimensionless numbers” so that they may be directly compared with each other and aggregated into the final *SNI* (Mazziotta & Pareto, 2013, p. 70).

Z-scores are normally applied to datasets with symmetric statistical distributions, where the values above and below the mean occur at almost equal frequencies. The distributions for unemployment rate and the percentage of households spending more than 30% of income on shelter costs are fairly symmetrical (see the Appendix for the distribution of each *SNI* variable). However, the distributions for average household income and immigration rate are skewed right. Despite their skewedness, these variables were converted into z-scores for ease of merging the four *SNI* variables into a single index. As will be discussed in the results, this method did not inhibit the accurate identification of areas with higher and lower socioeconomic need when compared to findings from existing research.

The z-scores for unemployment rate, recent immigration rate, and the percentage of households spending more than 30% of income on shelter costs were multiplied by -1 in order to reverse the scores. This was done to ensure that negative z-scores indicate greater socioeconomic

disadvantage (i.e. higher unemployment, larger proportion of recent immigrants, and larger proportion of households spending greater than 30% of income on shelter costs) and vice-versa.

The *SNI* for each TAZ was calculated by summing the z-scores for each variable. Each z-score was given equal weighting in the *SNI* calculation for ease of interpretation and calculation (Foth, Manaugh, & El-Geneidy, 2013; Mazziotta & Pareto, 2013). Some studies use more complex methods for aggregation, such as summing the weighted values of each variable in an index (Salzman, 2003); however, determining the level of influence that each variable has on socioeconomic need is beyond the scope of this research.

3.4 Identifying transport disadvantage

One objective of this thesis is to explore how different interventions impact accessibility in transport disadvantaged areas. Transport disadvantage is the combination of limited accessibility to destinations (measured by *API*) with different socioeconomic constraints (measured by *SNI*) that impede one's ability to travel. To quantitatively identify areas that experience more transport disadvantage than others, an accessibility need measure, *ANM*, was developed by multiplying the *SNI* and *API* for each TAZ together after standardizing and scaling up their values.

To calculate the *ANM*, the *API* in each TAZ was first converted into a z-score to be consistent with the standardized format used to develop the *SNI*⁶. Because z-scores take on both positive and negative values, the *SNI* and *API* z-scores were scaled up by adding one plus the minimum *SNI* and *API* z-score, respectively. This was done to make each *SNI* and *API* z-score greater than or equal to one so that negative and zero values do not interfere with the *ANM* calculation. For example, if a TAZ has an average level of accessibility, it would have an *API* z-

⁶ Recall that the *SNI* is the sum of z-scores for each of the variables used to develop the *SNI*.

score of zero. Without scaling up the *API* z-score, that TAZ would have a resulting *ANM* of zero when the *API* z-score and *SNI* are multiplied together, regardless of the level of socioeconomic need for that TAZ. Scaling up the *SNI* and *API* z-scores prevents such perverse results when calculating the *ANM*.

Multiplying the *API* z-scores and *SNI* together to determine the *ANM* is intended to measure the risk of transport disadvantage in each TAZ. Salzman (2003) explains that multiplicative approaches to aggregating variables in an index are used to represent conditional probabilities—that is, the probability of one event occurring (e.g. experiencing low accessibility) given that another event has already occurred (e.g. experiencing high socioeconomic need) (Salzman, 2003). A TAZ with a lower *ANM* has relatively low accessibility levels and high socioeconomic need compared to other TAZs, and therefore experiences greater transport disadvantage.

3.5 Accessibility Interventions

One of the outcomes of this thesis is to measure the impacts of different interventions on accessibility for transport disadvantaged areas. Different interventions are often proposed in public discourse to improve accessibility, but it is not always clear what the impacts of these interventions will be in quantitative and spatial terms. In this research, four types of interventions are applied to determine how accessibility levels to non-work destinations change under different conditions. These interventions include parking charges, reduced transit fares, improved transit service, and lands use changes (see Table 4).

Each intervention was selected for its applicability to the Toronto context, either because the intervention has already been implemented in some form or it has been identified as a potential action to improve accessibility in political discourse. Street parking charges, for

example, already exist in the city and are enforced by the City of Toronto (Toronto Parking Authority, 2018; see Figure 8). Reduced transit fare and, more specifically, free transit fare have become common topics of debate in Toronto politics. In the recent 2018 mayoral race, many candidates advocated for affordable transit fares while one candidate campaigned on free transit as a core component of her platform (Spurr, 2018). Transit service improvements are part of ongoing discussions at both the municipal and provincial levels of government. Policymakers generally agree that existing transit services require upgrades and expansions, however, there is disagreement on the design and prioritization of new projects (e.g. Elliott, 2019; Spurr, 2019). Land use changes are also common policy topics in Ontario, specifically regarding land use intensification to achieve denser urban form and transit supportive development (Ministry of Municipal Affairs and Housing, 2014; 2017).

Table 4: Accessibility interventions and applications.

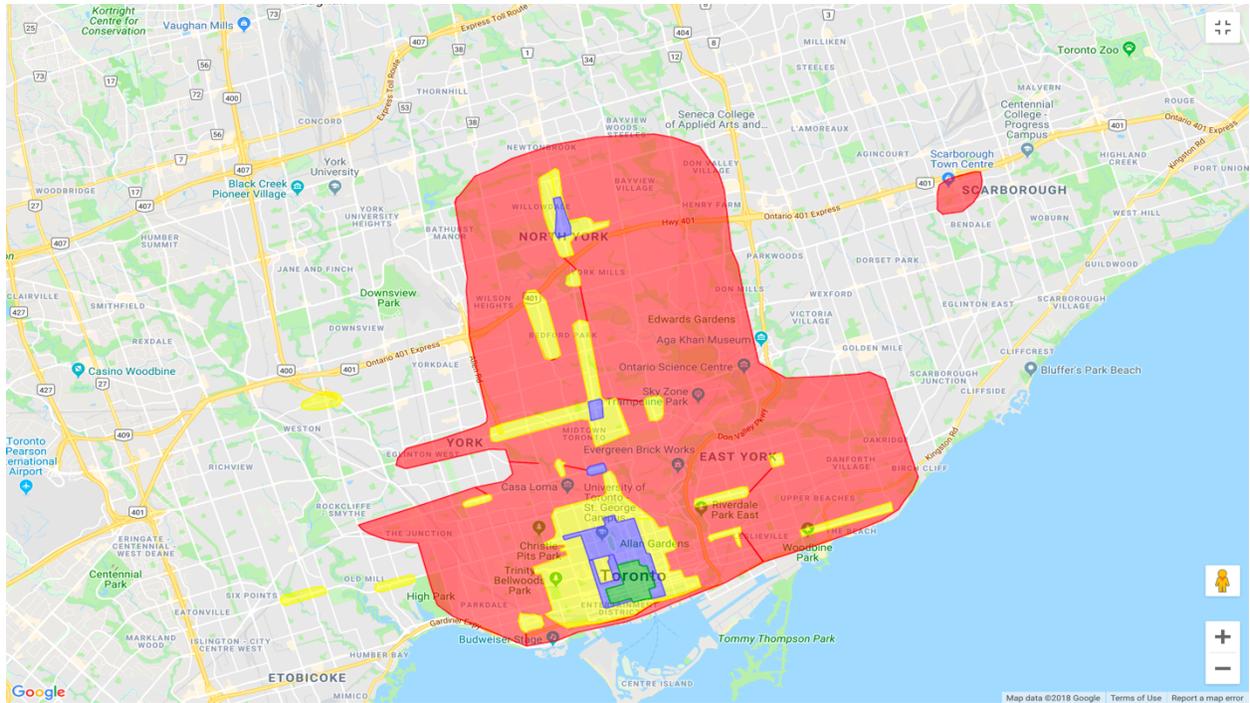
Intervention category	Application
Parking charges	Low parking charge (five parking zones ranging from \$1 to \$5 per hour)
	High parking charge (five parking zones ranging from \$2 to \$10 per hour)
Reduced transit fare	30% reduced fare
	50% reduced fare
	Free fare
Improved transit service	Extrapolated transit improvements (based on historical improvements to transit times from 2013-2017)
	Conservative transit improvements (one-third of improved transit times from 2013-2017)
	Moderate transit improvements (two-thirds of improved transit times from 2013-2017)
Land use changes	Addition of seven new hospital locations

3.5.1 Parking charges

The first intervention implements different levels of parking charges to different parts of the city. Unlike the other interventions applied in this thesis, parking charges reduce accessibility

levels because they add an additional cost to travel. Because of this additional cost, parking charges can disincentivize driving and encourage alternative forms of transport, such as transit or active transportation (Vuchic, 1999). Although it may be a worthwhile goal to discourage auto travel and incentivise more sustainable modes of transportation, there are potential implications to equity when implementing parking charges. There is sometimes concern that additional charges may price out lower income households from having the option to drive (Deakin, Harvey, Pozdena, & Yarema, 1996). This is particularly problematic for low-income households located in areas where there are limited transportation alternatives available. It is therefore useful to quantify and map the distribution of impacts resulting from parking charges to understand whether such pricing schemes will create inequitable outcomes.

The parking charges used in this thesis were implemented in five different parking zones based on the street parking scheme imposed by the Toronto Parking Authority (2018) (see Figures 8 and 9). Areas in the downtown are subject to higher parking charges since the value of land is more expensive and because it discourages auto travel in core urban areas where space is limited, and pedestrian networks and transit services tend to be more robust. Table 5 shows the parking charges that were applied in each parking zone under a low and high parking charge scenario. The higher parking charges are double those of the lower parking charge scenario and were implemented in order to investigate the sensitivity of accessibility to parking costs. The parking charges were added as an additional term to the baseline GC_{ij}^{auto} calculation (see Equation 2) in order to calculate the generalized cost of auto trips between each OD pair when parking charges are implemented. For example, a \$5 and \$10 charge would be added to the GC_{ij}^{auto} calculation for a trip that ends in parking zone 1 under the low and high parking charge scenarios, respectively.



● \$5.00/hr ● \$4.00/hr ● \$3.00/hr ● \$2.00/hr

Figure 8: Street parking charges in Toronto (from Toronto Parking Authority, 2018).

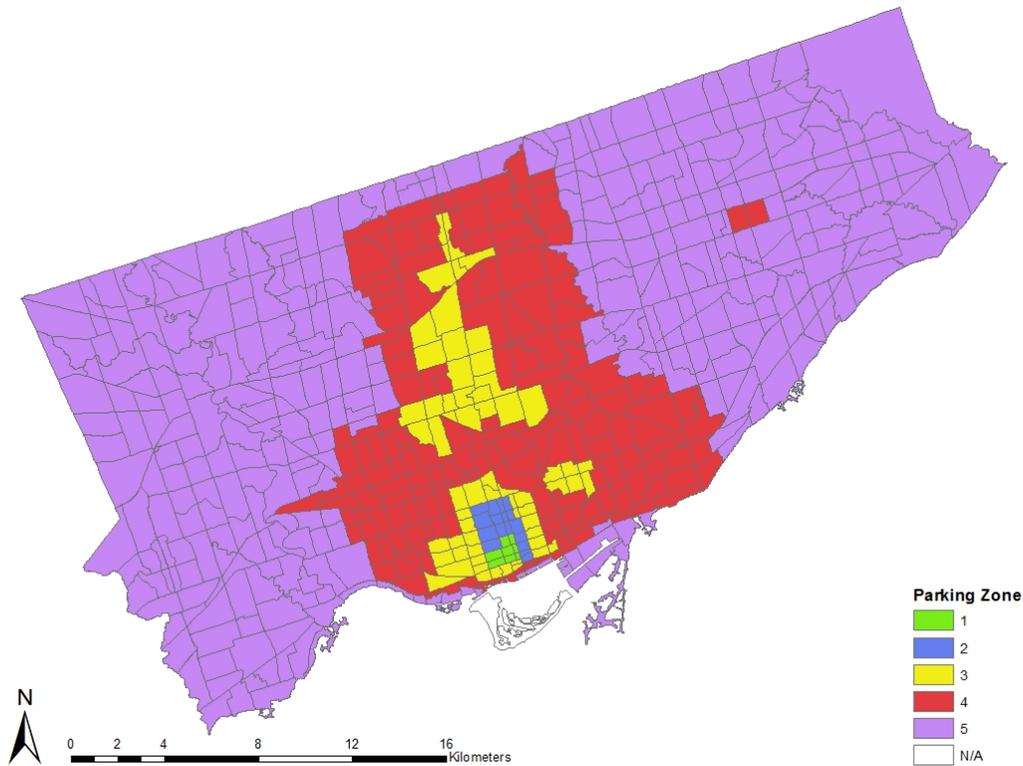


Figure 9: Parking zones applied in this research.

Table 5: The cost of parking in each parking zone.

Parking Zone	Low Parking Charge	High Parking Charge
1	\$5	\$10
2	\$4	\$8
3	\$3	\$6
4	\$2	\$4
5	\$1	\$2

3.5.2 Reduced transit fare

The second intervention reduces transit fare by 30%, 50%, and 100%, which translates into fares of \$1.46, \$1.05, and \$0 (i.e. free transit), respectively⁷. Different levels of fare reduction were applied to investigate the sensitivity of accessibility levels to fare decreases. Note that reducing transit fares only alters the monetary costs of taking transit; the time costs remain the same since trip times are unchanged in this intervention.

3.5.3 Transit service improvements

The third intervention represents improvements to existing transit services by reducing the transit travel time between OD pairs. It is assumed that improvements to transit infrastructure and operations are manifested in shorter trips, which decreases the time costs of transit travel. Transit travel times were decreased according to the historical changes to transit travel times over five years from 2013 to 2017.⁸ Travel times for trips between each OD pair were calculated using the 2013 TTC transit network by inputting 2013 GTFS data (retrieved from TransitFeeds, 2013) into GIS using the *Add GTFS to a Network Dataset* tool (Morang, 2018). Transit trip times were then compared between 2013 and 2017 by calculating the average time savings for trips with varying duration (see Figure 10). For example, transit trips with a duration of 30 to 60

⁷ Recall that a fare of \$2.09 is used when calculating the baseline generalized cost of transit travel, $GC_{ij}^{transit}$.

⁸ The baseline transit travel times calculated in section 3.2.2.2 are based on the 2017 transit network.

minutes in 2013 experienced an average decrease of 40% in trip time in 2017 when compared to 2013. The same 40% reduction was then applied to trips that take between 30 to 60 minutes in 2017 to represent “extrapolated transit improvements” (i.e. improvements based on the historical changes to transit trip times between 2013 to 2017). Table 6 lists the different percentage decreases to travel time that were applied to transit trips with different duration. Note that according to Figure 10, the duration of trips that are less than 10 minutes should increase by 19%; however, for the purpose of illustrating transit improvements and their resulting time savings, this time increase was nulled. In other words, it was assumed that the duration of transit trips that are less than 10 minutes does not change from baseline conditions when transit service improvements are applied.

Table 6 also shows the percentage decrease to transit trip times under scenarios where only one-third and two-thirds of the extrapolated time savings are realized to represent more conservative and modest transit improvements, respectively. New transit trip times were generated between each OD pair based on the travel time reductions in Table 6. These trip times were used to calculate the new generalized cost of transit trips, $GC_{ij}^{transit}$, under each transit service improvement scenario.

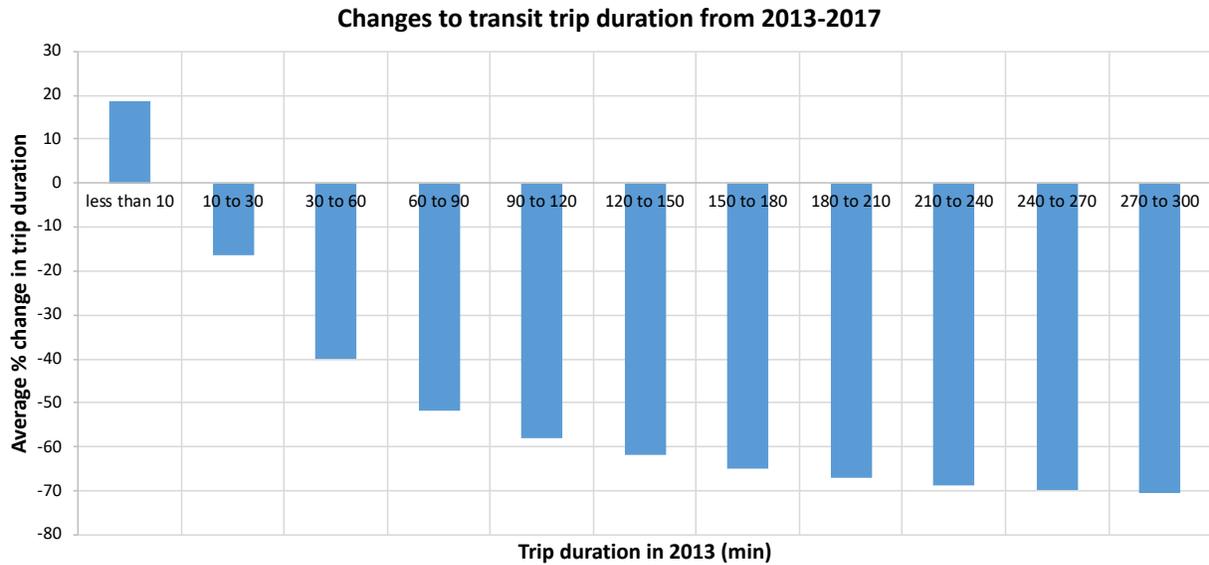


Figure 10: Average change in transit travel times from 2013 to 2017.

Table 6: Reductions to transit trip times to represent different levels of transit service improvement.⁹

Duration of transit trip in 2017	Transit trip time reductions based on extrapolated transit improvements	Transit trip time reductions based on conservative transit improvements	Transit trip time reductions based on moderate transit improvements
< 10 min	0%	0%	0%
10 to 30 min	-16%	-5%	-11%
30 to 60 min	-40%	-13%	-27%
60 to 90 min	-52%	-17%	-35%
90 to 120 min	-58%	-19%	-39%
120 to 150 min	-62%	-21%	-41%
150 to 180 min	-65%	-22%	-43%

⁹ The maximum transit trip time in 2017 is 178 minutes and therefore Table 6 does not include transit trip time reductions for trips longer than 180 minutes.

3.5.4 Land use changes

The fourth intervention assesses how accessibility levels change if land use changes were to occur. Seven new hospital locations were added to the city to represent land use changes, such as infills or land development projects that increase in the number of available destinations in a city. To determine the location of each new hospital, spatial gaps in hospital service were identified by mapping the service areas for each of the existing 33 hospitals in Toronto (see Figures 11 and 12). The buffers surrounding each existing hospital show the extent of the hospital's service area if a traveler spends \$3, \$5, \$7, or \$8 in time and money (i.e. *GC*) to access the hospital using the pedestrian or transit network. A *GC* of \$3 was selected as the smallest buffer threshold since a transit user must spend a minimum of \$2.09 (the price of transit fare) for any trip.

The hospital service areas in Figures 11 and 12 are overlaid on a map of TAZs and their level of transport disadvantage to hospital locations, as measured by the accessibility need measure (*ANM*). The *ANM* in this application is calculated by multiplying the level of socioeconomic need (*SNI*) by the level of accessibility (*API*) to hospital locations (as opposed to the level of accessibility to all of the non-work destinations included in this thesis). TAZs with a darker colour gradient in Figures 11 and 12 experience greater transport disadvantage to hospitals—that is, they have lower accessibility to hospitals and higher levels of socioeconomic need.

Based on the level of transport disadvantage to hospitals and the service areas of existing facilities, the locations of seven new hospitals were visually determined by selecting locations that could ameliorate the lack of accessibility to hospitals in areas that experience high transport disadvantage. Once the new hospital locations were identified, the level of accessibility, *API*,

was calculated from each origin TAZ to all 40 hospital locations. These *API* values were then compared to baseline levels of accessibility when only 33 hospitals are available.

Note that for the purpose of this research, the study area is considered in isolation and therefore the service areas of hospitals in municipalities adjacent to Toronto were not considered when determining new hospital locations. The intent of this thesis is not to conduct a robust service gap analysis to identify new facilities, but to demonstrate the effects of an increased number of available destinations on accessibility levels.

