GIS Tools to Improve the Transit Planning Process

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.

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Abstract

Public transit provides an important community service by reducing pollution, traffic congestion, and by providing transportation for those who do not or cannot drive. Yet since the 1950s, real investment levels in transit have declined in many North American cities which has resulted in diminished service levels and ridership. In order for transit agencies to attract more riders, transit service must be competitive with alternative modes of transport, particularly private automobiles. However, since funding is limited, planning staff must ensure that the service changes that are implemented result in the greatest benefits to the system.

This thesis presents an iterative approach to evaluating service changes in a transit network that combines the output from sophisticated transportation models, demographic data, and software analysis with local knowledge and expertise. The thesis focuses specifically on three common challenges in transit planning: quantifying costs of transfers between destinations within a system, examining access distances to transit as a measure of transit supportiveness, and estimating ridership changes resulting from small route adjustments. Three GIS-based tools, referred to as the Transfer, Access and Route Planning Tools, were developed to address these challenges and were demonstrated using transit system data from the Region of Waterloo in Southwestern Ontario. The Transfer Tool was used to highlight trips with high transfer costs to determine which changes in the route structure would result in the greatest reduction of the generalized cost of a trip attributed to transfers. Results from the Access Tool and Route Planning Tools demonstrated how changes to the streets along which transit routes operate influence access distances to transit, and further, transit ridership. The Access Tool also demonstrated how the design of the street network and the presence of pedestrian paths may affect access distances. Finally, this thesis concludes by recommending areas of future research.

Acknowledgements

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Dedication

For my Dad, who looked forward to reading the final result.

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Glossary of Terms

Access cost – A function of the access distance to transit and a relative weight that reflects the contribution to a trip’s overall disutility, measured in minutes.

Generalized cost (GC) - A function used to estimate the perceived cost, or burden, of travel between destinations by disaggregating the various components (monetary and non-monetary) within a trip.

GIS – Geographic Information Systems. A set of tools used to describe and analyse the earth for the purpose of analysing and visualising geographically referenced data.

Headway – A measure of the time between vehicles in a transit system.

IVTT - In-vehicle travel time, measured in minutes.

Multimodal network – A travel network consisting of more than one form of transportation, such as a combined transit, pedestrian, and cycling network.

Network dataset – A set of nodes and edges that represents the line network over which commodities flow in a GIS.

OD pairs – Origin-Destination pairs. Used as start and end points for trip purposes.

TAZs – Traffic Analysis Zones. Polygons created by transportation officials or local governments to act as study areas for traffic related data. Normally comprised of census blocks.

Transfer penalty – A combined cost that represents the negative components of a transfer during a trip. Typically measured as the equivalent of in-vehicle travel time expressed in minutes.

Travel forecasting model – A tool used in transportation studies to model current and future travel demand. A typical form of this model consists of four main steps: trip generation, trip distribution, mode choice, and trip assignment.

CHAPTER 1: INTRODUCTION

Public transit helps to reduce traffic congestion and the need for on-site parking, provides an important public service for those who choose not to drive, or for those who cannot drive due to age, physical or financial restrictions. For these people, lack of transit availability can result in social exclusion and may limit access to employment, goods, and services (Transport Canada, 1997). Despite these concerns, following WWII, planning policies as well as private and public investments began to promote travel by automobile over travel by public transit, resulting in dispersed growth away from city centres. High demand for low density development occurred at the periphery of cities, away from employment and shopping. Expressways were built to accommodate car travel into the city centre, and at the same time, parking in the CBD was increased to accommodate an inflow of auto traffic. Zoning bylaws mandated that houses have garages and that commercial and industrial land uses supply a minimum number of parking spaces (Hodges and Gordon, 2008). This has resulted in low density development that is difficult to serve through mass transit, inefficient use of land and infrastructure, less walking, increased pollution levels, and increased social inequality and disparity resulting from fewer travel options (Hodges and Gordon, 2008).

While transit is more effective if it is supported by urban design practices that promote greater density, pedestrian connections, and mixed land uses, the availability transit services can also be used to help shape the urban form to support less consumptive land uses. Transit promotes denser and more sustainable development that reduces congestion on roadways, the need for greater transportation infrastructure, and pollution (Saha & Devashree, 2008). In order to attract “choice users” - those who have access to alternative means of transportation - transit must provide convenient and reliable service that competes with the alternative modes, particularly private vehicles. Yet, investment in transit services and infrastructure has generally not matched population growth or changes to urban development (Christopher, 2006) – new residential settlements often wait years before receiving regular transit service.

In Canada it is estimated that the government must invest billions of dollars into transit in order to attract a substantial amount of discretionary riders (Canadian Chamber of Commerce, 2006). Yet there are few Federal programs that fund transit projects, and there is often little room in municipal budgets to expand transit service levels or capacity. Many agencies struggle to maintain their current fleet and service levels (Canadian Chamber of Commerce, 2006). If transit agencies wish to improve their service under tight budgetary constraints they must make investment decisions that are more responsive to changing patterns of demand, and enhance the quality of service offered to their passengers.

1.1 MOTIVATION

To provide better service that is sustainable and competitive with private automobiles, transit agencies must reduce the perceived costs associated with transit trips by making them more convenient to a greater number of people. Several factors contribute to the overall trip experience, such as: the amount of time it takes to walk to and from transit stops; the walking environment; the amount of time spent travelling in-vehicle; time necessary to complete a transfer between routes and/or modes (e.g. bus, walk, subway); and the convenience of that transfer. Unpleasant conditions or long walking distances result in even higher costs and reduced transit use. While the quality of transfers can be improved by coordinating schedules, providing traveller information, and pedestrian facilities; transfers are generally perceived to add a significant burden to the trip regardless of the amount of time spent between transfers (Litman, 2010).

Additionally, focusing transit improvements on areas that are more transit supportive will likely garner greater ridership growth compared to service expansion in areas that are less transit supportive. This means targeting areas that have higher residential and employment densities, as well as areas with a greater concentration of populations known to have a higher dependence on, or a greater willingness to use transit.

Adopting planning methods that give weight to improved comfort and convenience will likely achieve higher ridership, particularly if the perceived costs of a trip are reduced significantly. Likewise, prioritizing improvements that will benefit the greatest amount of potential riders will result in greater ridership growth.

This thesis proposes tools that enhance transit agencies' ability to evaluate proposed service changes' impact on users and, as a result, increase ridership with limited resources.

1.2 GOALS AND OBJECTIVES

Advancements in information technology provide transit planners with new capabilities to gather data concerning passengers' use of a system and the performance of the system itself. For example, use of simpler, less formal methods of transit planning activities (such as route analysis) have become easier and more sophisticated with the use of technology such as Automatic Passenger Counters (APC) which track the number of passengers boarding and alighting a vehicle at each stop, automatic vehicle location (AVL) systems which record the location of a vehicle throughout a trip, and Geographic Information Systems (GIS) that store and display geographically referenced data. GIS allow for simpler and more effective integration of data sources, are helpful in data analysis, and can communicate information more clearly to stakeholders. The use of GIS allow transit agencies to relate demographic data to routes and ridership, and provides a new means of forecasting and analysing data (Boyle, 2006).

The main goal of this thesis is to demonstrate a spatially explicit approach to transit planning through the use of GIS in order to provide more structured methods to better transit agencies' decision making processes. The methods presented provide a set of tools to evaluate the anticipated impacts that service changes would have on current and potential users in order to assist in the implementation of changes that minimize deterrents associated with using transit, and optimize transit operations by focusing on corridors that are transit supportive.

The research specifically focuses on addressing three challenges within transit planning: measuring transfer penalties, developing a method to calculate access costs at the parcel-level (or building) as a measure of transit supportiveness, and estimating ridership for route alignment alternatives.

In order to address these issues, the following questions are asked:

1) How can the dimensions of transfer penalties be operationalized in a GIS?
2) Given the data resources available to most transit agencies, is it feasible to use property level data to analyze spatial access to transit as a measure of transit supportiveness?
3) How can transit agencies use access distances and demographic data to help predict the ridership impacts related to changes in route alignments?
4) How do changes to the above variables affect the generalized cost, and therefore ridership, associated with transit?

Each question is explored more fully in the following sections.

1.2.1 Transfer Penalty

While automobile travel typically provides service from "door-to-door", public transit networks run along fixed routes with fixed schedules, serving large areas with numerous trip origins and destinations. Since it would be inefficient and uneconomical to provide direct service between all origins and destinations, most transit agencies use transfers between routes or modes to provide complete network coverage. Passengers are required to change vehicles at a transit station or bus stop, resulting in increased physical and mental effort (Desautlels, 2006).

The need to physically change vehicles necessitates additional walking distance, exposure to traffic and weather, extended trip times and reduced reliability (Desautlels, 2006). Passengers often find the time spent transferring to be about two or three times more arduous compared to time spent travelling within the vehicle itself (Paulleya et al. 2006; Iseki & Taylor, 2009). The negative aspects of transfers are jointly referred to as a "transfer penalty". In order to quantify how transfers affect the quality of the transit service, a penalty value can be assigned to transfer locations between the various routes within a network, based on selected criteria (Guo & Wilson, 2007).

The presence of a transfer is perceived as one of the most negative aspects of a transit trip, due to the need to physically change vehicles. Even if the presence of a transfer results in total travel time savings, passengers are still reluctant to transfer (Hensher, 2007). While it is not practical to provide direct connections between every origin and destination within a region, origin destination (OD) pairs with high travel volumes should be targeted for direct transit service to provide convenient trips for a greater amount of people, thus making the service more appealing. Travel routes with high transfer penalties may be targeted for service changes to improve passenger convenience and level of service through route alterations to prove direct service, or better coordination of transfers through improved scheduling.

This research presents a GIS-based method to assess the transfer penalties associated with travel between multiple OD pairs. Those trips with higher volumes for which transfer penalties are high, are targeted for operational improvements.

1.2.2 Access and Egress

Similar to the time spent transferring, walking times to and from bus stops are seen as being more onerous that time spent actually travelling on transit. Access times to stops are perceived by travellers as being between 1.4 and 2.0 times as arduous as in-vehicle time (Paulleya et al. 2006; Wardman, 2001). Customers who live closer to a transit stop and whose destinations are close to transit are more likely to take transit than those whose homes or destinations are located further away. Likewise, transit is more likely to be effective if stops are located in areas with higher densities and easy pedestrian paths to stops, or smaller building setbacks, as this increases accessibility for a greater number of people. Analyzing access distances to and from transit can help to determine which areas or neighbourhoods are more transit supportive, and can help to determine where routes and stops should be located.

The sophistication of existing methods to quantify access varies. This thesis presents a method that computes access and egress time for an individual building or parcel along available walking paths – both roadway and pedestrian trail networks. The work presented here also demonstrates the importance of neighbourhood design in influencing potential transit access.

1.2.3 Route Calibration

Another important consideration in transit planning is conducting ridership forecasts. These studies help prioritize projects, plan budgets, and can also help to estimate the impacts of service changes such as introducing a new route or revising a current route (Boyle, 2006). However, there are often discrepancies between forecasted and observed ridership values.

Various studies undertaken by transit agencies and academics have found that demographic data - population density, age, citizenship status, and auto ownership - help to explain differences in the propensity to use transit as predicted by forecast models. It is noted that external factors outside of the transit agencies control (such as density and demographics) account for a much greater variation in ridership among transit systems than policies such as frequency of service or fares (Taylor et al. 2008). Being able to calibrate ridership forecasts against demographic data may increase the accuracy of forecasted values, and can help to estimate ridership impacts related to changes in route alignment.

Most municipalities generate transit ridership estimates through a traditional travel forecasting model (see section 2.5). Despite nearly five decades of use, there are several known challenges associated with these models' suitability for transit ridership estimation. First, they tend to be resource intensive. Second, the spatial scale for which these models are developed limits their sensitivities to small changes in the transit network. As a result, transit agencies typically do not develop or routinely apply these kinds of models when conducting operational planning. This thesis proposes a method to update transit ridership estimates after a transit route realignment, while incorporating socio-demographic data which are reflective of a demographic group's tendency to use transit. Demographic data are integrated through the inclusion of a bias into the travel mode split equation. This bias represents the demographic and social characteristics of a TAZ, and classifies the TAZ as either highly transit supportive, low transit supportive, or transit neutral.

1.3 CHAPTER SUMMARY

The concepts described in this chapter help to demonstrate some of the challenges faced by transit planners when changes are needed to improve both transit competitiveness and inequalities in transit access and connectivity. Further, these issues may be viewed differently by transit users and when viewed from a transit agency's perspective (summarized in Table 1.1). This thesis seeks to provide methods that utilize an iterative approach to evaluating service changes in a transit network that combines the output from sophisticated modelling, demographic data, and software analysis with local knowledge and expertise in order to balance both the needs of the transit agency and users, and also to balance improvements in efficiency and inequality.

Table 1.1 Comparing users' and agencies' perspectives on transit services

Tool	Users' Perspectives	Transit Agencies' Perspectives	Bridging the Gap
Transfer Tool	• The presence of transfers decrease reliability of trips and increase travel times • Transfers result in greater physical and mental effort	• Transfers increase connections within a service area • Transfers minimize amount of resources required to run network (fewer routes required)	• Analyze cost/impacts of transfers on a transit trip • Balance presence of transfers against ridership demand
Access Tool	• Shorter access distances to transit are more convenient	• Increase service coverage can result in indirect routes and longer in-vehicle travel times	• Demonstrate importance of pedestrian connections among neighbourhoods and arterial roads • Balance service coverage with direct service through strategic route alignments • Predict probability of transit ridership
Route Planning Tool	• Shorter access distances are more convenient • Certain demographic groups are more likely to utilize transit	• Difficult to predict areas of demand and where riders are coming from/going to • Travel forecasting models are resource intensive	• Provides an analysis of which corridors are more transit supportive • Help to prioritize projects • Predict ridership

1.4 THESIS ORGANIZATION

This chapter introduced current challenges in transit planning arising from a need to improve services with limited resources to plan and evaluate possible system improvements. It is believed that agencies can overcome these challenges through a greater understanding of their network and passengers, and through more efficient use of resources. The goal of this thesis is to develop tools that allow agencies to maximize their limited resources to make appropriate investments.

The remainder of this thesis is organized into four additional chapters. Chapter Two discusses the relevant literature with regard to the use of GIS in transit planning and the effects of transfers, access distance, and demographics and density on ridership levels. Chapter Three provides the methodology used in this study to improve the efficiency of service planning and the development of the three tools (the Transfer Tool, Access Tool, and Route Planning Tool). Chapter Four applies the methodology to the Region of Waterloo and analysis the findings of the study. Finally, Chapter Five reviews the contribution of the work into the wider area of transit planning, limitations of the study, and future extensions to the work.

CHAPTER 2: LITERATURE REVIEW

Public transportation is central for the economic and social wellbeing of a region's population (CUTA, 2003). It provides mobility to those who may otherwise not have access to viable transportation options and also provides a sustainable transportation choice that can serve as an important economic stimulant, reduce congestion and pollution levels, and encourage physical activity. Providing service area coverage (accessibility) and connectivity within the transit network are important considerations for any transit system. Transit agencies must also operate within a limited budget, and must justify the existence of service through ridership numbers and cost recovery (fare collection). A need exists for tools and methods that enable transit planners to improve system operation from both the rider's and the agency's perspective. This section reviews literature related to transportation planning and the variables that affect transit ridership, such as access distance, the presence of transfers, and demographics. Moreover, the use of GIS in transportation planning is discussed.

2.1 TRANSPORTATION PLANNING

Broadly speaking, transportation studies focus on the movement of goods and services and the infrastructure along which these commodities flow. Objectives in transit planning are often to minimize congestion, maximise safety, and to plan corridors to meet the transportation needs of the future. To accomplish this, the movements of traffic – be it auto, transit, or pedestrian traffic – are modelled to represent current and estimate future travel demand and system performance.

These travel flows are typically modelled between aggregated traffic analysis zones (TAZs) that serve as origin and destination (OD) pairs. The boundaries of TAZs are primarily defined by the socio-demographic and economic characteristics of the basic spatial units they represent, and also by geographic location (You, Nedovic-Budu, & Kim, 1999). Modelling travel between OD pairs allows agencies to study aggregated travel demands rather than individual trips which would be resource intensive. Furthermore, the use of TAZs provides the aggregated level of data from which economic and demographic data can be collected in order to generate estimates of travel flows (Miller & Shaw, 2001). TAZs are the spatial level of disaggregation used in this thesis.

Conventional transportation planning in North America has typically centred on the automobile (Hodge & Gordon, 2008). More recently, greater attention has been directed toward planning for alternative modes, such as transit or cycling. Transportation models have improved to include various modes as well as the land use and environmental impacts of various transportation options (Ortuzar & Willumsen, 2011).

However, full scale, multimodal, robust travel forecasting models are typically resource intensive in their development and maintenance. Many transit agencies receive limited resources for planning and operations compared to groups dedicated to highways and roadways, leaving them understaffed to undertake large planning exercises. Moreover, transit agencies typically do not receive stable funding for service expansion from year to year, further limiting their abilities to plan for service changes or upgrades. Often if any funding is received, it is limited. As a result, transit agencies must develop less resource intensive planning methods that are sufficiently sophisticated to identify investments that attract and maintain riders (Hodge & Gordon, 2008). These are the transit planning challenges that this thesis addresses.

2.2 GIS AND TRANSIT PLANNING

A broad definition of GIS is given by Burrough (1986) as a "set of tools for collecting, storing, retrieving at will, transforming, and displaying spatial data from the real world for a particular set of purposes". The key difference between GIS and other data storage mechanisms such as a relational database management system is the way in which data are referenced. Generally, GIS are used to manipulate and analyze spatial data that are tied to a unique geographic location. Within a GIS, data can be organized and displayed efficiently, integrated with additional data sets, analyzed, and manipulated to create new data useful for decision making (Carver et al., 2002; Thill, 2000).

GIS handle two types of data – geographical data and attribute data. Geographical data represent the spatial characteristics of real world features, while the non-spatial attribute data provide descriptive information of these features (Carver et al., 2002). Data analysis within a GIS can be classified into three broad categories: storage and retrieval, queries to explore patterns within the data, and modelling procedures for the prediction of what data may be under various circumstances. After analysis, data output can take several forms, such as visual displays like maps, tables or graphs, or digital outputs for further analysis (Carver et al., 2002).

A GIS represents, or models, real-world phenomena in two different contexts as shown in Figure 2.1. Field models (raster datasets) represent continuous observations over space, such as elevation or temperature. Discrete models (vector datasets) represent separate or distinct entities in space, such as a building or lake. As part of discrete models, network models are organized as a series of interconnected lines that make up a system of features through which resources can flow, such as a roads or a utility network (Thill, 2000).

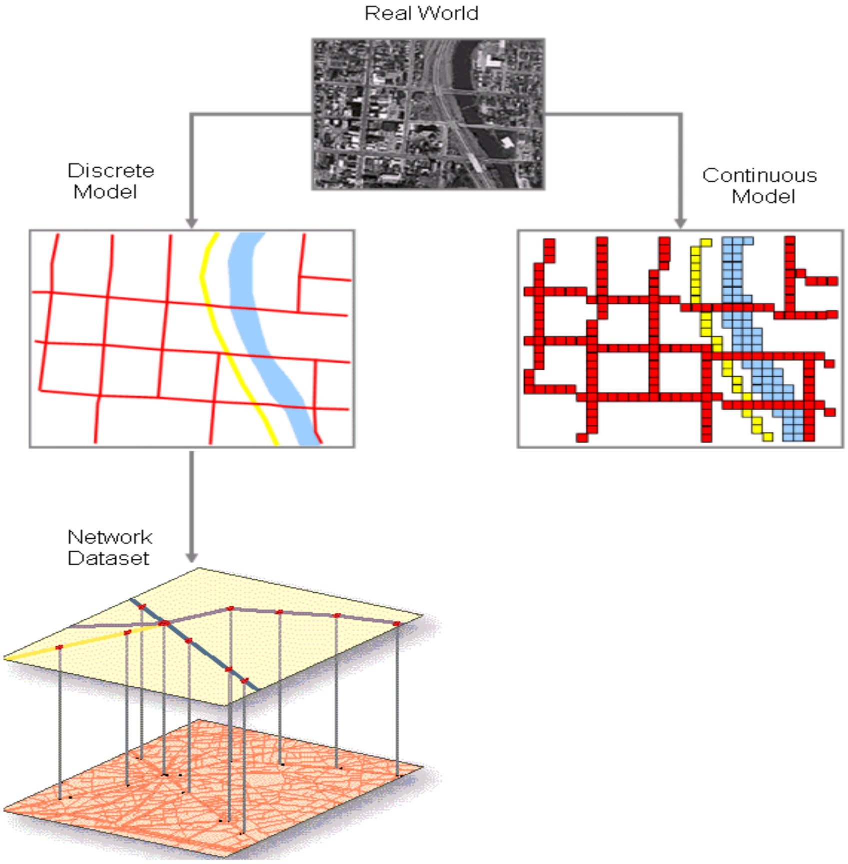


Figure 2.1. Transportation systems represented in GIS. Source: The Geography of Transportation Systems, ArcGIS Help.

The network model is the most natural representation of the movement of goods and people from a transportation perspective. Network models are constructed with a series of connected edges (arcs) and points (nodes, or junctions). This connectivity is referred to as the topology of the network. A common network analysis function is the calculation of the shortest path between points within a network. Traditional shortest path algorithms model travel paths across networks that minimize a user specified single or combined impedance – such as travel time or distance (Huang, 2007; Carver et al., 2002).

Conceptually, a transit system can be represented through a simple structure composed of edges and nodes. Edges represent portions of the transit routes themselves while nodes connect the route segments together. Bus stops are also represented by nodes, or points, where passengers can enter and exit the system. Within a GIS, the geographic elements of the network (the routes and bus stops) are stored as edges and nodes, while attribute information (such as route name, route length, or the number of boardings at each stop) are stored in a table attached to these features (Dueker, Groff, & Peng, 1998).

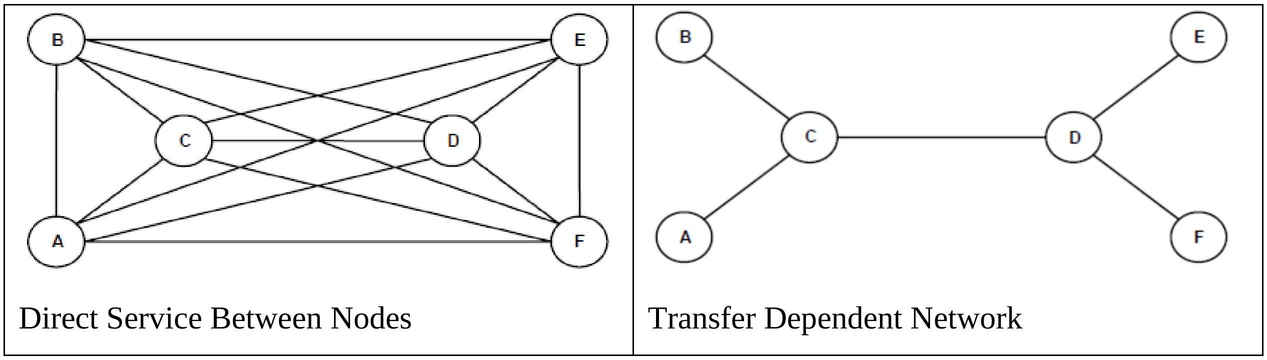
This thesis utilizes the Network Analyst extension from the ArcGIS suite of tools which allows users to build and manage network datasets in order to solve common network problems. In reality, there are *n* combinations of edges (or potential paths) between two destinations. The Network Analysis software is beneficial, as it encompasses algorithms to calculate the best set of edges (best route) according to the known objectives (e.g. minutes of travel time) and constraints (one way streets, speed limits). Primarily, the software uses Dijkstra's algorithm, a weighted graph algorithm, commonly used to find the shortest path between destinations. The algorithm constructs a tree with the minimum length between all nodes and continuously solves for a travel path between destinations until the shortest path is calculated. This algorithm can be used to solve problems such as finding the shortest path between stops, or to calculate the number of facilities within *x* metres of a specified location. The latter problem is useful for exercises such as determining the number of houses within a certain distance of a transit stop or coffee shop.

The use of GIS in transit planning studies varies widely. The focus of these studies include the use of GIS to: measure accessibility to transit facilities (Grengs, 2004; Lei & Church, 2010; Kuby et al., 2004), develop and select transit lines (Ramirez & Seneviratne, 1996; Simard, 2010), optimize bus stop placement and spacing (Furth & Rahbee, 2000; Murray, 2001), analyze potential markets for transit (Murray, Davis, Stimson, & Ferreira, 1998), and analyze the efficiency of transit systems (Lao & Liu, 2010). Within transit agencies themselves, a 2003 survey of over 100 transit agencies in the US found that 74% of respondents did use some sort of GIS. Most commonly, GIS were employed to aid in service planning (visualization and presentation), map production, scheduling for paratransit services, market analysis, and ADA compliance (Sutton, 2005).

2.3 TRANSFER PENALTIES

Incorporating transfers into transit service offers various advantages, such as more efficient and flexible routing compared to networks with few or no transfers. The presence of transfers allow the transit agency to provide a wider selection of travel routes that are designed to suit each area within the network most efficiently depending on local topography, passenger volumes, and character of demand (Vuchic, 2005).

The importance of transfers is illustrated by the diagrams below of a simple transit network consisting of six nodes (Figure 2.2) and 15 origin destination (OD) pairs. If direct service (no transfers) is provided between each pair of nodes a total 15 routes are required (as displayed on the left hand side of the diagram). Alternatively, nodes C and D could serve as transfer points or 'hubs' in order to facilitate connections between each set of nodes, requiring only five routes to link each origin to each destination (Desautlels, 2006). This arrangement represents a 'hub and spoke' system. By reducing the number of routes required to serve all OD pairs, these routes can operate on much higher frequencies compared to a network that provides direct service between all destinations; however the latter network introduces the need to transfer. In the hub and spoke network, there are five, six and four OD pairs that require 0, 1 and 2 transfers respectively. If heavy demand existed between nodes B and E, for example, the system would be much improved by providing a direct route between the nodes, thereby eliminating two transfers for this high-volume travel pair.



Direct Service Between Nodes

Transfer Dependent Network

Figure 2.2. Example of a direct network and a hub and spoke system. Source: Desautlels, 2006

Aside from transit networks, hub and spoke systems are widely used in air passenger, air freight, and trucking industries. These structures are arranged so that strategically located ‘hubs’ act as central nodes in a network – facilitating connections within the system via ‘spokes’ that feed into them. Additional considerations in planning hub and spoke systems include the layout of the spoke lines throughout the network in order to ensure that service does not fall below a certain level so as to drive off demand (O’Kelly, 1998). Hubs act as locations to and from which materials are consolidated and distributed. Although they require circuitous routing, these systems are widely used as they provide greater connectivity between locations and economies of scale. O’Kelly (1998, p. 183) cautions that hub and spoke networks must be designed so that they do not ‘lock in on flows which will inevitably change over time.’

