Understanding Accessibility, Analyzing Policy: New Approaches for a New Paradigm

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Jason Neudorf

August 30, 2014

Abstract

Accessibility is a concept based on the interaction between transportation and land use systems, and reflects the ability of individuals to reach destinations. A new tool to measure and represent accessibility called Access Profile Analysis (APA) is developed in this thesis. I use APA to explore two general research questions. First, how do various transportation and land use policies affect job accessibility in Kitchener-Waterloo? Second, how is job accessibility distributed in relation to other socio-economic variables in Kitchener-Waterloo? To analyze these questions I developed six specific applications of APA for the Kitchener-Waterloo area. The findings indicate that transportation and land use policies have a direct and measurable impact on job accessibility. Moreover, the accessibility implications of these policies vary for different socio-economic groups.

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List of Abbreviations

AIM	Accessibility Income Measure
APA	Access Profile Analysis
API	Access Profile Indicator
ATT	ArcGIS Transit Tool
CAA	Canadian Automobile Association
CUTA	Canadian Urban Transit Association
DA	Dissemination Area
GC	Generalized Travel Cost
GMTT	Google Maps Travel Times
GRT	Grand River Transit
GTFS	Generalized Transit Feed Specification
IVT	In-Vehicle Time
MPAC	Municipal Property Assessment Corporation
MRCI	Modal Redundancy Cost Indicator
OD	Origin Destination (pair)
STT	Study Travel Times
TAZ	Traffic Analysis Zone
TTS	Transportation Tomorrow Survey
VOT	Value of Travel Time

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Chapter 1:

Introduction

1.1 Why Accessibility?

the fundamental goal of access

This thesis is inspired by two rather broad questions: *'What is the purpose of transportation?'* and *'What is the purpose of cities?'* Transportation researchers David Levinson, Kevin Krizek, and David Gillen (2005) answer these questions with an analogy. If a house is a machine for living, as the 20^{th} century architect and planner Le Corbusier famously argued, then transportation is a machine for moving, and a city is a machine for access (Levinson et al., 2005). With respect to the first question, this analogy reflects that transportation is not an end in itself, but a means to an end (Ortúzar & Willumsen, 2001; Tumlin, 2012). The vast majority of transportation is motivated not by the joy of movement, but the desire to reach a destination.

With respect to the second question, the analogy highlights how fundamental accessibility is to the function of cities. People are drawn to cities because they provide access to employment, leisure opportunities, services, and other people. As Handy and Niemeier state,

> *"In short, what keeps residents in metropolitan areas is accessibility, the potential for interaction, both social and economic, the possibility of getting from home to a multitude of destinations offering a spectrum of opportunities for work and play*" (1997, p. 1175)

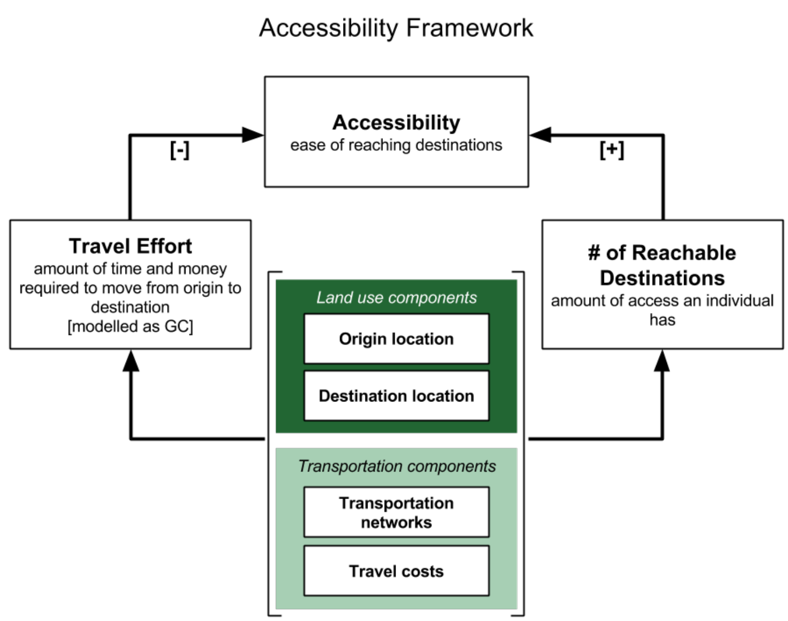
Accessibility—the ease with which individuals can reach destinations associated with employment and other quality of life enhancing activities (Dalvi, 1978)—is a fundamental aspect of society. Improving accessibility, particularly for those who are comparatively deprived of it, is therefore an important societal goal, and the underlying motivation for this thesis.

1.2 What is Accessibility?

defining accessibility

The conceptual framework of accessibility that I developed for this thesis is shown in Figure 1. In this framework, accessibility is negatively related to the amount of travel effort and positively associated with the number of destinations that can be reached. Accessibility can be thought of as a measure of how effectively travel effort is translated into destination access. Both travel effort and the number of destinations that can be reached are shaped by four core accessibility components—origins, destinations, transportation networks, and travel costs—which are explored in the paragraphs below.

Figure 1: Accessibility Framework



origins and destinations

Origin and destination locations are the land use components of accessibility. Since this study focuses on job accessibility, origins are defined as household locations and destinations are defined as job locations. In order to illustrate the relationship between origins, destinations, and accessibility, consider an origin that is relatively isolated from destinations. On the one hand, an individual could expend a lot of travel effort and reach the destinations. The other option is to expend a moderate amount of travel effort and reach relatively few destinations. Either way, the travel effort is not very effective in providing destination access—accessibility is low. If there are many destinations in close proximity to an origin, however, a moderate amount of travel effort can be very effective in providing destination access. In this case, accessibility is high. Land use patterns such as the concentration of origins and destinations, and the extent to which they are spatially integrated or segregated, therefore influence accessibility (see Bertolini, le Clercq, & Kapoen, 2005).

transportation networks and travel costs

Accessibility, however, depends not only on the location of origins and destinations, but on the travel effort required to move between them. In this analysis, the travel effort required to move from an origin to a destination—referred to as an OD pair—is modelled as a *generalized cost* (GC) of travel. Generalized costs are derived by converting travel time into monetary units, or vice versa, and summing the monetary and time costs of travel (see Section 3.2.4). The travel time between an OD pair depends on the length of the route, and the travel speed along the route. Both route length and travel speed are determined by the transportation network of the travel mode used to make the trip. Monetary travel costs also depend on the travel mode, and can be categorized as either fixed costs, which do not vary based on route properties, or variable costs, which are a function of route properties. The transportation components of accessibility can be summarized as follows: for any given set of origins and destinations, transportation networks determine travel time, which, along with monetary travel costs, determines travel effort.

land use and transportation interactions

All four of these components—origins, destinations, transportation networks, and travel costs—interact to determine the number of destinations that can be reached and the travel effort required to reach them. These components, however, do not exist in isolation. Conversely, many of them exist in tension with one another. Increasing land use density, for example, typically results in higher traffic volumes, which *may* in turn reduce travel speeds and increase travel times (Levine, Grengs, Shen, & Shen, 2012). Accessibility is determined by how effectively these components interact. This complex web of relationships underscores the importance of comprehensive analysis and measurement.

1.3 Research Motivations

In this thesis, I demonstrate a relatively novel approach to modelling accessibility, which I refer to as access profile analysis (APA). This model builds on earlier work done by Black and Conroy (1977) several decades ago.[1] In demonstrating this modelling approach, I had two goals. First, I wanted to explore the methodological strengths and weaknesses of this approach, relative to commonly used accessibility tools. Second, I wanted to demonstrate potential policy applications for this approach. Both of these research goals are addressed through a case study of Kitchener-Waterloo, Ontario, which is introduced in Chapter 3.

methodological improvements

The accessibility tools that are widely used today exhibit a number of methodological limitations that can reduce their efficacy in some contexts (see Chapter 2). APA addresses several of these limitations and expands the number of tools available to accessibility researchers and planners. Specifically, APA improves upon alternative accessibility measures by (a) not requiring assumptions about the amount of time and money an individual is willing to spend on travel, (b) measuring and representing accessibility for multiple modes within a common framework, and (c) producing visual outputs that are easy to interpret and communicate.

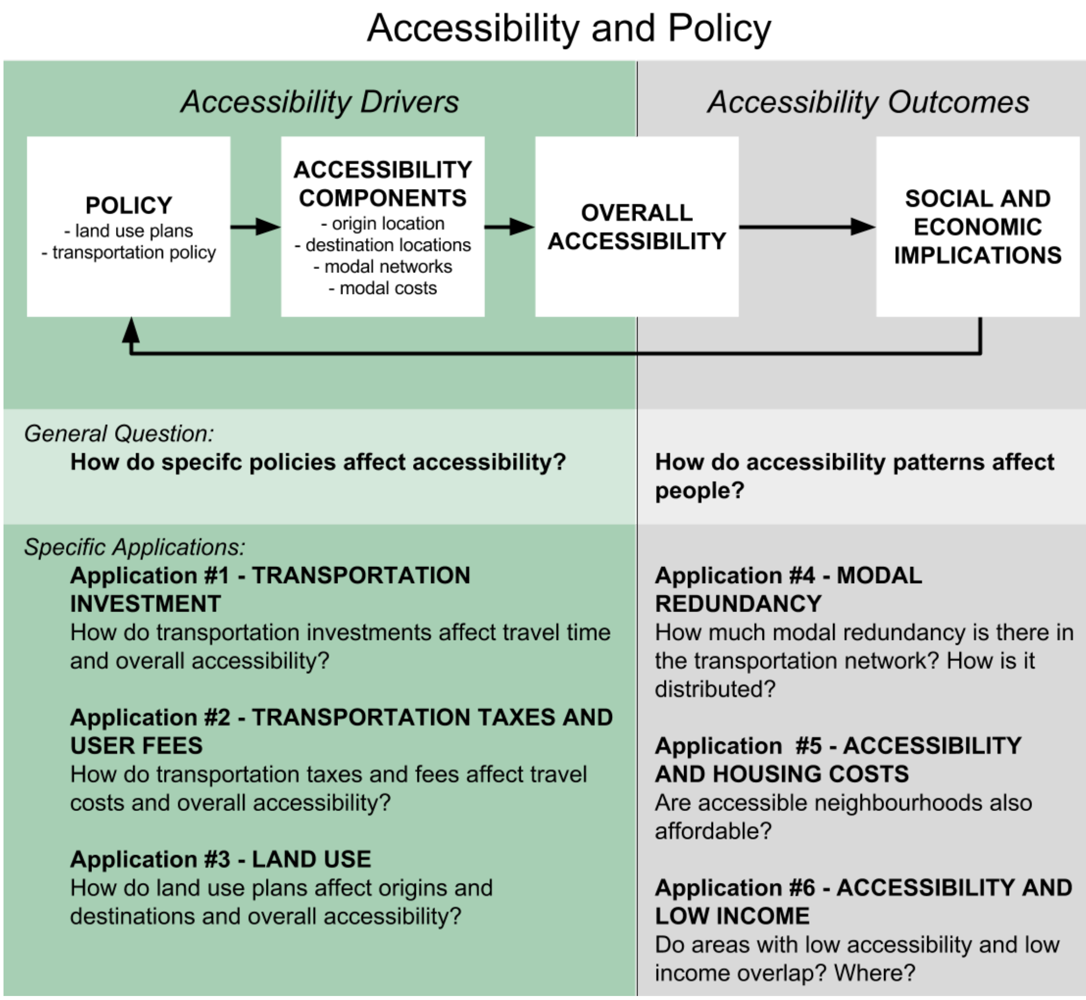
policy analysis

The second motivation for this research is to demonstrate how APA can help bridge the gap between accessibility scholarship and accessibility practice. I developed six applications, which are shown in Figure 2, to test how the model responds to various policy scenarios and show how it could be used in a policy context. The first three applications examine policy as a driver of accessibility. Each of these applications evaluates either how specific policies retrospectively affected accessibility or how specific policy scenarios could prospectively impact accessibility. Applications 4-6 explore some of the broader socio-economic implications of observed accessibility patterns. Figure 2 illustrates the relationship between policy, accessibility, and socio-economic outcomes, and situates each application in this context. The paragraphs

[1] Note that the discovery of the work by Black and Conroy (1977) occurred after the analysis for this research was complete. While I developed APA independently, I acknowledge that it is not the first presentation of this methodology in the literature.

below describe the accessibility implications of each application, and highlight why these implications are important for policy.

Figure 2: Accessibility and Policy



Application #1: Transportation Investment

The first application examines how transportation investments affect accessibility. From the construction of rapid transit lines to the expansion of highway capacity, transportation investments typically aim to improve accessibility by increasing travel speeds, increasing directness, decreasing travel time, and / or improving reliability. Since most of these projects require substantial public funding, a comprehensive understanding of how effectively they improve accessibility is important to ensure that scarce public resources are being used efficiently.

Application #2 Transportation Taxes and User Fees

The second application explores the accessibility implications of transportation taxes and user fees such as road tolls, gas taxes, transit fares, etc. There are three ways that transportation taxes and user fees could theoretically affect accessibility. First, transportation taxes and user fees influence the monetary costs of making any given trip with any given mode. Second, they provide funding for the operation and expansion of transportation networks. If more revenue is generated, there could also be more funding available for operations and investments (see above). Third, transportation taxes and user fees affect travel behaviour, which can subsequently influence the performance of transportation systems. Road tolls, for example, may reduce traffic volumes and subsequently increase travel speeds. A comprehensive understanding of how a transportation tax or user fee affects accessibility is important to ensure that (a) undue negative accessibility impacts are avoided, particularly for travellers with limited financial resources, (b) necessary revenues are generated, and (c) desired behaviour changes are achieved.

Application #3 Land Use

Application three explores how land use policies and plans affect accessibility. Along with market forces, land use policies determine the location, density, and diversity of new development through Official Plans, Secondary Plans, and Zoning By-Laws. The land use patterns that are shaped by these policies have a direct impact on the origin and destination components of accessibility. It is therefore important to understand how different kinds of development will affect accessibility, in order to leverage public policy to achieve greater accessibility.

Application #4 Modal Redundancy

The concept of modal redundancy is introduced in application four, and refers to the number of modes that connect an origin to a destination, and the relative effectiveness of these modes. Modal redundancy indicates the accessibility gap between modes. The most important socio-economic implication of low modal redundancy is single mode dependency, which in the North American context typically implies auto dependency. Auto dependency is a concern because it restricts the mobility of those who are unable to drive and financially strains low income households. As inclusiveness, age-friendly cities, and energy costs become more important issues, the measurement of modal redundancy will also become more important. An understanding of the degree and distribution of modal redundancy can be used to develop policies that support multi-modal transportation options.

Application #5 Accessibility and Housing Costs

This application explores the accessibility implications of housing costs. If housing costs and accessibility are strongly and positively related, the location choice of low income households may be restricted to low accessibility areas. The double burden of low income and low accessibility is generally problematic, and is discussed in the following application. If affordable neighbourhoods are not accessible, and the problem is clearly identified and understood, a variety of policy instruments can be used to both preserve existing affordable housing and encourage new affordable housing development in accessible locations (see Haughey & Sherriff, 2010).

Application #6 Accessibility and Low Income

This application examines the degree of overlap between low accessibility areas and low income areas. The spatial overlap of low income and low accessibility may be a result of prohibitively high housing costs in more accessible neighbourhoods or other factors. A particular concern addressed in this application is the potential for a positive feedback loop to develop, where low job accessibility negatively impacts employment prospects, which in turn negatively impacts income and the ability to afford sufficient job accessibility. It is important to understand the combined spatial patterns of income and accessibility because a variety of policy responses can potentially prevent the positive feedback loop described above from occurring. Appropriate policy responses could range from improved unemployment / job search services to additional transit service for affected neighbourhoods.

thesis structure

In this chapter, I have defined accessibility, developed a conceptual framework of the relationship between accessibility and policy, and presented six policy relevant applications (see Figure 3). In Chapter 2 I focus on the first research motivation and review other methodological approaches for accessibility analysis and highlight the need for an expanded accessibility toolkit. 0 includes a description of the case study area, and an introduction to the APA methodological framework. In Chapter 4, I use the APA framework to operationalize each of the six policy applications. The results from these policy applications are presented and discussed in Chapter 5. I also use these results to evaluate the methodological performance of APA. Reflections about the contributions of this research, along with areas for further research, are offered in Chapter 6.

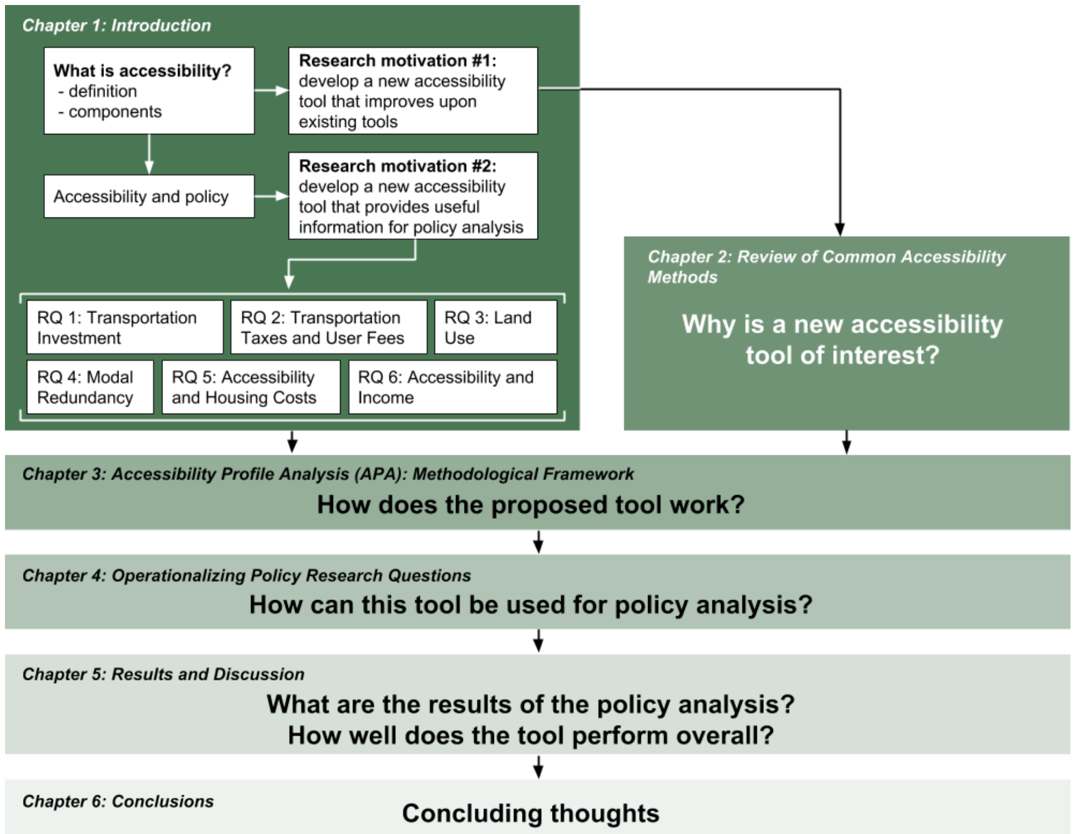


Figure 3: Chapter 1 in Context

Chapter 2:

Review of Common Accessibility Tools

chapter abstract

In this chapter I outline a set of criteria for evaluating the performance of accessibility tools. I then use these criteria to explore the methodological strengths and weaknesses of two commonly used accessibility tools: cumulative opportunity models and gravity models. After briefly considering other approaches, I argue that accessibility scholarship and planning practice can benefit from an expanded accessibility toolbox (see Figure 4).

2.1 Accessibility Tool Criteria

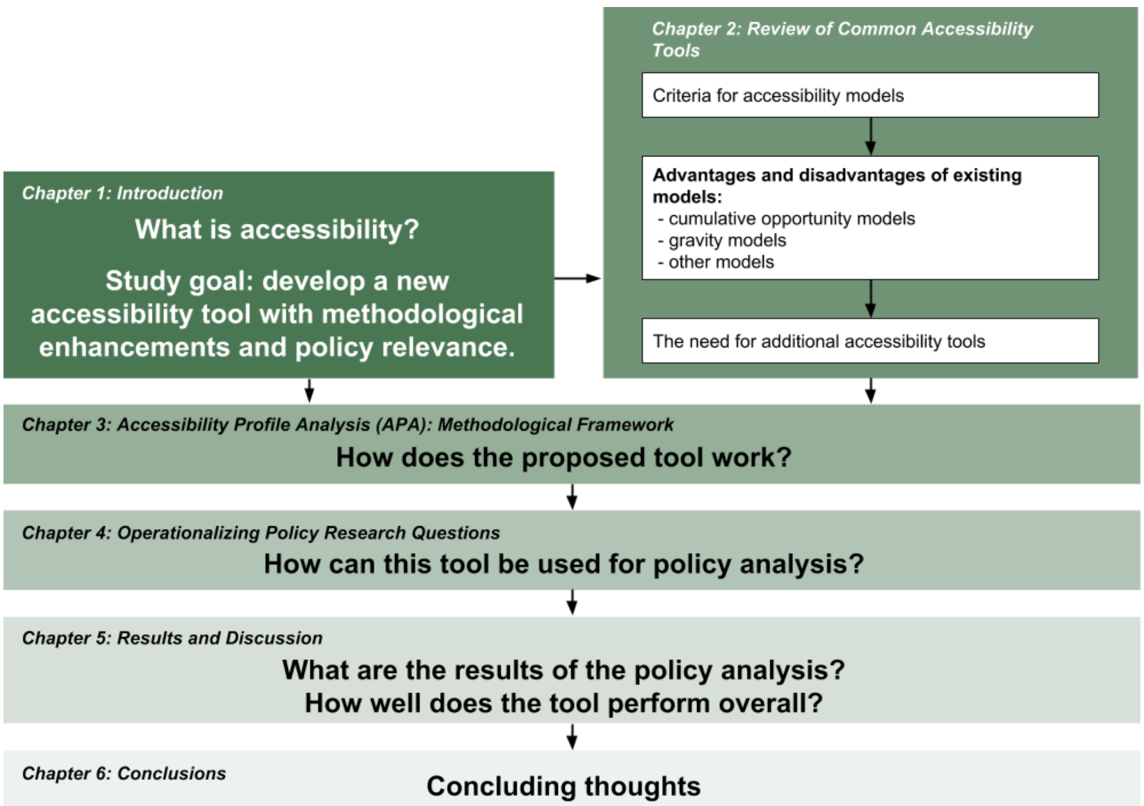
challenges in measurement and representation

As with any complex construct, the measurement and representation of accessibility can be challenging. On the one hand, an accessibility tool should capture the complexity of transportation and land use interactions in order to be accurate and meaningful. On the other hand, an accessibility tool should not be so complex that it becomes onerous to implement in practice. Thus accessibility tools are inherently characterized by trade-offs between theoretical rigour and operational ease (Curtis & Scheurer, 2010). In order to appreciate the trade-offs associated with any given tool, a set of methodological evaluation criteria are needed.

evaluation criteria

Several examples of such criteria can be found in the literature (e.g. Curtis & Scheurer, 2010; Geurs & van Wee, 2004; Morris, Dumble, & Wigan, 1979). I use the criteria outlined by Geurs and van Wee (2004), with two minor additions that I note below. Each criterion is outlined in this section, and then applied to two common accessibility tools in the following sections. The same criteria are used again in Chapter 5 to evaluate access profile analysis (APA).

Figure 4: Chapter 2 in Context



theoretical soundness

The first general criterion proposed by Geurs and van Wee (2004) is theoretical soundness, which the authors define on the basis of five characteristics. The first of these is sensitivity to changes in the transportation system. Any change to transportation networks or travel costs that increases the travel effort associated with reaching a destination should decrease accessibility, and vice versa. Sensitivity to land use changes is the second characteristic discussed by Geurs and van Wee (2004). Any change in the location of origins or destinations should be reflected in overall accessibility. The third characteristic of theoretical soundness involves the inclusion of destination competition effects. Since many destinations, including jobs, have limited capacity, both the supply and the demand for destinations should be considered. If the number of jobs (supply) remains constant, for example, but the number of individuals seeking jobs (demand) increases, accessibility should decrease. Fourth, an accessibility measure should be sensitive to the temporal constraints of destinations. For example, job accessibility should be sensitive to job shifts, since congestion, transit service, and other factors that influence the ease of reaching a job, such as safety, vary temporally. Finally, Geurs and van Wee (2004) suggest that accessibility measures should be sensitive to the characteristics of individuals that affect their accessibility, such as the amount of time and money they have available for travel, and their ability to use different travel modes.

In addition to the five characteristics of theoretical soundness proposed by Geurs and van Wee (2004), I have added a sixth characteristic: the ability to distinguish between local and regional accessibility. Local accessibility refers to the number of destinations that can be reached with relatively little travel effort, whereas regional accessibility refers to the number of destinations that can be reached with greater travel effort. An origin on a main street in a small town may have high local accessibility, and relatively low regional accessibility; the opposite may be true of an origin in a residential suburb that is well connected to a major employment centre (see left and right diagrams in Figure 5 respectively). The distinction between local and regional accessibility is important because (a) local and regional accessibility are relatively independent of one another (b) some individuals may not be able to afford the higher travel costs and travel times associated with regional accessibility, and (c) improving local and regional accessibility may require different strategies.[2] The ability to distinguish between local and regional accessibility is therefore considered an important aspect of theoretical soundness.

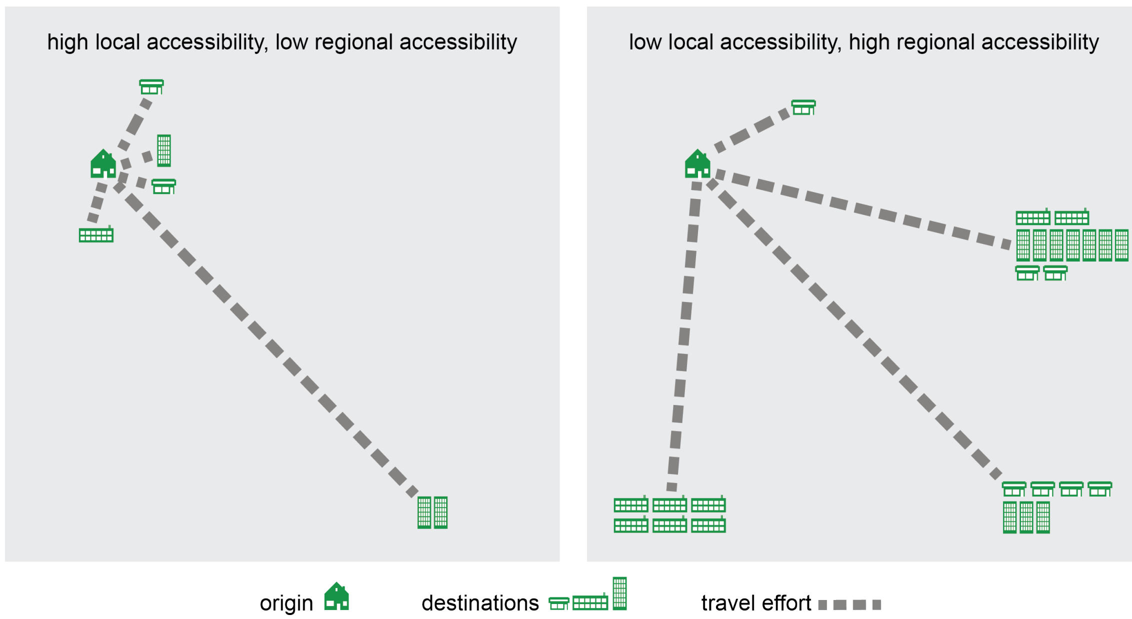
operationalization

The second category of evaluation criteria is operationalization, which refers to the level of expertise and resources required to use an accessibility tool. An important goal of accessibility analysis is to affect policy and ultimately improve accessibility outcomes.

[2] For example, strategies to improve regional accessibility in the small town case may involve better transportation connections to the nearest metropolitan centre. Strategies for improving local accessibility in the residential suburb case may require the introduction of new land uses near the origin.

Since measures that can be more readily implemented are more likely to be embraced by planners and policy makers, operationalization is a critical criterion.

