

The Development and Deployment of a GIS tool for Transit Network Design

by

Stephanie Simard

A thesis
presented to the University of Waterloo
in fulfilment of the
thesis requirement for the degree of
Master of Applied Science
in
Civil Engineering

Waterloo, Ontario, Canada, 2010

© Stephanie Simard 2010

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

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

Abstract

Public transportation contributes to sustainable transportation in urban areas. Unfortunately, in some cases public transit systems have been underperforming. Over the years, factors such as urban sprawl and the increase in private vehicle ownership have led to challenges for public transportation providers. The lack of investment in transit infrastructure has resulted in transit agencies being under resourced which further limit the agencies' ability to respond. Realizing the need to change and move towards a more sustainable and balanced transportation system, governments have begun to invest more and more in transportation infrastructure projects.

In order to encourage public transportation, focus has shifted to improving the quality of transit service being provided. There are many ways in which transit improvements can be made. The problem that describes the design of a public transportation network is referred to as the transit network design problem (TNDP). Much of the existing literature that addresses the TNDP describes methods that are rigorous and complex and have limited application in practice. Given the emergence of geographic information systems (GIS), there exists new opportunities to address the TNDP.

This thesis presents a customized GIS tool that assists transit network design. The approach utilizes GIS to identify desire lines or major travel demand corridors from which trunk transit routes are proposed and evaluated. The GIS tool is built using VBA scripting in ArcMap 9.3 part of ESRI's general ArcGIS suite but the underlying GIS functionality needed by the tool is not limited to ESRI software. The tool offers a proven methodology for use within transit network design and evaluation at a level of resource requirement that is consistent with most transit agencies. The tool has been customized to minimize the need for GIS training and to maximize its adaptability for application in multiple cities. The analyst applying the tools must have substantial knowledge of local conditions.

The tool is applied to the Regional Municipality of Waterloo, Ontario, Canada, at the TAZ (traffic analysis zone) level using population and employment data. A street network with corresponding posted speeds on each link and the location of signalized intersections were also used in the analysis. The results of the analysis depicted major flows throughout Kitchener, Waterloo and Cambridge. Unique flows from students, major employers and an analysis of average income levels also provide input into the major demand corridors. From these results seven high order transit routes were designed to accommodate the major demand corridors.

From the results it was found that GIS can be used to depict major demand corridors and inform transit network design. GIS is an excellent tool that can display complex information and visually identify spatial patterns. Further research includes the development of a model that evaluates network alternatives or the development of quantitative methods by which limits on aggregation can be automated.

Acknowledgments

There are a number of people without whom this thesis might not have been written, and to whom I am greatly indebted.

I owe my deepest gratitude to my advisor Dr. Jeffrey Casello who has taught and encouraged me to meet challenges that I had never before thought possible. I appreciate his support and guidance. I would also like to thank him for his financial support.

I would like to express my thanks to my co-supervisor, Dr. Bruce Hellinga. I appreciate his time and advice. I thank him for his financial support.

Special thanks to all of my transportation friends and the members of the Waterloo Public Transportation Institute who made it an enjoyable place to work and learn.

Many thanks to the Regional Municipality of Waterloo for providing me with the data needed for my case study application as well as their financial support.

Lastly, I would like to thank my parents and my sister for their continued love and support. I thank my parents for their encouragement especially when I encountered difficulties. I thank my sister, who has been a constant role model to me and who has been one of my best counsellors. This thesis is simply impossible without them.

Dedication

This thesis is dedicated to my loving parents, Barry and Denise, who have taught me that anything is possible as long as you put your mind to it. It is also dedicated to my sister, Kim, who has always been there to support me throughout the years.

Table of Contents

List of Figures	viii
List of Tables	ix
Chapter 1	1
1.1 Introduction.....	1
1.2 Motivation.....	2
1.3 Goals and Objectives	3
1.4 Thesis organization	3
Chapter 2.....	5
2.1 Solving the TNDP without GIS	5
2.1.1 Constrained optimization models.....	5
2.1.2 Heuristic approaches	6
2.1.3 Practical guidelines or ad hoc procedures.....	9
2.2 GIS methods addressing the TNDP	10
2.2.1 Spatial Analysis using Demographic Data.....	10
2.2.2 Model Integration and Graphical Representation	11
2.3 Spatial Aggregation based on Transit Supportive Land Uses.....	12
2.4 Travel Forecasting Models.....	13
2.5 Summary	13
Chapter 3.....	15
3.1 Identifying transit supportive land uses	17
3.2 Zonal aggregation procedure	17
3.3 Aggregating flows.....	18
3.4 Major flow representation.....	19
3.5 Route design.....	19
3.6 Route evaluation	20
3.7 GIS component	22
3.7.1 Data requirements	22
3.7.2 Identifying transit-supportive land uses	23
3.7.3 Zonal aggregation procedure	24
3.7.4 Aggregating flows.....	25
3.7.5 Major flow representation.....	27

3.7.6 Route design.....	27
3.7.7 Route evaluation	28
3.8 Unique Flows	30
3.9 Calibrating delay parameters	30
Chapter 4.....	33
4.1 The Region of Waterloo.....	33
4.1.1 Grand River Transit	35
4.2 The Regional Municipality land use model	37
4.3 Regional Travel Forecasting Model.....	38
4.4 Summary	39
Chapter 5.....	40
5.1 Transit Supportive land uses and activity centre creation.....	40
5.2 Major flow representation.....	43
5.3 Unique travel flows.....	47
5.3.1 Student flows	47
5.3.2 Low income flows.....	49
5.3.3 Unique employer flows.....	50
5.4 Route design.....	51
5.5 Route Evaluation.....	54
5.6 Calibrating delay parameters	55
5.7 Summary of Findings.....	58
Chapter 6.....	59
6.1 Conclusion	59
6.2 Transferability and Limitations.....	60
6.2.1 Transferability.....	60
6.2.2 Limitations	60
6.3 Future Research	61
APPENDICES	63
Appendix A.....	64
Appendix B	71
References.....	90

List of Figures

- Figure 3.1: Flow chart summarizing the proposed methodology 17
- Figure 3.2: User form for identifying transit-supportive TAZs 24
- Figure 3.3: User form for the aggregation procedure 25
- Figure 3.4: Simple example of the zonal and flow aggregation procedures 26
- Figure 3.5: User form for route evaluation 28
- Figure 4.1: Map showing the location of Waterloo Region..... 34
- Figure 4.2: GRT performance history (Source: Regional Municipality of Waterloo, 2010)..... 35
- Figure 4.3: iXpress performance history and service upgrades (Source: Regional Municipality of Waterloo, 2010) 36
- Figure 4.4: Map of the Region of Waterloo showing iXpress and proposed rapid transit alignment..... 37
- Figure 5.1: Population and employment activity centres in the Region of Waterloo 41
- Figure 5.2: Histogram displaying trip frequency per TAZ 44
- Figure 5.3: Histogram displaying trip frequency per megazone 45
- Figure 5.4: Major travel flows throughout Waterloo Region during the AM peak hour (all modes)..... 46
- Figure 5.5: Map displaying the transit routes that have 30% or more student boardings 48
- Figure 5.6: Mean income levels in the Region at the TAZ level 49
- Figure 5.7: TAZs where 40% of the population earns less than \$20,000 50
- Figure 5.8: Proportion of RIM and Maple Grove employees living in each TAZ..... 51
- Figure 5.9: Trunk routes and Rapid Transit system..... 52
- Figure 6.1: Example of alternative routing alignments..... 62

List of Tables

Table 3.1: Summary of equations used to calculate route characteristics.....	21
Table 3.2: Summary of required data.....	23
Table 3.3: Example of flow matrix in column form	27
Table 3.4: Summary of Methodological Steps, Outputs and GIS Functions	29
Table 4.1: Characteristics of Regional TAZs.....	38
Table 5.1: Descriptive Statistics for Employment Megazones	42
Table 5.2: Descriptive Statistics for Population Megazones	42
Table 5.3: Transit routes where 30% or more of boardings are students.....	48
Table 5.4: Proposed Trunk Routes in the Redesigned GRT System	52
Table 5.5: Routes' operating characteristics and fleet sizes	55
Table 5.6: Annual vehicle operating hours for the trunk routes	55
Table 5.7: Coefficient Results.....	56
Table 5.8: Regression Results.....	57

Chapter 1

Introduction

1.1 Introduction

Public transportation contributes to sustainable transportation in urban areas. It offers many advantages such as reducing congestion and air pollution along with enhanced mobility, as well as offering meaningful travel alternatives for users who might choose transit for the sake of cost, speed, safety, convenience, traffic avoidance, or environmental issues. Unfortunately, in some cases public transit systems have been underperforming. Over the years, factors such as urban sprawl (the spreading outwards of a city and its suburbs to its outskirts to low-density, auto-dependent development on rural land) and the increase in private vehicle ownership have led to challenges for public transportation providers. The lack of investment in transit infrastructure has resulted in transit agencies being under resourced which further limit the agencies' ability to respond. Levels of congestion on the road network are growing in many cities. In cities with expected population growth, the congestion is likely to continue to worsen.

Realizing the need to change and move towards a more sustainable and balanced transportation system, governments are investing more and more in transportation infrastructure projects. In Canada alone, the last four years have seen several important shifts in the approach to transit investment taken by the Federal and Provincial governments. A substantial increase in public transit funding has been accompanied by widespread recognition of transit's role in keeping Canada's cities healthy and competitive (Action Transport, 2010).

In order to encourage public transportation, focus has shifted to improving the quality of transit service being provided. Transit improvements may include operational changes, such as increasing the frequency of routes. Additionally, system upgrades may be implemented in which there may be right-of-way changes or investments in infrastructure such as transit signal priority (TSP). These system upgrades will increase operating speeds and improve the reliability of transit service. Finally, a redesign of the transit network may be necessary. This includes modifying existing routes or perhaps a major service addition (such as light rail) that warrants the redesign of existing conventional service. All of these transit improvements will help public transit improve its competitiveness in the transportation system.

The problem that describes the design of a public transportation network is referred to as the transit network design problem (TNDP). When approaching the TNDP a hierarchy of routes is

determined by the differentiation of technology. For example, a system may be composed of light rail, bus rapid transit, signature trunk routes and feeder routes. All of the technologies are integrated together to provide an efficient and effective transit service. To do this, the TNDP is approached in the following way:

1. Identify major route alignments (identify major terminals and appropriate paths in between);
2. Estimate operating parameters (run times, vehicle allocation, operating hours and costs);
3. Estimate ridership;
4. Identify feeder routes.

The first step is to identify major transit terminals and appropriate paths in between the terminals. This identifies the core routes and establishes the structure of the network. These routes are designed for major demand corridors where intensification is possible. Once these routes are identified, estimating the operating parameters will allow the transit agency to assess the required resources needed for the network. Transit agencies then proceed to estimate the ridership along these major routes to ensure efficiency. Finally, feeder routes are designed to tie into the major routes. The research contained in this thesis focuses on steps one and two and informs steps three and four.

1.2 Motivation

Public transportation serves as an essential component of the transportation system providing an alternative mode of transport from the automobile, as well as providing a mode of transport for those who cannot drive for financial, physical and age-related reasons. Transit agencies seek to provide good transit service at the lowest possible operating cost. When developing a transit network there are a number of issues that must be considered, making it a complex problem to solve.

As previously mentioned, the first step involves identifying major route alignments within a study area. This step can be approached by analyzing land use densities. Concentrations of population and employment densities provide transit-supportive (a higher than average number of trips are made by transit) hubs for which transit service is feasible. Analyzing the travel flows amongst these hubs allows transit agencies to identify “desire lines”, origin-destination (OD) travel pairs, between which heavier than average travel demand exists. Directly connecting these OD pairs with transit service via high demand locations is likely to provide competitive transit service which generates strong ridership.

By having identified desire lines and possible paths within the transit network, it becomes easy to quickly estimate the required operating parameters such as, frequencies, travel times, cycle times, vehicle allocation and operating costs for the transit system.

With the advancement of technology and the emergence of geographic information systems (GIS), there exists new opportunities to address the TNDP. GIS can be used as a decision-support tool for route planning as it is well suited for identifying spatial relationships (i.e. Does a specific relationship exist between a pair of spatial geometries?). GIS can also be used to create visual representations to help interpret results and display complex information. While GIS has already been used for transportation planning, there exists room to expand upon how GIS can address the TNDP.

In this study, a customized GIS tool is developed to help inform and assist in transit network design. The tool specifically addresses steps one and two and informs steps three and four. The tool makes use of demographic data and trip tables from a travel forecasting model to identify travel demand corridors between OD pairs. This information is then used to design transit service that will accommodate travel along the major demand corridors.

1.3 Goals and Objectives

The main goal of this research is to develop and implement a methodology within a GIS framework that helps assist transit network design using demographic data and trip tables from a travel forecasting model. As a result, the primary research question for this study is: “Can GIS be used as a tool to analyze travel demand corridors in order to inform transit network design?”

This thesis has the following objectives:

1. Use demographic data to identify transit supportive areas and agglomerate these areas into ‘activity centres’.
2. Use trip tables from the travel demand forecasting model to create a visual representation of major flows to and from activity centres.
3. Design transit routes to accommodate major demand corridors.
4. Estimate the operating costs and characteristics of candidate transit routes.
5. Automate the methodology within a GIS framework.

This study provides a practical tool for transit network design that can easily be implemented and is easy to use.

1.4 Thesis organization

Chapter 1 has provided an introduction into the transit network design problem; in addition to the motivation for the research and the goals and objectives presented in this thesis. Chapter 2 presents a review of previous research that has been conducted with regards to transit network design. Chapter 3 presents the proposed methodology. Chapter 4 introduces a case study of the

Regional Municipality of Waterloo. Chapter 5 presents the results of the application of the methodology to the Region of Waterloo. Finally, Chapter 6 discusses the conclusions of the research, the limitations of the methodology and identifies the potential for future extensions to the work.

Chapter 2

Literature Review

The TNDP may be considered as an optimization problem where objectives are defined, constraints are determined, and a methodology is selected and validated for obtaining an optimal solution. This has resulted in a variety of methodologies for solving the TNDP; the literature reviewed in this chapter describes the various approaches that have been taken. First, methods for solving the TNDP without the application of GIS are described followed by a description of the methods in which GIS is applied. While nearly all approaches to solving the TNDP involve some level of spatial aggregation to reduce complexity, an aggregation method which emphasizes transit-supportive land uses is suggested in this thesis. As such, the literature surrounding spatial aggregation and the development of activity centres is also briefly reviewed in this chapter. Finally, the classic travel forecasting model is reviewed as well.

2.1 Solving the TNDP without GIS

Non-GIS methods used to solve the TNDP can be classified into three categories: 1) constrained optimization models; 2) heuristic approaches; 3) practical guidelines or ad hoc procedures. Each is described here.

2.1.1 Constrained optimization models

Early models were proposed by Holroyd (1967), Hurdle (1973), Byrne (1975, 1976), and Kocur and Hendrickson (1982). Subsequently, many of the optimization frameworks proposed to solve the TNDP are based on the works of Ceder and Wilson (1986). These models focus on developing relationships between elements of the transit system that are usually applied to smaller sized networks with a simple structure (Ceder and Wilson, 1986). The objective functions of these formulations minimize some combination of passenger expenses and operator costs. Constraint sets include budgetary limits, fleet sizes and human resources.

Ceder and Wilson outlined a conceptual five-level design model for a complete transit network planning process that included: design of routes; setting frequencies; developing timetables; scheduling buses; and scheduling drivers. They proposed a new approach that was intended to be easier to implement and less demanding in terms of data requirements and computational effort than previous methods. The algorithm was used to design new bus routes while taking into

consideration passenger and operating costs. However, the algorithm only focused on a single aspect (network design) of the entire planning process described.

While many approaches have applied constrained optimization models, the disadvantages to using these models have been indicated by many researchers. In 2001, Ceder noted that these models are suited for analyzing policies where approximate design values are needed as opposed to a complete design. Tom and Mohan (2003) indicated because these models can only handle small sized or regular shaped networks, network size is a major constraint for these approaches. Consequently, they have a limited application in practice. Although these models could assure optimal solutions for specific constraints, the complexity and difficulty in adequately representing the transit network in addition to the extensive computational requirements have resulted in these methods not being widely implemented.

2.1.2 Heuristic approaches

In response to the disadvantages of optimization models, heuristic approaches have been proposed. Heuristic algorithms are formulated in an effort to improve the TNDP representation and results while at the same time reducing the required computational effort. They are used when the size of the network is no longer small. Most of these models consist of procedures that generate candidate routes and route configurations. Generally, using an optimization algorithm, a set of candidate routes is generated according to specified criteria and then optimal subsets of routes are selected with or without their frequencies determined (Kepaptsoglou and Karlaftis, 2009). Typically, these approaches incorporate a heuristic for generating candidate routes and then apply another heuristic or metaheuristic algorithm in order to determine the optimal route configuration. However, there are some alternative approaches in which initial routes are developed and consequently are improved (Mandl, 1980) or metaheuristics can be applied to construct directly the optimal routes (Yang et al., 2007). Examples of heuristic approaches can be found in the following papers: Boyce and Janson, 1980; Duff-Riddell and Bester, 2005; Szeto and Hong, 2006; Fernandez et al., 2008; and Beltran et al., 2009. Heuristic and metaheuristic approaches can be classified into four main groups:

1. Specific and ad hoc heuristics which often follow the greedy construction principle;
2. Neighbourhood search such as simulated annealing and tabu search;
3. Evolutionary search such as genetic algorithms (GA);
4. Hybrid search which combines two or more solution methods.

The Greedy construction principle seeks to divide the problem into a set of incremental problems, where each problem is solved sequentially. The goal is to find a local optimum choice at each stage of the problem in hopes of finding the global optimum solution. Often the solutions found are sub-optimal ones.

The bi-level model applies a general greedy algorithm. Gao et al. (2004) presented a bi-level programming model for transit network design problems that included the interactions between the demand and supply, which was illustrated through a small example. The upper-level model is a normal network design model whose objective function is to minimize the total deterrence of the transit system and cost caused by frequency settings. The lower-level model is a transit equilibrium assignment model which is used to describe path alternative activities of transit users. This algorithm is designed to help the planners adjust existing routes to changes in demand and various other parameters. The bi-level programming method can represent the different decisions of demand and supply and the interaction between the two. While the results are good, applying the method to a real sized network would greatly increase the computational and mathematical effort required. This may become impractical to apply to a large scale network. Similarly, Fernandez et al. (2008) also propose a bi-level model for the physical and operational design of transit systems.

Lee and Vuchic (2000) suggest an iterative method to tackle the TNDP. The objective of this approach was to minimize user total travel time while applying frequency constraints on each route. To estimate transit demand and generate the optimal transit network at the same time, a modal split model was proposed. The approach begins with all origin-destination pairs being connected by individual routes. These routes are then collapsed to eliminate redundancy and to increase frequencies on productive routes. After each iteration the mode split is computed for a given level of service. The algorithm stops when further consolidation of routes yields no benefits. The method was applied to an example network of 16 nodes where 28 routes were generated. It took 31 iterations in order to optimize the example and estimate transit demand.

Neighbourhood search techniques involve an iterative search method that systematically considers a neighbour of the current state and decides between moving from the current state to the neighbouring state. The search stops when a local optimum has been obtained. Often, the local optimum is a mediocre solution and not the system optimal solution (Kepaptsoglou and Karlaftis, 2009). The quality of the solution obtained and computing times are usually highly dependent on the set of transformations considered at each iteration of the heuristic. The choice of neighbourhood structures can also have a great effect on the performance of the algorithm.

Recent work by Fan and Machemehl (2008) proposes a multi-objective, mixed integer model of stop location. Three variations of tabu search are then employed and compared as the solution method for finding an optimum set of routes from the huge solution space. A sensitivity analysis is also conducted in order to determine parameters such as how many generations should be computed in order to find a solution. The objective is to minimize the sum of operator cost, user cost and unsatisfied demand costs for the studied bus transit network. In this case, 30 generations is recommended for a small sample network of 15 nodes. The results of the study show that as the number of generations increased, the objective function value decreased. Furthermore, the larger the chosen number of generations, computational time increased. One

can imagine that the number of generations would greatly increase for a larger more realistic sized network, making it impractical to employ such a method.

Drezner and Wesolowsky (2003) conducted a study in which the network design problem was solved using a descent algorithm, simulated annealing, tabu search, and a genetic algorithm. The results for all four methods were then compared. First the objective function was presented as to minimize the total construction and transportation costs. The algorithms were tested on four different transit networks: a small network consisting of 14 nodes and 20 links; and 3 medium sized networks consisting of 40 nodes and 65, 99 and 164 links respectively. The study concluded that the GA performed the best. The results presented from the study show very lengthy run times for the sample networks in all four heuristic methods. The descent algorithm was run 1000 times, while the simulated annealing and tabu search were run 100 times and the genetic algorithm 10 times. Run times for the most complicated network ranged from 643 minutes to 111.1 minutes. These are lengthy run times making it difficult for transit agencies to implement regularly. The process is often repetitive and if model run times are high it becomes infeasible to implement them.

Evolutionary search techniques apply an iterative approach where new candidate solutions are determined by a “mutation” of one solution or by combining two solutions together. A pool of solutions is maintained as opposed to just one. Tom and Mohan (2003) present a genetic algorithm based method that simultaneously determines transit line routes and frequencies, with the objective of minimizing both operating costs and passengers total travel time. What distinguishes this method from others is the coding scheme that represents the line frequency as a variable (Guihaire and Hao, 2008). This helps enhance the performance of the model.

There have been mixed results when comparing neighbourhood and evolutionary search techniques. Tom and Mohan (2003) and Drezner and Wesolowsky (2003) and Chackroborty and Dwivedi (2002) reported that GAs were found to be superior to existing heuristics. On the contrary, Fan and Machemehl (2006) concluded that simulated annealing outperformed the GA in terms of the quality of route configurations. One thing that remains constant is the high run times required to solve each problem.

An artificial intelligence based heuristic approach was developed by Baaj and Mahmassani (1991), which involved the evaluation of objective functions and feasibility constraints at various solution search stages. Baaj and Mahmassani suggest a route generation heuristic algorithm (RGA) for transit network design. The algorithm generates a set of routes that covers the whole demand from a blank slate. RGA was designed to take into account the practitioners knowledge. The algorithm includes a mechanism that will explicitly cover the demand (with or without transfers). One of the limitations to this method is that the cost for the operators of the resulting set of routes produced by the RGA remains very high when the level of demand is increased. The goal of the transit agency is to minimize its operating costs and if the model results produce high operating costs, it will be difficult for transit agencies to implement.

Zhao and Zeng (2008) present a metaheuristic method for optimizing transit networks. The method includes route network design, vehicle headway, and timetable assignment. The goal is to identify a transit network that minimizes a passenger cost function. The proposed methodology is based on an iteratively defined local solution search space combined with an integrated simulated annealing, tabu, and greedy search algorithm. The method is tested on a large scale realistic network. While the results of the study show that the methodology can produce good results for a large scale network the computation time required is lengthy. The method is first tested by applying a zero transfer cost function. The CPU time required is approximately 20 minutes. Next, the method is tested by applying a one or less transfer cost function. The required CPU time rises to just under 24 hours. Evidently, as the function becomes more complex the rise in CPU time is extremely high. While 20 minutes is an acceptable run time, it is unrealistic to think that transit agencies would apply a zero transfer cost function.

It is evident that there are a number of heuristic approaches that can be applied when addressing the TNDP. One of the advantages of using a heuristic or metaheuristic approach is that they are not designed for a particular mathematical model. The solution methods define very general search frameworks and can be adapted to almost any form of constraint and objective. However, there are still many limitations when implementing these methods. For large scale problems, one of the main limitations of heuristic search is its computational complexity. As a result, no single heuristic method has been widely implemented.

2.1.3 Practical guidelines or ad hoc procedures

Due to the complexity of optimization and heuristic models, many transit agencies rely on ad hoc methods to conduct network designs such as those suggested by the NCHRP (1980). There are also two textbooks by Black (1995) and Vuchic (2004) that outline frameworks that can be followed by planners when designing a transit network.

An ad hoc procedure utilizes the experience and expertise of the local planning professional to design a transit network. While these methods require fewer resources, the adequacy of the networks produced depends heavily upon the capabilities and decision-making of the planner. In order to provide additional structure to the route planning procedure, expert systems have been proposed (Liao, 2005). They have been applied in Mumbai, India (Dashora and Dhingra, 1998) and Concepcion, Chile (Fernandez, 1993).

Despite the extensive use of practical guidelines and expert systems, researchers have argued that empirical rules may not be sufficient for designing an efficient transit network (Kepaptsoglou and Karlaftis, 2009). More and more researchers are realizing that a systematic and integrated approach is essential for designing economically and operationally efficient transit networks (Fan and Machemehl, 2004).

2.2 GIS methods addressing the TNDP

GIS is being used in many ways to address the TNDP. Many methodologies use GIS by analyzing demographic variables and making use of overlay and buffer techniques to aid in route design. Other methods simply use GIS to create a visual representation of model results. Finally, some of the methods have begun to integrate travel forecasting models within a GIS. Several methods are discussed here.

2.2.1 Spatial Analysis using Demographic Data

GIS software provides a platform for managing data, computing spatial relationships such as distance, and directional relationships between spatial units, and visualizing both the raw data and spatial analytic results within a geographic context. Spatial analysis consists of conducting a study based on the geographic properties of the data.