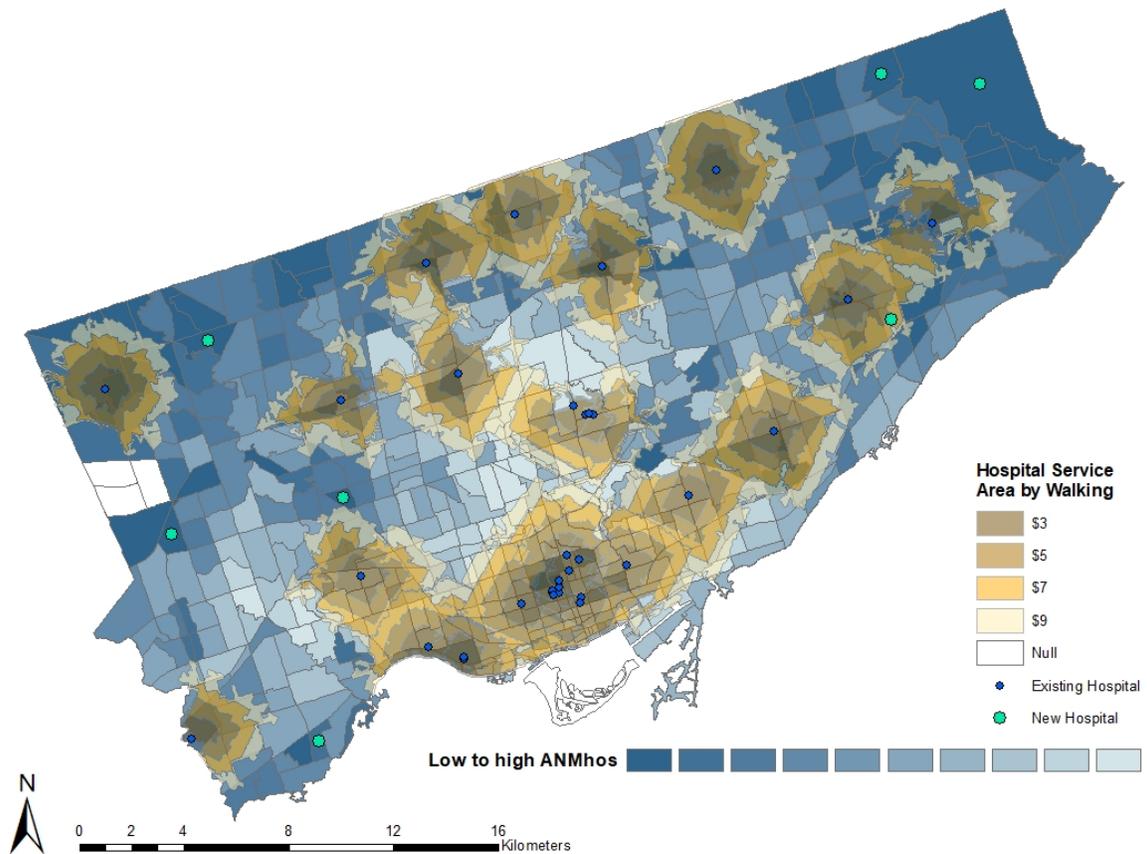


Figure 11: Identifying new hospital locations based on transport disadvantage (ANMhos) and the service areas of existing hospitals by walking.

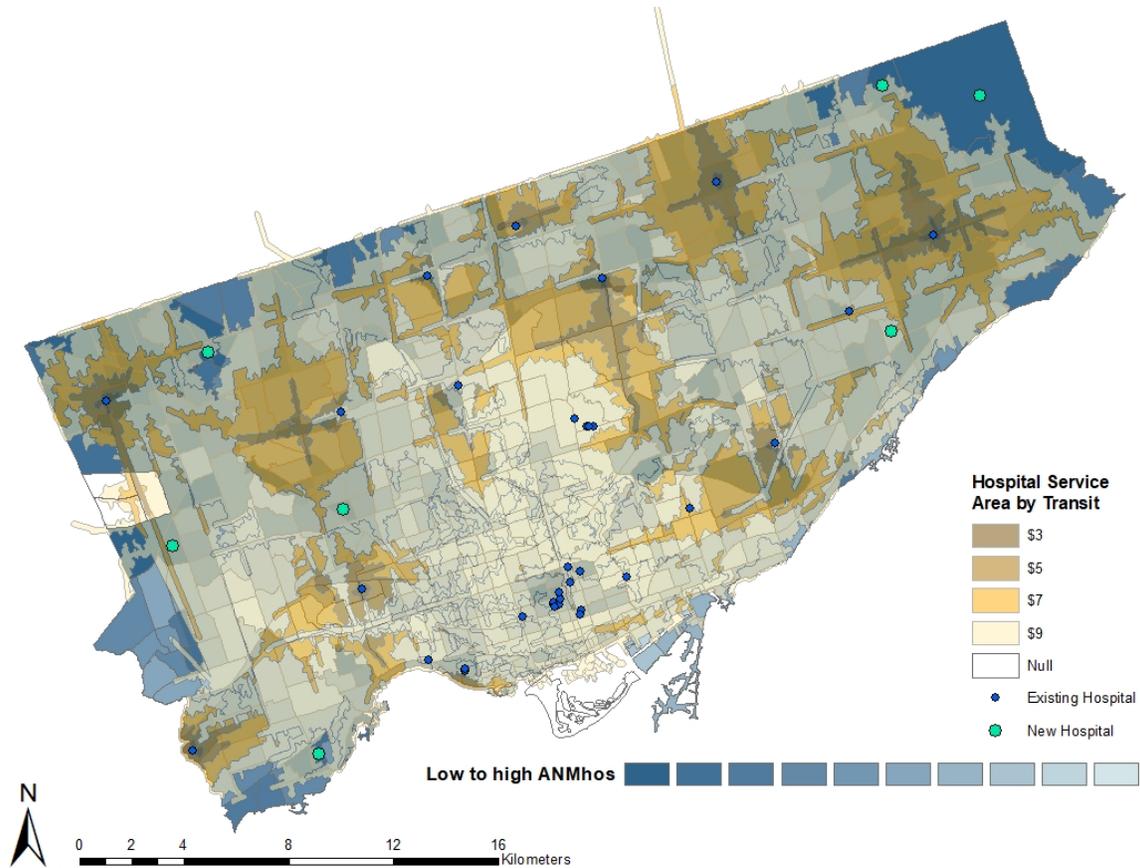


Figure 12: Identifying new hospital locations based on transport disadvantage (ANMhos) and the service areas of existing hospitals by transit.

3.6 Methods summary

In this thesis, Toronto is used as a case study to identify, analyze, and understand existing accessibility conditions to non-work destinations and to measure the impacts of different interventions on accessibility for transport disadvantaged neighbourhoods. The access profile analysis (APA) method is used to measure the level of accessibility to five types of non-work destinations: post-secondary institutions, hospitals, recreation centres, public libraries, and centres with early childhood development programming. The APA method measures accessibility through an access profile indicator, *API*. The *API* indicates the cumulative number of destinations that can be reached from an origin using a specific mode at varying levels of

generalized cost, *GC*, as a proportion of the total number of destinations that can be reached at all *GC* levels. The *GC* represents both the time and monetary costs of travel.

To identify areas in the city that experience transport disadvantage, the *API* is combined with a socioeconomic need index, *SNI*, to quantitatively determine which areas have lower accessibility levels to destinations and higher levels of socioeconomic need. The *SNI* measures socioeconomic need by aggregating four variables from the Canadian census: average household income, unemployment rate, recent immigration rate, and the proportion of households spending more than 30% of their income on shelter costs. After identifying transport disadvantage by combining the *API* and *SNI*, four types of interventions are applied to quantify their impacts of on the accessibility levels of transport disadvantaged areas. These interventions include parking charges, reduced transit fare, transit service improvements, and land use changes.

4.0 Results

This section presents and discusses the results based on the methods described in section 3.0. Baseline levels of accessibility and socioeconomic need in Toronto are presented in order to identify areas in the city that are transport disadvantaged. The impacts of the different economic, land use, and transit service interventions applied in this research are then compared to assess how accessibility levels change under different scenarios.

4.1 Interpreting the results

Recall that the access profile curve illustrates the cumulative number of destinations that can be reached from an origin at increasing GC intervals using a particular mode. The access profile indicator, or API , is the area under the access profile curve as a proportion of the total graph area. The API represents the level of accessibility to destinations from an origin using a specific mode. An access profile curve that encompasses the entire graph area (i.e. the total number of destinations multiplied by the maximum GC required to reach all destinations) indicates that an origin experiences perfect accessibility and has an API of 1. An API value closer to 1 therefore indicates better accessibility because more destinations can be reached at a lower cost.

API^{tran} , API^{auto} , and API^{ped} refer to the level of accessibility to destinations from an origin using transit, auto, and pedestrian modes, respectively. API^{max} indicates the highest level of accessibility offered among these three modes at a given GC interval. Different modes will offer access to the greatest number of destinations depending on the GC interval in question. For ease of communication, API^{tran} , API^{auto} , API^{ped} , and API^{max} will also be referred to as

transit accessibility, auto accessibility, pedestrian accessibility, and maximum accessibility, respectively, throughout the remainder of this thesis.

Note that some of the figures in this section illustrate different access profiles that do not show the full range of the x- and y-axes in order to focus on the *GC* intervals and destination ranges that illustrate the most relevant information.¹⁰ Also note that unless a figure indicates that an access profile represents accessibility for a particular origin zone, then the access profile illustrates the *average* cumulative number of destinations that can be reached by a mode at each *GC* interval. These figures are referred to as ‘average access profiles’ and are meant to be representative of the average accessibility conditions in Toronto when all origin zones are considered.

4.2 Baseline accessibility conditions

This section presents the baseline accessibility conditions in Toronto before any economic, land use, or transit service interventions are applied. In general, pedestrian travel provides better accessibility at lower *GC* intervals, transit at mid-*GC* intervals, and auto at higher *GC* intervals. Figure 13 shows the average access profile for each mode between a *GC* of \$0 and \$30. For trips with a *GC* under \$6, the average maximum accessibility curve closely resembles the average pedestrian accessibility curve, suggesting that on average walking provides the best accessibility for shorter trips. This makes sense given that walking has no monetary cost—the only price associated with pedestrian travel is the time it takes to walk. Furthermore, pedestrians do not face the same time impedances as transit or auto users, such as waiting for a bus or traffic

¹⁰ For the purpose of calculating *API*, the y-axis of each access profile ends at 449 since there are a total of 449 destinations used in this study. The x-axis of the access profiles indicates the *GC* required to travel between an origin and a destination, ranging from \$0 to \$129. The x-axis ends at \$129 since it is the highest cost required to reach all 449 destinations.

congestion, which can make walking the fastest mode when a trip's origin and destination are close together. As such, more destinations can be reached at lower *GC* intervals by walking.

For *GC* intervals between \$6 and \$22, Figure 13 shows that the average maximum accessibility curve is aligned with the average transit accessibility curve, indicating that on average transit provides the best accessibility between these *GC* intervals. This may be surprising given that auto travel is sometimes assumed to provide better accessibility than all other modes since cars are faster, provide door-to-door access, and do not require transfers as sometimes necessary during transit trips. However, the results suggest that when the monetary costs of car ownership are accounted for, transit is the most competitive mode for trips that cost between \$6 and \$22. In other words, the cheaper cost of transit fare compared to the higher cost of car ownership is what makes transit travel more competitive at mid-*GC* intervals.

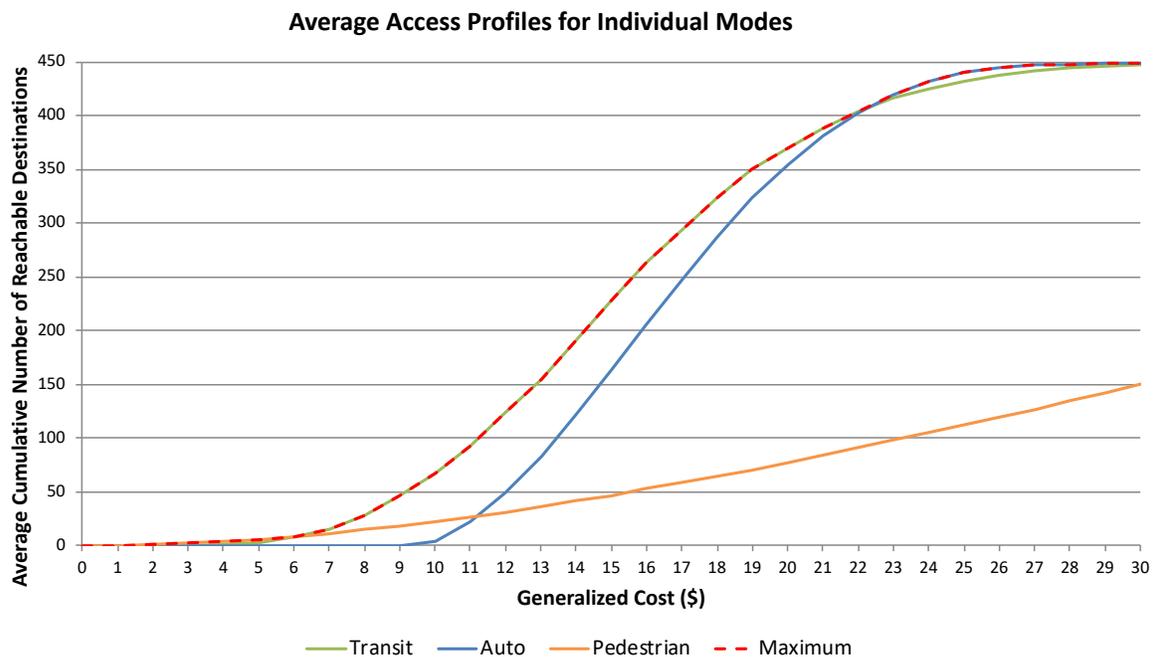


Figure 13: Comparing access profiles for each mode under baseline accessibility conditions.

In order for auto travel to be equally or more competitive with transit travel to reach all available destinations, the *GC* of driving must decrease by at least \$5.21 per trip on average. This

was determined using Figure 14, which illustrates the average difference in GC between transit and auto travel as a function of the cumulative number of reachable destinations. A positive difference in GC indicates that on average transit is cheaper than auto travel to reach a given number of destinations, while a negative difference indicates the reverse.¹¹ The exact difference in GC between transit and auto travel zone will vary for each zone. In zones where auto travel offers the most competitive level of accessibility at most GC intervals, the difference in GC will be more negative. On average though, Figure 14 shows that the maximum difference in GC between transit and auto travel is \$5.21. If auto costs were decreased by \$3, then driving would cost the same as transit to reach approximately the first 30 destinations from any given origin (this is indicated by the leftmost arrow in Figure 14). Similarly, if auto costs were decreased by \$2 or \$1, then driving would cost the same as transit to reach approximately the first 105 and 330 destinations from any given origin.

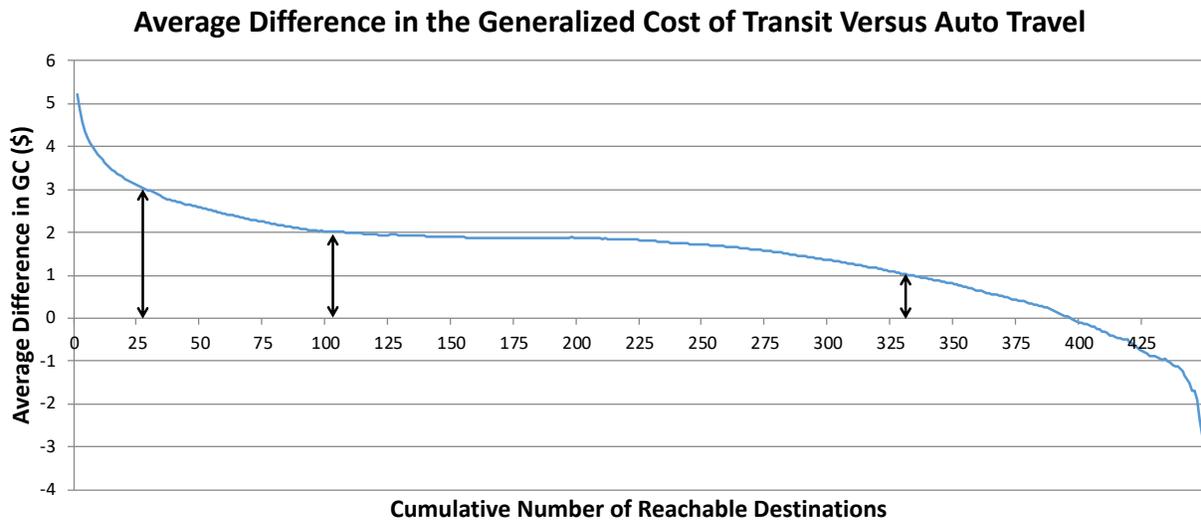


Figure 14: Comparing the average difference in GC to reach all destinations between transit and auto travel.

¹¹ The difference in GC is calculated by taking $GC^{auto} - GC^{tran}$.

For longer trips, specifically trips that cost between \$23 and \$42, auto travel provides higher accessibility than transit (see Figure 13), suggesting that travel speed is the critical factor in determining accessibility to destinations that are further away. Although auto travel has a higher monetary cost than transit, driving provides faster speeds that produce shorter travel times so that auto accessibility is higher than transit accessibility for longer trips. The impact of travel speed on accessibility levels is illustrated by the slope of the average access profile curves. Since driving is faster than taking transit or walking (all else equal), more destinations can be reached by driving for each additional unit of *GC*. This results in a steeper average auto accessibility curve compared to that of transit or walking. Because of this, the average auto accessibility curve is able to reach accessibility saturation—"the point along the *GC* spectrum where all [destinations] can be reached" (Neudorf, 2014, p. 50)—at a lower cost than the average transit and walking accessibility curves despite auto travel having a higher barrier-to-entry cost. On average, all 449 destinations can be reached by driving at \$31 compared to transit at \$42 and walking at \$129.

Figures 16 to 19 show the same average access profiles illustrated in Figure 13 overlaid with box and whisker plots that show the variability in the cumulative number of reachable destinations at each *GC* interval. The top and bottom whiskers of each plot indicate the cumulative number of destinations that can be reached from the origin zones with the highest and lowest accessibility levels at a particular *GC* interval, respectively (i.e. maximum and minimum cumulative number of reachable destinations; see Figure 15 for an example). The bottom, middle, and top lines of the box plots mark the cumulative number of destinations that can be reached from origin zones that have accessibility levels ranked at the first, second (i.e. median), and third quartile, respectively, at a particular *GC* interval.

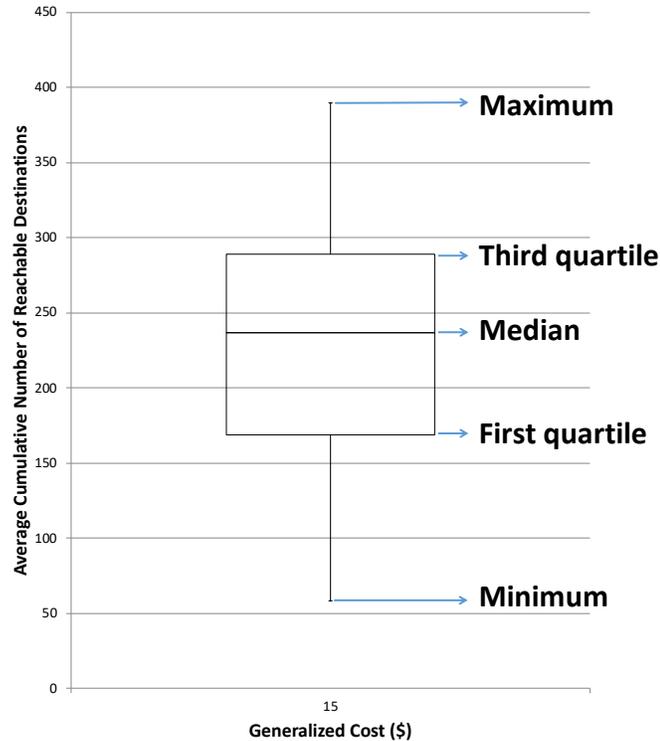


Figure 15: Example box and whisker plot at a GC of \$15.

The box and whisker plots show the variability in accessibility among all zones, which is particularly widespread for pedestrian travel. This reflects the wide range in travel time for walking trips compared to transit or auto trips. The larger variability in pedestrian accessibility makes sense given that walking is the slowest mode; the difference in travel time between walking 500m and 5km, for example, is much larger than taking transit or driving, all else equal. The origin zone with the highest pedestrian accessibility has an API^{ped} of 0.7696 compared to 0.4086 for the zone with the lowest pedestrian accessibility (see Table 7). As will be illustrated in section 4.2.1, zones with high pedestrian accessibility are located in high density areas where more destinations are available and there is better connectivity in the pedestrian network, which reduces walking time and increases pedestrian accessibility. In zones with low pedestrian accessibility, origins and destinations are farther apart and the pedestrian network is sparser. As such, trip distances are longer and it takes more time to complete a trip by walking.