Figure 5: Local and Regional Accessibility Illustration



interpretability

Interpretability, the third criterion proposed by Geurs and van Wee (Geurs & van Wee, 2004), refers to how readily the meaning of an accessibility measure can be understood and articulated. Two issues underscore the importance of interpretability for an accessibility measure. First, unlike travel speed or highway level of service, accessibility is a multi-faceted and abstract concept; it cannot be observed visually, and does not have any natural units of measurement. Second, the goal of accessibility analysis is to affect policy, a process that involves a broad range of non-expert participants. Since accessibility measures are not inherently intuitive, and must be communicated effectively to a broad audience, many authors have emphasized the need for readily interpretable measures (Benenson, Martens, Rofé, & Kwartler, 2011; Bertolini et al., 2005; Curl, Nelson, & Anable, 2011).

social and economic evaluation

Suitability for social and economic evaluation is the fourth general criterion suggested by Geurs and van Wee (2004). To be useful for social and economic evaluation, an accessibility tool should be able to help predict the social and economic outcomes of various accessibility conditions or scenarios. The aim of social evaluation is to understand both *who* is affected by accessibility and *how* they are affected. This typically involves disaggregate analysis with particular attention devoted to disadvantaged groups (e.g. Foth, Manaugh, & El-Geneidy, 2013; Páez, Mercado, Farber, Morency, & Roorda, 2009). Economic evaluation focuses on either direct micro-economic benefits for individuals, such as travel time savings, or macro economic benefits for the general economy, such as increased GDP (Geurs & van Wee, 2004). Any measure of accessibility that can be linked to economic theory will be suitable as an economic indicator and satisfy this criterion.

In this review, I have added comparative analysis as an additional criterion related to social and economic evaluation. There are two reasons for including comparative analysis as a distinct criterion. First, the purpose of accessibility analysis is often to compare the level of accessibility between different regions (e.g. Grengs, Levine, Shen, & Shen, 2010), different socio-economic groups (e.g. Foth et al., 2013), or different travel modes (e.g. Benenson et al., 2011). As discussed below however, the methodology of some accessibility tools can make comparative analysis challenging. In order to explicitly consider these challenges I chose to include suitability for comparative analysis as an additional criterion.

usefulness of evaluation criteria

These four criteria categories—theoretical soundness, operationalization, interpretability, and suitability for social and economic evaluation—are useful to understand the strengths and weaknesses of various accessibility measures. Several of these criteria exist in tension with one another, particularly theoretical soundness vis-à-vis operationalization and interpretability. It is not surprising, therefore, that no accessibility measures fully satisfy all of the criteria (Handy & Niemeier, 1997; Geurs & van Wee, 2004). Nevertheless, an understanding of the strengths and weaknesses of different measures is useful in two ways. First, it enables researchers and practitioners to select the measure that fits the most relevant criteria for any given situation. Once a measure has been selected and implemented, an awareness of its strengths and weaknesses is useful to define reasonable limitations of the analysis and to identify ways of addressing these limitations. In the following sections, the strengths and weaknesses of two widely used accessibility measures are discussed, with reference to the criteria outlined above.

2.2 Cumulative Opportunity Model

overview

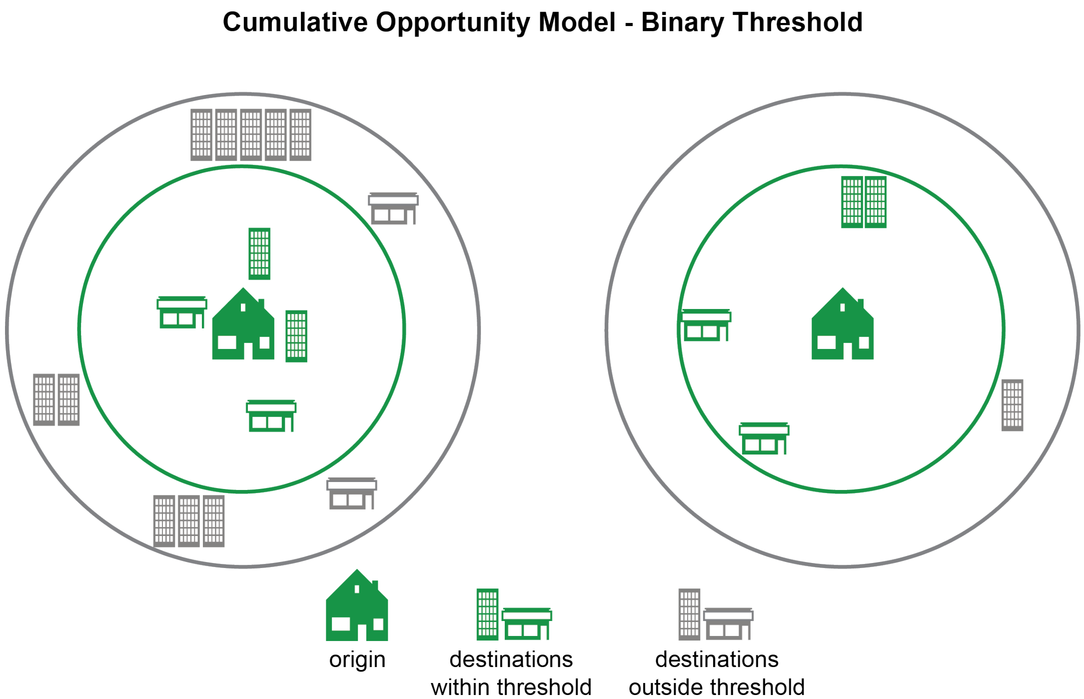
Cumulative opportunity models, also known as isochronic measures or contour measures, are the simplest form of accessibility models (Handy & Niemeier, 1997). The basic principle involves establishing an upper threshold of travel effort (typically expressed as travel time, distance, or cost) and constructing a contour or isochrone around an origin based on this upper threshold. The destinations lying in the area bounded by this contour are then counted, and this count reflects the accessibility for the respective origin. The concept of cumulative opportunity models is illustrated in Figure 6. Using the outer ring as a travel threshold, the origin on the left would have an accessibility score of 16 destinations, whereas the origin on the right would have an accessibility score of five destinations. The simple and intuitive nature of these models has contributed to their popularity in urban planning practice (Geurs & van Wee, 2004; Curl et al., 2011).

theoretical soundness

Theoretical soundness is generally considered a weakness of cumulative opportunity models (Geurs & van Wee, 2004). While these models are sensitive to origin and destination locations, transportation networks, and potentially even travel costs (if travel effort is modelled as generalized cost for example), the binary nature of the travel threshold is considered a poor representation of the ease of reaching destinations. For example, the ease of reaching destinations adjacent to the origin is considered equal to the ease of reaching destinations that are located just within the threshold. Destinations located just beyond the travel threshold have absolutely no bearing on accessibility, even though they may only be marginally more difficult to reach than destinations located just within the threshold.

As one might expect, cumulative opportunity model outputs are highly sensitive to the threshold value (Handy & Niemeier, 1997). The selection of a threshold value is therefore an important and somewhat contentious step in operationalizing a cumulative opportunity model. Some authors argue that the definition of a binary threshold is inevitably arbitrary (Curtis & Scheurer, 2010; Geurs & van Wee, 2004). Others rely on relevant empirical travel behaviour data to specify a threshold value. For example, Gutiérrez (2001) uses a 4 hour travel time contour to evaluate the impact of high-speed rail on interregional accessibility. The 4 hour threshold is based on evidence suggesting this is the maximum travel time that most people are willing to accept for single day round trips between cities. Bertolini et al. (2005) explore commuting accessibility and select a 30 minute threshold based on data indicating that the journey to work is 30 minutes or less for more than 80% of commuters in their study area.

Figure 6: Cumulative Opportunity Model - Binary Threshold



Both of these issues—the binary nature of travel threshold, and the difficulty of establishing an appropriate threshold value—are illustrated in Figure 6. Using the smaller circle as the travel threshold, the left and right scenarios are considered to have the same accessibility value (4 destinations), even though the destinations in the left scenario are much closer to the origin than those in the right scenario. If the threshold value changes, and the larger circle is used, the scenarios suddenly have very different accessibility values (16 destinations on the left, and 5 destinations on the right).

Beyond the specification of threshold values, cumulative opportunity models also suffer from other theoretical shortcomings. The models are not sensitive to competition effects or the temporal constraints of destinations (Geurs & van Wee, 2004). Similarly, variations in the amount of time and money individuals have available for travel cannot be reflected in the model. With respect to distinguishing between local and regional accessibility, cumulative opportunity models could achieve this to some extent by using two distinct travel thresholds. The limitations associated with using a binary and arguably arbitrary threshold apply here as well however, and limit the ability of cumulative opportunity models to effectively make this distinction.

A novel approach that potentially overcomes the problems of an arbitrarily defined threshold, and lack of sensitivity to the characteristics of individuals has been proposed by Páez, Scott, & Morency (2012). Their approach uses travel survey data to generate spatially and socio-demographically disaggregate estimates of how far individuals actually travel. The authors identify several socio-demographic profiles of interest, and then calculate an accessibility score for each zone in their study area based on these disaggregate travel thresholds. While this approach shows promise it does not yet appear to have been replicated by other authors, and further research is needed to fully appreciate its merits and limitations.

operationalization

While the simplicity of cumulative opportunity models is a disadvantage from a theoretical perspective, it is a major advantage for operationalization (Geurs & van Wee, 2004). Data requirements are comparatively modest, and can be as simple as a set of travel distances between defined origins and destinations. More robust models may incorporate mode-specific travel times or generalized costs as well as more detailed destination information. For example, the magnitude of activity at a destination—such as the number of jobs, retail floor area, or number of hospital beds—could be used to provide a more accurate reflection of the overall attractiveness of a destination, as opposed to simply counting destination locations. Computation is also straightforward, and can be achieved with standard GIS software.

interpretability

From the perspective of interpretation and communication, cumulative opportunity models are advantageous because the model outputs are tangible and intuitive. Outputs are expressed as the number of opportunities that can be reached from a given origin within a given travel threshold. Results, such as *'58,384 jobs can be reached by car within 30 minutes from neighbourhood x*' are meaningful to non-experts. These results can be generated for various travel modes, destination sets, and travel thresholds. Results can also be compared, ranked, and mapped. Since cumulative opportunity models are intuitive enough for planners, policy-makers, and the public to understand, they can also be used effectively in participatory planning processes.

social and economic evaluation

The usefulness of cumulative opportunity measures for social and economic impact analysis is debated in the literature. Geurs and van Wee (2004) argue that the theoretical shortcomings of cumulative opportunity models preclude their usefulness as social and economic indicators. Many widely cited studies have, however, used cumulative opportunity measures as social or economic indicators (see Wachs & Kumagai, 1973; Gutiérrez, 2001; Bertolini et al., 2005). The two main arguments in support of using cumulative opportunity measures for social and economic analysis are that the benefits of interpretability outweigh the theoretical shortcomings, and that the theoretical shortcomings can be mitigated with the use of a travel threshold derived from observed travel behaviour patterns (Bertolini et al., 2005). With respect to comparative analysis, different modes, regions, and socio-economic groups can be compared using the same travel thresholds. However, the challenge of identifying a suitable travel threshold becomes even more difficult when disparate modes, regions, or socio-economic groups are being compared. Overall, the lack of consensus in the literature suggests that while cumulative opportunity models have some value, especially where public engagement is emphasized, the results produced by these models must be interpreted with an understanding of their theoretical limitations.

2.3 Gravity Model

overview

Gravity models, also known as potential measures, have been widely used to analyze accessibility for more than a half century (see Hansen, 1959 for an early example). In a gravity model, accessibility is positively related to the number or magnitude of destinations and negatively related to the impedance[3] associated with reaching them. Therefore, if the number or magnitude of destinations increases, or if impedance decreases, accessibility will increase. The basic formulation of a gravity model is given in Equation 1:

Equation 1: Gravity Model Formulation

$$A_i = \sum_{j=1}^{J} D_j f(c_{ij})$$

where A_i is an accessibility index, reflecting the accessibility from zone *i*, to all destination zones *J*. D_j indicates the magnitude of each destination zone *j*, and $f(c_{ij})$ is an impedance function representing the travel effort of moving from zone *i* to zone *j*.

[3] Impedance is synonymous with travel effort; the term impedance is used in the discussion of gravity models in order to be consistent with the literature on gravity models.

The impedance function is the defining element of any gravity model (Iacono, Krizek, & El-Geneidy, 2008). Typically, local travel survey data are used to estimate an impedance function (Grengs et al., 2010). This is achieved by generating observed travel time distributions from the local travel survey data, either in aggregate, or for a small number of segmentations based on trip purpose, mode, etc. Various estimation techniques are then used to derive a mathematical formulation that approximates the observed distribution of travel time (McNally, 2008). A number of formulations can be found in the literature (Reggiani, Bucci, & Russo, 2011) with the most common being exponential decay functions and power decay functions, shown in Equation 2 and Equation 3 respectively:

Equation 2: Exponential Decay Function

$$f(c_{ij}) = e^{-\beta t_{ij}}$$

Equation 3: Power Decay Function

$$f(c_{ij}) = t_{ij}^{-\gamma}$$

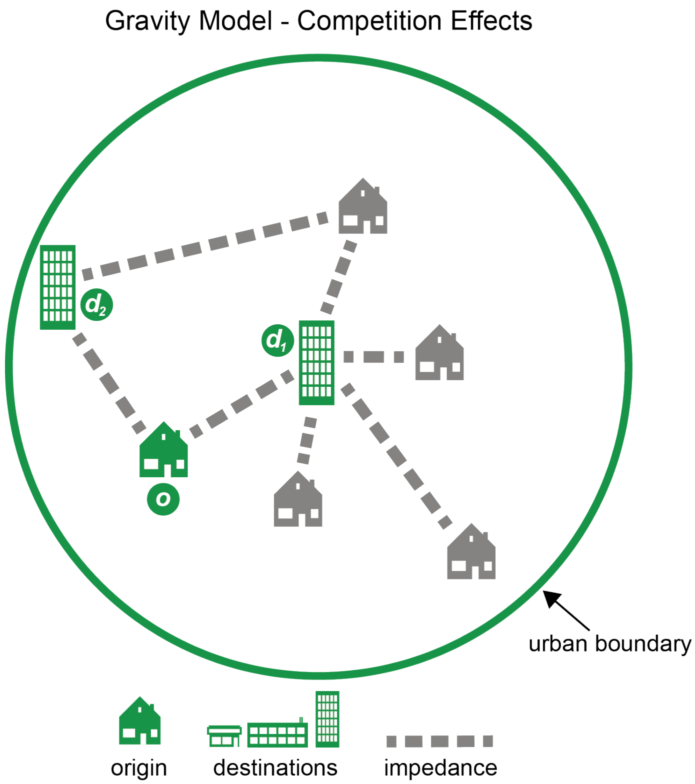
where t_{ij} is the travel time (or distance, or cost) from origin i to destination j, and β and γ are impedance coefficients derived using the estimation techniques.

These impedance coefficients are assumed to represent willingness to travel (Harris, 2001; Iacono et al., 2008). Distinct impedance coefficients can be estimated for different trip purposes, travel modes, regions, and socio-economic groups (Cheng & Bertolini, 2013; Grengs et al., 2010; Iacono et al., 2008). For example, observed travel patterns might indicate that the average traveller is willing to travel 45 minutes to reach their job, but only 15 minutes to reach a shopping destination, or that the average transit user is willing to travel 60 minutes, whereas the average auto user is only willing to travel 45 minutes, etc. (Iacono et al., 2008). As one might expect, the results of a gravity model are significantly influenced by the formulation of the Impedance function (Geurs & van Wee, 2004) the implications of which are discussed below.

theoretical soundness

Gravity models improve upon the theoretical soundness of cumulative opportunity models with respect to transportation, land use, and competition effects (Geurs & van Wee, 2004). The use of a continuous impedance function to weight destinations based on the ease of reaching them generally satisfies the transportation and land use aspects of theoretical soundness (Geurs & van Wee, 2004). And while basic gravity models do not account for competition effects, they can be modified to do so.

Figure 7: Gravity Model - Competition Effects



Consider the following scenario, illustrated in Figure 7. An origin *o* is equidistant from two destinations d_1 and d_2 which are equal in magnitude. Since the demand from other origins is much higher for d_1 than it is for d_2 however, the magnitude of d_2 that is available to *o* is greater than the magnitude of d_1 that is available to *o*. In order to capture this effect, the magnitude of a given destination relative to a given origin must be modified to reflect demand for the destination from all other origins. This can be achieved by dividing the accessibility function presented in Equation 1, which reflects the destination supply, by a demand factor representing the demand for each destination zone, as shown in Equation 4:

Equation 4: Gravity Model with Competition Effects

$$A_i = \sum_{j=1}^{J} \frac{D_j f(c_{ij})}{\sum_l^n W_{lj} f(c_{ij})}$$

where l is one of n origins where competition for destinations in zone j originates, and W_{lj} represents the demand for destination zone j originating in zone l. In the case of employment accessibility, for example, W_{lj} would be the number of workers in zone l competing for jobs in zone j.

Other approaches have also been developed to adapt gravity models to account for competition effects. For example, Geurs and van Wee (2004) argue that the balancing factors from a doubly constrained gravity model serve as an inverse measure of accessibility. Cheng and Bertolini (2013) point out, however, that this approach is better suited to analyse spatial matching of jobs than actual job opportunities. Overall, the method shown in Equation 4 appears to be the more common approach (see for example Sanchez, Shen, & Peng, 2004; Wang, 2003).

While gravity models perform well with respect to the first three theoretical criteria—transportation, land use, and competition effects—they are less successful at addressing the remaining three aspects of theoretical soundness. The aggregate nature of gravity models means that temporal constraints of destinations are difficult to accommodate (Dong, Ben-Akiva, Bowman, & Walker, 2006). Gravity models are somewhat better than cumulative opportunity models at reflecting the amount of time and money that individuals have available for travel because they are based on actual travel time or cost distributions. The aggregate nature of gravity models once again prevents them from reflecting *individual* variations in the amount of time or money available for travel however. Finally, the accessibility score produced by gravity models reflects the *combination* of both local and regional accessibility, making distinctions between the two virtually impossible. Generating distinct local and regional accessibility scores would also be problematic since it would require distinct travel time or cost distributions for local and regional trips. Therefore, the temporal constraints criterion is not satisfied, the individual characteristics criterion is somewhat satisfied, and the local/regional distinction criterion is not satisfied.

operationalization

While gravity models are somewhat data intensive, the required data—zone delineation, zone attributes such as employment and population, travel time or cost matrices, and one or more calibrated impedance factors—are frequently available from travel forecasting exercises (McNally, 2008). The data overlap between travel forecasting and accessibility analysis is a consequence of the widespread use of gravity models for trip distribution purposes in traditional travel forecasting methods (National Research Council (U.S.), 2007). The need for one or more calibrated impedance factors makes the operationalization of gravity models somewhat more complex than the operationalization of cumulative opportunity models however.

interpretability

Interpretability is often seen as a weakness of gravity models (Curl et al., 2011; Curtis & Scheurer, 2010; Geurs & van Wee, 2004). Gravity models produce an abstract accessibility index that does not readily translate into real-world terms. Whereas cumulative opportunity models produce absolute results—e.g. 35,492 jobs can be reached within 30 minutes of auto travel from this particular origin—gravity models produce results that are relative in nature, and have little meaning to non-experts (Cheng & Bertolini, 2013). A UK study based on interviews with accessibility planners found that practitioners, particularly those working at the local scale, favoured cumulative opportunity models over gravity models in part due to the challenges around interpreting and communicating the results of gravity models:

> *"Respondents were hesitant to discuss the use of more complex measures such as gravity-based measures…and where these were discussed they were dismissed as being flawed, too difficult to explain to stakeholders, as well as being difficult to compare longitudinally"* (Curl et al., 2011, p. 7)

Other studies have also noted that difficulties around interpretability limit the use and efficacy of gravity models in planning practice (Benenson et al., 2011; Gutiérrez, 2001).

social and economic evaluation

Gravity models have been effectively used for social evaluation (e.g. Foth et al., 2013; Sanchez et al., 2004; Wang, 2003) and economic evaluation (e.g. Gutiérrez, 2001; see also: Geurs & van Wee, 2004). A conceptual limitation related to impedance functions curtails their effectiveness for comparative analysis however. Recall that impedance coefficients, which are assumed to reflect willingness to travel, vary based on trip purpose, mode, region, and socio-economic characteristics of the traveller. Where analysis involves comparisons along these lines, i.e. between modes, etc. two options are available: (a) specification of unique impedance coefficients for each comparison group, or (b) specification of the same impedance coefficient for all comparison groups. Both options are problematic.

The specification of a unique impedance coefficient for each comparison group is problematic because it obscures comparison results. Consider a comparison between transit users and auto users. Observed travel data typically indicate that transit users have longer travel times than auto users (Grengs et al., 2010). Longer travel times, in turn, produce lower impedance coefficients. When these coefficients are used for accessibility analysis, transit users essentially get 'credited' for their greater 'willingness' to travel greater distances[4] (Grengs et al., 2010). If the same hypothetical travel time and destination set were applied to both transit users and auto users, the accessibility index for transit users would be higher than the auto accessibility index, due to the difference in impedance coefficients. This creates an obvious problem for the interpretation of results, because it is difficult to know whether a measured difference in accessibility between auto and transit reflects actual differences in accessibility or is simply a bias caused by the use of distinct impedance coefficients. Grengs et al. (2010) explore these issues in a study comparing transit and auto accessibility in two metropolitan areas in the US, and ultimately specify a single impedance coefficient for all of their comparison groups.

While the use of a single impedance coefficient for all comparison groups is preferable to the use of multiple impedance coefficients, it also presents another challenge: how does one arrive at a single impedance coefficient to represent trips that are traditionally modelled with distinct impedance coefficients? This has only recently become an area of research interest in the literature, and the best approach has not yet been well established (see Levine et al., 2012). Moreover, the implications of using a single impedance factor have not been explored in the literature. Due to these complexities, Benenson et al. (2011) note that most multi-modal accessibility studies use cumulative opportunity models rather than gravity models.

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[4] The use of distinct impedance functions is based on the assumption that differences in trip length distributions for different travel modes, trip purposes, and socio-economic groups reflect differences in personal choice. This assumption is not always valid because while trip length may be influenced by personal choice, it is also influenced by aspects of accessibility that are beyond an individual's control such as land use or the availability of alternate travel modes (Ewing & Cervero, 2010; Foth, Manaugh, & El-Geneidy, 2013). The failure to make this distinction is important because it means that accessibility is not only the dependent variable of a gravity model, it is also represented in the coefficient of an independent variable (impedance).

2.4 Other Models

This chapter has focussed on cumulative opportunity and gravity models because these are the approaches most often used in policy making and planning practice (Curl et al., 2011). Several other accessibility tools can be found in the literature however, including economic utility approaches (Geurs & van Wee, 2004), time-space geography measures (Geurs & van Wee, 2004), and the approach introduced by Black and Conroy (1977) which this model resembles. While both the economic utility measures and the time-space geography measures offer theoretical improvements over gravity and cumulative opportunity models, the difficulties in operationalizing these measures and interpreting their results have restricted their use in planning practice and policy-making (Curl et al., 2011; Curtis & Scheurer, 2010). Since policy relevance is a key consideration for this research, I do not explore these tools in greater detail here. I explore the approach presented by Black and Conroy (1977) with particular attention to the similarities and differences between their methods and APA in Section 0, after introducing the basic APA framework.

2.5 Expanding the Accessibility Toolbox

the need for new tools

Table 1 shows the assessed relative performance of cumulative opportunity models, gravity models, and gravity models with competition effects, based on the criteria used in this chapter. In summary, cumulative opportunity models are easy to interpret, somewhat useful for comparative analysis, but not very comprehensive due to the use of an arbitrary and binary travel threshold. Gravity models are more comprehensive, but also more difficult to interpret, and can be problematic for comparative analysis. Both of these tools face serious shortcomings in contexts requiring (a) comprehensive analysis, (b) results that can be understood by a range of stakeholders, and (c) comparisons between modes, local and regional scales, etc. There is a need therefore to expand the accessibility toolbox, and provide practitioners and researchers with additional analytic tools. The next chapter aims to achieve this by introducing APA, an accessibility tool that is comprehensive, interpretable, and well suited for comparative analysis.

Table 1: Accessibility Tool Evaluation

Accessibility Measure	**Theoretical - Transportation**	**Theoretical - Land Use**	**Theoretical - Land Use Competition**	**Theoretical - Temporal Constraints**	**Theoretical - Individual Characteristics**	**Theoretical - Local/Regional**	**Operationalization**	**Interpretability**	**Social Indicator**	**Economic Indicator**	**Comparative Analysis**
Cumulative Opportunity	•	•	–	–	–	•	••	••	•	•	•
Gravity	••	••	–	–	•	–	•	•	•	•	–
Gravity with Competition Effects	••	••	•	–	•	–	•	–	•	•	–

•• criterion comprehensively satisfied
• criterion somewhat satisfied
— criterion not satisfied

Chapter 3:

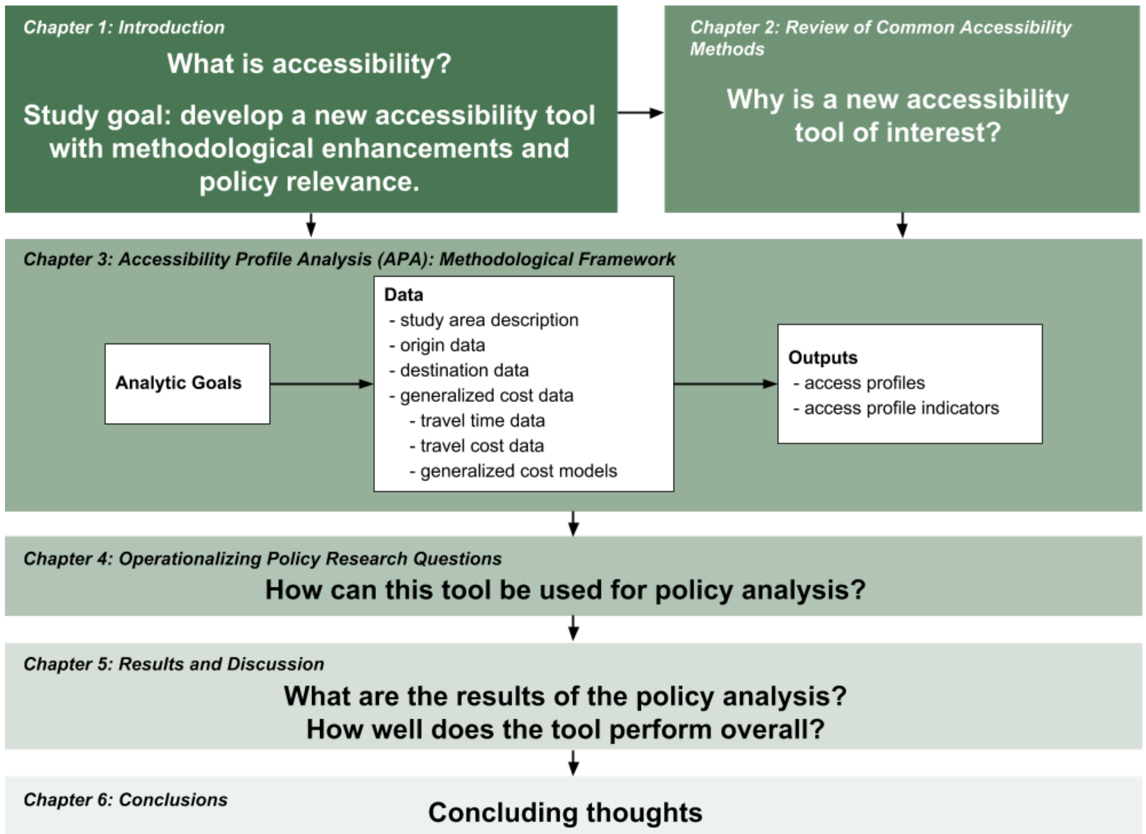
Access Profile Analysis: Methodological Framework

chapter abstract This chapter introduces the concept of access profile analysis (APA). A three part methodological framework is used to broadly describe how APA works (see Figure 8). The first section outlines general analytic goals for APA. Using a case study, the next section describes the data on which access profiles are based. Since several data inputs are generated specifically for this study, a review of how these inputs are generated is also included in this section. The third section explains what access profiles are, how the data are used to generate them, and how they can be interpreted. This three part methodological framework is used as a template in the following chapter, where it is adapted to address the six applications outlined in Chapter 1.

3.1 Analytic Goals

The basic analytic goal of APA is to measure the ease of reaching destinations using various travel modes. To illustrate how APA works, two specific goals are identified for this chapter. The first goal is to compare the average level of job accessibility provided by pedestrian, transit, and auto modes in the study area. The second goal is to calculate a disaggregate measure of job accessibility, and show spatial accessibility patterns in the study area.

Figure 8: Chapter 3 in Context



3.2 Data

After a brief outline of the study area, the following subsections describe the different kinds of data I used to operationalize APA: origin data, destination data, and generalized travel cost (GC) data. The GC data subsection includes an overview of how I generated pedestrian and transit travel time data for this study.

3.2.1 Study Area

To demonstrate how APA works, I did a case study of Kitchener-Waterloo. Located in south western Ontario, approximately 100 kilometres west of Toronto, Kitchener-Waterloo has a population of approximately 300,000 residents (Data Management Group, 2006c). While Kitchener and Waterloo are separate municipalities, they form one continuous urban area. The study area includes two downtown centres, Downtown

Kitchener and Uptown Waterloo, which are located approximately 3 kilometres apart along a central corridor. Much of the study area outside of these centres is suburban in nature, transitioning to rural around the study area borders. The transportation network includes the street network, two highways, a number of pedestrian/bike trails, and a bus transit system. A single operator, Grand River Transit (GRT), oversees the operation of buses, a central transit terminal, and a number of smaller satellite terminals. A map illustrating the relevant features of the study area is shown in Figure 9.