As mentioned previously, transit networks are reliant on transfers to make travel to every destination serviced by transit possible, while minimizing operational resources such as the number of routes. Yet many studies acknowledge that the presence of a transfer significantly reduces ridership (Liu et al., 2009; Iseki & Taylor, 2009; Guo & Wilson, 2009; Newman et al., 1983). Many transit agencies believe that users are not willing to make more than one transfer during their trip (Stern, 1996). The factors that affect willingness to transfer vary between individuals, though generally they may include: extended trip times, possible risk of missed connections, increased physical and mental effort, additional trip costs, and if occurring at street level, exposure to externalities such as weather and traffic. Passengers must exert additional mental effort when locating the stop at which the transfer occurs (Vuchic, 2005; Iseki & Taylor, 2009) and personal security may also be a concern, especially during the evening (Stern, 1996).

The elimination or coordination of transfers within a system is generally an important consideration for transit system design (Zhao & Gan, 2003). In order to study the impacts of transfers within a system, transportation studies combine the negative components of a transfer into an overall transfer penalty measure. The penalty is a cost associated with the presence of a transfer during a trip, typically measured as the equivalent of in-vehicle travel time expressed in minutes. This cost is in addition to in-vehicle travel time (Currie, 2005). In order to quantify how transfers affect the quality of the transit service, a penalty value can be assigned to each transfer location between the various routes within a network, based on selected criteria (Guo & Wilson, 2007).

2.3.1 Travel Costs and Transfers

Travel is often described as a derived demand – an activity that is conducted as a means to achieve other goals, such as commuting to work or shopping. Therefore, rather than attempting to maximize utility (benefits) from a trip, travelers choose alternatives (departure times, paths or modes) to minimize disutility (or costs) associated with the trip (Casello & Hellinga, 2008).

In transportation analyses, the overall disutility calculation for a mode or travel pair is known as a generalized cost (GC) function (Ortuzar & Williumsen, 2001). The GC function is used to estimate the cost of travel between OD pairs by disaggregating the various components within a trip. The GC function also converts the various attributes into a common unit, allowing comparison of the level of importance of each attribute. When alternative travel modes are available, users will make their choice based on the generalized costs of competing modes (Casello & Hellinga, 2008).

For travel by public transit, the associated disutility of a trip can be grouped into several categories: access time, initial waiting time, in-vehicle travel time, and a transfer penalty, as well as out of pocket costs (Casello & Hellinga, 2008). Since passengers generally perceive these components of a trip differently, they are weighted accordingly to determine their contribution to a trip's overall disutility. The GC for a transit trip may be calculated by an equation of the form:

$$CG_{OD}^{i} = (\alpha_1 AC + \alpha_2 WT + \alpha_3 IVTT + \alpha_4 TT + TP)\frac{VOT}{60} + fare \qquad (2.1)$$

Where:

GC is the generalized cost for travel from origin *O* to destination *D* via route *i*, measured in dollars;
α is the relative weight of the cost component*;*
AC is the access time for walking to transit, measured in minutes;
WT is the initial waiting time, measured in minutes;
INVT is the in-vehicle travel time, measured in minutes;
TT is the transfer time, measured in minutes;
TP is the transfer penalty, measured in minutes;
VOT is the value of time, measured as dollars per hour; and
fare is the value of the transit fare, measured in dollars.

The costs associated with each of these travel components are based on a person's perception of the relative disutility of that component. Typically, in-vehicle travel time is assigned a value of 1.0 – users perceive in-vehicle time as the actual travel time – and all other variables are weighted as either more or less important (Casello et al., 2009). These relative values can be ascertained from surveys, or can be taken from mean values derived from previous studies. Value of time (VOT) is typically measured on a regional basis as a function of the average income (Casello & Hellinga, 2008). It represents the monetary amount for compensation of lost time or the amount that one would be willing to pay in order to save time (Wardman, 2004).

Various studies have found that users perceive transfer time to be “more onerous” than time spent traveling within the vehicle (Casello & Hellinga, 2008). This is to say that people perceive the burden of transferring to be greater than the actual time associated with the transfer (Liu et al. 1998; Hess et al., 2005; Iseki & Taylor, 2009). An active area of research is this mapping of actual transfer times (*TT*) to users’ perceptions of these times (*TP*). Previous reports have placed the average value of transfers at 8 minutes upward to 49 minutes (Currie, 2005; Iseki & Taylor, 2009; Wardman, 2001). The value typically ranges depending on what mode of transit is utilized. Algers et al. (1975) found that the transfer penalty between subways was the lowest, followed by rail, with transfers between buses having a substantially higher transfer penalty. Bus transfers are likely higher because they generally occur on the street level and normally leave passengers exposed to weather, often involve crossing at an intersection, and tend to have limited passenger facilities and information. Transfers may also be more unreliable between buses as vehicles operate in mixed traffic. Meanwhile, subway systems have more facilities and typically occur inside (Currie, 2005; Algers et al., 1975; Iseki & Taylor, 2009).

2.3.2 Factors that Influence the Transfer Penalty

Many of the previous studies on transfers have applied a general transfer penalty to the entire network, such as a penalty of 22 minutes within a bus network. Additional studies have disaggregated components of the transfer penalty and have individually considered the waiting time between transferring vehicles, as well as the time required to walk between stops or stations with these times generally being weighted as twice the value of IVTT, or twice as onerous as time spent traveling within the vehicle (Iseki & Taylor, 2009; Wardman, 2001).

A few more recent studies have begun to further break down the transfer penalty, considering individual station attributes such as the presence of an escalator, shelters, or available information (Guo & Wilson, 2004; Wardman et al., 2001). Several stated preference studies have used survey data and GIS to analyze the effects of transfers on travel behaviour.

Iseki et al. (2009) conducted a survey of 750 transit passengers in Los Angeles County and 175 transit agencies in the US, asking them to rank 16 attributes in terms of importance when completing a transfer. The effect that these variables had on the overall perception of transfers varied depending on the type of statistical test used, although connection and reliability, feeling safe and secure, as well as the ease of being able to navigate around the stops/station (available information) consistently ranked among the highest.

Guo & Wilson (2004, 2007) and Guo & Ferreira (2008) used discrete choice models to analyze the relationship between travel paths within a transit network and the attributes of rail stations. Discrete choice models are used to predict or model how people make decisions between a set of finite options. Decisions are related back to the variables of each option available and the attributes of the person making the choice. The above studies used on-board surveys and inferred alternative routes - generated in GIS - to observe whether people chose to walk from commuter rail to their destination or transfer to the subway. These choices were then related back to the station design and location, as well as the effects of surrounding land uses. It was found that inter-modal (between various transit modes) transfers were thought to be more cumbersome than intra-modal (between the same mode). Additionally, longer walk distances between vehicles, complicated connections, and additional fares contributed to higher penalty costs associated with transfers. The study found that people are more willing to walk, and are willing to walk longer distances to avoid transfers if the area through which they walk is pedestrian friendly. If the area is not conducive to pedestrian travel, passengers transfer to avoid additional walk time.

Mathematical optimization methods have been developed to produce transit networks that minimize the number of transfers within a system. See for example Baaj & Mahmassani, (1995); Zhao (2003); and Zhao & Ubaka, (2004). Mathematical models are composed of a set of variables such as passenger flow or length of the line, and a set of functions or equations which define the relationships between the variables (Yang et al., 2005). These methods employ algorithms to optimize a transit network within a matrix of nodes and lines until an optimal solution is reached given a set of requirements or constraints, such as the maximum length of a route (Zhao & Gan, 2004). However, these models are often so complex that they are not practical to implement by transit agencies (Yu et al., 2005; Zhoa & Gan 2003).

Some studies have begun to compute scheduled-based path finding algorithms to help model travel across transit networks. These studies generally search for the most efficient path across a network considering planned departure and expected arrival times, and may include considerations such as the presence of a transfer (Huang & Peng, 2002). Yet, similar to mathematical optimization methods, because of the more complicated nature of these algorithms, they are rarely put into practice within transit agencies.

As noted previously, studies are beginning to disaggregate the various components of transfers that contribute to the overall perception of a transfer penalty. Yet the relative weight or importance of variables – such as the quality of the pedestrian environment, available lighting, or the presence of washroom facilities – have yet to be classified. Also, studies that have broken down the transfer penalty tend to focus on small study areas centred around stations within downtown cores which typically have greater public facilities. There is still little focus on a system-wide analysis of the effect of transfers. Moreover, studies have shown that even when the impacts of transfers are minimized, the mere presence of a transfer continues to have a negative impact on ridership (Liu et al. 2009; Iseki & Taylor 2009; Guo & Wilson, 2009; Newman et al. 1983).

This study develops a method to scan a network in order to determine which trips require one or more transfers in comparison to the number of potential riders affected by the transfer. In doing so, trips with high travel flows may be targeted for service improvements resulting in transit service that is more appealing to a greater number of current and potential customers.

2.4 TRANSIT ACCESSIBILITY

Murray et al. (1998, p 2) define access as “the opportunity for system use based upon proximity to the service and its cost.” They further recognize that “if the distances or barriers to access a service are too great at either the trip origin or destination, then it is unlikely to be utilized as a mode of travel.” Based on these commonly understood relationships, many municipal and regional transportation plans specify desired percentages of the population within certain access distances or times to transit.

This section reviews the literature on the importance of access to transit systems in generating ridership. Moreover, studies which correlate neighborhood design and accessibility are examined. This section concludes with a summary of previous methods to quantify accessibility to transit systems.

2.4.1 Importance of Access

Previous research suggests that most transit users walk to a transit stop or station in order to access the service as opposed to arriving by modes such as automobiles or bicycles. Travel surveys in California and Florida found that 80% of transit users walked to the stop from their origin, while 90% and 75%, respectively, walked from transit to their destination (Hsiao et al. 1997, Zhao et al., 2003). Loutzenheiser (1997) conducted an access study involving rail transit, in which 24% of passengers walked to stations, while more than 75% walked from the stations to access their destinations.

Research also shows that as walking distance to a transit stop or station increases, the likelihood of utilizing transit decreases. For instance, Dill (2003) found that a 10% increase in walking distances to transit resulted in a 10% decline in ridership. Similarly, Loutzenheiser's study (1997) found that the probability of a passenger accessing a transit station by walking decreased by 50% for every additional 500 metres of walking distance. Many studies model the relationship between transit use and access distances through the use of distance decay functions which model the rate at which transit patronage decreases as walking distances to transit increase. Typically, transit patronage begins to decline after approximately 100 metres and cease after approximately 600 metres (Levinson & Brown-West, 1984; Zhoa et al., 2003; Lam & Morral, 1982; Kimpel et al., 2007). Through this relationship, access distances become the primary consideration in determining transit patronage while additional concerns – such as cost, comfort, or even travel time – are secondary (Beimborn et al., 2003).

Transit planners and researchers generally agree that most passengers are willing to walk 400 metres to the closest stop (O'Neill et al., 1992; Hsiao et al., 1997). The unwillingness to walk long distances to access transit may be partially attributed to the cost, or disutility, perceived with the walk. Studies have found that walking time to and from a bus stop or station is weighted at 1.4 to 2.0 times more arduous than in-vehicle time (Paulleya et al., 2006). The US Environmental Protection Agency's review of 50 US studies placed walk time costs somewhere between 2 and 2.72 times as arduous as actual walking time (Iseki & Taylor, 2009). Therefore, someone who lives and works near transit stops is likely to perceive a transit trip as less onerous (lower cost) than someone who lives or works further from transit stops. As user costs for transit are decreased, we expect ridership to increase. Given this sensitivity between access distances and ridership, improved estimates of actual walking distances may improve transit planning methods.

Proximity to transit, in large part, may depend on neighborhood design. Older neighborhoods are typically laid out in a grid pattern, with smaller blocks and greater connectivity, providing more direct access to main streets where transit stops are often located. Newer neighborhoods, normally designed with cul-de-sacs and crescents, are more often closed off to surrounding neighborhoods by a loop road or "community wall" (Zhao et al., 2003). This results in several issues: pedestrian access to main roads (and therefore transit) is limited; a transit vehicle's ability to penetrate the neighborhood is restricted; and routes where vehicles must make many turns are inefficient as they result in indirect paths and also limit vehicle acceleration (Zhao et al., 2003; Mackey, 1990).

The most basic metric of transit accessibility is the percentage or proportion of the population within a specified distance to transit, typically 400 metres, or 0.25 miles (Zhao et al., 2003). Various approaches to measure access distances include the buffer, raster, network ratio, and parcel based methods.

Initial studies of access distances utilized methods that relied on extensive data collection. For instance, Levinson and Brown-West (1984) estimated how route changes – such as a route extension – would affect ridership levels according to changing access distances within a neighborhood and car ownership. Estimates were projected based on data obtained from on-board surveys in which people were asked how far they lived from a transit stop, and the number of cars in their household. These data were manipulated to create "ridership penetration curves" which were then used to predict ridership for future changes.

Since this study, the use of GIS to estimate access distances has become widely accepted and implemented. The simplest technique is the buffer method. Using GIS software, buffers – or polycentric rings at specified distances – are generated around the current transit network structure. If a street falls within the buffer, it is presumed that the area has a reasonable accessibility to transit service. If a street falls outside of a buffered area, then it is considered to be under serviced by transit (Lei & Church, 2010). A similar approach to the buffer-based approach is the raster method. Again, within a GIS, the study area is divided into a grid with each cell containing the value of the distance from the transit network providing a better representation of the continuous nature of distance compared to the buffer approach (Kuby et al., 2004). These methods are compared in Figure 2.3.

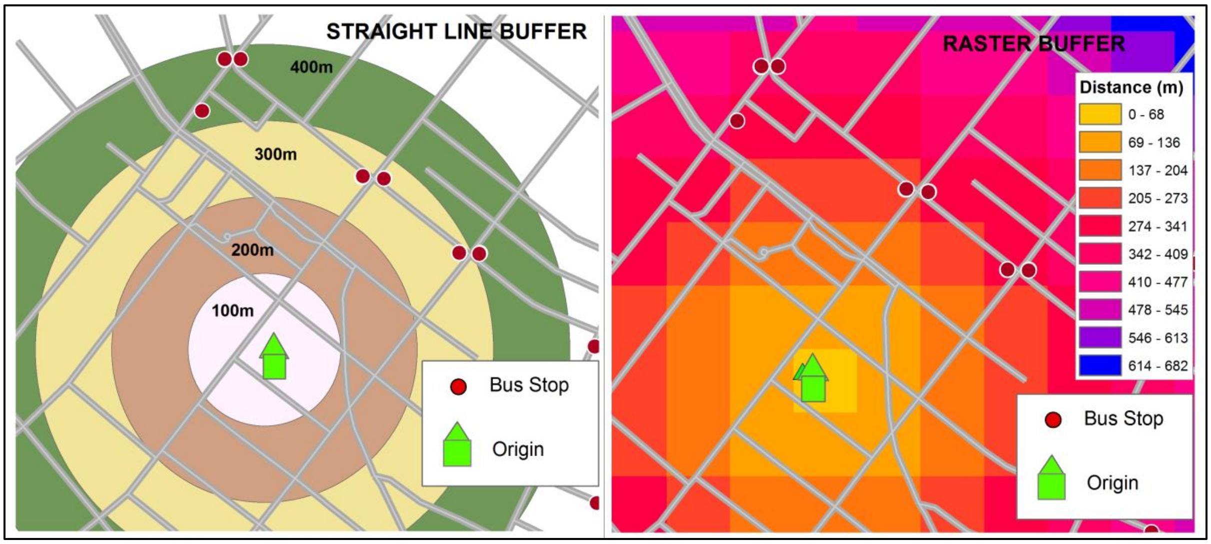


Figure 2.3 Comparing straight line buffers and raster methods

Both the buffer and raster approaches calculate a Euclidean – or straight-line – access distance from transit, and do not consider the layout of the street or pedestrian networks, or barriers such as rivers, fences, or highways. Typically, the actual distance that pedestrians must walk to transit is significantly farther than the Euclidean distance (Zhao, 1998; Zhao et al., 2003; Biba et al., 2010; Dill 2003; O’Neill et al., 1992). Hoback et al. (2008) found that in the city of Detroit actual walking distances were 2.49 times longer than the straight lines distances, and that in the suburban areas, actual distances would likely be greater.

Several methods have been developed to address the shortcomings of the buffer method. The network ratio method, developed by O'Neill (1992), estimates the residential population as follows. The total length of the street segments within 400 metres of a transit stop is measured and is divided by the total length of all the streets within the neighborhood in order to obtain a ratio of the streets served by transit. The percentage of street lengths served is then multiplied by the total population of the study area to generate a percentage of population served by transit. However, this method assumes that population is distributed evenly along the road network, and does not consider non-residential uses such as commercial lands or green space.

Building upon the network ratio method, Zhao (1998) incorporated residential data in his study, and only selected land uses that were zoned as single and multi-family residential. The study also involved collecting spatial information of man-made barriers. While it was found that including land use data improved the accuracy of the estimations, the main limitation to this study was the significant amount of time and effort required to collect information on what barriers were present.

Hoback et al. (2008) used Monte Carlo simulation to determine walking distances to transit in Detroit. A small subset of homes was randomly selected to represent the total population. Distances were calculated from the front of each house to a bus stop from which travel in all directions was possible. Only stops within a 20 minute walk along the street network were considered. While the method requires little data acquisition or processing, it does not provide a complete picture of the different types of neighborhoods, provide access estimates for individual routes, nor does it highlight which areas have poor transit access.

Zhao et al., (2003) used a distance decay regression model to analyze and forecast residential access to transit based on data collected from onboard transit surveys. Information regarding the street layout was also included based on how many streets within a TAZ intersect the TAZ boundary. This study again involves fairly extensive data collection. The function produced the curve depicted in Figure 2.4 which indicates that transit patronage practically ceases after approximately 2600 feet (just under 800 metres).

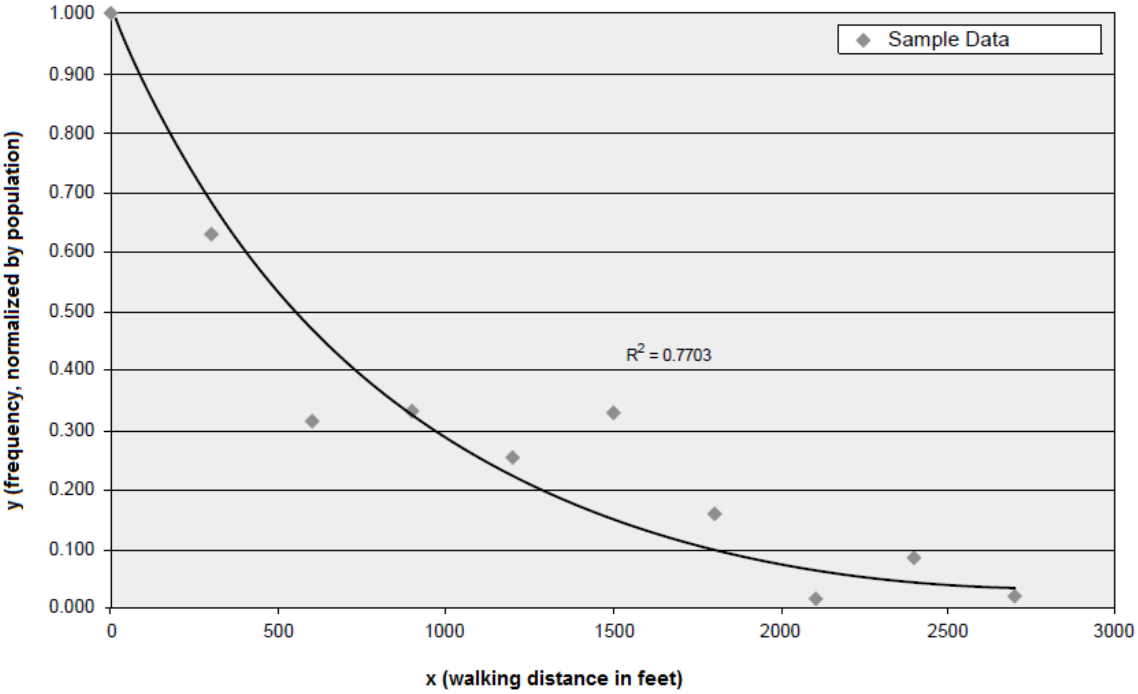


Figure 2.4. Estimation of the decay function of service population Source: Zhao et al., 2003

Kimpel et al. (2007) developed a distance decay function that measures the level of accessibility from features to transit facilities. The function reflects a gradual decline in transit usage as distance from transit increases, a steeper decline around a ¼ mile (some 400 metres), and a gradual tail. Various parameters were tested for the function to determine the best fit of the data, as demonstrated in Figure 2.5. Based on this, the probability of demand (level of activity) at a transit stop is estimated. As opposed to simply taking the population served by a transit stop or route, the function quantifies the sum of probability of demand for all facilities of interest (those within a transit service area) generating the total probability, or likelihood, of the population using each particular transit stop.

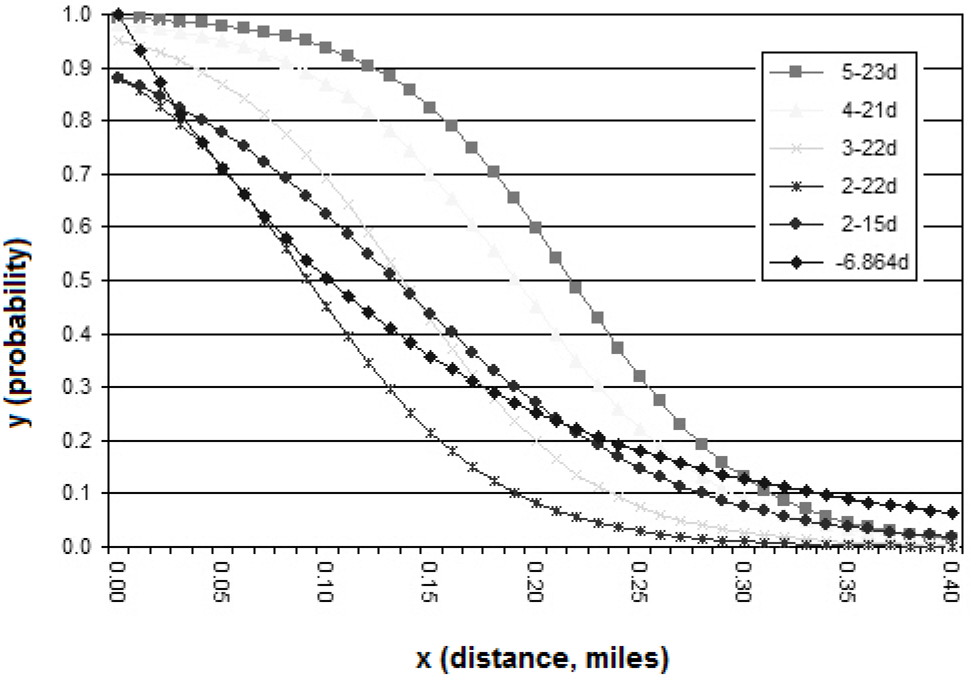


Figure 2.5. Estimates of probability of demand for transit using various exponential functions
Source: Kimpel et al., 2007

Biba et al. (2010) used disaggregate data at the parcel level to analyze access to transit from residential neighbourhoods. Their method generated lines from the centroid of the parcel to the street network, and then measured the distance along the street to the closest transit stop. In order to estimate the population of each parcel, the total population of a census tract was divided by the total number of parcels within the tract, distributing the population evenly amongst the parcels. While this method captures access distances accurately from each parcel, assuming uniform population distribution across the census tract negates the ability to capture the true significance of access distance at each parcel. Because census tracts normally have populations ranging from 2,500 to 8,000, this can introduce significant error.

Many of the previous studies focus on residential access at an aggregated level that does not consider how neighborhood design or the densities of local neighbourhoods influence transit usage. The majority of current studies use Euclidean distances and buffers to measure access.

Those methods that do follow the street network continue to ignore trails and paths that make up an important part of the true pedestrian network.

The methodology used in this thesis measures transit accessibility from each building in a study area to generate a distribution of access distances to the system. This technique also can be used to differentiate access distances from buildings with different sizes (footprints). These approaches are applied to neighbourhoods with different street configurations to analyze the impacts of local networks on accessibility.

2.5 RIDERSHIP FORECASTS AND CALBIRATION

In order to estimate the amount of transportation resources required to accommodate future travel demand and to allocate trips accordingly, municipalities often develop travel forecasting models. These forecasts are used to calculate the utilization of infrastructure, estimate levels of service, and predict travel patterns under current and future conditions. They are also used to evaluate social or financial implications and the feasibility of projects – such as the introduction of a new transit route, or the construction of a new bridge. These models are also used to estimate modal splits between the various transportation options (such as auto, transit, or walk). Travel forecasts are therefore a useful tool when planning projects and policies, and when allocating resources to transportation infrastructure (Metropolitan Washington Council of Governments – MWCG, 2011).

Some larger transit agencies use travel forecasting models to predict ridership on their systems. By examining current patterns of demand and forecasts to predict future demand, transit planners are able to identify areas where additional resources – higher service frequencies or new routes – are necessary to accommodate demand or attract potential riders.

In this section, the most commonly used travel forecasting model – the four step travel model – is explained and its limitations are highlighted. The effects of operational and demographic variables on ridership are discussed. A brief overview of studies where variables have be applied to output generated from travel forecast models to predict ridership is included.

2.5.1 Four Step Models – Explained

Many cities use a similar approach to model and forecast travel behaviour. This method, known as the Four Step Travel model, consists of the following main steps: trip generation, trip distribution, mode choice, and trip assignment. Data fed into the model varies between organizations, but generally include land use; road, highway and transit networks; and socio-demographic data collected at the Traffic Analysis Zone (TAZ) level. TAZs are spatial constructs created by transportation officials or local governments to act as study areas for traffic related data and are normally comprised of census blocks (U.S. Census Bureau, 2001). Often, household travel surveys and traffic studies are conducted for additional input into the model. Some models may also include demographic information such as household income to help predict travel patterns (Ortuzar & Willumsen, 2011). The four steps are explained in further detail below.

Trip Generation/Attraction – Each zone within the study area is thought to produce (starting origin) and attract (end destination) trips. The number of trips predicted is based on assumptions drawn from land use and demographic data input into the model. For instance, it is assumed that households with one car are likely to generate fewer trips than households with two or more cars; zones with high employment numbers are assumed to attract more trips compared to zones with low employment. The end result of this step is the number of trips beginning and ending in each zone, though it is not determined at this stage how these trips relate to each other (Ortuzar & Willumsen, 2011).

Trip Distribution – Once the number of trips has been predicted, each origin is linked to a specific destination – that is, a start and end point is determined for each trip. These OD pairs are most often created using a gravity model (Ortuzar & Willumsen, 2011). Gravity models are a form of interaction model that predict the movement of people, information, or commodities between various locations as a function of the mass or population of each location and the distance between them. Larger (or more populated) zones attract a greater number of trips or commodities. The strength of the pull between the two zones is a function of the distance between them, with zones closer together having a stronger attraction (Haynes & Fotheringham, 1984). As such, a greater number of trips are assigned between proximate zones and zones with higher population and employment values. Fewer trips are assumed between zones that are moderately close, while still fewer trips will be attracted to distant zones or zones with lower population and employment densities. The analysis results in a matrix of trip volumes between each origin and each destination zone (Ortuzar & Willumsen, 2011).