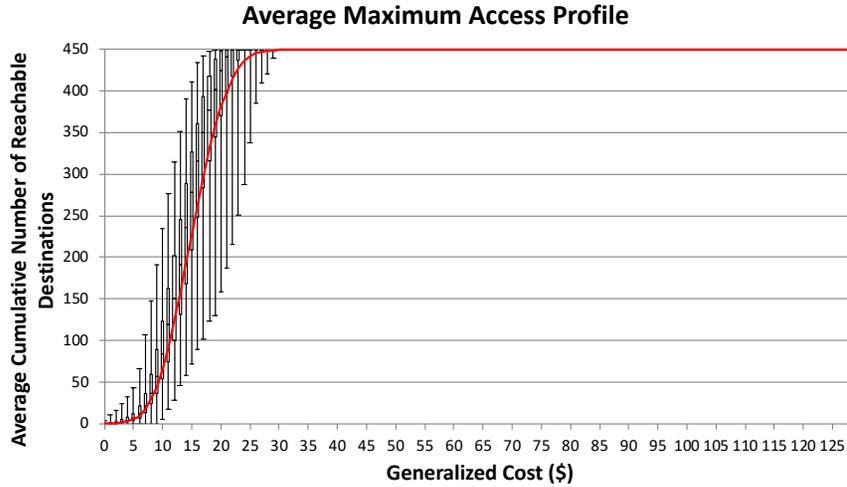


Figure 16: Average access profile for maximum level of accessibility when all modes are considered.

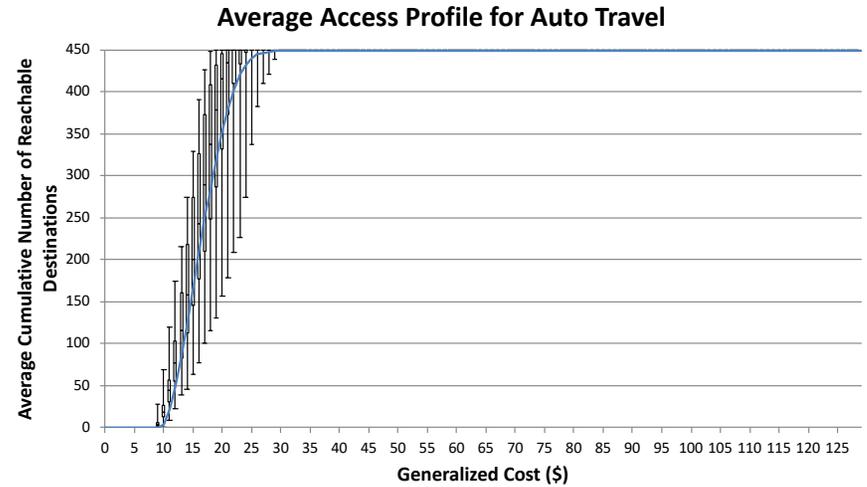


Figure 18: Average access profile for auto travel under baseline accessibility conditions.

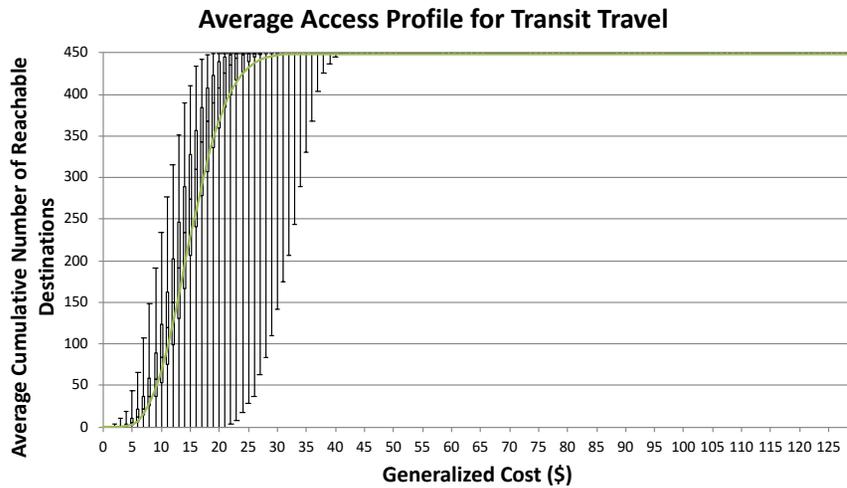


Figure 17: Average access profile for transit travel under baseline accessibility conditions.

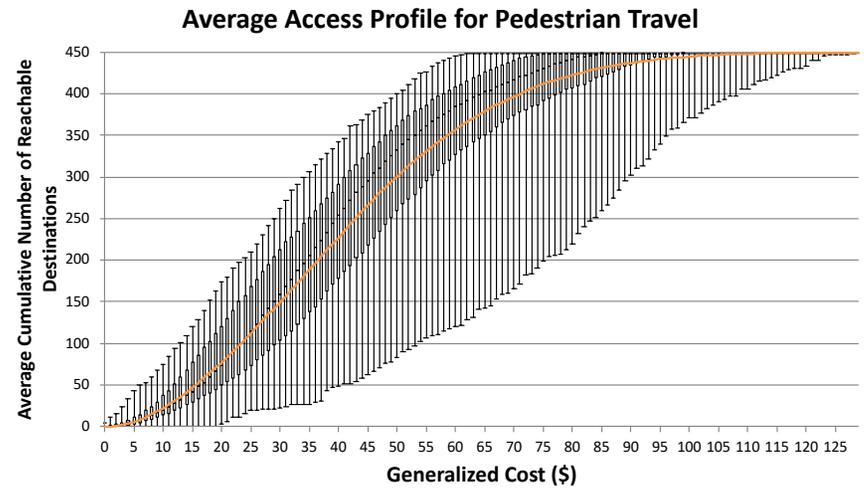


Figure 19: Average access profile for pedestrian travel under baseline accessibility conditions

Comparing Figures 17 and 18 reveals that transit accessibility is more variable than auto accessibility. Table 7 also indicates this, noting that the range of API^{tran} values is larger than the range of API^{auto} values. Presumably this is because the road network is more ubiquitous than the transit network, meaning that auto trip times are more consistent across the city than transit trip times.

Table 7: Descriptive statistics for absolute accessibility levels for each mode.

	API^{tran}	API^{auto}	API^{ped}
Mean	0.8855	0.8740	0.6796
Standard deviation	0.0183	0.0139	0.0689
Minimum	0.7480	0.8308	0.4086
First quartile	0.8751	0.8649	0.6360
Median	0.8880	0.8762	0.6980
Third quartile	0.8982	0.8861	0.7355
Maximum	0.9192	0.8928	0.7696
Range	0.1712	0.0621	0.3610

4.2.1 Spatial distribution of baseline accessibility levels

Figures 20 to 22 show the spatial distribution of accessibility levels for each mode grouped by decile. Each colour gradient contains 10% of the TAZs that are included in the analysis. These maps reveal clear spatial patterns with core areas of the city experiencing higher accessibility than zones that are closer to the city border. This makes sense given that land use density is higher in and around the downtown and therefore more destinations can be reached at a lower GC . The quality of transit service and connectivity of the pedestrian network are also better in the downtown core, which increases transit and pedestrian accessibility in central parts of the city.

This spatial pattern in Figure 20, which shows the distribution of API^{tran} values, is particularly interesting because it closely resembles the subway network. Zones with high transit

accessibility are located on or near the subway lines. The bus and streetcar network, however, does not appear to have any strong relationship with the spatial distribution of transit accessibility levels. This suggests that higher order transit, such as subways, has more bearing on determining transit accessibility. Allen and Farber (2019) find similar spatial patterns in their research—areas in Toronto that are located near and along the subway lines have higher accessibility to jobs by transit than other areas (see Vendeville, 2019). The fact that better transit accessibility occurs in areas that are near higher-order transit service supports policies such as transit oriented development, which concentrate growth near major transit stations and corridors.

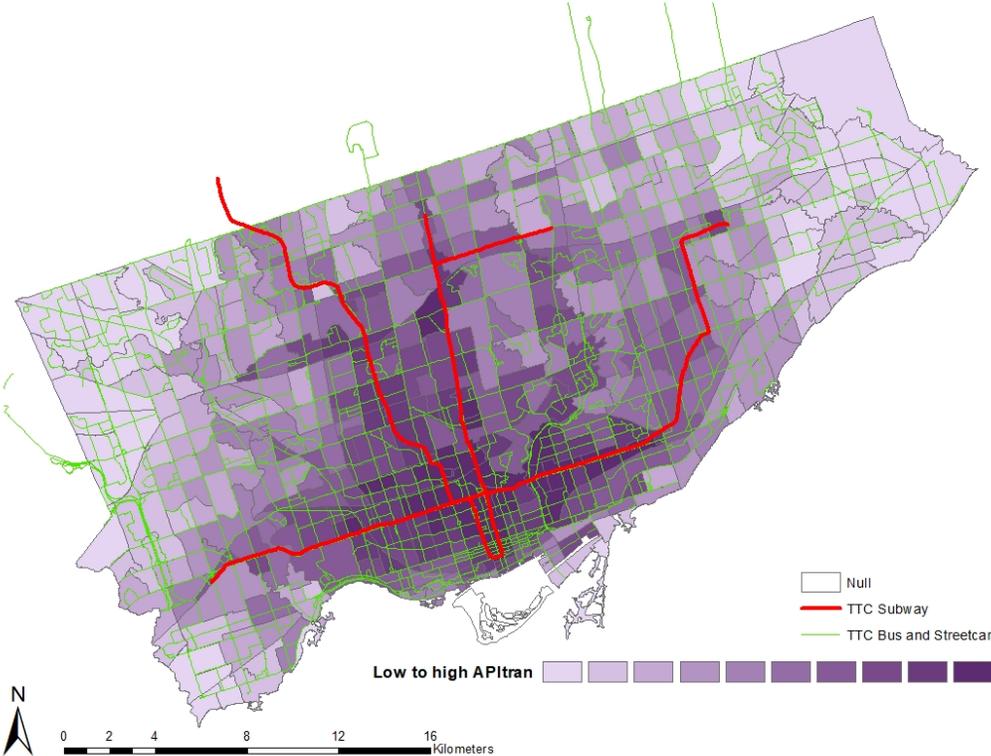


Figure 20: Relative transit accessibility levels (API^{tran}) by decile under baseline conditions.

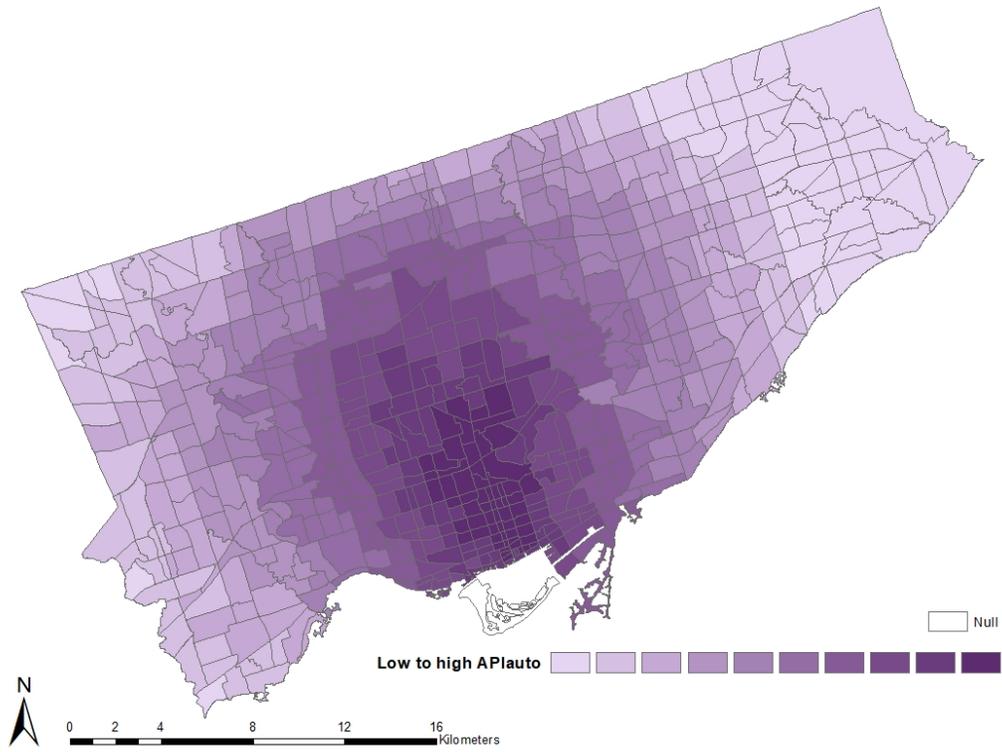


Figure 21: Relative auto accessibility levels (API^{auto}) by decile under baseline conditions.

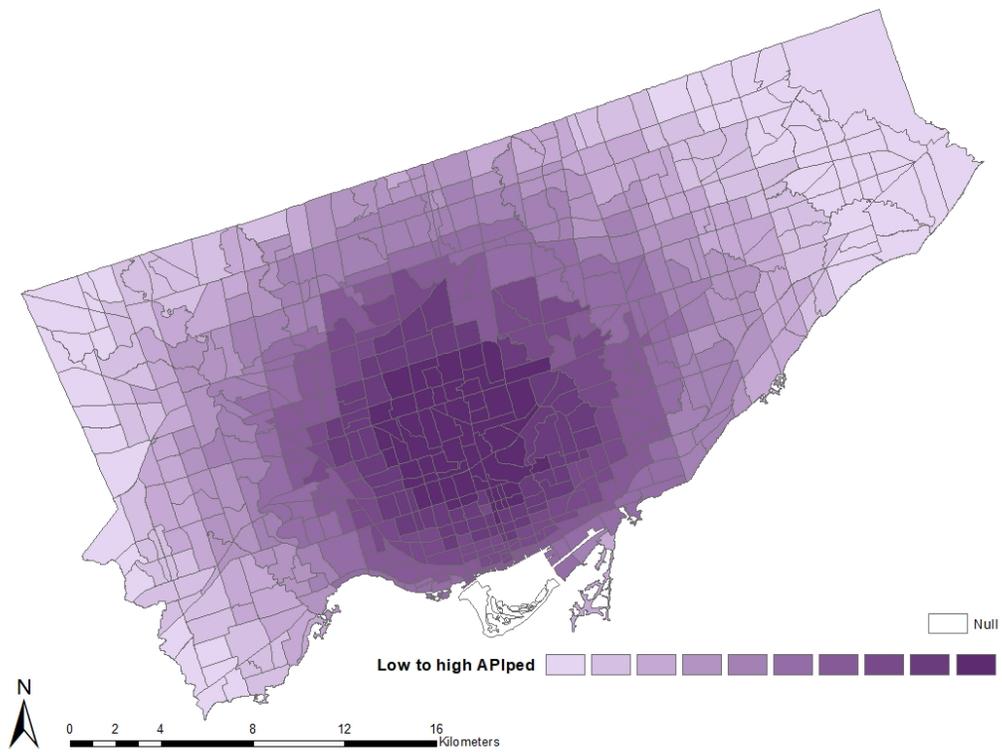


Figure 22: Relative pedestrian accessibility levels (API^{ped}) by decile under baseline conditions.

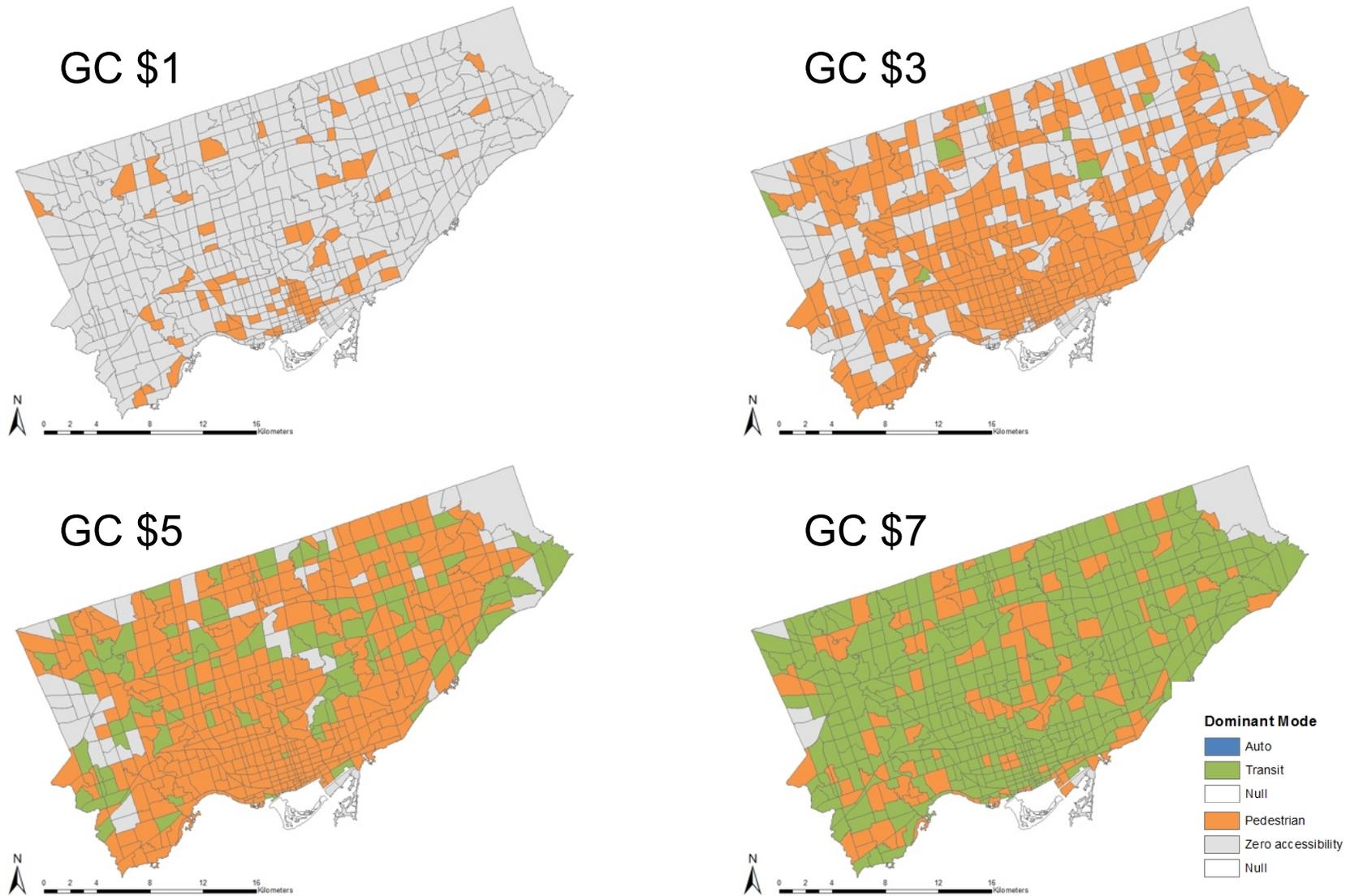


Figure 23: Mode that provides the best accessibility from each zone at GC intervals of \$1, \$3, \$3, and \$7 under baseline conditions.

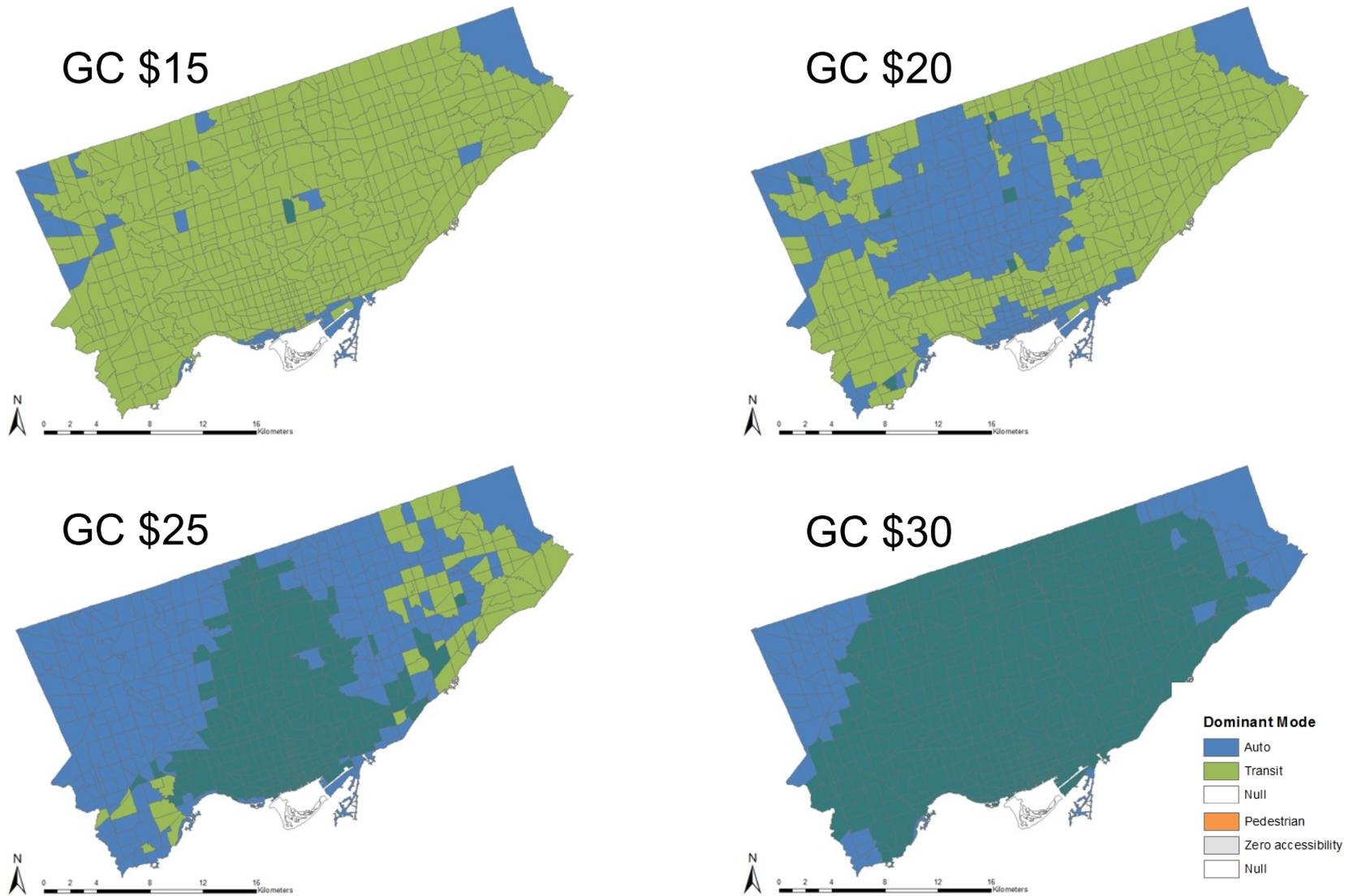


Figure 24: Mode that provides the best accessibility from each zone at GC intervals of \$15, \$20, \$25, and \$30 under baseline conditions.