Figure 9: Study Area

I chose Kitchener-Waterloo as the case study area for pragmatic reasons—data availability, manageable size and complexity, personal familiarity with the area—and also because a number of interesting developments are currently underway in Kitchener-Waterloo that have direct accessibility implications. These developments include (a) the construction of a Light Rail Transit (LRT) line along the central corridor, (b) the construction of a mobility hub in downtown Kitchener, (c) the introduction of new express bus routes that feed into the planned LRT line, and (d) policies that foster more intensive land uses along the central corridor. These developments make Kitchener-Waterloo a particularly interesting location to implement APA; moreover the results of this study provide a benchmark for future accessibility analysis.

3.2.2 Origin Data

defining origins

Since this study examines job accessibility, origins are defined as the residential locations of individuals. Due to data availability, household origin locations are aggregated into zones. This approach is common for both cumulative opportunity and gravity model accessibility studies (e.g. Foth et al., 2013; Bertolini et al., 2005; Levinson, 1998); it also facilitates regional scale operationalization. Since origins in close proximity with one another have similar access to transportation networks and similar travel distances to destinations, spatial aggregation can effectively represent a cluster of origins while reducing complexity for analysis at larger spatial extents.

origin scale, extent, resolution

The zonal system used in this study is taken from the Transportation Tomorrow Survey (TTS), which is the regional household travel survey (Data Management Group, 2006c). The TTS divides Kitchener-Waterloo into 270 Traffic Analysis Zones (TAZs). The shape and size of TAZs vary, with TAZ boundaries typically following major roads, rivers, or railways. Geographically smaller TAZs are generally located in denser areas, and larger TAZs located toward the urban periphery, as shown in Figure 10. The centroid of each TAZ is used as the origin point for travel time generation. The spatial and socio-demographic extent and resolution of the study area are summarized in Table 2.

Table 2: Study Area Extent and Resolution

	Total Study Area (extent)	**TAZs (resolution)**			
Unit		*min*	*mean*	*max*	*SD*
Geographic Area (ha)	20,356	3.2	75.4	528	72.5
Population	300,104	0	1111	8223	1329
TAZs	270	-	-	-	-

origin attributes Origin TAZs can be characterized by a number of attributes such as population or socio-economic indicators that are relevant to accessibility. The only attribute used in the basic methodological framework discussed in this chapter is origin TAZ population. This is used to derive population-weighted averages of accessibility (see Subsection 3.3.1), as a way of compensating for the wide range of origin TAZ populations (see Table 2). Socio-economic origin attributes are discussed in Chapter 4, where they are used to operationalize several applications.

Figure 10: Study Area TAZs

3.2.3 Destination Data

defining destinations Destinations are defined as jobs in this study. Job data are taken from the TTS, which indicates that a total of 138,797 jobs exist in the study area (Data Management Group, 2006c). Both the scope of this study and data availability preclude job sector or salary disaggregation, and all jobs are therefore considered equal to one another. Since any given worker is only qualified for—and perhaps only willing to accept—a small fraction of the total jobs that exist in a study area, the number of jobs that are relevant for any given worker will be much lower than what is indicated in this general accessibility study. A further limitation arises from this, because the spatial distribution of jobs may be very uneven in terms of where different job sectors are located. A worker with manufacturing qualifications living in a downtown area, for example, may be considered to have excellent job accessibility in a general analysis, as presented here, but may in fact have low job accessibility if all the manufacturing jobs are located near the urban periphery. Consequently, this analysis only provides broad findings about accessibility to the employment market as a whole, and is not capable of identifying sector specific patterns.

If job sector data for both jobs and workers were available, two extensions of this analysis could be explored. First, sector specific analyses could be undertaken. This would be particularly useful from a social equity perspective, since it could, for example, provide greater insight on the employment challenges faced by workers in declining job sectors. Second, data from service / retail job sectors may also be useful as a proxy for access to retail and service destinations. Consideration of retail and service destinations would be a helpful first step to consider more realistic travel patterns such as trip chaining, as opposed to the simple origin-destination trips considered here. In a recent study, Cheng and Berolini (2013) found that relatively few job accessibility studies have included job sector disaggregation, noting also that this is an important area for further research.

spatial extent of destinations

The spatial extent used to define origins is also used to define destinations—i.e. only jobs located in Kitchener-Waterloo are considered in this study. While there are important employment centres located in close proximity to the study area—most notably the City of Cambridge, and to some extent the four townships located in the Region of Waterloo—I decided to exclude these areas for four reasons. First, the study area is characterized by a relatively simple land use pattern—two proximate downtown centres, and an overall pattern of diminishing densities with increasing distance from these centres—which is well suited for an initial application of this model. Adding centres outside of Kitchener-Waterloo to the study area would have increased the complexity of land use, and would be more appropriate for subsequent applications of this model. Second, the City of Cambridge and the four townships contain many rural TAZs. Since the rural areas of Waterloo Region are typically relatively inaccessible by pedestrian and transit modes, and since the focus of this model is multi-modal accessibility, I wanted to keep the number of rural origins and destinations to a minimum. Third, the City of

Cambridge appears to have a greater proportion of interregional commuting than the study area (Herhalt, 2014), which may be due to the proximity of Highway 401. Fourth, while employment centres outside of Kitchener-Waterloo may be moderately accessible for some study area workers, the most accessible jobs—and therefore the jobs of greatest interest in this study—are those located in the study area itself. A limitation of the study area delineation is that auto and perhaps even transit accessibility for some origins may be slightly underestimated.[5]

spatial resolution of destinations

The employment data included in the TTS are provided at TAZ resolution. This resolution is well suited for transit and auto accessibility measurement, and many transit and auto job accessibility studies define destinations at this resolution (e.g. Foth et al., 2013; Grengs et al., 2010; Sanchez et al., 2004). For pedestrian analysis, however, this resolution is problematic because pedestrian travel is comparatively slow, and pedestrian accessibility is most relevant at the local scale (Iacono, Krizek, & El-Geneidy, 2010). A finer destination resolution is therefore needed to measure pedestrian accessibility.

pedestrian travel destination resolution

Parcel level employment data is available in many regions, but is often expensive to procure (Iacono et al., 2010). I therefore used available generic land parcel data to downscale TAZ resolution employment data. This method is based on the assumption that employment is distributed among employment parcels in proportion to the area of each parcel. Three steps are involved:

1. **Identification of employment parcels.** First, I acquired parcel data (MPAC, 2013) from the Region of Waterloo. Each parcel in this dataset is assigned a Municipal Property Assessment Corporation (MPAC) code, which reflects the dominant use of a parcel (see MPAC, 2014). In order to identify plausible employment parcels, I sorted these codes into employment-related and non-employment-related categories, as shown in Table 3. While most codes were sorted by series, several exceptions were made for specific codes such as golf courses, where parcel area was not considered proportionate to employment potential.

[5] According to the TTS, 73% of workers living in the study area also work in the study area, while 5% work at undefined locations and 22% work in TAZs outside the study area (Data Management Group, 2006a). This suggests that while the study area is not a self contained system, the majority of workers living in the study area also work there.

2. **Calculation of proportionate parcel area**. For each TAZ, I summed the total area of all employment-related parcels. I then divided the area of each individual parcel by the total employment area in the respective TAZ. The quotient represents the proportion of TAZ employment area associated with an individual parcel.

3. **Allocation of parcel employment.** Finally, I allocated the jobs contained in each TAZ to individual parcels based on the area quotient derived in Step 2, as shown in Equation 5:

Equation 5: Parcel Employment Allocation

$$\mathrm{Emp}_{\mathrm{parcel\ i}} = \frac{\mathrm{Area}_{\mathrm{parcel\ i}}}{\sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{Area}_{\mathrm{parcel\ i}}} \cdot \mathrm{Emp}_{\mathrm{TAZ}}$$

where *parcel i* is one of *n* parcels within a TAZ.

Table 3: MPAC Property Codes

MPAC Code Series	Employment Related?	Exceptions
100 series – Vacant Land	✗	
200 series – Farm	✗	
300 series – Residential	✗	
400 series – Commercial	✓	except *golf courses (490)*
500 series – Industrial	✓	except *rail and hydro rights of way (561, 562, 597)*
600 series – Institutional	✓	
700 series – Special & Exempt	✓	except *cemetery* and *non-commercial sports complex (702, 721)*
800 series – Government	✓	

Several assumptions and limitations are implied in this approach. First, it is assumed that parcels with MPAC codes that are not considered employment-related do not have any employment, and vice versa. Moreover, the number of jobs allocated to a parcel is assumed to be proportional to the area of the parcel relative to the area of other employment parcels in the TAZ. Another limitation arises from an alignment issue between the TAZ employment dataset and the MPAC parcel dataset. Nineteen TAZs contain no parcels that are considered to be employment-related. Of these, eleven TAZs also have zero jobs according to TTS data. This creates a problem for eight TAZs, which, according to TTS data have employment, but do not contain any employment-related parcels. The affected TAZs contain less than 1% of the jobs in the study area and are mostly located at the periphery of the study area. Since the magnitude of these jobs is negligible, they are omitted from the pedestrian analysis. While this method is subject to some limitations, it does estimate job data at a suitable resolution for pedestrian analysis, based on the best available data.

3.2.4 Generalized Cost Data

definition and data requirements

Travel effort in this study is quantified as generalized travel cost (GC). GC models convert non-monetary travel costs such as travel time into monetary units, or vice versa, to combine the different aspects of travel effort into a single measure (Ortúzar & Willumsen, 2001). The following subsections describe the travel time and travel cost data used to generate GCs in this study. Since pedestrian and transit travel times were generated specifically for this research, the derivation methods are also presented here, along with a validation exercise. Specific GC models for each mode are then given in Subsection 3.2.4.3.

3.2.4.1 Travel Time Data

pedestrian travel time

Recall that the destinations for pedestrian travel are considered at the parcel scale. This results in a very large number of origin destination (OD) pairs (nearly 1 million). As expected, no pre-existing travel time data were available for this set of OD pairs, nor was it considered feasible or necessary to generate travel time data for each individual OD pair. Instead, I used an alternative approach to generate the necessary data for APA without generating individual OD pairs.

APA requires data that indicate how many destinations can be reached at specific GC intervals. I achieved this by translating GC intervals into pedestrian travel time intervals,[6]

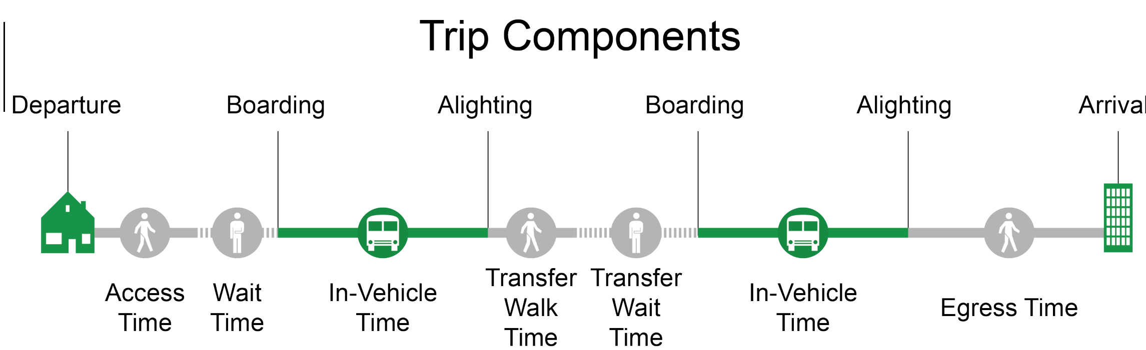
[6] This conversion is straightforward: pedestrian travel involves no monetary costs, therefore GC is linearly related to travel time; travel time is linearly related to distance, since pedestrians are considered to travel at a constant speed. If the value of time and walking speed are known, GC units can be converted into distance units.

and then into travel distance intervals, based on a standard walking speed of 5.0 km/h.[7] Using a pedestrian travel network dataset that was provided by the Region of Waterloo (Region of Waterloo, 2011b), I then generated a service area (i.e. buffer area based on travel through the network) for each origin and each distance interval in ArcGIS. Next I created a spatial join to link each service area to the employment parcel layer and sum the number of jobs within each service area. This provides the number of jobs that are reachable from each origin at each GC interval, satisfying the APA travel time requirement (see Section 3.3)

transit travel times

In this study I generated transit travel times using an ArcGIS extension.[8] A number of factors need to be considered to generate accurate transit travel times that reflect door-to-door travel. As shown in Figure 11, a transit trip is comprised of access time, wait time, in-vehicle time (IVT), egress time, and in some cases transfer walk time and transfer wait time. In order to model all of these trip components accurately, a tool is needed to (a) integrate a pedestrian network with the transit network, (b) read transit schedule data, and (c) interpret exogenous trip parameters such as origin/destination locations and departure or arrival times.

Figure 11: Trip Components



ArcGIS transit tool (ATT)

I chose to use a new ArcGIS extension, referred to here as the ArcGIS transit tool (ATT),[9] to generate transit travel times. Not only does the ATT satisfy the three

[7] Walking speeds vary in the literature between 4.2 km/h and 5.5 km/h (see Foth et al., 2013; Knoblauch, Pietrucha, & Nitzburg, 1996; Salonen & Toivonen, 2013); 5.0 km/h was found to be an approximate average of walking speeds used in the literature.
[8] Initially I attempted to use a transit travel time matrix provided by the Region of Waterloo, however these data proved to be insufficient for APA.
[9] This tool does not yet have an official name as it is still under development; in the tool documentation (Morang, 2014) it is simply referred to as *Add GTFS to a Network Dataset – version 0.3.0*.

requirements outlined above, it also made use of available data and available software. These features suggest that this tool could readily be used for APA analysis in other metropolitan areas.

building the transit network

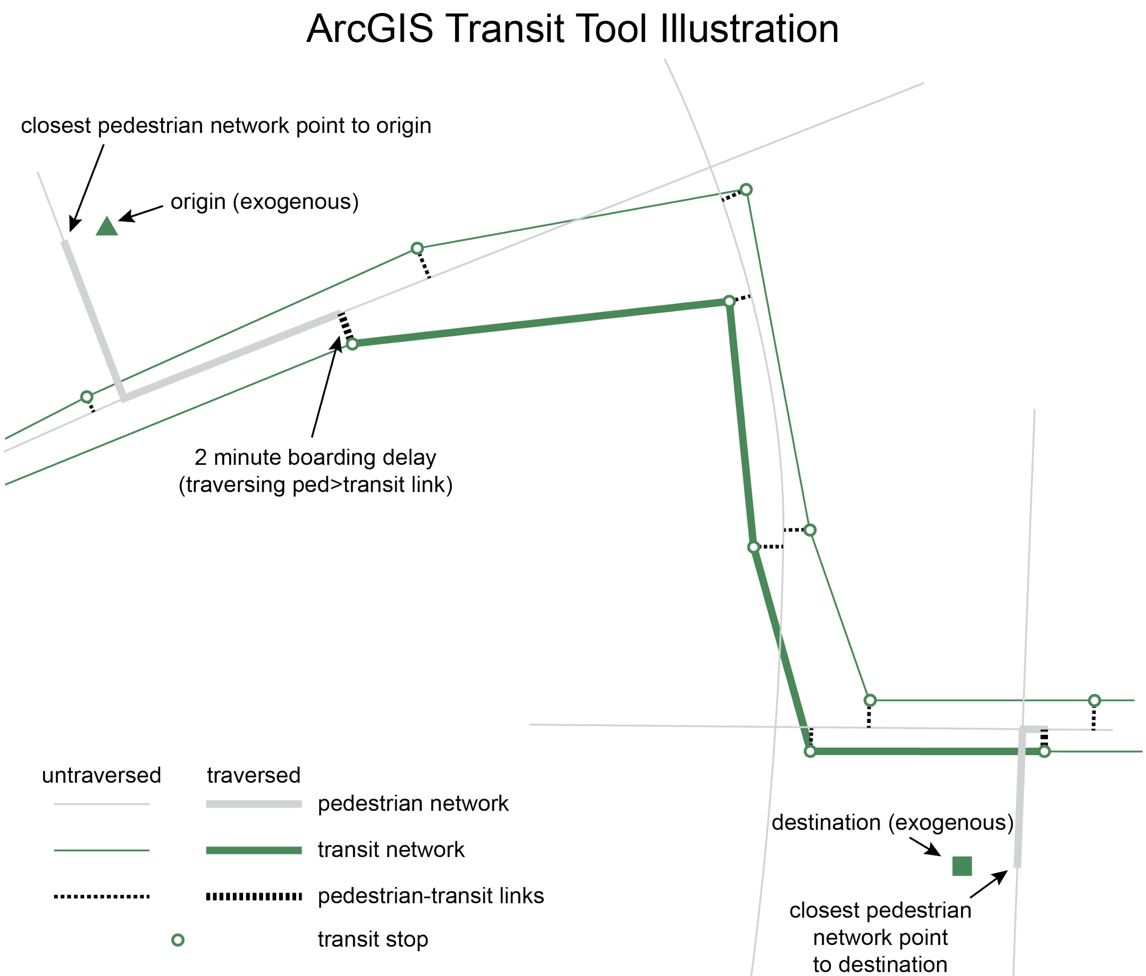
The first step in using the ATT is to build the transit network using Generalized Transit Feed Specification (GTFS) data. This data format is widely used by many transit agencies around the world, and is frequently published by transit agencies in open data libraries (e.g. Region of Waterloo, 2013b). GTFS data includes information about routes, trips, stops (including longitude and latitude), stop times, and calendar dates. The ATT uses the stop location data in the GTFS dataset to create transit stops in an ArcGIS shapefile. Next, the ATT creates direct links between stops according to their route sequence in the GTFS dataset. The next step is to import a pedestrian network to enable the access, transfer, and egress trip components. I used the same pedestrian network (Region of Waterloo, 2011b) here that I used earlier to generate pedestrian travel times. The ATT then connects each transit stop to the closest point on the pedestrian network with a special link.[10] With the transit route network connected to the pedestrian network, the ATT is able to read schedule data and model realistic transit trips based on exogenously determined origins, destinations, and departure or arrival times. Figure 12 shows a simple transit trip modelled with the ATT, including the access, wait, in-vehicle, and egress trip components. In order to appreciate how modelled transit trips compare with realistic transit travel behaviour, each trip component is discussed in greater detail below.

transit travel times – fixed arrival time

In modelling a transit trip, the first factor considered by the ATT is the exogenously determined departure or arrival time. Since this study examines job accessibility, I chose to specify a fixed destination arrival time of 8:30 AM on a weekday, reflecting a typical start time for many jobs. Given an arrival time, an origin location, and a destination location, the ATT uses an algorithm to identify the trip route with the latest possible departure time that does not violate the fixed arrival time.

[10] The properties of this link are described below.

Figure 12: ArcGIS Transit Tool (ATT) Illustration



transit travel times – in-vehicle time (IVT)

In-vehicle times (IVTs) form the skeleton of any trip, since this trip component is restricted by transit schedules. IVTs are also relatively simple to model since they are taken directly from the GTFS schedule data. A minor limitation in this regard is that IVTs generated by the ATT assume perfect schedule adherence. In actual transit operations there is always some deviation from scheduled travel times, though the extent of this deviation for GRT buses—and the impact of this deviation on modelled travel times—is unknown.

transit travel times – wait times

The process of modelling wait and transfer times is complicated by two factors: (a) a lack of consensus in the literature about what constitutes appropriate wait and transfer times, and (b) limited options to implement this behaviour in the ATT. Half the headway time[11]

[11] Headway time refers to the amount of time between transit vehicle arrivals/departures at any given stop.

is frequently recommended as an appropriate wait time, however Salonen & Toivonen (2013) suggest that commuters are likely to minimize their wait time by consulting transit schedules and adjusting their departure time accordingly. This is the approach taken here, and a traversal time of 2 minutes is assigned to the connectors that link the pedestrian network to transit stops,[12] as shown in Figure 12. This behaviour reflects a traveller arriving at a bus stop 2 minutes before the bus is scheduled to depart.

transit travel times – transfer times

Limited options exist in the ATT to implement accurate transfer behaviour. For transfers that involve alighting at one bus stop and boarding at another nearby bus stop—i.e. when transferring at a terminal or between routes that are perpendicular to one another—the 2 minute boarding time applies, in addition to any walking time involved between the two stops. I acknowledge that 2 minutes plus walking time may not be sufficient to reliably transfer between routes in some cases. Increasing this delay factor, however, would also affect initial wait times for all trips, and an initial wait time greater than 2 minutes is considered to be higher than necessary. A 2 minute delay, in my view, is a reasonable compromise to approximate both initial wait time and transfer time. Another limitation arises, however, for transfers that involve alighting and boarding at exactly the same transit stop. Since the connector link does not need to be traversed in this case, a transfer can theoretically happen instantaneously. This is a weakness in the ATT that currently cannot be avoided; the impact of this shortcoming on travel times is explored in the travel time validation section below.

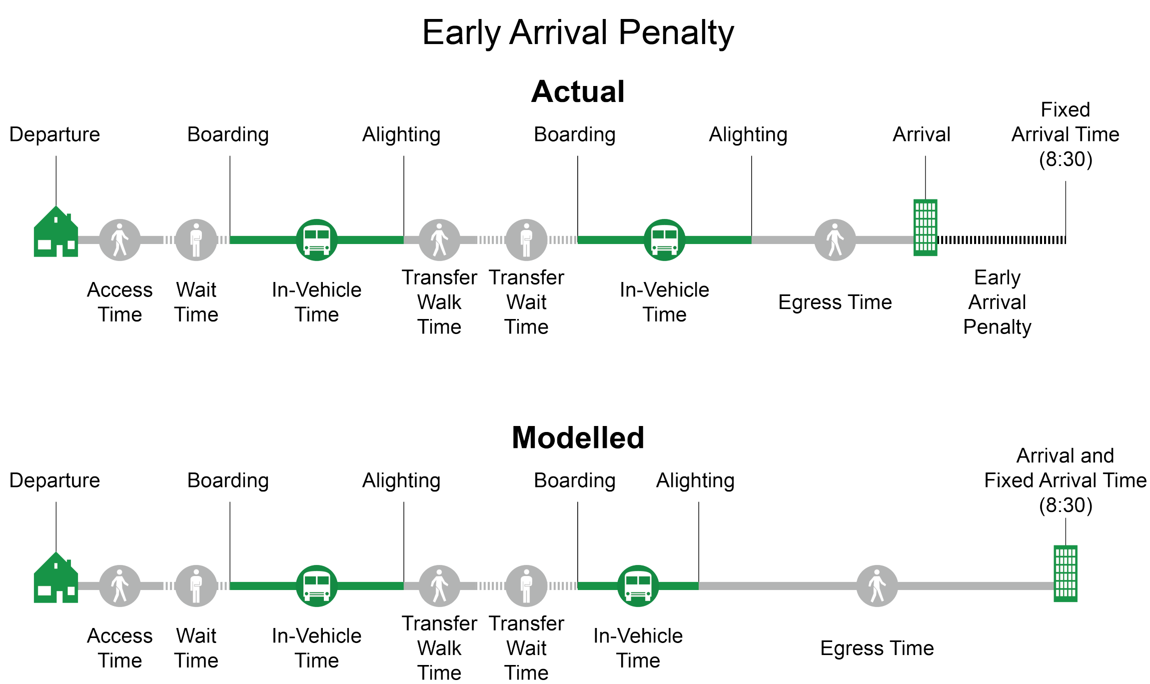
transit travel times – access and egress times

Access time and egress times are calculated based on walking via the pedestrian network from the origin to the initial boarding location, and from the final alighting location to the destination location respectively. Two aspects of the modelled access and egress behaviour deviate somewhat from realistic behaviour. First, the ATT does not limit the amount of walking that can be included in a trip. This is not considered a major limitation, since (a) excessive walking is an infrequent occurrence in the ATT because travel in a transit vehicle usually results in shorter travel times than walking, and (b) excessive walking may be necessary in some cases to generate travel times for origin-destination (OD) pairs that are not well served by transit.

[12] Note that this traversal time is uni-directional and only applies for movement from the pedestrian network to a stop (i.e. boarding). Movement in the other direction (i.e. alighting) is not subject to this traversal time.

Second, ATT egress times are somewhat distorted because they include an early arrival penalty. A transit user incurs an early arrival penalty when they arrive at a destination ahead of a fixed desired arrival time due to transit scheduling (Casello, Nour, & Hellinga, 2009). This distortion occurs because the ATT does not permit arrival in advance of the fixed arrival time. In cases where the actual arrival time would normally be ahead of the fixed arrival time, the ATT pushes the alighting time/location forward to the earliest possible point where the destination can still be reached before the fixed arrival time by walking. This distortion is shown in Figure 13. Again, this is not seen as a major limitation because early arrival penalties are very relevant to job accessibility, where desired arrival times at a job are often fixed. Since an early arrival penalty is a legitimate component of total travel time in the context of job accessibility, the modelled total travel times are considered a reasonable reflection of actual total travel time.

Figure 13: Early Arrival Penalty



calculating transit travel times

Given the complexity of each trip component, the calculation of total travel times is surprisingly straightforward. Using the closest facility tool in ArcGIS, I calculated the travel time to the n closest destinations for each origin. The closest facility tool uses the ATT travel network with 8:30 AM set as the destination arrival time. This produces a total travel time estimate for each OD pair in the study. A further tool contained within the ATT can be used to disaggregate total travel times and indicate the amount of time allocated to each trip component. Since the ATT distorts the amount of time allocated to each trip component, however, disaggregated travel times are not used in this study.[13]

auto travel times Unlike pedestrian and transit travel times, I did not independently generate auto travel times for this study. Instead, I obtained an auto travel time matrix from the Region of Waterloo (Region of Waterloo, 2011a), which was generated using VISUM travel forecasting software. The travel times in this matrix are based on actual travel speeds under PM peak period conditions. A very minor limitation in this data is the omission of 51 OD pairs. It is not known why travel times are not provided for these OD pairs. Since they constitute 0.07% of the full OD matrix, however, I consider the impact of the omission to be negligible.

travel time validation Since travel times play a central role in APA, an indication of their validity is useful to assess the overall robustness of APA results. Unfortunately, modelled travel times cannot be validated against some 'true' set of travel times, since actual travel times vary based on normal fluctuations in transportation network performance.[14] I therefore used validation as a strategy to assess the general alignment between study travel times (STT) and a set of independently generated travel time estimates. This validation approach indicates whether STTs are plausible, and whether discrepancies between the two travel time datasets are random or attributable to systemic factors. An independently generated multi-modal travel time data source was therefore needed.

I selected Google Maps Travel Times (GMTTs) as a suitable source of validation data for a number of reasons. First, GMTTs meet the criterion of independence, since they are not generated with any of the same software or algorithms as STTs.[15] Second, GMTTs are available, convenient, and could be acquired without exceeding the financial or time constraints of this research. Third, GMTTs are available for all three modes including transit. Finally, the widespread use of Google Maps for pedestrian, transit, and auto

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[13] Disaggregated travel times—if they were available—could be used to assign different weights to each trip component in a GC model; this approach is frequently used to incorporate travelers' perceptions into GC models (Ortúzar & Willumsen, 2001).
[14] The travel time of all modes is affected by variables such as weather, construction, congestion, signal delay, etc.
[15] This is assumed to be the case, though the proprietary nature of the algorithms used by Google, ArcGIS, and VISUM make this a difficult assumption to verify.

directions suggests that routes and travel times align reasonably well with actual travel behaviour.

Having established a source of validation data, I then randomly selected 10 TAZs to use as both origin and destination locations (see Appendix A). This resulted in a 90 OD pair matrix, since 10 OD pairs have identical origins and destinations. For each OD pair, I generated and then compared travel times for with both STT and GMTT methodologies. The results of this comparison is discussed in the following paragraphs, and then summarized in Table 4.

pedestrian validation

The average STT for pedestrian trips was 101.2 minutes, whereas the average GMTT for pedestrian trips was 105.3 minutes. Average delta travel time is therefore -4.1 minutes or -4% of travel time, and the standard deviation of the delta travel time is 2.7 minutes. This means that the study methodology predicts travel times that are consistently slightly shorter than the travel times predicted by Google Maps. This can probably be attributed to a slight difference in walking speed, though the actual walking speed used in Google Maps is unknown.[16] Given the relatively close agreement in STT and GMTT estimates, and the small standard deviation of delta travel time, the STTs are considered plausible, and no problematic estimation biases are noted.

transit validation

The average STT for transit trips was 62.6 minutes whereas the average GMTT for transit trips was 68.2 minutes.[17] The delta travel time was -5.6 minutes or -8.9% of travel time, and the standard deviation of the delta travel time was 9.3 minutes. This means that STTs are typically shorter than GMTTs, and range from being much shorter to slightly longer than GMTTs. The moderate discrepancy between these two travel time datasets was investigated, and it was found that much of the discrepancy was associated with two particular TAZs. Both of these TAZs are located on the periphery of the study area, and neither of them have transit service within or along their boundaries. Consequently, long walking distances were associated with trips to and from these TAZs,

[16] There are indications that Google uses a variable pedestrian travel speed, determined by variables such as grade (see Google, 2010).
[17] In order to compare like figures, an early arrival penalty was included in both STT and GMTT (i.e. travel time begins at departure and ends at the fixed arrival time, 8:30 AM).

which is handled differently by Google Maps than it is with ATT.[18] Further analysis revealed that the random sample of 10 TAZs used for validation purposes overrepresented TAZs with no transit service, which constitute less than 10% of all study area TAZs. In order to understand how much of the travel time discrepancy could be attributed to these two TAZs, I conducted a second analysis omitting the OD pairs involving these TAZs.