Mode Choice – The next step is to split the total trips between the various modes of travel available which typically include: auto alone, auto passenger, transit, bike, and walk. Typically a logit model is used to determine modal split based on the availability and attractiveness of each mode (Ben-Akiva & Lerman, 1985). A logit model works as follows: the probability of selecting a mode *m* for a trip from origin *O* to destination *D* depends on the generalized cost of mode *m* relative to the generalized costs of the same trip by other available modes. In a simple example, a person may evaluate travel by transit versus auto. If the travel time by transit is one hour while the travel time by auto is 20 minutes, the likelihood of choosing transit is very low. If the travel times are equal, the likelihoods are equal.

In addition to “measurable” components of travel costs, generalized cost functions may also include a bias factor that represents a characteristic or variable that could affect mode choice, such as increased privacy for automobiles over transit (Southern California Association of Governments, 2011). Naturally, the presence and importance of these mode biases depend heavily on the population in the zones being serviced. For example, in very high income areas, with high auto ownership, travelers are often unwilling to use transit, even if the service is relatively competitive to other modes. On the other hand, in lower income areas, with low auto ownership, transit tends to attract a higher than expected number of riders. The mode bias parameter is used as a calibration tool to minimize region-wide error in transit mode share predictions (Casello and Jung, under review).

Trip Assignment – The final step assigns the actual path or route that will be used for each trip. An algorithm is used to select the `best path` to travel along based on distance and time (MWCG, 2011).

In this study we are most interested in the third step – how modal share is assigned. We are particularly interested in understanding how small changes in the transit network, particularly route alignments, influence the propensity to use transit in the area containing the proposed alignment change.

2.5.2 Limitations to the Four Step Model

While the Four Step model is widely used in transportation planning, many transit agencies are unsatisfied with these models' abilities to predict transit ridership. In a survey of 36 agencies in Canada and the US, a common statement was the need for simpler approaches to ridership forecasting that are more sophisticated, consistent, and easier to apply (Boyle, 2006).As previously indicated, most forecast models are data and resource intensive – data collection, processing, and analysis of the model may take several years to complete (McNally, 2008) making them costly to perform in terms of finances, time and employee resources. Therefore they are not undertaken very frequently, often only every ten years or so (TRB, 2007).

Generally, the focus of these models is long-range, capital investments, aimed at developing highways or major corridors. As such, they are not well suited to "scenario testing", or to modelling changes in developments and services at the neighbourhood level (Cervero, 2006; Pas, 2005). Additionally, future changes such as additions to the transit system sometimes are not incorporated into the model and will have no effect on modal split (TRB, 2007). Many models do not include walking or cycling, as these household travel surveys used as input into models often exclude these modes (Cervero, 2006). This in turn may lead to reduced funding for transit services (TRB, 2007).

The four step model is also constrained to modelling changes at the TAZ level, which is typically too large to pick up information made to individual neighbourhoods. For instance, it has been shown that transit ridership declines sharply as distance from a stop or station increases (Zhoa et al. 2003, Levinson & Brown-West, 1984). Therefore, if residential or employment densities are high immediately around a stop location, the likelihood of high ridership generation is far greater. However, it is unlikely that forecast models will pick this up, as density is averaged out over the entire TAZ (Bernick & Cervero, 1997).

Forecast models are slowly being altered or improved. Certain models are beginning to include a level of auto ownership, improving predictions of intra-zonal travel, or including data that represent the quality of the pedestrian environment and street connectivity. The latter improvements better capture the benefits of transit oriented development or mixed land uses on promoting non-motorized methods of travel (Cervero, 2006). However, many of these models are still being developed. As such, various efforts have been directed towards enhancing or supplementing the four-step method in the form of post-process analysis or the development of alternative direct models (Cervero, 2006).

Post-process analysis typically involves applying elasticities to the output generated from a four-step model in order to account for variables left out of the original model input that may affect modal split or trip generation (Cervero, 2006). Elasticity values are generally measured as the percent change in the demand or quantity of a service or commodity in response to a 1% change in price or level of service. Elasticities help to measure a change in the demand for transportation in relation to changes in service frequencies, transit fares, land use, or the cost of gasoline (Kuzmyak et al., 2003). Post- process analysis allows the inclusion of additional variables, or changes in land use or development without having to gather further information or recalibrate the model (Cervero, 2006).

Alternative direct models predict ridership based on localized transit service features, the quality of facilities, and changes in land use rather than using modal split results from larger forecasting models. In practice, these generally focus on specific nodes rather than corridors, and have been used to predict ridership for proposed rail projects at specific stations based on a small number of samples of other transit projects (Cervero, 2006). For example, Bay Area Transit (San Francisco) used regression analysis to correlation variables such as availability of parking, surrounding socio-demographic data, and transit service characteristics (i.e. frequency) against boarding and alighting counts at BART rail stations to predict ridership at a proposed station location (Fehr & Peers, 2004).

The approach in this thesis is to quantify the changes in users' costs as a result of minor changes in route alignment or operations and, as a result, estimate changes in ridership. The approach taken is to utilize the output from travel forecasting models – the disaggregate transit generalized costs – and to determine how the route alignment changes influences the access costs to the system. Moreover, the approach considers the populations influenced by the route change as described in the next section.

2.5.3 The Effect of Operational and Demographic Factors on Ridership

Numerous studies highlight various factors that influence one's willingness to use transit or the likelihood of being a captive transit user. Socio-demographic and economic variables such as income, age, citizenship status, auto ownership, as well as the percentage of post-secondary students have been found to explain a large variation in ridership levels. Additionally, population density and city size have a strong correlation to transit ridership (Kain & Liu, 1999; Holmgren, 2007; Taylor et al., 2009; Albalate & Bel, 2010).

The above mentioned factors are outside of a transit agency's control and may affect ridership levels differently at various times throughout the day. Peng et al. (1997) found that during peak periods the average income of transit riders was higher than those surveyed during the off-peak periods, suggesting that users who ride transit to commute during peak hours are more likely to be choice riders, compared to those who travel in off-peak periods. Kaplan et al. (2004) found that adding income distribution data to the St. Louis MetroLink forecasting model helped to improve accuracy of trip distribution. The model had previously assigned many trips from the CBD to a neighbouring community, though in reality, many of these trips began in upper class suburbs further away from the CBD. The study also found that the adjustments helped to account for non-home based work trips. In their meta-analysis on elasticities in transit demand models, Holmgren (2007) concludes that auto ownership, gas prices, and household income should be included as variables in demand models.

Public policies and land uses also impact ridership. Albalate and Bel (2010) reported that transit ridership declined with a large supply of parking in the CBD while focusing development around station areas helped to increase ridership. Operational variables (those controlled by a transit agency), such as fares or vehicle comfort, play a large role as well. The average operating speed of transit has a positive effect on ridership, while increased fares are typically correlated with a decline in ridership (Albalate & Bel, 2010). However, Bresson et al. (2004) found that an increase in fares could likely be offset by service improvements.

Taylor et al.'s (2009) meta-analysis of 265 urbanized areas in the US concluded that fares and service frequencies could explain about half of transit ridership. If the data were normalized for urbanized areas, approximately 25% of the variance in ridership per capita could be attributed to service frequency and fare levels.

To provide an accurate measure of transit utilization, the methods employed in this thesis to estimate ridership incorporate population and employment densities surrounding transit facilities. Using work done by Casello and Jung (under review), the methods utilized here measure if those areas for which the route change improves access are more or less transit supportive than the areas for which the route change decreases accessibility. In other words, by considering mode bias, this approach determines if a proposed change in alignment brings better service to those more likely to use transit.

2.5.4 Calibrating Models

In order to improve the accuracy of forecasted ridership impacts related to changes in transit route alignment, the output from travel forecast models can be calibrated against access distances to transit and demographic variables. The use of elasticity values is widespread in transit agencies when making changes to existing service, especially when it comes to changes in frequency (Boyle, 2006). Studies predicting ridership for proposed rail service also apply elasticities or post-processing techniques that modify results from travel forecast models.

When predicting ridership for proposed service changes, TriMet (the transit authority in Portland, Oregon) weighs population and employment data of properties within a ¼ mile buffer of transit, then applies elasticities based on service frequency (Boyle, 2006). This process is made easier with use of GIS to attach census data to associated routes and ridership (Boyle, 2006).

Cervero (2006) used post-processing methods to incorporate the influence of suburban employment on ridership for a proposed extension to a rail network. Experiences from various North American cities with commuter rail were used to introduce reverse commuter trips to ridership estimates. Auto-ownership rates (which influence modal splits) were also adjusted in areas with high densities or both employment and population.

Lane et al. (2006) generated an alternative model to predict ridership at proposed rail stations in small and mid-sized cities. Their model used ridership and demographic data from rail systems in 17 US regions to incorporate elasticities related to reverse-commute trips, the impact of higher operating speeds, higher frequencies during the mid-day period, and lower fares. Their resulting model was able to provide accurate predictions for commuter and light rail systems in the US.

This study proposes to apply a post-processing method of analysis to examine the impacts of transit route alterations on the generalized cost (GC) of transit (the combined monetary and non-monetary costs associated with a trip) for the affected regions as predicted by a four-step forecasting model. The GC of transit is measured as a function of access distance to transit and a transit bias (the willingness to use transit given certain demographic considerations). Bias values are typically used to bring estimated mode split values into agreement with observed values, and are often used to represent factors that are less tangible, such as the level of comfort or reliability of the mode (Boyce & Bar-Gera, 2003). In this study, bias values are a function of age, population density, and employment density.

2.6 SUMMARY OF LITERATURE REVIEW

The literature shows that numerous factors influence the perceived convenience of a transit trip, and therefore, transit ridership. It is generally accepted that the presence of a transfer on a trip can significantly reduce ridership as time spent transferring is considered to be much less acceptable compared to the time spent travelling in-vehicle. However, little is known about the effect of individual components involved in a transfer (such as the pedestrian environment or availability of facilities). Further, most transfer studies focus on the effects of transfers at a single station or core area rather than the wider transit network.

Access distances are another important consideration in transit planning, as most transit customers begin and end their transit trips on foot. Studies have shown that transit use decreases dramatically after 600 metres. Additional factors which influence transit ridership include demographic and economic characteristics. The literature suggests that income, age, and the amount of students in an area can all influence the propensity to use transit.

While travel forecast models typically include access and egress costs when calculating modal splits, these values often don't reflect actual walking distances. Additionally, while some travel forecast models now include variables such as auto ownership which helps to explain modal splits, often transit use is either under or over estimated. Moreover, creating and maintaining these models are time and resource intensive.

The techniques proposed in this thesis build off of current studies by using GIS software to provide a broad overview of the transfer costs within a transit network. GIS are also employed to generate accurate measurements of access distances to transit along true pedestrian networks, while at the same time, accounting for population and employment densities and neighbourhood street design. Further, the route planning tool presents a simple technique to produce transit mode split estimates for small changes in route alignment.

CHAPTER 3: METHODS

The focus of this thesis is to develop and apply easy-to-implement techniques for transit network planning and optimization. While travel forecasting models exist which help to plan and prioritize transportation infrastructure, they were largely developed to focus on the automobile and are generally used for long range planning (Ortuzar & Willumsen, 2011). However, these models output data that are beneficial for transit planning exercises – such as total travel volumes between TAZs, access costs and generalized costs for the various transportation modes, and modal splits. Yet these data are largely unused by transit agencies.

Three tools are developed in this thesis, all of which utilize GIS software and output generated from a travel forecasting model. These tools analyze:

1) Travel between OD pairs with a focus on identifying transfers which have a greater impact on customers travelling within the system;
2) Pedestrian access, considering the impacts of neighbourhood design on transit accessibility through a quantitative model that measures access via roadways and pedestrian (multi-purpose) paths at the parcel or building level;
3) Ridership impacts resulting from a route realignment that produces changes to access distances, population and employment density, and demographic data.

GIS software provides a platform to manage, manipulate, analyze, and display data; it is an ideal tool when studying spatial relationships. This thesis employs the ability to spatially reference data and automatically calculate geometric measurements, such as area and shape length, to produce a geographic analysis of bus stops locations and proximity to residences and businesses. Overlay, proximity, and buffer techniques are used to capture the demographic data within a defined study area, and the ArcMap Network Analyst extension is used to determine the best route between OD pairs.

The remainder of this chapter provides a description of software requirements and data organization, followed by a description of the methods used to develop the three tools presented in this study.

3.1 SOFTWARE REQUIREMENTS

The research presented in this thesis employs GIS software to model pedestrian and transit travel paths. GIS are also used to capture demographic and property information surrounding transit routes, and to create visual displays of travel path information. In addition to GIS data, information from travel forecasting models, including travel volumes and generalized costs, are used to determine the potential number of transit users for OD pairs and to produce transit ridership estimates.

The analysis for this study was conducted using traffic analysis zones (TAZs) which is the level of spatial disaggregation at which most travel forecasting models and various other transportation studies are conducted. The GIS software used was ESRI's ArcMap and its built-in suite of tools, ArcMap's Network Analyst extension, as well as some custom scripts.

Generally, transit applications in a GIS require transit route and transit stop datasets that are defined by a series of lines and nodes (Dueker et al., 1998). Lines or "edges", represent the routes along which vehicles travel, while nodes are used to represent stops where boarding and alighting take place. The Network Analyst extension requires that a network dataset be built which represents the line network over which transit or pedestrian traffic will flow. The dataset also contains connectivity rules which define how travel across the various layers or modes can occur, and attribute values, such as: length; drive-time; or walk-time, that the user may choose to define.

Within a network dataset, three types of network elements exist: edges (lines), junctions (points, or nodes), and turns. Edges and junctions make up the basic structure of a network (see Figure 3.1). Edges connect to other elements within the network and are the source along which resources flow. Junctions connect edges. This connectivity is referred to as the topology of the network. Turn features are optional elements that allow information to be stored regarding the movement between edges – such as an extra impedance at a left hand turn.

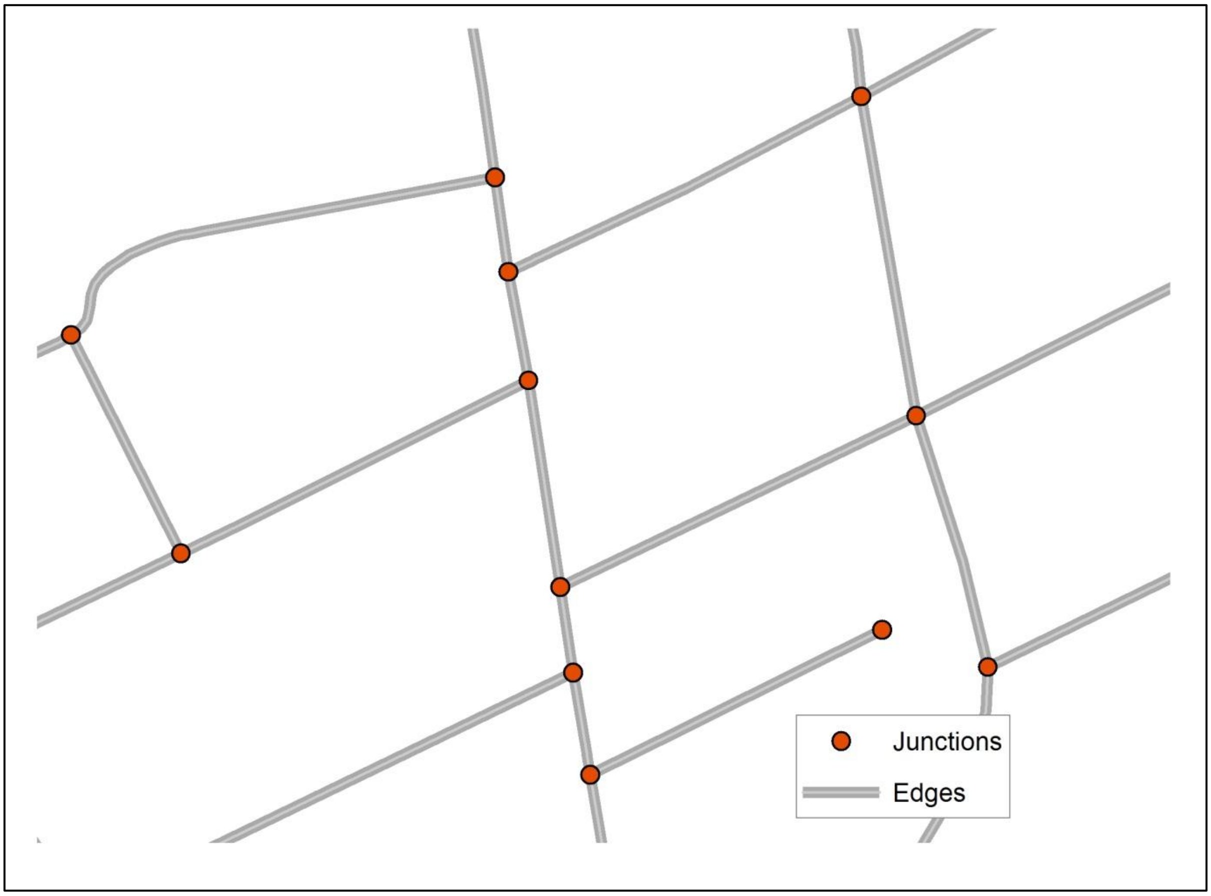


Figure 3.1 Nodes and edges in a network dataset

Connectivity Policies in Network Analyst

Connectivity policies and rules are used to create network datasets for modelling pedestrian and transit movements. The Transfer Tool, presented in Section 3.2, requires the use of a multimodal network that allows free flow of travel along a network consisting of both pedestrian and transit routes in order to analyze transit network design in relation to actual travel flows. The Access and Route Planning Tools use a pedestrian network dataset that only model pedestrian travel paths to transit along pathways and roads.

When a network dataset is created, connectivity policies must be set to define how the various network elements connect to one another and allow travel across and between layers (i.e. transfer locations where travel between a pedestrian network and a transit network are permitted). Connectivity is established based on features coinciding at vertices. It is not enough for layers to simply overlap. For line and point features to be connected they must meet at a shared vertex and/or line endpoint. To ensure that proper connectivity exists between the layers, network datasets must be “cleaned”. This can be accomplished in ArcMap using the “intersect” tool which splits layers where they intersect, thereby ensuring that the layers will share a vertex when the network is built.

Connectivity *between* datasets within a network begins with defining connectivity groups. Each edge source (line) can only be assigned to one connectivity group, while junction sources (points) can be assigned to one or more connectivity groups. Connectivity between edges in different connectivity groups can only exist if a common junction exists in both groups (the common junction layer forms the relationship between edge sources). In Figure 3.2, the Metro_Entrance layer acts as a shared junction for the Metro_Line and Street connectivity groups.

Connectivity rules are then applied which further define how datasets connect. Edges in the same connectivity group can connect in two ways: either only at end points of the lines (shown on the left side of Figure 3.3), or at any shared/coincident vertex (as shown on the right side of Figure 3.3). Similar to connectivity among edges, junctions can be set to connect at edge sources at end points of lines only, or at any vertex.

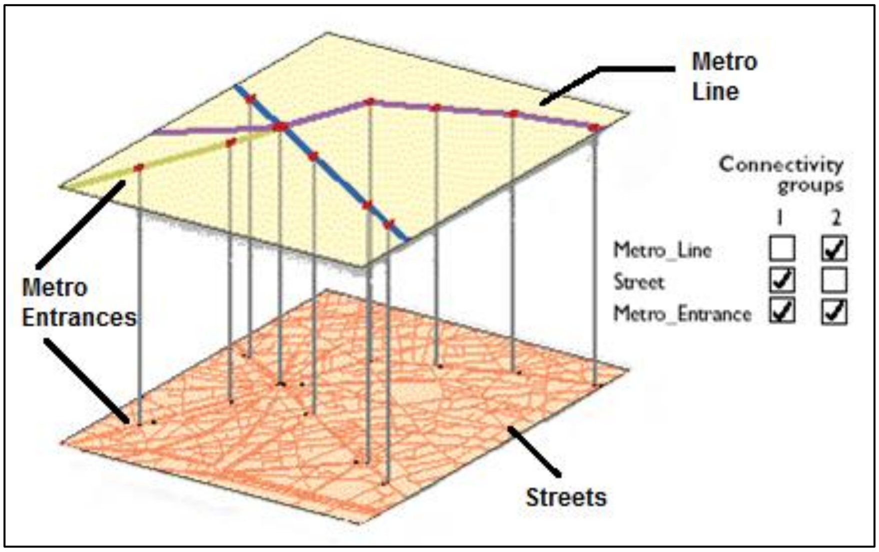


Figure 3.2. Connectivity groups in network datasets (ArcGIS Help)

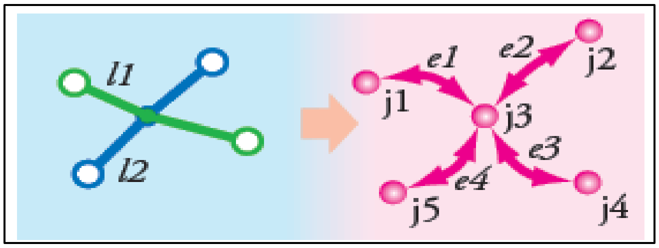


Figure 3.3. Connectivity in network datasets (ArcGIS Help)

Once connectivity is achieved, attributes are defined for the network dataset. Attributes describe characteristics of the network, and help to control how travel occurs along features. Attributes can include direction of travel (one way streets), travel time along a route segment, or length of a segment. For edge layers, if an attribute has a cost (such as travel time), the cost is divided proportionately along the length of each line segment.

3.1.1 Creating Networks for Analysis

As previously noted, the three tools presented in this thesis model pedestrian travel paths to transit facilities. The base GIS datasets required include the centrelines of roadways and off road trails which are combined to create a ubiquitous pedestrian network dataset. The locations of bus facilities are represented by a point layer, while building or parcel centroids are used to serve as origins when calculating access distances. A TAZ layer is constructed from polygons that store population and employment data. TAZs serve to define the study areas used for each tool.

Both the Access Tool (see Section 3.3.3) and the Route Planning Tool (Section 3.4) model pedestrian distances to the *closest* transit facility. In order to calculate shortest paths, a measure of impedance must be defined. One of the benefits of a GIS is its ability to automatically calculate geometries. In this case, the length of each link along the pedestrian network is calculated. For comparison, these lengths are then translated into walking times assuming walk speeds of five kilometres per hour using the equation:

$$WalkTime = \frac{[Shape\_Length] * 60}{5 * 1000} \qquad (3.1)$$

Where:

Walk time is in minutes;
Shape_length is measured in metres;
the 60 converts hours to minutes;
and the 1000 converts km/hr to metres /hr;

Next, access distances and times are calculated from each building or parcel to the nearest transit stop using a built-in shortest path algorithm – based on equation 3.4 – within the Network Analyst extension. The result is a table of shortest distances between the centre of each building to the closest transit stop. See Appendix A for an example of the GUI used by Network Analyst.

The network dataset used for the Transfer Tool differs. This tool requires that complete trip paths (from an origin to a final destination) are modelled. Therefore, a multimodal network is created that is comprised of both a pedestrian and transit network. Pedestrian speeds of five kilometres per hour are still defined for this network; however, the impedance value that is minimized by the shortest path algorithm considers the total trip costs, including in-vehicle travel time along the transit network and a transfer penalty. Attributes and connectivity settings for this dataset are explained in further detail in Section 3.2.4.

3.2 TRANSFER TOOL

The presence of a transfer along a travel path can significantly reduce transit ridership (Liu et al. 2009; Iseki & Taylor 2009; Guo & Wilson, 2009; Newman et al. 1983). Although no network is able to provide direct connections between every origin and destination, ideally transit networks should provide such connections between travel pairs for which high travel volumes exist. Doing so provides more convenient trips for a greater number of customers and can attract or maintain greater ridership. However, as development and travel patterns within a region change, the structure of a transit network does not always reflect current travel demands. Therefore, transit networks should be reviewed periodically to examine which connections are provided and which connections are missed.

3.2.1 Objectives

The purpose of the Transfer Tool is to analyze transit network design and evaluate: 1) the number of transit trips between OD pairs for which transfers are necessary, and 2) the cost implications of the transfers in relation to travel flows. From this analysis, it is possible to create direct trips for corridors with the highest demand – connecting destinations where people want to travel while balancing service with a limited number of resources.

When choosing a trip path, travellers often have various route alternatives available to them. In theory, the decision process to select a preferred route is based on weighing the generalized cost (see Section 2.3.1) of each trip and selecting the option which is perceived to have a lesser disutility (lower cost) associated with it. For instance, Figure 3.4 portrays two different trip options between the same OD pair.

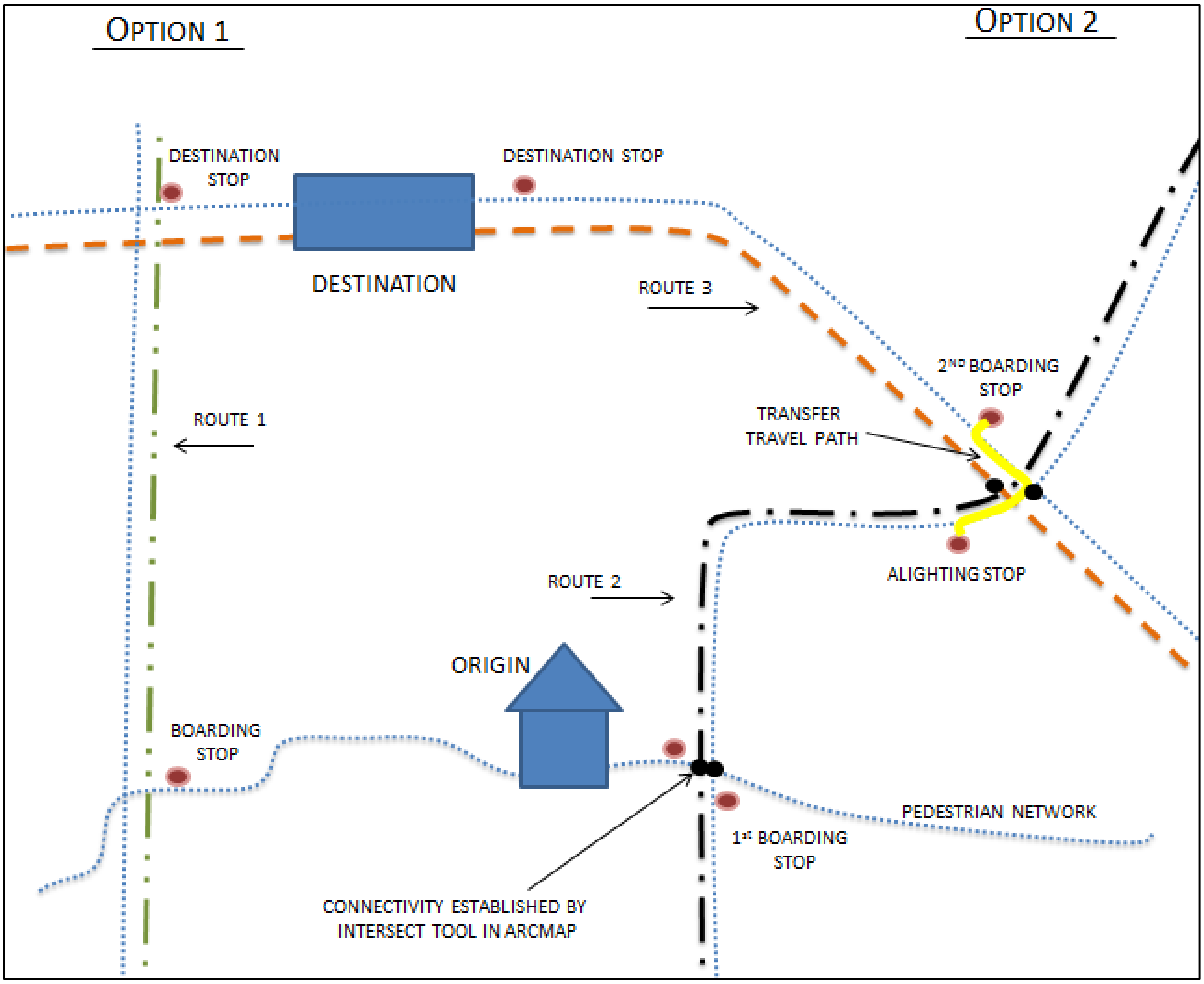


Figure 3.4. Passenger travel path between an origin and destination

The first option involves three legs to the trip:

1) First the user must walk a slightly longer distance from her origin to the bus stop for transit route 1
2) The user takes Route 1 to the alighting bus stop closest to her destination location
3) The user then walks from the alighting stop to her final destination building.