GIS software contains a suite of spatial analysis tools enabling users to conduct spatial analysis with demographic data. Overlay and buffer techniques are primarily used to calculate transit network service coverage and specific characteristics within defined service areas. This information has proven valuable when designing new transit routes or improving the transit network structure and service. Abkowitz et al. (1988) apply overlay procedures to determine the best route for the shipment of hazardous materials. Using demographic data and the street network they determine how many people would be affected if an accident occurred by calculating coverage statistics using a buffer technique. A network algorithm is then applied to choose the best path based on specified criteria (such as: minimize travel time or minimize population exposure). One of the limitations of this method is the assumption that the population is uniformly distributed throughout the study area.

Horner and Grubestic (2001) make use of demographic data and GIS to determine the best location for urban rail terminals. They begin by constructing an index of derived demand for rail usage based on the local demographics. Next, trade areas or commuter sheds are calculated for each candidate park-and-ride location based on realistic measures of accessibility and network based drive times, taking into account competition among candidates for riders. Following the analysis, the candidate locations and their commuter sheds are delineated and visualized in the GIS environment. Rail locations can then be chosen based on the results. Limitations in the details of the commuter shed can be encountered. As the level of detail in the commuter shed increases so does the level of computation time. The time required to compute detailed commuter sheds may be impractical for everyday application. It is also very important to have up to date network data, as the construction of the commuter sheds relies on this information.

Ramirez and Seneviratne (1996) propose two methods for designing and improving public transportation routes with the aid of commercial travel forecasting software (TransCAD). The

first method uses a direct demand model to estimate transit trips originating within a given spatial zone based on socio-economic and demographic variables. The authors then use TransCAD's shortest path algorithms to maximize the number of trips served while minimizing the operating cost. The second method uses origin and destination data and TransCAD's address matching capabilities to improve the transit coverage for major employment centres, similar to Azar and Ferreira (1994). The visualization of employee addresses on top of existing transit services helped clearly and quickly understand the nature of the problem. Such a tool can help transit planners become aware of problems quickly that would be hard to recognize otherwise. Furthermore, "what if" scenarios can be generated easily by being able to graphically visualize the problem (Azar and Ferreira, 1994). Various options can be tested without further data collection. Some of the limitations of this study include the fact that the data may not always be available and preparation of the data can be complex. This method will only target one employment centre at a time. However, optimization techniques could be applied if multiple centres are being considered at once.

A similar method is applied within a GIS by Sekhar et al. (2004) where a multi-criteria approach has been developed to maximise a range of objectives using census data. First a service coverage buffer is applied along the street network. Within the service coverage buffer for each link in the street network, the number of dwellings, the area of the attracting land uses, the percentage of low income households and the Level of Service (based on current peak hour transit service) is determined and added into the attribute table. A score for each criterion is then assigned to each link. Finally, a combined score is calculated by summing up the component scores on each link. Using a generalized impedance function the optimized route alignment is determined. The alignment is then compared with the shortest path alignment to ensure appropriate route length. This method will only take into consideration data within the buffer zone, which may result in some exclusion.

2.2.2 Model Integration and Graphical Representation

Other methods have begun to incorporate travel demand models and optimization models within a GIS environment (Lao and Liu, 2009; Gebeyehu and Takano, 2008). GIS is then used to create graphical representations of the model results. Miller and Storm (1996) present a prototype GIS design to support network equilibrium based travel demand models while Azar and Ferreira (2005) demonstrate the integration of a transit ridership estimation model.

Verma and Dhingra (2005) make use of TransCAD to implement a heuristic algorithm for determining an optimal urban rail transit corridor. The objective function takes into consideration user and operator costs. The user cost component consists of minimizing travel time, and at the same time maximizing comfort while the operator cost component consists of maximizing ridership. The objective function has been integrated into TransCAD along with the use of GISDK macro language. The GIS platform is able to provide efficient spatial data management, user accessibility, and graphic displays of the model results. The data overlay capacity of the GIS

allows these models to improve data integration related to the geographical layout of the transit routes.

Travel demand models are also used in conjunction with spatial analysis. Sanchez (2002) reports on a method for rural public transportation that combines the use of overlay procedures and a gravity model that determines accessibility to the transit system. Service areas are defined along with origins and destinations. The transportation and supply characteristics are then overlaid to determine the accessibility levels to the transit system. A gravity model is used to assess transit accessibility within each defined service area. Accessibility maps are then created within the GIS to aid in performance evaluation.

These examples show that there is no shortage of opportunities to apply GIS technology to transportation planning. One of the strengths of using GIS to help solve the TNDP is the ability to create a visual display of the results. Being able to visually see the results of the model that was applied helps better understand the findings. It also helps in communicating the results to the public. GIS provides a means for graphically conveying complex information.

2.3 Spatial Aggregation based on Transit Supportive Land Uses

The literature suggests that transit competitiveness (in terms of its ability to attract riders) increases in areas of higher land use densities (Pushkarev and Zuppan, 1982; Cervero, 1986). Areas of high residential and employment density will result in greater transit ridership. Given this relationship, changes made for improving transit service should focus on high density origins and destinations. In past decades, development in urban areas has evolved from monocentric areas into polycentric regions. Urban areas now consist of multiple high density cores, as opposed to just one. While these areas have reached high densities that can support transit, transit ridership remains low. There is a potential to increase transit ridership in these outer area cores (Casello, 2007).

In the Regional Economics literature, methods have been adopted to identify concentrations of high density land uses - known as urban activity centres - outside of traditional cores. Giuliano and Small (1991) define an activity centre as a contiguous set of zones, each with employment density and total employment greater than a threshold value. Bogart and Ferry (1999) apply a similar methodology in an analysis of the Cleveland, Ohio metropolitan area. They identified nine centres in the Cleveland region in which more than 30% of employment was represented. Bogart and Ferry create activity centres by identifying traffic analysis zones (TAZs) that meet the total employment and employment density thresholds; adjacent zones are then added in order of decreasing employment density, given that the density of the activity centre remains above a

certain threshold level. A similar approach to Bogart and Ferry is adopted in the spatial aggregation step in this research.

2.4 Travel Forecasting Models

Metropolitan regions (a large population center consisting of a large metropolis and adjacent counties that are economically integrated with the core area) develop travel forecasting models which estimate inter- and intra-TAZ travel demand for various time periods of the day. The estimated travel demand is then output into a trip table, which is a matrix of demand from all origins to all destinations. The classic model employs a four-step procedure in which trip generation; trip distribution; modal split; and trip assignment steps are solved sequentially (Ortuzar and Willumsen, 2006). There are some limitations to the classic model. The process focuses on one step at a time which can often fail to look at the problem from a more holistic approach. An important issue in the four-stage model is the consistent use of variables affecting demand. For example, at the end of the traffic assignment stage new flow levels and new travel times are obtained. These travel times are unlikely to be the same as was assumed during the distribution and mode split stages. This will require the use of a feedback loop. However, repeating the process does not lead to a stable set of models that will be consistent with the travel times. It is also difficult to model travel behaviour on a wide range of travellers' responses (Ortuzar and Willumsen, 2006). Often, models concentrate on a limited range. Moreover, the entire process requires extensive data resources.

Recognizing that travel forecasting models have significant weaknesses (Boyce, 2002), these models have very positive characteristics as well. First, these models are widely available. In the United States, every MPO maintains a travel forecasting model from which travel demands can be derived; in Canada, travel forecasting models developed for various cities, some with populations of approximately 100,000 are being utilized. Travel forecasting models also utilize the TAZ level of spatial disaggregation. In this thesis, trip tables are used to create visual representations of major travel demand corridors.

2.5 Summary

This chapter presented a review of previous research aimed at addressing the TNDP. A variety of methods have been described in addition to their limitations. Non-GIS methods were first described outlining optimization and heuristic methods. These methods while theoretically well grounded have not been widely implemented. Transit agencies have implemented ad hoc procedures, where the experience and expertise of the local planning professional is utilized to design a transit network.

Next, methods that incorporated the use of GIS to address the TNDP were described. GIS technology has been applied to conduct spatial analysis using demographic data. Other applications include the integration of travel forecasting models and using GIS to create visual representations of analysis results. GIS technology can be a useful decision-support tool for transit route planning and can be used in a variety of ways.

Finally, spatial aggregation methodologies in which transit-supportive land uses are emphasized were described in addition to describing the process in which activity centres are developed. The classic travel forecasting model was also reviewed.

The purpose of this thesis is to develop an integrated methodology within a GIS framework for transit network design. The research aims to develop a GIS tool that incorporates travel forecasting and demographic data to inform of major travel flows throughout the study area. Bus routes are then designed to accommodate these flows. GIS is used to perform the analysis and visually display the results. The following chapter outlines in detail the proposed methodology.

Chapter 3

Methodology

As discussed in Chapter 1, public transportation has the potential to contribute to a more balanced transportation system in many cities. However, over past decades, transit mode share has been declining. Automobile use has been challenging public transportation systems making it increasingly difficult for transit agencies to provide competitive service. Improving the transit level of service has become a focus of many transit agencies. Due to the complexity of the problem, the TNDP has been addressed in numerous ways as discussed in Chapter 2. Although many methods have already been proposed, there has not been one method that has been widely implemented.

One of the biggest challenges that transit agencies face today is maintaining ridership. Transit agencies must provide efficient and reliable service in order to make transit a viable option for the public. Transit service should allow people to travel to and from their destinations in a timely manner. In order to increase ridership levels, routes should be designed to accommodate heavy travel demand corridors. By accommodating the origin-destination pairs with the heaviest demand, transit ridership can be maximized and a greater level of service can be provided along those routes. This concept has motivated the approach taken in this thesis.

One of the objectives of this thesis is to develop a methodology that can be readily replicated to address the TNDP. The approach is to utilize GIS to identify travel desire lines from which trunk transit routes are proposed and evaluated. A GIS “toolbar” is built using VBA scripting in ArcMap 9.3 part of ESRI’s general ArcGIS suite which incorporates general GIS functionality including spatial query, feature dissolve and overlay functions in addition to the use of the network analyst extension.

One of the primary goals in route design is to maximize ridership. As such, it is helpful to review mode choice behavioural models. The logit model is one form of discrete choice models that is used to determine the mode split within a transportation system. The model determines the probability of taking each mode found within the system. To determine the probability of taking each mode the generalized cost (GC) must first be determined. The GC is a linear function representing the summation of many variables affecting the decision to choose a particular transport mode. It is the total cost associated with a trip including monetary costs (fare) and nonmonetary costs (such as in-vehicle time). Typically, GC functions include in-vehicle time, out of vehicle time, transfer penalties and a mode specific constant (bias). An example of a GC formulation for transit is:

$$GC_{ij}^T = (AT + WT + IVT + Transfer + Egress)VOT + Fare + \delta \quad (3.1)$$

where:

GC_{ij}^T	Cost of making a trip from i to j by transit (\$)
AT	Access time: the time it takes to access the station from the actual origin (minutes)
WT	Waiting time: the difference between passenger arrival time at a station and the transit unit departure time from the station (minutes)
IVT	In-vehicle time: travel time taken by a transit unit to travel from origin station to destination station (minutes)
Transfer	Time spent waiting to transfer from one transit unit to another (minutes)
Egress	Walking time from destination station to destination (minutes)
VOT	Value of time (\$/minutes)
δ	Transit mode penalty, bias representing factors that are difficult to quantify (such as reliability) (\$)

Using the logit model, the probability of taking transit is determined by the generalized cost of using that mode relative to the generalized cost of all other available modes (Equation 3.2). By minimizing the GC of transit, the probability of taking transit increases.

$$P_T = \frac{\exp^{-GC_{ij}^T}}{\sum_{ij}^m \exp^{-GC_{ij}^m}} \quad (3.2)$$

The ridership, R for each OD pair is then determined by multiplying the probability of taking transit by the travel demand (Equation 3.3).

$$R = P_T * demand \quad (3.3)$$

The fundamental premise of this research is that attracting travelers to transit can be accomplished by identifying transit-supportive land uses and providing high order transit, thereby lowering the GC_{ij}^T of transit, between the transit-supportive land uses with the highest total travel demands. This leads to increasing R in Equation 3.3.

Figure 3.1 outlines the major components of the methodology; the shaded boxes indicate steps which are completed within the GIS framework. Each of the steps is described in detail in following sections.

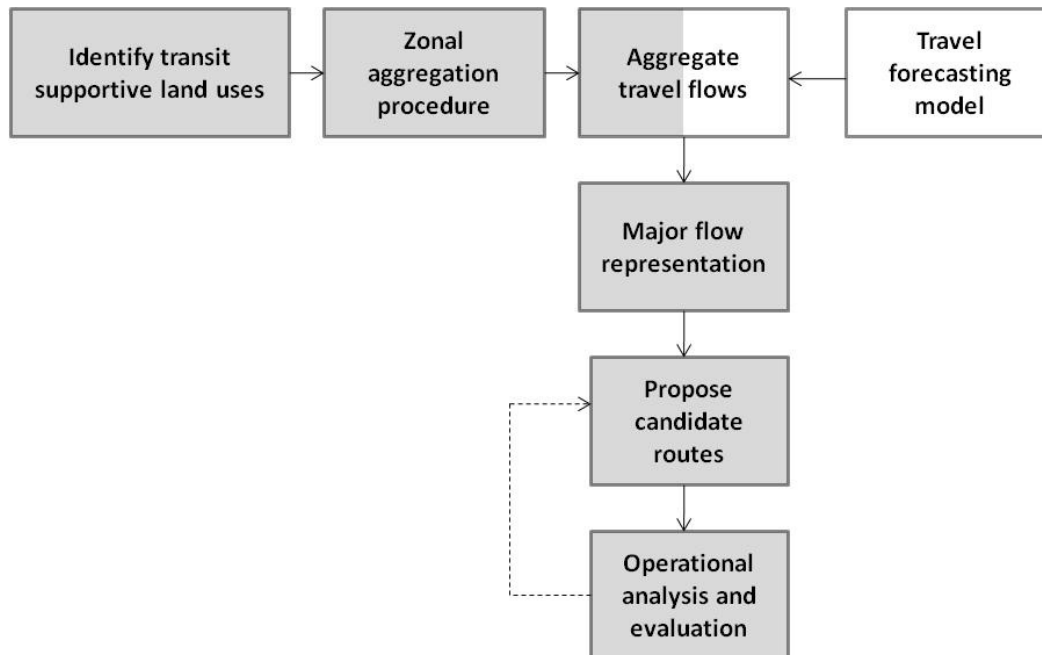


Figure 3.1: Flow chart summarizing the proposed methodology

3.1 Identifying transit supportive land uses

As previously mentioned in Chapter 2, regional land areas (neighbourhoods) with higher population or employment densities are considered to be transit-supportive - that is a higher than average proportion of trips originating from or destined for these areas are made by transit. For this research, transit-supportive areas are identified at the TAZ level.

The intention of this step is to identify areas with concentrations of employment and population density that are distinctly greater than their surroundings. The mean and the standard deviation of the population and employment density for all TAZs are first determined to provide guidance on the range of observed local values. This helps identify appropriate thresholds for what is considered to be transit-supportive. Each municipality or region is different; therefore, a standard set of thresholds cannot be applied. The thresholds will vary depending on the local characteristics. From previous literature thresholds have varied from 18.5 to 25 jobs or persons per hectare (Casello and Smith, 2006). In this study, major activity TAZs are identified as those with densities which are one standard deviation from the mean. This step allows the user to quickly identify the areas in which a higher than average proportion of trips are made by transit.

3.2 Zonal aggregation procedure

Having identified transit-supportive land uses (areas with high density land use that could be effectively served by higher order transit), individual transit-supportive TAZs are then

agglomerated to create activity centres (or megazones) to reduce complexity and aggregate flows such that major desire lines become more obvious. Typical levels of disaggregation produce hundreds of TAZs. Conducting meaningful analysis with this many zones becomes a difficult task. Having a large number of zones makes it difficult to identify major demand corridors. Without aggregating the TAZs together the demand remains spread out and demand corridors are not inherently obvious. By combining zones together and reducing the number of zones that need to be analyzed, desire lines become more obvious. It is also easier to manipulate the data when dealing with a smaller number of zones.

Adjacent TAZs are aggregated together so long as the total population and/or employment density of the cluster remains above the criterion threshold. The clusters must remain transit-supportive. Statistical characteristics associated with the selected TAZs are determined to ensure the threshold is being met. Characteristics from the individual TAZs contained in each activity centre are then aggregated together to form attribute information for the newly created activity centres. This step requires significant user input and substantial local knowledge regarding transportation facilities and land uses. The approach in this research is to generate megazones that meet the following qualitative criteria:

1. Each megazone contains homogenous land uses - for example predominantly residential, commercial or industrial;
2. Limits of megazones do not contain existing physical or topographical boundaries, including major freeways, rivers, etc.;
3. Megazones correspond to catchment areas for major transportation routes.

At the end of this stage of the methodology, the number of zones which are to be used for identifying major demand corridors has been greatly reduced. Zones where density is low and, as a consequence, have a low probability of generating transit trips have been eliminated from the study. Zones that have been identified as transit-supportive and, therefore, likely to produce a higher proportion of transit trips have been aggregated together to make the analysis more manageable. Given that each study area varies in size, a manageable number of zones can range from 40 to 50, creating a sufficient amount of OD pairs for analysis. This greatly reduces the complexity of the analysis and helps identify major origins and destinations.

3.3 Aggregating flows

To identify those activity centres within and between which the travel demand is highest in the study area, data on the total travel demand are necessary. To estimate the travel demand between activity centres, a travel forecasting model is used. Travel forecasting models' trip data are stored in what is known as trip tables - matrices of total travel demand from all origins to all destinations. To use the trip data in the proposed methodology, the data must be aggregated commensurately with the TAZ aggregation process. The travel demand between each TAZ is

summed to become the appropriate activity centres' demand. If the TAZ does not belong to an activity centre the travel demand is eliminated. In this step, the trip matrix is reduced in complexity such that it only contains travel demand to and from the activity centres. All TAZs not belonging to an activity centre are eliminated to simplify travel analyses in the study area.

3.4 Major flow representation

From the preceding step, travel flow data are contained in a matrix. Analyzing the data in this way can be difficult because in matrix form relationships between the travel data and the geographic location are unknown. Using GIS software, the travel flow data is used to create a visual representation of where the travel is occurring between OD pairs throughout the study area. The flow lines can also be presented using proportional symbology: varying the thickness of the line according to the magnitude of travel flow. Creating a visual representation of the major flows allows the user to quickly identify where the heaviest travel demand is occurring and where spatial relationships exist.

3.5 Route design

The desire lines depicted in the major flow representation identify OD pairs and paths for which the highest quality of transit service is provided. Higher order transit consists of high frequency service with limited stops. Typical headway values for small to mid-sized cities are fifteen minutes; in larger cities the frequency should be increased. Stop spacing is set to approximately one kilometre. Appropriate roadway alignments are selected based on:

1. the directness of service provided;
2. limited stops;
3. the suitability of the roadway infrastructure for higher transit service;
4. the intensification potential along the corridor;

Each transit route is designed to collect and distribute passengers and transport them over some distance. The guidelines provided for selecting the route alignments assist in minimizing the GC of taking transit, therefore, increasing the probability of taking transit. Recall Equation 3.1:

$$GC_{ij}^T = (AT + WT + IVT + Transfer + Egress)VOT + Fare + \delta \quad (3.1)$$

Providing direct service from origins to destinations with minimal route deviations greatly reduces in-vehicle travel time and the need for transfers. With a limited number of stops and higher frequencies, the bus is able to reach a higher travelling speed which minimizes travel time and wait time, making transit a competitive option. Characteristics associated with the suitability of roadway infrastructure include: land use density, roadway geometry and connectivity. The routes are designed to run on roadways where high land use densities are present. This provides

good accessibility and reduces the access time required to arrive at a station. The routes are chosen to be on roadways with appropriate turning radiuses and multiple lanes. In addition, routes are also chosen to run on roadways that intersect with other major roads in order to provide good connectivity throughout the network. The intensification potential along the corridor is defined as the potential to increase land use densities. Corridors where future growth is targeted will experience an increase in land use density. These corridors will become more and more transit-supportive, consequently, increasing the number of trips that will be made by transit.

3.6 Route evaluation

Once routes are designed, an evaluation is conducted to assess the quality of the routes. Global route parameters such as minimum headways, terminal times, service hours and labour costs are used to make route calculations. Analysis of the routes includes determining running time, fleet size, operating speed, route length, and cycle time. The data used to make these calculations are road segment length, posted speed limit and the number of signalized intersections for each route. The data are extracted from the GIS and VBA coding is used to perform the calculations. First, the route length and running time are calculated. These two calculations are then used to calculate the operating speed. Next, the cycle time and fleet size are calculated using the operating speed, the length of the route and the user specified headway and terminal time. Finally, the total vehicle hours are computed for the route based on the previous calculations. The calculations are done using the following equations:

Table 3.1: Summary of equations used to calculate route characteristics

Route Characteristic	Equation Number	Equation	Variables
Route length	3.4	$L = \sum_i L_i$	L Total route length (km) L_i Length of roadway segment (km)
Running time	3.5	$R = \sum_i \frac{L_i}{V_{pi}} + \alpha(\# sig.) + \sigma(\# stops)$	R Running Time (hrs) L_i Length of roadway segment (km) V_p Posted speed limit (km/h) α Delay parameter # Sig. intersections σ Delay parameter
Operating speed	3.6	$V_o = \left(\frac{L}{R}\right)$	V_o Operating speed (km/h) L Route length (km) R Running time (hrs)
Cycle time	3.7	$T = \frac{120 * L}{V_o} + 2t_t$	T Cycle time (min) L Route length (km) V_o Operating speed (km/h) t_t Terminal time (min)
Headway	3.8	User specified or calculated by: $H = \frac{Alpha * TUCap * 60}{Pmax}$	Alpha (ranges from 0 to 1) TUCap Transit Unit Capacity (# of passengers) Pmax Maximum load section (pax/hr)
Fleet size	3.9	$N = \left[\frac{T}{h}\right]^+$	N Fleet size T Cycle time (min) h Headway (min) + indicates rounding up
Total Vehicle Hours	3.10	$TVH = \sum \# days * service hours$	# days Saturday, Sunday Weekdays
Costing Model 1	3.11	$TC = veh. hrs * \$ per vehicle hour$	TC Total cost to run the route per year
Costing Model 2	3.12	$TC = veh. hrs * \$ per vehicle hour + kms traveled * \$ per veh - km$	TC Total cost to run the route per year

Another evaluation measure employed is the estimation of the operational costs of running each route. The GIS tool allows the user to convert the operating characteristics to a monetary cost in two ways. The first model computes the cost based on a user-defined hourly rate (\$ per vehicle-hour); the second option is to compute costs based on both time and distance (\$ per vehicle-hour + \$ per vehicle-km) (See Equations 3.11 and 3.12, Table 3.1).

By determining these route characteristics, transit agencies can assess the level of service and efficiency of the newly proposed routes. If the results are unsatisfactory, adjustments to the alignment of the routes can be made to improve the service. The route design and evaluation procedures are repeated until appropriate route alignments are determined. One criterion for assessing the quality of transit routes is the number of riders; however, determining ridership estimates are beyond the scope of this research.

3.7 GIS component

Previous sections described the major components of the methodology. This section seeks to describe how GIS is used to implement each step. A customized GIS toolbar is built using VBA scripting in ArcMap 9.3 part of ESRI's general ArcGIS suite. The toolbar makes use of simple user forms on which the user provides the necessary information and the tool conducts the analysis. Some of the procedures have preliminary forms in which the user specifies the files that contain the required information. Error checking within the VBA code is also implemented to ensure that the tool does not crash during operation. If the user fails to fill out a portion of the form, the tool will prompt the user to fill in the necessary information. Finally, a user manual has been created to provide step-by-step procedures on how to use the tool (See Appendix B).

3.7.1 Data requirements

For this research, the TAZ is used as the base unit of analysis. The TAZ contains various attribute data such as population, employment, land use and public transportation characteristics contained in an attribute table that can be joined to a shapefile. Moreover, the TAZ is disaggregated at an appropriate level to provide enough detail for transportation studies. In this research, employment and population density are required to identify transit-supportive areas. The TAZ data are required in the form of a shapefile. A shapefile is a geospatial vector data format file. The shapefile is used to spatially describe the geometry of the data. They are in the form of points, polygons or polylines. A base street network is also required and must contain segment length, travel time and posted speed limits. A shapefile containing the locations of signalized intersections is used for the operational analysis and evaluation phase. The methodology also makes use of predicted trip tables output from a travel forecasting model. Table 3.2 provides a summary of the required data.

Table 3.2: Summary of required data

Name	Description
TAZ	A shapefile containing the TAZ polygons that includes population and employment density information.
Street network	A polyline shapefile that includes all streets in the network and length, travel time and the posted speed limit for each link.
Signalized intersections	A point shapefile containing the location of all signalized intersections.
Trip table	A matrix containing travel demand to and from each TAZ (output from a travel forecasting model).

3.7.2 Identifying transit-supportive land uses

Using current or forecast data, the GIS tool allows the user to query the TAZs to identify zones that meet or exceed threshold levels of population, employment or their densities (See Figure 3.2). The user is first required to specify the appropriate criteria for which the analysis is conducted (for example: population density). This input is labelled as point “A” on Figure 3.2. Once this information is specified, the tool computes and displays the corresponding mean and standard deviation of the threshold criteria (See input “B” on Figure 3.2). This allows the user to determine appropriate threshold values for each type of activity. Three levels of activity are determined: major, secondary and suburban. The user may choose how many levels of activity they wish to identify. The user then inputs the determined threshold values for each type of activity centre in the corresponding boxes on the form (See input “C” on Figure 3.2). ArcMap queries through all of the TAZs and selects the ones that meet the threshold levels. A new data layer that contains all of the TAZs meeting the threshold levels is created to create a visual representation. This allows the user to geographically identify which areas have transit-supportive land uses.