Among the remaining 56 OD pairs, the average STT was 45.0 minutes, and the average GMTT was 46.9 minutes. Delta travel time is therefore -1.9 minutes or -4.2% of travel time, and the standard deviation of delta travel time is 4.6 minutes. This means that STTs are slightly shorter on average than GMTTs, with a moderate range of dissimilarity. These results are in line with expectation, and the remaining minor discrepancy can be attributed to differences in transfer rules, boarding times, walking speed, and a minor schedule issue.[19] While the STTs for transit trips to or from locations with poor transit service may be underestimated, overall the STTs for other cases are closely aligned with GMTTs.

auto validation

The average STT for auto trips was 15.2 minutes, whereas the average GMTT for auto trips was 12.1 minutes. The delta travel time is 3.2 minutes or 26% of travel time, and the standard deviation of the delta travel time was 5.2 minutes. These results were expected since GMTTs are based on free flow conditions, and the STTs are based on peak period congested conditions. Consequently, the STTs may well be a more accurate reflection of actual travel time than the GMTTs. Further investigation of the discrepancy confirmed that delta travel times generally increased in proportion to travel time—i.e. longer trips had greater delta travel times—and for routes that included significant highway travel. This is consistent with congestion being the primary difference between the two sets of travel times. Given the logical explanation for the

[18] For trips that involve significant amounts of walking, Google Maps appears to minimize walking by always using the nearest transit stop, even when walking to a slightly further transit stop with better service reduces overall trip time. As discussed earlier, the ATT behaviour has no aversion to walking.

[19] After completion of the validation exercise it was discovered that GRT made minor schedule adjustments on 5 of their routes in early January 2014; the GTFS dataset used in the study does not reflect these changes, whereas the GTFS dataset used by Google does.

moderate alignment between the two datasets, STTs for auto trips are considered very plausible.

travel time validation summary

The results of the validation exercise are shown in Table 4. STTs for all modes were closely and consistently aligned with the corresponding GMTTs, with caveats noted above. The average discrepancy between the two datasets was less than 5 minutes for each mode, though the inclusion of origins and destinations poorly served by transit lead to slightly higher average discrepancies for transit travel times.

Table 4: Travel Time Validation Summary

Statistic	**Pedestrian**	**Transit (90 OD pairs)**	**Transit (56 OD pairs)**	**Auto**
STT Sample Mean (min)	101.2	62.6	45.0	15.2
GMTT Sample Mean (min)	105.3	68.2	46.9	12.1
Min Delta (min)	-11.0	-36.4	-15.4	-3.8
Mean Delta (min)	-4.1	-5.6	-1.9	3.2
Mean Delta as % of Travel Time	-4.0%	-8.9%	-4.2%	20.7%
Max Delta (min)	-0.2	3.0	2.3	20.0
St Dev of Delta (min)	2.7	9.3	4.6	5.2
Comments	Slightly slower walking speed suspected for GMTT	Poor alignment for TAZs with no transit service	Minor differences with transfers, boarding, walk speed	GMTT based on free flow conditions; STT based on peak hour conditions

*Delta = STT - GMTT

3.2.4.2 Travel Cost Data

pedestrian and transit costs

This subsection reviews the monetary travel cost inputs used in the GC models. Pedestrian travel is the simplest mode in this regard, as it does not entail any monetary costs. Transit service in the study area is priced using a flat fare (i.e. not distance based), with various fare structures available such as single fares, monthly passes, student fares, etc. In order to calculate a meaningful average fare cost among the different fare structures, I divided the annual farebox revenue received by Grand River Transit (GRT) by the number of annual passenger trips that were taken on the GRT, as shown in Equation 6:

Equation 6: Average Fare Calculation

$$\text{average fare} = \frac{\text{Passenger Revenue}}{\text{Passenger Trips}} = \frac{\$17{,}368{,}537}{13{,}726{,}874} = \$1.27$$

The average monetary cost of transit use is therefore $1.27 per trip (Canadian Urban Transit Association, 2007).[20] While this may seem like a low average fare considering that cash fare in 2006 was $2.25, only approximately 15% of passenger trips were paid as cash fare (Canadian Urban Transit Association, 2007). An overview of the variables collected by the Canadian Urban Transit Association (CUTA) for each transit agency in Canada is provided in Appendix B.

auto costs

Estimating the monetary cost of travel for auto is considerably more complex than for either of the other modes. This is because auto travel entails fixed costs that are unrelated to the number or length of trips made. Fixed costs include insurance, depreciation, and financing costs, and are typically expressed as annual figures. In the literature, fixed auto costs are frequently excluded from generalized cost models (e.g. Koopmans, Groot, Warffemius, Annema, & Hoogendoorn-Lanser, 2013). In my view, the exclusion of fixed costs could only be justified if all potential workers in the study area owned a car, which is of course not the case. In the real world auto use is not possible if fixed costs are not paid, and there is no reason why they should be left unaccounted for in modelled behaviour aimed at measuring the ease of reaching destinations. The question is how—not whether—fixed costs should be modelled. Since these costs do not vary based on trip length, it is not appropriate to include them with variable costs such as fuel. The only alternative is to allocate a portion of these costs to each trip, independent of trip length.

Estimates of both fixed and variable auto costs are taken from the Canadian Automobile Association (CAA) (2007). These estimates are based on the purchase of a new compact car, with retention and financing over a four year period. Financing is based on a 10% down payment, with 7.75% interest (Canadian Automobile Association, 2007). Variable costs accounting for fuel, maintenance, and tire costs are estimated at 12.5¢ per kilometre; fixed costs are estimated at $7,080 per year based on insurance, licence/registration fees, depreciation, and financing costs (Canadian Automobile Association, 2007).

[20] 2006 data are used to align with the 2006 TTS data in this study.

I allocate fixed auto costs to individual trips on the basis of average trip making rates. The TTS indicates that the average resident in the study area made 2.43 trips per day (Data Management Group, 2006b), resulting in 888 trips per person annually. While the survey was only conducted on weekdays, I assume the same trip rate for weekend travel. To calculate the fixed costs per trip, I divide the annual fixed costs by the number of the number of annual trips, as shown in Equation 7:

Equation 7: Fixed Cost of Auto Travel per Trip

$$\text{Fixed costs per trip} = \frac{\text{Annual Fixed Costs}}{\text{trips per day } \cdot \text{days per year}} = \frac{\$7{,}080}{2.43 \cdot 365} = \$7.97$$

3.2.4.3 Generalized Cost Models

value of time

In order to convert non-monetary travel costs (i.e. travel time costs) into dollars, the value of time must be established. Empirical estimates suggest that the value of travel time (VOT) for commuting purposes is frequently estimated at 50% of the gross wage rate (Small, 2012, p. 5). The average wage in Ontario ranged between \$20.47 and \$23.59 from 2006 to 2010[21] (Statistics Canada, 2014), suggesting a VOT between \$10.25 and \$11.75. The Region of Waterloo employs a VOT of \$12.35 for their modeling (Region of Waterloo, 2013a), whereas the Toronto regional transit authority, Metrolinx, uses \$13.02 (Steer Davies Gleave, 2010). Based on these estimates, I specified a VOT of \$12.00 per hour. While the actual value of travel time for a specific individual depends on a range of personal and environmental factors such as income, comfort, etc., a more heterogeneous formulation of travel time was beyond the scope of this research.

GC model specification

Based on the data introduced above, the three generalized cost models used in this study are as follows:

Equation 8: Pedestrian Generalized Cost Model

$$\mathrm{GC_{ped}} = \mathrm{VOT} \cdot t_{ij\,(ped)} = \mathrm{VOT} \cdot \frac{\text{Distance}}{\text{Speed}} = \frac{\$12}{\mathrm{h}} \cdot \frac{\text{Distance}}{5\ \mathrm{km/h}}$$

Equation 9: Transit Generalized Cost Model

$$\mathrm{GC_{trans}} = \left(\mathrm{VOT} \cdot t_{ij\,(trans)}\right) + \text{average fare} = (\$12/\mathrm{h} \cdot \mathrm{t}) + \$1.26$$

[21] 2006-2010 represents the time range of data sources used in this study

Equation 10: Auto Generalized Cost Model

$$\mathrm{GC_{auto}} = (\mathrm{VOT} \cdot \mathrm{t_{ij\,(auto)}}) + (\mathrm{C_{var}} \cdot \mathrm{d_{ij\,(auto)}}) + \mathrm{C_{fixed}} = (\$12/\mathrm{h} \cdot \mathrm{t}) + (\$0.125 \cdot \mathrm{d}) + \$7.97$$

where t_{ij} and d_{ij} represent travel time and travel distance from origin *i* to destination *j* respectively, and C_{var} and C_{fixed} are variable and fixed costs of travel respectively.

With the data described in this section, a generalized cost can be calculated for travel between all origins and destinations, for all three modes. The use of GC models in APA is described in the following section.

3.3 Generating Outputs and Representations

Having explored the analytic goals and data requirements of APA, this section provides a detailed explanation of what access profiles are and how they are generated.

3.3.1 Calculating Access Profiles

illustration

Consider a simple scenario with a single origin and seven destinations, as shown in Figure 14. Based on the data generated in Section 3.2, the generalized cost of travel from the origin to each destination is known (for simplicity, this scenario considers only one travel mode). The number of jobs at each destination is also known. If I define a set of GC intervals—$1 increments in this case—I can sum the number of jobs that can be reached at each GC interval. These data point can then be plotted on a graph, with GC on the horizontal axis and the number of jobs on the vertical axis, as shown in Figure 15. I refer to the line on this graph as an access profile.

Figure 14: Access Profile Scenario

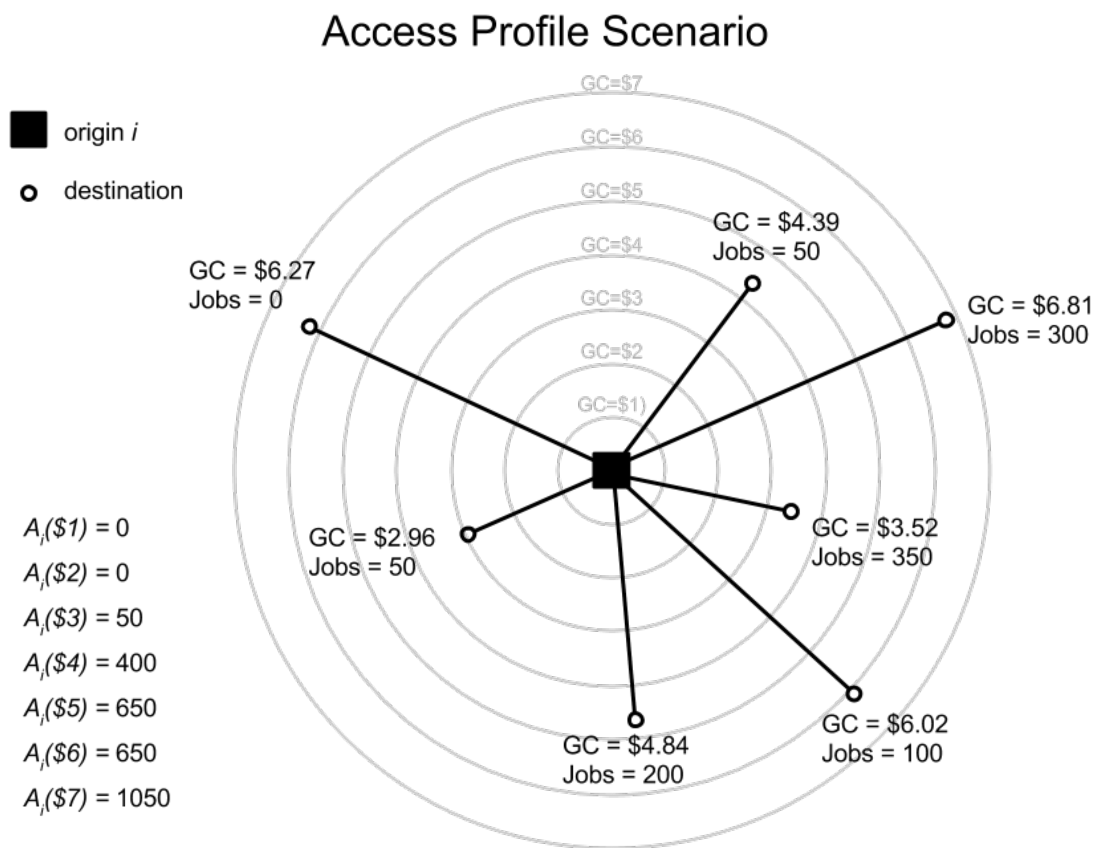
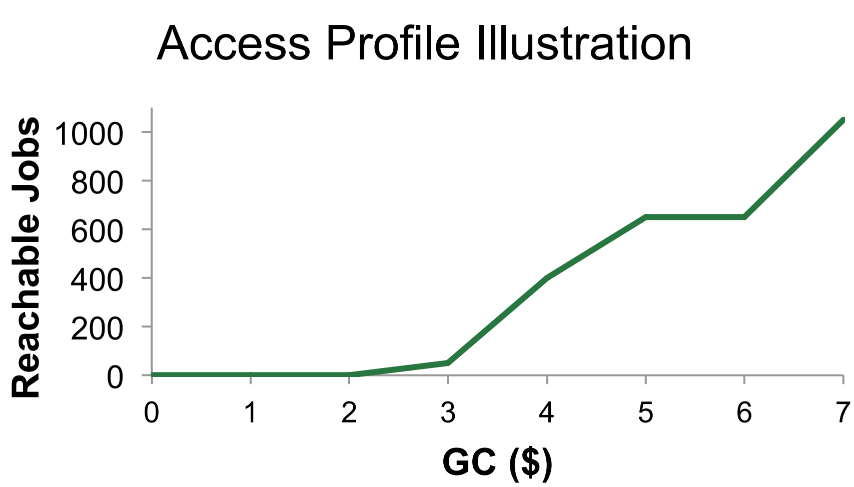


Figure 15: Access Profile Illustration



An access profile, therefore, is a graphical representation of accessibility, where the cumulative number of reachable destinations is modelled as a function of GC. The summation of a basic access profile is represented mathematically in Equation 11:

Equation 11: Access Profile for a Single Origin

$$A_i^x = \sum_{j=1}^{J} \text{jobs}_j\,;\ \forall\ j \text{ where } GC_{ij} \leq x$$

where A_i^x is the number of jobs located at all destinations *j* that can be reached from origin *i* without exceeding the GC interval *x*.

One of the consequences of aggregating jobs into destination zones is that access profiles may resemble step functions, with the number of reachable jobs increasing sharply between some intervals, and not at all between others. This is shown in Figure 15 where the number of reachable jobs increases significantly for GC intervals $3-$4, $4-$5, and $6-$7, but not for $5-$6, since there are no destination TAZs associated with a GC in the $5-$6 range.

calculation for a set of origins

Access profiles can be generated not only to represent specific origins, but also to represent average accessibility for multiple origins. When considering multiple origins it is important to distinguish between accessibility *at the average origin* and accessibility *for the average individual* at all origins. This distinction is particularly important for the case study used in this research, since the population of TAZs varies widely, with a number of TAZs having zero population (see Table 2). In order to avoid having uninhabited TAZs—which frequently have poor accessibility—skew the accessibility results, average access profiles must be weighted by origin population. This can be achieved by weighting the number of destination jobs for each OD pair based on origin population:

Equation 12: Population Weighting

$$\text{weighted jobs}_{ij} = \frac{\text{pop}_i}{\sum_{i=1}^{n} \text{pop}_i} \cdot \text{jobs}_j$$

where the weighted jobs at destination *j* for OD pair *ij* is proportional to the population of origin *i* divided by the total population of all *n* origins.

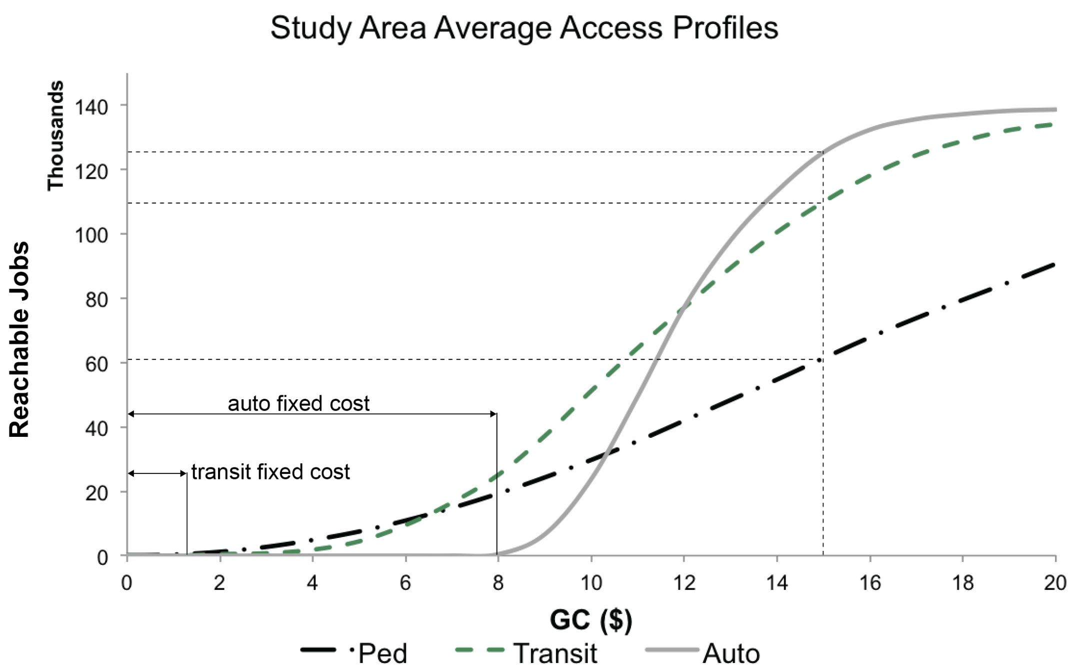
The population weighted average number of reachable jobs for origin *i* at GC *x* is then:

Equation 13: Population Weighted Average Access Profile

$$\overline{A}_i^x = \sum_{i=1}^{n} \sum_{j=1}^{J} \frac{\text{pop}_i}{\sum_{i=1}^{n} \text{pop}_i} \cdot \text{jobs}_j\,;\ \forall\ j \text{ where } GC_{ij} \leq x$$

Using the data outlined in Section 3.2, access profiles can be generated for any mode(s) and any origin(s) in the study area. Figure 16 shows pedestrian, transit, and auto access profiles representing the population weighted average accessibility of all TAZs. Each access profile is calculated based on $1 GC intervals.

Figure 16: Average Access Profiles for Pedestrian, Transit, and Auto Modes



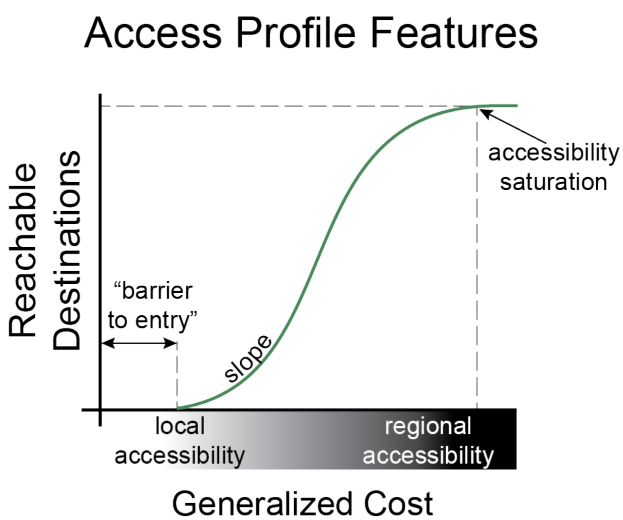
These access profiles show that at a GC of $15 for example, the average pedestrian in the study area can reach 61,403 jobs, the average transit user can reach 109,972 jobs, and the average auto user can reach 125,394 jobs. The interpretation of access profiles is explored further in the next subsection.

3.3.2 Access Profile Features

fixed costs and the "barrier to entry"

Several key access profile features are highlighted in Figure 17. The first feature to consider is the point along the GC axis where an access profile begins to rise and destinations first become reachable. This point indicates the minimum GC that is incurred to reach any destinations at all—a sort of "barrier to entry" for the mode in question. For an origin that is in close proximity to destinations, the barrier to entry is effectively the fixed monetary costs of travel—$0 for pedestrian travel, $1.27 for transit travel, and $7.97 for auto travel in this study. For an origin that is isolated from destinations, the barrier to entry will also include the travel time to reach the first destination. In urban contexts, therefore, the barrier to entry is typically lowest for pedestrian travel and highest for auto travel; in more suburban or rural contexts, the barrier to entry for auto travel may be more comparable or even lower than the barrier to entry for other modes, since it may take a particularly long time to reach destinations by pedestrian or transit modes in such cases.

Figure 17: Access Profile Features



access profile slope

Whereas the fixed cost component of GC—along with land use—determines *where* on the GC spectrum an access profile begins to increase, the variable cost component determines the *rate* at which it increases. The rate of increase, i.e. the slope of an access profile, represents the relative accessibility gain for a unit increase in GC. From the variable cost perspective, travel speed is the main determinant of slope. Travel speed indicates distance travelled per unit time, and since travel time is the most important variable component of GC,[22] travel speed also reflects distance travelled per unit GC. *If all other things are equal*, a greater travel distance per GC interval will also mean access to more destinations per GC interval, and thereby result in a steeper access profile slope. Not surprisingly, auto travel has the steepest slope, followed by transit travel, while pedestrian travel typically has the smallest slope, as shown in Figure

[22] Recall that travel time is the only variable cost component of GC for pedestrian and transit travel; therefore travel time and GC have a linear relationship for these modes. Although auto travel includes variable monetary costs, such as fuel, travel time is still the most important variable cost component.

16. The value of time (VOT) also influences access profile slope, with higher VOTs creating smaller slopes, and lower VOTs producing steeper slopes.

All other things are not always equal however. In addition to variable costs, land use also shapes the slope of an access profile. A higher density of destinations increases the slope of an access profile because each unit of travel time or distance provides access to more destinations than would be the case in a low density environment. Levine et al. (2012) point out that density and travel speed often exist in tension with each other, with higher density urban areas exhibiting lower travel speeds than less dense urban areas. The slope of an access profile therefore does not directly indicate density or travel speed; rather, it indicates how effectively these factors are balanced. A steeper slope indicates that the combined impact of speed and density is supportive of accessibility, whereas a small slope indicates either very low density or very low travel speed, or both.

local and regional accessibility

Access profiles also reveal information about both regional and local accessibility. At the lower end of the GC spectrum, the shape of an access profile indicates how many destinations can be reached in a short amount of time with low monetary costs. Local accessibility favours pedestrian and transit travel, since the high fixed costs of auto use prevent auto travel from being competitive at the low end of the GC spectrum. At the upper end of the GC spectrum, the shape of an access profile indicates the level of accessibility to regional destinations. The shape of an access profile at this end of the GC spectrum is only relevant to those individuals who are willing and able to incur the high travel costs associated with regional travel.

accessibility saturation

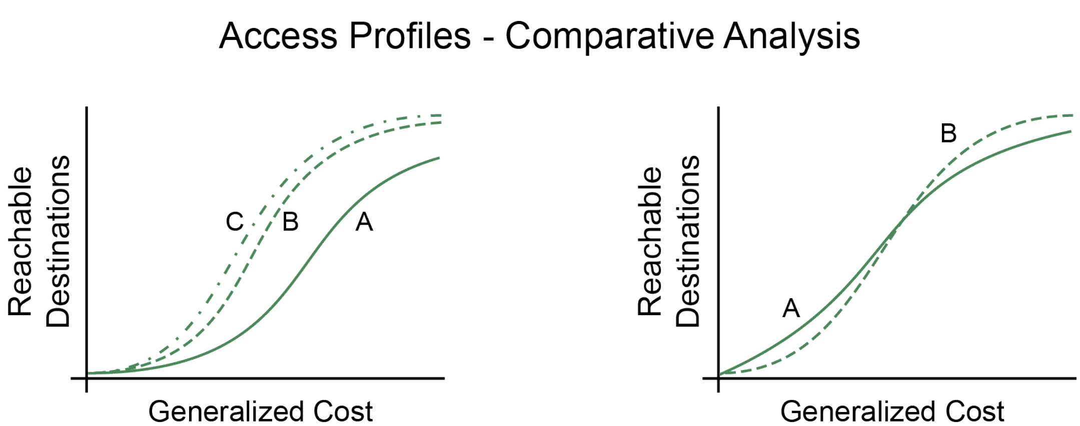
The upper end of the GC spectrum also indicates “accessibility saturation,” the point along the GC spectrum where all jobs can be reached (see Figure 17). Accessibility saturation only occurs in a closed system, where the number of potential destinations is finite. In this study, auto is typically the first mode to achieve accessibility saturation, though in some cases transit may reach saturation at an even lower GC. Virtually all TAZs reach auto accessibility saturation by GC=$20, and most TAZs achieve transit accessibility saturation at this point as well, which is why $20 is used as the upper GC limit on most of the diagrams in this thesis.

3.3.3 Access Profile Analysis (APA)

comparative analysis

Access profiles can be used for various kinds of analysis. The basic principle of APA is that the greater the magnitude of destinations that can be reached at any given GC interval, the better the accessibility is at that origin. In the left diagram in Figure 18, the best accessibility is achieved by access profile *C*; the accessibility of access profile *B* is almost as good as access profile *C*, whereas access profile *A* has much poorer accessibility. Comparison may, in some cases, be more complicated, as seen in the right diagram in Figure 18, where access profile *A* has better local accessibility, while access profile *B* has better regional accessibility. Specific analytic goals must be defined in order to determine whether access profile *A* or access profile *B* offers better accessibility in any given context.

Figure 18: Comparative Analysis



policy scenario analysis

APA can be applied to policy scenarios by modelling how a scenario would change one or more accessibility components. In the left diagram in Figure 18 for example, access profile *A* could represent a hypothetical base case. Access profiles *B* and *C* could represent accessibility outcomes resulting from planned accessibility interventions (e.g. a new bridge, a rapid transit line, or the intensification of land uses). In this case, APA indicates that intervention *C* is more effective at increasing accessibility than intervention *B*. This information can be used alongside other project criteria such as cost, to evaluate the merits of competing proposals. The first three applications in this study analyze policy scenarios and *ex post* policy implementations to understand how various interventions affect accessibility.

spatial analysis Spatial APA involves comparing access profiles for multiple destinations. For a small number of origins (5-10), access profiles can be visually interpreted on a graph with relative ease. As the number of origins increases, however, it becomes increasingly difficult to identify individual access profiles on a graph, and patterns become lost as the graph becomes overcrowded. A graph showing the unique access profile for all origins in this case study would be completely illegible. Access profiles also fail to show the spatial relationship between origins. Therefore, while access profiles are useful for evaluating either a few individual origins or a few aggregated sets of origins, a different approach must be taken for disaggregate spatial analysis.

API calculation There are two basic ways of deriving an indicator value from an access profile. The first option is to measure the distance from the vertical (i.e. destination) axis to the access profile at regular intervals. This approach indicates the overall cost of accessibility. To illustrate how this works, consider a theoretical scenario of perfect accessibility where all destinations can be reached at GC=0. The GC associated with each destination interval, the average of these intervals, and the total of these intervals would all equal zero. In a theoretical *no accessibility* scenario, the GC associated with each destination interval, and the average of these, would be equivalent to the upper GC bound. The total sum of these intervals would be equal to the product of the upper GC bound and the number of intervals used for calculation. In any scenario between no accessibility and perfect accessibility, the average GC calculated from all the destination intervals would indicate the average GC of destination access. A lower value of this indicator corresponds to better accessibility. I develop an indicator that is similar to this approach to measure modal redundancy in Section 4.4.