Figures 23 and 24 identify the mode that provides the highest accessibility from each zone to destinations at different *GC* intervals. Similar to findings from Figure 13, the maps show that pedestrian travel provides the best accessibility at lower *GC* intervals, transit at mid-*GC* intervals, and auto at higher *GC* intervals. More specifically though, Figures 23 and 24 show that certain parts of Toronto are better served by auto travel than transit travel, as indicated by zones coloured in blue. At *GC* intervals of \$25 and \$30, auto travel is more competitive than transit in zones near the city border, particularly in the north east and north west corners of Toronto. This is not surprising given that suburban neighbourhoods outside of the city's downtown core are not served by subways and bus service is less frequent and ubiquitous. As such, driving offers better accessibility for these areas than taking transit at specific *GC* intervals.

4.3 Socioeconomic need

As discussed in section 3.0, a socioeconomic need indicator, *SNI*, is used to determine the different levels of socioeconomic need across zones in Toronto in order to help identify areas in the city that experience transport disadvantage. The *SNI* is the sum of the z-scores for the distributions of four variables: average income, unemployment rate, percentage of recent immigrants, and percentage of households that spend more than 30% of household income on shelter costs. Lower *SNI* values indicate higher socioeconomic need and vice versa. As shown in Table 8, the *SNI* values range from -9.77 to 23.75. Figure 25 shows the spatial distribution of *SNI* values by decile. Each colour gradient includes 10% of the TAZs included in the analysis.¹²

¹² The *SNI* was only calculated for 622 of the 625 TAZs in Toronto. Three TAZs are excluded because of unavailable census data.

Table 8: Descriptive statistics of SNI values.

	<i>SNI</i>
Mean	0.00
Standard deviation	2.92
Minimum	-9.77
First quartile	-1.81
Median	0.12
Third quartile	1.85
Maximum	13.99
Range	23.75

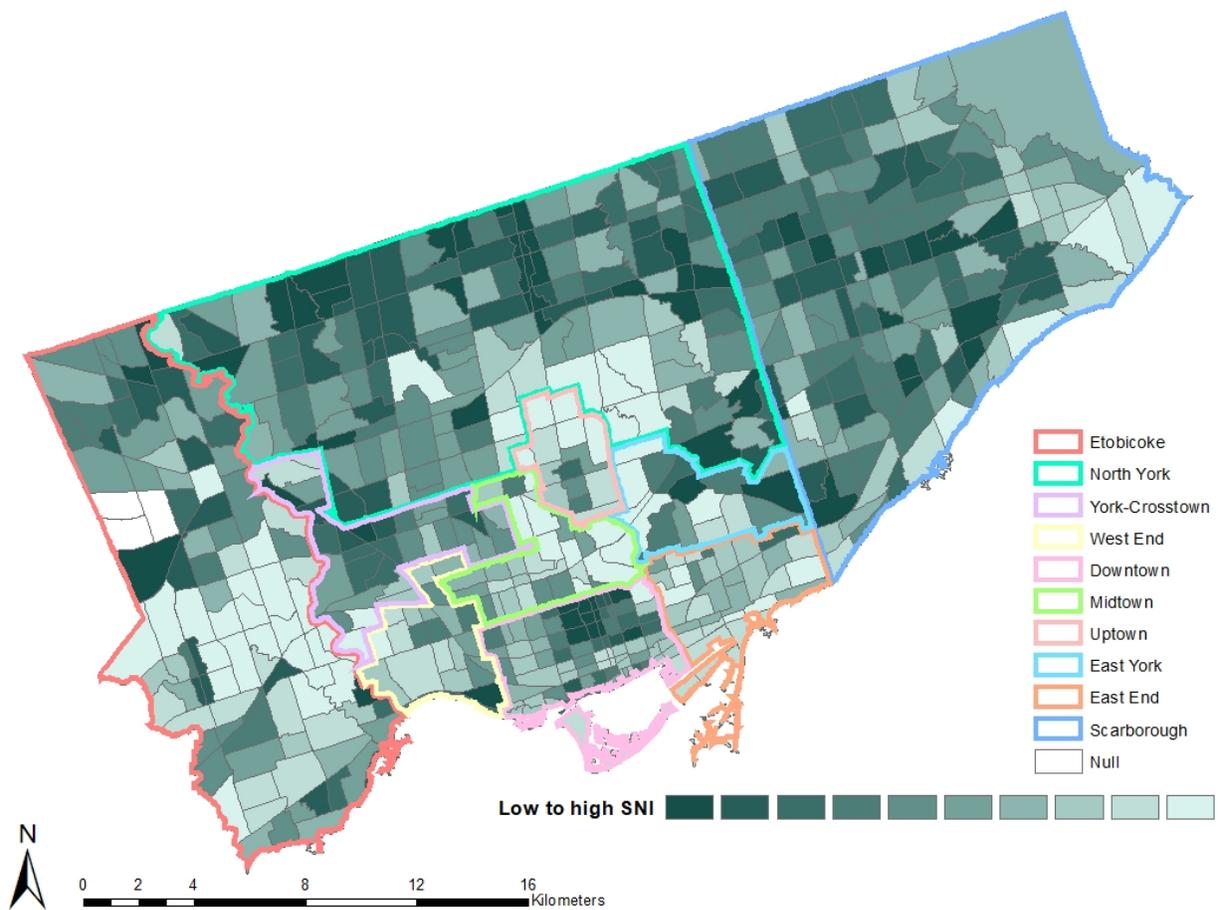


Figure 25: Spatial distribution of SNI values in Toronto by decile. Darker zones indicate higher levels of need.

Areas with high socioeconomic need are dispersed in Toronto, but spatial patterns are still evident (see Figure 25). Most zones that experience the highest levels of socioeconomic

need occur outside of the West End, Midtown, and East End boundaries. In particular, Scarborough, North York, York-Crosstown, and northern Etobicoke contain most of the zones with the highest socioeconomic need. This is not surprising given that low-income households in Toronto have been pushed to the peripheries of the city in the last few decades (Toronto Foundation, 2017). However, there also exists a small cluster of zones in the downtown with high socioeconomic need. These zones occur near two major post-secondary institutions in Toronto, the University of Toronto and Ryerson University, where many student populations live. They also occur near neighbourhoods such as Regent Park, which is identified by the City of Toronto (2014) as a Neighbourhood Improvement Area (NIA). NIAs are priority areas designated by the city that require further investment to combat social and economic challenges such as crime, unemployment, low income, and marginalization. Other zones in Figure 25 that have high socioeconomic need also occur in other NIAs identified by the City. The consistency between the spatial distribution of NIAs with the zones identified in Figure 25 as having high socioeconomic need help validate the *SNI* results.

Figure 25 also closely resembles findings from Hulchanski's (2010) work, which predicted the changes to individual incomes up to 2025 based on historical income changes from 1970 to 2005. His work shows that there is a clear spatial pattern between areas in the city that will experience an income increase of 20% or more and areas that experience an income decrease of 20% or more. Few parts of the city will face income increases or decreases less than 20%, suggesting further income polarization over time. Areas that are projected to experience the greatest decrease in income in Hulchanski's research are closely aligned with zones in Figure 25 that experience the highest levels of socioeconomic need, and vice versa. Again, the similarity in findings helps validate the *SNI* results produced in this thesis. Using these *SNI* results and the

accessibility levels (*API*) determined in the previous section, the following discussion will identify which areas in Toronto experience transport disadvantage.

4.4 Identifying transport disadvantage

Recall that transport disadvantage is the combination of limited accessibility with different socioeconomic constraints that impede one's ability to travel. The purpose of identifying transport disadvantage is to help planners and decision-makers prioritize areas where populations struggle to reach destinations which, ultimately, limits people's economic mobility and quality of life. The accessibility need measure (*ANM*) combines the *API* and *SNI* to determine the level of transport disadvantage in a zone (see section 3.4). Lower *ANM* values signify low accessibility and high socioeconomic need, and therefore greater transport disadvantage.

Figure 26 shows the spatial distribution of *ANM* values in Toronto by decile (see Table 9 for corresponding descriptive statistics). Each colour gradient includes 10% of the TAZs included in the analysis. Darker gradients indicate zones that experience greater transport disadvantage. In general, transport disadvantaged zones in Toronto are located in the city's suburbs, particularly in Scarborough, northern Etobicoke, and North York. As discussed in section 4.2, these areas are not well served by higher order transit, have less comprehensive and connected pedestrian networks, and do not have as many destinations available within close proximity. These areas also experience some of the highest levels of socioeconomic need in the city. All of these factors combined result in higher transport disadvantage in the suburbs. It should be noted that the results here may also be reflective of boundary effects occurring around the edges of the study area. Since destinations outside of Toronto are not included in the analysis, origin zones near the city border may appear to have worse accessibility, and therefore transport

disadvantage, than they do in reality. If destinations in neighbouring municipalities were included in the analysis, then origin zones along Toronto’s border would likely have better accessibility than reported here since more destinations would be nearer and available.

Table 9: Descriptive statistics of ANM values.

	ANM
Mean	47.4
Standard deviation	17.7
Minimum	6.1
First quartile	34.0
Median	45.7
Third quartile	59.6
Maximum	113.2
Range	107.1

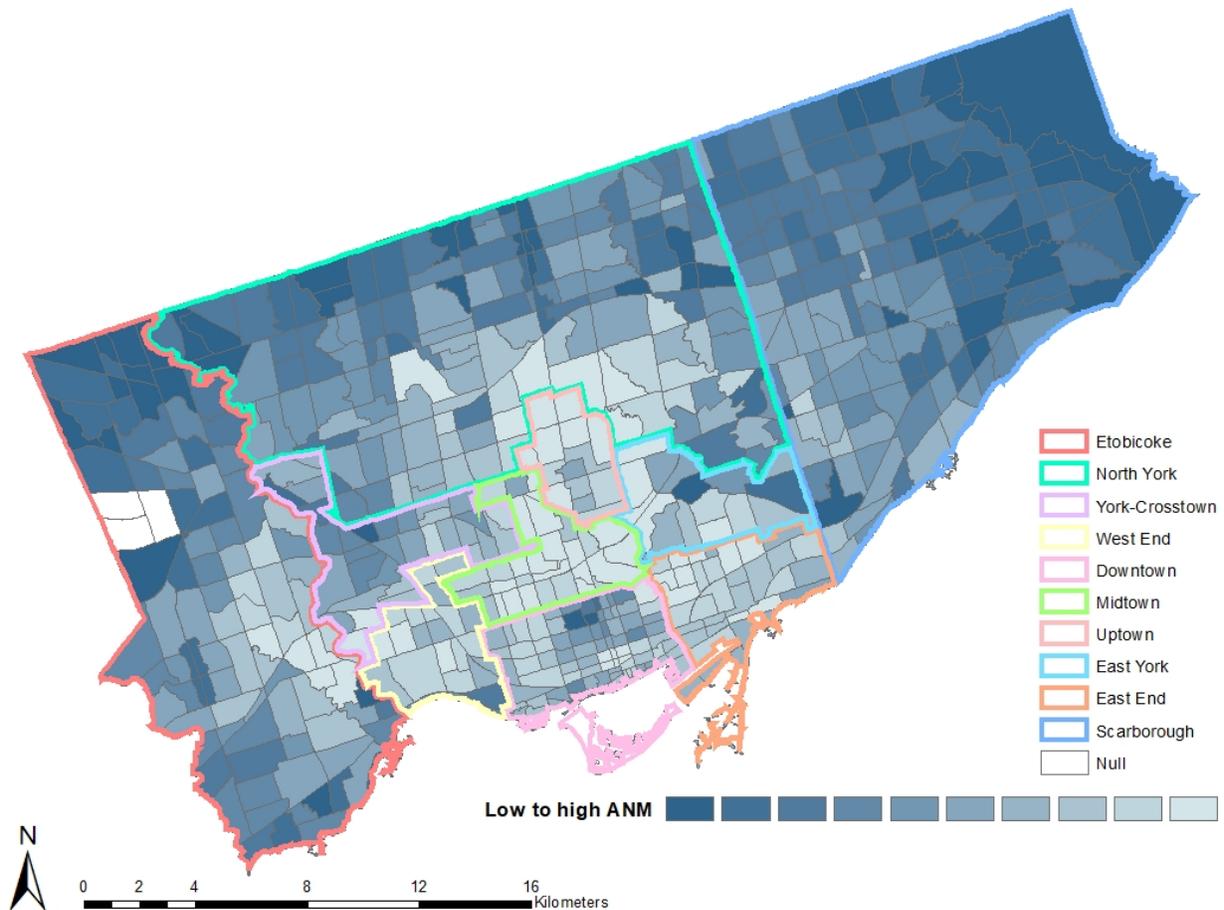


Figure 26: Distribution of ANM values in Toronto by decile. Darker zones have a lower ANM value and therefore experience greater transport disadvantage.

Figure 26 also shows that there are cases where zones with high transport disadvantage occur in areas that have high accessibility. In the downtown, for example, there is a small cluster of zones that experience high transport disadvantage but also have some of the best accessibility in the city because they are located along the subway line. Due to the high socioeconomic need in these zones, however, these areas are considered transport disadvantaged. Herein lies the value of evaluating transport disadvantage—although some areas may experience great accessibility from the transportation network, it does not preclude the fact that other barriers may exist in people’s ability to reach destinations, such as financial constraints, language barriers, or unfamiliarity with navigating a foreign transportation system (Allen & Farber, 2019; Farber, et al., 2018; Foth, Manaugh, & El-Geneidy, 2013).

4.5 Accessibility Interventions

Having identified baseline accessibility conditions and areas of the city that experience high transport disadvantage, this section demonstrates how different interventions impact accessibility levels for transport disadvantaged areas. These interventions include:

- Parking charges: Two parking charge schemes are implemented based on the street parking charges that are already implemented by the Toronto Parking Authority;
- Reduced transit fare: The average transit fare is lowered by 30%, 50%, and 100%;
- Transit service improvements: Transit trip times are decreased based on historical reductions to transit travel times; and
- Land use changes: Additional hospitals are added to increase the number of available locations.

In order to compare each intervention’s impact on accessibility, the percentage change to maximum accessibility, API^{max} , is calculated from baseline levels for each origin zone. Figure

27 uses a box and whisker plot to compare the percentage change to maximum accessibility to all destinations when parking charges, reduced transit fare, and shorter transit trip times are implemented. The percentage change to maximum accessibility resulting from land use changes is presented separately in section 4.5.4 since this intervention only applies to hospital destinations. The first three interventions are compared in parallel in Figure 27 because they impact accessibility to all the destinations types included in this thesis.

The top and bottom whiskers in Figure 27 indicate the percentage change to API^{max} for zones that experience the highest and lowest change under each intervention, respectively. The bottom, middle, and top lines of each box plot mark the percentage change to API^{max} , for zones that experience a percentage change ranked at the first, second, and third quartile, respectively. Table 10 provides the percentage change to API^{max} resulting from each intervention.

The results indicate that each intervention impacts accessibility with differing magnitudes and some interventions have more variable impacts to API^{max} across zones. In general, transit improvements result in the greatest increase to maximum accessibility levels but also produce the most variable results. Transit fare reductions also increase accessibility, although the increase is modest in comparison. Parking charges decrease accessibility levels but often by less than 1%. The following sections will provide a deeper analysis of the results for each intervention.

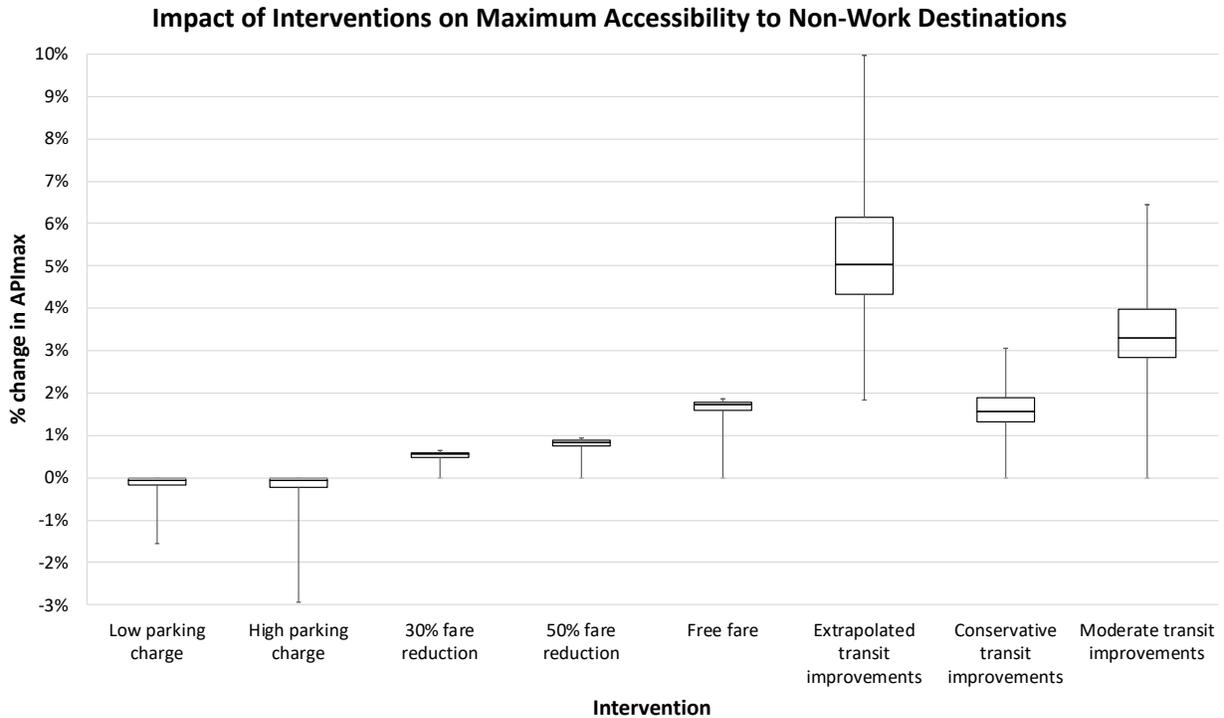


Figure 27: Box and whisker plot of the percentage change to maximum accessibility levels (API^{max}) to all non-work destinations resulting from different interventions.

Table 10: Descriptive statistics for percentage change to API^{max} from baseline conditions after each intervention is applied.

	Parking Charge		Transit Fare Reduction			Transit Improvements		
	Low	High	30%	50%	Free	Extrapolated	Conservative	Moderate
Mean	-0.14%	-0.20%	0.52%	0.79%	1.65%	5.30%	1.62%	3.46%
St. Dev	0.23%	0.36%	0.11%	0.15%	0.25%	1.33%	0.43%	0.87%
Max	0%	0%	0.65%	0.94%	1.88%	9.97%	3.06%	6.45%
Q3	-0.01%	-0.01%	0.59%	0.88%	1.79%	6.15%	1.88%	3.97%
Median	-0.05%	-0.06%	0.56%	0.83%	1.73%	5.03%	1.55%	3.31%
Q1	-0.16%	-0.24%	0.49%	0.76%	1.60%	4.32%	1.31%	2.84%
Min	-1.55%	-2.92%	0%	0%	0%	1.84%	0%	0%
Range	1.55%	2.92%	0.65%	0.94%	1.88%	8.13%	3.06%	6.45%

4.5.1 Parking charges

Two different parking charge schemes were implemented for this intervention. The first closely resembles the City of Toronto’s existing street parking charges and the second doubles

these charges (see section 3.5.1). Both schemes are designed so that core areas of the city (e.g. Downtown and Midtown) have higher parking charges while peripheral areas (e.g. Etobicoke, North York, and Scarborough) have lower parking charges.