The user has the option of identifying TAZs based on one criterion or two criteria. For example, the user may choose to query the TAZs based on population and population density or simply query the TAZs based on employment density. When identifying TAZs based on two criteria, the tool allows for logical operations such as ‘AND’ (meeting the thresholds for both criteria) and ‘OR’ (meeting the threshold for any of the criteria) (See input “D” on Figure 3.2).

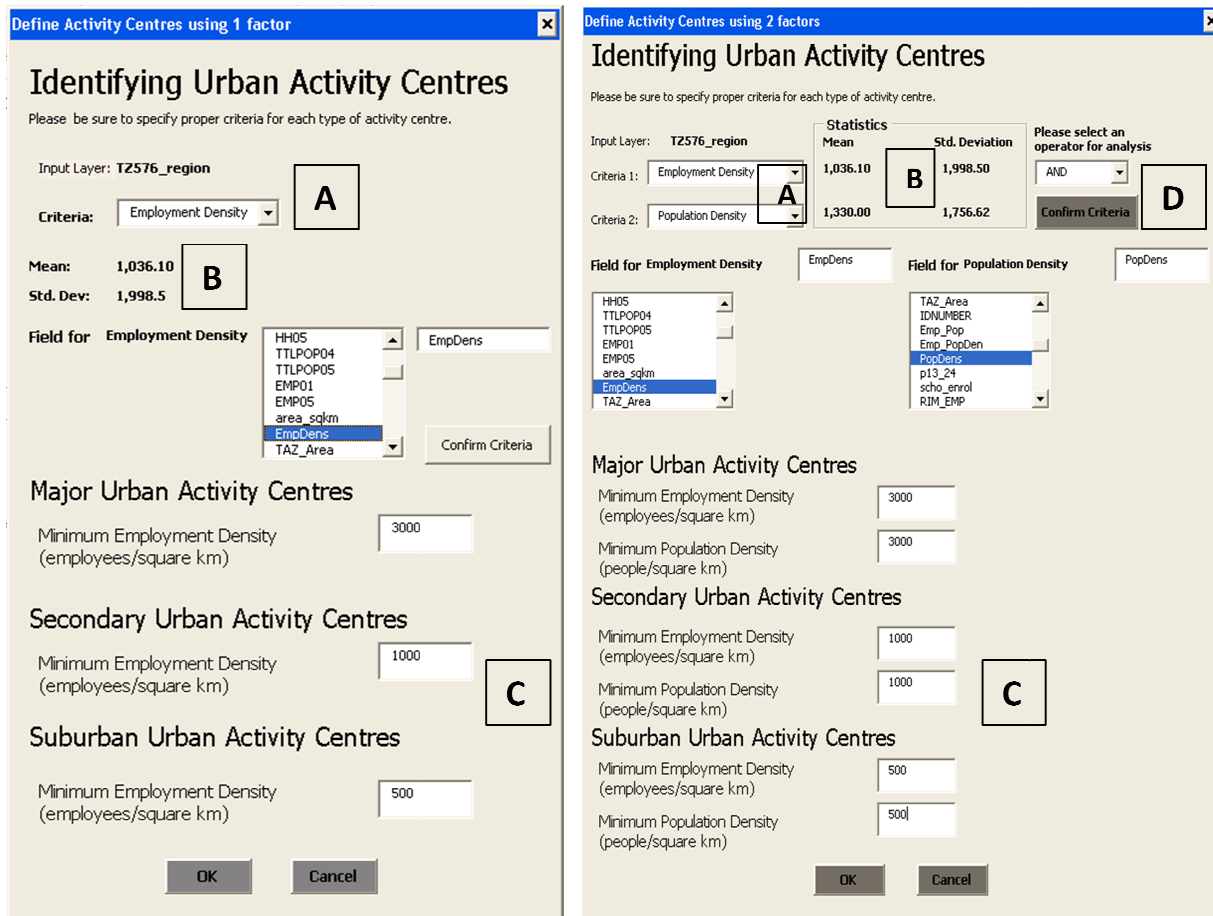


Figure 3.2: User form for identifying transit-supportive TAZs

3.7.3 Zonal aggregation procedure

Because this step requires significant user knowledge, the process is semi-automated within the GIS. The user is able to select interactively zones to be merged into an activity centre (See Figure 3.3). The user begins by selecting one of the transit-supportive TAZs. Adjacent TAZs are then added to the selection individually to form an activity centre. The user may select any adjacent TAZ to add to the activity centre. When adding zones together, the user can display statistical information regarding the centre’s current properties (See input “A” on Figure 3.3). This ensures that the user’s selection remains transit-supportive. Once the user is satisfied with the selection, the user specifies the corresponding attribute information from a list on the form that is aggregated for the centre (See input “B” on Figure 3.3). A unique ID for the activity centre is specified. The individual TAZs are then dissolved into one spatial entity with the aggregated attribute information (See input “C” on Figure 3.3). This creates an individual shapefile for the activity centre. This process is repeated until the user is satisfied with the number of activity centres that have been created. During this process the tool will also write the IDs for each individual TAZ contained in an activity centre in a text file (See input “D” on

Figure 3.3). This allows the user to keep a record of the individual TAZs contained in each of the activity centres. This file will be used in a subsequent step.

When all of the activity centres are created, the user is left with a large number of shapefiles. The merge button allows the user to merge all of the individual activity centre shapefiles into one shapefile. At the end of this step, the user is left with a shapefile that graphically displays the location of the activity centres which are deemed to be transit-supportive.

Figure 3.3: User form for the aggregation procedure

3.7.4 Aggregating flows

In this step, the user makes use of the trip table output from the travel forecasting model. For these tables to provide value in this analysis method, two modifications are made. First, the travel demand between each TAZ is included in the appropriate activity centres' demands or eliminated if the TAZ is not part of an activity centre. Second, the data are formatted such that

they can be used by the GIS tool to display desire lines. Figure 3.4 displays a simple example of how the zonal and flow aggregation procedures are completed.

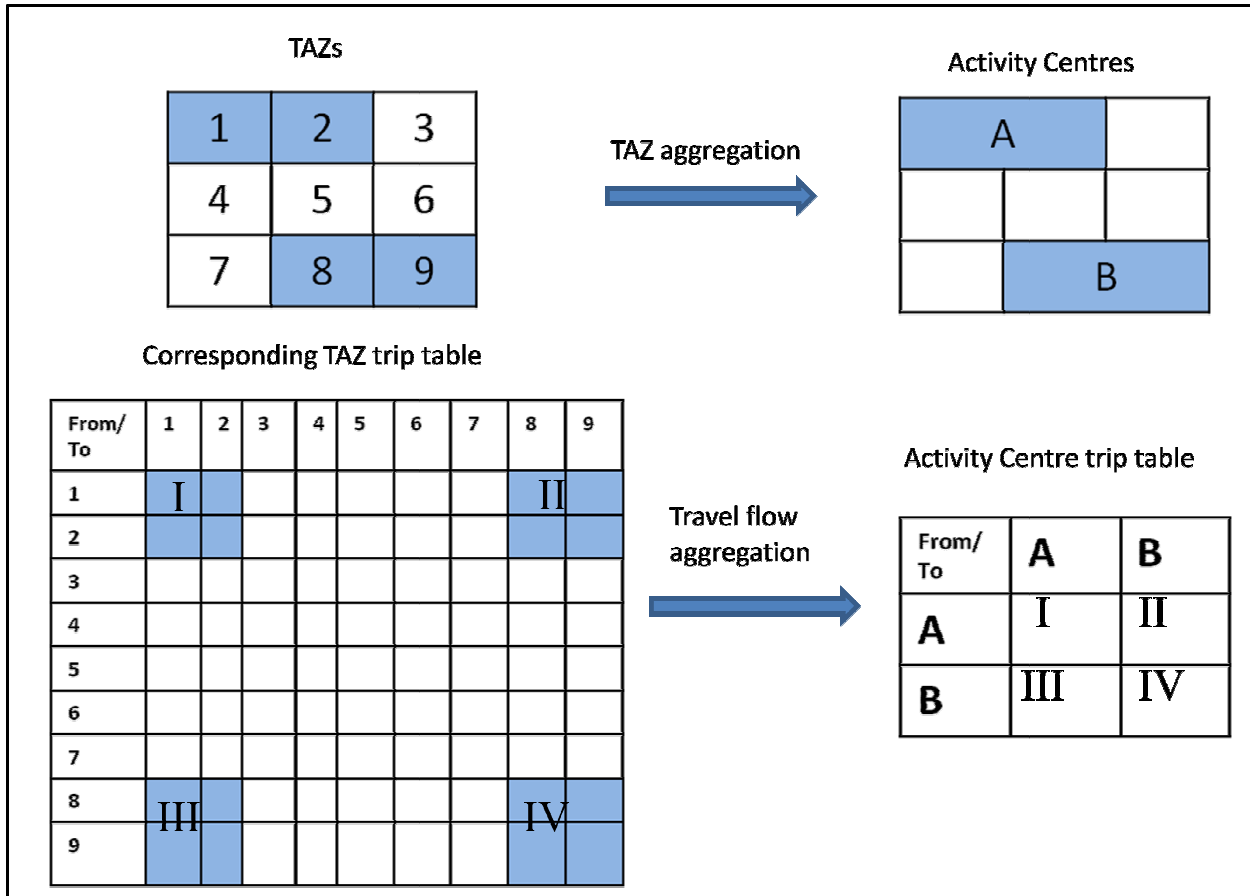


Figure 3.4: Simple example of the zonal and flow aggregation procedures

The process of agglomerating the travel demand between individual TAZs to travel between activity centres is automated using Visual Basic code within a Microsoft Excel macro (See Appendix A). The exported text files from the previous step are used to identify the activity centres and their constituent TAZs. From this list the macro searches through the trip table and sums up the demand for each activity centre. A new matrix of intra- and inter-activity centre travel demand is generated. Next, the data is converted from a matrix to two columns. The first column contains a unique “from_to” (origin to destination) identifier and the second contains the flow. Formatting the data in this way provides a common field by which the travel demand data may be joined to the spatial activity centre data in the GIS (See Table 3.3).

Table 3.3: Example of flow matrix in column form

From_To	Flow
1_1	515.60
1_16	167.88
1_3	149.77
1_33	79.94
1_41	114.69
1_4	131.19
1_42	139.22
1_2	539.87
1_40	759.05
1_31	45.36
1_39	147.14
1_11	159.68
1_17	81.45

3.7.5 Major flow representation

To generate visual representations of major flows, the network analyst extension in ArcMap is used. First, the activity centre's layer is converted to a point layer. Then, ESRI's built-in OD cost matrix function is used to generate graphic connections to and from the centroid of every activity centre. The resulting attribute table for the OD cost matrix contains origin and destination ID fields. A new field is created to concatenate the two fields together. This field matches the "from_to" field created in the travel demand table.

Using the join operation in ArcMap, the travel demand table can be joined to the OD cost matrix shapefile. This assigns the flow to each corresponding OD pair in the matrix. The display properties of the shapefile are then adjusted using proportional symbology to display the relative value of flows between OD pairs. Definition queries are also set to which a threshold of flow is specified and flows that are below the threshold are not displayed.

3.7.6 Route design

To input new routes, the network analyst extension is used. The user specifies a new alignment by identifying stops along the road network. Network analyst then creates a route from the stops by developing a direction alignment which connects the stops between the first and last nodes. Modifications may be made interactively by the user to satisfy local route limitations (for example roadway geometries). Once satisfied with the new route, the user exports the alignment data; it is then saved as a shapefile containing total length and number of stops.

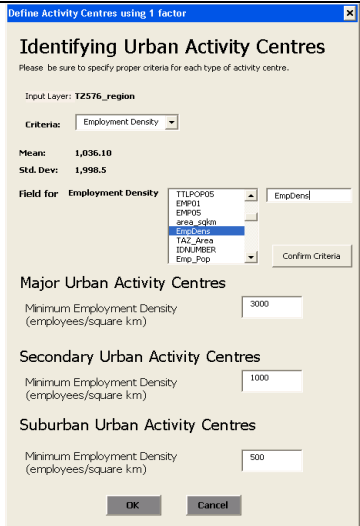
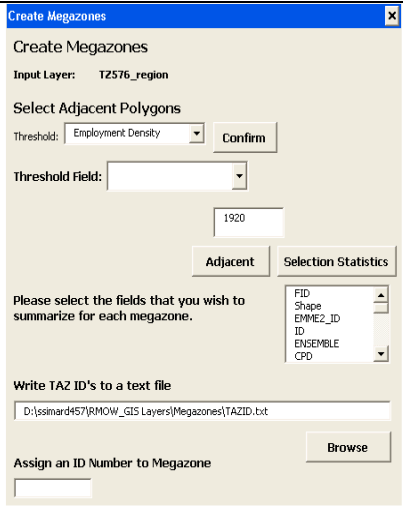
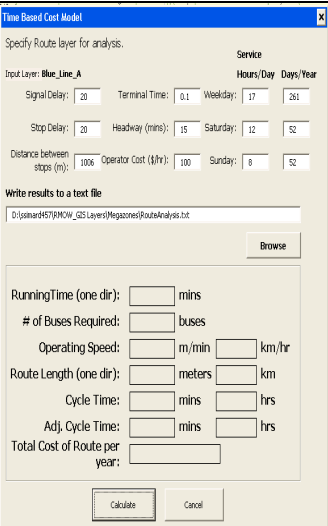
3.7.7 Route evaluation

To determine the operator’s resource requirements for the newly proposed routes, the user is prompted to specify global route parameters on the user form (See input “A” on Figure 3.5). These parameters include minimum headways, terminal times, service hours and labour costs, as well as the number of days per year the route will run. The user may also allow the tool to compute the necessary headway based on a maximum load section and transit unit capacity. The tool then makes use of ArcMap’s overlay function to extract segment length, posted speed and the number of signalized intersections for each route alignment from which an approximate travel time can be generated. Visual Basic code is then used to perform additional calculations to determine route length, cycle time, fleet size, operating speed and operating costs using the process described in section 3.6. When performing the route evaluation step, the tool will display the results on the user form and export the route characteristics to a text file (See input “B” on Figure 3.5).

Figure 3.5: User form for route evaluation

Table 3.4 summarizes the methodology, identifying the output, the level of automation and the role of the GIS tool in completing each step.

Table 3.4: Summary of Methodological Steps, Outputs and GIS Functions

Step inputs	Transit-supportive land uses	Merging TAZs to create Activity Centres	Trip Aggregation	Flow Display	Cost Evaluation
Criteria	<ul style="list-style-type: none"> • Population • Employment • Densities • AND / OR logic 	<ul style="list-style-type: none"> • Semi-automatically done • Maintain neighborhood cohesiveness • Aggregation reduces complexity 	<ul style="list-style-type: none"> • List of TAZs in activity centres 	<ul style="list-style-type: none"> • Sorted major flows • Display threshold % of activity centre total 	<ul style="list-style-type: none"> • Frequency of service: policy or maximum load section
Output	<ul style="list-style-type: none"> • TAZs meeting thresholds 	<ul style="list-style-type: none"> • Activity centres with consolidated statistics • List of TAZs contained in activity centres 	<ul style="list-style-type: none"> • Column of activity centre flows 	<ul style="list-style-type: none"> • Graphical representation of subset of all flows 	<ul style="list-style-type: none"> • Cycle time • Fleet size • Operating speed • Total operating costs
GIS/VB Code	<ul style="list-style-type: none"> • Identifies TAZs • Provides guidance on criteria statistics 	<ul style="list-style-type: none"> • Allows for manual creation of activity centres • Dissolves and stores activity centre information • Exports IDs to text file 	<ul style="list-style-type: none"> • Fully automated 	<ul style="list-style-type: none"> • Network analyst connects centroids of activity centres • Join with flows • Display thresholds • Proportional symbology to show importance 	<ul style="list-style-type: none"> • Network analyst tool to input new routes • Overlay functions to perform calculations
Graphical Interface					

3.8 Unique Flows

The major travel demand flows are augmented with an analysis of unique flows: students, low income or unique employer data where data are available.

Student boarding data for each transit route is imported into GIS and joined to the transit route shapefile. Using proportional symbology, the thickness of the line is varied according to the magnitude of the proportion of student boardings. A visual representation of the transit network is then made to identify which routes are primarily used by students.

To identify low income areas, the overlay procedure is used to combine census data with the TAZ shapefile. Low income areas are identified visually and transit service is designed to service these areas.

Unique employer data is analyzed using employee postal codes. Some data manipulation is required to determine the number of employees per TAZ. A postal code area shapefile is required. The employee postal code information is joined to the postal code shapefile. The dissolve function is then used to determine the number of employees per postal code area. Next, the intersect tool is used to intersect the postal code layer with the TAZ layer to determine which postal code areas are within the TAZ boundaries. The resulting layer includes a field with the number of employees per TAZ. Using the population data, the proportion of employees per TAZ is calculated by adding a new field. Finally, proportional symbology is used to visually identify the areas with the highest proportion of employees for a major employer.

3.9 Calibrating delay parameters

When evaluating the operating characteristics for each route the user is asked to input global route parameters. These parameters include an average delay (in seconds) associated with each signalized intersection the route passes and an average delay (in seconds) for each stop the bus makes along the route. For initial route evaluations, base parameters are chosen from local knowledge.

Subsequently, it is of value to acquire data to calibrate a regression model in which appropriate coefficients for signalized intersection delay and stop delay are determined. Using the street network data within a GIS, the length of the bus routes is extracted and divided by road type (i.e. arterial, collector, highway etc.). Using the posted speed limit and the sum of the length for each type of road, expected travel times along each bus route is calculated by road category. The number of signalized intersections and bus stops along each route are also extracted. Scheduled or observed travel times, from automatic vehicle location data (AVL), for transit routes are used

to determine average travel times along the routes. The average travel time is then used as the dependent variable in the model.

There are various ways in which this problem can be approached. Simple linear regression is used in an effort to describe the general trends observed and any possible relationships. This model is chosen because of its simplicity and ease with which it can be applied. The following equations are thought to be possible models for how delay can be explained for a transit route:

$$ABTT = \beta (ETT) + \alpha(\#sig.inter) + \delta(\#stops) \quad (3.13)$$

where:

ABTT Average bus travel time (seconds)

ETT Sum of expected total travel time for all road segments (seconds)

β Delay coefficient for travel time along the route

α Delay parameter for signalized intersections (seconds)

δ Delay parameter for bus stop dwell time (seconds)

The motivation for Equation 3.13 is that the bus travel time for a route is a function of the expected travel time (travelling the posted speed limit) and the number of signalized intersections and bus stops along the route. The ETT is calculated by summing up the travel time of each street link belonging to that bus route. The expected total travel time along a link in the street network is calculated by dividing the length of the link by the posted speed limit (See Equation 3.14).

$$ETT = \sum_i \frac{L_i}{V_{pi}} \quad (3.14)$$

The coefficients of Equation 3.13 serve as delay parameters. The expected results would yield coefficients greater than 1. The bus will travel longer than the expected travel time and will experience some delay at signalized intersections and bus stops.

Given that it is possible to categorize the data acquired on street links by type of road (highway, major and local roads), Equation 3.15 is developed. It is thought that the bus travel time would vary according to the type of road it was travelling along. Local and major roads may introduce an increase in travel time given that they may experience higher congestion levels. By determining a delay coefficient for each type of road, travel time along a bus route may be explained in greater detail.

$$ABTT = \sum_{i=1}^n \beta_i ETTR_i + \alpha(\#sig.inter) + \delta(\#stops) \quad (3.15)$$

where:

β_i Delay coefficient for travel time along road type

ETTR_i Expected travel time along road type (seconds)

n Number of roadway classifications

A final approach to modeling travel time is to make use of the relationship that exists between the delay a bus experiences and the length of the route (along with the number of signalized intersections and the numbers of bus stops along the route). A bus would experience longer delays if the route were very long. Equation 3.16 is proposed, where delay (actual bus travel time – expected travel time) is a function of the length of the route and the number of signalized intersections and bus stops. β represents the delay (in seconds) associated with each meter the bus travels. It is expected that this value would be low, implying that the bus experiences a small delay for each meter traveled.

$$Delay = \beta (leng) + \alpha(\#sig.inter) + \delta(\#stops) \quad (3.16)$$

where:

Delay Average bus travel time – expected bus travel time (seconds)

leng Total length of route (meters)

β Delay experienced for each meter travelled (seconds/m)

Delay is calculated using the following equation:

$$Delay = Observed\ TT - \sum_i \frac{L_i}{V_{pi}} \quad (3.17)$$

where:

Observed TT Observed travel time (seconds)

L_i Length of the road segment

V_{pi} Posted speed limit for the road segment

Alternatives to Equation 3.16 include replacing the length with a constant and eliminating the constant term altogether. These two other formulations are shown in Equations 3.18 and 3.19.

$$Delay = \sigma + \alpha(\#sig.inter) + \delta(\#stops) \quad (3.18)$$

$$Delay = \alpha(\#sig.inter) + \delta(\#stops) \quad (3.19)$$

This chapter has provided a detailed overview of the proposed methodology. Chapter 4 presents an overview of the Regional Municipality of Waterloo in which the methodology is applied.

Chapter 4

Region of Waterloo

4.1 The Region of Waterloo

The Region of Waterloo, located approximately 100 km west of Toronto in southern Ontario, is comprised of three cities – Kitchener, Waterloo and Cambridge – and four rural townships (See Figure 4.1). The Region has a population of approximately 500,000 persons but is expected to grow to 720,000 by 2031 (Regional Municipality of Waterloo, 2003). In anticipation of this growth, the Regional government has implemented a series of policies and programs to ensure the functioning of the transportation system. In 2003, the Region adopted the Regional Growth Management Strategy (RGMS). The strategy is structured around six main goals one of which is to provide greater transportation choice that will meet the future travel demands and have a positive influence on land use.

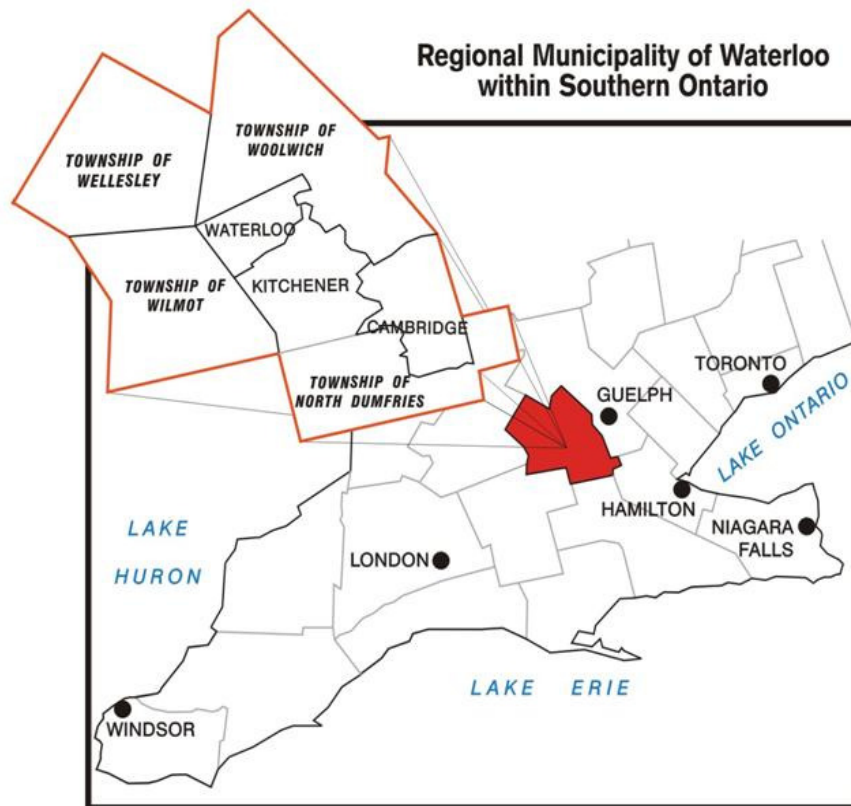


Figure 4.1: Map showing the location of Waterloo Region

Kitchener, Waterloo and Cambridge are also recognized as Urban Growth Centres (UGC) by the Proposed Growth Plan for the Greater Golden Horseshoe (GGH) (Ministry of Public Infrastructure Renewal, 2006). This growth plan was put in to place under the Places to Grow Act, legislation that helps identify and designate growth plan areas and develop strategic growth plans. UGCs are areas that will support major transit infrastructure and become hubs for employment. Kitchener, Waterloo and Cambridge will play a significant role in shaping and contributing to the economic and cultural fabric of Waterloo Region. A main component of the Growth Plan and the RGMS is intensification. The Region will look to use infill, adaptive reuse and redevelopment as tools to help intensify the UGCs.

The associated density target for existing built areas, such as downtown Cambridge, Kitchener, and Waterloo will be 200 people and jobs per hectare; in areas of new community development, such as subdivisions, the density target will be 50 jobs per hectare by 2031 (Regional Municipality of Waterloo, 2006). In addition, the proposed Growth Plan identifies proposed higher order transit facilities connecting the UGCs of Cambridge, Kitchener and Waterloo.

Both the RGMS and Places to Grow identified the need for rapid transit in the Waterloo Region. The Region has conducted multiple rapid transit initiative technical studies to evaluate whether rapid transit is a feasible transportation alternative. The studies concluded that rapid transit would be a feasible transportation alternative and a strategic financial investment that would support the Region’s economy, competitiveness and prosperity over the next 30 years while meeting Provincial and Regional goals.

4.1.1 Grand River Transit

Grand River Transit (GRT) is the public transit operator for the Region of Waterloo. GRT was formed in 2000, when Kitchener Transit and Cambridge Transit were joined. GRT now provides service that connects the three cities – Kitchener, Waterloo and Cambridge – together. Figure 4.2 presents an overview of GRT’s performance history relative to population growth, revenue hours and ridership estimates. Over the years, transit demand has continued to increase. In response to the communities growing needs, GRT has made many improvements, such as upgrading the bus fleet to include low floor buses, wheelchair accessibility and bike racks. Routing and scheduling have also been improved. One of the biggest improvements has been the implementation of the iXpress service.