Option Two consists of five legs to the trip:

1) First the user walks a short distance from her origin location to the bus stop for transit route 2,
2) The user rides along Route 2 to the transferring location and alights at the first transfer bus stop,
3) The user then walks to the bus stop for transit route 3,
4) Route 3 connects the user to the destination bus stop,
5) Finally, the user walks the remaining distance to her destination building.

While Option One involves a greater walking distance on either end of the transit trip, it provides a direct route between the user’s origin and destination, eliminating the need for a transfer. Compared to Option Two, Option One has a lower GC; the literature has found that the time spent transferring is perceived to be more onerous compared to time spent walking to or from transit (within a certain threshold), and would therefore be the most likely travel path for a user.

The objective of the Transfer Tool is to capture realistic travel patterns and total travel demand between OD pairs in order to model where trips with high transfer costs exist in a system. In order to capture travel patterns that would be reflective of the real-world decision making process for transit users, GIS are used to determine the number of transfers, walking time, and in-vehicle travel times (IVTT) required for travel between each OD pair, thus capturing the GC of each trip. The number of transfers present in each trip can then be compared against a table of total travel volumes between OD pairs in order to determine the impact of the transfer on the network (the number of potential customers affected by the transfer).

3.2.2 Ideal Method

Various components contribute to a user's perceived cost (or user experience) of a transfer. These include the spatial and temporal qualities of each individual transfer within a system, such as: the amount of time spent waiting between transfers, the walking distance between transfers, the grade of the land (vertical elevation changes), the number of traffic lanes that must be crossed, and way-finding information available along the way. The quality of the pedestrian environment, including the feeling/level of security, available shelter from elements, and the availability of washroom or shopping facilities may also influence a user's willingness to transfer.

Preferably, all of the above attributes would be measured and quantified for each transfer in a system. For instance, temporal attributes could be measured through the comparison of route schedules. Security could be analyzed by measuring the level of lighting available, pedestrian activity, and crime in an area. Elevation data, the number of traffic lanes at intersections, traffic speeds, and weather conditions could also be analyzed to determine the level of difficulty or comfort associated with walking between transfer locations. Combining this information for each potential transfer location within a network would provide transit agencies with a detailed overview of how transit users perceive the quality or "cost" of transfers within a transit system, and in turn, how ridership is affected by this cost.

3.2.3 Method Limitations

Various challenges exist which prevent a detailed review of the quality of transfers within a system. First, there are data collection and storage limitations. For example, the ‘coarseness’ of elevation data is often not detailed enough to measure changes in elevation over a short distance. Also, road information is typically stored as centre lines which do not capture how roads change at intersection locations where pedestrians would be crossing. Additionally, the inclusion of temporal data in GIS software is relatively new, restricting the ability to easily calculate wait times between transfers based on scheduled trip times. In ArcGIS, it is recommended that temporal data be stored as a date type (ArcGIS Help), with a focus on changes over months or years as opposed to working with hours and minutes.

Further to software restrictions, little information is available in the current literature regarding the influence of each transfer component on the overall transfer penalty. For instance, it is not known whether having to climb a steep hill to reach a transfer location is perceived as being more inconvenient than not having washroom facilities available at a transfer location. Also, understanding how people perceive changes in elevation is poorly understood. This limits the ability to create a transfer penalty cost even if this detailed information were available. This restriction is heightened as perceptions of safety or acceptable walking distances are quite variable across different groups.

3.2.4 Thesis Methods

As stated previously, the Transfer Tool presented in this thesis analyzes the influence of transfers within a transit network so that travel paths may be targeted for service improvements. This is done by:

1. Creating a multi-modal network within a GIS to model realistic travel paths along a pedestrian and transit network between OD pairs;

2. Calculating the number of transfers required in each trip given the current route and stop configuration;
3. Computing a network transfer penalty as the product of travel flows and the number of transfers along each trip;
4. Highlighting trips with high transfer penalties.

The above process is further summarized by Figure 3.5.

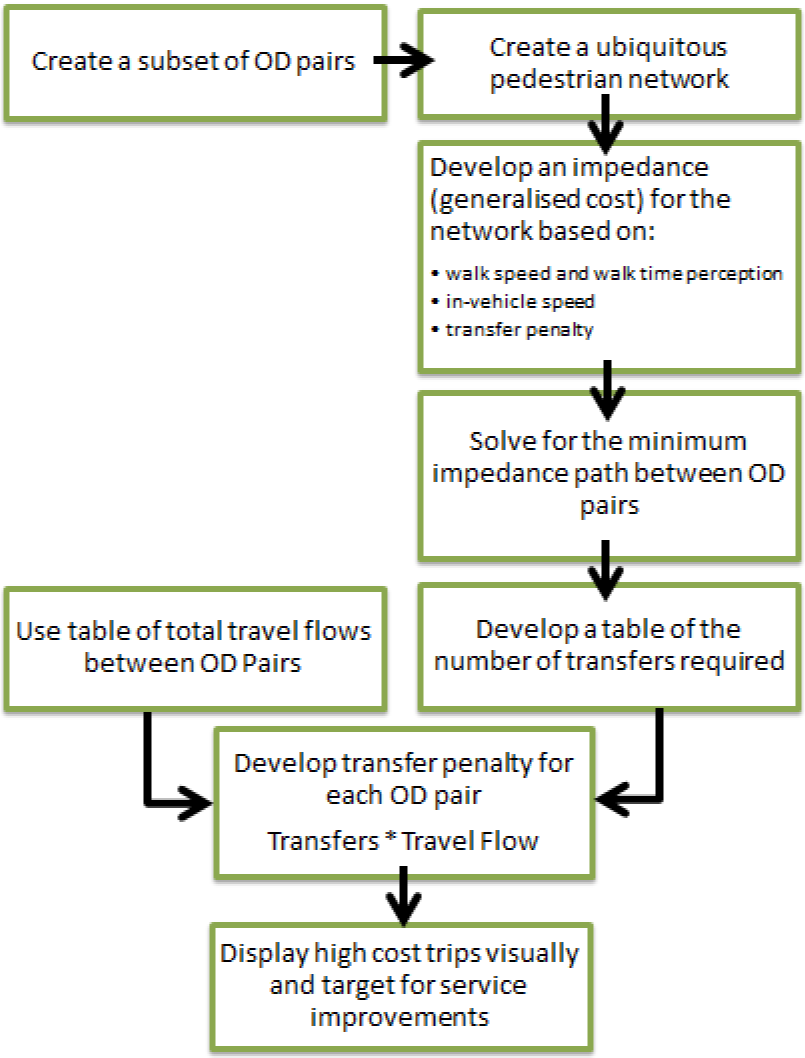


Figure 3.5. Transfer Tool Process Flow

The remainder of this section provides an overview of the GIS process used to model transit paths between a predefined set of OD pairs. First, the process used to select a subset of OD pairs is outlined. Next, the steps to create the network dataset used for this tool are described, as are the connectivity policies and layer attributes. Finally, the steps taken to create the actual travel paths and then calculate the transfer impact costs are detailed.

Selecting OD Pairs

As an alternative to modelling transit trips between every possibly origin-destination path, a subset of OD pairs are selected for analysis. These pairs were selected based on their geographic distribution and their level of trip generation (trips originating from a zone) or trip attraction (trips destined/ending in a zone) in the AM peak hour. Traffic levels are defined as: high generation, high attraction, medium generation, medium attraction, low generation, or low attraction. Zones classified as “high” had traffic levels greater than one standard deviation above the average number of trips either starting (origin locations) or ending (for destination locations) in all zones. Medium zones were close to the average value of travel flows originating or ending in all zones, while low zones had less than half of the average value of flows starting or ending in a zone.

Transfer Tool GIS Component

Because travel paths are subjective, traveler behaviour is often modelled based on representations of travel costs. The tool presented here uses a multimodal network to estimate the generalized cost of trips between OD pairs, taking into account both pedestrian travel times, in-vehicle travel times, and the number of transfers. Each leg of a trip is captured: pedestrian travel times to access transit stops; walk time between transit vehicles; walk times from transit stops to a destination; time traveling within a transit vehicle; and a transfer penalty. These values are combined to create an overall impedance (or generalized cost), associated with the trip; a typical generalized cost formulation is shown in equation 3.2.

$$GC = Access\ Cost + IVTT + Transfer\ Penalty \tag{3.2}$$

The tool works as follows. For a predefined set of origins and destinations, ArcMap's Network Analyst tool calculates a generalized cost of the form shown in Equation 3.1 for multiple paths and identifies the lowest impedance route. The tool then outputs a table that reflects the IVTT, the number of alightings along the shortest path (from which the number of transfers can be derived), the walk time, and a combined GC between each OD pair.

As noted above, it is desirable to reduce the number of transfers for OD pairs with the highest flows. In other words, the highest demand corridors should be connected by direct transit service. To identify those high-demand OD pairs that do require one or more transfers, the tool applies equation 3.2 to measure the transfer impact. These travel volumes are generally available to transit agencies as output from a travel forecasting model, and are captured at the TAZ level.

$$Transfer\ Impact = Transfer_{ij} \cdot Travel\ Flow_{ij} \tag{3.3}$$

Where:

Transfer$_{ij}$ is the number of transfers from origin *i* to destination *j*

Travel Flow$_{ij}$ is the total volume of trips during the AM peak period between origin *i* and destination *j*

The process described above serves to highlight where trips with higher penalty values exist. High penalty values stem from either travel paths with greater traffic flows and one or more transfers, or trips with lower travel flows that require multiple transfers. Trips with a high transfer impact should be considered for service improvements to improve passenger convenience.

Creating the Network Dataset

To create the multimodal network dataset that will be used to model trips between OD pairs, spatial data must be created which represent pedestrian and transit travel. Pedestrian travel occurs along a layer of combined road and path edges, as well as a 'boarding link' layer which connects the pedestrian and transit networks. The transit layers include bus routes, bus stops, and a 'boarding points' layer. The bus stops, boarding points, and boarding link layers are locations where transfers between the pedestrian and transit layers may occur. Figure 3.5 demonstrates what the network looks like in ArcGIS with the transit network and pedestrian network connected by the boarding links.

The pedestrian layer is used to model three aspects of pedestrian travel across a network: a) from an origin to a transit stop, b) between transit vehicles if a transfer is present, and c) from a transit stop along the egress path to a final destination.

The transit network is used to model bus route alignments and IVTT based on the assumed operating speed of 20 km/hr. The bus stops layer and the boarding points' layer represent boarding and alighting locations. The boarding links are created from bus stop locations to the pedestrian network using a custom script, these links provide the connection between the transit and pedestrian layer, and also capture the number of boardings (and therefore transfers) that take place.

Figure 3.6 Features in the multimodal network

Connectivity in the Network Dataset

As indicated earlier, flows along network datasets are governed by connectivity policies. The connectivity must be set so that the pedestrian network, boarding links, and the transit routes are in separate connectivity groups. Connectivity between these groups is established through the bus stop point layer (which connects the bus routes to the pedestrian links) and the boarding points layer (the shared vertices at the junction of the links and the pedestrian network which connect the links to the pedestrian network). Table 3.1 outlines the connectivity policies and groups used to create the multimodal network.

Table 3.1 Connectivity polices and groups for the multimodal network

Layer	Shape Type	Description	Connectivity	Connectivity Group
Bus Routes	Edge	Provides travel along the transit network	Connects to bus stops at vertices	1
Pedestrian Network	Edge	Provides pedestrian travel to and from transit facilities, and between transfers	Connects to boarding points at vertices	2
Boarding Links	Edge	Creates a link to facilitate connections between the pedestrian and transit networks	Connects to bus stops and boarding points at start and end points	3
Bus Stops	Node	Location on bus route where boarding and alighting can occur	Coincident with end point of boarding link and vertex of bus route layer	1, 3
Boarding Points	Node	Location on pedestrian network where boarding and alighting on the transit route may occur	Coincident with start point of boarding link and vertex of pedestrian layer	2, 3

Defining Attributes and Costs for Trip Components

For this tool, separate attributes were defined for each type of edge layer in the multimodal network dataset (the bus routes, pedestrian network, and boarding links). The number of boardings onto a transit vehicle during a trip is stored in the boarding links layer. This number is used to identify the presence and number of transfers. Travel times were assigned to both the bus route layer and the pedestrian network. Pedestrian speeds along the network are assumed to be five kilometres per hour, representing an average walking pace (Furth & Rahbee, 2000). The transit routes layer was assigned in-vehicle travel time (IVTT) on the base assumption that a bus would travel at 20 kilometres per hour (Furth & Rahbee, 2000). These attributes and costs are summarised in Table 3.2.

Table 3.2 Defining network dataset attributes

Layer	Attribute	Cost
Bus Routes	• Direction • Travel Time	• Restricts travel to defined direction • 20 km/hr
Pedestrian Network	• Travel Time	• Distance traveled at a speed of 5 km/hr
Boarding Links	• Direction • Boardings	• Restricts travel to defined direction • 1

Once all of the attributes are set, they can be combined to create an overall impedance for the network, similar to a generalized cost, which will be minimized in the shortest path algorithm to select the travel route that minimizes the combined cost of walk time, IVTT, and transfers. This impedance value combines the travel time along the transit network, the pedestrian network, and the presence of transfers into one cost that represents total travel time in minutes. Following the GC equation which weighs components of a transit trip according to their perceived disutility, or burden, weights are applied to walk distances and the number of transfers that make up the trip. Transfers are defined as the equivalent of 20 minutes of IVTT. Commonly, transfers penalties range between 10 to 15 minutes (Iseki & Taylor, 2009). However, this study assigns a higher penalty to transfers in order to find trips requiring a transfer rather than finding trips that minimize the overall cost associated with the trip such as those involving a transfer but less IVTT. Following Wardman's (2001) study, walk times (those to and from transit, as well as walk time between transfers) are calculated assuming a speed of five kilometres per hour and are weighted as the equivalent of 1.7 minutes of IVTT in the GC equation. The cost of IVTT remains constant at 20 kilometres per hour. This calculation of total trip time can be expressed as (equation 3.3):

$$Total\ Travel\ Time = \left\{\frac{1.7 \cdot Walk\ Distance}{5\frac{km}{hr}} + \frac{In\ Vehicle\ Trip\ Distance}{20\frac{km}{hr}}\right\} 60 + Transfer\ Penalty\ (20\ minutes) \qquad (3.3)$$

Given the defined impedance values, a trip path with longer walking distances will be selected if a transfer can be avoided. Similarly, a trip with slightly longer walking distances will be selected if it results in a route with less IVTT. In other words, the algorithm would select a travel path with greater travel time if a transfer could be avoided as this is expected travel behaviour (Hensher, 2007; Litman, 2007). The network allows free flow of travel from an origin to any transit facility that minimizes the overall cost of the trip.

Producing Travel Paths

Once the process of creating the network dataset is complete, OD pairs are loaded into the OD Cost Matrix tool. This tool then uses a shortest path algorithm to simultaneously calculate the travel paths along the network with the lowest cost impedance for each OD pair. The analysis results in a layer of polylines connecting each OD that contains the total impedance cost (GC) between each pair, the number of alightings from which the number of transfers are derived, total IVTT, and total walk time for each trip.

Calculating the Transfer Impact

The final step is to compare the number of transfers required between each OD pair against travel volumes between the same locations. These travel volumes are generated by a travel forecast model and represent *total* travel volumes – including auto and transit trips during the peak AM period. The forecast model outputs the data into a matrix of volumes between OD pairs. For this study, the process of organizing the matrix into a table that can be compared against the number of transfers was automated using Visual Basic code to create a macro within Microsoft Excel.

The number of transfers for each trip is entered into a table of OD pairs, with a value of zero for pairs between which no transfers are required, 1 for one transfer, 2 for two transfers, and so on. These are multiplied against the table of travel flows between the same zones. Cells with high values then represent OD pairs with a high transfer penalty that should be targeted for service improvements to reduce or eliminate the transfer costs associated with the trip. OD pairs with high penalty values but with low travel flows will have a reduced cost, while OD pairs with mid-range travel flows but multiple transfers will be heightened. Trips not requiring any transfers are disregarded in this tool.

3.2.5 Summary of Work Flow

This work flow for the Transfer Tool is summarized as follows:

1) Create a subset of OD pairs
2) Create a "connected" network such that all ODs are accessible along the network via transit and pedestrian paths
3) Develop a Cost (impedance) function based on:
    a. Walk speed of 5 km/hr
    b. In-vehicle speed of 20 km/hr
    c. A walk time perception equivalent to 1.7 actual walk time
    d. A transfer penalty equivalent to 20 minutes of IVTT
4) "Solve" for the minimum impedance path between all ODs
5) Develop an OD matrix of the number of transfers required
6) Use OD matrix of travel demand from travel forecast model
7) Find the product of transfers and travel demand
8) $\sum_{ij} Transfer_{ij} \cdot Travel\ flow_{ij} \Longrightarrow$ yields Transfer Penalty, and identifies OD pairs for which direct service may be warranted

3.3 ACCESS TOOL

Since the majority of transit users walk to transit stops, as opposed to driving or cycling, there are limitations on the distance people are willing or able to travel to reach the service. Generally it is accepted that transit use declines steeply after access distances surpass 100 metres, and virtually disappears after 600 metres. The relationship between access distances and transit patronage is therefore the primary consideration when estimating ridership.

3.3.1 Objectives

The objective of this tool is to provide an accurate method of analyzing access distances to transit using relatively common GIS functions and readily available data. Typical travel forecasting models generate average access distances to transit on a zonal (TAZ) level. Some simple models use Euclidean distances rather than actual walking distances. These methods overestimate and underestimate access distances from individual parcels. Moreover, this method does not differentiate amongst origin points with various trip generating strengths. The approach developed here is intended to employ GIS methods that capture actual travel paths from individual origin locations, specifically building footprints. These distances are then used to compare transit ridership at the neighbourhood level, and the strength of service areas at the TAZ or route level.

3.3.2 Ideal Method

An ideal access distance model would compute a user’s perception of the travel cost from her origin to the transit stop that provides the best service to her destination. The access impedance is certainly a function of distance, though research has shown that impedance does not vary linearly with distance (Kittleson & Associates, 2003). An access distance of 150 metres, for example, is considered less than twice as onerous as a distance of 75 metres because both distances are relatively short. On the other hand, an access distance of 500 metres is considered as more than twice as onerous as a distance of 250 metres, because the change from 250 to 500 metres requires significant more access time and effort.

In addition to distance, a user may consider the quality of the travel environment as described above: the sense of safety/security, lighting, grade separations, etc. The importance of these characteristics may also depend on the choice of access modes. Pedestrians and cyclists would have different cost perceptions than those accessing the system by auto.

An increasingly important component is accessibility. Even for short distances, with pleasant surroundings, the presence or absence of some infrastructure requirements may make a transit system completely inaccessible for those with mobility limitations. For instance, it is difficult for users who require wheelchairs or scooters to board transit buses if there are no curbs or concrete landing pads adjacent to a transit stop.

3.3.3 Method Limitations

As noted earlier, it is difficult to capture micro-level data in a GIS. As such, it is a challenge to model the impacts of both access environments and accessibility as part of the Access Tool. While it is certainly possible to develop data structures that reflect these characteristics, such information is resource-intensive to collect. Moreover, the relative importance of these data in determining access impedance is not established in the literature. Therefore, the model developed here excludes these inputs. The analysis is also limited to pedestrian access to the transit system.

3.3.4 Methods Used

Unlike most previous methods that measure straight line distances outward from a transit route, this study measures walking distances along a pedestrian network from all building footprints within the study area to the closest transit stop. The process used in this tool is summarized in Figure 3.7.

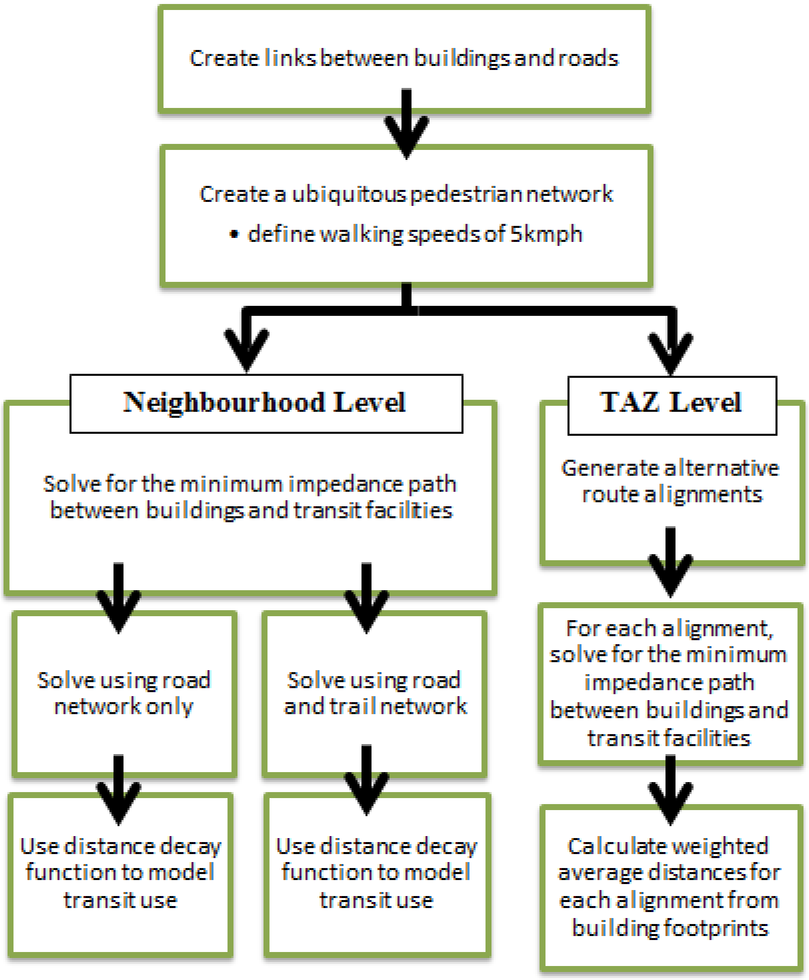


Figure 3.7. Access Tool Process Flow

At the neighbourhood level, a technique is applied that captures the non-linearity of the relationship between distances and costs. To estimate accessibility to transit, the observed access distances from all buildings in a neighbourhood are input into a distance decay function developed by Kimpel et al. (2007) that represents a gradual decline in transit demand as access distances to transit facilities increase. This function is used in order to calculate the probability of that transit stop being utilized from a given distance away, and to compare the influence of neighbourhood design and the presence of pedestrian trails on transit ridership.

This first model is extended to a second method applied to the TAZ level which compares access distances from a transit route to surrounding buildings (and therefore service areas) along the length of two alternative route structures. This model also considers the size of the building footprint when computing distances. The logic is that shorter access distances are more important for larger buildings that are likely to generate more potential riders. Any data available at the building level can be included in this centroid table to reflect the strength of origin, such as building area, number of stories, number of units, and so on.

The methods employed by this tool, which generate pedestrian access distances from building centroids to transit facilities along a true pedestrian network, are compared against the network ratio methods developed by O'Neill et al. (1992). The network ratio method assumes that population is distributed evenly along a road network. As stated in section 2.4.3, it works as follows: first, the total length of the street network within 400 metres of a transit stop is measured and divided by the total length of streets within a neighbourhood. Next, the percentage of streets that are within the 400 metre service area are multiplied by the total population, resulting in a percentage of the population served by transit.

Access Tool GIS Component

As stated previously, a pedestrian network – comprised of road and trail centre lines – is created in GIS to measure access distances. Distances are measured from building centroids to the closest transit facility. To address the problem of connection between individual buildings and appropriate roadways, links were automatically created between buildings and the nearest roadway segment using a custom script. In very rare cases, this connection is made to a roadway that differs from the roadway which is the building's legal address. But, it is believed that the ease of applying this automated connection technique outweighs the marginal loss in accuracy in measuring access. Once the network is created, the Network Analyst extension in ArcMap is used to generate a table of access distances.

Calculating Probability of Transit Demand at the Neighbourhood Level

To compare the influence of neighbourhood design on access distances, two neighbourhoods are analyzed that have similar levels of transit service. The first neighbourhood is characterized by cul-de-sacs and winding streets, while the second neighbourhood has a more traditional grid-like street network. Once access distances are calculated from buildings to the closest transit stop in each neighbourhood, the distances are used to calculate probability of transit demand at the neighbourhood level.

In order to represent a gradual decline in demand for transit, access distances (in miles) are input into the following equation (equation 3.4) developed by Kimpel et al. (2007) (shown graphically in Section 2.4):

$$P\ =\ e\ (a - b \cdot dij)\ /\ 1 + e\ (a - b \cdot dij) \qquad (3.4)$$

Where: P = probability of demand
a = intercept parameter
b = slope parameter
d_{ij} = walking distance from parcel i to transit stop j
(Kimpel et al., 2007).

In this model, the parameter values proposed by Kimpel et al. – 2 and 15 for a and b, respectively – are used.

Access distances (and resulting ridership estimates) are first compared between the two neighbourhoods modelling pedestrian traffic along the street network only. The analysis is then repeated with the inclusion of pedestrian pathways and trails to evaluate how access distances are impacted.

Calculating Service Areas at the TAZ Level

Access distances are also used evaluate how changes in a route alignment can affect the number of buildings serviced by that route. To do so, an alternative route alignment and corresponding bus stop locations are created within a GIS. Access distances are first generated from transit stops of the original route structure and then from the alternative route structure to all buildings that are within 400 metres following the pedestrian network. Finally, to represent activity levels at building locations, access distances are weighted against the size of the building footprint using the following equation (equation 3.5):

$$TAZ_{Access} = \frac{1}{n} \sum_i Access_i * Weight_i \tag{3.5}$$

Where:

Access is the distance from transit stop *i* building centroids within 400 metres; and
Weight is the area of a building footprint in metres^2.