As illustrated in Figure 27, parking charges decrease accessibility levels. This is because parking charges add an additional cost to travel, making it more expensive to reach available destinations. Since the second parking charge scheme applies a more expensive parking fee, accessibility levels decrease more than when the first parking charge scheme is applied (see Table 10). Figure 28 shows the percentage change to maximum accessibility levels, API^{max} , in each zone resulting from the lower parking charge. The map reveals that zones in Scarborough, North York, and northern Etobicoke experience the greatest decrease to maximum accessibility despite being subject to some of the lowest parking charges. Conversely, maximum accessibility levels for zones in the downtown and midtown barely change even though they are located in areas with higher parking charges. This may not be initially intuitive given that higher parking fees should result in greater decreases to accessibility and vice versa.

When interpreting these results, however, the accessibility levels offered by each mode must be compared. In zones that experience the greatest decrease to maximum accessibility resulting from parking charges, auto travel is the most competitive mode—driving offers access to the greatest number of destinations at a lower cost (see Figure 24). TAZ 382, identified in Figure 28, is an example. As shown in Figure 29, the shape of the maximum accessibility curve for TAZ 382 is largely dependent on the auto accessibility curve. An increase to driving costs will decrease auto accessibility and, in turn, will lower maximum accessibility to the level where transit becomes the most competitive mode.

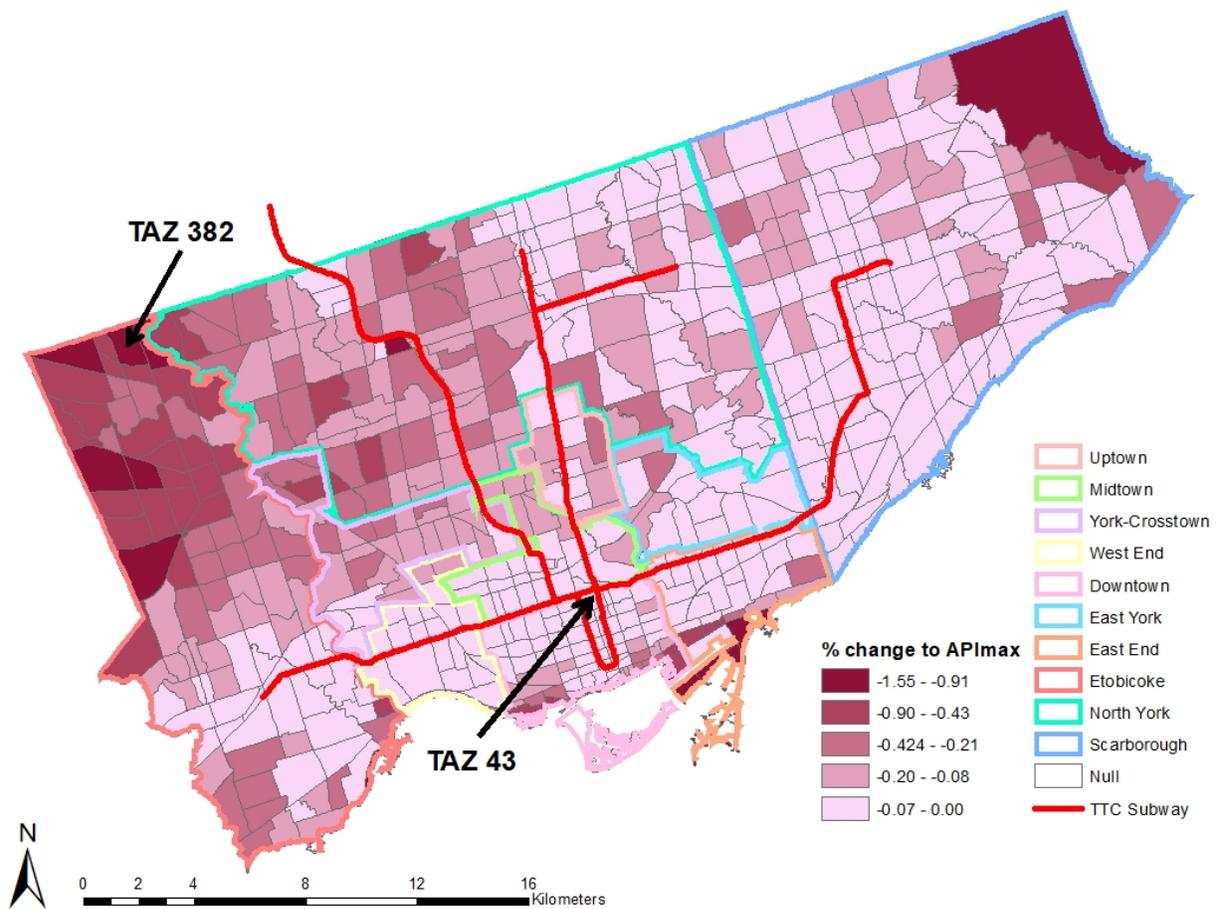


Figure 28: Changes to maximum accessibility levels (API^{max}) resulting from a low parking charge. Darker areas indicate a greater decrease in maximum accessibility.

Conversely, zones that experience minimal or no change to maximum accessibility after a parking charge is implemented are located in areas where transit is the most competitive mode. TAZ 43, for example, occurs at the intersection of two subway lines (see Figure 28). The shape of its maximum accessibility curve, illustrated in Figure 30, is determined by the transit curve because transit provides access to the most destinations at almost every GC level. Although implementing a parking charge will decrease the number of destinations that can be reached at any given cost by driving, it has no bearing on maximum accessibility levels since maximum accessibility is dependent on transit in this zone. In other words, parking charges decrease

maximum accessibility levels the most in areas where auto travel offers the most competitive levels of accessibility.

This finding is an important consideration for planners—especially from an equity perspective—when deciding whether to implement parking charges, where they should be implemented, and at what price point. Although parking charges are often implemented to discourage driving and incentivize transit and active transportation, it may have a disproportionate impact on households that are located in transport disadvantaged areas and where auto travel offers the best accessibility. In the case of Toronto, for example, many of the zones that experience high transport disadvantage in Scarborough, North York, and northern Etobicoke occur in areas where auto is the most competitive mode (see Figure 26). Implementing a parking charge would decrease maximum accessibility levels for households in these zones that already experience low levels of accessibility and are additionally burdened with high socioeconomic need.

In order to circumvent further transport disadvantage and minimize negative impacts to equity, parking charges should be supplemented with other interventions before parking charges are implemented to ensure that economically viable alternatives to driving exist. Reduced transit fare or improved transit service, for example, would increase the competitiveness of transit and provide households in transport disadvantaged areas that are auto dominant with a viable alternative. The impacts of such interventions are discussed in the following sections.

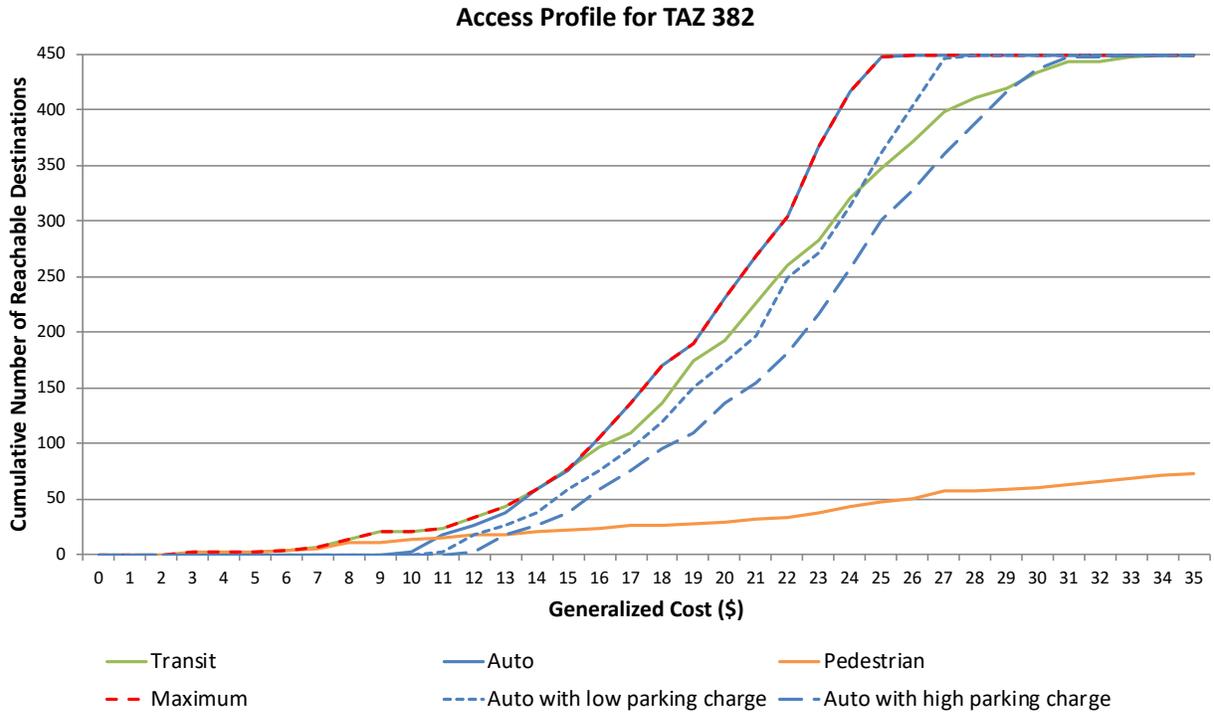


Figure 29: Baseline accessibility levels for trips originating from TAZ 382. An example where auto travel is the most dominant mode.

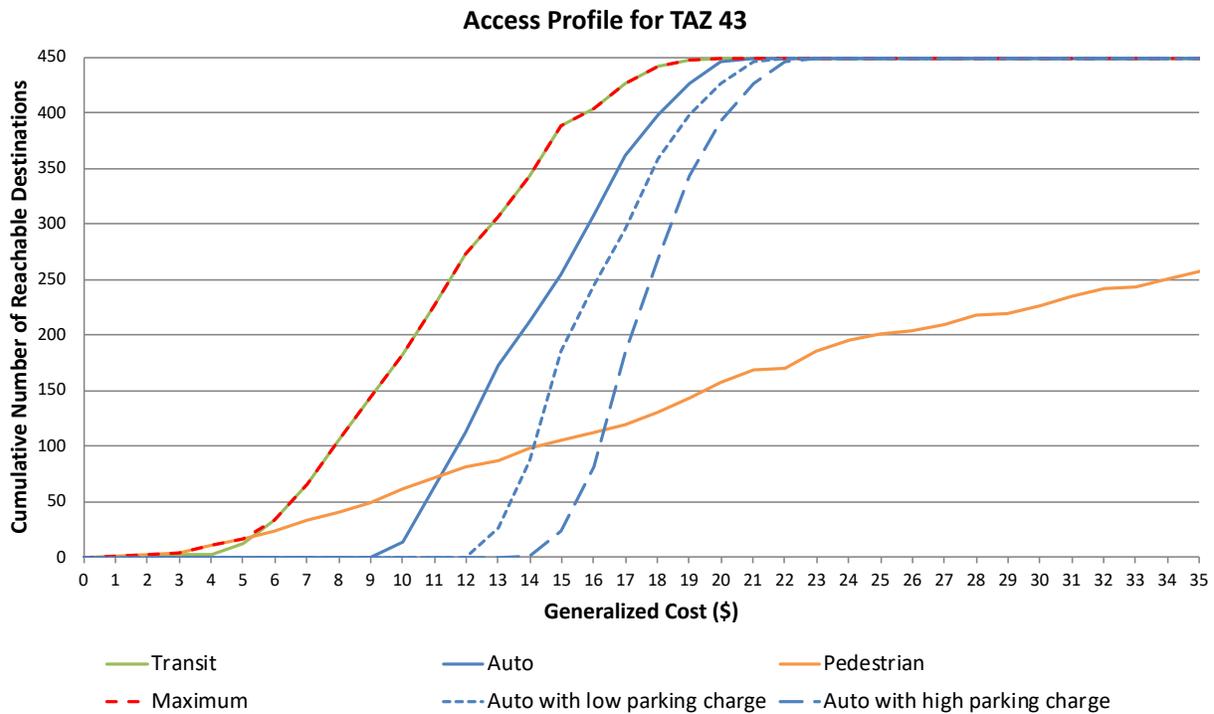


Figure 30: Baseline accessibility levels for trips originating from TAZ 43. An example where transit travel is the most dominant mode.

4.5.2 Reduced transit fares

For this intervention, the cost of transit fare was reduced by 30%, 50%, and 100% (i.e. free transit) from the baseline price of \$2.09. Recall that \$2.09 represents the average fare and was calculated by dividing the TTC's total passenger revenue in 2016 by the number of annual passenger trips taken that year. As Figure 27 shows, reducing transit fare increases maximum accessibility; greater fare reductions result in greater increases to API^{max} . This is because lowering transit fare reduces the GC of making a trip and more destinations can be reached at a lower cost. On average, a 30%, 50%, and 100% fare reduction results in a 0.52%, 0.79%, and 1.65% increase to maximum accessibility levels, respectively (see Table 10). These increases may be considered marginal, but on average they have a greater impact on maximum accessibility levels than the parking charge intervention.

Table 10 also shows that the minimum percentage change to API^{max} resulting from each level of fare reduction is 0%. This minimum percentage change occurs in TAZ 7, which is Tommy Thompson Park located in Toronto's port lands in the East End (see Figure 32). A 0% change to API^{max} indicates that auto travel is so competitive in TAZ 7 that implementing free transit fare has no impact on its maximum accessibility levels. Figure 31 illustrates this by comparing the level of accessibility provided by each mode for trips originating in TAZ 7. It shows that auto travel provides access to the greatest number of destinations at all GC intervals, even when transit is free. This is because there is no transit service that directly serves Tommy Thompson Park and the level of transit service in surrounding areas is limited. Transit trips from the park therefore take much longer than auto trips, so much so that it is cheaper to access destinations from the park by driving rather than taking transit. As a result, transit fare reductions

have no bearing on maximum accessibility levels in TAZ 7—the maximum level of accessibility is solely determined by the level of accessibility provided by auto travel.

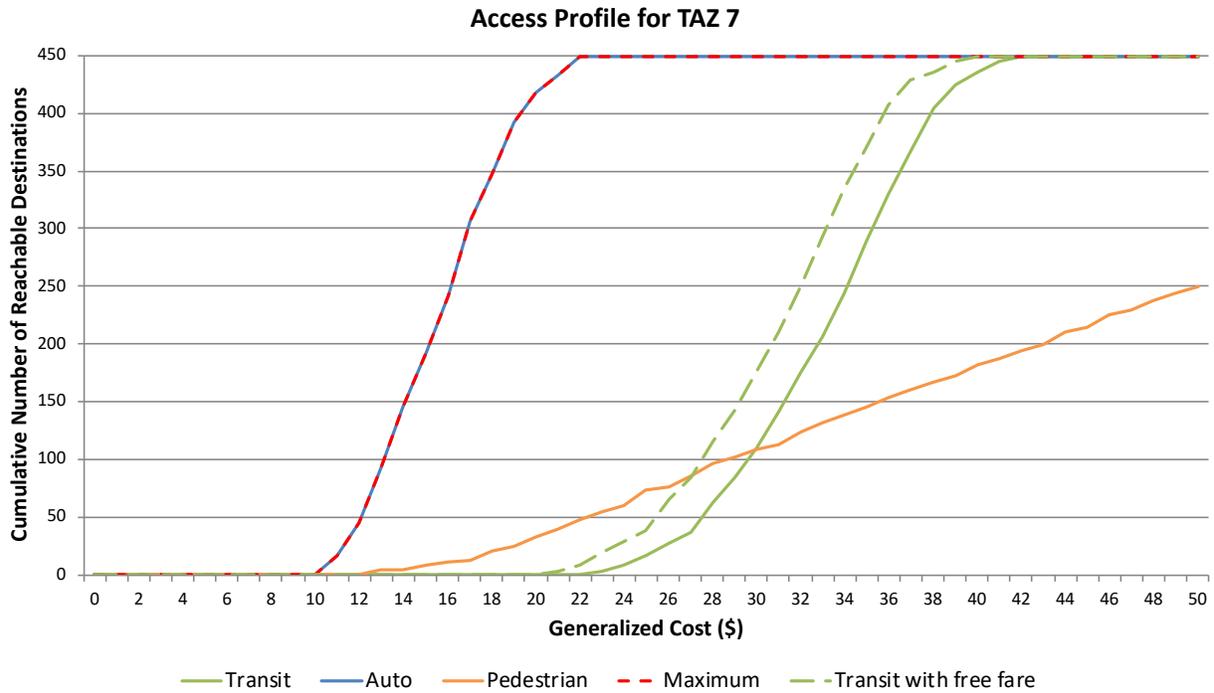


Figure 31: Baseline accessibility levels for trips originating from TAZ 7.

Figure 32 shows the percentage change to maximum accessibility levels, API^{max} , in each zone resulting from free transit fare. Zones with lighter colour gradients, which indicate relatively lower increases to API^{max} , mostly occur in northern Etobicoke and the western half of North York. Similar to TAZ 7, these are areas where auto travel provides better accessibility than transit (see Figure 24), and therefore implementing free transit fare has minimal impact on maximum accessibility for these zones.

Many zones, however, experience relatively higher increases to maximum accessibility when free transit is implemented. Figure 32 shows that many of these zones occur along the east-west subway line through the East End, East York, Downtown, Midtown, and the West End, which are some of the least transport disadvantaged areas in the city (see Figure 26). There are

some areas in Scarborough and the eastern half of North York that have high transport disadvantage and also benefit from higher increases to maximum accessibility levels when transit fare is free. However, the maximum accessibility levels in these transport disadvantaged areas remain relatively low even after free transit fare is implemented (see Figure 33). In other words, reducing transit fares may increase accessibility for some transport disadvantaged zones, but it may not be effective at equalizing accessibility levels between advantaged and disadvantaged areas. Even after free transit fares are implemented, areas that were previously transport disadvantaged remain disadvantaged relative to areas where maximum accessibility levels are already high under baseline conditions.

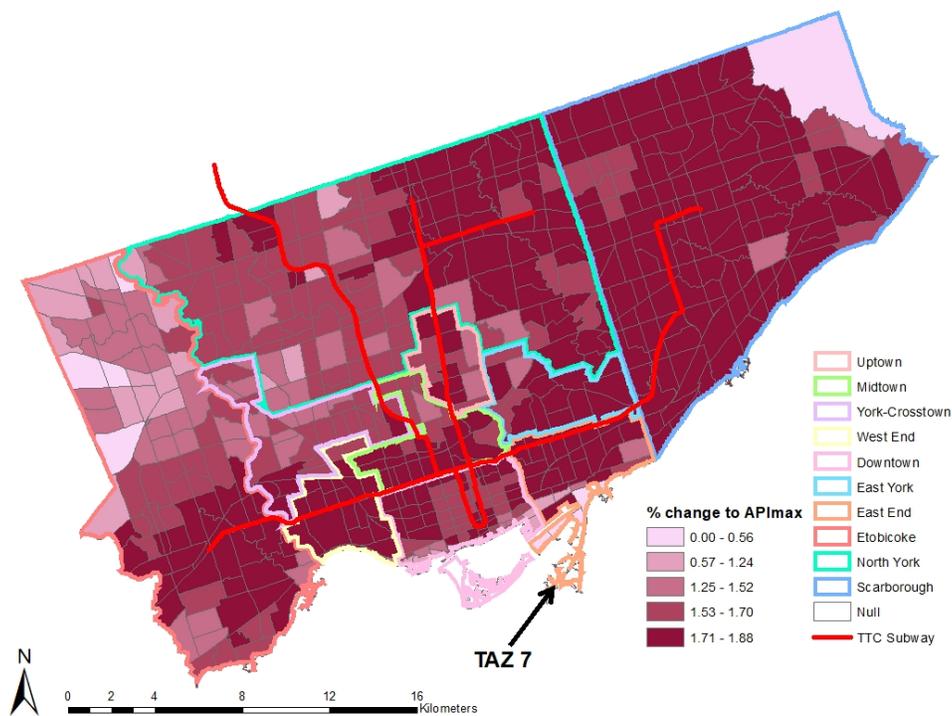


Figure 32: Changes to maximum accessibility levels (API^{max}) resulting from free transit fare. Darker areas indicate a greater increase in maximum accessibility.