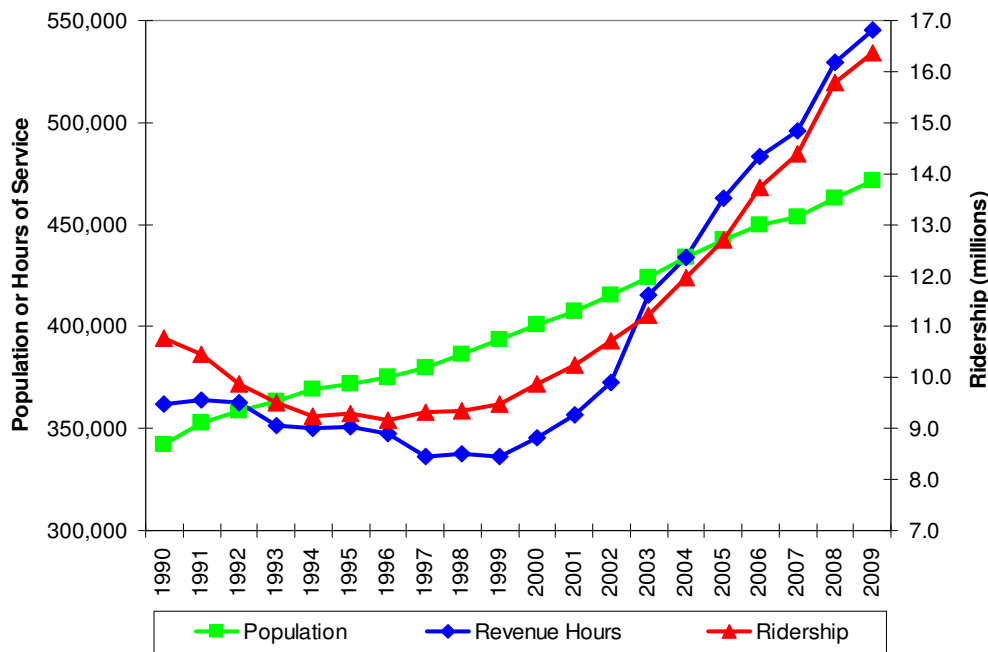


Figure 4.2: GRT performance history (Source: Regional Municipality of Waterloo, 2010)

In 2005, GRT introduced an express bus service known as iXpress to connect the three urban centres along the Central Transit Corridor (CTC) (See Figure 4.4). The service is a limited stop express service that has a length of approximately 37 km with 13 bus stops along the route. Upon implementation, service was provided Monday to Friday from 6 am to 7 pm with 15 minute

headways during peaks hours and 30 minute headways in off-peak hours. This was the Region’s first attempt at attracting long trips along the CTC to build ridership levels and travel patterns for a future rapid transit system. To date ridership growth along this route is exceeding the latest ridership target of 5,700 riders (See Figure 4.3). Since September of 2005, there have also been a number of improvements made to the iXpress service. Weekend service has been added along with evening service during the weekdays. Figure 4.3 outlines the performance history and service upgrades for the iXpress service. Currently, the iXpress service has approximately 9,000 daily boardings.

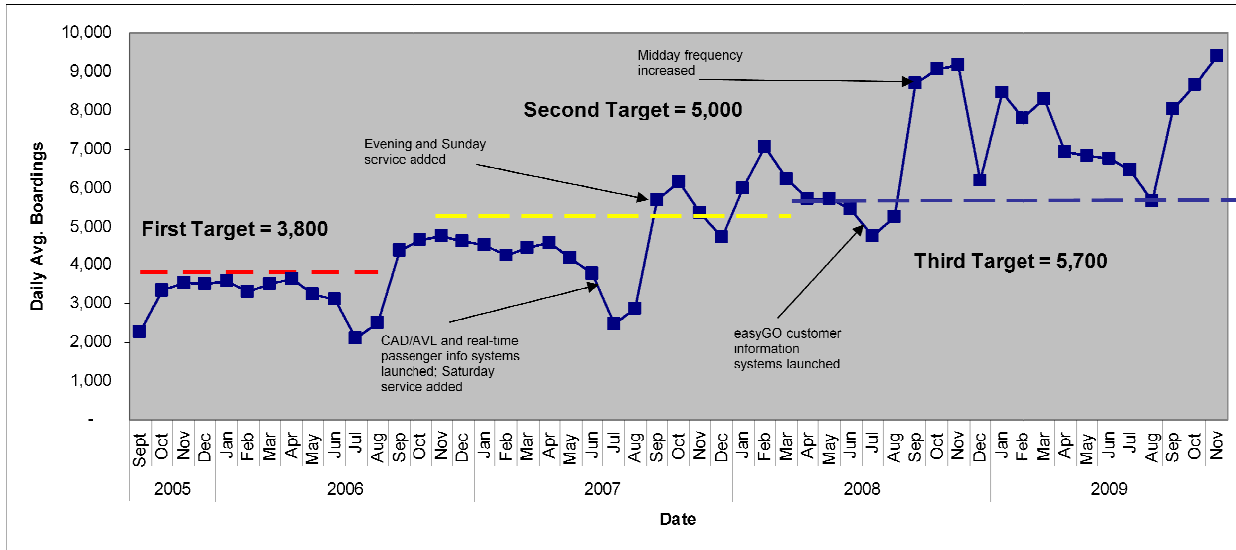


Figure 4.3: iXpress performance history and service upgrades (Source: Regional Municipality of Waterloo, 2010)

Given the success of the iXpress service, in conjunction with the goals of the RGMS and Places to Grow, Regional Council has approved plans for a \$790M (CDN) Light Rail Transit and Adapted Bus Rapid Transit to upgrade iXpress service along the CTC. A map of the Region showing both the iXpress and proposed rapid transit routes is shown in Figure 4.4.

To support the implementation of the rapid transit system, the Region and the University of Waterloo have been engaged in a network redesign project. This first part of the project is to develop a methodology to redesign the conventional bus service and make recommendations regarding route structure. It is this network redesign that motivated the development of the GIS tool presented in this thesis.

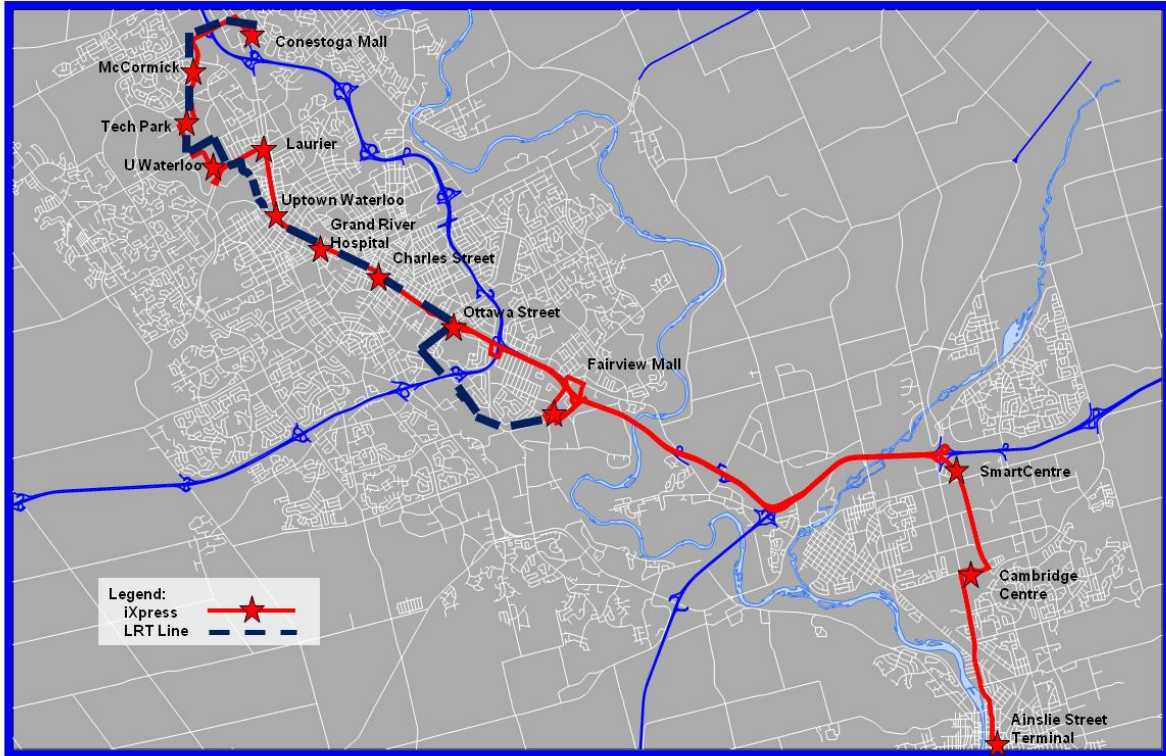


Figure 4.4: Map of the Region of Waterloo showing iXpress and proposed rapid transit alignment

4.2 The Regional Municipality land use model

To apply the study methods, the Regional Municipality land use model was used as the unit of analysis. The Regional Municipality land use model contains a total area of approximately 1382 square kilometres subdivided into 576 TAZs. Characteristic data for the Region’s TAZs are shown in Table 4.1.

Table 4.1: Characteristics of Regional TAZs

Characteristic	Max	Mean	Std. Deviation
Regional Totals			
TAZ size (ha)	2,210	240	390
Employment per TAZ (employees)	8,910	468	718
Population per TAZ (persons)	6,919	684	1,157
Employment density (employees / ha)	228.4	10.4	20.0
Population density (persons / ha)	140.4	13.3	17.6
Excluding Rural Townships			
TAZ size (ha)	1,000	110	150
Employment per TAZ (employees)	8,910	562	776
Population per TAZ (persons)	6,919	1,027	1,234
Employment density (employees / ha)	22,840	13.5	22.1
Population density (persons / ha)	14,044	17.1	18.6

4.3 Regional Travel Forecasting Model

The methodology also applies the resulting trip table from the Region’s travel forecasting model. The Region of Waterloo’s regional travel forecasting model is calibrated and validated for the am peak hour (8 am to 9 am). The model is based on the standard four stage modelling procedure (trip generation, trip distribution, mode choice and trip assignment). Four main trip categories are established within the model: to work, to high school, to post secondary and to other. The model has been developed based on a variety of information sources including the Auto and Transit OD and SP surveys, the 1996 Transportation Tomorrow Study (TTS), the latest traffic and transit count information within the Waterloo Region. The model has been developed for the 2004 base year in addition to transportation network scenarios for 2011, 2021 and 2041.

The 2004 traffic zone system developed for the model was an amalgamation of two current zone systems used by the Region: the Planning Land Use Model (PLUM) and the traffic zone system from the 2001 Waterloo Travel Demand Model Development project. The traffic zone system for the study contains 567 internal zones and 21 external zones.

Demographic inputs into the model are current and future year demographics by traffic zone. These include population by age category, employment, post secondary enrolment and housing location data.

The model also makes some auto and transit cost assumptions in the generalized cost formulation. The generalized cost is an important component of the transportation model as it influences the destination choice in addition to the mode choice. The travel costs included in the regional model include auto-operating costs, parking charges and transit fares. These costs are converted to time and added to the travel time to estimate the generalized cost between OD pairs.

The auto operating cost used in the model was 12.2 cents/km and a parking charge survey was conducted to determine average parking charges per TAZ. The average GRT fare of \$1.50 was used for the transit fare assumption. The model incorporates the 2004 street network and the transit network based on the 2004 fall transit schedule.

Three volume delay functions have been incorporated into the model to estimate the link travel time in minutes. These functions take into consideration the length of the link, the number of lanes, the posted free flow speed, and the traffic volume. The equations represent three different roadway types: local congested link, arterial link and free-flow link.

Finally, the model was validated by comparing the base year predictions with information other than that used to estimate and calibrate the model. A sensitivity analysis was also conducted to understand how the model reacts to changes in cost and service assumptions. It was concluded that the am peak hour model calibrates closely to the survey targets and the sensitivity testing shows that the model's elasticities appear to be reasonable (Regional of Waterloo, 2005).

4.4 Summary

This chapter has provided an overview of the Region of Waterloo. Details for the motivation of the implementation of a rapid transit system in addition to characteristics regarding the unit of analysis for the study were provided. In the next chapter, the results of the study are presented, analyzed and interpreted.

Chapter 5

Results and Discussion

To demonstrate the use of the GIS toolbar, the methodology described in Chapter 3 is applied to the Region of Waterloo. This chapter presents the results of the analysis.

5.1 Transit Supportive land uses and activity centre creation

Using 2004 socio-economic and demographic data TAZs with transit-supportive land uses are identified. Table 4.1 shows that the average employment density (using Regional totals) is 10.4 jobs per ha with a standard deviation of about 20 jobs per ha. A threshold value of one standard deviation from the mean, or 30 jobs per ha is used. Coincidentally, the population density threshold (also one standard deviation from the mean) ($13.3 + 17.6$) is also approximately 30 persons per ha. In this analysis, 60 TAZs meet the employment density threshold and 112 meet the population density limit. The results of aggregating the TAZs together produce 33 population activity centres and 14 employment centres. The employment activity centres are found along the central transit corridor of the Region, while the population activity centres are concentrated to the east and west of the transit corridor (Figure 5.1).

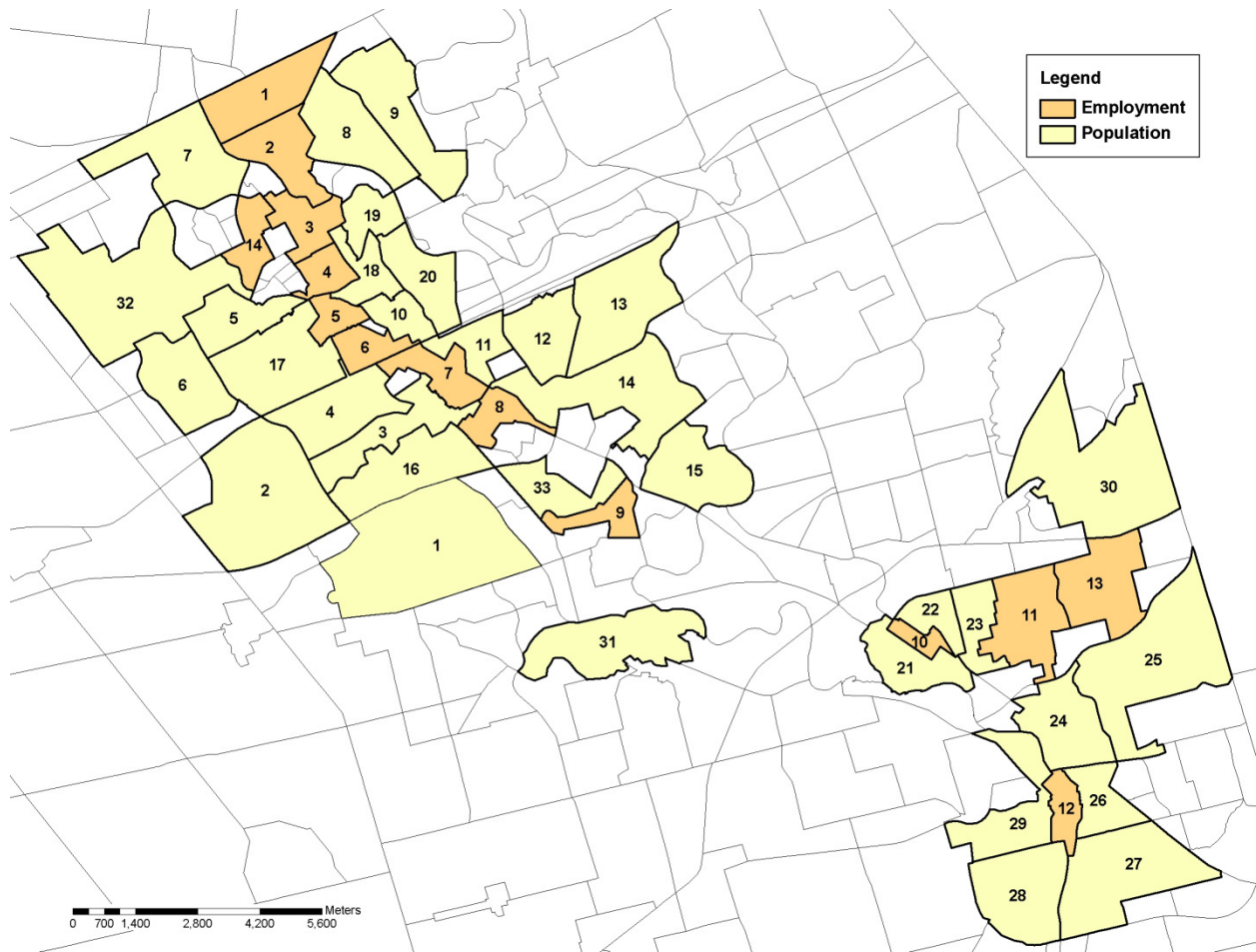


Figure 5.1: Population and employment activity centres in the Region of Waterloo

The characteristics of the megazones are presented in Table 5.1 and Table 5.2. Note that in most cases, employment megazones attract far more trips than are generated (in the am peak period) while population zones tend to generate higher trip volumes than are attracted.

Table 5.1: Descriptive Statistics for Employment Megazones

Employment Megazones						
ID	Neighbourhood Description	Employment (jobs)	Area (sq. km)	Employment Density (Jobs / ha)	Trips Originating	Trips Destined
1	Northland	11884	3.05	39	312	2256
2	Conestoga	10043	2.41	42	587	3369
3	Central Waterloo	5960	1.65	36	1627	4809
4	Uptown North	3913	1.05	37	1421	1651
5	Uptown South	6999	0.88	79	1175	3484
6	Grand River Hospital	6332	1.15	55	922	3310
7	Kitchener Core	16240	1.67	97	1827	8837
8	Ottawa	4024	1.25	32	584	892
9	Fairway	5023	1.23	41	179	1098
10	Preston	1685	0.57	30	549	582
11	Cambridge Centre	11018	3.26	34	308	1756
12	Galt Core	4260	1.05	41	510	1506
13	Lovell Park	8026	3.42	23	34	1138
14	UWaterloo-Columbia	7589	1.36	56	944	4696
Totals		102,996	24.00	43	10979	39,384

Table 5.2: Descriptive Statistics for Population Megazones

Population Megazones						
ID	Neighbourhood Description	Population (prs)	Area (sq. km)	Population Density (prs / ha)	Trips Originating	Trips Destined
1	Laurentian-Country Hills	29441	9.18	32	4986	1559
2	Highland West-Forest Heights	24167	7.60	32	4753	2996
3	St Mary's	10066	2.77	36	1972	1147
4	Victoria Hills	13202	3.22	41	2735	1121
5	Erb West	7217	2.18	33	1692	762
6	Westvale	10119	3.19	32	1883	535
7	Lakeshore	14605	4.39	33	3519	701
8	Lincoln	8980	3.42	26	1895	370
9	Eastbridge-Lexington	11172	4.01	28	2273	474
10	Mt Hope-Huron Park	4685	1.18	40	1119	691
11	Frederick	6772	1.47	46	1780	1895
12	Rosemount	5754	2.44	24	1136	349
13	Heritage Park	12090	4.67	26	2511	2034
14	Stanley Park-Idlewood	14551	5.45	27	2843	2413
15	Chicopee	6195	3.28	19	1110	291

Population Megazones						
ID	Neighbourhood Description	Population (prs)	Area (sq. km)	Population Density (prs / ha)	Trips Originating	Trips Destined
16	Forest Hill-Southdale	9900	3.79	26	2054	914
17	Westmount	10265	4.28	24	2260	1020
18	Weber	4191	1.41	30	1894	1428
19	Willowdale	3749	1.38	27	818	288
20	Fairfield	5122	2.33	22	1131	2154
21	West Preston	4233	2.22	19	1071	1561
22	Central Preston	3246	1.17	28	624	287
23	Lang's Farm	5617	1.55	36	1122	384
24	Riverview	9385	3.11	30	1780	1818
25	Shades Mills	18016	7.28	25	3328	2129
26	Lincoln Oaks	5088	1.72	30	1730	2076
27	Glenview-Southview-Branchton	15261	5.31	29	2531	1735
28	Southwood	10717	3.84	28	2061	1252
29	West Galt	6364	3.09	21	1309	565
30	Hespeler	20602	8.25	25	3525	2733
31	Pioneer Park	9763	4.33	23	1542	274
32	Laurelwood-Beechwood	17732	8.51	21	3254	2920
33	Vanier	9782	2.00	49	1557	512
Totals		348049	124.02	28	69798	41388

5.2 Major flow representation

To generate desire lines, the estimated travel between and within the activity centres from the Region's travel forecasting model is aggregated. The Region of Waterloo's model estimates a total of 118,967 trips in the peak hour (between 8 and 9 am) for the 576 x 576 origin-destination pairs. Figure 5.2 displays a histogram of the distribution of the OD pair trips. From the histogram, it is evident that the majority of the TAZs generate fewer than 10 trips.

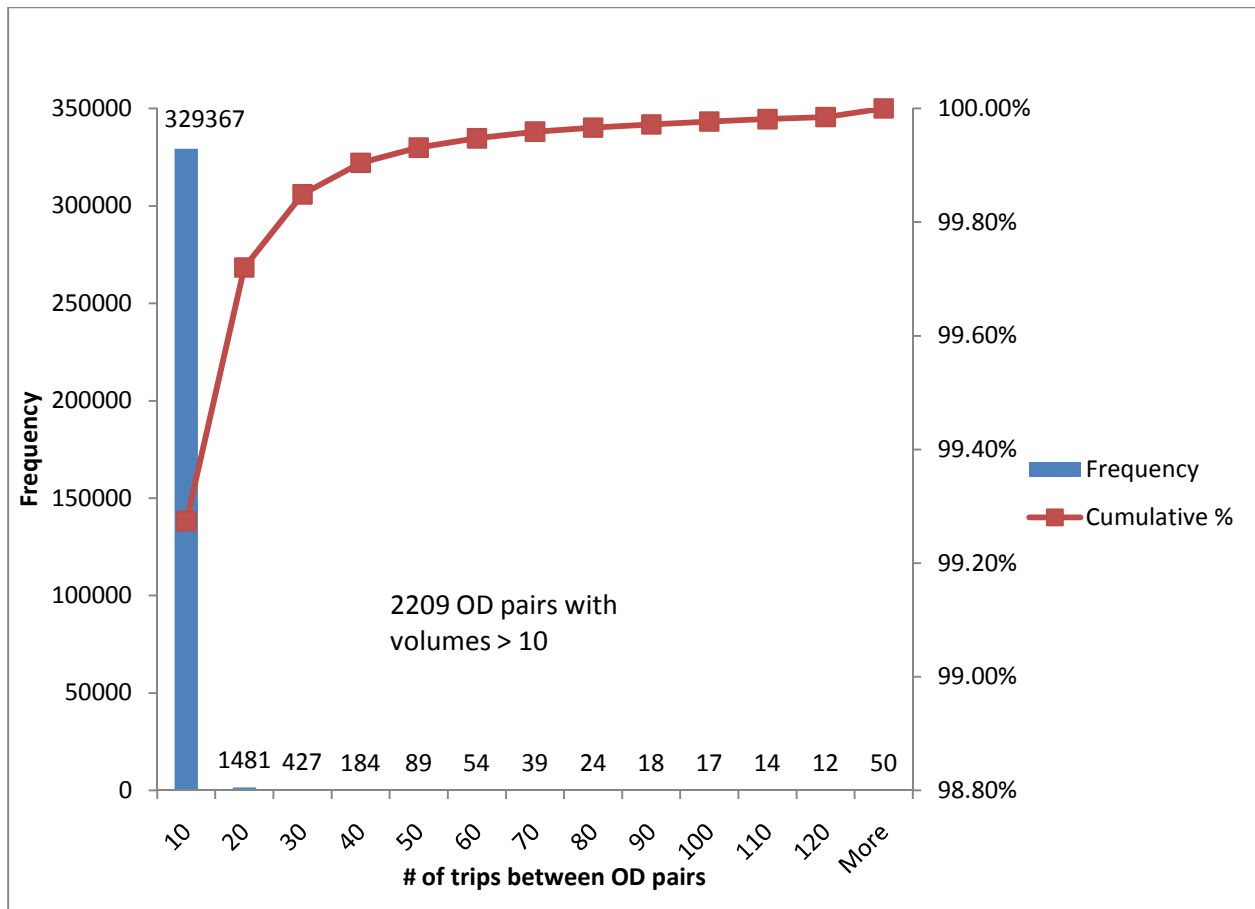


Figure 5.2: Histogram displaying trip frequency per TAZ

After the aggregation procedure, a 47 x 47 matrix of travel flows between and within the 33 population and 14 employment activity centres is developed. The total number of trips between and within activity centres is 69,574, or 58% of total peak hour trips. Thus, through the amalgamation process, 400 TAZs were eliminated from the analysis (or 70%) and only 42% of trips were eliminated; further the eliminated trips are those that begin or end in zones of lower population or employment density and are, therefore, much less likely to be adequately served by transit.