3.3.5 Summary of Work Flow

This work flow for the Access Tool is summarized as follows:

1) Generate links from building centroids to street network;
2) Create a “connected” pedestrian network consisting of building links, pedestrian trails, and roads;

3) Define walking speeds of 5 km/hr;
4) "Solve" for the minimum impedance path between all buildings and transit facilities;
5) For study at the neighbourhood level, input resulting access distances into a distance decay function to estimate probability of demand at each transit facility.
6) Generate distributions of access distances and propensity to use transit for neighbourhoods and weighted values for TAZs.
7) At the TAZ level, compute the weighted average access distance for alternative route alignments

3.4 ROUTE PLANNING TOOL

Transit ridership is often estimated through travel forecasting models. These models predict the number of total trips between TAZs and assigns trips to various transportation modes (such as transit or auto) and possible route alignments. The mode split model is usually based on the availability and generalized cost of each mode. As previously mentioned, the GC is calculated from variables such as access distances to reach the mode and in-vehicle travel times. The cost may also include a bias factor that represents components included in a traveller's decision making process, but is not explicitly included in the GC equation, such as such as income levels, density, or auto ownership.

3.4.1 Objectives

Generally, a transit route can follow various road alignments between its terminus locations. If a transit route is altered to follow a different alignment, it is expected that resulting changes in access distances would impact ridership on the route. If a transit agency sought to compare changes in ridership between a current route structure and an alternative alignment, they could potentially re-run a travel forecasting model with the new alignment in place. However, the time and employee resources required to run the model would likely prohibit this option. The objective of the Route Planning Tool developed here is to generate ridership estimates for minor changes in route alignments, such as the one shown in Figure 3.8, without having to re-run a traditional four step travel model.

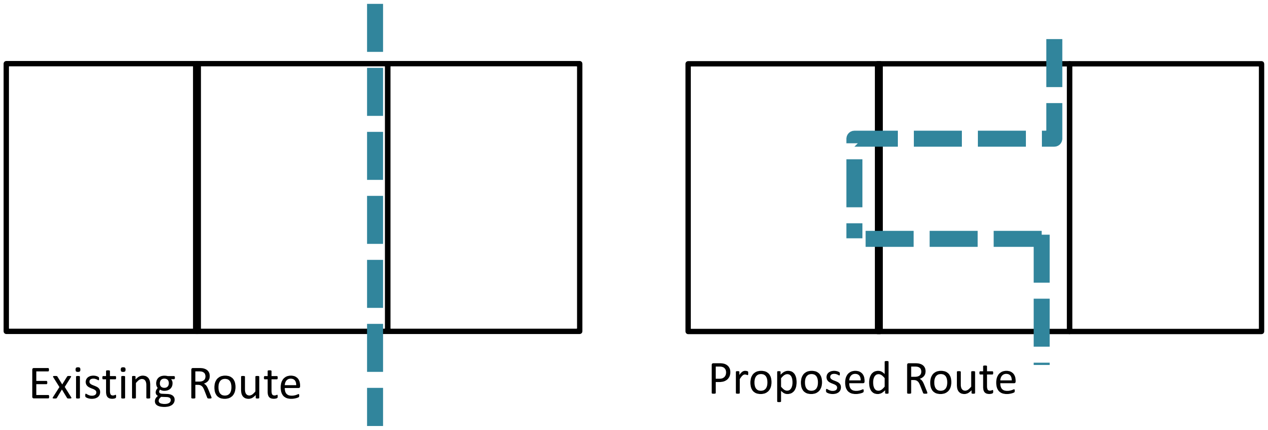


Figure 3.8. Theoretical route change

3.4.2 Ideal Method

Working within a generalized cost framework, a route change has the following impacts:

1. Those transit users who typically board prior to the proposed route change will experience a change of in-vehicle time;
2. Those transit users who typically board in the area of the route change will experience a change in access time;
3. There will be a population for whom the route change decreases access time and, as a result increases their likelihood to use transit;
4. There will be a population for whom the route change increases access time and, as a result, decreases their likelihood to use transit;

The ideal model would quantify the change in transit generalized cost as a result of the proposed route alignment change for each of these populations. This could occur on a sub-zonal (neighbourhood) level. The new transit generalized cost would be entered into the zonal mode choice model to estimate new transit ridership as a function of total travel demand and the socio-demographic characteristics of the populations in each zone.

3.4.3 Limitations

In essence, the method described above is what occurs in the most robust travel forecasting model. But, these models require extensive time and resources to develop, maintain and utilize. The method presented here makes the following simplifying assumptions to reduce the resource the requirements without greatly compromising the accuracy of the prediction. First, this model does not consider the impacts on in-vehicle travel time. Next, the model is evaluated at the TAZ level for simplicity and consistency with other data sources.

3.4.4 Thesis Methods

Forecasting models often predict transit ridership based on a comparison of the GC of all available modes. The share of travellers for each mode is based on the magnitude of a mode's cost relative to the cost of all modes combined (OTA, 1975). As an alternative to running a travel forecasting model every time a route change is proposed, this thesis uses post-processing analysis and GIS to update the access cost component of the generalized cost equation in order to examine ridership impacts of suggested route alterations. Once the GC is revised, modal splits for each alternative alignment can be produced to generate ridership estimates.

Route Planning Tool GIS Component

To measure calculate access distances, this tool uses a pedestrian network dataset consisting of road and trail centerline shapefiles, as described in section 3.1. Access distances are measured between parcel centroids and the closest transit stop. Each parcel is categorized as residential or employment. Residential parcels have an attribute that indicates the number of residents; these data are available in property assessments. For employment parcels, the number of jobs contained in an individual parcel is assumed to be proportional to the area of the parcel. Mathematically, this is computed as follows:

$$jobs_i = \frac{Employment\ area_i}{\sum_j Employment\ area_j} \cdot Employment_{TAZ} \tag{3.6}$$

Where:

Employment $Area_i$ is the area of the employment parcel in question (in m2)
Employment $Area_j$ is the area of the remaining employment parcels in a given TAZ
Employment is the total employment value for a given TAZ

The first step in the modeling process is to calculate the access distances from all parcels to the nearest transit stop on the existing route alignment for TAZs that are adjacent to the proposed routes alignments. These distances are weighted based on the strength of origin and an average figure is calculated for each TAZ as described in Section 3.3.4. Mathematically, this can be expressed as:

$$TAZ_{Access} = \frac{1}{n} \sum_i Access_i * Weight_i \tag{3.7}$$

Where:

Access is the distance from parcel *i* to the nearest transit stop and
Weight is the number of residents or employees for the parcel
n is the total number of parcels in the TAZ.

The next step is for the user to input the proposed realignment as a shape file in the GIS. The user may identify individual stop locations, or the stops may be auto-generated at locations where the proposed route intersects with the roadway network using the built-in intersect tool. The calculations reflected in the two previous equations are repeated for access to the proposed realignment.

Calculating Generalized Costs and Transit Ridership

The weighted access distance in both cases – original and proposed realignment – for each TAZ in the study area are exported to a spreadsheet. The format of each export is two columns: TAZ # and weighted access distance. In the spreadsheet, these access distances are converted to access costs using a penalty that reflects users' perceptions of disutility. A typical value is 1.6. This reflects how a traveler perceives the time spent accessing the system relative to other cost components such as in-vehicle time.

As discussed in section 2.5.1, ridership estimates are made at the TAZ level using logit models that estimate the likelihood of using transit by comparing the generalized cost of travel by one alternative relative to other available modes. The total transit ridership is quantified as the product of the probability of using transit and the total demand originating in a zone. Total flows, and therefore ridership, are calculated for an origin zone to all other zones within the study area.

The model intends to estimate changes in ridership before and after the change in alignment. As such, the model compares the following choices:

1. making the trip by transit under the original route alignment versus making the trip by auto;
2. making the trip by transit with the revised alignment versus making the trip by auto.

Recall that the generalized cost of transit contains access costs, waiting costs, in-vehicle costs, transfer penalties and out of pocket expenses. Auto generalized costs contain in-vehicle time, a distance cost and out of pocket expenses. When comparing case 1 to case 2, the model assumes that all auto costs remain unchanged. For transit, the model assumes that in-vehicle times, transfer penalties and fares, remain constant. The only variable changing between case 1 and 2 is the access cost to transit. The model also assumes that total demand is constant. These comparisons are made for travel between all TAZs in the study area.

The model calculates a revised generalized cost of transit based on the new weighted access distance. Mathematically, this can be expressed as follows:

$$GC_{OD}^{T} = (\boldsymbol{Access\ cost} + in\ vehicle\ cost + transfer\ penalty) + fare \qquad (3.8)$$

The data for in-vehicle cost, transfer penalty and fare for all OD pairs are typically available from travel forecasting models.

When these values are combined with the access cost computed for scenarios 1 and 2, GC values can be calculated for the differing route alignments and entered into the logit model function to predict ridership in each case. To account for socio-demographic variables which influence travel choice, the model incorporates a mode bias into the logit function. A separate bias value is assigned to zones that are highly transit supportive, transit neutral, or low-transit supportive, as classified by Casello and Jung (to be published). The impacts of the changed route alignment are calculated as the difference in predicted ridership between cases 1 and 2.

3.4.5 Summary of Work Flow

This work flow is summarized as follows:

1) Create new route alignments within a GIS
2) Generate bus stops for new alignments at every street intersection
3) Calculate access distances between parcel centroids and bus stop locations for each route alignment
4) Calculate weighted average access distance for each TAZ

5) Convert the access distances for each TAZ into access costs by applying a weight factor
6) Update GC equation with the new access cost
7) Calculate the transit mode share using the updated GC^T and the transit bias
8) Calculate transit ridership as : total trips * fractional mode share of transit

3.5 SUMMARY OF METHODS

The objective of the research present here is to provide techniques that evaluate proposed transit service changes that blend the experience and local knowledge of transit agencies with more sophisticated modelling outputs and GIS software. Three specific tools are proposed: a Transfer Tool, Access Tool, and Route Planning Tool. All three tools utilize ArcGIS' network analyst extension.

The Transfer Tool captures the relative level of connectivity that a transit network provides between OD pairs and generates an overview of the impact of transfers within a study area. The number of transfers required to travel by transit between OD pairs are modelled over a multimodal network in GIS. These numbers are then compared against total travel volumes between the same pairs to determine the impact of the transfers against current or potential transit users – highlighting areas where service changes could prove most effective.

The Access Tool provides a more accurate measure of access distances to transit that follow actual street and trail networks within GIS as opposed to typical buffer techniques. These distances are then used to calculate the probability of stop usage (boardings) via a distance decay function.

Building off of the Access Tool, the Route Planning Tool generates estimates of transit ridership arising from potential route changes. Access distances, demographic characteristics, and data from travel forecast models are used to generate new generalized costs of transit for each alternative route alignment. From this, the probability of transit ridership for each alignment is calculated – which can be used to analyze the effectiveness of proposed service changes and gauge which alignment would attract the most customers, or if status quo is preferred.

CHAPTER 4: CASE STUDY OF WATERLOO REGION

This chapter introduces the Region of Waterloo, its transit system, and identifies transit planning needs. The techniques described in the previous chapter are then applied to the Region as a case study.

4.1 REGION OF WATERLOO

The Region of Waterloo (ROW) is located in Southwestern Ontario, approximately 100 kilometres from Toronto (Figure 4.1). It is comprised of the cities of Kitchener, Waterloo, and Cambridge (the "Tri-Cities"), as well as four rural townships. While the cities of Kitchener and Waterloo developed as separate entities, today the cities have grown together and lack a distinct border. The City of Cambridge was created in 1973 through the merger of the city of Galt, the towns of Preston and Hespeler, and the village of Blair (City of Cambridge, 2011). The number of roads connecting these areas in Cambridge are limited, as are linear connections to Kitchener and Waterloo.

The current Regional population of 525,000 is expected to increase to 729,000 by 2031, making the Region one of the fastest growing communities in Canada. Much of the anticipated growth is expected to occur through infill development and intensification, although some will occur through greenfield development, creating new pockets of dense population as well as new development on the edge of the cities.

Waterloo Region is representative of many cities experiencing rapid population growth with a mandate to increase their transit modal share in order to reduce the strain and congestion on current infrastructure. Typically these cities are operating with a limited budget for improving transit services. The intention of the methods presented here is to assist growing municipalities with their transit decision-making processes. The methodology presented may also be used in cities with stagnant or declining populations that must scale back their transit service. For these cities, service changes that reduce the number of routes or hours of operation must be planned carefully in order to minimize the negative impacts on transit users. Strategic route changes may reduce the loss in service area coverage or the number of people who may lose direct service.

Figure 4.1. Region of Waterloo Source: Region of Waterloo, 2011

Transportation policies within the Region are not only governed by Official Plans created at the Regional level, but also by policy dictated by the Provincial government. In 2006, the Province of Ontario passed the Places To Grow Act (P2G) which legislated many municipalities around the Greater Toronto Area to limit their growth through greenfield development and focus on intensifying existing areas of development to create nodes and corridors of high employment and population densities (Figure 4.2). This Act identified the downtown cores of Kitchener, Waterloo, and Cambridge as Urban Growth Centres, and mandated that density targets of 200 people and jobs per hectare be reached in these areas.

In concert with P2G, the Region of Waterloo's Regional Growth Management Strategy (RGMS, 2003) calls for focusing growth and development within urban areas, particularly along the central transportation corridor (CTC) which runs through the centre of the Tri-Cities. The RGMS and the Regional Transportation Master Plan (RTMP, 2011) outline the need to provide a more balanced transportation system with greater emphasis on transit, cycling, and walking. With little room for the expansion of the current road network, and a planned increase in density along the CTC, the Region has elected to implement Light Rail Transit and adapted Bus Rapid Transit (aBRT), along with a network of express routes (Region of Waterloo, 2011). Given that approximately 42% of commuters in the Region travel less than 5 kilometres to work, the Region plans to achieve an increase in the peak hour transit mode share from approximately 4% to 17% of all motorized trips by 2031 (RTMP, 2011).

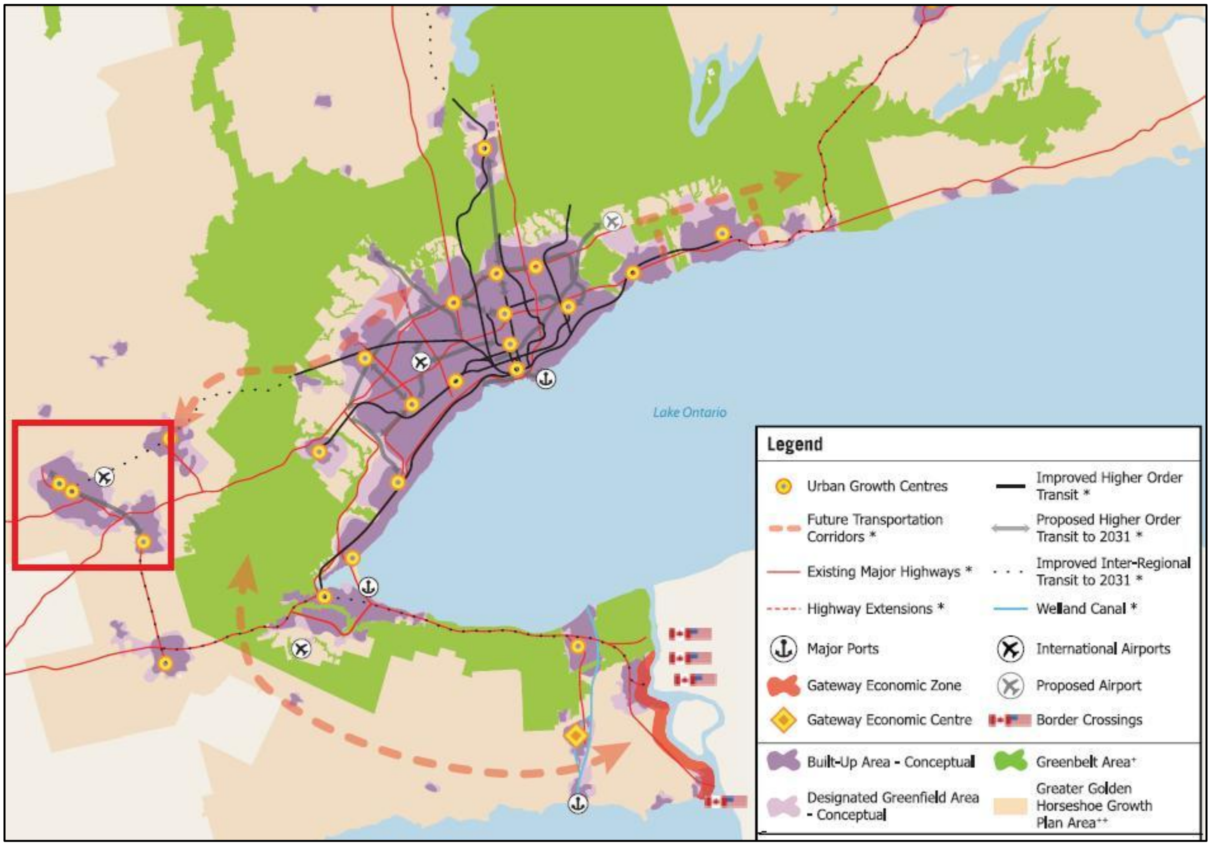


Figure 4.2. Map of mandated nodes and corridors in the Places to Grow Act. Source: Government of Ontario, 2006

In addition to shorter commute distances which make transit a viable alternative in the Region of Waterloo, the area has additional populations that have been shown to be more inclined towards the use of public transit, including a large student population. The Region is home to three post-secondary institutes: the University of Waterloo, Wilfrid Laurier University, and Conestoga College. It is also hailed as Canada's technology triangle, and is home to various advanced technology businesses that attract a high number of young workers. Further, the Region is characteristic of many Canadian cities that have an aging population base that may become more reliant on alternative modes of transportation. Finally, a significant immigrant population, which is likely to rely on transit, exists within the Region as shown in Table 4.1.

Table 4.1. Municipal statistics for Waterloo Region (McLeod, 2011)

Municipal Statistic		Region of Waterloo
Population		543,700
Population growth	Average annual growth: 2001-2006	1.74%
	Forecast average annual: growth 2010-2031	1.49%
Population density		40 people/ha^2 (397 people/km^2)
Demographics:	% seniors 65+	12.0%
	% students post-secondary	14.5%
	% immigrants	22.0%
Significant provincial policies/programs:	Required to follow Provincial Policy Statement?	Yes
	Required to follow Places to Grow?	Yes
	Receives gas tax revenues?	Yes

The Regional government provides transit through Grand River Transit (GRT), operating approximately 66 bus routes throughout the Tri-Cities. The average annual ridership for the system is approximately 18 million, and has been growing at some 6.5% over the past seven years (Table 4.2). In GRT's service design guidelines, it is stated that a bus stop should be located within 450 metres of 95% of all residences, workplaces, and public facilities.

Table 4.2 Comparing transit statistics between Waterloo Region and mid-sized municipalities in Ontario (McLeod, 2011)

Transit Statistic	**Region of Waterloo**	**Ontario Mid-sized Municipalities (average among the 50,000-500,000 pop. group)**
Annual ridership (revenue passengers)	18,055,000	4,137,728
Annual ridership change (average 2002-2009)	+6.57%	+5.17%
Service provided (# revenue vehicle kilometres (RVK))	11,271,570 km	3,618,937 km
Service utilization (transit trips/capita)	39 trips/person	26 trips/person
Service efficiency (riders/RVK)	1.47 riders	1.03 riders
Cost efficiency (operating cost/RVK)	$5.16/RVK	$4.21/RVK

While the majority of routes operate with 30 minute headways, a number of routes operate with 15 minute intervals during the peak periods. There are also five routes that travel along main corridors through the cities that operate with shorter headways of ten minutes or less. The agency maintains two central terminals located in downtown Kitchener and downtown Galt in Cambridge. An additional six satellite terminals exist, mainly on the periphery of the cities. The system operates on a timed transfer system where a number of routes pulse and meet at terminals on the hour, half hour, or quarter hour.

The Regions' newly approved RTMP calls for rapid transit (RT), in the form of light rail transit and adapted bus rapid transit, to help shape future growth and provide more convenient forms of transit. In addition to RT, the RTMP calls for the creation of numerous express lines that would feed into the RT stations and serve major corridors within the city, while local routes would continue to provide service into neighbourhoods (Figure 4.3). Currently, the Region operates two express bus lines which provide more direct connections.

The first express route, introduced in 2005, runs along the Region's central transportation corridor through the three cities. The second express route, which was introduced in 2011, travels along a major north-south corridor on the west side of Kitchener and Waterloo.

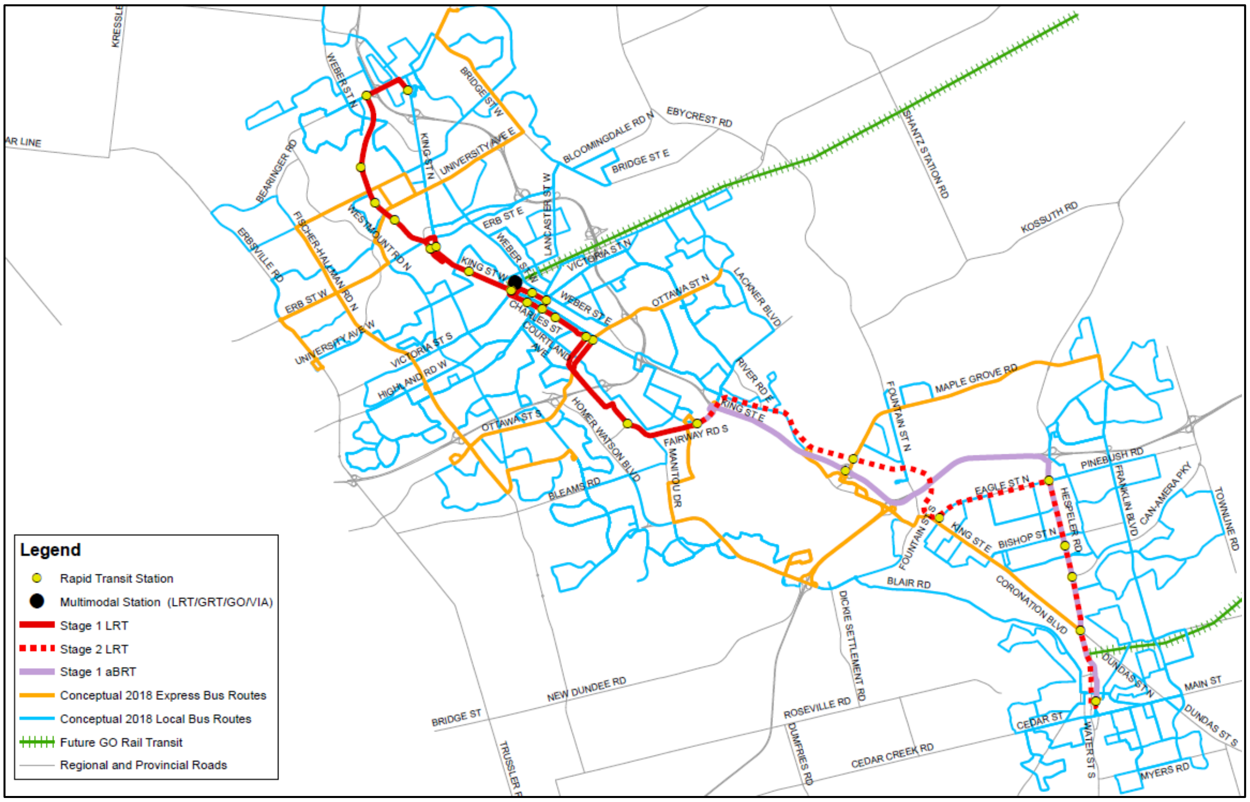


Figure 4.3. Proposed rapid transit route, express routes, and local routes Source: Region of Waterloo

A series of additional express routes are also planned to support the proposed RT services. Ridership along these routes will be influenced by their chosen alignments and the placement of transit stops, as these will directly impact the number of homes and businesses that are within the routes' service areas. With the addition of these new routes comes the need to alter local routes to provide connections to the express network and to service locations that are outside of the range of the express routes. Again, changes to the local routes should be examined to identify potential changes to passenger convenience and accessibility.

The methodology for this thesis applies data generated by the Region of Waterloo's travel forecasting model which represents current travel patterns and forecasts future patterns at the TAZ level. The model forecasts travel flows by mode and generalized costs for the AM peak hour. Data inputs into the model include:

- Traffic and transit counts;
- The Transportation Tomorrow Survey (1996) (a joint provincial and municipal undertaking to collect data on travel behavior in Southern Ontario);
- Auto and transit OD surveys within the Region.

The model was developed in 2004 with additional scenarios forecasted for 2011, 2021, and 2031. Key data included in the model are: population (by age); employment; post-secondary enrolment; and the location of housing. Additional variables included in the model as part of the GC function were: costs associated with operating a vehicle; the price of parking; transit fares; and a mode bias for trip purpose and mode.

4.1.1 Applying Thesis Methodologies to the Region of Waterloo

In addition to data from the Region of Waterloo travel forecasting model, the following GIS layers were gathered from the Region: roads, trails, buildings, transit routes and bus stops, TAZ boundaries, and land use designations at the parcel level. The Transfer Tool evaluates the level of connectivity that GRT provides between select OD pairs throughout the Region and compares it against total travel volumes. The Access Tool analyzes a population's accessibility to transit at both the neighbourhood and TAZ level and allows potential neighbourhood design impacts on accessibility to be quantified. Access distances and demographic data were also used to help predict expected levels of transit ridership for various route alternatives using the Route Planning Tool. Key data sources are listed in Table 4.3.

Table 4.3. Region of Waterloo Data Layers and Sources

Data Layer	Source	Description	Format
TAZ Boundaries	Region of Waterloo	A polygon layer of TAZs	Shapefile
ROW SLRN	Region of Waterloo and trimet??	The single line road network for the Region of Waterloo	Shapefile
ROW Trails	Region of Waterloo	Single line network or tails and paths	Shapefile
GRT Bus Routes	Region of Waterloo	Polyline layer of the bus routes in Waterloo Region	Shapefile
GRT Bus Stops	Region of Waterloo	Point layer of bus stop locations	Shapefile
ROW Parcels	Teranet	Land parcel information with PIN.	Shapefile
ROW Assessment Points	MPAC	Unique assessment roll numbers and associated property information for individual parcels	Shapefile
ROW Building footprints	City of Waterloo, City of Kitchener	Building footprint and location	Shapefile
Travel Flows	Region of Waterloo	AM peak period forecasted travel flows	Spreadsheet
Access Costs	Region of Waterloo	Cost to access transit service	Spreadsheet
Generalised Cost	Region of Waterloo	The model cost or burden associated with a trip. Separate values are calculated for auto and transit	Spreadsheet

4.2 TRANSFER TOOL

The Transfer Tool allows the user to assess the relative costs of transfers as a function of transit network design. To test the tool, a subset of TAZs in the Region of Waterloo were chosen for analysis based on their geographic distribution and their level of traffic generation or attraction (high, medium, or low) as described in Section 3.2.4.

Three origin TAZs and three destination TAZs from each of the three categories of activity were chosen for each of the Tri-Cities, resulting in a total of 54 TAZs (see Table 4.3). Therefore, a 54 by 54 travel matrix was created resulting in 2862 OD pairs, excluding intra-zonal travel.