If equalizing accessibility levels among transport advantaged and disadvantaged zones is a priority, then the results suggest that applying a universal transit fare reduction is ineffective. It is possible that an alternative transit fare reduction scheme could be more effective. For example,

free transit could be offered to transport disadvantaged households while non-disadvantaged households continue paying the regular transit fare. However, this strategy is only effective insofar as the level of accessibility provided by free transit is competitive with auto travel in transport disadvantaged areas. If transit service is so limited in transport disadvantaged zones that it makes more economic sense to drive even when transit is free, then accessibility levels will not improve for these transport disadvantaged zones. This highlights the importance of understanding baseline accessibility conditions before implementing any intervention. In order to have a meaningful impact on transport disadvantage, planners and decision makers must first assess the existing levels of accessibility by different modes because it will inform the efficacy of an intervention.

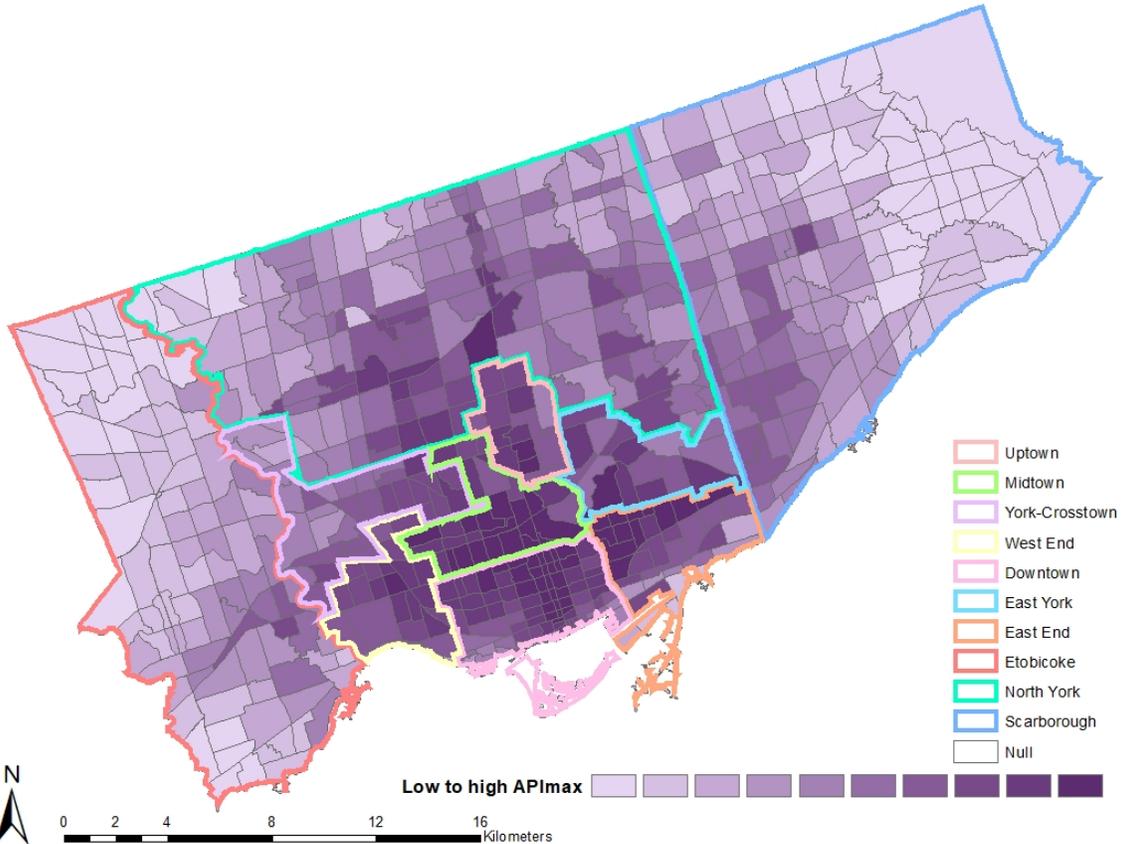


Figure 33: Accessibility levels by transit (API^{max}) from each origin zone to all non-work destinations with free transit fare.

The results here also raise an important question for planners and policymakers regarding the level of accessibility that is considered sufficient. To some extent, there will always be differences in accessibility levels between different parts of the city, as seen in Figure 33. Areas in the downtown core will inevitably have better accessibility than suburban areas because of differences in land use and the fact that higher order transit usually serves areas with denser populations. Given that differences in accessibility exist, what, if any, should be the “minimum threshold level of accessibility to key destinations” (Lucas, van Wee, & Maat, 2016, p. 477)? Defining such a threshold would help clarify the level of accessibility that is considered acceptable in different contexts, thereby helping policymakers direct their efforts in addressing transport disadvantage.

Based on the results of this research under baseline conditions (i.e. before any intervention is applied), there is a clear point at which some level of *GC* provides access to at least one of each non-work destination type. On average, a *GC* of \$5 is required to reach at least one hospital, \$4 to reach at least one library, \$6 to reach at least one post-secondary institution, \$3 to reach at least one Early Years centre, and \$3 to reach at least one recreation centre. These average *GC* thresholds can be used to determine a guaranteed minimum level of accessibility such that origin zones that have accessibility levels below average should have their accessibility conditions improved. For example, for origin zones where a trip to the closest destination costs more than the average *GC*, conditions in these zones should be improved (either through transit service improvements, land use changes, reduced transit fare, etc.) such that average *GC* is sufficient to reach that destination. This would ensure that everyone can access at least one location of different key destination types, regardless of where a trip originates, at a reasonable cost.

4.5.3 Transit service improvements

Transit service improvements are represented in this research by reducing transit trip times. It was assumed that service improvements, whether through increased frequency, new transit lines, priority signals, dedicated right of way, integrated fare, or other actions, would be manifested through shorter transit trips. Three transit improvement scenarios were tested:

1. *Extrapolated transit improvements.* Transit trip times were reduced from baseline levels using the percentage decrease in travel time for transit trips from 2013 to 2017.
2. *Conservative transit improvements.* Transit trip times were reduced from baseline levels using one-third of the percentage decrease from the first scenario.
3. *Moderate transit improvements.* Transit trip times were reduced from baseline levels using two-thirds of the percentage decrease from the first scenario.

Figure 27 shows that transit service improvements increase maximum accessibility because transit service improvements reduce transit travel time and, therefore, decrease the time cost of travel, so that more destinations can be reached at lower GC intervals. Extrapolated transit improvements result in the greatest increase to API^{max} because they shorten travel times the most, while conservative improvements result in the smallest increase to API^{max} because they reduce travel times the least.

For zones where auto travel is the most dominant mode, transit service improvements are able to make transit more competitive than auto travel. TAZ 382, for example, is a residential area located in northern Etobicoke (see Figure 28) where auto travel offers higher accessibility than transit. As indicated by the horizontal arrow in Figure 34, conservative transit improvements shift the transit accessibility curve to the left of the auto accessibility curve for almost all GC intervals. In other words, conservative transit improvements alone are able to make transit the

more competitive mode to nearly all destinations for trips originating in TAZ 382. This is a promising finding for governments, given that moderate and extrapolated levels of transit improvements would likely be much more costly.

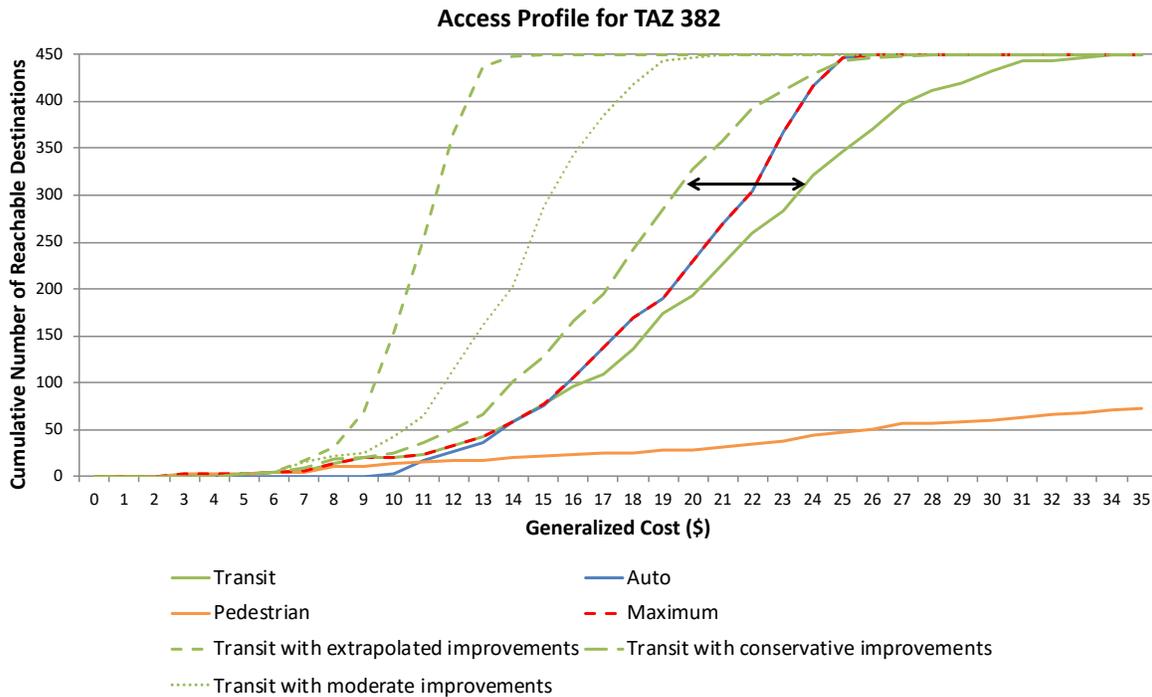


Figure 34: Comparing accessibility levels for trips originating from TAZ 382 under baseline conditions with different transit improvement scenarios.

Figure 35 shows the percentage change to maximum accessibility levels, API^{max} , in each zone after extrapolated improvements have been implemented. Zones with a darker colour gradient indicate a greater increase to maximum accessibility. These zones occur in the peripheral parts of the city, specifically in Etobicoke, North York, and Scarborough. Zones that experience some of the smallest increases to maximum accessibility occur in central parts of the city, including Downtown, Midtown, and Uptown.

The spatial distribution of the results in Figure 35 is expected given the way that transit service improvements were applied in this research. Unlike transit fare reductions, which were applied universally across all zones, different levels of transit service improvements were applied

according to the length of a transit trip. Greater transit time reductions were applied to longer trips (i.e. more improvement) whereas smaller transit time reductions were applied to shorter trips (i.e. less improvement). Since transport disadvantaged zones generally experience poor accessibility and, by extension, some of the longest transit trips, they were subject to greater trip time reductions. As such, zones in Etobicoke, North York, and Scarborough, which tend to have greater transport disadvantage, experience larger increases to maximum accessibility levels. The results therefore suggest that transit service improvements may be more effective at closing the “accessibility gap” between advantaged and disadvantaged zones than transit fare reductions. The extrapolated transit service improvements applied here, for example, reduce the accessibility gap more than any other intervention applied in this research.

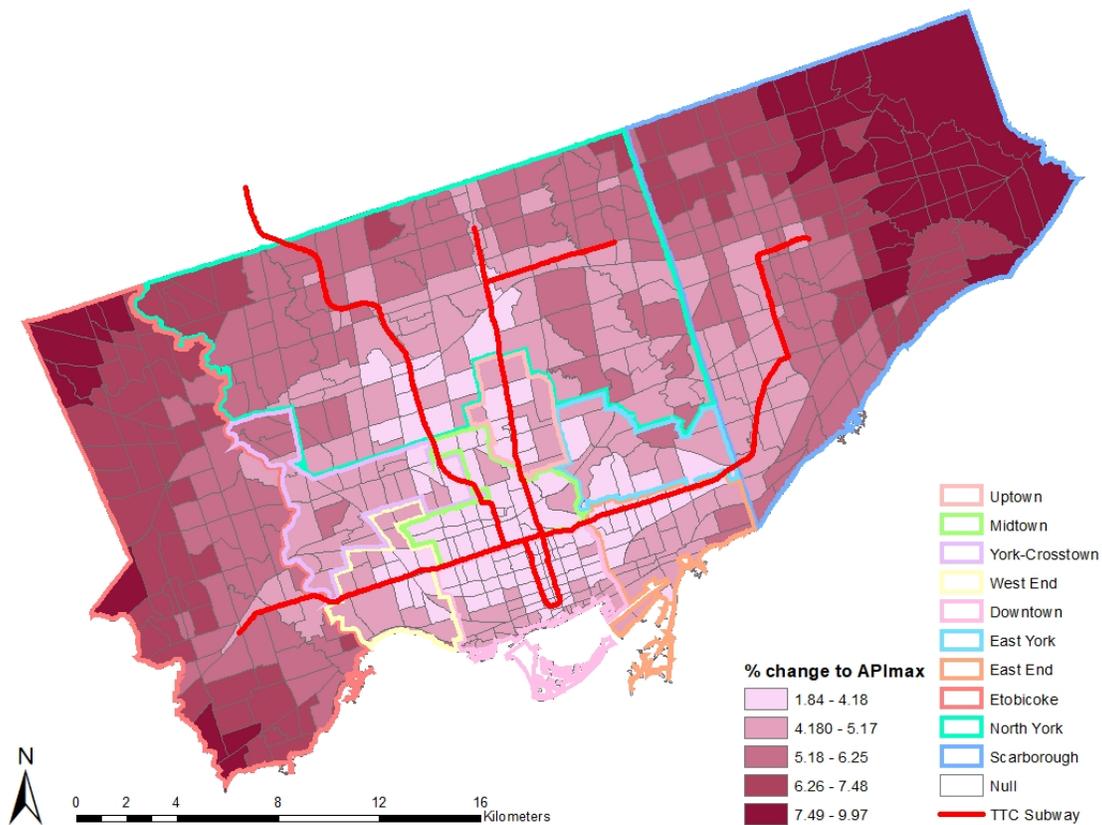


Figure 35: Changes to maximum accessibility levels (API^{max}) resulting from extrapolated transit improvements. Darker areas indicate a greater increase in maximum accessibility.

It is important to note, however, that implementing conservative transit improvements and free transit fare result in similar increases to maximum accessibility levels (see Figure 27). The efficacy of transit service improvements is therefore dependent on the extent to which these improvements reduce transit travel times. Greater investments into transit service will presumably result in shorter transit trips, which will produce greater increases to accessibility. Because larger investments can always be made to improve transit, it is difficult for fare reductions to have the same level of impact on accessibility as transit service improvements since transit fares can only be lowered so much (i.e. free transit). That said, policies could be implemented to subsidize transit fares, in which case accessibility would increase.

Given that transit service improvements have the potential to close the accessibility gap more than the other interventions applied in this research, the results suggest that travel time is a bigger impedance to transport disadvantaged households than the out-of-pocket cost of taking transit. The impedance of longer trip times is also compounded by the time constraints that households with higher socioeconomic need may face. Insofar as planners and policymakers seek to address equity issues by increasing accessibility levels for transport disadvantaged households, improvements to transit service—specifically to reduce the duration of long trips—should be prioritized. That said, it should also be noted that the results here may vary significantly based on the assumed value of time (*VOT*). Future research should consider the sensitivity of accessibility levels to a higher or lower *VOT*. A lower *VOT*, for example, would result in an access profile curve with a steeper slope since more destinations can be reached for each additional unit of *GC*. Hence, when the *VOT* is lower, travel time becomes less of an impedance to accessibility levels.

4.5.4 Land use changes

The land use changes applied in this thesis represent infills or land development projects that add new destinations to a city. Unlike the previous interventions, the impacts of land use changes on accessibility were studied by focusing on access to hospitals rather than all of the non-work destinations included in this research. Seven new hospitals were added to areas that have high socioeconomic need and low accessibility to existing hospitals to evaluate the extent to which more destinations increase accessibility.¹³ In general, more destinations result in higher accessibility because there is a larger number of possible locations that people can travel to. Furthermore, new destinations may be located closer to an origin zone than existing destinations, which decreases travel time and therefore increases accessibility from that origin.

The box and whisker plot in Figure 36 shows how land use changes alter the maximum level of accessibility (API^{max}) to hospital locations compared to the other interventions applied in the previous sections. The top and bottom whiskers of each plot indicate the highest and lowest percentage change to maximum accessibility to hospitals, respectively, resulting from each intervention. The bottom, middle, and top lines of each box plot mark the percentage change to maximum accessibility to hospitals for zones that experience a percentage change ranked at the first, second, and third quartile, respectively. On average, adding seven new hospital locations increases maximum accessibility to hospitals by 4.57%, which is comparable to the 4.02% average increase resulting from extrapolated transit service improvements. This suggests that land use changes can result in substantial improvements to accessibility given that their average impact is similar in magnitude as implementing five-year's worth of transit service improvements from 2013 to 2017.

¹³ Refer to section 3.5.4 for a detailed explanation of how new hospital locations were determined.

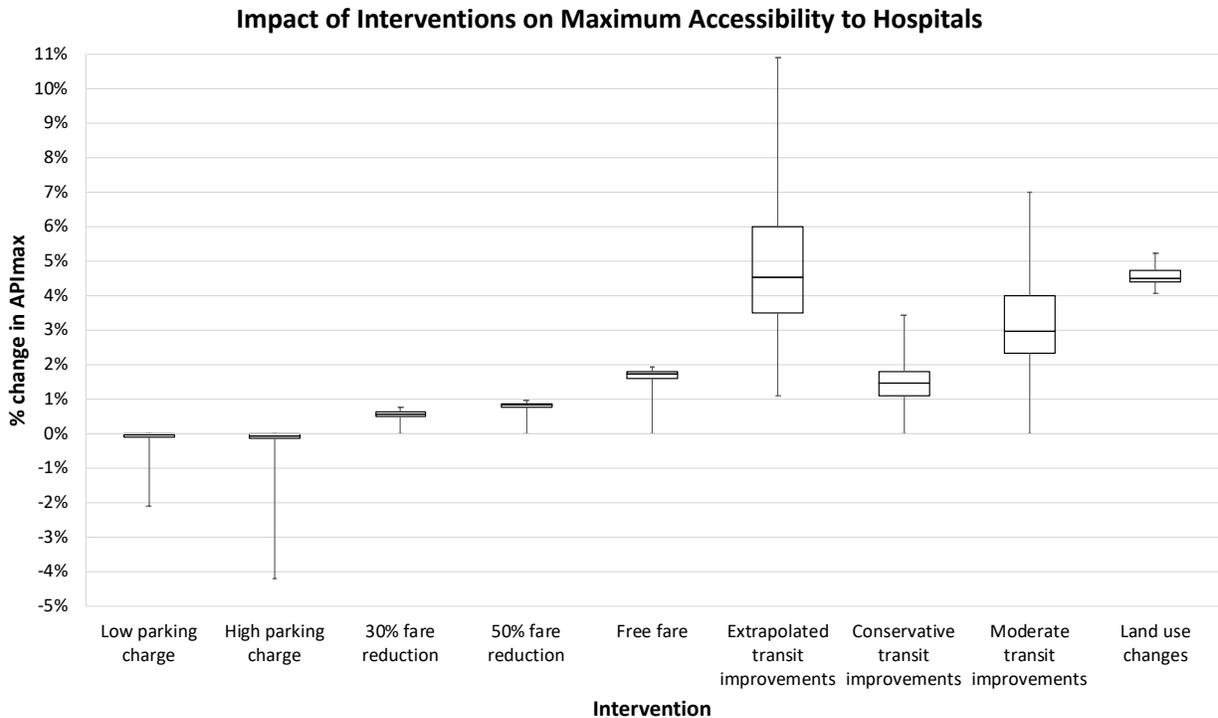


Figure 36: Box and whisker plot of the percentage change to maximum accessibility levels (API^{max}) to hospitals resulting from different interventions.

Figure 37 shows the percentage change to maximum accessibility levels, API^{max} , to hospitals in each zone after seven new hospitals are added. In general, zones near and around new hospital locations experience higher increases to maximum accessibility to hospitals, as indicated by darker colour gradients; however, the difference in percentage change to API^{max} between the darkest and lightest gradient is minimal, ranging from 4.06% to 5.24%. This is small compared to the range of percentage increase to maximum accessibility to hospitals when extrapolated transit improvements are applied: 0.58% to 9.32% (see Figure 36). A smaller range in the percentage increase to maximum accessibility indicates that all zones experience a similar improvement in their ability to reach available destinations, regardless if they experience higher or lower transport disadvantage. This suggests that adding new destinations in targeted transport disadvantaged zones is less effective at closing the gap in maximum accessibility compared to implementing extrapolated levels of transit service improvements.