Even after the aggregation of zones and flows, there remains 2209 (47x47) travel flows between activity centres. It is difficult to display this much data in a meaningful way. The flows between zones contained in the central transit corridor (approximately 6,235) are first eliminated based on the assumption that these flows would be accommodated by the proposed rapid transit system. For the remaining zones, the activity centre flows are sorted in GIS and then a display threshold is set such that 50% of all activity centre travel demand is displayed. Approximately 35,000 trips are contained in only 135 OD pairs and produce 29% of total regional trips. A histogram showing the frequency distribution of megazone flows is found in Figure 5.3. The top 50 flows produce 31.5% of total activity centre trips and 18.4% of total regional trips. The aggregation

procedure has resulted in obvious demand corridors throughout the study area. The trips from the 135 OD pairs serve as the input into the desire line graphical representations shown in Figure 5.4.

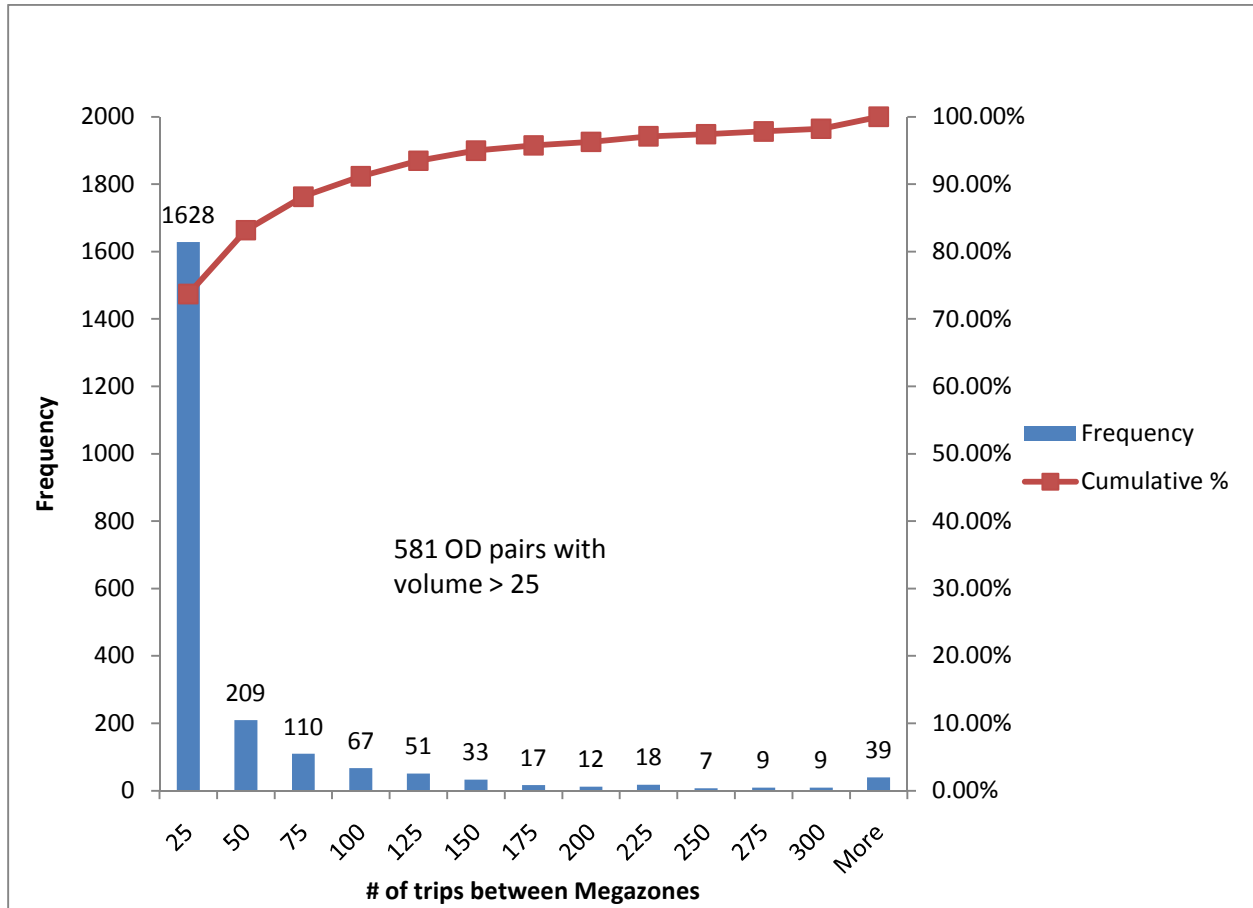


Figure 5.3: Histogram displaying trip frequency per megazone

From the desire lines, there are two approaches which can be followed in generating transit routes. The first and simplest approach is to connect directly the desire line endpoints. This is the approach taken here and described in subsequent paragraphs. An alternative, more robust approach is to design routes which maximize corridor flows or the sum of flows between multiple activity centres while minimizing total travel distance. For example, two paths connect megazones 2 and 13 between which major flows exist. These paths include 2-7-13 and 2-1-14-13. The comparison of these routes should consider demand between megazone 1 and 33, 33 and 14 for example to determine which corridor maximizes ridership relative to travel distance. This research is ongoing.

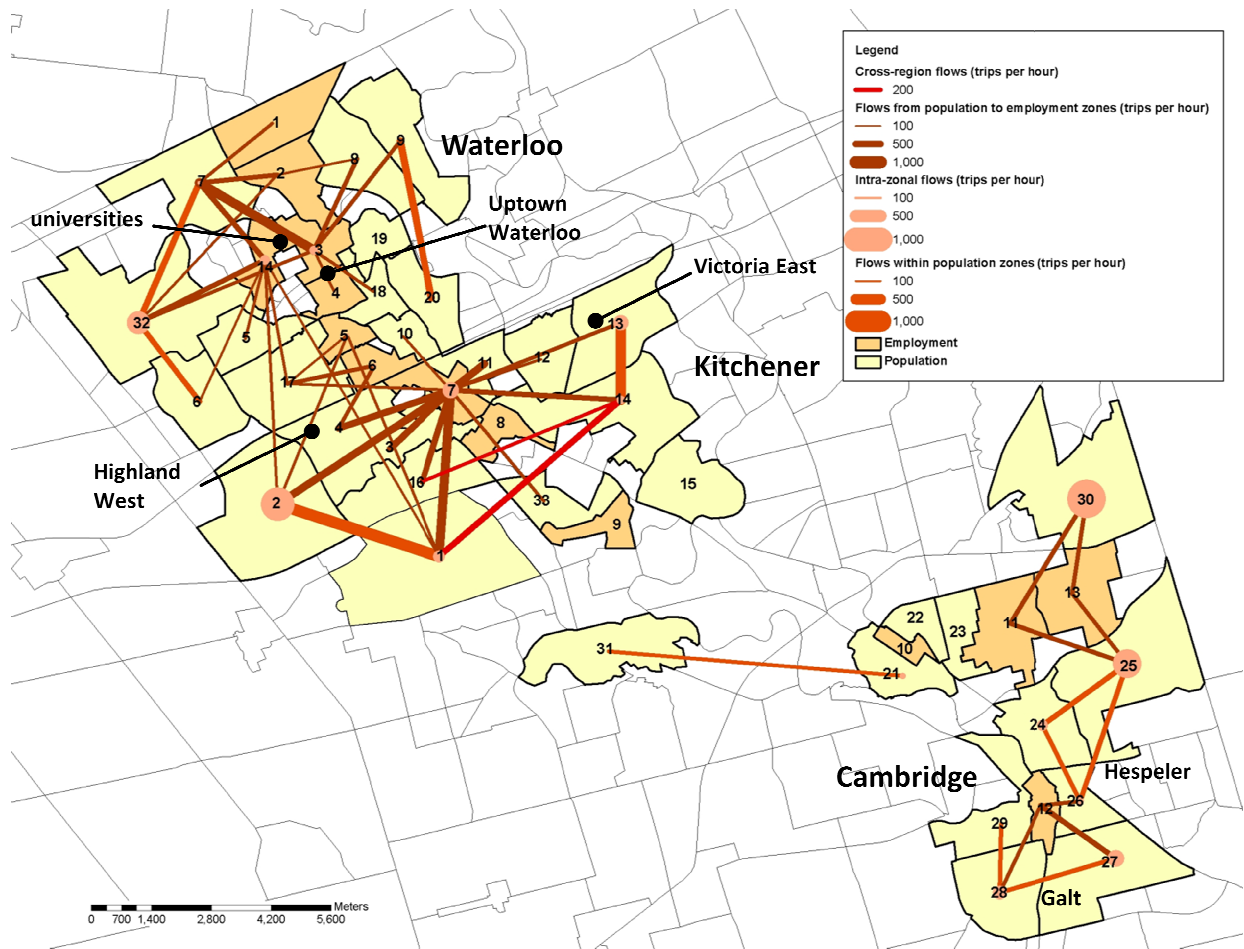


Figure 5.4: Major travel flows throughout Waterloo Region during the AM peak hour (all modes)

The major travel demands in the Region of Waterloo can be described as follows:

In Kitchener:

- There exists heavy east west travel demand destined for the downtown (7E) originating in both the Highland west corridor (2, 3 and 4) and the Victoria east corridor (11, 12 and 13);
- There exists heavy east west travel demand through and bypassing the downtown beginning in the southeast (1 and 16) and southwest (14);

In Waterloo:

- There exists reasonably heavy travel demand destined for the universities (3E and 14E) from both the east and west of the City (32, 5, 6, 8 and 9);
- There exists heavy demand to uptown Waterloo (3E and 4E) from areas north and east of the University of Waterloo (7, 8 and 9);

In Cambridge:

- There exists relatively heavy demand in Hespeler Road (24, 25, 26, 30, 13E and 14E) corridor along the east side of the city;
- There exists relatively heavy travel demand into the Galt section of the City (26 through 29 and 12E);

Region-Wide:

- Relatively heavy demand exists along the west side, connecting Kitchener to Waterloo (1 to 2, 32 to 6).

5.3 Unique travel flows

The major demand flows were augmented with an analysis of student flows, low income flows, and unique employer data throughout the Region. Data were obtained for all three cases and using GIS, student flows were plotted, low income areas were identified and the residences of employees belonging to major employers were plotted. This was to ensure the desire lines were capturing the groups from which a high percentage is likely to take transit.

5.3.1 Student flows

Data were obtained for student boardings on existing transit routes throughout the Region for a four month period from September to December of 2009. Both the University of Waterloo and Wilfrid Laurier have UPasses where students display their student cards to board the bus. The driver keeps a record of every time a student boards. While the location of where the student boards the bus cannot be mapped spatially, the proportion of students who ride each route can be displayed. Table 5.3 displays the student boarding numbers for each of these routes. Figure 5.5 displays visually the routes that have a proportion of 30% or higher of student boardings.

Table 5.3: Transit routes where 30% or more of boardings are students

Route	Total Boardings	WLU	UW	Total % of UPasses
29	37,192	2,664	24,252	72%
31	62,847	3,743	40,011	70%
13	125,254	8,952	63,143	58%
9	272,737	21,599	124,207	53%
35	101,836	7,321	39,224	46%
200 (iXpress)	861,979	66,334	288,787	41%
12	708,724	58,322	228,560	40%
27	35,334	2,829	11,023	39%
5	64,209	4,321	16,210	32%
7	1,416,266	174,772	245,829	30%
14	27,732	3,463	4,854	30%
8	600,957	48,541	132,919	30%

Bus Routes where the percentage of Student Boardings is > 30%

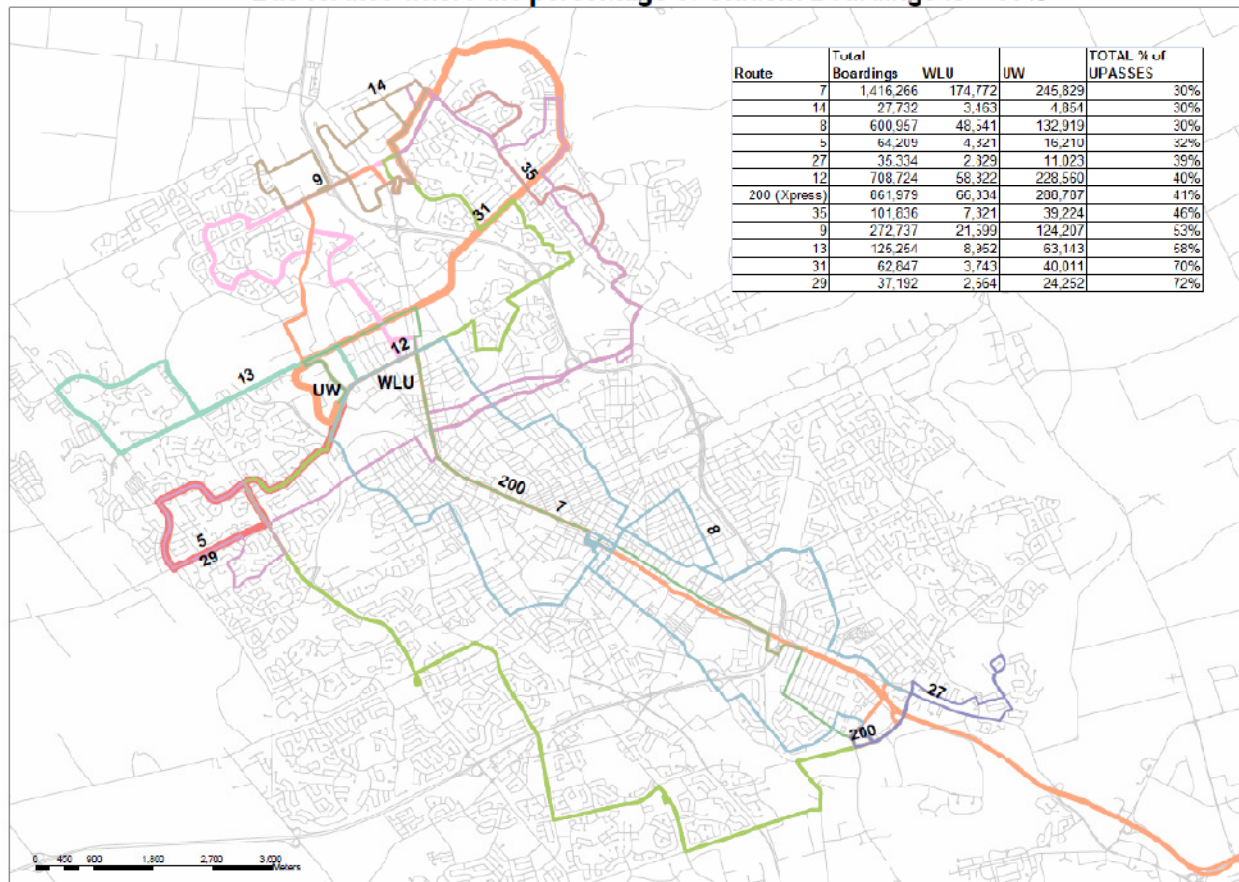


Figure 5.5: Map displaying the transit routes that have 30% or more student boardings

5.3.2 Low income flows

Income data were obtained for the entire Region. Figure 5.6 presents the analysis of the Region's average income distribution at the TAZ level. The lighter areas represent those TAZs in which the average household income is less than \$30,000. Looking within the three Regional Cities, concentrations of low income were identified which are not along the previously identified corridors and, as such, would otherwise not be serviced by higher order transit. These areas exist in the Hespeler section of Cambridge (north of the 401) and in the area surrounding Sportsworld (at the intersection of the 401 and Highway 8). TAZs in which 40% or more of the population earns less than \$20,000 were also identified in Figure 5.7.

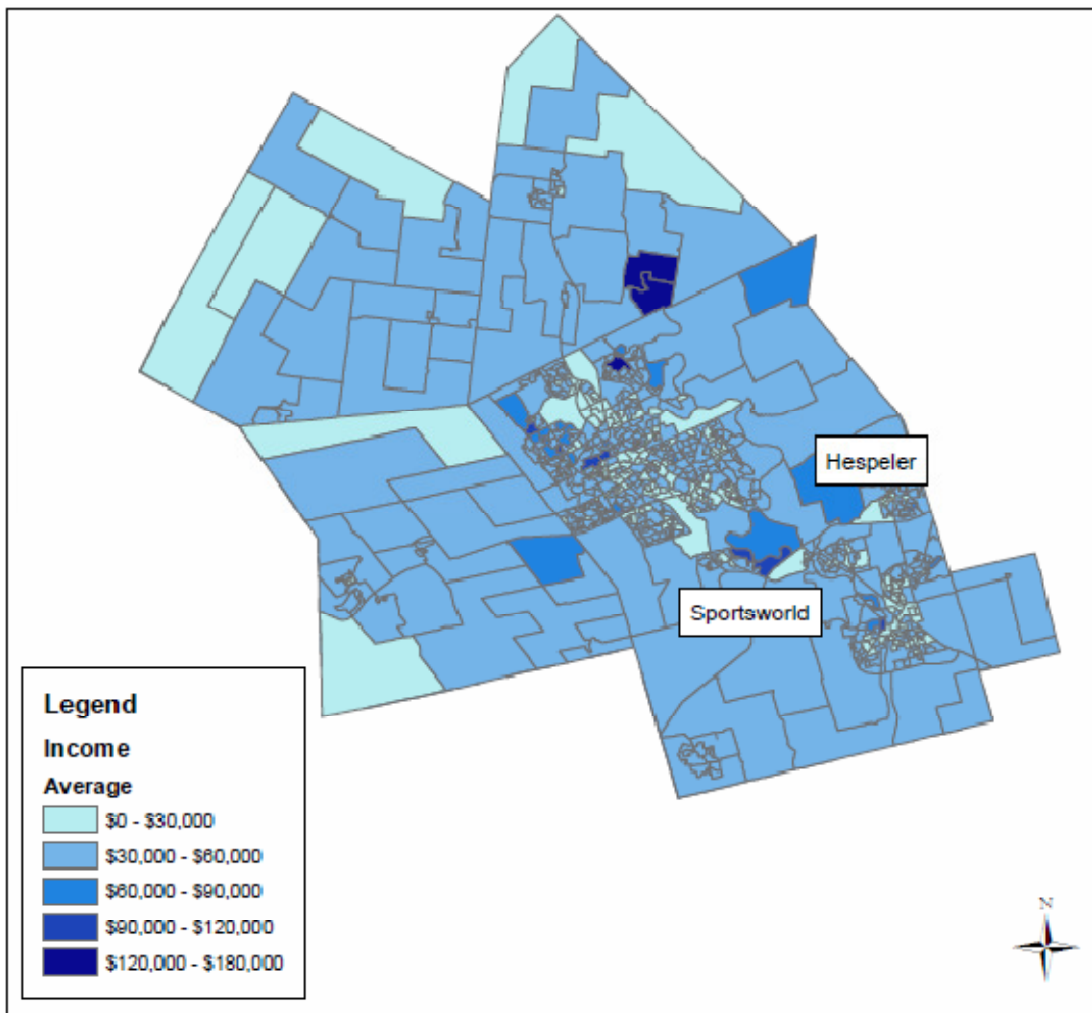


Figure 5.6: Mean income levels in the Region at the TAZ level

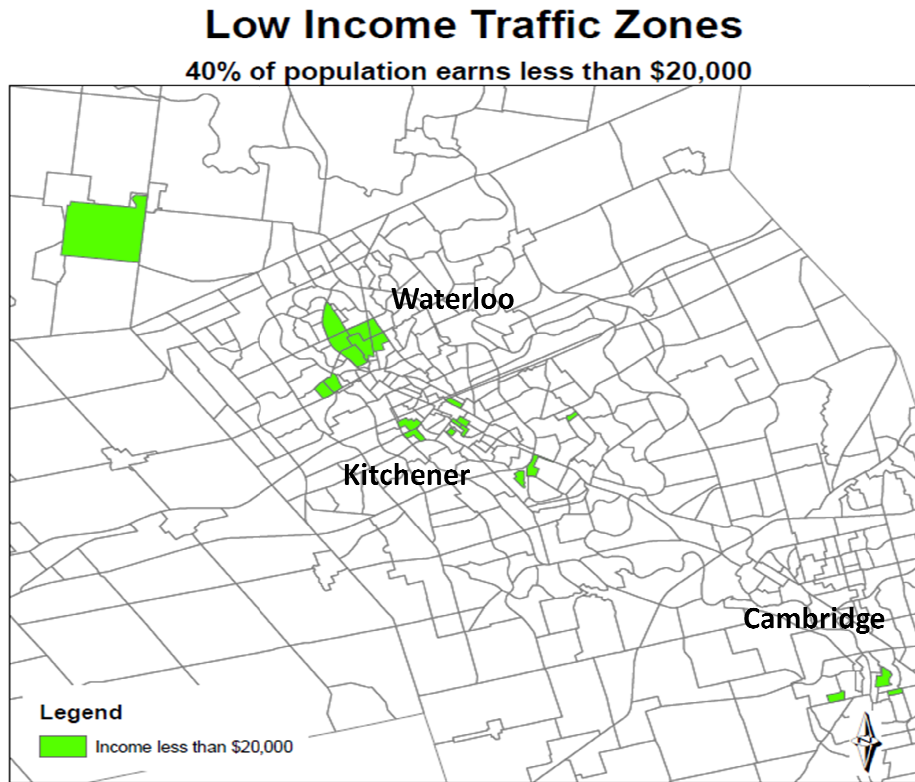


Figure 5.7: TAZs where 40% of the population earns less than \$20,000

5.3.3 Unique employer flows

Data were also obtained for two major employers within the Region. The first is Research in Motion (RIM) a worldwide mobile communications company. The second is the Maple Grove Distribution Centre, a food distribution facility. Employee postal code data were obtained for each facility. The postal codes were plotted within a GIS. They were then joined to the TAZ file to determine how many employees lived in each TAZ. A visual representation of the proportion of employees living in each TAZ was created (See Figure 5.8).

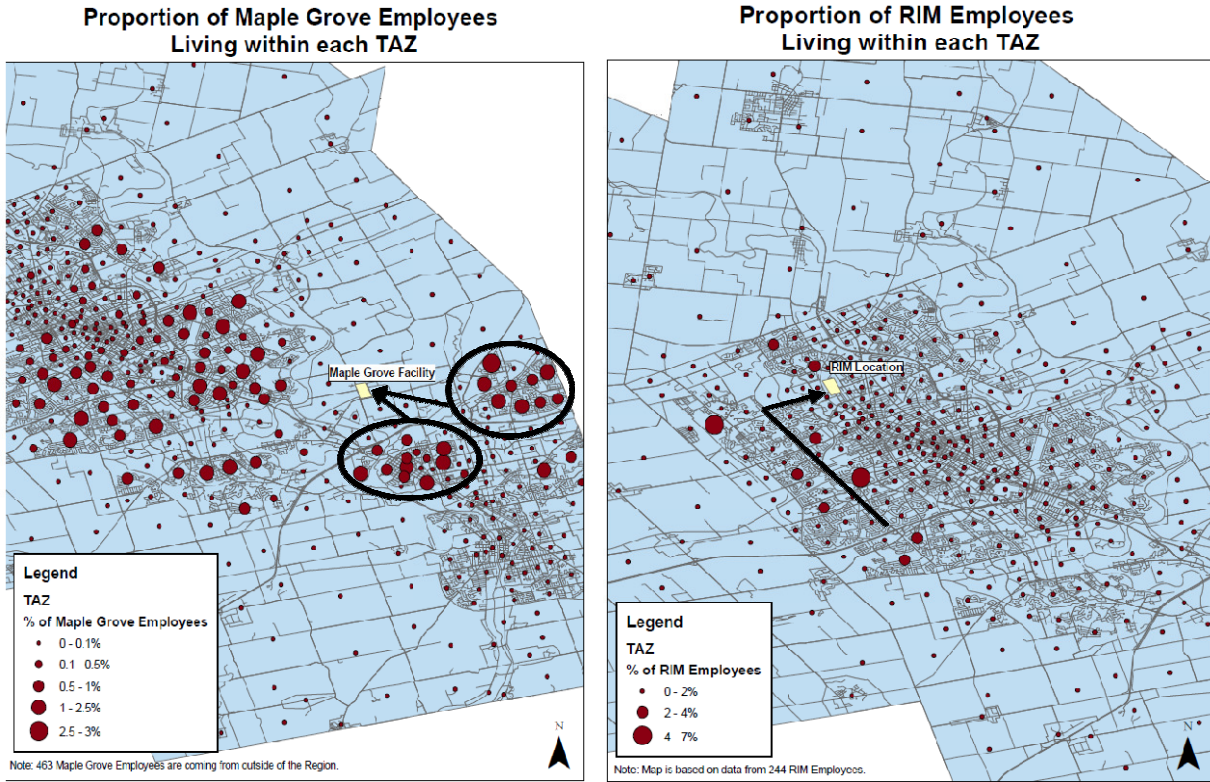


Figure 5.8: Proportion of RIM and Maple Grove employees living in each TAZ

5.4 Route design

The desire lines that were identified were then used to provide input into which OD pairs warrant direct transit service. To maximize transit ridership, the highest quality of service connecting the transit-supportive origins and destinations between which the greatest travel demand exists is provided. To provide mobility, the highest quality of service connecting low income areas is provided. As such, transit alignments were constructed to match the desire lines formed by the generalized origins and destinations described above. Appropriate roadway alignments were selected based on:

1. the directness of service provided;
2. limited stops;
3. the suitability of the roadway infrastructure for higher transit service;
4. the intensification potential along the corridor;
5. the point at which the roadways intersected with the proposed rapid transit system.

Using these criteria, the following seven routes were developed in conjunction with Regional Staff. These routes are presented in Figure 5.9 and are described in Table 5.4.