The locations of the chosen TAZs included downtown centres representing areas with high densities of employment and population, as well as industrial areas representing low densities of employment. Areas along the CTC with higher density residential dwellings were also included, as were medium density and low density residential on the fringe of the Tri-Cities.

Travel flows between the chosen pairs ranged from 150 trips per hour to less than 0.01 trips per hour with an average of 1.4. Approximately 30 zones had travel flows greater than 25. The majority of trips had flows that ranged from 1 to 4.

The chosen TAZs were used as inputs in the shortest path algorithm to model trips between each location along a multimodal network consisting of the pedestrian and transit networks in ArcGIS. Figure 4.4 depicts the locations of the OD pairs and the TAZs within the Region. The shortest paths were determined based on the generalized cost of each trip as defined by the attributes of the network. Here, the shortest path was conceptualised not solely in geographic terms, but rather as a combined cost of in-vehicle travel time, walk time, and a transfer penalty (see equation 3.3 in Section 3.2.4).

Table 4.4. Travel flows between OD pairs output from the Region of Waterloo travel forecasting model (2004)

Municipality	Origin TAZ ID	Origin Flows	Destination TAZ ID	Destination Flows	Flow Category
Waterloo	124	6579	70	12903	High
Waterloo	59	2289	63	10133	High
Waterloo	282	1408	138	8945	High
Kitchener	156	4696	162	12012	High
Kitchener	183	3333	133	8625	High
Kitchener	134	1188	200	3620	High
Cambridge	430	693	366	4298	High
Cambridge	390	643	411	3455	High
Cambridge	352	297	396	3864	High
Waterloo	33	360	129	1316	Medium
Waterloo	55	338	22	2158	Medium
Waterloo	132	328	125	1129	Medium
Kitchener	298	344	104	974	Medium
Kitchener	159	527	169	907	Medium
Kitchener	297	279	256	1138	Medium
Cambridge	333	81	335	503	Medium
Cambridge	416	119	431	458	Medium
Cambridge	421	103	358	574	Medium
Waterloo	286	81	280	367	Low
Waterloo	27	56	273	407	Low
Waterloo	268	160	175	384	Low
Kitchener	108	146	310	441	Low
Kitchener	304	121	194	484	Low
Kitchener	249	76	245	396	Low
Cambridge	388	46	349	129	Low
Cambridge	426	45	387	200	Low
Cambridge	384	36	420	111	Low

After running the algorithm, the costs are output to a table showing the number of transfers between each pair, the transfer penalty, walk distance, walk penalty, IVTT, and the combined penalty cost. For the trips (OD pairs) included in the analysis, 1119 required zero transfers, 1272 required one transfer, 399 necessitated two transfers, and 72 required three transfers (Figure 4.5). To gain a further understanding of the overall influence of transfers on potential customers, the percentage of total trips requiring 0, 1, 2, or 3 transfers are calculated (Figure 4.6).

Once this table has been created, the impact of the transfers within the network is calculated by multiplying the number of transfers between OD pairs against total travel flows (equation 4.1).

$$Transfer\ Impact = \sum_{ij} Transfer_{ij} \cdot Travel\ flow_{ij} \tag{4.1}$$

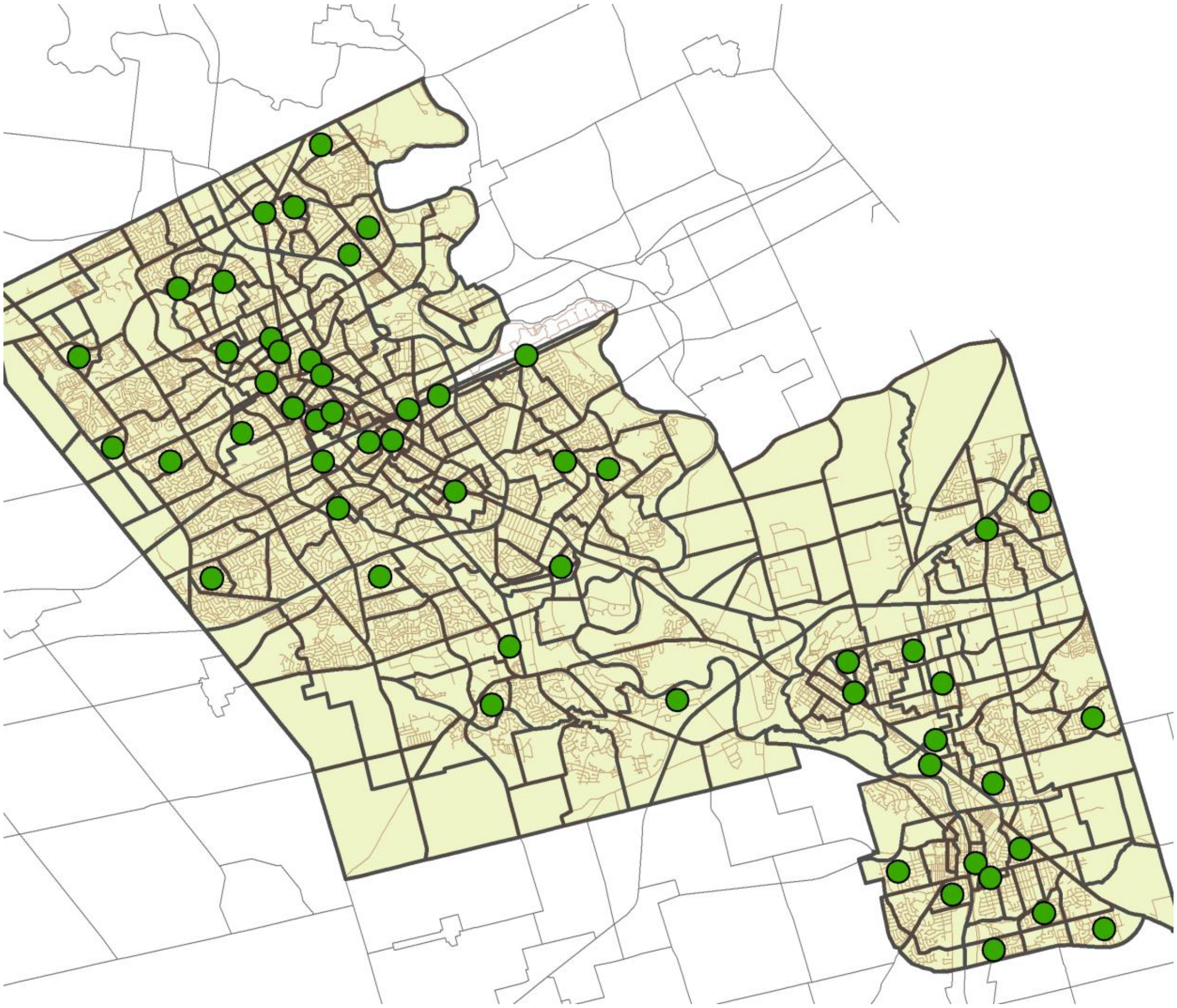


Figure 4.4. Chosen OD pairs in Waterloo Region

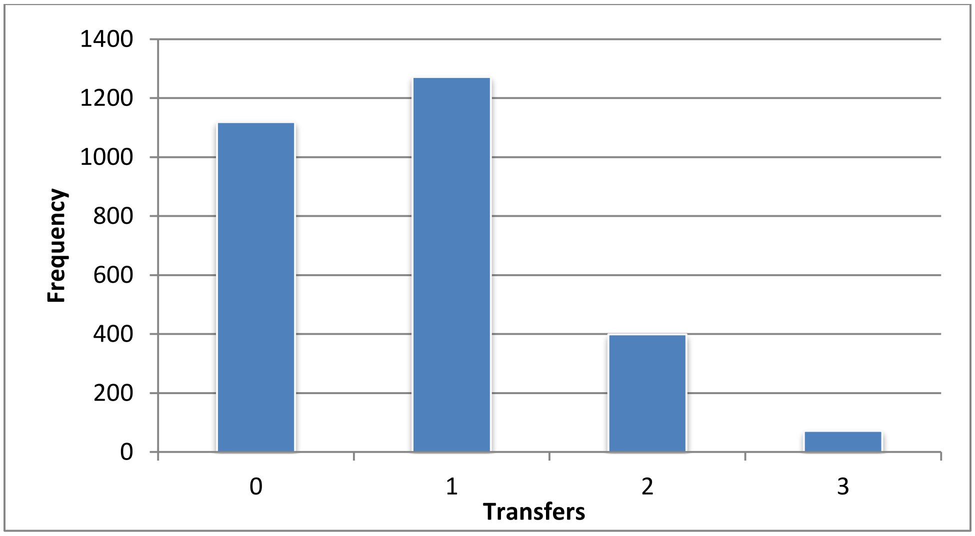


Figure 4.5. Number of transfers between select OD pairs

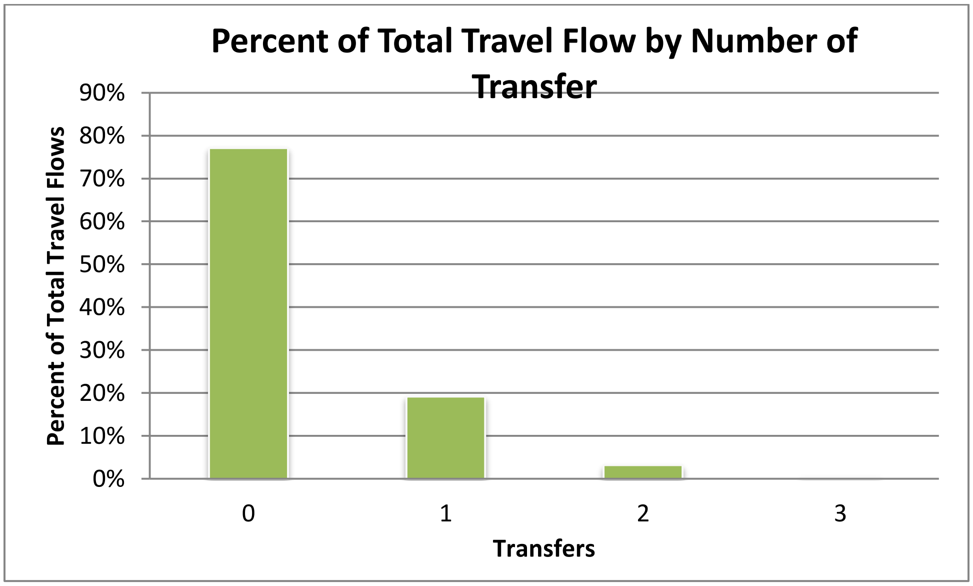


Figure 4.6. Percent of travel flow by number of transfers

The transfer impact cost represents the significance of the need for passengers to transfer between routes. This highlights trips with high overall costs due to high travel flows between which one transfer exists, or low or medium travel flows between which a high number of transfers exists. The resulting costs ranged from 0 (no transfers) to 22 with an average cost of 0.04. Some 39% of the trips (a total of 1119 trips) had a transfer impact of zero which represents trips with no transfers. If trips involving walking only are excluded (where the distance between OD pairs did not necessitate travel by transit), some 32% of trips did not involve transfers. An additional 59% of the trips represented had transfer impact costs of less than 4, leaving only 2% of trips with higher costs (a total of 60 trips).

The majority of trips with the highest costs consisted of a single transfer with higher travel volumes, although there were a significant number of high cost trips with lower travel flows and two transfers. Additionally, some of the high cost trips had three transfers present and low travel flows.

Figure 4.7 displays the OD pairs with high transfer impact costs. The trips with the greatest transfer impact costs are located between central-east Waterloo (where there is medium density residential development) and downtown Kitchener (high density employment), and between downtown Kitchener and north Cambridge (medium density residential). Additional high cost trips exist between north Waterloo (a mix of low density residential and a cluster of office buildings) and east Kitchener (low and medium density residential), between central-east and north-east Waterloo to south-west Waterloo and mid-west Kitchener, and from south-west Kitchener to west Waterloo. Some higher costs also exist in the City of Cambridge between north-west Cambridge (low density residential) and the centre of the city (medium density employment).

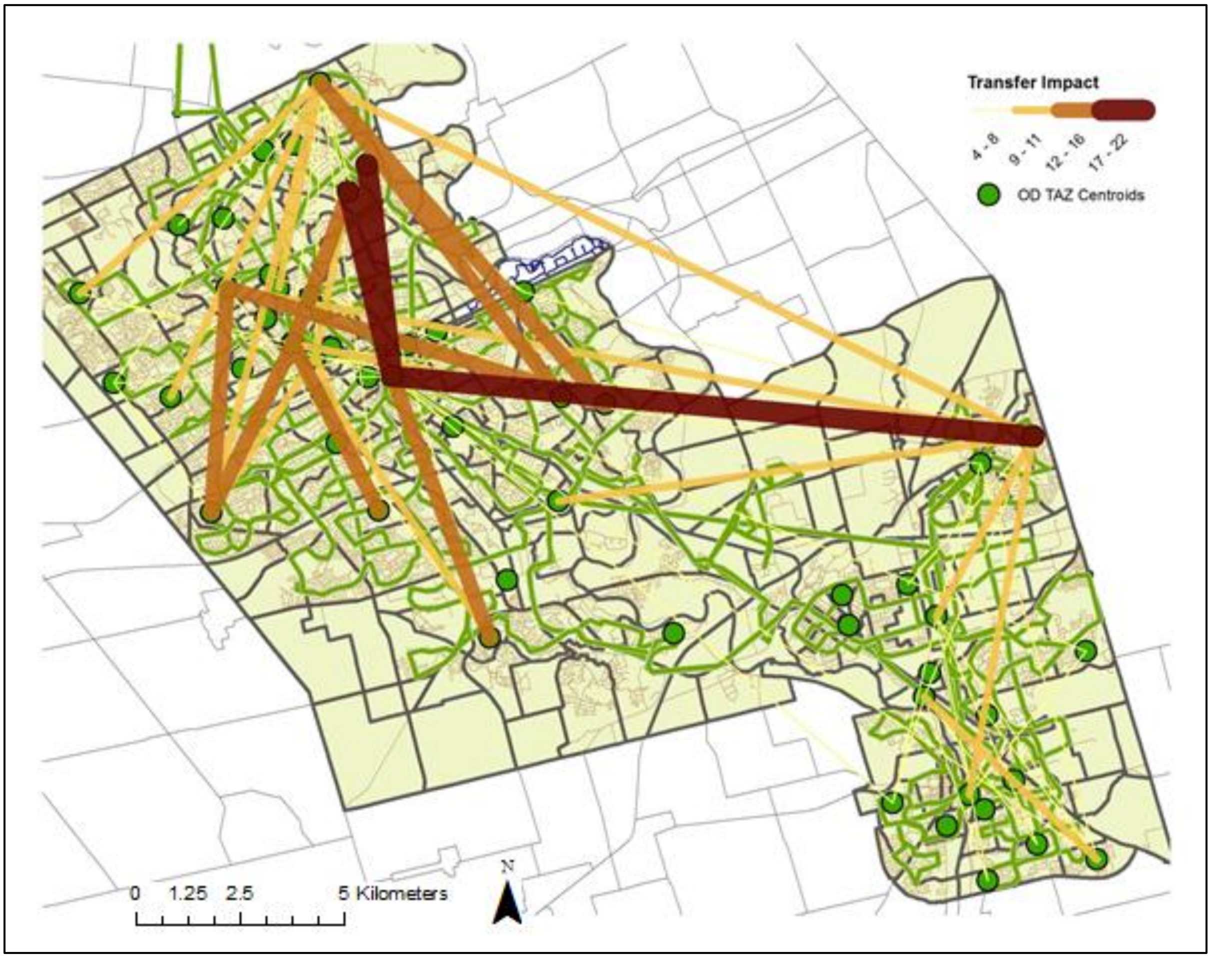


Figure 4.7. Trips with high transfer impact costs

<u>Analyzing the Generalized Cost</u>

In addition to calculating a transfer impact cost, the methodology used in this thesis produces a generalized cost of the trip between each OD pair consists of a walk cost, IVTT, and a transfer penalty as defined by equation 4.2. These costs can be used to determine the portion of the GC of each trip that can be attributed the presence of a transfer(s), the amount of time spent walking, or the amount of time spent travelling in a vehicle. Recall that time spent transferring and time spent walking are perceived to be more onerous compared to time spent travelling within a vehicle; therefore, it is preferable to keep these portions of the GC of transit to a lower percentage compared to IVTT.

$$GC = \frac{1.7 \cdot Walk\ Distance}{5\frac{km}{hr}} + \frac{In\ Vehicle\ Trip\ Distance}{20\frac{km}{hr}} + Transfer\ Penalty(20\ minutes) \quad (4.2)$$

As Figure 4.8 depicts, the transfer penalty accounts for 10% or less of the overall GC for a large portion of trips studied. This is due in part to the fact that many trips do not involve any transfers. However, for 10% of the trips studied, the transfer penalty contributed to over 50% of the GC, representing the majority of the cost component of the entire trip for these travel pairs (the remaining 50% of the GC is attributed to a combination of IVTT and walktime). Comparatively, the portion of the GC attributed to the walk time penalty had a wider distribution, as all transit trips started and ended in at least a small amount of pedestrian travel. The walk penalty accounted for 20% to 40% of the total GC for some 62% of the trips, while IVTT contributed to 40% to 60% of the GC for 65% of all trips.

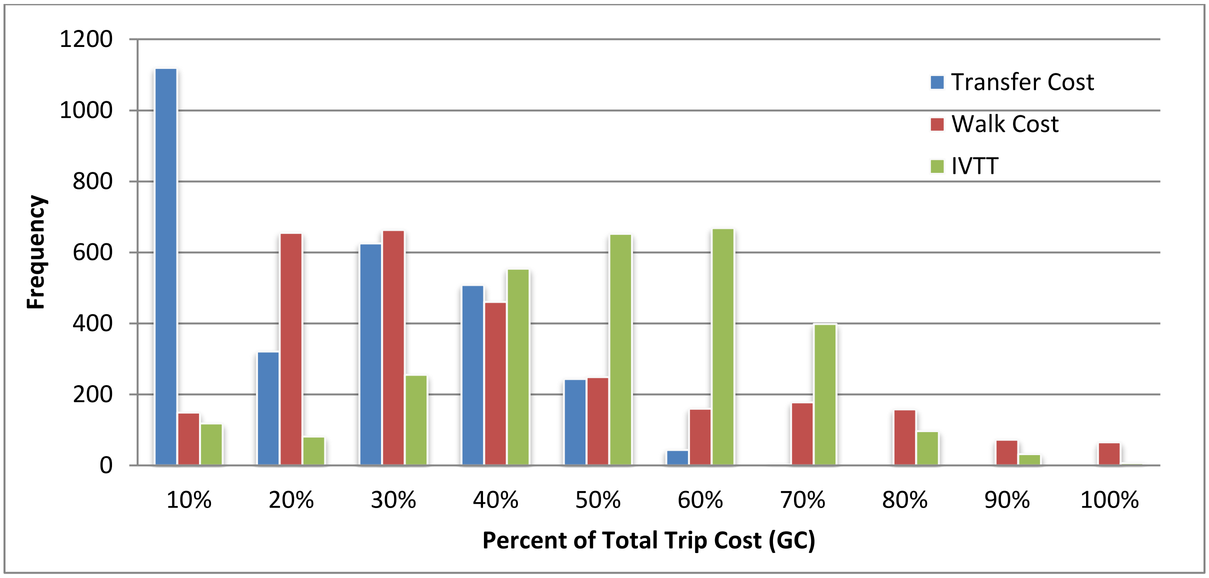


Figure 4.8. Breakdown of trip cost components

Analyzing the geographic distribution of travel paths with high transfer impacts allows planners to visualize where the addition of new routes or where altering current routes could reduce the need for transfers, particularly among OD pairs that have high transfer costs. Within a GIS, a series of lines were drawn to provide direct links between OD pairs with high transfer costs. It is unlikely that an agency would have the resources to accommodate all high cost trips, this is where the expertise of the local transit agency comes into play, as they would have a better understanding of which OD pairs make more logical sense to connect. The lines were then transferred to follow the street network, generating four new routes (Figure 4.9).

To determine how the addition of these routes would alter transfers and their costs within the system, the Transfer Tool was rerun to calculate new costs. In order to do this, the new routes were added to the route layer in the network dataset. Stop locations for the new routes were generated at the intersections of the street network and were added to the stops layer. New boarding links and boardings points were created to connect the new bus stop locations to the pedestrian network.

The resulting changes in the total costs (the combined GC) and the transfer impact costs reveal that the proposed route changes result in both a decreased amount and significance of transfers within the system. However, it is likely that the transit agency would reiterate the process with various route alterations before implementing any service changes.

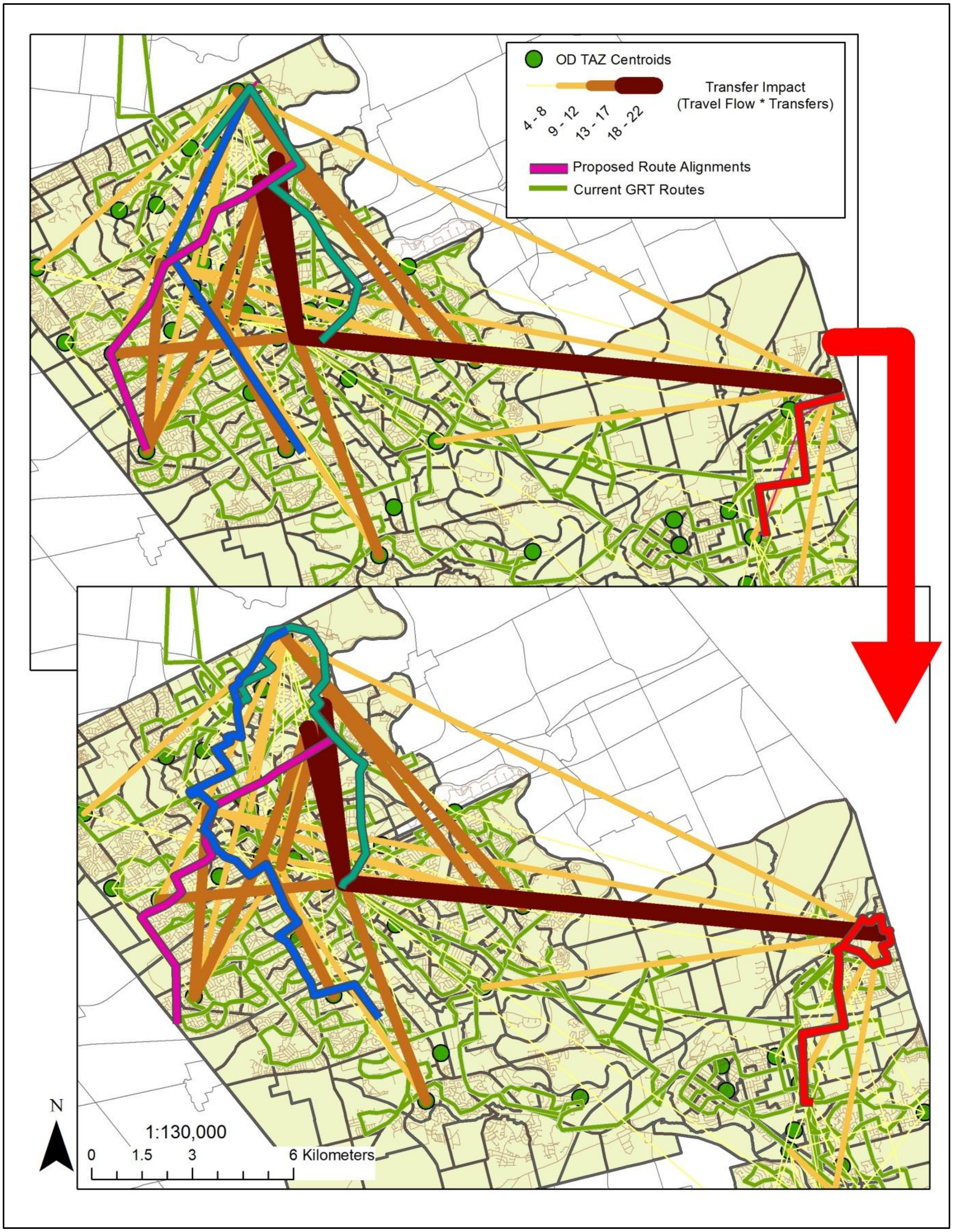


Figure 4.9. Creating new routes from trips with high transfer impact costs

A comparison of the number of transfers within the system reveals that the proposed changes would increase the number of direct trips (by 10%) and the number of trips requiring only one transfer (by 4%), while significantly reducing the number of trips requiring two or three transfers (by -26% and -89%, respectively). Trips requiring one transfer increased as the number of trips previously requiring two or three transfers moved down into these classes (Figure 4.10). The total percentage of trips (total travel flows) requiring one or more transfers was also reduced with the proposed route changes (Figure 4.11).

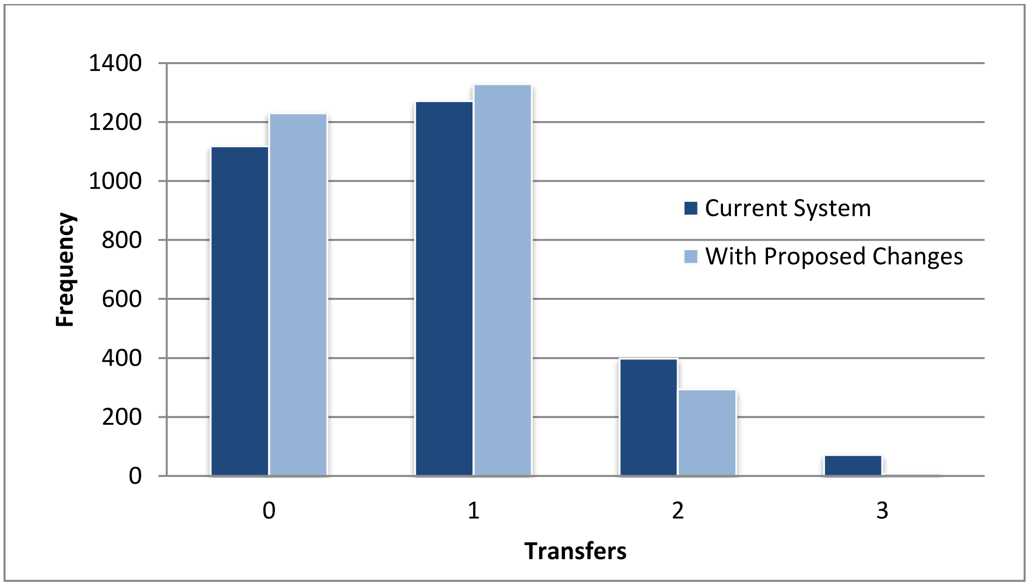


Figure 4.10. Comparing transfers between the current and proposed transit network

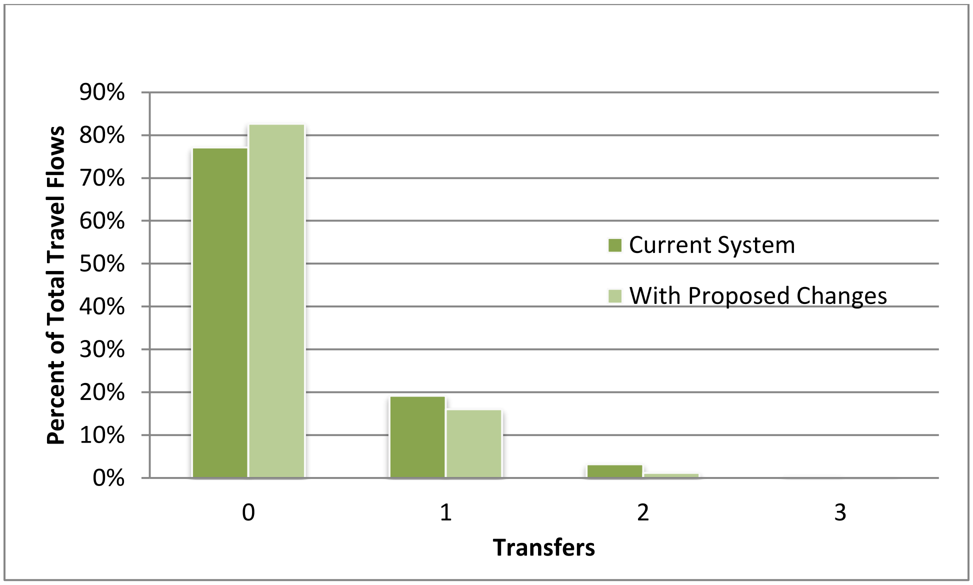


Figure 4.11. Comparing the percentage of trips requiring transfers between the current and proposed transit network

The transfer impact within the system also experienced substantial decreases, as can be seen in the updated map of high transfer impact costs (Figure 4.12). The maximum transfer impact cost was reduced from 22.1 to 15.5 (a 30% decrease). Based on the GC equation used in this study, the total minutes saved between all OD pairs were 7,835 – a 4% reduction across the chosen OD pairs.