The second approach is to measure the distance from the horizontal (i.e. GC) axis to the access profile at regular intervals. This approach indicates the overall level of destination access. In a perfect accessibility scenario, the destination access associated with each GC interval, and the average of these, would equal either 1 (if destinations are measured proportionately) or the total number of destinations contained in the scenario (if destinations are measured absolutely). The sum total of these intervals would either equal the number of intervals or the product of the number of intervals and the total number of jobs, respectively. In a *no accessibility* scenario, each interval, and therefore their total and average, would equal zero. In any scenario between no accessibility and perfect accessibility, the average of these intervals indicates average destination access; a higher value indicates better accessibility.

I use the second approach to develop an indicator of accessibility in this research, which I refer to as the API (Access Profile Indicator). The indicator is based on average destination access calculated at $1 GC intervals. To provide a normalized scale, I measure destination access proportionately (i.e. total study area jobs = 1). The calculation of API is given in Equation 14:

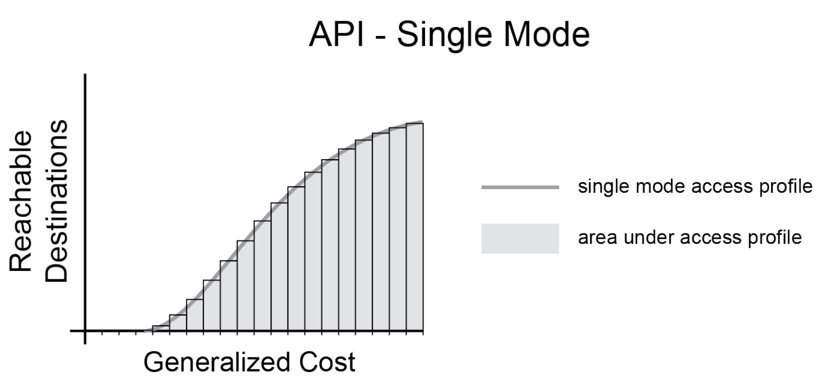
Equation 14: API Formulation

$$\mathrm{API_i} = \frac{\sum_{\mathrm{GC}=1}^{20} \frac{\text{accessible jobs}_{\mathrm{GC}}^{\mathrm{i}}}{\text{total jobs}}}{20}$$

where *API_i* is the Access Profile Indicator for origin *i.*

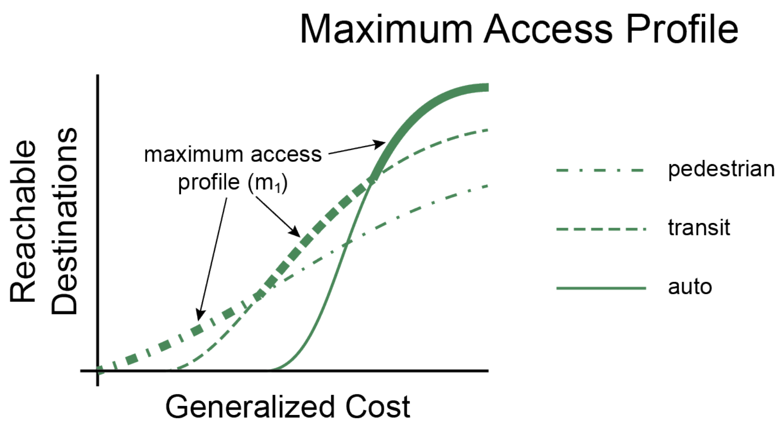
Figure 19 shows a simple access profile, with a bar representing the number of reachable jobs at each GC interval. Allowing the size of the interval to go to zero would produce the mathematical integral of the accessibility function, indicating the exact area under the curve. In the interest of simplicity, I chose to use the approach shown in Equation 14, which provides sufficient precision for this context.

Figure 19: API Single Mode



To reflect the combined level of accessibility provided by multiple modes, I calculated a variation of the API, based on the maximum access profile. The maximum access profile indicates the highest level of accessibility that can be achieved with any mode at any given GC interval, as shown in Figure 20. I refer to the API based on the maximum access profile as $\mathrm{API_{max}}$.

Figure 20: Maximum Access Profiles and API_{max}



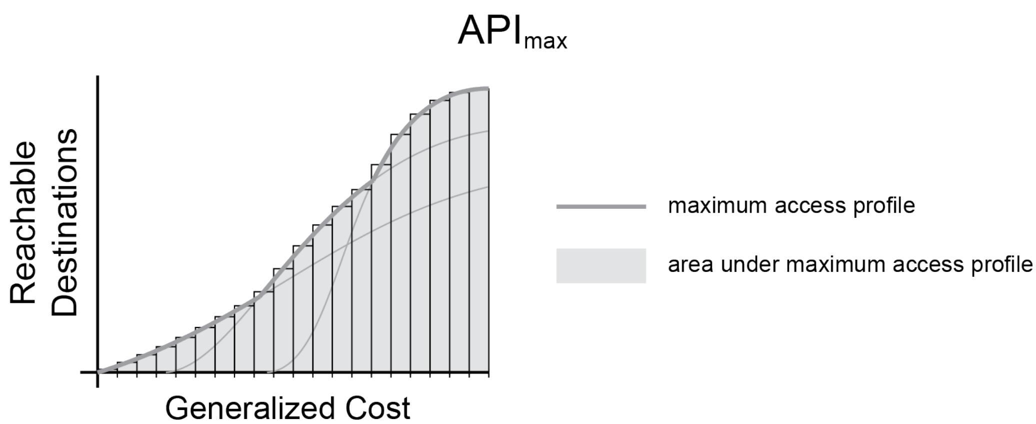
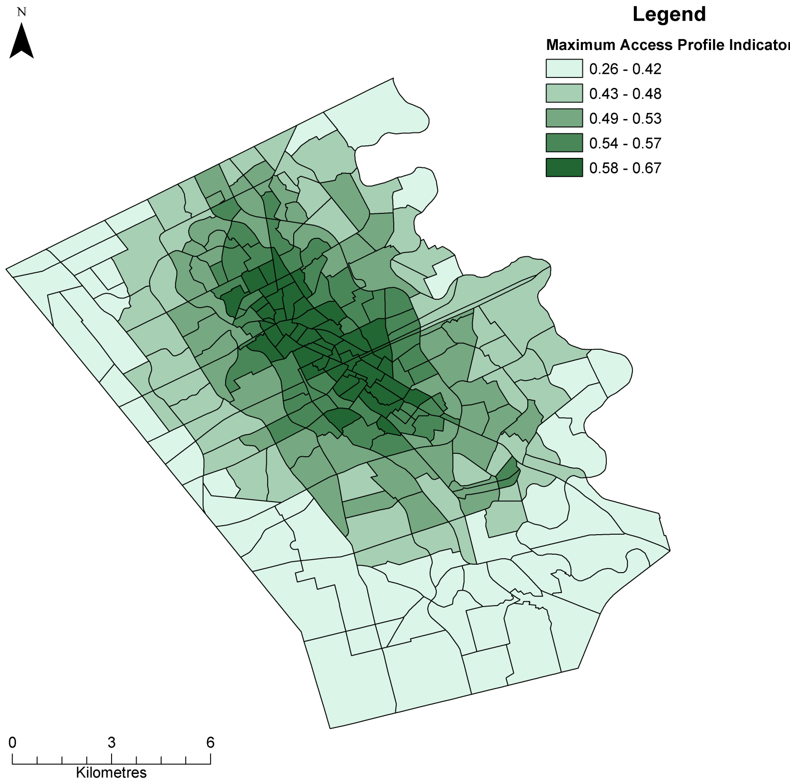


Figure 21 shows a map of API_{max} across the study area. The values of API_{max} range from 0.26 to 0.67, suggesting that in the least accessible TAZ, 26% of study area jobs can be reached at the average GC interval, whereas 67% of jobs can be reached at the average GC interval in the most accessible TAZ. More accessible TAZs appear to be located near the downtown areas, while less accessible TAZs are located near the study area periphery. Applications 4-6 in this study use APIs and related measures to represent the spatial variation of accessibility across the study area.

Figure 21: Maximum Access Profile Indicator Map



3.3.4 Comparison with Black and Conroy

As mentioned in Chapters 1 and 2, the APA methodology outlined in this chapter shares similarities with previous research by Black and Conroy (1977). First, the basic underlying principle—graphically representing accessibility as a function of travel effort—is common among both studies (a replication of an "access profile" graph from Black and Conroy (1977) can be found in Appendix B). Second, Black and Conroy (1977) develop an indicator based on the area below an access profile, similar to the API. Finally, Black and Conroy also suggest that their approach can be used for the evaluation of transportation and land use plans.

While much of the conceptual approach is similar, there are several aspects in which this study differs from the study by Black and Conroy (1977). First, Black and Conroy (1977) model travel effort simply as travel time, whereas travel effort is modelled more comprehensively as GC for APA. This is a particularly relevant distinction for social equity analysis, where monetary travel costs can be a significant barrier to accessibility. Second, Black and Conroy (1977) only consider transit and auto modes, whereas APA is operationalized for transit, auto, and pedestrian modes, providing a more comprehensive understanding of local accessibility. Third, Black and Conroy (1977) only generate access profiles for a small number of specifically selected TAZs. In this study, both individual TAZ access profiles and aggregate average access profiles for groups of TAZs are generated, which means that APA can be applied on a much broader scale beyond just a few specific origins of interest. Fourth, in this study APA is operationalized to examine six policy relevant questions, only two of which—the evaluation of transportation plans and the evaluation of land use plans—are mentioned by Black and Conroy (1977). The applications of APA related to monetary transportation costs, modal redundancy, housing costs, and low income are therefore unique to this research.

Finally, I believe that APA is a much more powerful tool today than it would have been in the 1970s. The rise of open data, the emergence of common data formats such as the generalized transit feed specification (GTFS) format, the prevalence of powerful GIS software, and the general advances in computational capability that have occurred since the 1970s have made it much easier to implement APA and operationalize detailed scenarios. As discussed in Chapter 6, recognition of transportation-land use interactions has also increased since the 1970s, suggesting that there is greater interest in accessibility—and a greater need for accessibility tools—among planners today. It seems timely, therefore, to revisit and expand the concepts that Black and Conroy (1977) presented almost four decades ago, and demonstrate their potential in a contemporary context.

3.4 Methodological Framework Summary

In this chapter, I have developed a methodological framework to illustrate the basic concept of APA, which is summarized in Table 5. The methodological framework is divided into analytic goals, data, and outputs. In this chapter the analytic goals and subsequent outputs have been broad, and no attempts to answer specific policy related questions have been made. In Chapter 4, the methodological framework is used as a foundation and a template for operationalizing the six applications introduced in Chapter 1. This entails more focussed analytic goals, dataset modifications, and outputs tailored to the respective application. A modified version of Table 5 is developed for each application to show how the methodological framework is adapted in each case. The results for each application are then presented in Chapter 5.

Table 5: Methodological Framework

	Component / Type		*Description, Value, Source*
Analytic Goals	Multi-modal accessibility inventory		Understand the average accessibility of each mode for the entire study area
	Disaggregate, multi-modal spatial analysis		Illustrate variation in overall accessibility across study area
Data	Origins	Locations	TAZ centroids; n=270 (Data Management Group, 2006c)
		Attributes	TAZ population (Data Management Group, 2006c)
	Destinations	Locations	Pedestrian travel: parcels; n=3,192 (MPAC, 2013) Transit/Auto travel: TAZs; n=270 (Data Management Group, 2006c)
		Magnitude	Pedestrian travel: n=137,811 (Data Management Group, 2006c; MPAC, 2013) Transit/Auto travel: n=138,797 (Data Management Group, 2006c)
	Travel time	Pedestrian	Network Dataset (Region of Waterloo, 2011b) Travel speed: 5.0km/h Measurement: TAZ centroid - GC interval
		Transit	Network dataset constructed with ATT and 2010 GTFS data (Region of Waterloo, 2010) Measurement: TAZ centroid - TAZ centroid
		Auto	PM peak period travel time matrix (Region of Waterloo, 2011a)
	Travel cost	Value of time	$12.00/hr
		Pedestrian	No costs
		Transit	Fixed: $1.26 (Canadian Urban Transit Association, 2007)
		Auto	Variable: 12.5¢/km (Canadian Automobile Association, 2007) Fixed: $7,080/year (Canadian Automobile Association, 2007); $7.97/trip based on 2.43 trips/day (Data Management Group, 2006b)
Outputs	Aggregate access profiles		Generates one profile per mode based on the average of all origins
	API_{max} map		Generates and maps the API_{max} for each individual TAZ

Chapter 4:

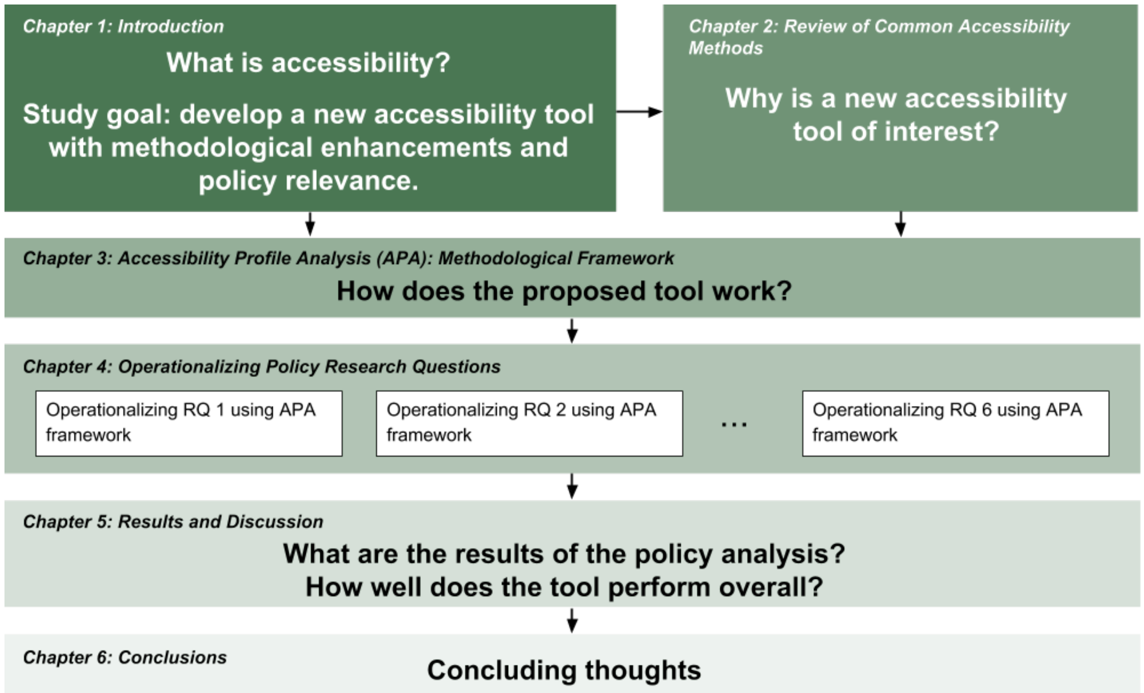
Operationalizing Policy Applications

chapter abstract This chapter adapts the APA methodological framework introduced in Chapter 3 to each of the six policy applications outlined in Chapter 1. Applications 1-3 evaluate specific policies to understand aggregate accessibility implications either for the study area as a whole or for a defined subset of traffic analysis zones (TAZs). This is achieved by modifying input data such as travel times, travel costs, or land uses to reflect either policy scenarios or *ex post* policy outcomes. Applications 4-6 focus on disaggregate distributions of accessibility. The disaggregate nature of these applications means that access profile indicators (APIs) and related measures are used to evaluate each TAZ individually.

4.1 Application #1: Transportation Investment

analytic goals In this application I used APA to evaluate the accessibility implications of transportation investments. To operationalize this application, I compared 2010 and 2013 Grand River Transit (GRT) GTFS schedule data to model how investments in better bus service affected accessibility. Between 2010 and 2013, GRT implemented several bus service improvements, most notably introducing two new express bus routes. These routes are a limited stop service operating in mixed traffic, through largely suburban areas. The analytic goal for this application is therefore to evaluate the extent and distribution of accessibility benefits that resulted from this investment.

Figure 22: Chapter 4 in Context



data Operationalizing this application required two extensions to the standard dataset. First, in addition to the 2010 transit travel time matrix, I needed a 2013 travel time matrix. I generated a 2013 transit travel time matrix by applying the same approach (using the ATT) to the 2013 GTFS dataset (Region of Waterloo, 2013b) that I had applied earlier to the 2010 GTFS dataset (see Section 3.2.4.1).

In order to evaluate how the accessibility impacts of the bus service improvements were distributed, I sorted TAZs into two categories based on their proximity to one of the two new express bus routes. To make this distinction, I created a 600 metre service area (i.e. buffer based on network travel) around each of the express bus route stops in ArcGIS. If more than 50% of the area of a TAZ overlapped with the express bus stop service areas, I categorized the TAZ as a *corridor TAZ*; if less than 50% of the area overlapped with the express stop area, I categorized the TAZ as a *non-corridor TAZ.*

outputs I generated the following four aggregated transit access profiles for this application: 2010 corridor TAZs; 2010 non-corridor TAZs; 2013 corridor TAZs; 2013 non-corridor TAZs.

The methodological framework for this application is summarized in Table 6; results are presented in Chapter 5.

Table 6: Application #1 - Methodological Framework

	Component / Type		Description, Value, Source
Analytic Goals	Policy analysis		**Did 2010-2013 transit investments improve accessibility? By how much? Where?**
Data	Origins	Locations	**Non Corridor: n=243 (TAZ centroids)** **Corridor: n=27 (TAZ centroids)**
		Attributes	Standard
	Destinations	Locations	Standard
		Magnitude	Standard
	Travel time	Pedestrian	N/A
		Transit	**2010 / 2013: Network dataset constructed with ATT and 2010 / 2013 GTFS data** (Region of Waterloo, 2010, 2013b)
		Auto	N/A
	Travel cost	Value of time	Standard
		Pedestrian	N/A
		Transit	Standard
		Auto	N/A
Outputs	Aggregate access profiles		**Four transit access profiles: 2010 corridor / non-corridor; 2013 corridor / non-corridor**

4.2 Application #2: Transportation Taxes and User Fees

analytic goals

For this application, I developed a fuel tax scenario to explore how transportation taxes and user fees affect accessibility. To provide a clear indication of accessibility impacts, I chose to double the fuel cost component of auto travel. As outlined in the introduction, a fuel tax could affect accessibility in a number of ways. In this analysis, only the direct impact of higher travel costs is considered; indirect impacts related to transportation investments enabled by the additional fuel tax revenue and behaviour changes resulting from the higher travel costs are not considered here due to lack of data.[23] The analytic goals of this application are to (a) determine how a fuel tax would affect the generalized cost of travel, and subsequently affect accessibility, and (b) compare the accessibility impacts for high and low income TAZs.

data

I operationalized the higher fuel tax by increasing the variable monetary costs of auto travel. According to the CAA, fuel accounts for 8.3¢ of the 12.5¢/km variable cost of auto travel (2007). For the higher fuel tax scenario I doubled this 16.6¢/km, making the total variable cost of auto travel 20.8¢/km. Based on this revised GC model, I calculated a new auto GC for each OD pair.

To compare the differential impacts of an increased fuel tax at both ends of the income spectrum, I divided TAZs into average income quintiles. Since average income is not included in the TTS, I used census income data (Geographic Research, Inc., 2006), at Dissemination Area (DA) resolution. DAs were the finest resolution available for the data, and are comparable in size to TAZs. While the approximate size of DAs and TAZs is comparable, they do not share common geographic boundaries however. To generate average income data for TAZs, I translated the income data from DA spatial units to TAZ spatial units using the following method in ArcGIS.

First, I intersected DAs with TAZs so that each spatial unit was associated with only one TAZ and only one DA $(\mathrm{Area_z} \cap \mathrm{Area_d})$. I then divided the area of each intersected spatial unit by the area of the associated DA, *Area*$_d$. Next, I multiplied this quotient by the total income of the DA, *Total Income*$_d$. The sum of total incomes for all intersected units *D* associated with TAZ *z*, yields the total income of TAZ *z*, as shown in Equation 15:

Equation 15: Geographic Unit Conversion - Step #1

$$\text{Total Income}_\mathrm{z} = \sum_{\mathrm{d}=1}^{\mathrm{D}} \frac{\mathrm{Area_z} \cap \mathrm{Area_d}}{\mathrm{Area_d}} \cdot \text{Total Income}_\mathrm{d}$$

[23] These impacts could be modelled in APA, but would require a more comprehensive scenario that would include (a) specific transportation investments and (b) travel time matrices that reflected these investments and any travel behaviour changes caused by the fuel tax increase itself.

I applied the same equation to translate the number of households from DA units to TAZ units, by substituting total income with total number of households. The calculation of average after-tax household income for TAZ *z* is shown in Equation 16:

Equation 16: Geographic Unit Conversion - Step #2

$$\text{Average Household Income}_z = \frac{\text{Total Income}_z}{\text{Total Number of Households}_z}$$

This method results in a 1:1 translation of data, where each dollar of income and each household in the Census data is included exactly once in the resulting TAZ data. After calculating the average household income for each TAZ, I ranked TAZs by income and categorized them into income quintiles.

outputs

I generated a total of eight average access profiles: a base case access profile for pedestrian, transit, and auto modes, and an auto access profile for the increased fuel cost scenario; these four access profiles were generated for both the highest and lowest income quintiles.

Table 7: Application #2 - Methodological Framework

	Component / Type		Description, Value, Source
Analytic Goals	Policy scenario analysis		**What impact would higher fuel costs have on high and low income TAZs?**
Data	Origins	Locations	**Lowest income quintile: n=54 (TAZ centroids)** **Highest income quintile: n=54 (TAZ centroids)**
		Attributes	**Average after-tax household income** (Geographic Research, Inc., 2006)
	Destinations	Locations	Standard
		Magnitude	Standard
	Travel time	Pedestrian	Standard
		Transit	Standard
		Auto	Standard
	Travel cost	Value of time	Standard
		Pedestrian	Standard
		Transit	Standard
		Auto	Increased fuel cost scenario: **Variable: 20.8¢/km** Fixed: Standard ($7.97/trip)
Outputs	Aggregate access profiles		**8 access profiles: base case (all modes) and higher fuel cost scenario (auto); highest and lowest income quintiles**

4.3 Application #3: Land Use

analytic goals

For this application I developed two contrasting land use scenarios and compared their accessibility impacts. The first scenario reflects intensification policies that prioritize urban employment growth. In this scenario, I increased the number of jobs in a downtown Kitchener TAZ where a future innovation district is planned. The second scenario reflects suburban development policies that do not restrict greenfield development. In this scenario, I added jobs to an undeveloped TAZ at the urban periphery.[24] The analytic goal in this case is to determine whether these scenarios have significantly different impacts on accessibility.

Figure 23: Land Use Scenario TAZs

data I operationalized these scenarios by adding new 10,000 jobs to the respective destination TAZ in each scenario. I chose 10,000 because (a) one TAZ could reasonably contain 10,000 jobs[25], and (b) the addition of 10,000 jobs would constitute a 7.2% growth in employment in the study area, an increase large enough to be readily measured in APA, yet not so large that it would be implausible for the study area. The respective TAZ locations are shown in Figure 23.

outputs I generated a total of nine aggregate access profiles to represent the three travel modes for each of the two scenarios and for the base case. These access profiles represent average accessibility from all origins to all destinations, including the respective modified

[24] Interestingly, both scenario TAZs have already experienced development since the data used in this study were generated.
[25] The TAZ with the highest employment in the study area, which incidentally is located in downtown Kitchener near the urban scenario TAZ, contains 7,437 jobs.

destinations. Since both scenarios increase the total number of destinations from 138,797 to 148,797, accessibility will also increase in both scenarios, relative to the base case. Comparing these access profiles will indicate how effectively each scenario increases accessibility for each mode.

Table 8: Application #3 - Methodological Framework

	Component / Type		*Description, Value, Source*
Analytic Goals	Policy scenario analysis		**What are the differential accessibility impacts of urban and suburban employment growth scenarios?**
Data	Origins	Locations	Standard
		Attributes	Standard
	Destinations	Locations	Standard
		Magnitude	**10,000 jobs added to TAZ 151 (urban scenario) and TAZ 242 (suburban scenario)**
	Travel time	Pedestrian	Standard
		Transit	Standard
		Auto	Standard
	Travel cost	Value of time	Standard
		Pedestrian	Standard
		Transit	Standard
		Auto	Standard
Outputs	Aggregate access profiles		**9 access profiles: two scenarios and base case (all modes)**

4.4 Application #4: Modal Redundancy

context – what is modal redundancy?

Redundancy is a common network concept that refers to the number of possible routes connecting an origin to a destination and the relative effectiveness of these routes (Jansuwan, Chen, Xu, & Yang, 2013; Immers, Yperman, Stada, & Bleukx, 2004). *Modal* redundancy is defined here as the number of *modes* that connect an origin to a destination, and the relative effectiveness of these modes. For example, an origin where the ease of reaching destinations is similar for multiple modes has high modal redundancy. Conversely, an origin where the ease of reaching destinations varies widely between modes has low modal redundancy.

While there are some TAZs where transit provides better accessibility than other modes, the greatest modal disparities in the study area occur in TAZs with poor transit and pedestrian accessibility. In these cases, accessibility is much higher for auto than it is for other modes, implying a degree of auto dependency. Both the lack of modal redundancy in general, and auto dependency in particular, have important social and economic implications, which are discussed below.

context – why does modal redundancy matter?

The freedom to choose one's travel mode is an important socio-economic aspect of modal redundancy because not everybody *wants* to drive. The propensity for auto travel among younger adults, for example, is declining (Delbosc & Currie, 2013; Goodwin & Van Dender, 2013). Similarly, the desire to live in walkable neighbourhoods, where auto travel is not required for all trips, appears to be shared not only by those living in walkable neighbourhoods, but also by a significant portion of those living in auto dominated neighbourhoods as well (Toronto Public Health, 2012). Modal redundancy provides choice for individuals with varying travel preferences.

Social equity is another important aspect of modal redundancy because not everybody is *able* to drive. If accessibility is a fundamental aspect of society (see Section 1.1), it is important that it be available to all members of society. While some barriers exist with regard to pedestrian and transit travel, the barriers associated with auto travel are much more restrictive. In order to travel by auto, an individual must be of a certain age, satisfy a range of health and physical ability requirements, possess a valid drivers licence, and have sufficient financial resources to own and operate an auto. In environments that are prone to auto dependency, modal redundancy provides an indication of the accessibility gap between those who are able to drive and those who are not able to drive.

Reliability is another aspect of modal redundancy. All modes are subject to various disruptions that can compromise an individual's ability to reach a destination. While certain disruptions, such as inclement weather, may affect all modes simultaneously, many other disruptions, such as traffic congestion or a transit strike, primarily affect only one mode. In these cases, modal redundancy allows individuals to travel with an alternate mode and avoid the disruption. A lack of modal redundancy, by contrast, would make individuals more vulnerable to potentially unpredictable disruptions. Consequences of this include a greater risk of not reaching a destination at the required time and / or individuals routinely increasing the amount of contingency or buffer time in their travel plans.

Modal redundancy also has broad implications for quality of life and the urban environment. Transportation systems that are heavily dominated by auto travel are associated with a variety of negative outcomes such as traffic congestion, environmental pollution, higher infrastructure costs etc. These outcomes ultimately reduce the livability of regions that are auto-dependent and lack modal redundancy (Vuchic, 1999).