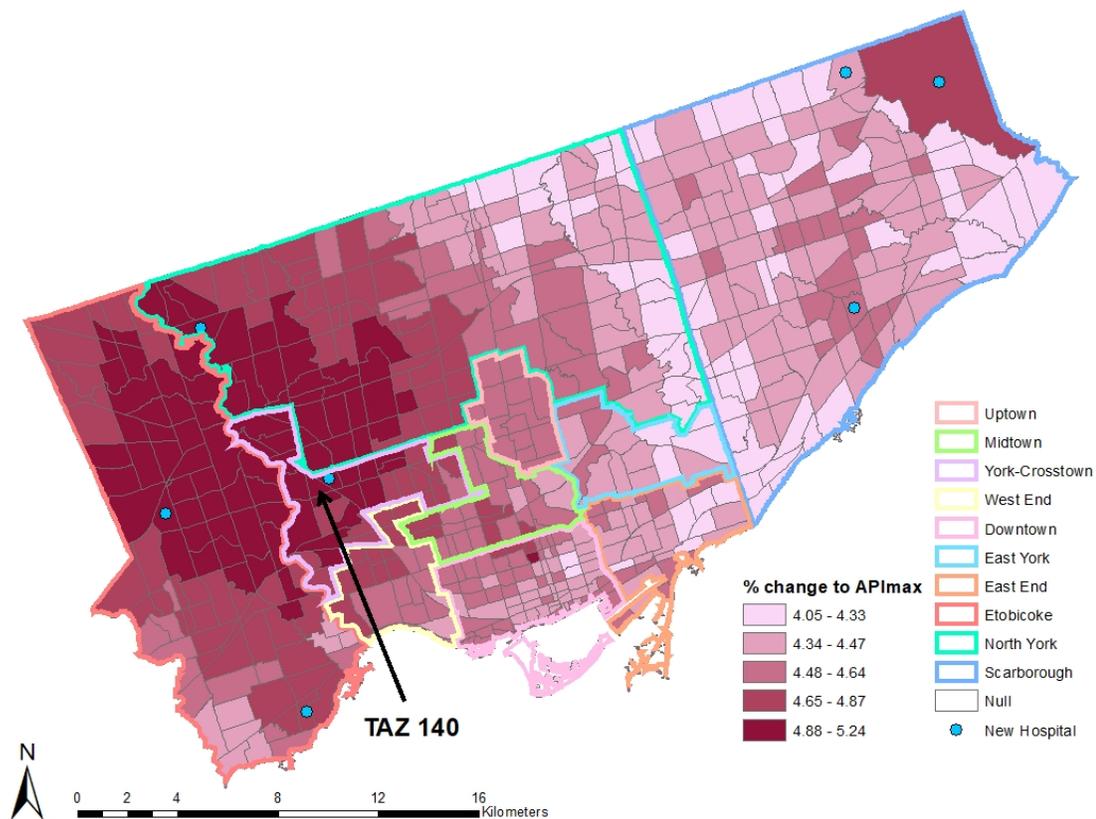


Figure 37: Changes to maximum accessibility levels (API^{max}) resulting from seven new hospital locations. Darker areas indicate a greater increase in maximum accessibility.

Although the land use changes applied here do not substantially improve maximum accessibility specifically for transport disadvantaged zones, the increased availability of nearby destinations means that more destinations can be reached at low GC intervals, especially by walking. In TAZ 140¹⁴, for example, adding a new hospital to an adjacent zone results in better access to hospitals by walking than by taking transit for GC intervals less than \$5 (see Figure 38). This is because the only cost associated with pedestrian travel is time, making it cheaper to walk to a new destination when it is located near an origin. Land use changes therefore have the potential to improve accessibility to the closest facility—in this case, a hospital—by making

¹⁴ TAZ 140 is identified in Figure 37Figure 37.

walking the most competitive mode at lower *GC* levels. Given the massive costs associated with constructing a new hospital, however, more modest land use changes such as establishing clinics may be useful in improving transport disadvantage in areas with the highest *ANM*.

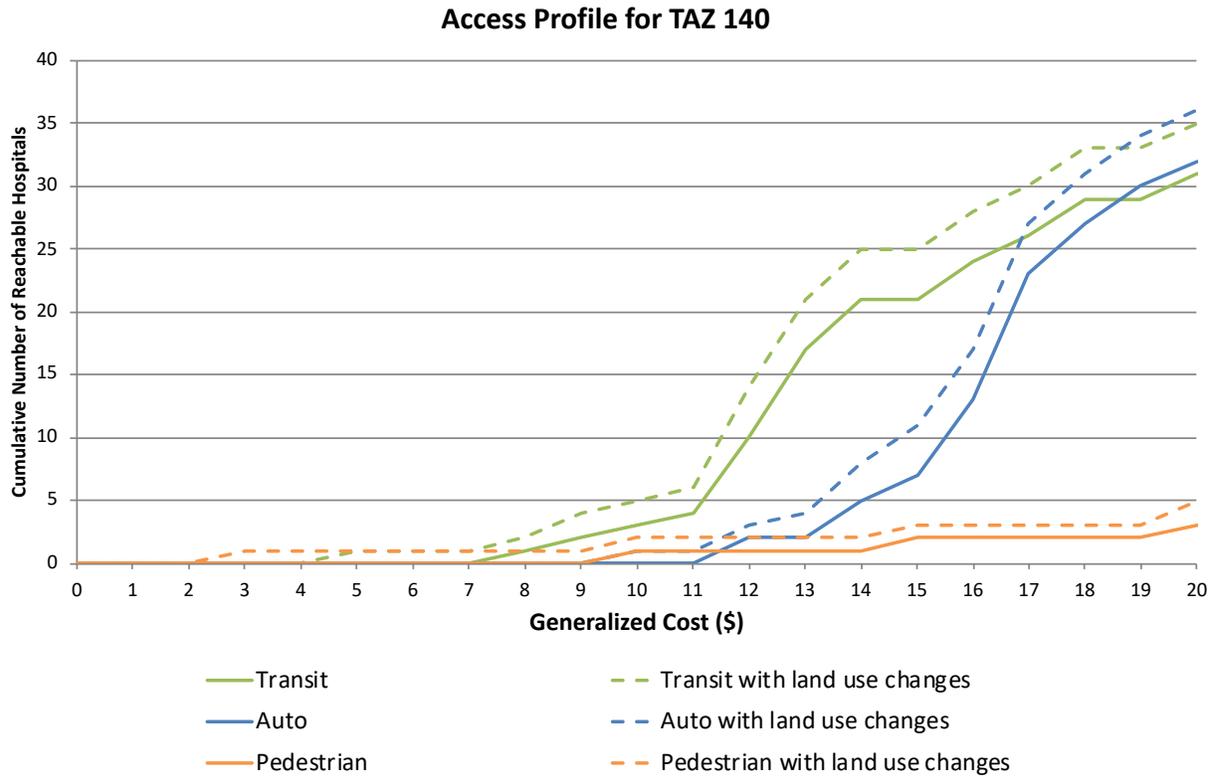


Figure 38: Comparing accessibility levels for trips originating from TAZ 140 when new hospitals are added.

Figure 39 compares the range of percentage increase to transit, auto, and pedestrian accessibility to hospitals after seven new hospitals are added. The range and level of increase to accessibility are much greater for pedestrian travel, indicating the high sensitivity of pedestrian accessibility to land use changes compared to other modes. Pedestrian accessibility is sensitive to land use changes because the availability of new destinations near an origin reduces travel time by walking more than it does for driving or taking transit. The time difference between walking to a destination that is 500 metres away versus 5 kilometres away, for example, is much greater

than if the trips were made by transit or car. Adding new destinations near an origin therefore increases pedestrian accessibility more than transit or auto accessibility.

Based on the impacts of the land use changes applied here, adding new destinations are a useful intervention if planners and policymakers seek to increase local levels of accessibility for transport disadvantaged areas. However, if the goal is to increase the overall accessibility for transport disadvantaged areas to be comparable with non-disadvantaged areas, then the land use changes applied here are not as effective when compared to other interventions.

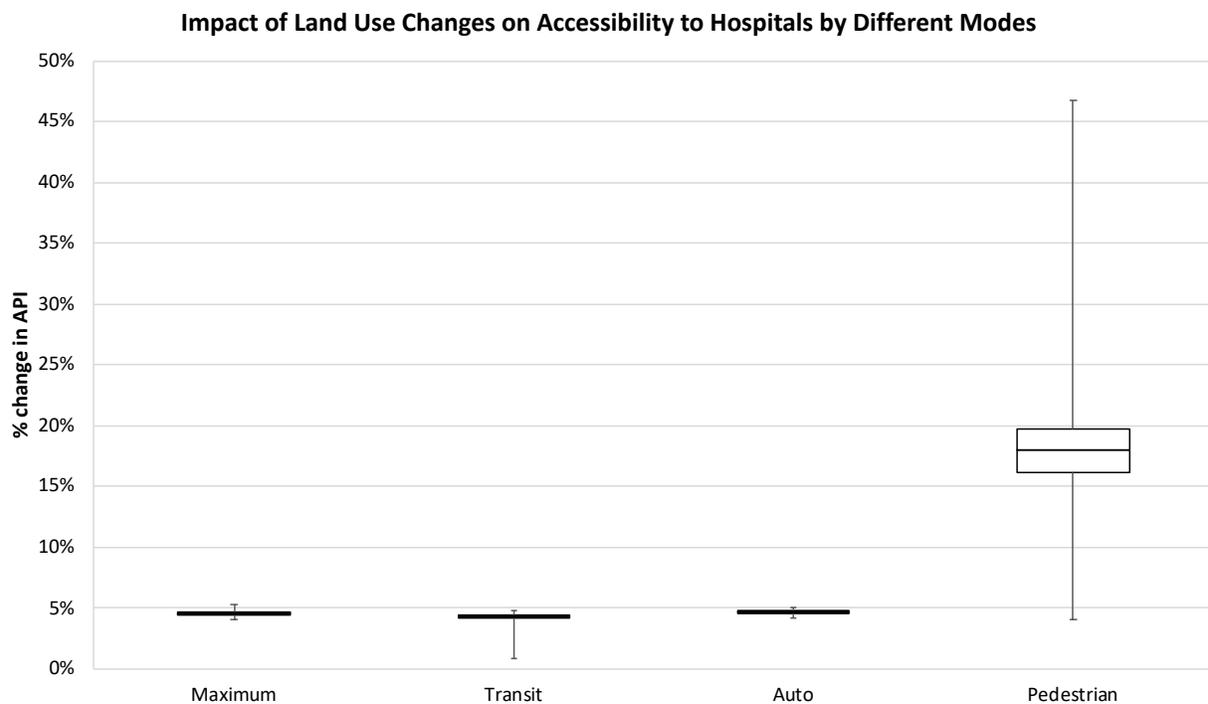


Figure 39: Box and whisker plot of the percentage change to accessibility levels by walking (API^{ped}) resulting from the addition of seven new hospitals.

4.6 Summary of findings

Overall, areas in and around the downtown core of Toronto experience higher accessibility to non-work destinations compared to suburban areas. Pedestrian travel tends to provide the best accessibility at lower levels of GC because walking is free and therefore closer destinations can be reached at a lower cost compared to taking transit or driving. On average,

transit provides the best accessibility for trips that have a *GC* between \$6 and \$23 largely because transit fare is cheaper than the costs of car ownership.¹⁵ A transit trip with a *GC* of \$6 and \$23 equates to a 18 minute and 97 minute transit trip, respectively given a fare of \$2.09. For trips that cost more than \$23, however, auto travel offers better accessibility than transit even though the monetary cost of driving is more expensive. This is because reaching destinations that are farther away is faster by driving than taking transit.

Transport disadvantage in Toronto tends to be concentrated in the city's suburbs, namely in North York, Scarborough, and the northern parts of Etobicoke. These areas experience higher levels of socioeconomic need and lower levels of accessibility to non-work destinations. Different interventions impact accessibility levels in transport disadvantaged areas in different ways. Overall, the extrapolated transit service improvements applied in this research are the most effective intervention at increasing accessibility and reducing the disparity in accessibility levels between zones with higher and lower transport disadvantage. To the extent that planners and policymakers believe that closing the accessibility gap should be a policy goal, transit service improvements should be prioritized over other interventions, including the implementation of free transit fare.

Although free transit fare eliminates the monetary impedance of transit travel, it is only effective at increasing accessibility if the transit system offers a level of service such that transit travel times result in accessibility levels that are competitive with auto travel. It is possible that free transit does not increase the maximum accessibility of an origin zone if transit service is so limited that auto travel provides better accessibility, even with the high costs of car ownership. Although this is a rare case in Toronto, the results demonstrate the importance of understanding

¹⁵ Recall that transit fare is assumed to be \$2.09 and the fixed cost of auto travel is \$9.23 per trip.

baseline accessibility conditions in order to select an intervention that will meaningfully improve accessibility levels.

The results of this research also suggest that planners and policymakers should consider the desired scale of impact when choosing which accessibility intervention to implement.

Although adding new destinations through land use changes may not substantially improve accessibility to all available destinations from all zones, they can increase the availability of destinations near a particular origin. In this way, the impacts of land use changes can be much more localized compared to reducing transit fare or improving transit service. If planners and policymakers seek to improve local levels of accessibility for specific zones (e.g. areas that experience the greatest transport disadvantage or are considered to have insufficient levels of accessibility, however defined), then land use changes are potentially an effective intervention.

Parking charges reduce the maximum level of accessibility for zones where auto travel provides the best accessibility. Although parking charges are often implemented to discourage driving and incentivize transit and active transportation, planners and policymakers should first assess the impacts of parking charges to evaluate whether transport disadvantaged populations will be disproportionately affected. Given that many zones in Toronto that experience higher transport disadvantage occur in areas where auto travel is the most competitive mode, implementing parking charges is problematic because it will worsen accessibility for these zones. If planners and policymakers implement parking charges to disincentivize driving, then they should also consider implementing other interventions such as transit service improvements to ensure that transport disadvantaged households have a viable alternative to driving.

5.0 Discussion and reflection on equity theories

Given that different interventions impact accessibility levels in different ways—both in terms of magnitude and the spatial distribution of impact—planners and policymakers must articulate the theory of equity that grounds their policy objectives in order to design and implement interventions that effectively achieve those objectives. As discussed in the literature review, different interpretations of equity will yield different policy objectives. For example, a utilitarian approach to equity in transportation planning seeks to maximize the collective utility or “good” of society. Traditionally, utility in a transportation context is represented as someone’s willingness to pay for travel time savings (Pereira, Schwanen, & Banister, 2017). As such, planners that adopt a utilitarian approach to equity would prioritize policies and interventions that reduce travel time—and therefore increase accessibility—the most for those with higher values of time.

But utilitarianism is an unsatisfactory way to evaluate equity in transportation insofar as those with lower values of time (and therefore fewer economic means to pay for transportation services) are given less consideration when designing interventions to increase accessibility. In other words, a utilitarian view of equity does little to improve the conditions of those who experience the most transport disadvantage. A universal transit fare reduction, for example, increases accessibility for everyone; however, results from this research show that many neighbourhoods in Toronto that would benefit the most from reduced transit fare already experience higher levels of accessibility because of their proximity to higher order transit. Transport disadvantaged populations often occur in the suburbs where driving is the most competitive mode of transportation and therefore a universal transit fare reduction does little to improve accessibility levels for those who are most disadvantaged.

Libertarianism is also an inadequate approach to address equity issues in a transportation context. The core principle of libertarianism is that each person has the freedom to make their own choices without impedance from other individuals or groups on the condition that one's choices do not impede the same decision-making freedoms of others (Kymlicka, 2002). When it comes to accessibility, however, people do not experience the same decision-making freedom given the socioeconomic constraints that may impede an individual's ability to travel or make trips using a particular mode. Libertarianism is also potentially problematic for planners when developing transportation policies. Parking charges, for example, are often implemented to discourage driving and incentivise other modes such as transit and active transportation with the ultimate policy goals of alleviating congestion, reducing transportation-related emissions, improving the liveability of cities, and so forth. From a libertarianism perspective, however, implementing parking charges is unjust because they infringe on one's individual liberty to drive. A tension therefore exists between individual liberties and the desire of planners and policymakers to shape our urban landscape.

Both intuitionism and spheres of justice are not very useful theories of equity when applied to a transportation context. The only guidance that both theories provide is that equitable outcomes are achieved when moral judgements based on socially-constructed values are exercised to determine the distribution of costs and benefits, however they are defined. In other words, neither approach provides clear direction on how equity is achieved in a transportation context, only that it is a subjective matter. This is problematic for planners given that people will have differing opinions on what is considered an equitable distribution of accessibility or whether certain populations should be prioritized when designing interventions to improve accessibility. Planners therefore require a theory of equity that provides more concrete direction

to establish policy objectives and effectively design and implement interventions to achieve those objectives.

Egalitarianism, sufficientarianism, and the capabilities approach have more useful applications when addressing equity issues in a transportation context. In many ways, the capabilities approach is a combination of egalitarian and sufficientarian ideas by proposing both the equality of capabilities and a guaranteed minimum level of capabilities (Pereira, Schwanen, & Banister, 2017). This also mirrors the hybrid theory of equity proposed by Lucas, van Wee, and Maat (2016), which combines both egalitarianism and sufficientarianism.

When thinking about equity in transportation, both the *gap in accessibility levels* between transport disadvantaged and non-disadvantaged populations (i.e. egalitarianism) as well as the *minimum level of accessibility* available to each individual (i.e. sufficientarianism) are important considerations. If the gap in accessibility levels is too large, it could lead to disparate levels of societal participation between populations. Those with higher accessibility are better positioned to reach different destinations and opportunities—such as post-secondary institutions, polling stations for voting, grocery stores, and places of worship—that improve their quality of life and allow them to engage in different economic, social, and political opportunities. Conversely, it is difficult for those with low accessibility levels to do the same. Such disparate levels of participation have the potential to feed a vicious cycle of unequal power distribution and incomparable qualities of life.

The minimum level of accessibility available to each individual of a population is also an important equity consideration. Even if accessibility levels were equal across an entire population, it does not guarantee that this level of accessibility is sufficient for meaningful participation in society or to achieve a decent quality of life; some minimum threshold of

accessibility needs to be defined. As discussed in section 4.5.2, the APA method can be used to help define this threshold by identifying a reasonable level of travel effort (both in time and out-of-pocket expenses) that is required to reach different key destinations.

If planners aim to both minimize the accessibility gap and ensure that everyone has a sufficient level of accessibility, then different interventions can be implemented to achieve these equity goals. This research demonstrates that improving transit service is an important intervention for planners insofar as it has the potential to equalize accessibility levels among transport disadvantaged and non-disadvantaged populations. Targeting transit service improvements in areas with the greatest transport disadvantage will help minimize the accessibility gap and ensure everyone has a sufficient level of accessibility to reach different destinations and opportunities. Similarly, this research demonstrates that land use changes are effective for improving accessibility, specifically local accessibility, for transport disadvantaged populations.

A targeted transit fare reduction scheme is potentially another useful tool to address transportation equity issues. Although this research shows that a universal transit fare reduction disproportionately benefits populations that already have high accessibility, an alternative transit fare reduction scheme or subsidy could be implemented that is only made available to transport disadvantaged populations. Further research is needed to investigate the impacts of such an intervention.

When planners design and implement interventions to address transport disadvantage, they should also consider the specific travel impedances that individuals face. It may be that some of the interventions explored in this research improve accessibility at an aggregate level (i.e. at the TAZ level); however, this research does not fully explore accessibility at the

individual level. Individuals experience much more nuanced and complex impedances to travel than simply travel time and cost. The ability to travel independently and one's familiarity and comfort with using different travel modes, for example, all contribute to an individual's ability to access different destinations. Individual accessibility levels are also contingent on the unique destinations that different people value. If an analysis of individual accessibility levels were to be conducted, it should evaluate access to destinations that are important for a particular person rather than using a generic set of destinations.

Ultimately, understanding accessibility and defining and achieving equity goals in a transportation context is complex. Nevertheless, it is important for planners and policymakers to be thoughtful and clear about how they define equity in order to design and implement interventions that effectively address transport disadvantage.

6.0 Study limitations and future work

This section presents some of the key assumptions and methodological limitations of this thesis that restrict the applicability and interpretation of the research findings. First, it is difficult to make meaningful comparisons between the impacts of different interventions on accessibility levels from an economic perspective. Although it is possible to report the percentage change to accessibility resulting from the interventions, it is difficult to say whether the magnitude of change is comparable in terms of the level of investment that is required to implement each intervention. For example, transit service improvements produce the greatest increase to accessibility; however, transit service improvements are likely to be significantly more expensive than other interventions due to the capital costs for new transit infrastructure and increased labour costs for improved operations.

Future research should scale the impacts of different interventions by looking at the return on investment—that is, what is the change to accessibility for every dollar spent on an intervention? This will allow for more meaningful comparisons of the impacts of different interventions. Similarly, future research should assess an intervention’s impact on accessibility while taking into account population density and existing land uses. Although some zones are identified as transport disadvantaged in this research, these zones may have a small population or are comprised primarily of industrial lands, in which case increasing accessibility in these areas may not be a priority.