The portion of the GC attributed to the transfer penalty (the 20 minute equivalent of IVTT for each transfer present in a trip) also declined for many trips (Table 4.5). This is most notably true for trips where 50% to 69% of the generalized cost of transit had been caused by the presence of one or more transfers. With the current structure, the transfer penalty represented 50% to 69% of the total GC for 287 trips. With the addition of the four routes, the transfer penalty represent 50% to 69% of the GC for only 160 trips. In other words, the number of trips for which the transfer penalty cost was most prevalent have been reduced with the proposed route additions.

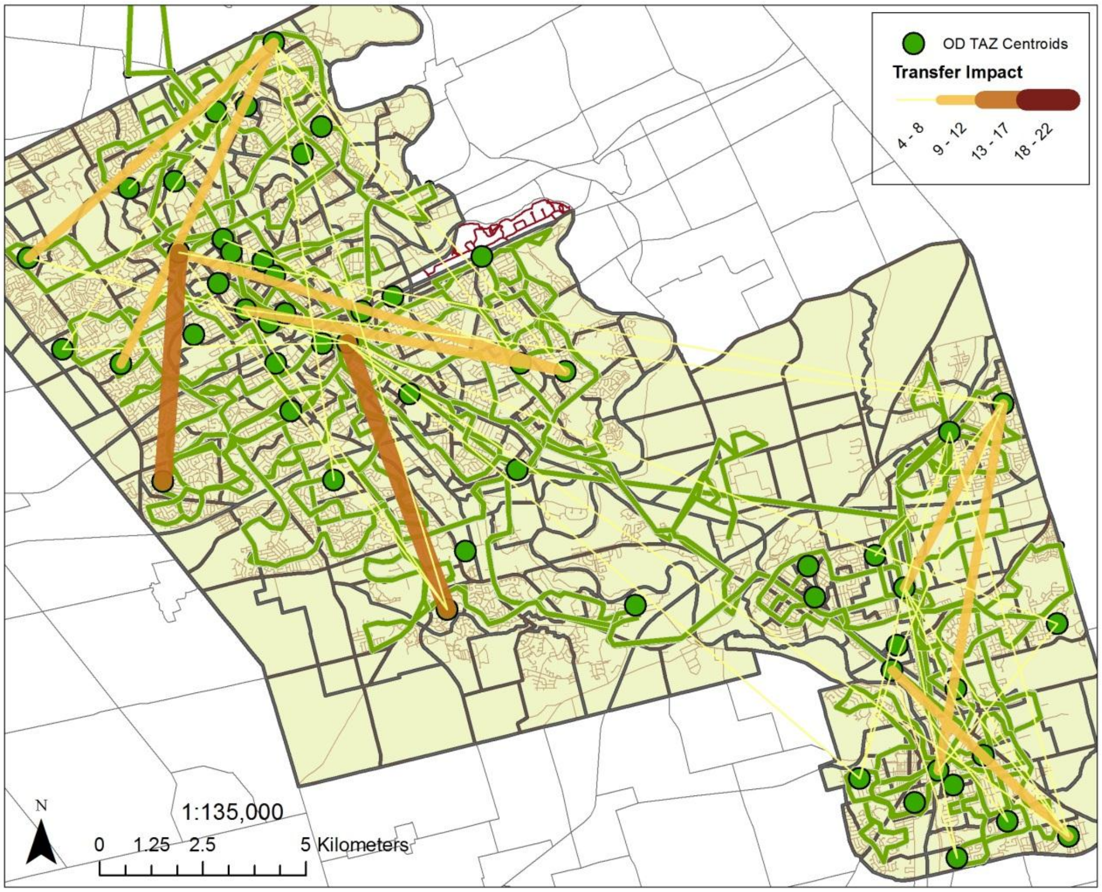


Figure 4.12. Remaining trips with higher transfer impact costs following the addition of new transit routes

Overall, the addition of the four transit routes (which provided direct trips between OD pairs with high transfer impact costs) resulted in a reduction in the number of trips with high costs. While transfers were not eliminated from the system, and the study focused on a subset of OD pairs within the Region, the results indicate that this method can be employed to significantly reduce the GC of trips with high transfer penalties. Additionally, the tool may also be used to evaluate how route changes – rather than the introduction of new routes – effect the transfer impacts throughout a system.

Table 4.5. Comparing the quantity of transfers between the current routes and following the addition of new routes

Percent of total trip cost attributed to transfer penalty	Number of Transfers, Current Route Structure	Number of Transfers, Proposed Route Structure	Percent Change	Total Change
10%	1119	1231	10%	+122
20%	321	342	7%	+21
30%	625	699	12%	+74
40%	508	428	-16%	-80
50%	243	133	-45%	-110
60%	44	27	-39%	-17
70%	2	2	0%	0

Further, as the Transfer Tool calculates saving to the generalized cost of transit trips resulting from the reduction or elimination of transfers, this tool can be used to compute the cost recovery ratio associated with implementing proposed service changes. Cost recovery is the ratio of fare revenue (ridership multiplied by the average fare) to system operating costs (service hours multiplied by average hourly operating costs). Ridership resulting from the proposed service changes may be estimated by applying elasticity values associated with the reduction of transfers, while operating costs can be estimated by determining the number of service hours required for the proposed changes. By calculating the cost recovery ratio of proposed service changes, a transit agency could determine if the potential ridership increases justified the cost of implementing the service.

4.3 ACCESS TOOL

The purpose of the Access Tool presented here is to generate accurate measures of access distances following true pedestrian paths to transit facilities. This tool is modelled at two levels of analysis. First, at the neighbourhood level, access distances are used to compare the effects of neighbourhood design on transit ridership. At the TAZ level, the tool is used to evaluate strength of service area for alternate route alignments by quantifying the change in the number of buildings encompassed in a service area.

The first TAZ used in this study (Neighbourhood A) is a newer Neighbourhood located in the west end of Waterloo, characterized by curved streets and cul-de-sacs. The TAZ is approximately 1,244 m^2, containing 812 buildings, and about 40 bus stops. The second TAZ (Neighbourhood B) is an older Neighbourhood with a grid street pattern in north Kitchener (see Figure 4.13). It is approximately 628 m^2, containing 485 buildings, and 20 bus stops. Both TAZs have relatively similar levels of transit service per square metre. Neighbourhood A has 5.6 km of transit coverage around the perimeter of the TAZ, while Neighbourhood B has 2.4 km of transit coverage crossing through the TAZ. These two neighbourhoods were chosen as they are characteristic of the two opposing neighbourhood styles found in the Region of Waterloo, and many communities in Canada.

After running the shortest path algorithm for all of the buildings in Neighbourhood A to all of the bus stops within and surrounding the TAZ, the process is repeated for Neighbourhood B, providing a disaggregate measure of access distances for both neighbourhoods. Shortest paths are calculated along the street network, without the inclusion of trails. Within Neighbourhood A, the average walking distance to a bus stop is 318 metres, with a maximum walking distance of 722 metres. From Neighbourhood B, the average walking distance is 198 metres, and the maximum walking distance is 644 metres.

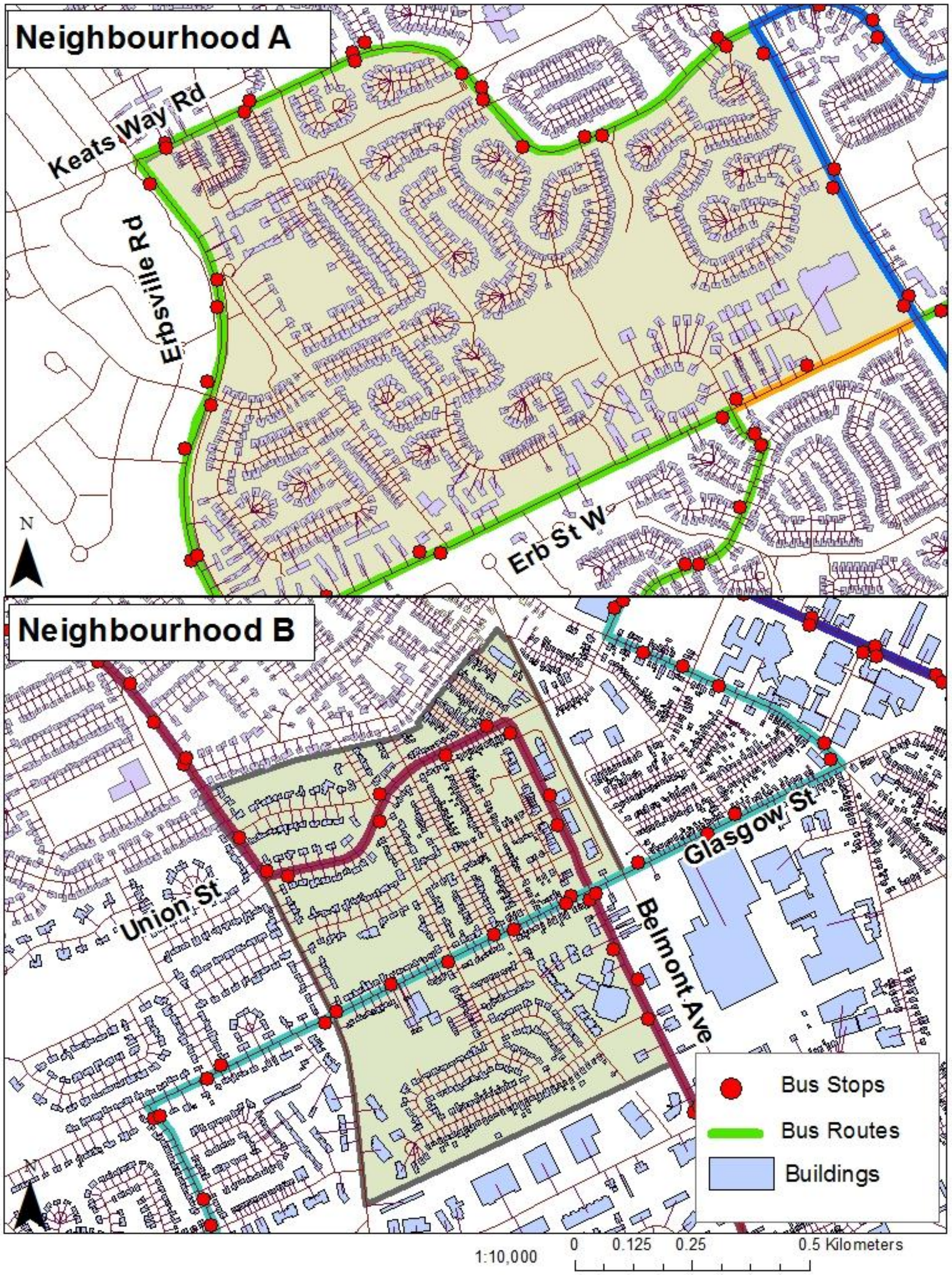


Figure 4.13. Study area and transit routes

The role that pedestrian paths may play in improving access to transit was evaluated by adding the current trail system into the network analysis. While trails are not prevalent in Neighbourhood B, there are many trails throughout Neighbourhood A. These trails often provide a through corridor for travel from cul-de-sacs or dead end streets. The shortest path algorithm was rerun for Neighbourhood A where the algorithm could choose a travel path either along the road network and/or the trail network. Note that sidewalks were present along all roads which allowed the road network to approximate the sidewalks that pedestrians would use. The addition of the trail system shortened the average transit access distance from 318 metres to 268 metres, and reduced the maximum walking distance to 628 metres from 644 metres. On certain trips, the walking distance was reduced by up to 80% (see Figure 4.14). Access distances for Neighbourhoods A and B are summarized in Figure 4.15.

Next, an estimate of transit ridership is calculated indirectly by applying Kimpel et al.'s (2007) distance decay function against the access distances. This function is used to provide an estimate of the probability of transit patronage at each building unit within the study areas. The sum of these probabilities for each unit represents an overall estimate of the probability of transit demand (passenger boardings per trip in the am peak hour) for each neighbourhood.

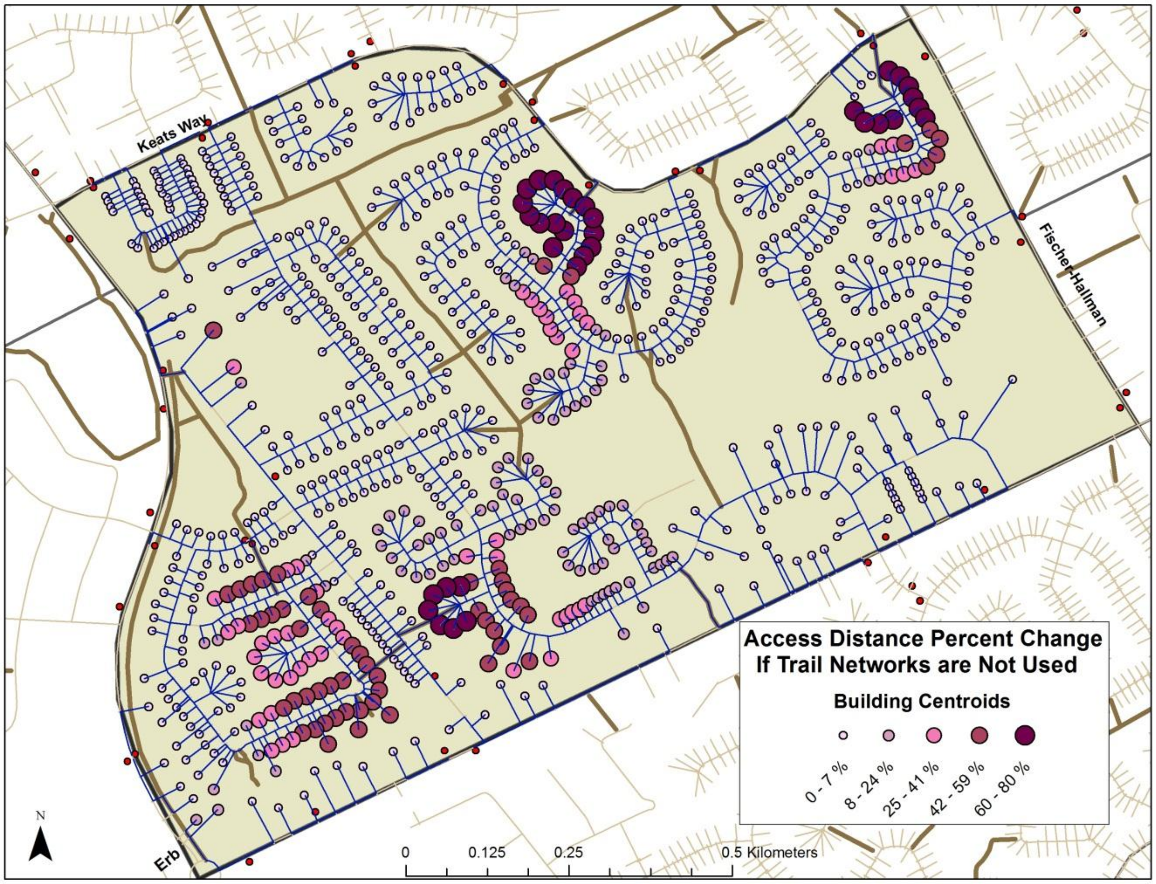


Figure 4.14. Percent reduction in pedestrian distances when trailed are used

The resulting estimated demand in Neighbourhood A was 269 without the inclusion of trails (from 812 buildings), compared to 281 in Neighbourhood B (from 485 buildings). When the trail network was included in the analysis, the likelihood of transit utilization increased by 18.5% to 333 (results are summarized in Table 4.6). However, in order to maintain this increase in accessibility – trails must be maintained over the winter months when there may be snow. There must also be sufficient lighting and security measures in order for them to be well used, particularly in the evenings.

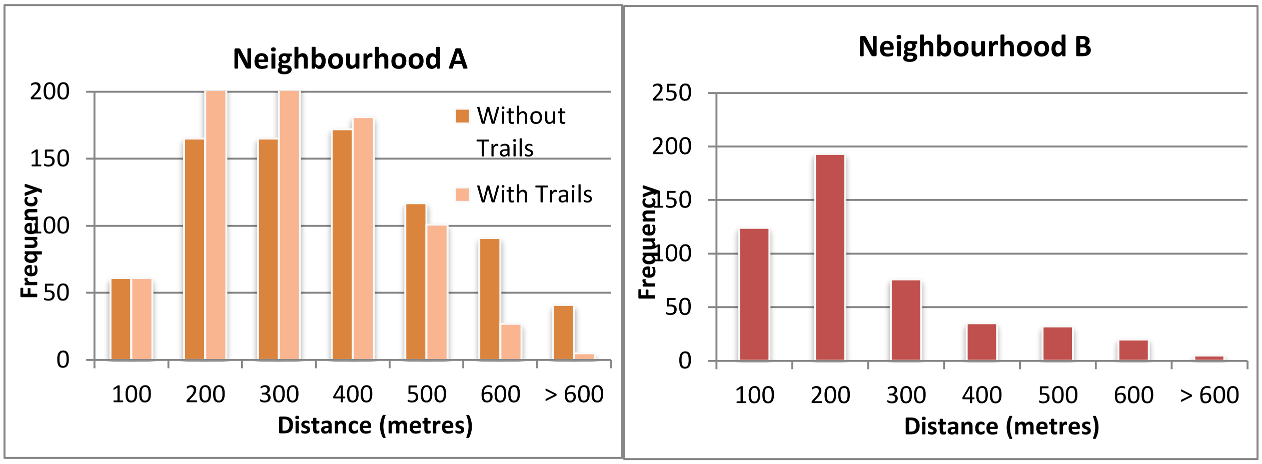


Figure 4.15. Access Distances to Transit in Study Areas

The neighbourhood level analysis of access distances was used to the effect that neighbourhood design and the presence of pedestrian paths can have accessibility and as a result, ridership.

The TAZ (or route) level analysis evaluates how changes in the roads on which a route operates affects access distance. Route 12 is a long, heavily used route in the Region that connects major retail centres to campuses of all three post-secondary institutions. The route runs from the south end of Kitchener to the north end of Waterloo along several main arterial streets (Westmount Road, Fischer-Hallman Road, and University Avenue). Again, a shortest path function was run to calculate the actual walking distances along the pedestrian network from each building within a 400 metre buffer of the existing route. This distance is used as studies have found that transit use begins to decline sharply after this distance (Kimpel et al., 2007; Zhao et al., 2003; O'Neill et al., 1992; Hsiao et al., 1997). Instead of bus stop locations, road intersections were used as points of access to the route, as typically stops are located at intersections.

Table 4.6. Comparing the probability of utilizing transit between study areas

	Number of Buildings	Expected Ridership (assuming 1 persons/building)	Ratio of Utilization (probability/building)
Neighbourhood A without Trails	812	269	0.33
Neighbourhood A with Trails	812	333	0.41
Neighbourhood B	458	281	0.58

For this alignment, the buffer method suggested that 11,201 buildings were within 400 metres of the route. However, since the pedestrian network does not extend in a straight line form all portions of the route, the actual number of buildings within a 400 metre walking distance was only 4,825 buildings. The average access distance for these building was 249 metres.

Approximately 4 km of the original route was then redesigned in GIS to remain along Westmount Road for north-south travel to simulate an alternative route structure (see Figure 4.16). The route level process was rerun for this revised alignment. After redesigning the route to run primarily along Westmount Rd., only 4,289 buildings were within 400 metres of the route, with a slightly shorter average access distance of 243 metres.

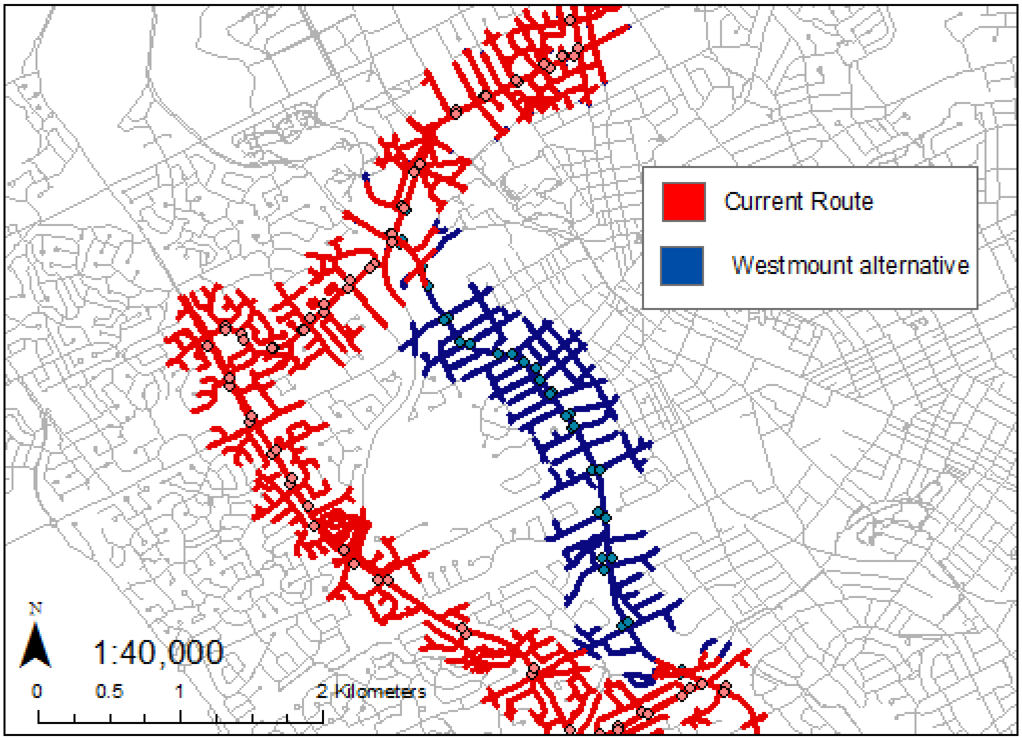


Figure 4.16. Comparing accessibility at the corridor level

The weighted averages of access distances to buildings along the existing route and the redesigned Route 12 were also computed. In this instance, building footprints (square metres) were used as the weighing factor to represent the strength of each building location as a generator for transit. Contrary to the previous findings, this weighting actually suggests that the redesign improves overall access in the corridor. The weighted average of the current routing is 250 metres – a slightly longer walking distance compared to the unweighted distances. The weighted average distance of the alternative routing was 239 metres, a slight decrease to average access distance, which suggests that there are a greater number of larger buildings (with higher trip generation) closer to the route compared to the original route structure. These findings indicate that although the current route structure provides access to a greater number of buildings, the alternate route alignment provides closer access to buildings which are likely greater trip generators.

When compared against other methods, the method employed here to measure access distances to transit provides a more exact representation of real world access distances. Using Neighborhood A as a case study, the buffer method estimated that all of the buildings were within a 400 metre access distance to transit services. A network ratio analysis, as developed by O'Neill (1992), was also completed for comparison. This analysis, which takes the percentage of the street lengths served by transit and multiplies it by the population within an area, predicted that 84% of the population in Neighbourhood A were within 400 metres to a transit stop. The method presented in this thesis which measures access distances from building centroids concluded that 69% of the buildings were within 400 metres of a transit stop if travel occurred along the road network alone. If trails were included in the analysis, 83% of the buildings were within 400 metres to transit.

The network ratio method provided a similar accessibility estimate to the method developed in this thesis when multi-use trails were utilized. This is consistent with the network ratio method's ability to better estimate access distances in areas with grid pattern road networks. In this instance, the trail network acted as connecting links that served to replicate a pedestrian grid network. However, in neighbourhoods where there are few trails, or alternatively, an abundance of trails, the accuracy of the network method would be impacted. Further, unlike our approach, this method is not able to provide average estimates of walking distances.

4.4 ROUTE PLANNING TOOL

Although travel forecasting models are commonly used to predict modal splits for auto and transit trips, often the amount of time and expertise required to run these models prohibit transit agencies from using them to estimate expected ridership impacts associated with a proposed route change. Additionally, travel forecasting models often over or under predict transit ridership. The purpose of the Route Planning Tool is to examine ridership impacts resulting from small changes in route alignment. Post-process analysis (analysis conducted after the travel forecasting model has been produced) is applied to determine how changes in access distances and local demographics affect transit patronage for various route alignments.

Route 12 in Kitchener and Waterloo was once again used to demonstrate the Route Planning Tool. Three alignment alternatives were chosen for the central section of Route 12 that runs between Highland Road and University Avenue (see Figure 4.17). The current alignment of this section runs along Fischer-Hallman Road and Keats Way Road. In this area, Fischer-Hallman Road is characterized primarily by back lotted, low density residential development with some neighbourhood shopping centres, while Keats Way Road is comprised of medium and low density residential development with a high student population. The alternative alignments chosen were via Westmount Road, University Avenue, and Erb Street. Westmount Road is characterized by low and medium density residential with some neighbourhood shopping centres. Erb Street is predominantly medium density residential with a high student population. The section of University Avenue chosen for the alternative route alignment is primarily open space and back lotted low density residential development.