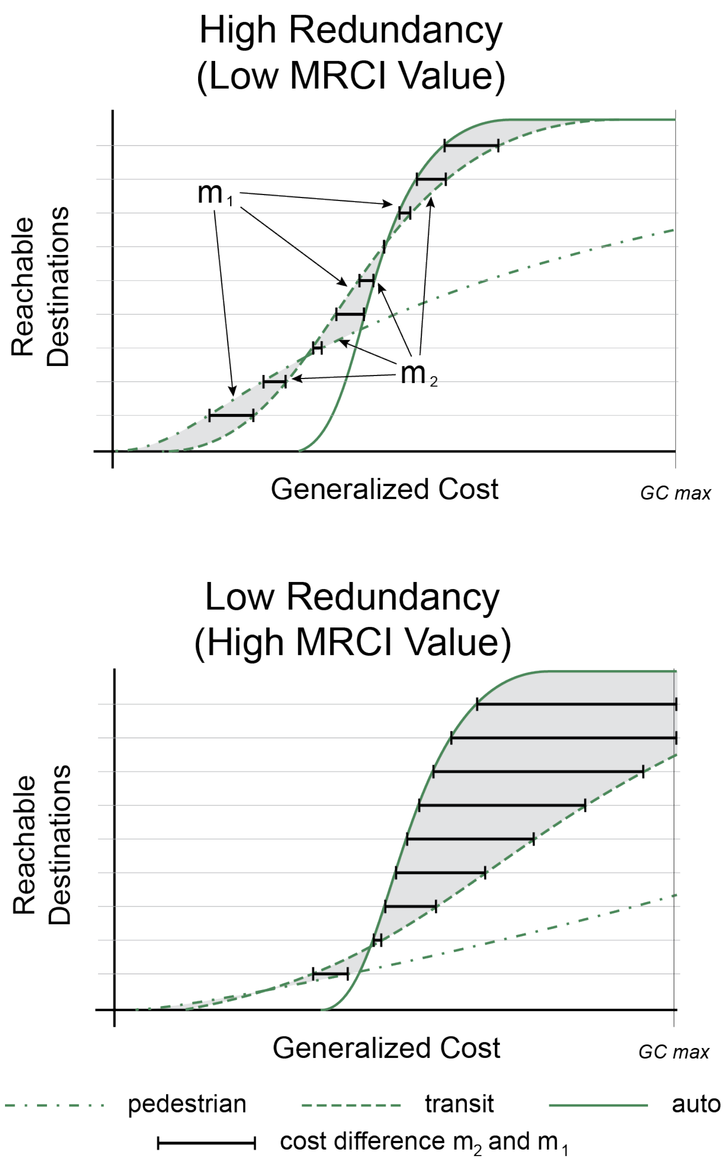
analytic goals This application aims to measure modal redundancy at the TAZ level. The specific analytic goals are to (a) gauge whether a policy response is necessary to address low modal redundancy, (b) develop the foundation for such a policy response, if it is necessary, and (c) establish a baseline to monitor the evolution of modal redundancy over time. Since there are no established ways of measuring modal redundancy, a further aim is to identify a meaningful metric of modal redundancy.

data No additional data are needed to estimate TAZ modal redundancy.

outputs To analyze modal redundancy I developed a measure that I refer to as the modal redundancy cost indicator (MRCI). The MRCI is similar to the API, but differs in two important ways. First, whereas the API reflects the *magnitude* of an access profile (i.e. how many jobs can be reached), the MRCI measures the *difference* between two access profiles. Any two access profiles can be used to calculate an MRCI value. To measure modal redundancy based on three modes, I measured the difference between the maximum access profile, and the secondary access profile. Recall that the maximum access profile *(*m_1*)* refers to the access profile of the mode that reaches the highest number of destinations at any given GC. The secondary access profile *(*m_2*)* therefore refers to the access profile of the mode that reaches the second greatest number of destinations at any given GC, as shown in Figure 24. The MRCI essentially represents the accessibility disparity between modes—a high MRCI value indicates *low* redundancy, while a low MRCI value indicates *high* redundancy

The other distinction between the MRCI and the API involves the unit of measurement. The API is expressed as the average percentage of jobs that are reachable across the GC spectrum. While the MRCI could also be expressed as percentage of jobs, it is expressed here as the average delta GC between m_2 and m_1. The MRCI therefore indicates the additional GC that would be incurred for travel with the second most GC effective mode (m_2) in comparison to the GC incurred for travel with the most effective mode (m_1). Using GC as the measurement unit conveys the concept of modal redundancy in very concrete terms that are easily communicated and interpreted.

Figure 24: Modal Redundancy Cost Indicator



Since the MRCI is measured in GC units, regular job intervals must be established to measure the delta GC between m_2 and m_1. For this analysis, intervals of 10% of the total number of study area jobs are used. As noted earlier, if the job intervals were allowed to go to zero, the MRCI would represent the difference between the integrals for m_1 and m_2.

In the interest of simplicity, I used the 10% intervals, which provide a reasonable degree of precision for this context. In cases where some jobs are reachable with only one mode—i.e. significant auto dependency—an upper GC threshold (*GC max*) may be necessary in order to establish an m_2 value for upper job intervals. The calculation of the MRCI is illustrated visually in Figure 24 with examples of high and low modal redundancy. The MRCI is defined mathematically in Equation 17:

Equation 17: Modal Redundancy Cost Indicator

$$\text{Modal Redundancy Cost Indicator (MRCI)} = \sum_{x}^{n} \frac{GC_x^{m_2} - GC_x^{m_1}}{N}$$

where *x* is one of *N* job intervals.

The primary output for this application is a map of the MRCI for each TAZ in the study area.

Table 9: Application #4 - Methodological Framework

	Component / Type		*Description, Value, Source*
Analytic Goals	Socio-economic outcome analysis		**How much modal redundancy is there across the entire transportation network? How is modal redundancy distributed?**
Data	Origins	Locations	Standard
		Attributes	Standard
	Destinations	Locations	Standard
		Magnitude	Standard
	Travel time	Pedestrian	Standard
		Transit	Standard
		Auto	Standard
	Travel cost	Value of time	Standard
		Pedestrian	Standard
		Transit	Standard
		Auto	Standard
Outputs	Disaggregate modal redundancy cost indicator (MRCI) analysis		**Map of MRCI scores**

4.5 Application #5: Accessibility and Housing Costs

context – why do housing costs matter?

In this application, I explore whether housing costs are likely to restrict accessibility for low income households. Housing costs are typically influenced by a number of variables related to the dwelling and its location, including job accessibility. If accessibility is strongly correlated with housing costs across an urban area, the location choice of low income households may be restricted to comparatively inaccessible locations. Section 4.6 explores the issue further by focusing specifically on the relationship between income and accessibility.

context – when are housing costs relevant?

A strong correlation between housing costs and accessibility is most likely to occur when the demand for access to a major employment centre is high, and the supply of accessible housing is relatively low. To the extent that housing costs are related to accessibility, they are an indication of how much competition exists for origin locations. While *destination* competition effects are frequently discussed in the accessibility literature (see Chapter 2), the notion of *origin* competition effects represented by housing costs is only beginning to be explored in the literature (see for example Center for Housing Policy & Center for Neighborhood Technology, 2012).

context – housing cost implications for accessibility

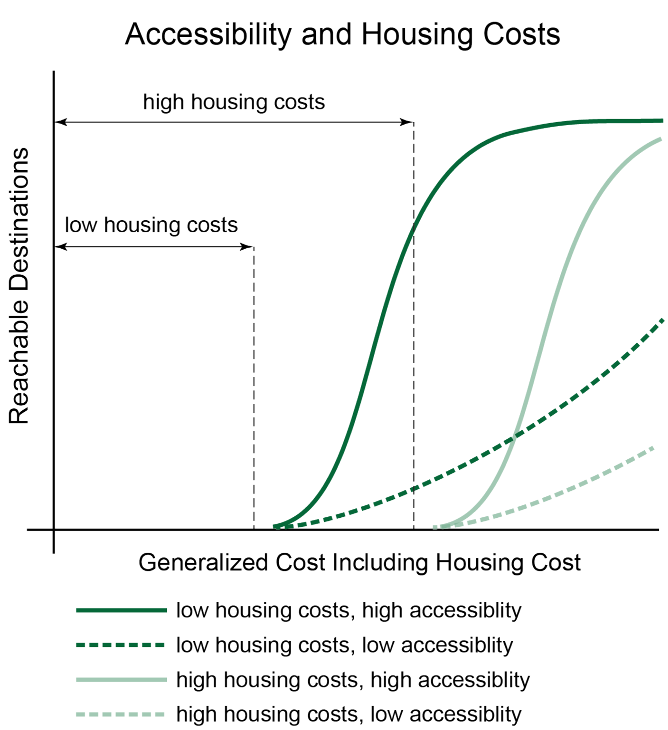
Since housing costs can be influenced by accessibility, and can also restrict the accessibility of low income households, they form an important part of the overall accessibility picture. Simply put, one cannot fairly compare differences in job accessibility in Manhattan and rural Manitoba, for example, without comparing the differences in housing costs. Wherever accessibility and housing costs are related, the ease of reaching destinations cannot be divorced from the ease (i.e. cost) of residing at the respective origin location. An understanding of the relationship between accessibility and housing costs is therefore essential, and where a strong relationship exists, housing costs should be integrated into an accessibility measure.

analytic goals

The analytic goal of this application is to evaluate the relationship between housing cost and accessibility. From a policy perspective, the analytic goal is to determine what kind of policy response, if any, may be warranted to address housing costs in accessible neighbourhoods.

data To evaluate housing costs, I used data from the Statistics Canada Household Expenditure Survey (Geographic Research, Inc., 2010). The variable that I used to represent housing costs was average household expenditure on the household's primary residence. These data were available at the Dissemination Area scale, and were translated to TAZ units using the method described for income data in Section 4.2. In the interpretation of these data, a distinction should be drawn between housing cost and housing affordability. While housing expenditure data is a reasonable indicator of housing cost, it is not, on its own, an adequate indicator of housing affordability. Typically, housing affordability is calculated as a percentage of income that is spent on housing, with housing costing more than 30% or 50% of household income typically considered to be unaffordable (e.g. Moore & Skaburskis, 2004; Skaburskis, 2004). Other conditions, such as housing tenure, and total household income are also frequently used to further define housing affordability (Moore & Skaburskis, 2004; Skaburskis, 2004). A rigorous analysis of housing affordability was beyond the scope of this research. The analysis in this application therefore provides an indication of how housing costs relate to accessibility patterns, and does not indicate the affordability of housing for any specific socio-economic groups.

Figure 25: Accessibility and Housing Costs



outputs I generated two kinds of outputs for this analysis. First, I produced maps of both housing costs and accessibility (based on API_{max}) and visually compared them to observe spatial patterns. Second, I adapted access profiles to include housing costs. I achieved this by scaling per trip generalized travel costs to annual costs using the average trip generation rate discussed in Section 3.2.4.2. Annual housing expenditures were then added as fixed costs to access profiles. Figure 25 illustrates conceptually how housing costs can be incorporated into access profiles. To compare the accessibility of TAZs with low housing costs to the accessibility of other TAZs, I divided TAZs into quintiles based on average housing expenditure. I then generated and compared the access profiles of the lowest housing cost quintile with the average access profiles of all other TAZs (the average of quintiles 2-5).

Table 10: Application #5 - Methodological Framework

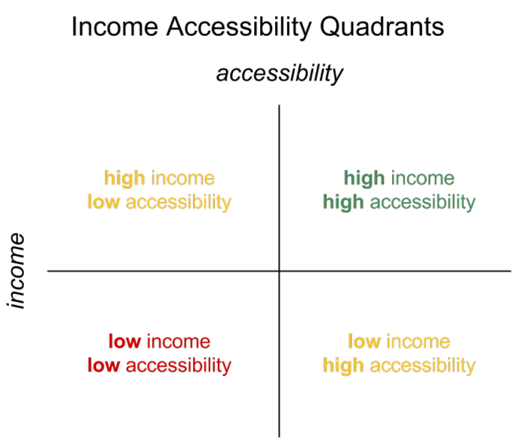
	Component / Type		*Description, Value, Source*
Analytic Goals	Socio-economic outcome analysis		**Do accessible neighbourhoods also contain low cost housing?**
Data	Origins	Locations	Standard
		Attributes	**Average household housing expenditure** (Geographic Research, Inc., 2010)
	Destinations	Locations	Standard
		Magnitude	Standard
	Travel time	Pedestrian	Standard
		Transit	Standard
		Auto	Standard
	Travel cost	Value of time	Standard
		Pedestrian	Standard
		Transit	Standard
		Auto	Standard
Outputs	API and housing cost analysis; Aggregate access profile analysis		**- Map comparison (APIs / Housing cost)** **- 6 access profiles including housing cost: lowest housing cost quintile TAZs and all other TAZs (all modes)**

4.6 Application #6: Accessibility and Low Income

context – why does income matter?

Consider the four possible combinations of income and accessibility shown in the matrix in Figure 26. The top left quadrant reflects households that have poor accessibility, but comparatively high income. While these households may not have good accessibility, they have financial resources to afford higher monetary travel costs or to relocate to a higher accessibility location. The top right quadrant contains households that have both good accessibility and financial resources to afford monetary travel costs. Moving clockwise to the bottom right quadrant, these households may not have financial resources, but they have the benefit of being able to reach a large number of destinations without incurring high monetary travel costs. From a social equity perspective, the bottom left quadrant is the most concerning, since these households may not have financial resources to afford high monetary travel costs or to relocate. Since they have low accessibility, their lack of resources could potentially limit their ability to access destinations.

Figure 26: Income Accessibility Quadrants



The challenge of low income coupled with low accessibility could theoretically be exacerbated by a positive feedback loop, as mentioned briefly in Chapter 1. As income decreases, sensitivity to GC increases because it becomes more difficult for a household to pay for monetary travel costs. On the other hand, the ability to earn an income depends, at least to some extent, on access to employment (e.g. Korsu & Wenglenski, 2010). Since accessibility is influenced by income, and the ability to afford access, and income is influenced by access to employment, the potential for a positive feedback loop exists. Evidence from the Greater Toronto Area suggests that low income households are increasingly located further away from both the central business district and areas served with rapid transit (Hulchanski, 2010), suggesting that the double burden of low income and low accessibility is becoming more prevalent. Since an income-accessibility feedback loop seems plausible in Toronto, I wanted to analyze whether such a feedback loop would also be plausible in Kitchener-Waterloo.

analytic goals The analytic goal for this application is to determine the extent of spatial overlap between low income and low accessibility, and identify TAZs where this overlap occurs.

data In addition to the standard dataset, I used average TAZ household income data, which I described in Section 4.2. I also calculated the percentile rank of each TAZ for both average household income and for accessibility, based on API_{max}.

outputs The first output that I generated was a quadrant designation for each TAZ based on the income and API_{max} percentile rank of the TAZ. I used the 50^{th} percentile as the threshold; a TAZ with an average income above the 50^{th} percentile and an API_{max} below the 50^{th} percentile was therefore designated as “high income, low accessibility” for example. This revealed the number of TAZs in each quadrant.

Since the low income, low accessibility quadrant is of greatest concern and interest from an equity perspective, I developed a further metric to evaluate TAZs in this category. For each TAZ, I multiplied the API_{max} percentile by the income percentile, to produce an *accessibility income measure (AIM)*. A TAZ ranked at the 20^{th} percentile for accessibility and 30^{th} percentile for income would therefore have an AIM value of 0.06. To identify the spatial patterns where low accessibility and low income overlap, I then mapped these AIM values. Note that I filtered out TAZs with negligible populations (<50).

Table 11: Application #6 - Methodological Framework

	Component / Type		Description, Value, Source
Analytic Goals	Socio-economic outcome analysis		**Do areas of low income and low accessibility overlap? If so, where?**
Data	Origins	Locations	Standard
		Attributes	**Average after tax household income** (Geographic Research, Inc., 2006)
	Destinations	Locations	Standard
		Magnitude	Standard
	Travel time	Pedestrian	Standard
		Transit	Standard
		Auto	Standard
	Travel cost	Value of time	Standard
		Pedestrian	Standard
		Transit	Standard
		Auto	Standard
Outputs	Accessibility income quadrants; Accessibility-Income measure (AIM)		# of TAZs in each accessibility-income quadrant; map of AIM values

Chapter 5:

Results and Discussion

chapter abstract In this chapter I present and interpret the results of the six analyses that were described in Chapter 4. I also discuss the insights that can be drawn from each analysis, particularly as they relate to the analytic goals that were outlined in Chapter 4. A summary of both the methodological framework and the results for each application can be found in Appendix D. After discussing the results of the policy applications, I evaluate the overall performance of APA based on the criteria outlined in Chapter 2 (see Figure 27).

5.1 Application #1: Transportation Investment

results For this application I generated four transit access profiles, which are shown in Figure 28 and Figure 29, to measure the effect of transit improvements between 2010 and 2013. The results show a small but significant accessibility improvement between 2010 and 2013 for both TAZs along the express bus corridors and—to a lesser extent—for all other TAZs in the study area. These results are in line with my expectations, since the transit investments that I analyzed were relatively incremental improvements.

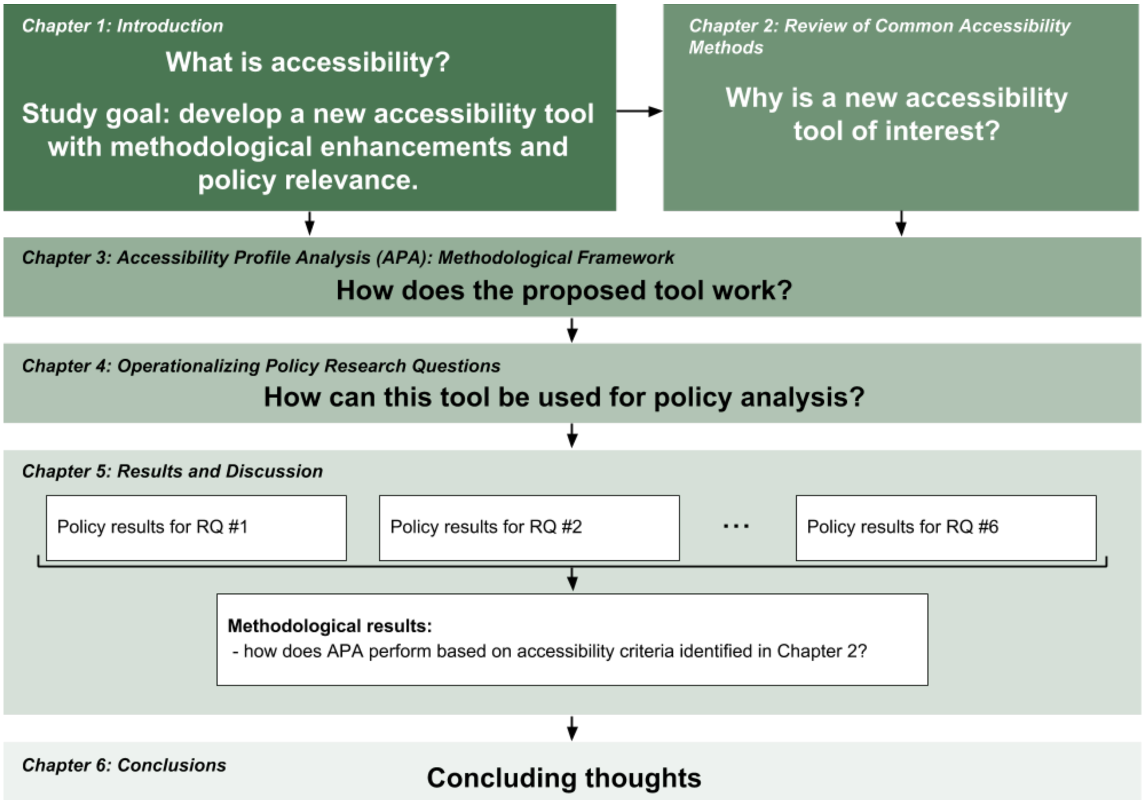


Figure 27: Chapter 5 in Context

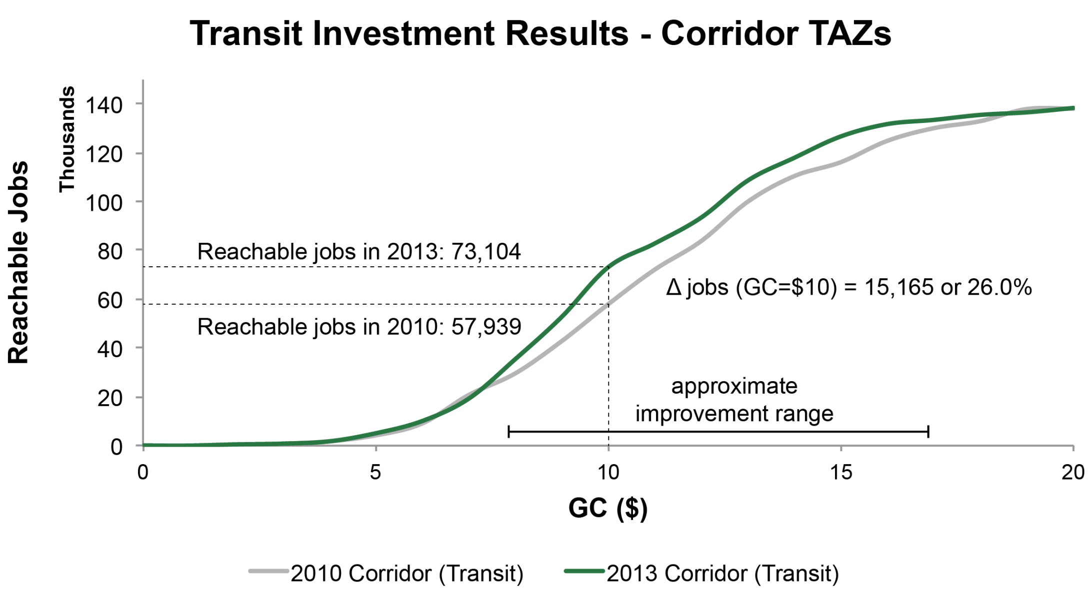
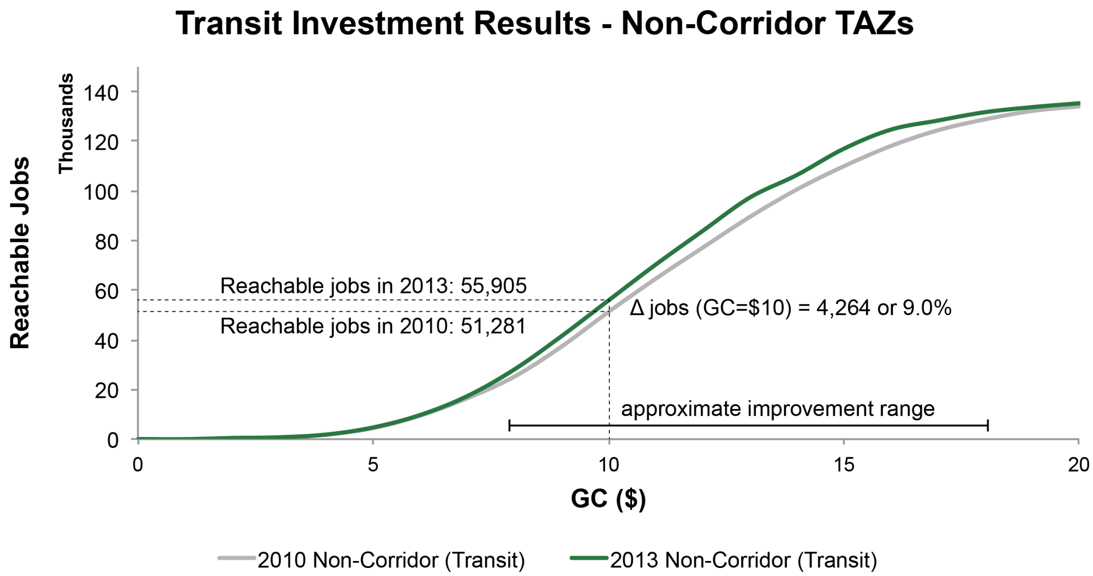


Figure 28: Transit Investment Results for Corridor TAZs

Figure 29: Transit Investment Results for Non-Corridor TAZs



insights The greatest improvement can be seen in the corridor TAZs in the GC range of $8 to $17, which translates into a total trip time of 34-79 minutes. In the lower GC range, which represents trips of 30 minutes or less, little improvement is noticed. This is not surprising, because trips in the lower GC range are already have short travel times, either because the origin and destination are in close proximity, or because the origins and destinations are well connected by transit. Improving travel times for these trips further may not be feasible or even necessary. For medium and long trips however, the 2010 – 2013 investments resulted in significant accessibility improvements, particularly for corridor TAZs. At a GC of $10 (44 min travel time) for example, the transit investments allow the average corridor resident to reach an additional 15,165 jobs, an increase of 26% (see Figure 28). Overall, the 2010 – 2013 transit investments resulted in a modest accessibility improvement for the average study area resident, with the greatest benefit affecting corridor residents making medium or long transit trips.

application potential APA has significant potential as a tool for transportation investment analysis for two reasons. First, APA can support decision-making processes by comparing different investment scenarios before they are approved, funded, and implemented. The main requirements for doing this type of analysis are travel time matrices for all affected modes in each scenario. The generation of scenario based travel time matrices can be greatly facilitated by traffic simulation models and transit scheduling software, which are used by many planning authorities.

APA also has potential for modelling scenarios that are more complex than the *ex post* policy analysis presented here. Consider, for example, investment in an extensive transit signal priority system. Transit signal priority works by manipulating traffic signals to reduce signal delay for transit vehicles, which may lead to increased signal delay for non-transit vehicles. The direct accessibility impact of such an investment would include shorter transit travel times and potentially longer auto travel times. There may, however, be important indirect accessibility impacts to consider. New transfer opportunities may become possible due to faster transit travel speeds. Congestion may compound signal delay for autos. APA can model the overall accessibility impact of all of these factors, provided that the changes can be reflected in modelled travel times.

limitations APA is well suited to evaluate transportation investments that aim to improve travel speeds, expand transportation networks, increase transit frequencies, or otherwise improve accessibility. For some transportation investments, however, improving accessibility may not be a central goal. Goals such as enhancing travel safety, comfort, reliability, or restoring aging infrastructure are certainly valid, but cannot be effectively measured with APA.

5.2 Application #2: Transportation Taxes and User Fees

results For this application I generated four access profiles for the lowest quintile TAZs (Figure 30) and four access profiles for the highest quintile TAZs (Figure 31). In both cases, the four access profiles consisted of the base case for each mode, and an auto access profile that reflects higher fuel costs. The higher fuel costs reduce auto accessibility in both income quintiles, as expected.

insights While auto accessibility for both income quintiles decreases with the higher fuel costs, there are different implications for both quintiles. First, the magnitude of the accessibility reduction caused by the fuel tax is greater for the highest income quintile than it is for the lowest income quintile. For example, at a GC of $12 the number of jobs that can be reached by autodecreases by 14% in the lowest income quintile, whereas the number of reachable jobs decreases by 30% in the highest income quintile; at a GC of $14 the decrease is 9% and 17% respectively. These results suggest that in this study area, a fuel tax is not entirely regressive, and is to some extent proportional to income. In other words, households in higher income TAZs would pay a higher cost than households in low income TAZs to maintain access to a constant number of jobs.

Figure 30: Impact of Higher Fuel Costs on Lowest Income Quintile

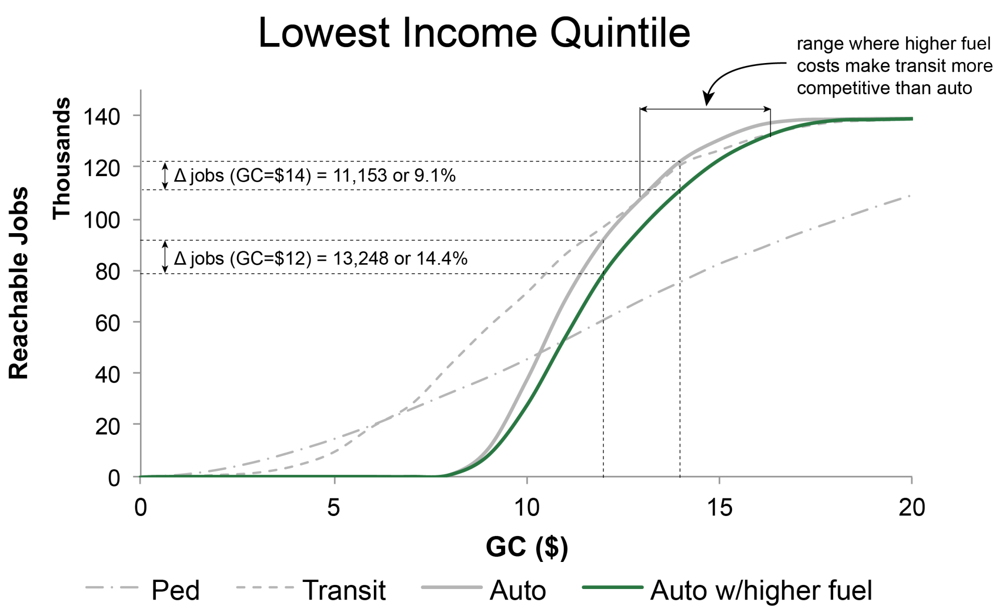
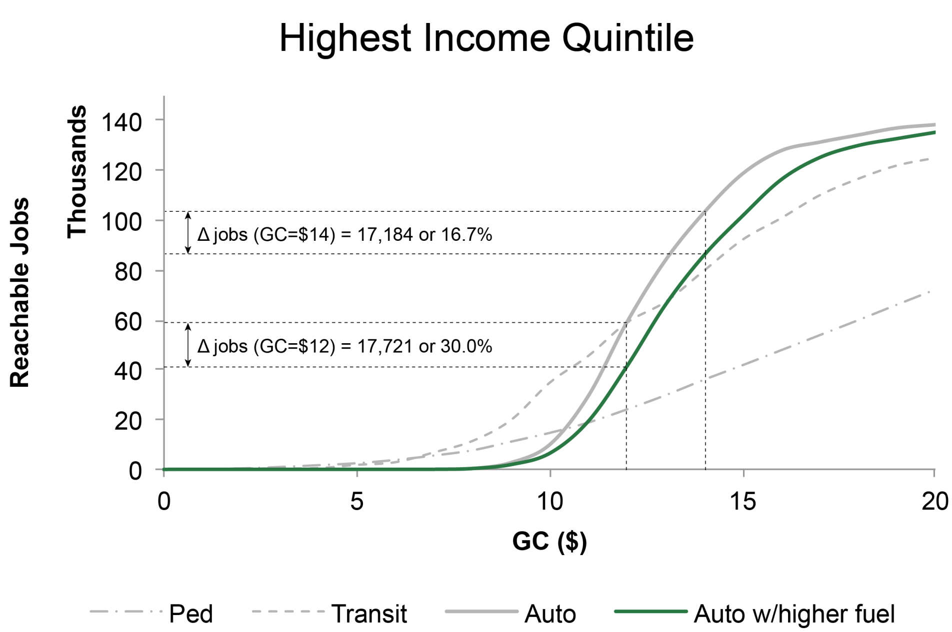


Figure 31: Impact of Higher Fuel Costs on Highest Income Quintile



Observing the overall accessibility landscape—i.e. the accessibility offered by multiple modes across the GC spectrum—reveals a second insight. In the lowest income quintile, transit appears to be competitive with the base cost of auto use across most of the GC spectrum, though auto becomes slightly more competitive at GC=$13. The average resident in one of these TAZs therefore has a viable alternative to auto use. Increasing the cost of fuel makes transit even more competitive relative to auto, with transit being the more competitive up to GC=$16, and both modes being equally competitive beyond that point. This suggests that the average low-income individual struggling to afford higher fuel costs is likely to have the option of taking the bus, without facing unreasonably long travel times or low frequency service. Transit, however, is much less competitive in the highest income quintile. The average individual in these high income TAZs, however, has a greater capacity to either pay for the higher fuel cost or to relocate to a more transit accessible location.