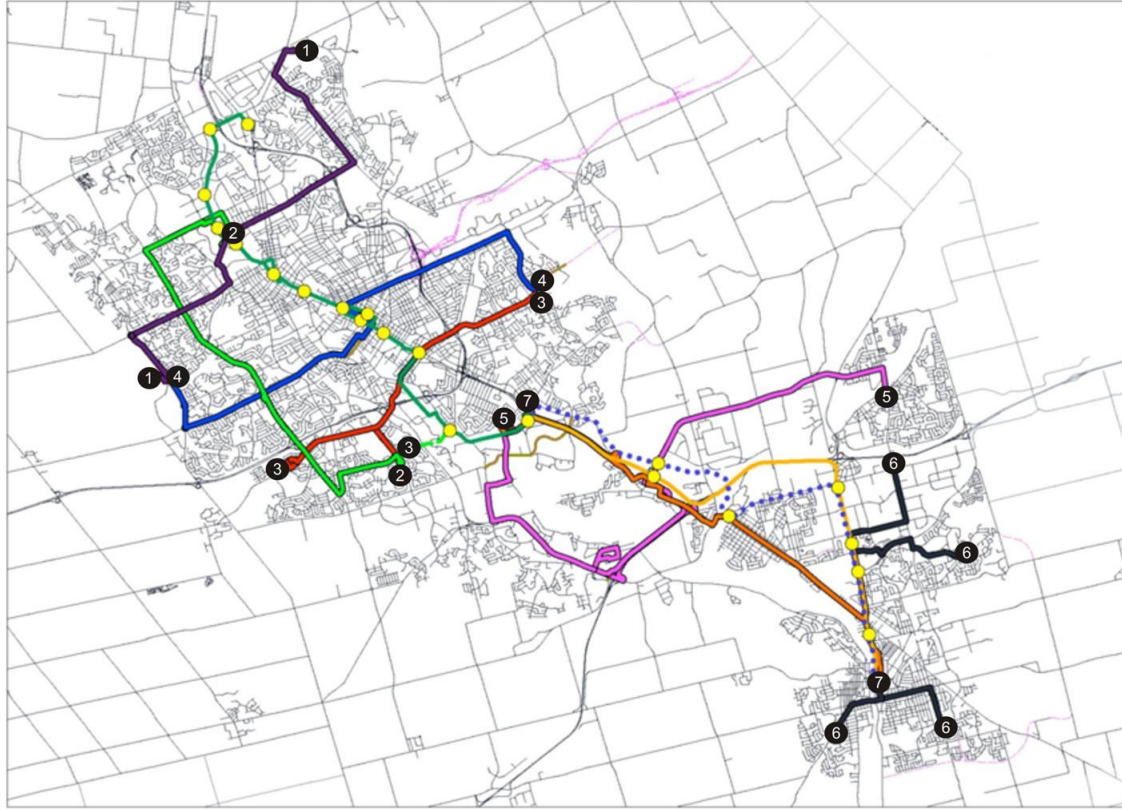


Figure 5.9: Trunk routes and Rapid Transit system

Table 5.4: Proposed Trunk Routes in the Redesigned GRT System

Route Designation	East / North Terminal(s)	West / South Terminal(s)	Alignment	Motivation / service provided
iX1 - “University Line”	RIM Northfield Campus at University Ave.	Ira Needles Blvd. at University Ave.	Northfield-Bridge-University-Erb-Ira Needles	This route provides service to the new Northfield RIM office campus, and connects along University Ave. both Wilfrid Laurier University and the University of Waterloo (where it intersects with the RT system), through the area of concentrated student housing west of the campuses, and to the rapidly growing Ira Needles Blvd. corridor.

iX2 - “West-side Express”	Phillip St. at Columbia Ave.	Block Line Rd. at Courtland RT Staion	Phillip- Columbia- Fischer Hallman- Westmount- Block Line	This route provides an alternative north south travel path for the Region for trips beginning and ending west of the RT system, eliminating circuitous travel and multiple transfers. The route is designed to connect with RT and GO service at its northern terminal at the University of Waterloo.
iX3 - “Ottawa St. Express”	Ottawa St. at Lackner Blvd.	Ottawa St. at Sunrise Centre; Strasburg Rd. at Block Line Rd.	Branch 1: Ottawa St.; Branch 2: Ottawa St.- Strasburg Rd.	This route provides east-west connection south of the Kitchener downtown area. It further connects with additional trunk service in the east and west, as well as the RT service.
iX4 - “Highland - Victoria Express”	Lackner Blvd. at Ottawa St.	Ira Needles Blvd. at University Ave.	Lackner- Victoria- King-Queen- Highland	This route provides a direct east-west connection through central Kitchener and supplements RT service through the Kitchener downtown. East of the central transit corridor, the route serves the commercial corridor along Victoria St. with the intention of stimulating land use changes.
iX5 - “Mid Region Express”	Guelph Ave. at Queen St. West	Fairview Park Mall	Guelph- Fisher Mills- Maple Grove- Hwy 8-Hwy 401-Homer Watson- Manitou- Wabanaki- Wilson	This route provides direct east-west service in the under-developed area of the Region surrounding the 401. The motivation is to connect the growing employment area along Maple Grove to residential areas in Hespeler; further, the line provides direct connection from the aBRT at Sportsworld to both Hespeler and to Conestoga College and Fairview Park Mall.

iX6 - “East Cambridge Express”	Branch 1: Franklin Blvd. at Pine Bush Branch 2: Saginaw Parkway at Burnett Ave.	Branch 1: St. Andrews St. at Stanley St. Branch 2: Elgin St. at Champlain Blvd.	Franklin-Bishop-Hespeler-Ainslie-Cedar-St. Andrews; Saginaw-Franklin-Can-Amara-Hespeler-Ainslie-Conession-Elgin	This route supplements the aBRT in the Hespeler Road corridor and provides excellent area coverage throughout the City of Cambridge. The two southern branches satisfy the heavy demand for travel between the St. Andrews corridor and the southeast side of the City.
iX7 - “Coronation Blvd. Express”	Fairview Park Mall	Ainslie St. Terminal	Fairway-King-Shantz Hill-Fountain-King-Coronation-Ainslie	This route also enhances service in Cambridge by directly connecting the historic Preston section to both the Ainslie terminal and to southern Kitchener and Fairview Park mall. From Fairview, connections can be made to iX5 and to the RT system.

5.5 Route Evaluation

The routes shown in Figure 5.7 were input into GIS from which route length is estimated. Operating speeds were provided by Regional staff. From these two data sources, annual operating costs were quantified using the tool shown in Figure 3.5 and based on the following assumptions:

1. schedules contain a minimum of 5 minutes of recovery time at each end of the route;
2. headways are 15 minutes in peak periods, and 30 minutes in the evening;
3. on routes with branches, headways are 20 minutes in peak periods and 40 minutes in the evening;
4. service operates for 18 hours weekdays (12 hours peak and 6 hour evening service) and 16 hours (base service) on Saturdays and Sundays;
5. service is operated for 261 weekdays, 52 Saturdays and 52 Sundays annually.

For routes with multiple branches (iX3 and iX6), the combined operating requirements were estimated. The results are contained in Tables 5.5 and 5.6.

Table 5.5: Routes' operating characteristics and fleet sizes

Routes	Two way length (km)	Region Vo estimate (km/hr)	One way travel time (min)	Min two way travel time (min)	Headways: peak, eve (mins)	Adjusted cycle time (mins)	Fleet Size
iX1 University	30.1	24.0	37.6	85.2	15, 30	90.0	6.0
iX2 West-side	34.7	24.3	42.8	95.7	15, 30	105.0	7.0
iX3 Ottawa St.	15.6	23.5	20.0	49.9	20, 40	60.0	3.0
iX3 Ottawa St. Branch 2	18.4	23.5	23.5	57.0	20, 40	60.0	3.0
iX4 Highland-	33.1	22.0	45.1	100.2	15, 30	105.0	7.0
iX5 Mid-Region	45.2	23.5	57.7	125.3	15, 30	135.0	9.0
iX6 East Cambridge	19.2	22.9	25.2	60.3	20, 40	80.0	4.0
iX6 East Cambridge Branch 2	20.8	24.8	25.2	60.4	20, 40	80.0	4.0
iX7 Coronation Blvd.	30.9	24.8	37.5	85.0	15, 30	90.0	6.0
						Total	49.0

Table 5.6: Annual vehicle operating hours for the trunk routes

Routes	Weekdays	Saturdays	Sundays	Totals
iX1 University	23,490	4,992	4,992	33,474
iX2 West-side	28,188	5,824	5,824	39,836
iX3 Ottawa St.	12,528	2,496	2,496	17,520
iX3 Ottawa St. Branch 2	12,528	2,496	2,496	17,520
iX4 Highland-Victoria	34,452	5,824	5,824	46,100
iX5 Mid-Region	43,848	7,488	7,488	58,824
iX6 East Cambridge	15,660	3,328	3,328	22,316
iX6 East Cambridge Branch 2	15,660	3,328	3,328	22,316
iX7 Coronation Blvd.	23,490	4,992	4,992	33,474
Totals	209,844	40,768	40,768	291,380

5.6 Calibrating delay parameters

The proposed equations in Chapter 3 (Equations 3.13, 3.15, 3.16, 3.18 and 3.19) for determining delay parameters were applied to the current GRT route system in place. Street segment information was extracted for approximately 34 routes currently in operation throughout the Region of Waterloo. The routes were separated by direction and the total length of major roads

and local roads for each route were calculated. AVL data from the Region of Waterloo were obtained to determine the average actual travel time along each route for each direction throughout the Region. The number of stops and the number of signalized intersections were also counted and summarized for each route. With these data regression is performed in SPSS (statistical software) to see which model returns the best results. All of the models resulted in high R and R² values, however, many coefficients were not consistent with expectations. Table 5.7 presents the coefficient results for each equation tested. Table 5.8 presents the regression results for each equation tested.

Table 5.7: Coefficient Results

Coefficients								
Equation		Expected Values		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		Sign (+ or -)	Range	B	Std. Error	Beta		
3.13	ETT	+	1 - 2	0.78	0.13	0.37	5.94	0
	# signalized intersections	+	25 - 45	34.85	4.73	0.42	7.37	0
	# bus stops	+	10 - 30	11.15	2.4	0.23	4.65	0
3.15	# signalized intersections	+	25 - 45	40.89	5.19	0.49	7.87	0
	# bus stops	+	10 - 30	10.07	3.55	0.21	2.83	0.01
	ETTR1	+	1 - 2	0.18	0.23	0.04	0.78	0.44
	ETTR2	+	1 - 2	1.12	0.22	0.27	5.02	0
	ETTR3	+	1 - 2	0.86	0.46	0.07	1.87	0.07
3.16	# signalized intersections	+	25 - 45	35.65	4.53	0.75	7.87	0
	# bus stops	+	10 - 30	12.69	2.64	0.47	4.81	0
	Total Length	+	0.01 - 0.5	-0.02	0.01	-0.25	-2.13	0.04
3.18	Constant	+	120 - 600	296.52	104.39		2.84	0.01
	# signalized intersections	+	25 - 45	27.93	3.62	0.7	7.71	0
	# bus stops	+	10 - 30	2.78	3.05	0.08	0.91	0.37
3.19	# signalized intersections	+	25 - 45	29.92	3.74	0.63	8.01	0
	# bus stops	+	10 - 30	9.24	2.13	0.34	4.33	0

Table 5.8: Regression Results

Model Summary				
Equation	R	R Square (b)	Adjusted R Square	Std. Error of the Estimate
3.13	0.98	0.96	0.96	351.20
3.15	0.98	0.97	0.96	328.75
3.16	0.94	0.88	0.88	346.81
3.18	0.74	0.54	0.53	338.40
3.19	0.94	0.88	0.87	355.80

b. For regression through the origin (the no-intercept model), R Square measures the proportion of the variability in the dependent variable about the origin explained by regression. This cannot be compared to R Square for models which include an intercept.

When looking at the coefficient results for Equation 3.13, a coefficient of less than one for ETT is illogical. This value means that the bus would travel faster than the speed limit along the route. This would never happen as the bus is often stopping along the route and the congestion would not allow the bus to travel at fast speeds. Similar results occurred for ETTR1 and ETTR3 in Equation 3.15. The results for Equation 3.16 are also not very good. It is impossible to have a negative value for the delay associated with the total length of the route. Equation 3.18 included a constant. This constant represents the extra delay associated with traffic congestion or other external factors. However, in these results, a delay of 2.78 seconds for each bus stop is too low and improbable. Equation 3.19 has the best results of all the models. This is also one of the simplest models. In this case, a signalized intersection would cause a delay of approximately 30 seconds, while the bus would stop for an average of 9.24 seconds for boardings and alightings.

For all of the models the R^2 value is very high. The R^2 value is used to explain the amount of variability in the data explained or accounted for by the regression model. In the case of Equation 3.13, the model accounts for 96% of the variability in the data. However, a high R^2 value does not always imply the regression model is a good one. For this case, although the R^2 values are high, the coefficients are not what were expected. A reason for this may be because the travel time along each road segment was considered to be independent of one another. However, in reality the link travel time may be dependent upon adjacent segments. Over fitting the data to the regression model may also be another cause of the high R^2 values. This happens when too many variables are introduced into the model in relation to the number of observations.

5.7 Summary of Findings

This chapter has presented the results of applying the proposed methodology to the Region of Waterloo. It is evident that the GIS tool presented allows the user to analyze major demand corridors and informs transit network design. In addition, the guidelines provided for selecting the route alignments assist in minimizing the GC of taking transit, thereby, increasing the probability of taking transit. This helps increase transit competitiveness with the automobile. Although, the aggregation procedure and route design step relies on local knowledge, the tool is intended to be used by local transit agencies that will possess the required information regarding the study area. The methodology can be easily replicated for various study areas. The level of automation that the tool provides allows a basic GIS user to implement and use the tool. Automating the process also facilitates repeating the methodology. This is a tool that can be used often to ensure transit routes are providing adequate service. If future demand trip tables were available, the tool can also be used to identify future demand corridors. This would allow transit agencies to look ahead and identify where service changes may be needed in the future.

Chapter 6

Conclusion and Future Research

6.1 Conclusion

This research focused on developing a methodology for addressing the TNDP within a GIS framework. A review of the literature demonstrated that there were various ways in which the TNDP had been addressed; however, various limitations were identified and few methodologies have been widely implemented. With the emergence of GIS in transit planning, GIS is identified as a valuable tool by which the TNDP could be addressed.

Based on these conclusions an automated GIS tool is proposed to address the TNDP. The method proposes a flexible methodology and requires resources that are available to most transit agencies and is customizable to local conditions.

The tool facilitates land use analysis and network design in transit planning. The method formalizes the “desire line” approach in which transportation facilities are proposed to accommodate the existing or predicted major demand corridors to solve the TNDP for a transit network. First, GIS is used to identify transit-supportive land uses at the TAZ level based on a user-defined combination of total population, total employment or their densities. Next, the tool allows the user to interactively merge TAZs to create activity centres between which statistically meaningful travel volumes are expected. In the third step, the tool allows the user to merge travel data to create a visual representation of major flows between the activity centres generated. From these visual representations, trunk transit routes are readily identified and input. Finally, the GIS application estimates the operating costs associated with candidate transit networks.

The tool is developed using VBA scripting in ArcMap 9.3 part of ESRI’s general ArcGIS suite. It incorporates specific GIS functionality including spatial query, feature dissolve and overlay functions in addition to the use of the network analyst extension. The tool is applied to the Regional Municipality of Waterloo at the TAZ level using population and employment data. A street network with corresponding posted speeds on each link and the location of signalized intersections were also used in the analysis.

The results of the analysis depicted major flows throughout Kitchener, Waterloo and Cambridge. Unique flows from students, major employers and an analysis of average income levels also provided input into the major demand corridors. From these results seven high order transit routes were designed to accommodate the major demand corridors.

These results illustrate that GIS can be used effectively to analyze major demand corridors and inform transit network design. The route design guidelines provide further guidance into producing adequate transit routes that minimize the GC of taking transit, making transit a competitive option. The methodology has been semi-automated within a GIS making it easy to use. There is very little training required in its use. The tool is also transferable and can be replicated for various datasets. It is evident that the combinations of a spatial aggregation procedure and trip tables from a travel forecasting model provide meaningful flow lines to inform transit network design.

6.2 Transferability and Limitations

6.2.1 Transferability

One of the goals of this study is to develop a methodology that is automated and easily transferable to various transit agencies. The data required to employ the network design tool are population and employment at a sufficiently disaggregate level (typically TAZs) and a travel demand matrix that shares the same spatial disaggregation. To compute the operating characteristics of proposed routes, the data required are GIS layers which contain the roadway network, the posted speeds on each link and the location of signalized intersections. These data are readily available in most municipalities. The tool has also been programmed in a way to work on any data set provided the required attributes are present. It is also important to note that while the tool has been programmed within ESRI's ArcGIS, the tool makes use of general GIS functionality in which the methodology can be replicated in various software packages.

6.2.2 Limitations

The limits of the transit network design tool include a trade-off in spatial aggregation. Representativeness of travel patterns is lost by aggregating all origins and destinations to an activity centre centroid. However, in the aggregation more meaningful flow lines are developed without a substantial loss in data quality. In the case of the Region of Waterloo, the methodology worked very well as such that there were several major demand corridors present throughout the Region. This method would not work as well for smaller municipalities in which the desire lines were not as prominent.

Another limitation is the GIS data. While postal and census data is often readily available and less expensive for transit agencies to use, accuracy of the data is sometimes questionable. Additionally, it is difficult to obtain sufficient and up to date data. Data is often obtained from various sources and it then becomes difficult to use various layers together. Manipulating data to the right format becomes a time consuming task.

With regards to estimating the operational times associated with routes, the method presented can be greatly improved if actual travel delays (based on link v/c ratios) were available in GIS format. These data are typically output from travel forecasting models but in this case did not contain a common link identifier to facilitate a join.

Finally, another limitation is the inability of the tool to determine ridership levels. The route evaluation procedure can be greatly improved if the tool were able to determine predicted ridership levels.

6.3 Future Research

This research looked to develop a semi-automated methodology within a GIS framework for transit network design, further research can be done to improve or extend the work presented. As previously mentioned, the methodology works well when major demand corridors are evident throughout the study area. If a study area did not have evident major demand corridors, one is able to perform the analysis on a zonal basis as opposed to creating the activity centres. Often, a smaller municipality will have fewer zones and the analysis may be easier to conduct on a zonal basis.

The zonal aggregation procedure is semi automated and requires extensive user input. Quantitative methods by which limits on aggregation can be automated is another opportunity for future research.

Future research can also be conducted with regards to the evaluation process. A better evaluation of network alternatives can make the route design and evaluation process more robust. Currently, routing alignments to connect major OD pairs are chosen based on a set of criteria. A model can be developed to propose multiple routing options to connect the OD pairs. Figure 6.1 displays an example. There exists heavy demand between OD pair A-C. Connecting A-C with direct service will minimize the GC of taking transit making transit a viable for those travelling from A to C. However, an alternative routing option is providing service that connects A-B-C. This routing option will increase the GC of taking transit for those travelling from A to C, nevertheless, ridership may increase by attracting more riders who travel from B-C or B-A. While, the GC cost may increase for certain riders, the increase in ridership from other minor flows may be worthwhile. A trade-off between directness of service can be made in order to maximize ridership levels. By developing a model in which different alternatives can be proposed and evaluated, transit agencies can decide which alternative best suits their needs.

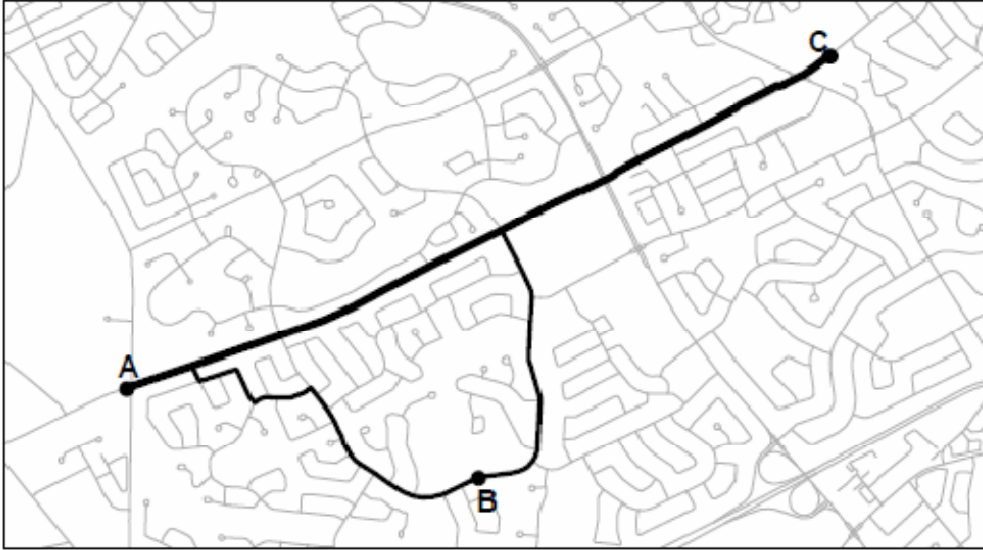


Figure 6.1: Example of alternative routing alignments

Finally, future research into the calibration of delay parameters is also needed. A more rigorous approach in which other variables are taken into consideration is better suited. If data were available regarding congestion levels or lane densities, running time and bus delay predictions can be improved.

APPENDICES

Appendix A

```
'-----  
'-----PROGRAM NOTES-----  
'For the macros to work correctly, make sure to utilize them  
'with the current active sheet  
'The list of megazones must all be in the first column,  
'with each set of subzones separated by some sort of text  
'to identify the separate megazones  
'  
'Also, the matrices should have the same general format, with  
'the labels along the left and the top, and the data starting  
'in cell B2  
'-----  
Public Sub CreateList()  
' CreateList Macro  
' Creates 3-Column Table From Matrix  
'  
'Declarations  
Dim a As Integer, b As Integer, i As Long, j As Integer  
Dim sheet_name As String  
Dim size As Integer  
  
sheet_name = InputBox("What would you like to name your new sheet?")  
  
size = InputBox("What size is the matrix you wish to put in list form? (i.e. 20, if dealing with a 20x20  
matrix)")  
  
'Declares array based on user input  
Dim list_array() As Double  
  
ReDim Preserve list_array(size, size)  
  
'Fills in array with data from matrix  
  
For i = 1 To size  
For j = 1 To size  
list_array(i, j) = Cells(i + 1, j + 1).Value  
Next  
Next  
  
'Creates new sheet and fills it in with array  
Sheets.Add.name = sheet_name  
  
Sheets(sheet_name).Activate
```

```
Cells(1, 1).Value = "Origin"  
Cells(1, 2).Value = "Destination"  
Cells(1, 3).Value = "Total Flow"
```

```
i = 2
```

```
For a = 1 To size  
For b = 1 To size  
Cells(i, 1).Value = a  
Cells(i, 2).Value = b  
Cells(i, 3).Value = list_array(a, b)  
i = i + 1  
Next  
Next
```

```
End Sub
```

```
Public Sub SortList()
```

```
' Sorts Trips From Greatest Flow To Least Flow  
' The HeapSort algorithm is used
```

```
Dim i As Long, j As Long, n As Long  
Dim flow_array() As Double  
Dim order() As Long  
'Gets flow numbers for the sorting process
```

```
i = 1
```

```
Do
```

```
ReDim Preserve flow_array(i)  
flow_array(i) = Cells(i + 1, 3).Value  
i = i + 1
```

```
Loop Until IsEmpty(Cells(i + 1, 3)) = True
```

```
'Ordered array is sent back
```

```
order = HeapSort(flow_array)
```

```
Dim chart_array() As Double
```

```
ReDim Preserve chart_array(UBound(flow_array), 4)
```

```
'Fills in chart array with original list
```

```
For i = 1 To UBound(chart_array, 1)
```

```
For n = 1 To UBound(chart_array, 2)  
chart_array(i, n) = Cells(i + 1, n).Value
```

```
Next
```

```
Next
```

```
'Utilizes ordered array to display sorted list
```

```
n = 2
```

```
For i = UBound(order) To 1 Step -1
```

```
For j = 1 To UBound(chart_array, 2)  
Cells(n, j).Value = chart_array(order(i), j)
```

```

    Next
    n = n + 1
Next
End Sub

Public Function HeapSort(Keys() As Double)
    ' Known sorting algorithm which is able to go through large amounts of data quickly
    Dim Base As Long: Base = LBound(Keys)           ' array index base
    Dim n As Long: n = UBound(Keys) - LBound(Keys) + 1 ' array size
    ReDim Index(Base To Base + n - 1) As Long      ' allocate index array
    Dim i As Long, m As Long

    For i = 0 To n - 1
        Index(Base + i) = Base + i                ' fill index array
    Next

    For i = n \ 2 - 1 To 0 Step -1                 ' generate ordered heap
        Heapify Keys, Index, i, n
    Next

    For m = n To 2 Step -1
        Exchange Index, 0, m - 1                  ' move highest element to top
        Heapify Keys, Index, 0, m - 1
    Next

    HeapSort = Index
End Function

Public Sub Heapify(Keys() As Double, Index() As Long, ByVal i1 As Long, ByVal n As Long)
    ' Initializes the Heap Sort procedure
    ' Heap order rule: a[i] >= a[2*i+1] and a[i] >= a[2*i+2]
    Dim Base As Long: Base = LBound(Index)
    Dim nDiv2 As Long: nDiv2 = n \ 2
    Dim i As Long: i = i1

    Do While i < nDiv2
        Dim k As Long: k = 2 * i + 1

        If k + 1 < n Then
            If Keys(Index(Base + k)) < Keys(Index(Base + k + 1)) Then
                k = k + 1
            End If
        End If

        If Keys(Index(Base + i)) >= Keys(Index(Base + k)) Then Exit Do
    End Do