Second, the impacts of the interventions modeled in this research should only be interpreted based on the methods used to apply these interventions. For example, fare reductions were applied universally across the study area rather than applying a fare-by-distance scheme or another fare structure. In other words, the research findings do not reflect how alternative transit

fare structures would impact accessibility. Similarly, land use changes were only applied to a limited number of zones by adding one new destination in each of these zones. Presumably the results would change if land use changes were applied at a larger scale—for example, adding many mid- and high-rise mixed used developments throughout the city. Future research should study the impacts of more intense land use, as well as other variations of different interventions, on accessibility and transport disadvantage.

Third, this research does not account for transit service reliability—it assumes that the transit system adheres perfectly to the schedule provided in the GTFS data, which is not always the case in reality. In Toronto, it is not uncommon to wait for multiple subways or buses to pass by a transit station or stop before there is enough room on the vehicle to board during peak hours. This adds time (and therefore cost) to transit trips, which was not accounted for in this research. This is an important caveat when interpreting the results. Although this research shows that zones near higher order transit experience the highest accessibility in the city, their levels of access may be inflated due to the realities of overcrowded subways, construction, technological failures, and accidents.

Fourth, this research does not account for everyone's unique behaviours, preferences, and abilities when measuring accessibility. For example, although certain zones have high accessibility by transit, not everyone taking a trip from that zone will be able to take transit either because of physical or cognitive abilities, safety concerns, or otherwise. People may also choose to make a trip by car despite higher levels of accessibility offered by transit because they prefer the freedom and independence of driving, can determine their own departure time, or need to transport large items in their vehicle. Results from this research should therefore be interpreted

as a representation of general accessibility conditions—the findings made here do not necessarily translate into people’s actual travel choices.

There are many opportunities to expand on this research, most notably in the destinations, interventions, and travel modes selected for study. Accessibility to other trip destinations, such as grocery stores, clinics, social services, and public green space, could be measured. Future research should assess the impact of a variety of interventions such as alternative transit fare schemes, HOV lanes, and land use intensification. Different modes can also be studied, including bicycles and electric scooters or mopeds. Additional research should also be done to measure accessibility levels when different modes are used in combination with each other since many trips are made using multiple modes. People may drive to a transit station, catch the subway, and then finish the last segment of their trip by walking. Measuring accessibility when multiple modes are integrated is complex, but more reflective of true travel behaviour.

7.0 Conclusions

The purpose of this thesis is to help planners and policymakers identify, analyze, and understand existing accessibility conditions to non-work destinations and to measure the impacts of different interventions on accessibility for transport disadvantaged neighbourhoods. Overall, the methods used in this thesis are successful in identifying areas of a city that experience higher transport disadvantage and modeling how different interventions change accessibility levels among populations with different socioeconomic constraints. By combining an accessibility measure, *API*, with a socioeconomic need index, *SNI*, to generate an accessibility need measure, *ANM*, this thesis demonstrates how planners and policymakers can quantify different travel impedances in order to measure transport disadvantage.

Findings from this thesis articulate the importance for planners and policymakers to be specific about their goals when addressing transport disadvantage since different interventions have different impacts on accessibility. Offering free transit fare, for example, increases accessibility for all zones but is less effective at reducing the difference in accessibility levels between disadvantaged and non-disadvantaged zones compared to implementing transit service improvements. Although transit service improvements are more effective at equalizing accessibility levels between zones overall, land use changes are potentially more effective at increasing accessibility for specific zones to a particular destination type. Choosing which intervention to implement therefore depends on the accessibility goals that planners and policymakers are trying to achieve.

This thesis also demonstrates the need to measure baseline accessibility conditions before implementing any intervention. Reducing transit fare, for example, may not improve accessibility if existing transit service is poor. People may still drive to their destination because

auto travel provides better accessibility even when transit is free. Planners may wish to impose a parking charge to encourage a mode shift to transit or active transportation, but this may have a disproportionate impact on transport disadvantaged households that are located in areas where auto travel offers the best accessibility. Understanding baseline accessibility conditions would help planners recognize that parking charges should be paired with other interventions that improve accessibility by other modes to prevent further transport disadvantage in these areas.

Ultimately, this research contributes to the literature in three essential ways: 1) by providing more research on accessibility to non-work destinations rather than employment opportunities, and 2) quantitatively evaluating how different interventions impact accessibility levels for transport disadvantaged areas, and 3) accounting for the monetary cost of travel in addition to travel time as an impedance to accessibility. More broadly, this research helps continue the conversation on equity in transportation in order to gain a deeper understanding of what equity means, how it can be evaluated, and how it can be achieved in a transportation context.

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Appendix

Table A-1: Correlations between SNI variables based on DA-level data.

	Unemployment rate	Recent immigration rate	Percentage of households spending greater than 30% of income on shelter costs	Average household income
Unemployment rate	1	0.22	0.21	-0.20
Recent immigration rate	0.22	1	0.46	-0.25
Percentage of households spending greater than 30% of income on shelter costs	0.21	0.46	1	-0.39
Average household income	-0.20	-0.25	-0.39	1

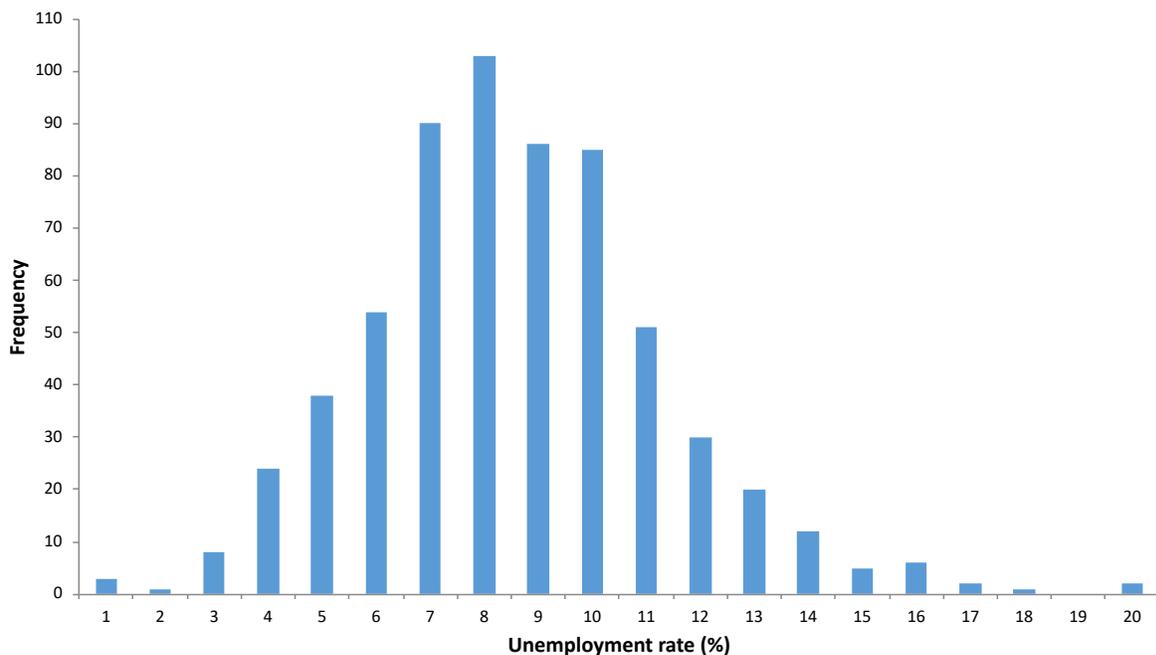


Figure A-1: Distribution of unemployment rate at the TAZ level in Toronto (2016).

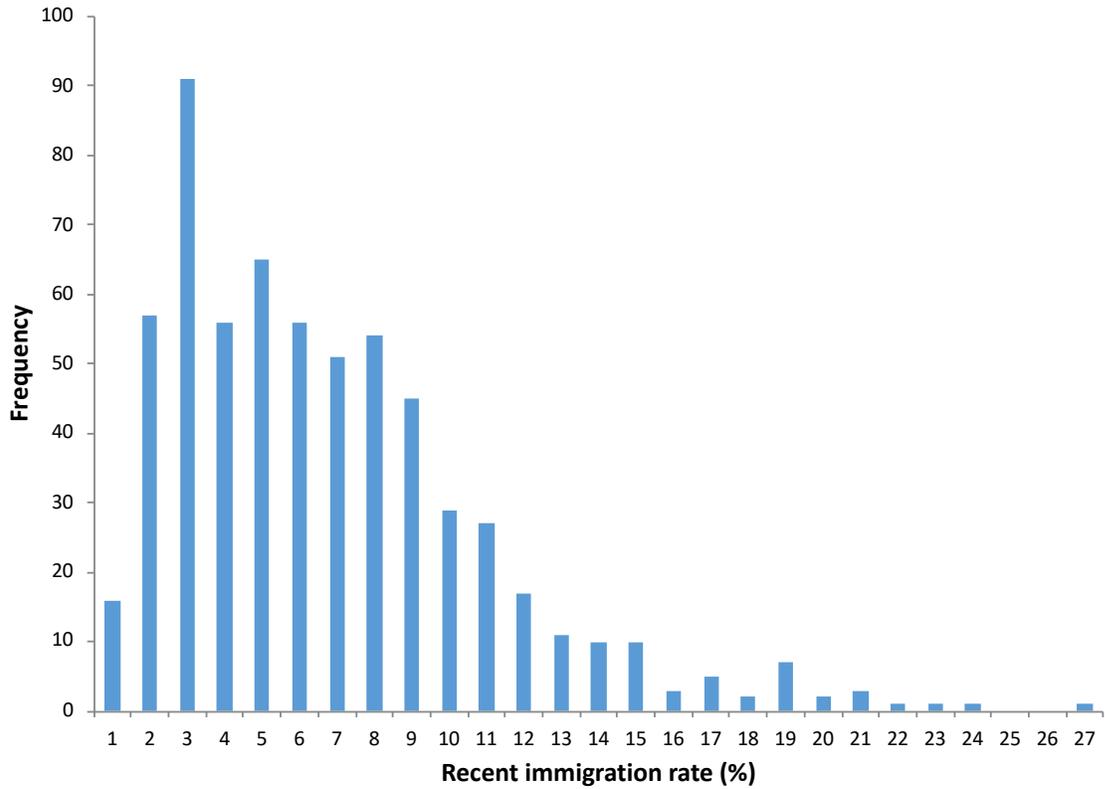


Figure A-2: Distribution of recent immigration rate at the TAZ level in Toronto (2016).

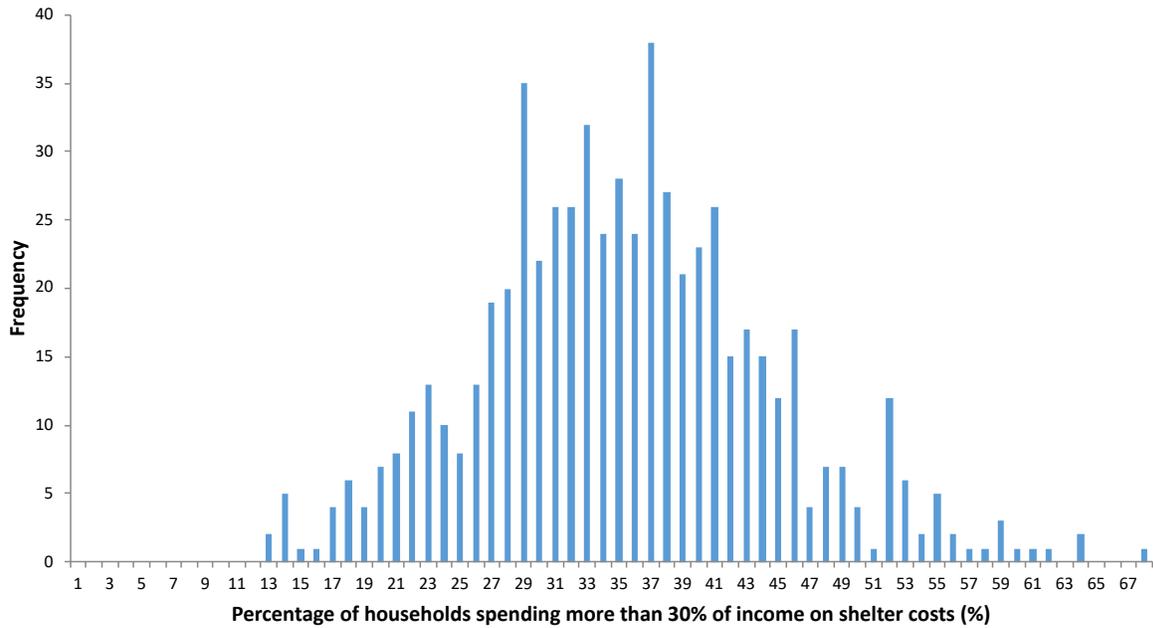


Figure A-3: Distribution of the percentage of households spending more than 30% of household income on shelter costs at the TAZ level in Toronto (2016).

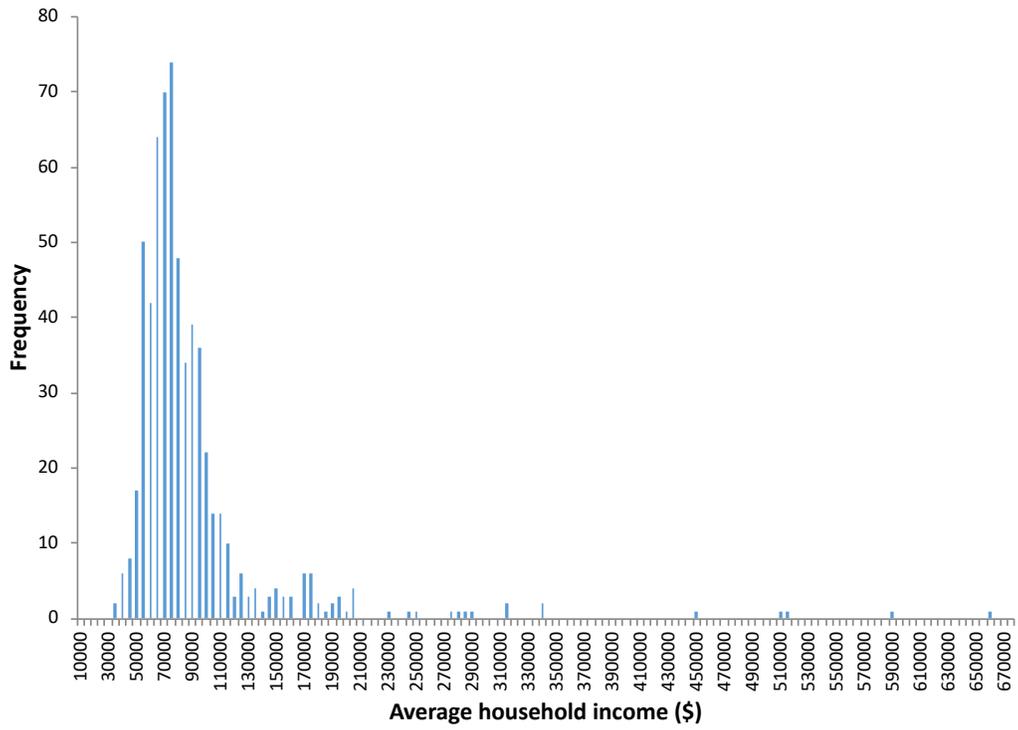


Figure A-4: Distribution of average household income at the TAZ level in Toronto (2016).

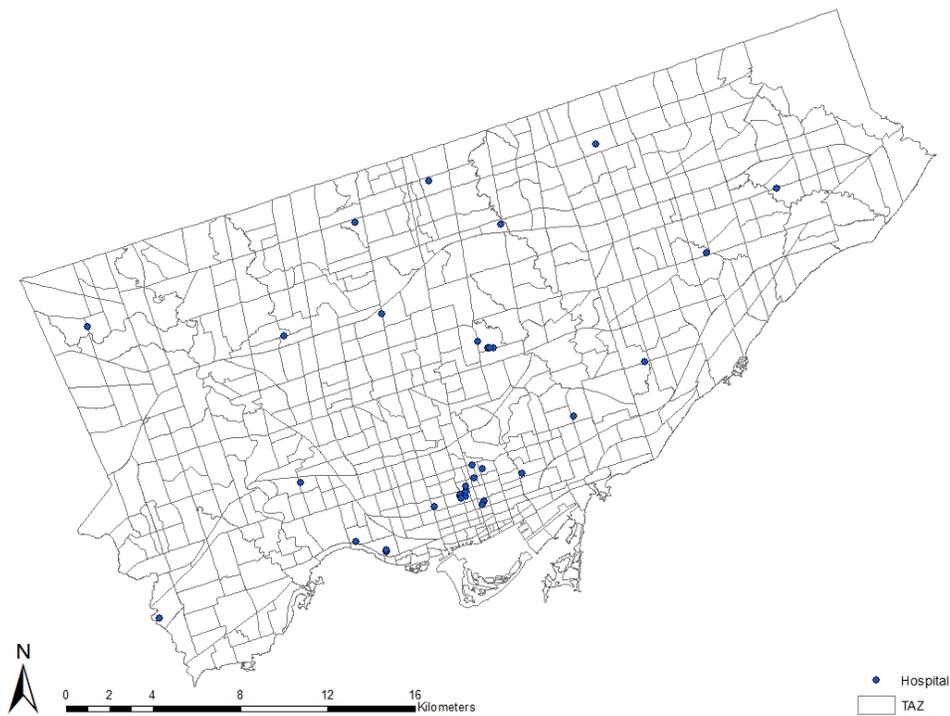


Figure A-5: Hospital locations in Toronto.



Figure A-6: Library locations in Toronto.



Figure A-7: Recreation centre locations in Toronto.



Figure A-8: Early Years Centre locations in Toronto.

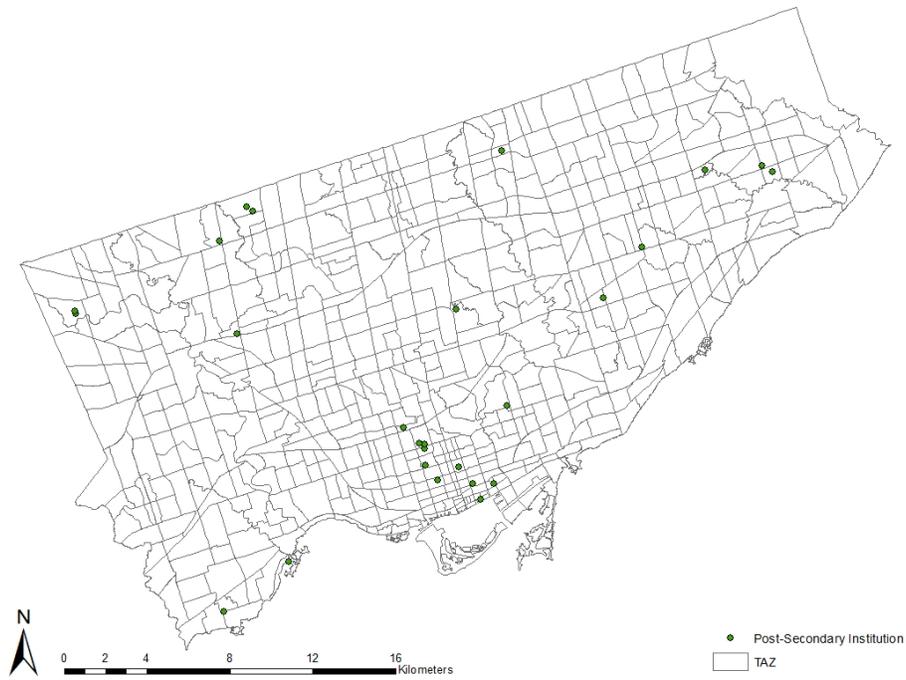


Figure A-9: Post-secondary institutions in Toronto.

List of sidewalk types included in pedestrian network:

- City walkway
- Desire line/goat path
- Laneway with at least partial sidewalk on one side
- Laneway with sidewalk on both sides
- Laneway with sidewalk on east side
- Laneway with sidewalk on north side
- Laneway with sidewalk on south side
- Laneway with sidewalk on west side
- Laneway without any sidewalks
- Partial sidewalk on at least one side
- Partially paved walkway
- Paved walkway
- Paved walkway between two streets
- Paved walkway through a city park
- Paved walkway to a community garden
- Paved walkway to a day care center
- Paved walkway to a family resource center
- Paved walkway to a food bank
- Paved walkway to a parking lot
- Paved walkway to a school
- Paved walkway to an outdoor pool
- Paved walkway to day care center
- Paved walkway to food bank
- Paved walkway to parking lot
- Privately owned publicly-accessible space
- Recreational trail
- Sidewalk on both sides
- Sidewalk on east side only
- Sidewalk on east side; partially on other side
- Sidewalk on north side only
- Sidewalk on north side; partially on other side
- Sidewalk on south side only
- Sidewalk on south side; partially on other side
- Sidewalk on west side only
- Sidewalk on west side; partially on other side
- St. James garden walkway