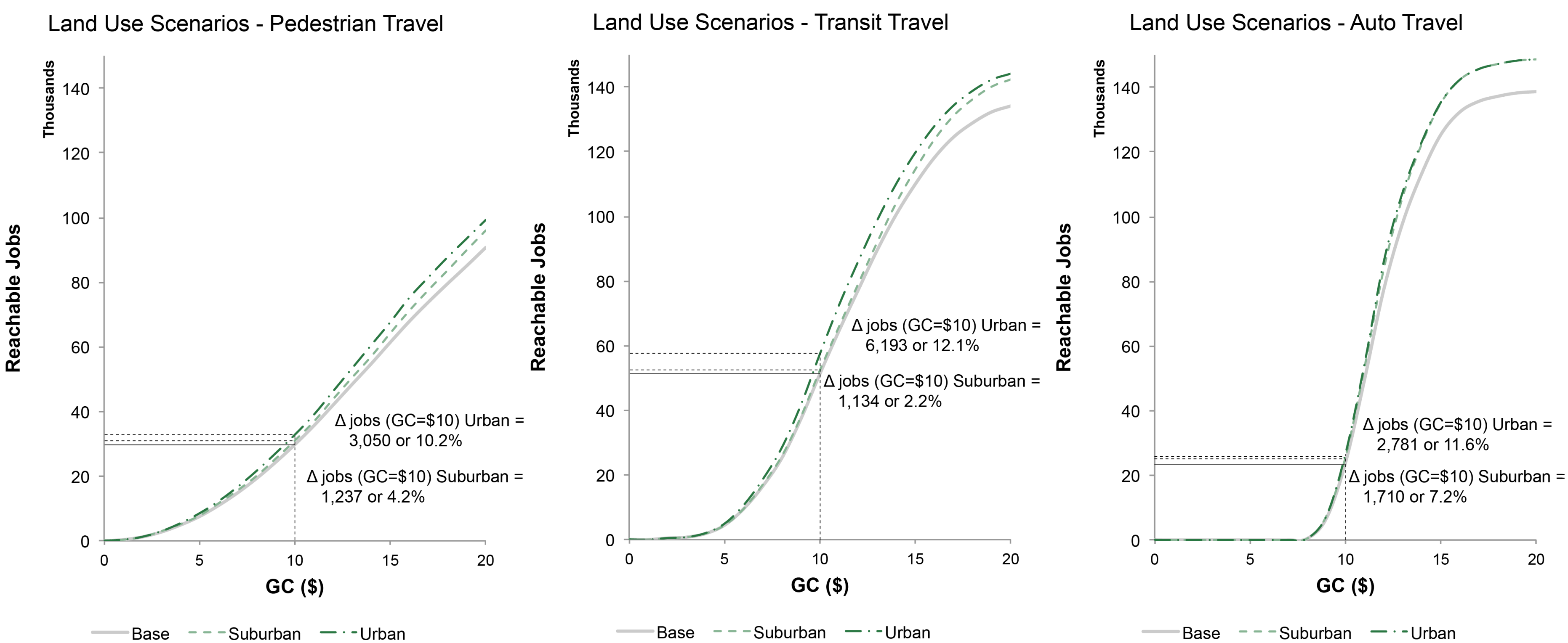
One of the arguments occasionally made in opposition to fuel taxes is that they negatively affect the poor, who will no longer be able to afford basic mobility (see discussion in Vuchic, 1999). The results from this study area however, suggest that households in low income TAZs are not only less affected than those in high income TAZs, but also have viable alternatives to auto travel. It should also be noted that a moderate fuel tax increase would have much less of an impact than the results of this analysis, where the total cost of fuel was doubled. As other authors have noted (Vuchic, 1999), the cost of fuel represents only a small fraction of the cost of auto ownership and use, and modest fuel tax increases are likely to have an almost negligible impact on the overall costs of auto travel.

5.3 Application #3: Land Use

results

For this application I developed two contrasting employment growth scenarios where 10,000 jobs were added to an urban TAZ and a suburban TAZ respectively. For each travel mode, I generated an access profile for the base case and each scenario (Figure 32). As expected, both scenarios resulted in a small accessibility improvement, though the improvement is generally greater for the urban employment growth scenario than for the suburban employment growth scenario.

Figure 32: Land Use Scenario Results



insights As Figure 32 indicates, the urban employment growth scenario increases pedestrian and transit accessibility considerably more than the suburban employment growth scenario. For example, in the base case (no additional jobs) the average transit user can access 51,281 jobs at a GC of $10. The addition of 10,000 suburban jobs allows the average transit user to access 52,415 jobs, an increase of 1,134 or 2.2%. The addition of 10,000 urban jobs allows the average transit user to access 57,474 jobs, an increase of 6,193, or 12.1%.

In contrast to pedestrian and transit travel, auto accessibility is affected in a similar way by both scenarios. One explanation for this is that the auto network, and consequently auto accessibility, is ubiquitous in the study area. A suburban auto user may, therefore, find the ease of reaching a job in another suburb to be comparable with the ease of reaching a downtown job. The transit network, in contrast, is shaped by demand for transit, which is typically higher in central, dense, urban areas than in outer suburban areas. A suburban transit user, therefore, may be able to reach a downtown job with much greater ease than a job located in another suburb, because transit service to the downtown is likely to be better than suburb-suburb service.

These results suggest two broad conclusions. First, urban employment growth is more effective at improving job accessibility for pedestrian and transit travelers than suburban employment growth. Second, in comparison with suburban employment growth, urban employment growth increases the relative competitiveness of pedestrian and transit travel vis-à-vis auto travel. I do not interpret these results as an argument for or against urban development however. Apart from accessibility, there are many factors that should inform growth policies, including market demand. However, if a modal shift away from auto to pedestrian and transit modes has been established as a policy goal, the findings presented in this section provide evidence that urban employment growth will be more effective at achieving this goal than suburban employment growth.

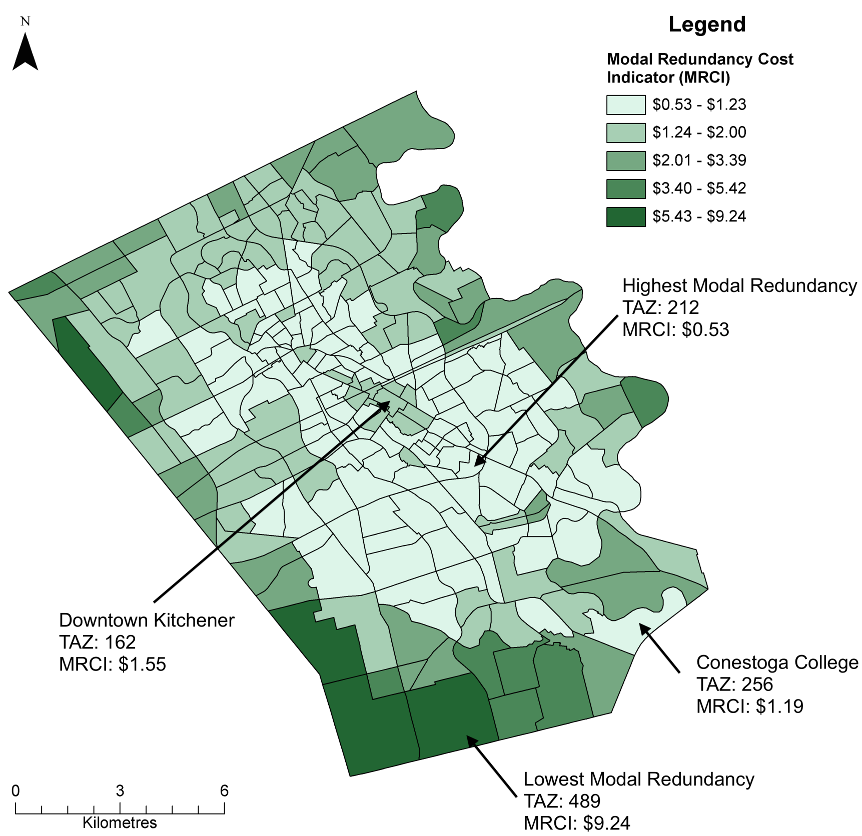
potential applications I developed these two diametrically opposed employment growth scenarios for illustrative purposes. Not surprisingly, the results from this example confirm what many planners and researchers might intuitively expect: the urban scenario is more effective at increasing pedestrian and transit accessibility. Similarly, the first two applications also explored relatively simple, single variable scenarios and policies. An interesting area for further research is to apply APA to more complex, integrated scenarios where the outcomes are less obvious. Job growth, for example, could be modelled together with residential growth and corresponding transportation investments and revenue schemes to estimate net accessibility outcomes for multiple variables. In my view, APA has significant potential to model detailed, integrated scenarios based on actual forecasts.

5.4 Application #4: Modal Redundancy

general results

For this application I developed a new indicator, which I refer to as the modal redundancy cost indicator (MRCI). Recall that the MRCI reflects the average GC of reaching jobs with the second most competitive mode relative to the most competitive mode. Figure 33 shows a map of MRCI values across the study area.

Figure 33: Modal Redundancy Cost Indicator Map



The MRCI ranges from \$0.53 to \$9.24 across the study area, with an average of \$1.54 (see Table 12). Overall, modal redundancy is higher near the downtowns, and lower toward the urban periphery.[26] There are important exceptions to this pattern, however,

[26] Recall that a low MRCI value indicates high redundancy and vice versa.

which can be illustrated by examining four TAZs of particular interest. Access profiles for the four TAZs labelled in Figure 33 are shown in Figure 34. The shaded area in each graph indicates the accessibility gap between the most and second most competitive modes, which is the basis for the MRCI. Note that individual TAZ transit access profiles are somewhat coarser or more discontinuous than pedestrian and auto access profiles due to transit schedules.[27]

Table 12: MRCI Descriptive Statistics

	MRCI
Min	$0.53
Mean	$1.54
Max	$9.24
SD	$1.11

results for specific TAZs

Modal redundancy is highest in the inner suburbs, with the lowest MRCI score achieved in TAZ 212. The access profile for TAZ 212 is shown in the top left of Figure 34. Below the $10 GC point, a similar number of jobs can be reached by pedestrian and transit travel; above the $10 GC point, transit and auto accessibility are very similar. If any mode were to become unavailable, individuals in this TAZ would be able to experience a similar level of accessibility with an alternate mode.

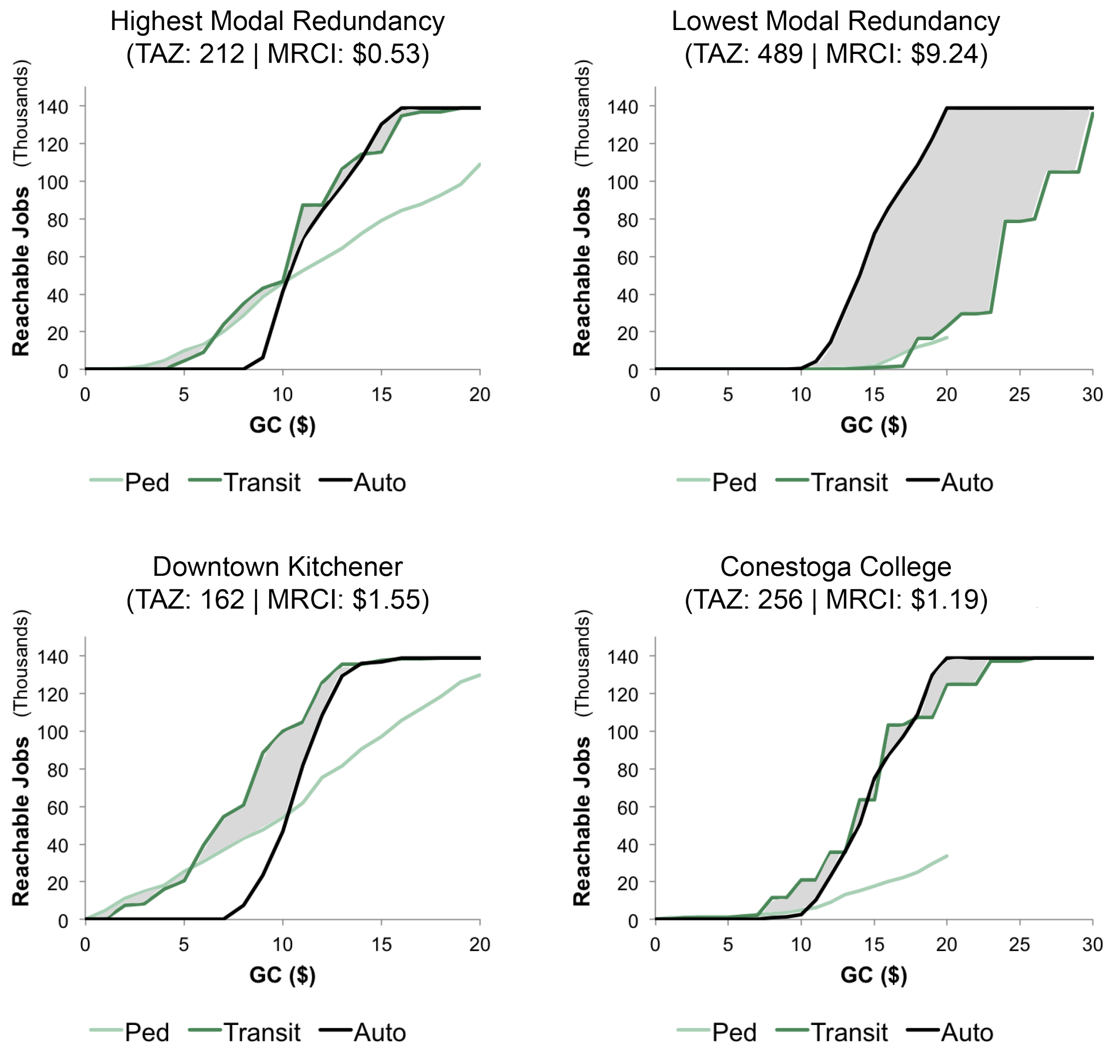
Interestingly, some of the very urban TAZs in downtown Kitchener have moderate MRCI scores. The access profile for TAZ 162, shown in the bottom right of Figure 34, illustrates why this is the case: transit outperforms both pedestrian and auto modes. While this TAZ has very high accessibility, modal redundancy is moderate because individuals would experience a reduction in their accessibility if transit were unavailable. The high level of transit accessibility in downtown Kitchener therefore increases the MRCI value of TAZ 162 and other nearby urban TAZs.

The highest MRCI values are found at the urban periphery, with the highest value occurring in TAZ 489. This TAZ is predominantly rural, with no transit service or employment areas in close proximity. Accessibility is therefore much higher for auto, than for other modes, and the TAZ can be considered auto dependent. Auto

[27] For example, the number of reachable jobs may be equal for two consecutive $1 GC intervals (equivalent to 5 minutes travel time) because no additional buses depart from nearby bus stops within those 5 minutes.

dependency, however, does not necessarily warrant a policy response. According to the TTS data, the population of TAZ 489 is zero. Given the sparse/non-existent population, improving transit or pedestrian accessibility in TAZs such as this one may not be the most efficient use of resources.

Figure 34: TAZ Access Profiles and MRCI



TAZ 256 is another interesting case because it appears to be an outlier. Modal redundancy in TAZ 256 appears to be high, despite its location at the urban periphery, and the low modal redundancy in adjacent TAZs. The access profiles for TAZ 256 are shown in the bottom right corner of Figure 34. Below the $10 GC point, accessibility by all modes is very poor, reflecting the relative isolation of TAZ 256 with respect to major employment areas. Above the $10 GC point, transit and auto modes offer similar accessibility.

TAZ 256 provides some insight about how transportation and land use affect modal redundancy and accessibility. Owing to the presence of Conestoga College, a major post-secondary educational institution, this TAZ—relative to other peripherally located TAZs—is well served by transit. The isolated location of this TAZ, however, means that even with high frequency bus service a significant amount of travel time is required to reach major employment areas. This travel time lag affects the transit access profile in much the same way that the fixed monetary costs of auto affect the auto access profile. Overall, the high quality of transit service in this TAZ increases modal redundancy considerably—as seen by the much lower MRCI score of this TAZ relative to other peripheral TAZs. The quality of transit service does not fully compensate for the relatively isolated location of this TAZ in terms of *accessibility* however, as TAZ 256 has one of the lowest API_{max} values (3^{rd} percentile) in the study area. The low API_{max} value for this TAZ illustrates that while transit investments can improve the competitiveness of transit relative to auto in relatively isolated locations—and thereby increase redundancy—they cannot fully compensate for the effect that dispersed land use patterns have on accessibility.

insights

Two broad insights can be drawn from this exploration of modal redundancy. First, accessibility and modal redundancy are distinct measures that do not necessarily coincide. An origin can have high accessibility and moderate redundancy, if one mode performs exceptionally well, and other modes perform moderately well, as is the case for TAZ 162. Alternatively, an origin can have high modal redundancy, with moderate or low accessibility, if multiple modes perform equally poorly, as is the case for TAZ 256.

The second insight that can be drawn from the results involves the sensitivity of modal redundancy to the formulation of GC. In this analysis modal redundancy appears to be relatively high.[28] This can be attributed in part to the high fixed cost associated with auto travel, which compensates for the comparatively longer travel times associated with

[28] While modal redundancy *appears* to be relatively high, it is difficult to make any assessment in absolute terms in the absence of other MRCI analyses that might serve as reference points. Additional applications of the MRCI are needed to develop a reasonable sense of what constitutes high and low modal redundancy.

transit travel. If modal redundancy were to be calculated exclusively on the basis of travel time, the results would indicate much lower modal redundancy in the study area.

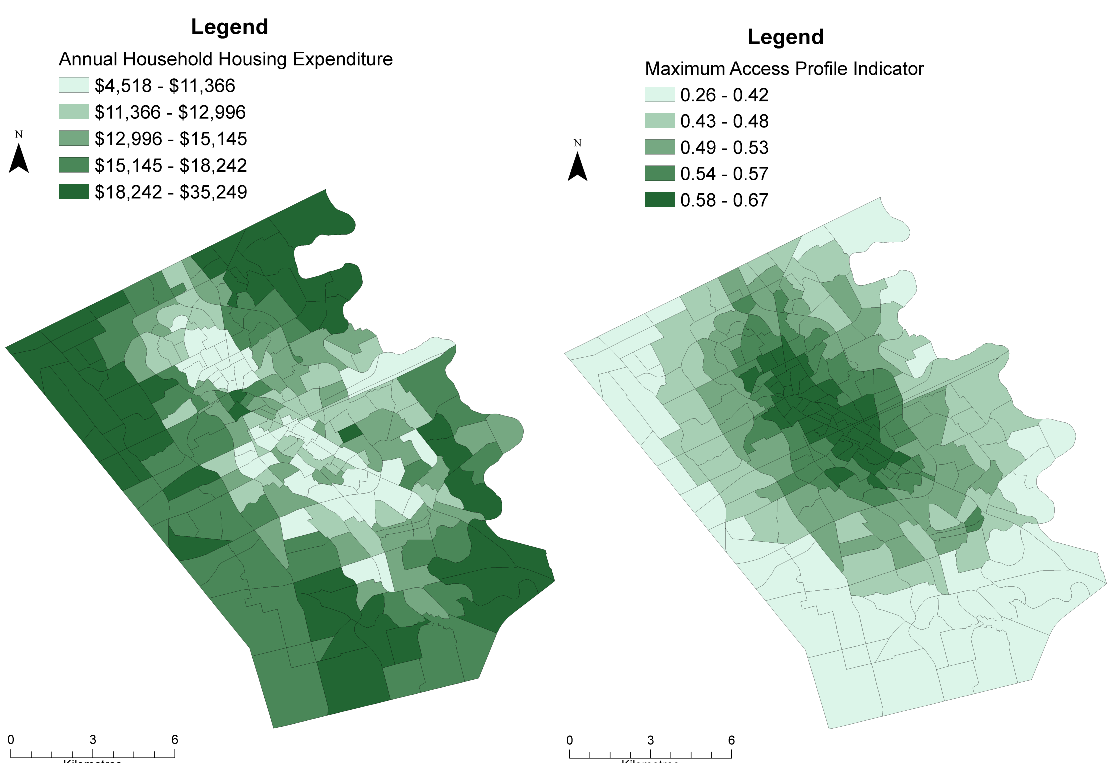
Given the sensitivity of modal redundancy to the formulation of GC, I am reluctant to make specific policy recommendations. Nevertheless, there are two general findings that emerge from this analysis. First, transit provides enough modal redundancy to most parts of the study area that relatively few TAZs can be considered auto-dependent. Second, further investment in transit would help reduce the travel time gap that exists between auto and transit modes across most of the study area.

5.5 Application #5: Accessibility and Housing Cost

map comparison results

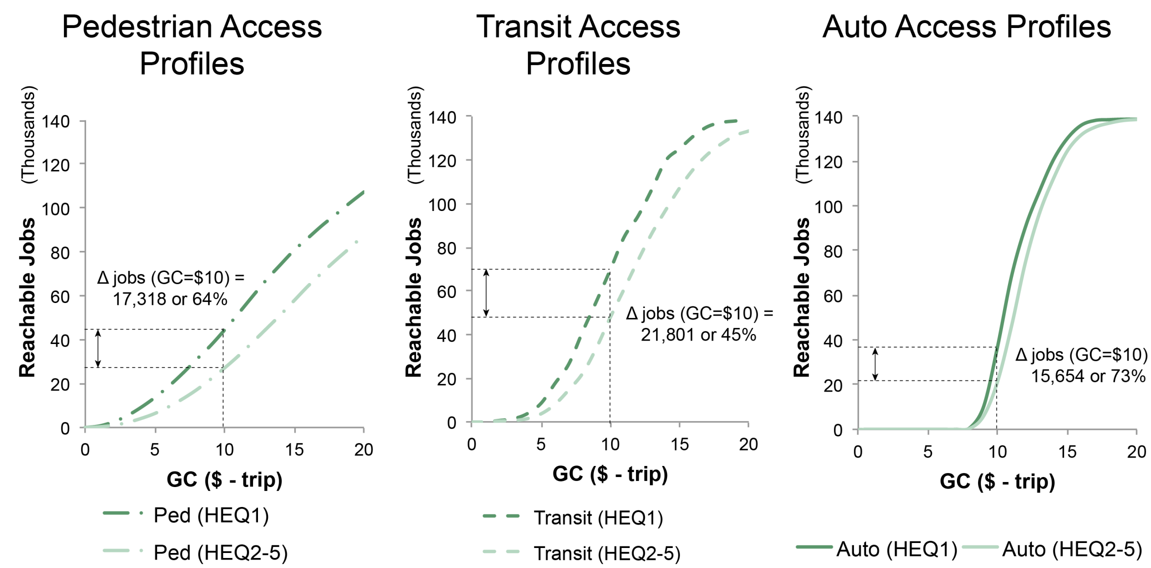
For this application I generated two outputs to analyze the relationship between accessibility and housing costs. First, I mapped both API_{max} and average housing expenditures to highlight spatial patterns in both variables (see Figure 35). The maps suggest that accessibility and housing cost are generally negatively related, with areas near the downtowns typically having higher accessibility and lower housing costs than areas near the urban periphery.

Figure 35: Housing Cost and Accessibility Map Comparison



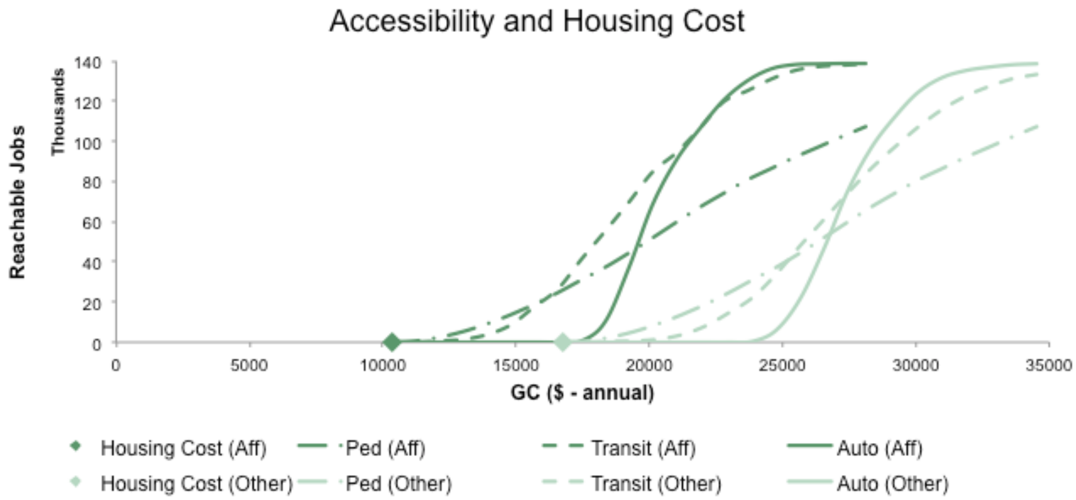
APA results I also evaluated the relationship between accessibility and housing costs by comparing average access profiles for TAZs in the lowest housing expenditure quintile (noted below as *HEQ1*) to average access profiles for all other TAZs (noted below as *HEQ2-5*). Figure 36 shows the pedestrian, transit, and auto access profiles for both groups, and reveals that the lower housing cost TAZs have significantly higher accessibility with all modes. The same access profiles are shown again in Figure 37, except this time housing costs are integrated into the access profiles as fixed costs. The access profiles in Figure 37 provide an indication of the full costs associated with accessibility—the cost of living at the origin, and the cost of moving from the origin to destinations.

Figure 36: APA Comparisons



HEQ1: Housing Expenditure Quintile 1
HEQ2-5: Housing Expenditure Quintile 2-5

Figure 37: Access Profiles with Housing Costs



insights Overall, these findings suggest that accessible neighbourhoods frequently contain low cost housing. Since housing costs are an indication of competition for origin locations, it appears that in the study area, origin competition effects do not restrict accessibility. This is an encouraging finding from a social equity perspective, because it suggests that low income households are unlikely to find themselves in a position where they must trade off accessibility for affordable housing.

While origin competition effects do not restrict accessibility in Kitchener-Waterloo, this may not be true for all metropolitan areas. Larger metros, particularly those dominated by a single central business district (CBD), will have much higher demand for accessible housing, due to the larger number of jobs in the CBD. Depending on the built form and the transportation networks, however, the supply of accessible housing may be proportionately less than the demand for it. An analysis of housing costs and accessibility in larger metros is therefore a particularly interesting area for further research.

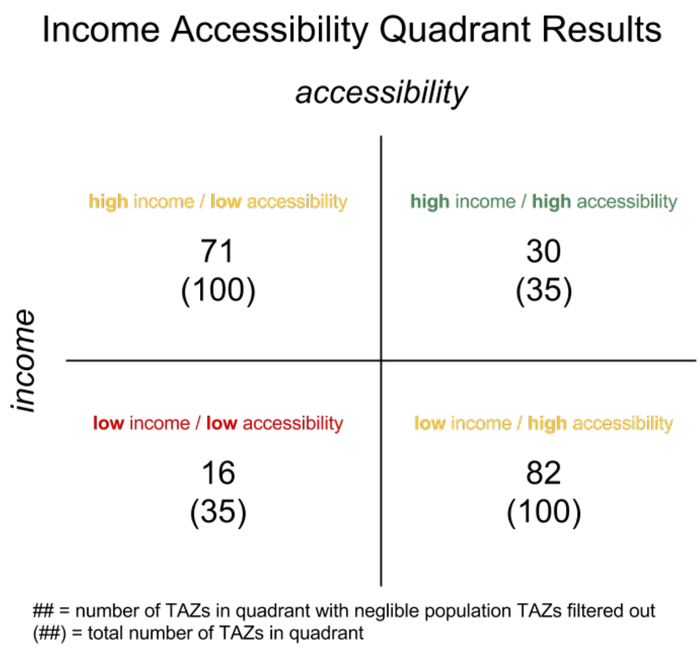
Even in the study area, the evolution of housing costs and accessibility is uncertain. A significant amount of both residential and employment development is currently underway in both downtowns, along with the construction of a new light rail transit line. If development leads to overall gentrification of the downtown areas, the cost of housing in the most accessible areas of Kitchener-Waterloo may increase, and low-income households may be pushed into less accessible neighbourhoods.. The analytic techniques described in this section could therefore be useful to monitor the coevolution of housing costs and accessibility in the study area.