```

```
Exchange Index, i, k
i = k
Loop
```

```
End Sub
```

```
Private Sub Exchange(a() As Long, ByVal i As Long, ByVal j As Long)
```

```
'Exchanges values for the HeapSort procedure
```

```
Dim Base As Long: Base = LBound(a)
```

```
Dim Temp As Long: Temp = a(Base + i)
```

```
a(Base + i) = a(Base + j)
```

```
a(Base + j) = Temp
```

```
End Sub
```

```
Public Sub Swap(ByRef a As Double, ByRef b As Double)
```

```
'Swaps two values
```

```
Dim Temp As Double
```

```
Temp = b
```

```
b = a
```

```
a = Temp
```

```
End Sub
```

```
Public Sub PercentColumn()
```

```
' PercentColumn Macro
```

```
' Calculates The Total Flow and The Percentages for Each Trip
```

```
,
```

```
Dim i As Long
```

```
Dim sum As Double
```

```
Dim count As Long
```

```
Cells(1, 4).Value = "Percentage Flow (%)"
```

```
sum = 0
```

```
count = 0
```

```
i = 2
```

```
Do
```

```
sum = sum + Cells(i, 3).Value
```

```
count = count + 1
```

```
If IsEmpty(Cells(i + 1, 3)) = True Then
```

```
Exit Do
```

```
End If
```

```
i = i + 1
```

```
Loop
```

```
For i = 2 To (count + 1)
```



```

        Cells(i, 4).Value = ((Cells(i, 3).Value) / sum) * 100
    Next
End Sub

Public Sub MegazoneMatrix()
'Utilizes a list of megazones to create a new trip table based on previous data

    Dim size As Integer

    size = 597 ' known value

    'Declares array based on known value
    Dim list_array() As Double

    ReDim Preserve list_array(size, size)

    'Fills in array with data from matrix
    Sheets("total_trips").Activate

    For i = 1 To size
        For j = 1 To size
            list_array(i, j) = Cells(i + 1, j + 1).Value ' holds the original trip table
        Next
    Next
    Next
    '-----
    Dim sName As String

    sName = InputBox("Please type the name of the sheet which contains the megazones you wish to
use.")

    Sheets(sName).Activate

    Dim mega_list() As Integer ' holds the subzones
    Dim n As Integer, a As Integer, b As Integer
    Dim mRow As Integer, mCol As Integer

    mRow = 0
    mCol = 0
    n = 1
    b = 0

    Do Until Cells(n, 1).Value = "END"
        If IsNumeric(Cells(n, 1).Value) = True Then
            b = b + 1
        Else
            mRow = mRow + 1 ' row count (megazones)
            b = 0
        End If
    Loop

```

```

End If
If b > mCol Then mCol = b ' column count (max. subzones)
n = n + 1
Loop

ReDim mega_list(mRow, mCol)

a = 0
b = 1
n = 1
' fills in the matrix with the subzones
Do Until Cells(n, 1).Value = "END"
If IsNumeric(Cells(n, 1).Value) = True Then
    mega_list(a, b) = Cells(n, 1).Value
    b = b + 1
Else
    a = a + 1
    b = 1
End If
n = n + 1
Loop
'-----
Dim mega_matrix() As Double
ReDim mega_matrix(mRow, mRow)

' Perform calculations using list_array and mega_list
' Put final sums into mega_matrix
For a = 1 To UBound(mega_matrix, 1)
For b = 1 To UBound(mega_matrix, 2)
    mega_matrix(a, b) = FlowSum(a, b, mega_list, list_array)
Next
Next

Dim new_sheet_name As String
new_sheet_name = InputBox("What would you like to name the new sheet?")

Sheets.Add.name = new_sheet_name
Sheets(new_sheet_name).Activate

'Displays new megazone-based matrix on sheet
For n = 1 To mRow
Cells(n + 1, 1).Value = n
Cells(1, n + 1).Value = n
Next

For a = 1 To UBound(mega_matrix, 1)
For b = 1 To UBound(mega_matrix, 2)
    Cells(a + 1, b + 1).Value = mega_matrix(a, b)

```

```
Next
Next
```

```
End Sub
```

```
Public Function FlowSum(mOri As Integer, mDes As Integer, mega() As Integer, list() As Double)
```

```
    Dim cR As Integer, cC As Integer
```

```
    Dim i As Integer, j As Integer
```

```
    Dim sum As Double
```

```
    sum = 0
```

```
    For i = 1 To UBound(mega, 2)
```

```
        For j = 1 To UBound(mega, 2)
```

```
            cR = mega(mOri, i)
```

```
            cC = mega(mDes, j)
```

```
            If (cR = 0) Or (cC = 0) Then Exit For
```

```
            sum = sum + list(cR, cC)
```

```
        Next
```

```
    If (cR = 0) Then Exit For
```

```
Next
```

```
FlowSum = sum
```

```
End Function
```

Appendix B

Identifying Transit-supportive Land Uses in GIS - custom toolbars

Prepared for:

The Regional Municipality of Waterloo

Prepared by:

Stephanie Simard

Waterloo Public Transportation Institute

University of Waterloo

Introduction

As part of an ongoing effort to improve transit service provision, the Regional Municipality of Waterloo and the University of Waterloo have entered into a research agreement to redesign conventional bus routes. This manual describes the workings of various Geographic Information System (GIS) tools which automate the processes of:

- identifying transit-supportive land uses;
- creating visual representations of major flows between transit supportive land uses;
- and estimating the operating costs associated with candidate transit networks.

The tools described here are created in ArcMap 9.3 part of ESRI's general ArcGIS suite working in Windows operating system. These tools are unlikely to work in other GIS software.

This manual is written with the expectation that the user has basic experience with GIS. For the uninitiated user, some general ArcMap functionality is described at the end of this manual.

Getting Started

To use the customized toolbar, load the *.mxd file containing the embedded toolbar. Then, load the necessary data files:

- the traffic analysis zone shape file;
- the street network shape file;
- the employment, population and densities data in a .dbf or .xls(x) file.

General Notes

The following notes are provided to decrease the likelihood of experiencing errors.

- Error checking has been implemented. Messages will appear if an error has occurred and if required fields have been left blank.
- Field names in attribute tables CANNOT start with a number. The program will not work if the field begins with a number.
- Certain layers are not permanent. If the tool is re-run, it will overwrite existing selections (i.e. the activity centre layers). You can export and save as a shapefile if desired.
- Ensure label options are turned on if you wish to see labels.
- In order for the tool to run successfully, the user must select the appropriate layer (shapefile) in the dropdown menu.

Step I: Defining Activity Centres


Data Requirements

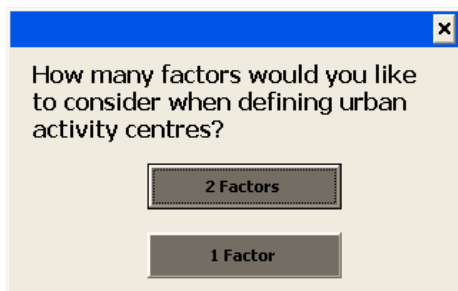
In order to use this component of the toolbar, population and employment data are required for each traffic analysis zone (TAZ). The attribute table for the TAZ layer should contain area, population density and employment density. If the data are not readily available they can be calculated in ArcMap by adding new fields and using the field calculator (See General ArcMap Functionalities). In preparing the data, you should also add in a field entitled "IDNUMBER" and specify it as a long integer. This field MUST be added to the TAZ layers attribute table in order for the tool to work.

Instructions

1. To begin identifying activity centres, specify the TAZ layer in the dropdown combo box on the toolbar.



2. Click the activity centre button .
3. Decide whether you'd like to create activity centres based on 1 factor or 2 factors - using population, employment, their densities or a combination of both.



4. If you have chosen 2 factors, you then begin to fill in the required fields on the form.

5. Here you have the option of performing an AND or OR operation with regards to the two factors you'd like to use. For example, you may find zones that exceed an employment density threshold AND a population density threshold. Alternatively, you may find zones that either satisfy a minimum population OR a minimum employment.
6. Select an operator in addition to specifying the two different factors. You must also specify the corresponding fields (found in the attribute table) for the 2 factors.
7. You may now click on "Confirm Criteria". This will display the mean and standard deviation for each factor. This can help you decide on your threshold values for each type of activity centre.
8. The form appears with default values for thresholds. These values should be consistent with those found in the literature, subject to local conditions. "Typical" range of employment density is 15 - 40 employees per hectare or 1500 to 4000 per square kilometer. Once your thresholds have been specified, click "OK". The program will output the corresponding activity centre layers.
9. If no TAZs have met the criteria for the activity centres a message will alert the user and no layer will be created.
10. If the initial results are unsatisfactory, you may repeat the procedure with revised thresholds or criteria. *However, the layers created in the previous iteration will be overwritten.* If you wish to save the previous results, you must export those results as layer files.

Step II: Creating Megazones

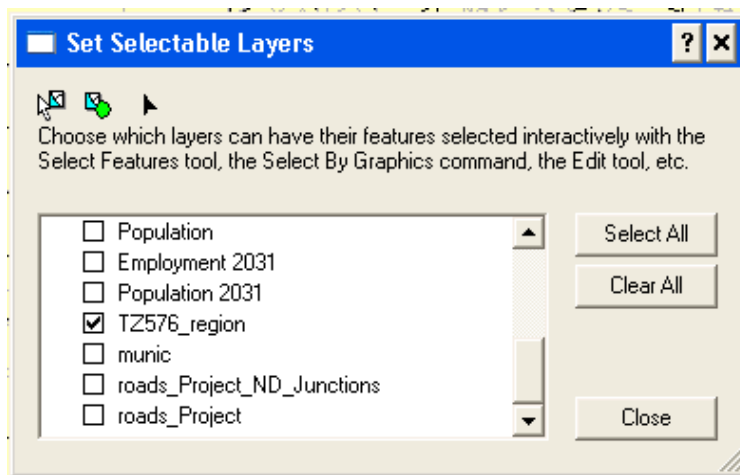
The original step identifies TAZs that meet appropriate thresholds. The travel flow analysis is simplified by creating “Megazones” or amalgamations of individual TAZs that are typically joined based on common threshold criteria. For example, several adjacent TAZs that exceed an employment threshold may be combined to create an employment megazone. This component of the toolbar allows the user to create megazones which store the aggregate data of the individual TAZs.

Data Requirements

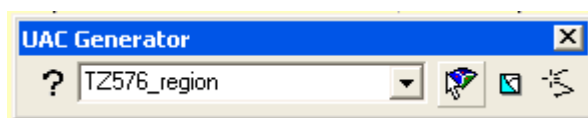
- TAZ shapefile
- Ensure that the field “IDNUMBER” has been added to the attribute table.


Instructions

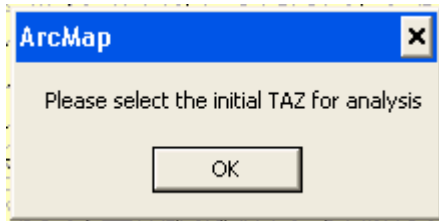
1. Before beginning set selectable layers so that only the TAZ layer can be selected: Selection > Set Selectable Layers > TAZ layer.



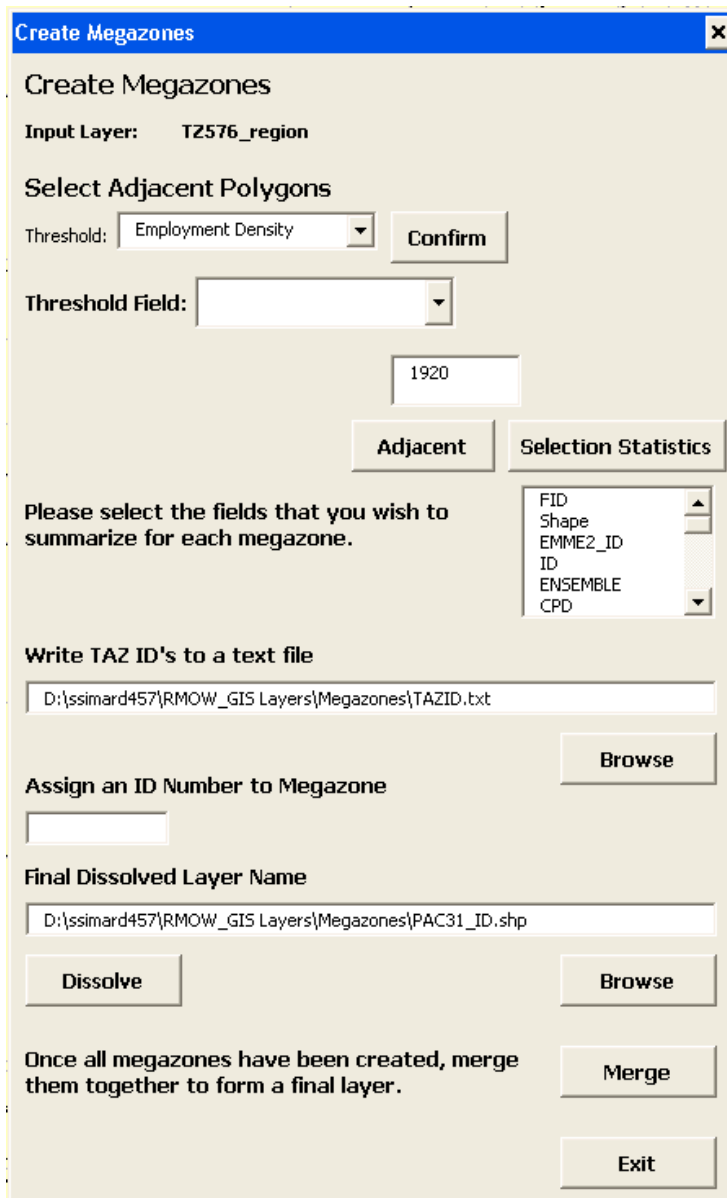
2. To begin creating megazones, specify the TAZ layer in the dropdown combo box on the toolbar.



3. Click on the megazone button .
4. A message will inform you to select an initial TAZ for analysis. This should be the TAZ to which you will add adjacent zones in order to create the megazone (ideally one of the TAZs identified as an activity centre).



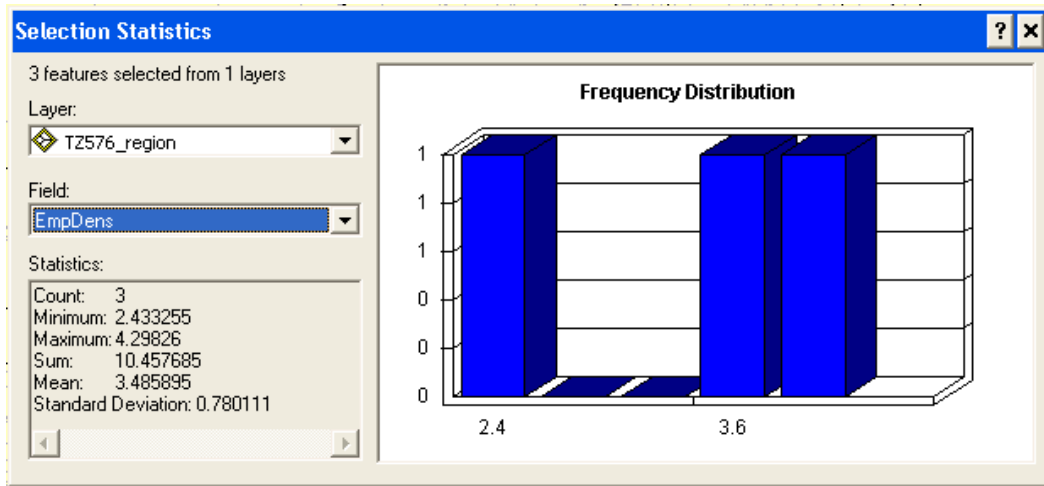
5. A form appears. You are required to specify the chosen factor in which the megazones will be created (for example: employment density). If the labels for the TAZ layer have been turned on (See General ArcMap Functionalities), labels will appear for the chosen factor for each TAZ allowing you to see statistics for adjacent TAZs.



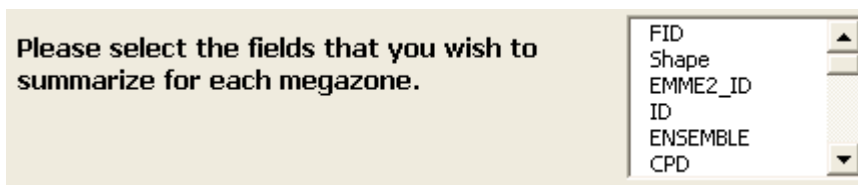
6. Clicking on the "Adjacent" button will select the TAZs that are adjacent to the initial TAZ. The

user must set a threshold value to be met when selecting adjacent TAZs to amalgamate with the initial selection.

7. If you would like to add multiple TAZs to the selection, simply use the select tool while holding down the “shift” key at the same time. This will add individually selected TAZs to the selection.
8. The “Selection Statistics” button allows the user to see statistics regarding the selected TAZs. The user may wish to add TAZs to the selection while at the same time keeping the average above a certain threshold.

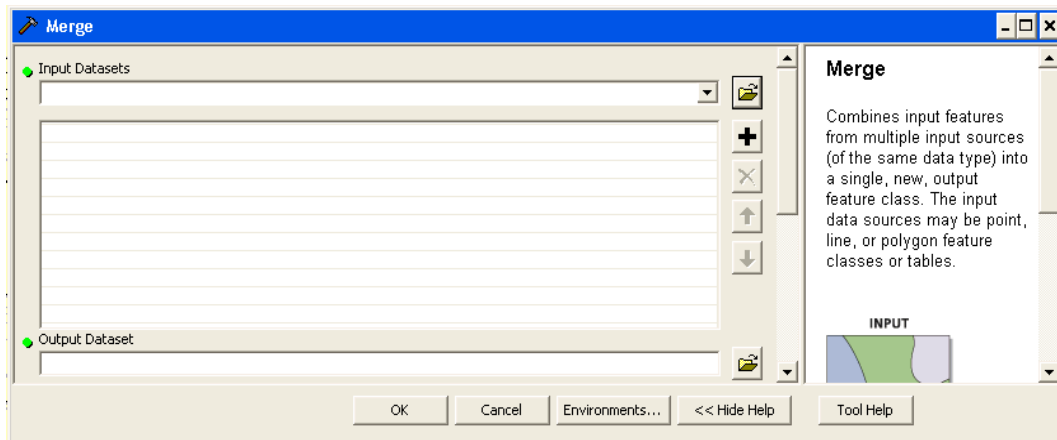


9. Once you are satisfied with the TAZ selection, you must then specify the fields that you wish to summarize when the megazone is created. The chosen fields will be summed and displayed in the attribute table for the new megazone.



10. You must also specify the location in which you wish to create a text file where the TAZs associated with each megazone will be recorded.
 - a. A text file is created in order to record the id numbers of each TAZ found in each megazone. This text file is then used to amalgamate corresponding trip tables in Excel.
 - b. It is important to select the same fields for each megazone, or the megazones will not merge together properly.
11. Megazones must also be assigned an id number which must be sequential (i.e no gaps).
12. The location to which you wish to save the megazone shapefile needs to be specified. You should also name the shapefile appropriately (e.g. pop_mzone_1).

13. You then click the “Dissolve” button. This will create a new shapefile with the selected megazone definition.
14. Once all of the megazones have been created, you can use the “Merge” button. This allows you to create one layer containing all of the megazones. Simply specify which layers (i.e. megazone layers) you wish to merge together.

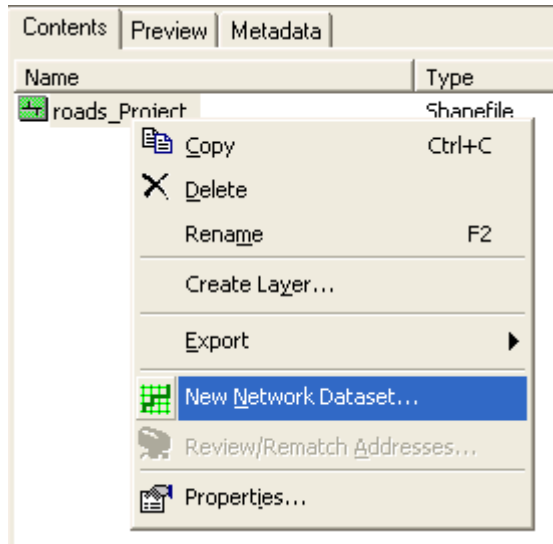


Step III: Generating Flows between Megazones

The text files created in step 10 above are then imported into MS excel (version 2007). An automated script has been prepared which converts a full travel matrix (flows between all TAZs) to flows between megazones. The output of the excel sheet are two columns: the first contains from node_ to node (e.g. 2_5) the second contains the flow. These columns are input into step 4.

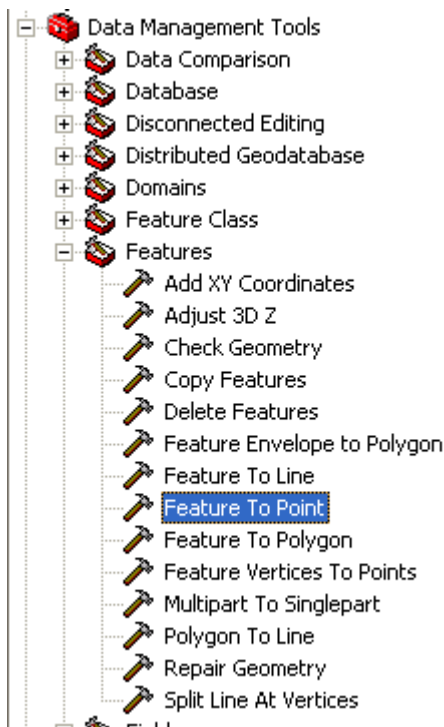
Step IV: Graphic Representation of Flows

Before using Network Analyst you must create a network dataset for your roads layer. To do this open ArcCatalog. Right-click the roads layer and select New Network Dataset. Step through the wizard with all default values and the new network dataset will be created. Add the new dataset to the map in ArcMap. You can now begin using network analyst.

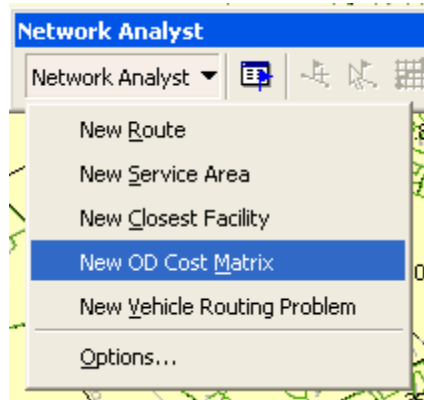


This task can be broken down into 4 steps.

1. The first step is to convert the megazone polygons into points. Use the “Feature to Point” tool found under data management tools in the ArcToolbox.

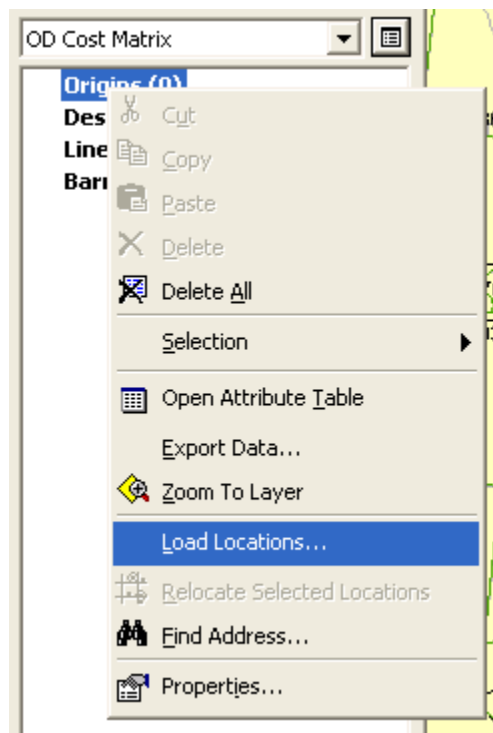


2. Once the megazones have been converted into points, you can use network analyst to create the OD cost matrix.
 - a. New OD Cost Matrix




b. Show/Hide Network Analyst Window

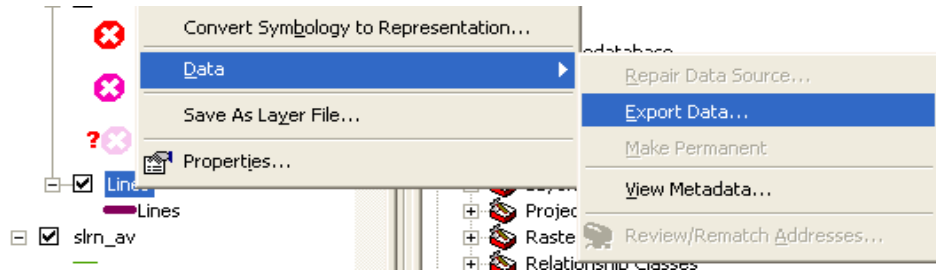
c. Right click Origins and select Load Locations. Specify the population point layer and specify the ID number as the sort field. Load locations a second time for the employment points layer.



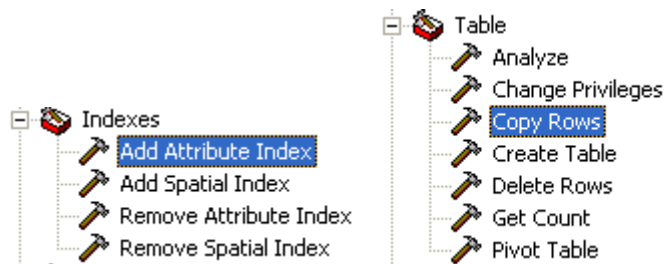
d. Do the same process for loading the Destinations.

e. Click the solve button . A matrix of lines should appear to and from all megazone points.

f. Right click on "Line" > Select Data > Export Data and save the line shapefile to an appropriate location. Add the shapefile to the display.