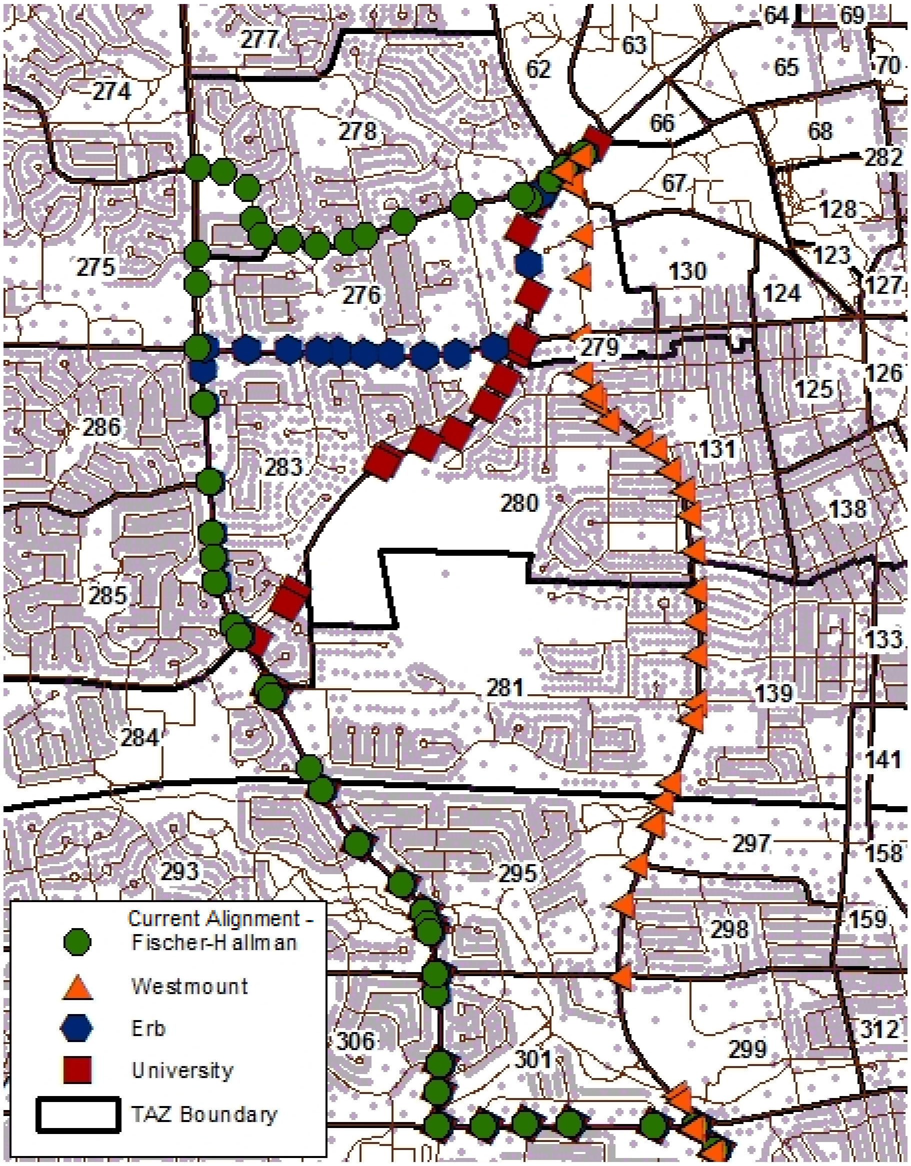


Figure 4.17 - Route 12 alignments options

The new alternative route alignments were created in GIS. Transit stop locations were generated at every location where the route intersected a cross street or pedestrian path. Some 20 TAZs were included in the study area which was defined as any TAZ adjacent to any of the route alignments.

This tool analyzes access distances between each parcel in the study area to the closest transit stop at the parcel level. Initially, distances were generated between parcels and transit facilities of the original Route 12 alignment along Fischer-Hallman Road and Keats Way Road to act as a baseline for comparison. In order to capture the strength of attraction for each parcel, access distances were weighted based on the population and employment figures. Weighted average access distances were then calculated for each TAZ. After this process was complete for the original route structure, it was repeated for the three alternative route alignments.

Next, the access distances for each alignment were exported to a spreadsheet to convert the distances into access costs. The travel forecasting model used by the Region of Waterloo calculates access costs as 1.6 times greater than access distances. Therefore, to calculate the new access costs for the alternative route alignments, weighted access distances for each TAZ were multiplied by 1.6.

Resulting access costs from the analysis are shown in Table 4.7. If access costs were examined for individual TAZs, the Westmount Road alignment has the lowest access cost for the greatest number of TAZs compared to the alternate alignments. However, overall, the Erb Street alignment was found to have the shortest combined cost distance for all TAZs in the study area, and thus the lowest access cost.

Once calculated, access costs for the alternative alignments are input into the GC equation The Region of Waterloo's travel forecasting model uses the following GC equation (equation 4.3):

$$\begin{aligned} GCT = \ & in\,vehicle\,cost + initial\,wait\,cost + transfer\,wait\,cost \\ & + transfer\,penalty\,cost + transfer\,walk\,cost + access\,walk\,cost \\ & + egress\,walk\,cost + access\,drive\,cost + dwelling\,cost) \end{aligned} \tag{4.3}$$

Table 4.7 – Access Costs for Alternate Route Alignments

TAZ ID	Average Model Access Cost (Fischer-Hallman alignment)	Fischer-Hallman Access Cost	University Access Cost	Westmount Access Cost	Erb Access Cost
67	20	13.3	13.3	10.1	13.3
131	23	29.1	21.1	6.5	23.0
139	17	42.2	39.8	10.2	40.5
275	23	21.1	46.7	52.5	26.2
276	19	7.2	14.9	19.7	6.0
278	11	6.6	15.7	17.6	11.9
279	21	18.8	9.8	6.6	11.7
280	21	29.7	21.8	7.0	23.7
281	28	24.3	24.2	14.3	24.3
283	17	9.5	16.1	29.6	5.3
284	15	15.7	16.9	50.0	15.8
285	21	17.4	22.4	55.4	17.4
286	20	15.4	30.7	47.6	15.6
293	19	21.7	21.8	41.4	21.7
295	22	12.1	12.1	14.3	12.1
297	20	28.6	28.6	9.0	28.6
298	15	24.0	24.0	8.5	24.0
299	19	20.5	20.5	12.6	20.5
301	6	5.6	5.6	10.4	5.6
306	15	9.5	9.5	26.1	9.5
Sum	**372.7**	**372.2**	**415.6**	**449.3**	**356.7**
Average	**18.6**	**18.6**	**20.8**	**22.5**	**17.8**

Using the variables in this equation (the values for which are generated by the travel forecasting model), the generalized cost of transit for each route alignment is calculated by replacing the model generated access cost with the new access costs generated in the GIS. The resulting generalized costs for each alignment are used to calculate the mode split (probability of transit utilization). The Region of Waterloo uses a mode share equation in the form of :

$$Probability\ of\ transit_{ij} \;=\; 1\,/\,1 + exp(0.06 * (transit\ GC_{ij} \;-\; auto\ GC_{ij})) \tag{4.4}$$

Where:

GC^T is the generalized cost of transit
GC^A is the generalized cost of auto

However, to incorporate the transit mode bias into the modal split calculation, this equation is re-written as:

$$Probability\ of\ transit \\ = \; 1\,/\,1 + exp(0.06 * (transit\ GC_i \;+\; mode\ bias_i \;-\; auto\ GC_i)) \tag{4.5}$$

To account for socio-demographic variables which may influence transit ridership, transit bias parameters are incorporated into the mode split equation. Separate bias parameters, as developed by Casello and Jung (2011), were determined for each TAZ according to the classification of the zones as highly transit supportive, neutral, or low transit supportive. These bias values can be found in Table 4.8.

Table 4.8. Bias Parameters

Transit Supportiveness	Mode Bias
High	-8.63
Medium	10.65
Low	30.96

The resulting transit mode split values, which represent the probability of using transit over auto, are applied against the total volume of traffic originating in each TAZ to calculate an estimate of transit ridership (equation 4.6). In this thesis, the ratio of transit usage was computed as the product of a combined value of traffic volumes originating from each TAZ in the study area to all other TAZs in the study area. That is, a sum of traffic volumes from one origin to all destinations in the study area was used.

$$Ridership = Probability\ of\ transit_i * Travel\ flow_{ij} \qquad (4.6)$$

Results

The results for the various route alignments can be examined on an individual TAZ bases or by summing the GC of all TAZs within the study area for each alignment. This combined value demonstrates how the route performs at the corridor level. As shown in table 4.9, the combined GC for the study area as output by the Regional travel forecasting model (with the current GRT route structure) was 992.8 for the study area. After the CG is calculated for each route alignment using the access distances generated within the Route Planning Tool, the Erb Street route alignment resulted in the lowest combined GC with 976.8. However, the Westmount Road alignment had the lowest GC for the greatest number of individual TAZs. The combined GC calculated using the Route Planning Tool for the original route structure along Fischer-Hallman Road was very similar to the combined model the GC; however, costs for individual TAZs varied.

Although the Erb Street alignment generated the lowest generalized cost, the original routing along Fischer-Hallman Road was shown to have slightly higher ridership potential. This is because the current route structure had greater transit mode splits in TAZs with higher travel flows. Table 4.10 provides the total travel flows (demand) from each TAZ and the transit mode splits for each route alignment. Table 4.11 lists predicted transit ridership for each route alignment. Ridership estimates are for the number of trips that utilise transit during the AM peak period.

Table 4.9. Updated GC^T

TAZ ID Zone	Model GC (based off AVG of GC for all TAZs)	Fischer-Hallman GC	University GC	Westmount GC	Erb Weighted Average GC
67	50.2	43.2	43.2	39.9	43.2
131	53.1	59.1	51.2	36.5	53.1
139	46.7	71.9	69.6	40.0	70.2
275	53.9	51.6	77.3	83.0	56.7
276	47.8	35.6	43.2	48.0	34.4
278	48.1	44.1	53.2	55.2	49.5
279	49.6	47.1	38.1	34.9	40.0
280	51.1	59.9	52.1	37.2	54.0
281	48.5	44.3	44.2	34.3	44.3
283	44.7	36.9	43.6	57.0	32.7
284	45.1	46.1	47.3	80.4	46.1
285	53.2	49.3	54.4	87.4	49.3
286	51.2	46.9	62.2	79.1	47.1
293	58.1	60.7	60.8	80.3	60.7
295	46.8	37.4	37.4	39.6	37.4
297	51.9	60.4	60.4	40.8	60.4
298	49.9	59.2	59.2	43.8	59.2
299	49.3	51.2	51.2	43.2	51.2
301	46.3	45.4	45.4	50.2	45.4
306	47.3	41.9	41.9	58.5	41.9
TOTAL:	**992.8**	**992.3**	**1035.7**	**1069.4**	**976.8**
AVERAGE:	**49.6**	**49.6**	**51.8**	**53.5**	**48.8**

Table 4.10. Transit Modal Spilt

From Zone	Sum of Total Travel Demand (Auto+Transit)	Probability of Transit - MODEL OUTPUT	Fischer-Hallman Probability of Transit	University Probability of Transit	Westmount Probability of Transit	Erb Probability of Transit
67	1.25	4%	6%	6%	7%	6%
131	28.47	1%	1%	1%	2%	1%
139	43.42	4%	1%	1%	6%	1%
275	143.36	3%	4%	1%	1%	3%
276	99.79	4%	8%	5%	4%	9%
278	127.83	1%	2%	1%	1%	1%
279	11.84	1%	1%	2%	3%	2%
280	24.78	1%	1%	1%	2%	1%
281	56.00	1%	1%	2%	3%	2%
283	81.75	2%	2%	2%	1%	3%
284	36.96	5%	5%	4%	1%	4%
285	142.62	3%	4%	3%	0%	4%
286	121.82	1%	1%	1%	0%	1%
293	97.46	1%	1%	1%	0%	1%
295	115.31	4%	7%	7%	7%	7%
297	13.62	3%	2%	2%	6%	2%
298	30.28	1%	1%	1%	2%	1%
299	31.58	12%	11%	11%	17%	11%
301	47.38	14%	15%	15%	11%	15%
306	54.69	13%	17%	17%	7%	17%

Transit mode split ratios varied between 17% of all trips in the AM peak hour and 1% of all trips. This range reflects the varied level of support, or inclination to use transit in each of the TAZs.

Table 4.11. Predicted ridership

From Zone	Ridership-MODEL OUTPUT	Fischer-Hallman Ridership	University Ridership	Westmount Ridership	Erb Ridership
67	0.05	0.07	0.07	0.09	0.07
131	0.26	0.18	0.29	0.69	0.26
139	1.88	0.43	0.49	2.76	0.47
275	4.43	5.05	1.12	0.79	3.77
276	4.15	8.28	5.38	4.10	8.83
278	1.81	2.30	1.34	1.19	1.67
279	0.13	0.16	0.26	0.32	0.24
280	0.25	0.15	0.24	0.57	0.21
281	0.66	0.84	0.85	1.51	0.84
283	1.23	1.94	1.32	0.59	2.48
284	1.77	1.67	1.56	0.22	1.66
285	4.65	5.82	4.34	0.62	5.82
286	1.35	1.74	0.70	0.26	1.72
293	0.75	0.65	0.64	0.20	0.65
295	5.02	8.56	8.56	7.55	8.56
297	0.45	0.27	0.27	0.85	0.27
298	0.35	0.20	0.20	0.50	0.20
299	3.86	3.50	3.50	5.28	3.50
301	6.57	6.89	6.89	5.35	6.89
306	7.10	9.33	9.33	3.88	9.33
TOTAL:	**46.72**	**58.02**	**47.35**	**37.31**	**57.44**

The Route Planning Tool produces transit ridership estimates for small changes in route alignments based on changes to access distances and by introducing a bias factor based on the level transit supportiveness within a TAZ. When the tool was applied to various realignments of Route 12 in the Region of Waterloo, it was found that a restructuring of the route which had it run along Erb Street resulted in a lower generalized cost within the effected TAZs. However, once ridership estimates were produced, which take into account the travel flows that begin in a TAZ and also the transit bias which defines neighbourhoods as highly transit supportive, transit neutral, or low transit supportive; it was found that the current alignment along Fisher-Hallman Road actually produced higher ridership estimates within the study area. The tool can therefore be used to evaluate potential route changes against current route structures, and to calibrate ridership estimates produced by travel forecasting models.

4.5 CHAPTER SUMMARY

This chapter applied the three tools developed in this thesis to the Region of Waterloo and its transit system. The Region is currently one of the fastest growing communities in Canada, and much of the future growth is expected to be accommodated within the current urban envelope, creating denser nodes and corridors of development which will result in greater pressure on the current transportation network. The Region has developed a goal to increase the peak hour mode share of transit from some 4% to approximately 17% over the next twenty years. Anticipated changes to the bus network, which includes additional express routes and alterations to local routes, must be planned to maximise the efficiency and convenience of the system.

The Route Planning Tool, when applied to the Region, demonstrated that current travel patterns exist for which transit costs are high. This tool can be used to help restructure routes within the Region to minimise these costs for heavy travel flows.

The Access Tool demonstrated the importance of pedestrian trails throughout a neighbourhood to improve accessibility to transit, which is a key consideration when planning new subdivisions. This tool also demonstrated that certain corridors may be considered more transit supportive than others.

Similarly, the Route Planning Tool was used to analyse ridership changes resulting several modifications to an existing route that serves Kitchener and Waterloo based on a change in access distances. It was found that while the proposed changes resulted in total savings to the generalized cost of transit, the current alignment provided more convenient service to key neighbourhoods and therefore had higher transit ridership potential. This highlights the need to examine route changes at both a local and corridor level.

CHAPTER 5: CONCLUSIONS

Transit plays an important role in the environmental, social, and economic development of our communities. Yet in order for transit services to attract riders, trips must be offered that are competitive when compared to travel by private vehicles. Focusing on planning methods that reduce the perceived costs of a trip will likely result in higher ridership, similarly, prioritising projects that result in improvements for the greatest number of potential riders will produce greater ridership growth.

The research presented in this thesis focused on developing three tools that better inform the transit planning decision making process through the evaluation of anticipated impacts on current and potential users resulting from service changes. These tools were the Transfer Tool, Access Tool, and the Route Planning Tool, all of which employed GIS to provide more sophisticated, yet simple methods that utilize demographic data and forecasting outputs readily available to most transit agencies. An iterative approach was presented, allowing the local knowledge of transit planners to be utilized in order to focus on decisions that balance the needs of the agency with the needs of the user and the larger community.

The techniques developed here specifically focused on developing tools to address three challenges in transit planning: analyzing the presence and costs of transfers within a system, examining access distances to transit as a measure of transit supportiveness, and estimating ridership resulting from small changes for route alignments. In order to demonstrate their use, the tools were applied to the Regional Municipality of Waterloo in South Western Ontario.

The effect of transfers within a system were analyzed through the Transfer Tool. Complete trip paths were modelled which reflected the decision making process of travellers and the generalized cost of separate trip components, such as: walk distance to and from a transit stop, in-vehicle travel time, and the number of transfers. The purpose of this tool was to measure the presence of transfers in a network against total travel flows between OD pairs, thus creating a transfer impact cost that may be used to evaluate the costs of transfers throughout a transit system. When applied to the Region of Waterloo, several trips with higher transfer impacts became apparent. These costs mainly resulted from trips where one transfer was present between OD pairs with higher travel flows, although there were some trips highlighted which consisted of multiple transfers with medium or low travel flows. OD patterns with higher costs were displayed visually in a GIS, allowing new routes to be created which improved connections between these pairs. Following the addition of the new routes into the network, the methodology was rerun to determine the resulting change in transfer costs and overall trip costs. The number of trips with high transfer costs was reduced, as were the number of transfers throughout the system.

Pedestrian access distances to transit were measured via the Access Tool. This tool provides a disaggregate measure of true walking distances along the pedestrian network between building centroids and the closest transit stop. This analysis was conducted at the neighbourhood level to examine how the design of the street network and the presence of pedestrian paths affect access distances, and thereby the propensity to use transit. Once calculated for each neighbourhood, distances were input into a distance decay function to produce ridership estimates for each transit stop in the form of utilization ratios for each stop. Based on the comparison of two representative neighbourhoods, it was found that the neighbourhood with the grid network street pattern resulted in a much higher ratio of estimated transit use per building compared to the neighbourhood characterised by cul de sacs. However, the presence of trails throughout the neighbourhood with cul de sacs was found to decrease access distances and result in greater transit usage.

Next, distances were compared at the TAZ level to evaluate how a change in the alignment of a route can influence the number of potential riders based on revised counts of buildings within a defined walking distance. It was found that altering the structure of a route to run along a parallel corridor resulted in a decrease to the number of buildings that fell within a

400 metre service area, but had the benefit of reducing the average access distance, particularly for larger buildings (which would likely be stronger trip generators). The results also found that measuring service areas along the street network produced much more accurate results compared to typical buffer methods.

The Route Planning Tool builds upon the methods used in the Access Tool to produce a more robust estimate of ridership changes following minor route changes using: access distances, demographic information, and output from travel forecast models. Three alternative route structures were chosen for a main line route that runs through the cities of Kitchener and Waterloo. Changes in access costs for the various route alignments were used to recalculate the GC of transit in the neighbourhoods affected by the route changes. Based on the revised GC values, the transit mode share and transit ridership for each route alignment were produced. A transit bias, based on socio demographic variables, was applied to each neighbourhood in the mode split equation to improve ridership estimates. Although some of the proposed route alignments had lower generalized costs compared to the current route structure, total ridership estimates remained highest for the current alignment which suggested that a route change is not warranted.

5.1 CONTRIBUTIONS

Transit agencies often have a large set of proposed service changes that staff believe will improve the system and increase ridership; however, limited budgets typically allow for a much smaller set of priority projects to actually be implemented. The tools presented here may be used to help agencies set these priorities based on the greatest reduction of users' perceived costs within the system, or higher ridership improvements. As the presence of a transfer in a trip has been shown to significantly reduce ridership, the iterative approach of the Transfer Tool can be used to determine which changes in a route structure would result in the greatest reduction of the generalized cost of a trip attributed to transfers. The Access Tool and Route Planning Tools were both developed to examine how changes to the streets along which transit routes operate influence access distances to transit, and further, transit ridership. As most users begin and end their transit trips by walking to a bus stop or facility, this is an important consideration when establishing service changes.

The application of these tools to the Region of Waterloo demonstrated that these methods may be used in practice to evaluate proposed changes to transit services. The techniques used in this thesis combine disaggregated data and more sophisticated spatial analysis with an iterative approach that incorporates local knowledge and judgment. Further, these methods utilise data output generated by travel forecasting models to analyse smaller service adjustments to an existing system without having to re-run a traditional four-step model. The methods produce results, such as ridership estimates or generalized costs, which allow clear comparison between various service change options and current service. Moreover, the data and software utilized in this study are generally widely available to transit agencies. By using a common software platform, the techniques presented here may be transferred easily to transit agencies.

5.2 LIMITATIONS

A common limitation in any GIS-based study is the availability and accuracy of data. Many layers are only updated occasionally and, as such, they may be out of date by the time of study. This limits the applicability of our techniques to newer neighbourhoods.

By creating a multimodal network and applying cost parameters, the Transfer Tool aims to predict human behaviour through the application of certain penalties aimed to mimic the decision making process such as the assumption that users will walk a slightly longer distance to avoid a transfer. However, such choices will vary based on individual abilities and preferences, and also on the environments of the paths themselves.

Further, the quality and impact of transfers are influenced by numerous variables such as the level of service (frequency), the length of time spent waiting and walking between transfers, the quality of the pedestrian environment, as well as the amount of physical and mental effort extended during the transfer process. In this thesis, all transfers are weighted equally; however, in reality their perceived costs could vary quite significantly. Preferably, the study should include various attributes that affect the transfer experience; however, as previously noted, the data required for such an analysis across a system or a larger study area would be difficult to gather, and also little is known about the weight or influence of each transfer component.

An additional limitation associated with the Transfer Tool is the method employed which used TAZ centroids as OD pair locations. This method generated some of the OD locations in areas inside of a TAZ that we would not typically expect to be served by transit, such as at the edge of a city where there is little or no development or in a park. Trips to or from these locations may therefore have exaggerated walk times. In order to negate this, origins could be placed more exactly inside of a TAZ. Alternatively, a more disaggregate level of study could be used; however, this would limit the ability to use data from travel forecasting models.

The Access Tool utilizes a building footprints layer. Such information is often created and maintained by various municipalities. Therefore, the potential exists for each layer to contain different information. The data used for the study of Waterloo Region, some building layers were very detailed, while others had few details other than the footprint itself. In this analysis, in was not possible to differentiate between multi-family and single-family units.

A second potential limitation exists related to the use of building layers in this study. If a building has a large setback from the street it is possible that the building centroid may be connected to a different street than the road onto which the building fronts and is therefore legally associated. In this case, if the parcel layer or building layers contain street address information, it can be used to ensure that linkages are made properly. Following Biba et al. (2010), it is assumed that there will be pedestrian access from buildings to the building's street address. The most important consideration; however, is that the level of service is not taken into account when considering probability of usage at each transit stop. As this variable has been shown to affect ridership, consequent studies should include the headways of each bus stop into the analysis when calculating probability of ridership at each stop.

Similar to the other studies, this Route Planning Tool does not account for level of service when predicting transit ridership, nor does it consider the presence of neighbouring or overlapping routes. An additional limitation exists related to the use of TAZs. Although the Route Planning Tool measures access distances at the parcel level, in order to compare the results to outputs from a travel forecast method the data must be aggregated to a TAZ level. Given that TAZ boundaries are typically defined by population and employment densities, the size of TAZs can vary quite significantly and some can be fairly large. Additionally, TAZ boundaries are often drawn along major road corridors which is typically where transit routes operate. Therefore, a number of parcels are likely to be located quite close to a transit route within a TAZ while those located at the edge of the transit route may be significantly further. When the access distances at the parcel level are combined into a singular value at the TAZ level, these differences in costs may be smoothed out. For example, if a transit route is located at the border of a TAZ, there may be significant population and employment density within 350 metres of the transit route that would have relatively small access distances and access costs. However, if the TAZ extends out 1 kilometre from the route (thereby resulting in long access distances for a significant proportion of parcels within the TAZ) the average access cost, and therefore predicted transit ridership, for that TAZ would be smoothed out, even though a significant base did exist immediate to the transit route.

5.3 FUTURE EXTENSIONS

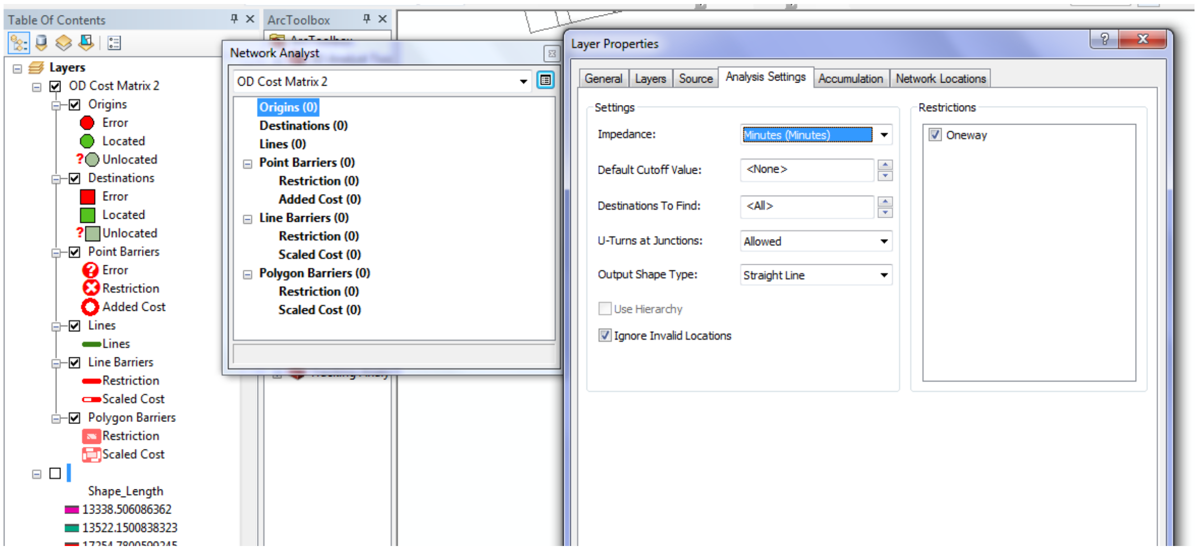
This research has examined the effect of access distances and densities on transit ridership. However, these are by no means the only factors that influence transit use. Similarly, while the Transfer Tool analyzes the number of transfers required between OD pairs and the potential number of customers that this transfer effects; it does not evaluate the various components that influence a passenger’s experience while transferring.

In order to further analyze accessibility within a neighbourhood and potential ridership gains related from route changes, future work that incorporates variables such as service hours and headways into the analysis is important for understanding overall accessibility, convenience, and passenger attraction of transit services. Additionally, to gain a better understanding of the temporal impact of transfers on a network, a study that incorporates trip tables in order to calculate wait times between transfers would be beneficial, as the amount of wait time involved in a transfer can have a large impact on the perceived penalty of that transfer. Further research into the relative weight of each transfer component on the transfer penalty is required. More detailed data regarding the pedestrian environment would likely enhance how transfers are modelled.

Additional exploration into developing new methods to visualize and communicate transit-cost competitiveness would also be beneficial. Such tools are important to clearly demonstrate the wider impacts of service changes, and for gaining political and financial support for such changes.

Appendix A

Network Analyst GUI



Impedance: Minutes (Minutes)

Default Cutoff Value: <None>

Destinations To Find: <All>

U-Turns at Junctions: Allowed

Output Shape Type: Straight Line

☐ Use Hierarchy

☑ Ignore Invalid Locations

☑ Oneway

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