5.6 Application #6: Accessibility and Low Income

results

While the findings from Section 5.5 suggest that housing costs do not prevent low income households from living in accessible areas, I explored relationship between income and accessibility directly in this application. For the first output, shown in Figure 38, I calculated the number of TAZs that are in each income accessibility quadrant. A total of 35 TAZs are in the low income, low accessibility quadrant, meaning that these TAZs fall below the 50th percentile for both income and accessibility. Of these 35 TAZs, only 16 have significant populations.

Figure 38: Income Accessibility Quadrant Results



For these 16 TAZs, I generated an accessibility income measure (AIM) by multiplying a TAZ's accessibility percentile by its income percentile. The AIM for these 16 TAZs is shown in Figure 39.

insight

The first insight that can be drawn from these results is that the double burden of low accessibility and low income is not very severe in the study area. Only 16 TAZs have both below median accessibility and below median income.[29] Furthermore, none of these TAZs have an average income below the national Low Income Measure for a four person household of $33,578 (Statistics Canada, 2013).

Figure 39: Accessibility Income Measure for 16 Low Accessibility, Low Income TAZs

The second insight revealed by this research is that the TAZs most likely to be affected by low accessibility and low income are clustered together. As a general strategy, improving transit service or adding employment in this part of the study area could help reduce the double burden of low accessibility and low income. Closer examination of the four TAZs with the lowest AIM values, which are highlighted in Figure 39, provides some insight into more specific policy recommendations. The three highlighted TAZs to the north have moderate accessibility—ranging from the 36th to the 45th percentile—but very low income—ranging from the 11th to the 16th percentile. Since these TAZs have moderate accessibility but very low income, efforts to reduce the monetary costs of travel would likely be most effective. One approach could be to offer low income residents

[29] This excludes TAZs with negligible populations.

living in these TAZs a discounted transit pass—an approach that is already implemented in other Ontario municipalities (Dale, 2014).

The fourth highlighted TAZ, in contrast, has a moderate average income (47th percentile), but very low accessibility (13th percentile). In this context, improving transit service is likely to be a more effective strategy than reducing monetary travel costs, because the average resident lacks accessibility more than income. Since the average income in this TAZ is nearly equivalent to the median income, an intervention may not be a high policy priority.

Overall, this analysis is useful in three ways. First, it has demonstrated that the double burden from low accessibility and low income is not an acute problem in the study area. Second, it has provided an indication of which parts of the study are most vulnerable to low accessibility and low income. Third, it has provided a baseline and demonstrated analytic tools that can be used to track the evolution of accessibility and income in the study area.

5.7 Methodological Results

context

Having discussed the results for the policy applications, it is now possible to reflect on how the APA methodology performs as an accessibility tool. The evaluation criteria introduced in Chapter 2 are used again here. The APA evaluation results are summarized in Table 13, along with the results for other accessibility tools for comparison purposes.

Table 13: APA Evaluation

Accessibility Measure	Theoretical - Transportation	Theoretical - Land Use	Theoretical - Land Use Competition	Theoretical - Temporal Constraints	Theoretical - Individual Characteristics	Theoretical - Local/Regional	Operationalization	Interpretability	Social Indicator	Economic Indicator	Comparative Analysis
Cumulative Opportunity	•	•	–	–	–	•	••	••	•	•	•
Gravity	••	••	–	–	•	–	•	•	•	•	–
Gravity with Competition Effects	••	••	•	–	•	–	•	–	•	•	–
APA	••	••	•	–	•	••	••	••	••	•	••

•• criterion comprehensively satisfied
• criterion somewhat satisfied
— criterion not satisfied

theoretical soundness

Six aspects of theoretical soundness were identified in Chapter 2. The results of applications 1 and 2, indicate that APA satisfies the first aspect of theoretical soundness—sensitivity to changes in the transportation system. In these applications, changes to both the transit network and the costs of auto use produced a measurable change in accessibility. The results of application 3, where employment growth scenarios were modelled, demonstrate the sensitivity of APA to changes in land use, satisfying the second aspect of theoretical soundness. The third aspect is the incorporation of competition effects. No attempt was made in this research to accommodate *destination* competition effects, which is an issue left to further research. However, I argued that *origin* competition effects are potentially manifested through housing costs, and I demonstrated how these can be incorporated in APA. Therefore APA somewhat satisfies the competition effects criterion. The next criterion, consideration of temporal constraints, is not satisfied by APA, and is another area for further research. APA somewhat satisfies the fifth aspect of theoretical soundness, which is sensitivity to individuals' characteristics. Characteristics such as household income and housing costs were considered in this analysis, but only as aggregate attributes that were averaged for the population of one or more TAZs. This approach can provide some sensitivity to the characteristics of individuals, as long as the variables exhibit spatial patterns, as income does. Deeper integration of individuals' characteristics is another matter left to further research. The final aspect of theoretical soundness involves distinguishing between local and regional accessibility. APA satisfies this theoretical aspect because accessibility is represented across the full GC spectrum with an access profile. Local and regional accessibility can be distinguished by generating API values based on specifically defined ranges of GC.[30] Overall, APA satisfies three of the theoretical criteria and somewhat satisfies two criteria, which leaves only a single theoretical criterion (temporal constraints) unsatisfied.

operationalization

The ease with which APA can be implemented depends on data availability and the complexity of analytic goals. If all the required data are available in appropriate formats, APA can be implemented very easily with basic spreadsheet or database tools. The operationalization of APA in this study was complicated by data that were (a) unavailable (e.g. transit travel times), (b) in dissimilar geographic units (e.g. Census data relative to TTS data), and (c) unavailable at the necessary scale (e.g. pedestrian destination set). Each of these issues arose as consequences of specific analytic goals, such as modal comparison and socio-economic analysis. The complexity of operationalizing APA will therefore vary from one circumstance to another.

Relative to the other accessibility tools discussed in Chapter 2, APA satisfies the criterion of operationalization. In comparison with gravity models, APA is somewhat easier to operationalize, because observed travel time distributions are not required to estimate impedance coefficients. Apart from the estimation of an impedance coefficients, gravity models, cumulative opportunity models, and APA rely on similar data, and the ease of operationalizing any of these models will therefore also be similar.

interpretability

One of the advantages of APA is the ease with which results can be interpreted and communicated. The underlying concept of APA—that the number of reachable destinations is a function of location, mode, and the amount of time and money available for travel—resonates intuitively with experts and non-experts alike. This concept is

[30] For example, a GC range of $0-$8 might be defined for generating local accessibility API values, and a GC range of $8-$16 could be defined for generating regional API values.

illustrated visually through access profiles, which show how accessibility is affected by various aspects of GC. The concept of GC is also relatively straightforward, especially in comparison with the impedance function used in gravity models. APA therefore satisfies the criterion of interpretability.

social and economic evaluation

The use of APA for social evaluation was illustrated in applications 2, 5, and 6. Each of these applications predicted the outcomes or impacts of accessibility, both in terms of *who* was affected by accessibility, and *how* they were affected by accessibility. APA therefore satisfies the social evaluation criterion.

With respect to economic evaluation, I did not attempt to link accessibility to macro or micro economic concepts such as GDP or travel time savings in this analysis. This is largely due to the limited scope of this particular research project and the data that were available. Conceptually, however, APA could be used for economic evaluation. Since economic evaluation is conceptually possible, but not yet demonstrated, this criterion is considered to be somewhat satisfied.

APA is well suited for comparative analysis relative to cumulative opportunity models and gravity models, and satisfies this criterion. The challenge with cumulative opportunity and gravity models in this regard is that they require assumptions about maximum travel thresholds and willingness to travel respectively. These assumptions are problematic because maximum travel thresholds and willingness to travel vary based on travel modes and socio-economic factors. APA circumvents these assumptions by modelling accessibility across the entire spectrum of travel effort. The ability to use APA to compare accessibility between modes and/or socio-economic groups was illustrated in five of the six applications.

limitations

As with any model, there are a number of assumptions and limitations associated with APA. Many of these assumptions and limitations relate to the formulation of GC, to which APA is very sensitive. There are many possible formulations of GC, and the most appropriate formulation will depend on the analytic goals in any given context. In this analysis, I chose to include the full fixed cost of auto travel in the auto GC model even though these costs may not be perceived by all drivers. In the context of this analysis, the inclusion of fixed costs was justified because they play an important role in social equity and can be a significant accessibility barrier for low income households. In a different context, the inclusion of fixed costs may not be justified. Overall, the sensitivity of APA to GC formulation can be addressed by (a) specifying a GC formulation that is appropriate for the analytic goals in any given context, (b) interpreting results with an awareness of how they were influenced by the GC formulation, and (c) developing more advanced GC formulations—an area for further research discussed in the following chapter.

Chapter 6:

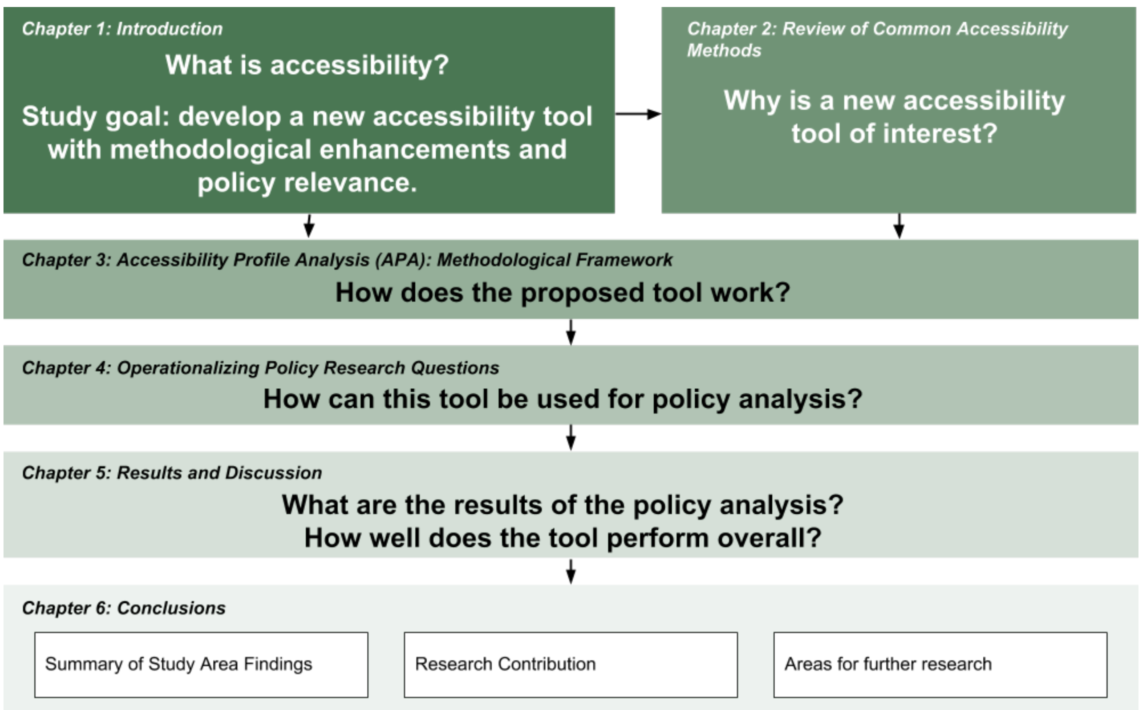
Conclusions

chapter abstract I begin this chapter by summarizing the findings for the study area. In the next Section, I outline the contributions this research has made, both to planning practice and to accessibility scholarship. I then suggest three areas for further research, and conclude this thesis with some final thoughts about the future of accessibility (see Figure 40)

6.1 Summary of Study Area Findings

The first general finding from the study area analysis is that various transportation and land use policies and / or policy scenarios have a direct and measurable impact on accessibility. The addition of two new express bus routes and other service improvements made by the GRT between 2010 and 2013 increased accessibility at the GC=$10 point by 26% for TAZs in proximity to the new express bus routes, and by 9% for other TAZs. The analysis of transportation taxes and user fees found that the highest income TAZs experienced a 30% and 17% decrease in accessibility in response to a higher fuel cost scenario, whereas the lowest income TAZs only experienced a 14% and 9% decrease in accessibility, at GC=$12 and GC=$14 respectively. Moreover, transit appears to be a viable alternative for the lowest income TAZs. A fuel tax is therefore not predicted to have a significant negative impact on the mobility of the average low income household in the study area. With respect to land use policies, employment growth in an urban location was found to be much more effective at increasing pedestrian and transit accessibility than employment growth in a suburban location. The difference between the two scenarios was much less pronounced for auto accessibility however.

Figure 40: Chapter 6 in Context



The study area analysis also revealed several interesting findings about the distribution of accessibility and modal redundancy. First, while more central areas tend to have both higher accessibility and higher modal redundancy than outlying areas, accessibility and modal redundancy are characterized by different spatial patterns. The highest levels of modal redundancy in this study were found in the inner suburbs rather than in the downtown areas. Moreover, outlying TAZs with strong transit connections achieved relatively high levels of modal redundancy.

Finally, from a social equity perspective, the findings suggest that housing costs do not prevent low income residents from living in accessible locations. While there appears to be relatively little overlap between areas of low income and areas of low accessibility, some overlap does exist in several suburban areas of Kitchener. Monitoring is recommended for these neighbourhoods, to ensure that lack of accessibility does not become a significant barrier to employment and general well-being.

As the economy, demographics, and government priorities in Kitchener-Waterloo evolve, transportation and land use patterns will inevitably change. The findings from this research provide a useful benchmark to track accessibility patterns through this period of community transformation.

6.2 Research Contributions

contributions for planning practitioners

For planning practitioners, this research presents a novel accessibility tool that can be used in a variety of policy domains. In particular, APA can help planning practitioners (a) recommend transportation investments that maximize accessibility gains, (b) recommend transportation revenue sources that minimize accessibility losses, (c) anticipate the accessibility impacts of land use plans, and (d) track and respond to social equity issues. This research also illustrates how APA can be operationalized to achieve these goals.

Many transportation scholars (Banister, 2008; Cervero, 2001) have argued that the field of transportation planning must shift from an auto-mobility paradigm to a multi-modal accessibility paradigm. This shift will require a change in the key metrics that are used to evaluate our transportation systems (Tumlin, 2012). It will also require broad stakeholder engagement (Banister, 2008). APA makes a valuable contribution to both of these issues, as it links policy to accessibility outcomes, and provides results that can engage a wide audience. As the paradigm shift progresses, meaningful accessibility tools and metrics will become increasingly important in transportation and land use planning.

contributions to accessibility scholarship

From an academic perspective, this research has revived a relatively obscure modelling approach and demonstrated its potential in a contemporary policy context. This modelling approach has been adapted to include motorized and non-motorized modes of travel, and reflect both monetary and non-monetary travel costs. Furthermore, the applications for this tool have been expanded, particularly with regard to modal redundancy and social equity aspects of accessibility. The merits of APA have been analyzed with regard to both theoretical rigour and practical usability. While several applications of APA have been demonstrated in this research, many more applications have been left for further research.

6.3 Areas for Further Research

replication

Since there do not appear to be any other applications of APA, with the exception of Black and Conroy (1977), the most obvious area for further research is simply replication of APA in other cities. This is important because the conclusions drawn about APA from this research are based on only one application. Additional methodological strengths and weaknesses are likely to be revealed from further applications. Beyond other cities, APA should also be applied to a variety of destination sets such as retail, educational, recreational, and medical destinations. Finally, as discussed in Section 5.3, APA should also be applied to more complex, integrated policy scenarios, since this research only investigated single variable scenarios.

advanced GC models

The GC models used in this research represent the value of travel time (VOT) in a simplistic way. More advanced formulations of GC aim to reflect travellers' perceptions of the ease of travel. A well accepted way of achieving this is to assign different weights to different kinds of travel time, such that the VOT for access, transfer, and egress times is higher than the in-vehicle VOT (Ortúzar & Willumsen, 2001).[31] More recent advances in GC modelling aim to capture traveller anxiety based on the reliability of transit service and an individual's level of risk aversion (Nour, Casello, & Hellinga, 2010). This highlights the potential to tailor a GC model not only to the attributes of a trip, but also to the characteristics of an individual.

In addition to perceptions of travel time, the ability and willingness to pay the monetary costs of travel also vary among individuals, particularly with regard to an individual's income (Giuliano, 2005). While there do not appear to be any precedents for this in the literature, the monetary costs in the GC model could be weighted based on an individual's income.

GC models are used in APA to model travel effort. The perception of travel effort is influenced not only by trip attributes, such as reliability or the amount of transfer time, but also individual characteristics such as risk aversion, income, and potentially many others. As more of these factors are integrated into a GC model, its ability to reflect actual perceptions of travel effort increases. Finding appropriate data sources and techniques

[31] This approach was not possible for this study due to the transit data that were available.

to integrate individualized GC models into APA is therefore an interesting and important area for further research.

travel barriers

Incorporating travel barriers that are not related to travel time or monetary expenses is another interesting area for further research. While non-time, non-monetary barriers apply to all modes, some modes have much more restrictive barriers than other modes. As discussed in application 4, auto travel involves barriers around age, health, ability, and possession of a valid license, which are not reflected in the GC models.

travel barriers and additional modes

Consideration of these barriers is especially important to expand the number of travel modes considered in APA. Several modes that were not considered in this analysis, such as cycling or carpooling, would likely have very favourable access profiles, but are also subject to non-monetary, non-time travel barriers. Cycling, for example, involves minimal monetary costs, is not restricted by schedules, and has moderate travel speeds. Access profiles for cycling may in some cases be more competitive than all other modes across a range of GC values in a study area such as Kitchener-Waterloo. Yet there are many barriers to cycling—such as weather, personal fitness, and safety concerns—that affect the ease of travel but are not typically considered in GC models,. One solution may be to find ways of incorporating these barriers directly into GC models (see for example Casello, Nour, Rewa, & Hill, 2011). Another approach may be to combine multiple modes, and develop an access profile that reflects, for example, making a trip by bicycle 80% of the time and by taxi 20% of the time. APA can potentially be expanded to include many additional modes and combinations of modes such as carpooling, carshare, taxis, mopeds, cycling, and bikeshare. In order to accurately reflect the ease of travel with any of these modes, however, consideration must be given to non-monetary, non-time travel barriers.

6.4 Concluding Thoughts

This is an exciting time to be involved in accessibility research. Both the rapidly growing body of academic literature on accessibility and the increasing alignment of transportation policies with accessibility concepts (e.g. City of Toronto, 2014) reflect the ongoing transition toward an accessibility paradigm. It is my hope that this research can provide a small, yet meaningful, contribution to this paradigm shift.

Appendix A: Map of Travel Time Validation OD Pairs

The TAZs without transit service are 236 and 489. Note that both of these TAZs have very few roads that run within them. As a result, Google shifted the origin / destination point to the closest point on the road network. To ensure both methods used the same origin / destination points, the centroids were manually shifted in ArcGIS to the same location used by Google for the validation exercise.

Appendix B: CUTA Data

OPERATING DATA:
Revenue Vehicle Kilometres
Total Vehicle Kilometres
Revenue Vehicle Hours
Auxiliary Revenue Vehicle Hours
Total Vehicle Hours

Operator Paid Hours
Mechanic Paid Hours
Total Employee Paid Hours

Adult Passenger Trips
Concession Fare Trips
- Child Passenger Trips
- Student Passenger Trips
- Senior Passenger Trips

REGULAR SERVICE PASSENGER TRIPS
Regular Service Passenger Kms
Auxiliary Serv. Pass. Trips

Transportation Operations Expenses
Fuel/Energy Exp. for Vehicles
Vehicle Maintenance Expenses
Plant Maintenance Expenses
General/Administration Expenses

TOTAL DIRECT OPERATING EXPENSES
Debt Service Payment
Total Operating Expenses

REGULAR SERV. PASS. REVENUES
TOTAL OPERATING REVENUES
Total Revenues

NET DIRECT OPERATING COST
NET OPERATING COST
Federal Operating Contribution
Provincial Operating Contribution
Municipal Operating Contribution
Other Operating Contributions
Provincial Debt Service Contribution
Municipal Debt Service Contribution
TOTAL CAPITAL EXPENDITURES
Total Capital Disposals
TOTAL CAPITAL FUNDING
Federal Capital Contribution
Provincial Capital Contribution
Municipal Capital Contribution
Other Capital Contributions

PERFORMANCE INDICATORS:

FINANCIAL PERFORMANCE
Tot. Oper. Rev. / Tot. Dir. Oper. Exp. (R/C Ratio)
Municipal Operating Contribution / Capita
Net Dir. Oper. Cost / Reg. Serv. Pass.

AVERAGE FARE
Reg. Serv. Pass. Rev. / Reg. Serv. Pass

COST EFFECTIVENESS
Tot. Dir. Oper. Exp. / Reg. Serv. Pass.

COST EFFICIENCY
Tot. Dir. & Aux. Oper. Exp. / Tot. Veh. Hr.

SERVICE UTILIZATION
Reg. Serv. Pass. / Capita
Reg. Serv. Pass. / Rev. Veh. Hr.

AMOUNT OF SERVICE
Rev. Veh. Hrs. / Capita

AVERAGE SPEED
Rev. Veh. Kms. / Rev. Veh. Hr.

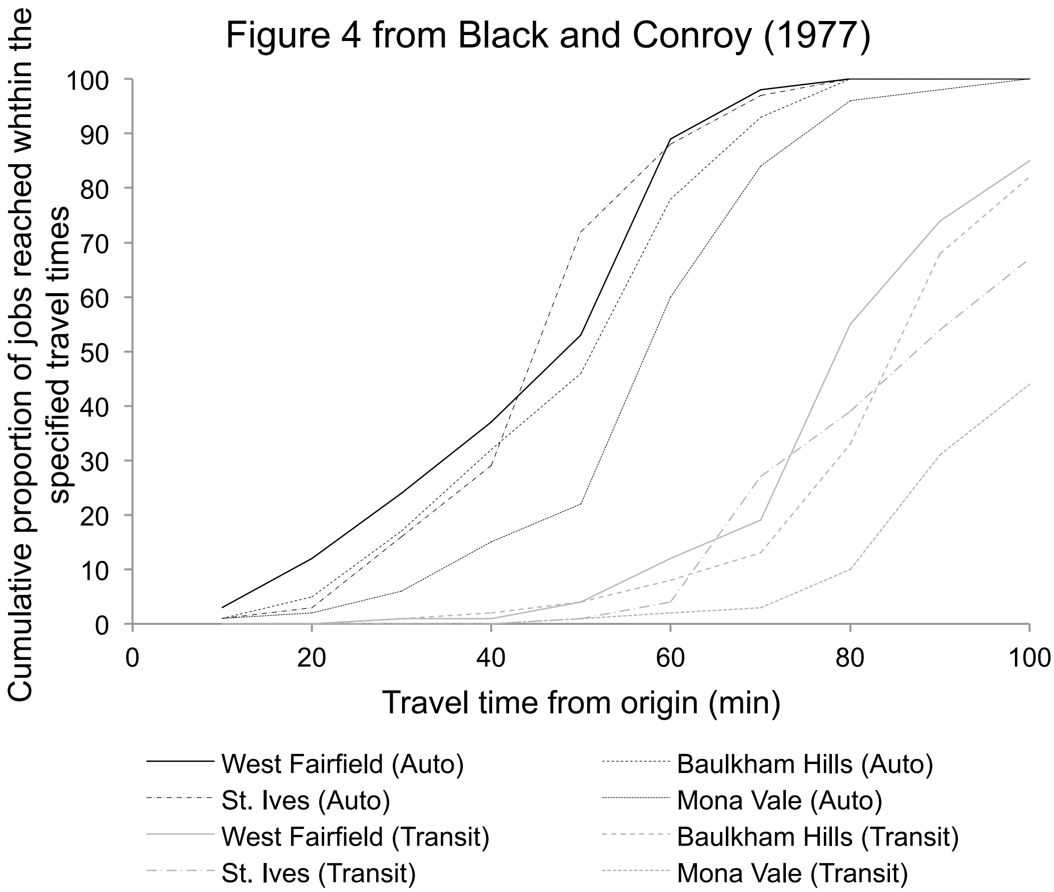
VEHICLE UTILIZATION
Tot. Veh. Kms. / Active Vehicle
LABOUR PRODUCTIVITY
Rev. & Aux. Rev. Veh. Hrs. / Oper. Paid Hr.

TOP WAGE RATES
Operators
Mechanics

**highlighting indicates variables used in this study*

(Canadian Urban Transit Association, 2007)

Appendix C: Sample Figure from Black and Conroy



Appendix D: Application Summary Table

			Application 1: Transportation Investment	***Application 2: Transportation Taxes and User Fees***	***Application 3: Land Use***
Analytic Goals			Did 2010-2013 transit investments improve accessibility? By how much? Where?	What impact would higher fuel costs have on high and low income TAZs?	What are the differential accessibility impacts of urban and suburban employment growth scenarios?
Data	*Origins*	*Locations*	Non Corridor: n=243 (TAZ centroids) Corridor: n=27 (TAZ centroids)	Lowest income quintile: n=54 (TAZ centroids) Highest income quintile: n=54 (TAZ centroids)	Standard
		Attributes	Standard	Average after-tax household income (Geographic Research, Inc., 2006)	Standard
	Destinations	*Locations*	Standard	Standard	Standard
		Magnitude	Standard	Standard	10,000 jobs added to TAZ 151 (urban scenario) and TAZ 242 (suburban scenario)
	Travel time	*Pedestrian*	N/A	Standard	Standard
		Transit	2010 / 2013: Network dataset constructed with ATT and 2010 / 2013 GTFS data (Region of Waterloo, 2010, 2013b)	Standard	Standard
		Auto	N/A	Standard	Standard
	Travel cost	*Value of time*	Standard	Standard	Standard
		Pedestrian	N/A	Standard	Standard
		Transit	Standard	Standard	Standard
		Auto	N/A	Increased fuel cost scenario: Variable: 20.8¢/km Fixed: Standard ($7.97/trip)	Standard
Outputs			Four transit access profiles: 2010 corridor / non-corridor; 2013 corridor / non-corridor	8 access profiles: base case (all modes) and higher fuel cost scenario (auto); highest and lowest income quintiles	9 access profiles: two scenarios and base case (all modes)
Results			Modest overall accessibility improvement; greatest impact along express bus corridors for medium and long trips.	High income TAZs experience a greater accessibility decrease than low income TAZs; low income TAZs also have viable alternative to auto travel.	Urban employment growth scenario results in significantly better pedestrian and transit accessibility than suburban scenario; auto accessibility impact is similar for both scenarios.

			Application 4: Modal Redundancy	Application 5: Accessibility and Housing Costs	Application 6: Accessibility and Income
Analytic Goals			How much modal redundancy is there across the entire transportation network? How is modal redundancy distributed?	Do accessible neighbourhoods also contain low cost housing?	Do areas of low income and low accessibility overlap? If so, where?
Data	*Origins*	*Locations*	Standard	Standard	Standard
		Attributes	Standard	Average household housing expenditure (Geographic Research, Inc., 2010)	Average after tax household income (Geographic Research, Inc., 2006)
	Destinations	*Locations*	Standard	Standard	Standard
		Magnitude	Standard	Standard	Standard
	Travel time	*Pedestrian*	Standard	Standard	Standard
		Transit	Standard	Standard	Standard
		Auto	Standard	Standard	Standard
	Travel cost	*Value of time*	Standard	Standard	Standard
		Pedestrian	Standard	Standard	Standard
		Transit	Standard	Standard	Standard
		Auto	Standard	Standard	Standard
Outputs			Map of MRI Scores	- Map comparison (APIs / Housing cost) - 6 access profiles including housing cost: lowest housing cost quintile TAZs and all other TAZs (all modes)	# of TAZs in each accessibility-income quadrant; map of AIM values
Results			Further analysis needed for absolute assessment of modal redundancy; relatively few areas are auto dependent; travel time gap between auto and transit could be reduced with further transit investment.	Housing costs and accessibility are negatively related; accessible neighbourhoods frequently contain low cost housing	There are virtually no areas where very low accessibility and very low income overlap; 3 TAZs in east Kitchener have moderately low income and moderately low accessibility.

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