- g. Remove the network analyst layer.
 - h. Open the attribute table. The Origin and Destination fields display to and from IDs for each megazone.
 - i. Create a new field in the attribute table in order to concatenate the origin and destination ID numbers together (for example: 1_3 would be from megazone 1 to megazone 3). The field MUST be a text field.
3. Using the excel spreadsheet tool you have a new table with a concatenated field displaying origin and destination IDs, along with the flow for each pair (as described in Step III above).
- a. Add a new field in the lines shapefile and call it flow_year (replace with appropriate year).
 - b. Add the excel table to the map.
 - c. Use the join tool in order to join the table to the lines shapefile.
 - i. It's important to note that you may be required to use the "Add Attribute Index" tool for the shapefile and the "Copy Rows" tool for the flow table. This adds the proper indexing to the files in order to be able to join the two together. These tools are found in the data management toolbox.



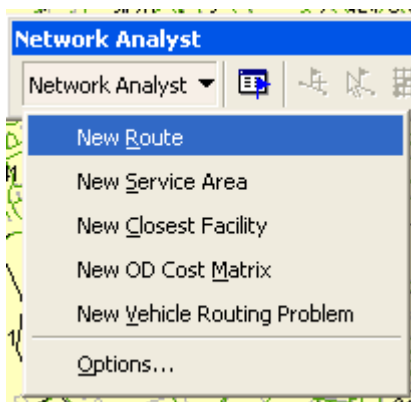
- d. Use the join tool (See General ArcMap Functionalities). The table should now be joined to the shapefile.
- e. Copy the flow field over to the new field you created (flow_year). Use "Field Calculator" to do so (See General ArcMap Functionalities).
- f. You can then remove the join and the flow should be permanently found in the attribute table to the lines shapefile.

4. You can now adjust the symbology properties of the lines layer in order to display flow lines.
 - a. Use proportional symbols under quantities and specify the flow field.
 - b. You can also choose to display only certain flows by setting a definition query. For example: In order to show flows greater than 300, use the following query: flows > 300
 - c. You can now adjust your map in layout view, add in a title, legend etc. and print your flow map.

Step V: Input New Routes

This portion allows the user to input new bus routes using the network analyst tool.


1. Use the New Route option in the network analyst extension.




2. Show/Hide Network Analyst Window .

3. Click on the "Create Network Location" button .

4. Begin clicking where the stops would roughly be on your new route.

5. Once satisfied with the stop locations, click the "solve" button . The route should solve along your desired bus route.

6. If the route does not follow the correct route adjust your stop locations  and re-solve the route.

7. Once the correct route has been drawn export the route and save as a shapefile.

8. Right click on "Route" > Select Data > Export Data and save the line shapefile to an appropriate location. Add the shapefile to the display.

9. Remove the network analyst layer.

Step VI: Route Costing Tool

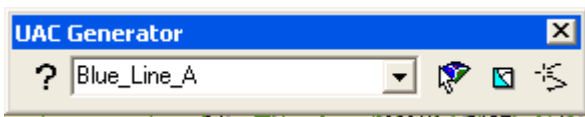
This component allows you to assess the performance and cost of the newly inputted routes.


Data Requirements

1. Route layer created in network analyst
2. Roads layer containing travel time and road length fields.
3. Intersection layer containing all signalized intersection locations.

Instructions

1. Before beginning please be sure to specify the chosen route for analysis in the dropdown menu on the toolbar.



2. Click the route analysis button . The first form that appears requires you to specify the required data layers and corresponding fields.

Please specify the following information

Route Layer Name: **Blue_Line_A**

Field for Route Length: Total_Leng Total_Leng

Field for Number of Stops: StopCount StopCount

Roads Layer Name: **roads** roads

Field for Travel Time: TRVLTIM TRVTIM

Field for Road Length: RDLEN_M RDLEN_M

Intersection Layer Name: **new_ints10000** new_ints10000

OK Cancel

3. The next step is to determine which costing model you wish to use. Two options are available. The first is to compute costs based on only an hourly rate (\$ per vehicle-hour) which the user can specify; the second option is to compute costs based on both time and distance (\$ per vehicle-hour + \$ per vehicle-km). You may also choose to compute the necessary frequency of service based on a policy headway (headway) or allow the model to compute necessary frequency based on the maximum load section (Pmax).

Choose Method for Analysis

Choose the method you wish to use to perform the analysis.

Time Based

Headway

Pmax

Time and Distance Based

Headway

Pmax

Cancel

- Once that has been chosen, simply fill out the field with corresponding requirements. The form appears with default values; however, the user may wish to change them.

Time Based Cost Model

Specify Route layer for analysis.

Input Layer: **Blue_Line_A**

Service

	Hours/Day	Days/Year	
Signal Delay: <input type="text" value="20"/>	Terminal Time: <input type="text" value="0.1"/>	Weekday: <input type="text" value="17"/>	<input type="text" value="261"/>
Stop Delay: <input type="text" value="20"/>	Headway (mins): <input type="text" value="15"/>	Saturday: <input type="text" value="12"/>	<input type="text" value="52"/>
Distance between stops (m): <input type="text" value="1006"/>	Operator Cost (\$/hr): <input type="text" value="100"/>	Sunday: <input type="text" value="8"/>	<input type="text" value="52"/>

Write results to a text file

RunningTime (one dir): mins

of Buses Required: buses

Operating Speed: m/min km/hr

Route Length (one dir): meters km

Cycle Time: mins hrs

Adj. Cycle Time: mins hrs

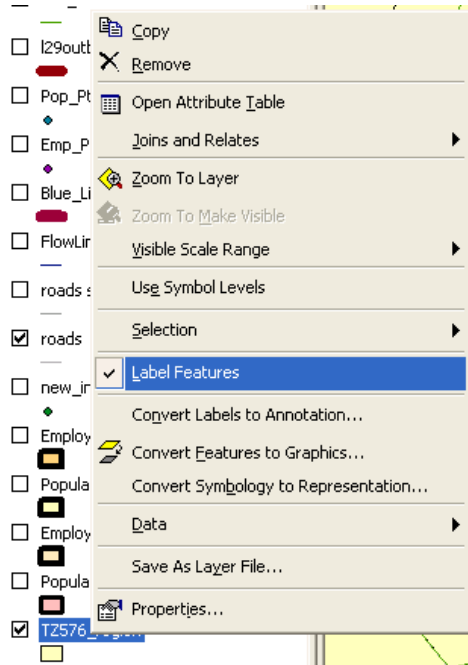
Total Cost of Route per year:

- Click "Calculate" and the corresponding route information are displayed on the form. The calculations are based on the scheduling methodology contained in Casello and Vuchic, 2009. Only clock headways are permitted (i.e. headways that are repeatable each hour).
- The "Calculate" button also creates a new text file where the results of the analysis are written. The user should specify an appropriate name and location for the text file.

General ArcMap Functionalities

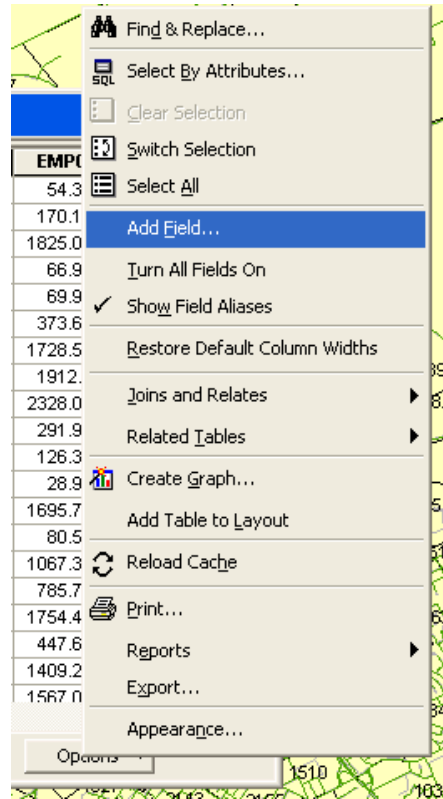
1. Turning Labels on and off

- a. Right click the layer and choose labels.



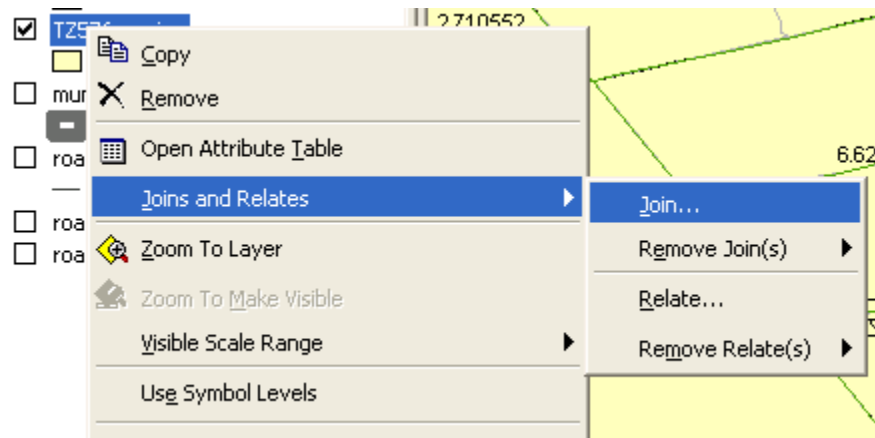
2. Adding a field

- a. Open the attribute table and click options > add field
- b. Name the field appropriately and the type (integer, double, text, etc.)



3. Adding a Join

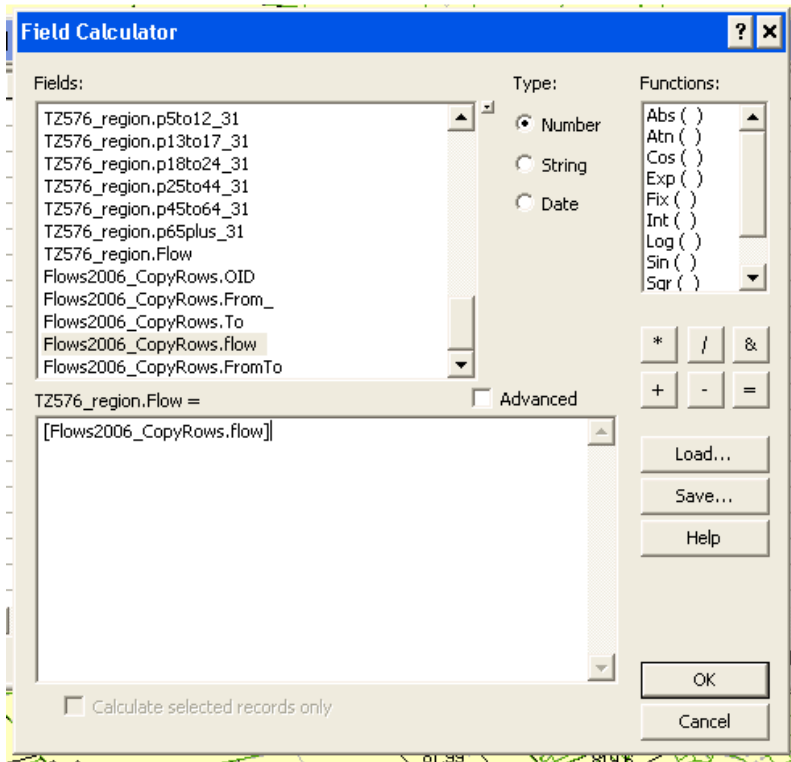
- a. Right click the layer > Joins and Relates > Join
- b. Specify common field in both the shapefile and table that allows the two to join together.



4. Copying fields from a join.

- a. Create a new field in the attribute table.
- b. Add the join

- c. Use field calculator (right click the field) to set the newly created field to the field you wish to copy.
- d. Remove the join.

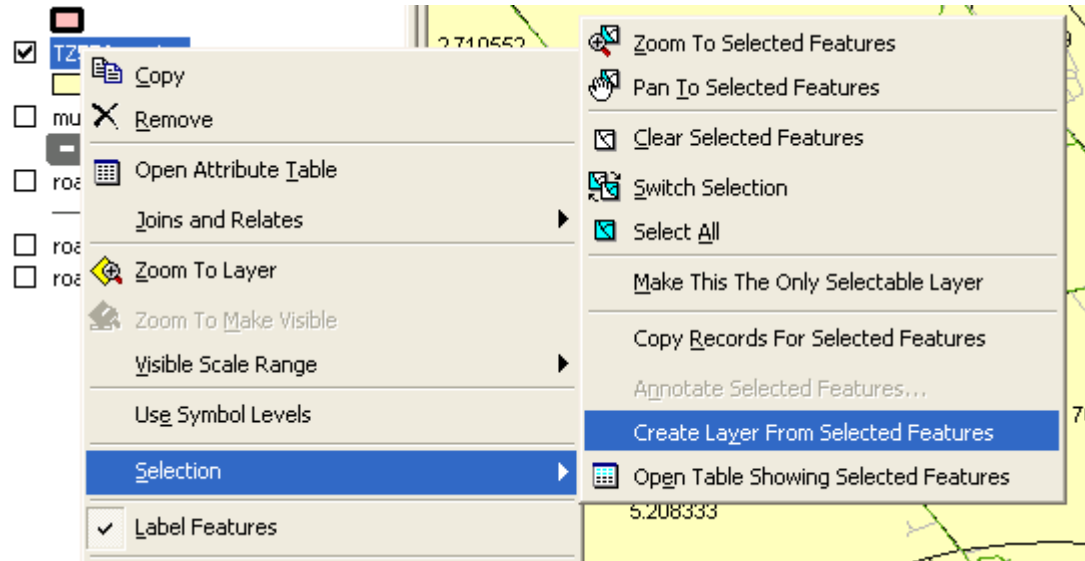


5. Select by attributes

- a. Selection > Select by Attributes
- b. Specify query selection

6. Create layer from selected features

- a. Right click the layer > Selection > Create Layer From Selected Features



7. Exporting to shapefile

- a. Right click layer > Data > Export Data

References

- Abdulaal M. and L. J. Leblan. Continuous equilibrium network design models. *Transportation Research Part B: Methodological*, 13(1): 19-32, 1979.
- Abkowitz M., P. D. M. Cheng, and M. Lepofsky. Use of Geographic Information Systems in managing hazardous materials shipments. *Transportation Research Record* 1261: 35-43, 1990.
- Action Transport, 2010. <http://www.actiontransport.ca/>
- Ashish, Verma, and S. L. Dhingra. GIS for identification of demand-oriented urban rail transit corridor. *Map India*, 2003.
- Azar, K. and J. Ferreira. Using GIS tools to improve transit ridership on routes serving large employment centres: The Boston South End Medical Area case study. *Computers, Environment and Urban Systems*, 18(3): 205-231, 1994.
- Azar, K.T. and J., Ferreira. Integrating geographic information systems into transit ridership forecast models. *Journal of Advanced Transportation*, 29(3): 263-279, 2005.
- Baaj, M. and H.S. Mahmassani. Hybrid route generation heuristic algorithm for the design of transit networks. *Transportation Research Part C: Emerging Technologies*, 3(1):31-50, 1995.
- Baaj M. H. And H.S. Mahmassani. An AI-based approach for transit route system planning and design. *Journal of Advanced Transportation*, 25: 187-210, 1991.
- Black, A. (1995). *Urban mass transportation planning*, McGraw-Hill series in transportation, McGraw-Hill, New York, 411.
- Beltran B., Carrese S., Cipriani E. and M. Petrelli. Transit network design with allocation of green vehicles: A genetic algorithm approach. *Transportation Research Part C: Emerging technologies*, 17(5): 475-483, 2009.
- Boyce, D. and B. Janson. A discrete transportation network design problem with combined trip distribution and assignment. *Transportation Research Part B: Methodological*, 14(1-2): 147-154, 1980.
- Bogart, W., and W. Ferry. Employment centres in greater Cleveland: Evidence of evolution in a formerly monocentric city. *Urban Stud.* 36(12): 2099-2110, 1999.
- Boyce, D. Is the Sequential Travel Forecasting Paradigm Counterproductive?. *Journal of Urban Planning and Development*, 128(4):169-183, 2002.
- Byrne, B. Public transportation line positions and headways for minimum user and system cost in a radial case. *Transp. Res. Rec.* (9):97-102, 1975.
- Byrne, B. Cost minimizing positions, lengths and headways for parallel public transit lines having different speeds. *Transp. Res. Rec.*, 10: 209-214, 1976.

- Casello, J and B. Hellinga. Impacts of Express Bus Service on Passenger Demand. *Journal of Public Transportation*, 11(4), 2008.
- Casello, J. M. and V.R. Vuchic. Urban Transit, Chapter 16 in Meyer, M. ed. *Transportation Planning Handbook* 3rd Edition, Institute of Transportation Engineers, Washington, DC. 2009.
- Casello, J. M. and T. E. Smith. Transportation Activity Centres for Urban Transportation Analysis, *Journal of Urban Planning and Development*, 2006, 247 – 257.
- Casello, J. Transit competitiveness in polycentric metropolitan areas. *TRV Transportation Research Part A*, (41): 19–40, 2007.
- Ceder A. and H.M. Wilson. Bus Network Design. *Transportation Research Part B: Methodological*, 20(4): 331-344, 1986.
- Ceder, A. Operational objective functions in designing public transport routes. *J. Adv. Transp.*, 35(2): 125–144, 2001.
- Cervero, R. Suburban Gridlock. Centre for Urban Policy Research, Rutgers University, New Brunswick, NJ, 1986.
- Chakroborty, P. and T. Dwivedi. Optimal route network design for transit systems using genetic algorithms. *Eng. Optimiz.*, 34(1),83–100, 2002.
- Dantzig G., R. Harvey, Z. Lansdowne, D. Robinson and S. Maier. Formulating and solving the network design problem by decomposition. *Transportation Research* 13B: 5–17, 1979.
- Dashora, M., and S. L. Dhingra. Expert system for bus routing and scheduling. *Computers in Urban Planning and Urban Management*. Vol. 2, P. K. Sikdar et al., eds., Narosa Publishing, New Delhi, India, pp. 841–853, 1998.
- Drezner, Z. and G. O. Wesolowsky. Network design: selection and design of links and facility location. *Transportation Research Part A*, 37: 241–256, 2003.
- Duff-Riddell, W. R. and C. J. Bester. Network Modeling Approach to Transit Network Design. *Journal of Urban Planning and Development*, 131: 87, 2005.
- Fan, W., and R. Machemehl. (2004a). Optimal transit route network design problem: Algorithms, implementations, and numerical results. Rep. SWUTC/04/167244-1, Center for Transportation Research, Univ. of Texas at Austin, Tex.
- Fan, W. and R. Machemehl. A Tabu Search based heuristic method for the transit route network design problem. *In: 9th International Conference on Computer Aided Scheduling of Public Transport*, San Diego, United States, 2004b.
- Fan, W. and R. Machemehl. Using a simulated annealing algorithm to solve the transit route network design problem. *J. Transp.Eng.*, 132(2), 122–132, 2006b.
- Fernandez, R. An expert system for the preliminary design and location of high capacity bus stops. *Traffic Eng. Control*. 34:533-539, 1993.

- Fernandez, J., Cea Ch, J. and H. Malbran. Demand responsive urban public transport system design: Methodology and application. *Transportation Research Part A: Policy and Practice*, 42(7): 951-972, 2008.
- Gao Z., Sun H. and L. Shan. A continuous equilibrium network design model and algorithm for transit systems. *Transportation Research Part B: Methodological*, 38(3): 235-250, 2004.
- Gebeyehu, M. and S. Takano. Demand Responsive Route Design: GIS Application to Link Downtowns with Expansion Areas. *Journal of Public Transportation*, 11(1): 43-62, 2008.
- Gipps, P., Gu, K., Held, A. and G. Barnett. New technologies for transport route selection. *Transportation Research Part C*, 9:135-154, 2001.
- Giuliano, G., and K. Small. Subcentres in the Los Angeles region. *Regional Science and Urban Economics*. 21(2):163–182, 1991.
- Holroyd, E. M. Optimum bus service: A theoretical model for a large uniform urban area. *Vehicular traffic science*, L. C. Edie, ed., Elsevier, New York, 308–328, 1967.
- Horner, M. and T. H. Grubestic. A GIS-based approach to locating urban rail terminals. *Transportation* 28: 55–77, 2001.
- Hurdle, V. F. Minimum cost locations for parallel public transit lines. *Transp. Sci.*, 7(4):340–350, 1973.
- Kepaptsoglou, K. and M. Karlaftis. Transit Network Design Problem: Review. *Journal of Transportation Engineering*, 135(8): 491-505, 2009.
- Kittelson and Associates, Inc. (2003) *Transit Capacity and Quality of Service Manual (TCQSM)*, 2nd edition. Prepared for Transit Cooperative Research Program, Transportation Research Board, Washington D.C.
- Kocur, G., and C. Hendrickson. Design of local bus service with demand equilibrium. *Transp. Sci.*, 16(4):359–394, 1982.
- Lao, Y. and L. Liu. Performance evaluation of bus lines with data envelopment analysis and geographic information systems. *Computers, Environment and Urban Systems*, 33(4): 247-255, 2009.
- Leblanc, L. Transit system network design. *Transportation Research Part B: Methodological*, 22(5): 383-390, 1988.
- Lee Y. and V. R. Vuchic. Transit Network Design with Variable Demand. *Journal of Transportation Engineering*, 131(1):1-10, 2005.
- Liao, S.H. Expert system methodologies and applications—a decade review from 1995 to 2004. *Expert Systems with Applications*. 28:93–103, 2005.
- Mandl, C. E. Evaluation and optimization of urban public transportation networks. *Eur. J. Oper. Res.*, 5(6):396–404, 1980.

- Miller, H. J. and J.D. Storm. Geographic information system design for network equilibrium-based travel demand models. *Transportation Research Part C: Emerging Technologies*, 4(6): 373-389, 1996.
- Ministry of Public Infrastructure Renewal. Growth Plan for the Greater Golden Horseshoe, 2006.
- National Cooperative Highway Research Program (NCHRP). Bus route and schedule planning guidelines. *Synthesis of Highway Practice 69*, Transportation Research Board, National Research Council, Washington, D.C. 1980.
- O'Neil, W. A. A comparison of accuracy and cost of attribute data in analysis of transit service areas using GIS. *Journal of Advanced Transportation*, 29(3): 299-320, 2005.
- Ortuzar, J. De D., and L.G. Willumsen. (1990). Modeling transport. New York: Wiley.
- Pushkarev, B. and J. Zuppan. *Where Transit Works: Urban Densities for Public Transportation*, in *Urban Transportation: perspectives and Prospects*, ed. By H.S. Levinson and R.A. Weant, Eno Foundation, Westport CT, 1982.
- Ramirez, A., and P. Seneviratne. Transit route design applications using Geographic Information Systems. *In Transportation Research Record: Journal of the Transportation Research Board*, No. 1557, Transportation Research Board of the National Academies, Washington, D.C., 1996, p. 123-139.
- Regional Municipality of Waterloo. Regional growth management strategy: Planning our Future, 2003.
- Regional Municipality of Waterloo. Growth Management Strategy & Transit Initiative, 2005.
- Regional Municipality of Waterloo. Regional Official Plan 2031 Newsletter Winter 2006. Retrieved April 5, 2010 from:
[http://www.region.waterloo.on.ca/85256AE80070E40F/0/9B5453039C8ED83C8525746A0056F5D7/\\$file/V2.pdf?openelement](http://www.region.waterloo.on.ca/85256AE80070E40F/0/9B5453039C8ED83C8525746A0056F5D7/$file/V2.pdf?openelement)
- Regional Municipality of Waterloo. Grand River Transit Presentation to the University of Waterloo, 2010.
- Sanchez, T. Rural Public Transportation: Using Geographic Information Systems to Guide Service Planning. Technical report. 2002.
- Sekhar, S. V. C., Wen Long Yue, and M. A. P. Taylor. An approach to transit path design using GIS. *Journal of Eastern Asia Society for Transportation Studies* 5: 414-425, 2003.
- Shaw, S. GIS for urban travel demand analysis: Requirements and alternatives. *Computers, Environment and Urban Systems*, 17(1): 15-29, 1993.
- Simkowitz, H. Transportation applications of geographic information systems. *Computers, Environment and Urban Systems*, 12(4): 253-271, 1988.
- Suljoadikusumo, G. S. and L. K. Nozick. Multi-objective routing and scheduling of hazardous materials shipments. *Transportation Research Record* 1613: 96-104, 1998.

Szeto, W.Y. and K. Lo Hong. Transportation network improvement and tolling strategies: The issue of intergeneration equity. *Transportation Research Part A: Policy and Practice*, 40(3): 227-243, 2006.

Tom, V. M. and S. Mohan. Transit Route Network Design Using Frequency Coded Genetic Algorithm. *Journal of Transportation Engineering*. 129(2):186-195, 2003.

Verma, A. and S. L. Dhingra. Optimal Urban Rail Transit Corridor Identification within Integrated Framework Using Geographical Information System. *Journal of Urban Planning and Development*, 131(2):98-111, 2005.

Vuchic, V. (2004). *Urban transit: Operations, planning and economics*, Wiley, Hoboken, N.J.

Vuchic, V. *Transit Lines and Networks*. In *Urban Transit: Operations, Planning, and Economics*. Hoboken: John Wiley & Sons, 2005.

Yang, Z., Yu, B., and C. Cheng. A parallel ant colony algorithm for bus network optimization. *Computer Aided Civil and Environmental Engineering*, 22(1):44-55, 2007.

Yao, X. Where are public transit needed – Examining potential demand for public transit for commuting trips. *Computers, Environment and Urban Systems*, 31(5): 535-550, 2007.

Zhao, F. and X. Zeng. Optimization of transit route network, vehicle headways and timetables for large-scale transit networks. *European Journal of Operational Research*, 186(2): 841-855, 2008.