Construction of a Detailed Deterministic User-Equilibrium Traffic Assignment Model for the Greater Montreal Area Using Geographic Information Systems

Timothy Spurr
Department of Civil Engineering and Applied Mechanics
McGill University, Montreal

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ABSTRACT

This dissertation describes the process of building a detailed traffic assignment model for the Greater Montreal region using Geographic Information Systems (GIS). Although deterministic user-equilibrium traffic models are widely used in planning practice, most contemporary research into transportation models attempts to deal with the numerous theoretical shortcomings of the static modeling framework through dynamic methods while the potential for improvements on conventional algorithms remains largely unexplored. GIS offer a powerful mechanism for achieving such improvements. This research demonstrates how GIS can be profitably applied in the construction of a traffic assignment model with a very fine spatial resolution. The time savings incurred through the application of GIS permit the construction of a very detailed metropolitan street network comprising approximately 245,000 directional links and a corresponding system of 981 traffic analysis zones.

SOMMAIRE

Cette mémoire décrit les étapes suivies dans la création d’un modèle de circulation détaillée de la grande région de Montréal en utilisant les systèmes d’information géographiques (SIG). La plupart de la recherche concernant la modélisation d’affectation des déplacements essaye de résoudre les défauts théoriques des modèles statiques, en ignorant pourtant les possibilités d’amélioration des méthodologies existantes malgré que ces derniers démeurent toujours favorisés par les planificateurs. Les SIG fournissent une occasion à effectuer de tels améliorations. Cette recherche démontre comment les SIG peuvent être employés dans le développement d’un modele d’affectation de déplacements ayant une résolution spatiale très détaillée. La reduction des heures de main-d’oeuvre fournie par les SIG rend possible la construction d’un réseau routier comprenant 245,000 liens directionnels ainsi que la délimitation d’un système de 981 zones correspondantes.

TABLE OF CONTENTS

Page

Chapter

1. INTRODUCTION

The city of Montreal faces numerous transportation challenges. The preliminary data from the latest travel behaviour survey show that rates of car use in the greater metropolitan region continue to grow (Bisson, 2005), reflecting a trend that has been ongoing for several decades. Automobile ownership and automobile mode share have increased despite an aging road infrastructure, worsening congestion, and concern over the environmental effects of car use.

The importance of the private car continues to increase despite the mounting costs of automobile use. In Québec, local and regional governments invest billions of dollars annually in road maintenance and upgrades yet the overall state of the infrastructure remains poor. Congestion costs the Montreal economy hundreds of millions of dollars every year. Air quality is declining in part due to the pollution generated by the transportation of people and goods. Since the Kyoto Accord came into effect on February 16th 2005, Canada is legally bound to reduce its greenhouse gas emissions – a significant portion of which come from the transportation sector – by at least 20% by 2012. Clearly, widespread changes in people's travel behaviour are needed. But how can these changes be effected?

One approach is to try model the travel behaviour of individuals and then use these models to test the impacts of various policy options. But accurate modeling of individual behaviour is not straightforward. Any analysis of travel behaviour requires an acknowledgement of a vast array of externalities and unpredictable outcomes. While this difficulty will never be completely resolved, the advent of low-cost computing power now affords researchers the capability to process enormous amounts of data quickly. As a result, complex models accounting for thousands or even millions of variables and observations can be constructed and evaluated. Given sufficient data, it is now possible to build - at relatively low-cost - detailed models of urban regions which can be useful in informing public policy.

From a modeling perspective, a city is generally considered as an economic unit with geographic boundaries. Its size is a function of the amount of economic opportunity that exists within these boundaries. It is a place where large numbers of people, attracted by these opportunities, choose to live, work and interact. The choice of where to live is captured by housing models, the location of different types of jobs is described by real-estate and land-use models, and the interactions between homes and jobs is described by transportation models. Ideally, all three models should interact with each other in an integrated platform.

Considered in isolation, a transportation model has its own set of definitions. In a transportation model, the activity of interest is a trip. A trip has several components. First of all, for the purpose of the present analysis, a single trip is performed by a single person. Secondly, the individual decides to make a trip for some defined purpose. Based on this purpose, the trip will have a specific origin and destination. Furthermore, the trip will occur at a specific time. Next - according to characteristics of the individual, the trip purpose, the location of the destination relative the origin and the time of day - the trip will be accomplished by one or more modes of transportation. And finally, the trip will trace a path through space and time which will vary according to the nature of the network corresponding to the modes employed. Each of these decision levels are usually modeled in four separate stages (Meyer and Miller, 2001). In the first stage, a trip generation model uses characteristics of people, firms or regional aggregations of demographic and economic characteristics as dependent variables in order to estimate the quantity of trips produced or attracted for a given purpose. In the second stage, a trip distribution model uses the results of the generation model, as well as characteristics of the regional geography and transportation systems to link origins to destinations through the construction of an origin-destination matrix. These trips are then classified by mode in the third stage, a mode choice model. Dependent variables in a mode choice model include characteristics of individuals as well as characteristics of the types of transportation services available to them. The last stage is trip assignment, which generates as output the volume of traffic on each link in a transportation network. This dissertation describes the construction of a trip assignment model.

In effect, the first three stages are just a means to an end. The generation, distribution, and mode split models are usually used to provide input to an assignment model because it is the assignment model that yields results most relevant to the urban transportation challenges. The assignment model generates traffic flows on the network and calculations of traffic congestion, levels-of-service, travel times, energy consumption and emissions are all estimated based upon these flows. As such, traffic assignment models stand to play an important role in the formulation of transportation policy.

For example, suppose the regional government, in response to heavy congestion on a major highway, decides to study the effects of building a new, parallel highway to improve the situation. A traffic assignment model alone can provide rough estimates of the amount by which congestion will be reduced. An emissions model can be estimated based upon the vehicle flows and speeds to estimate air-quality improvements, if any. The traffic assignment model can also provide travel time estimates which can be used to measure access to opportunity in different parts of the city. The new road may improve access of underdeveloped areas which may in turn spur new residential or commercial development. This new development may cause traffic levels to increase, thereby worsening congestion. These secondary feedback effects can be captured in an integrated land-use and transportation economic model (Miller and Salvini, 1998). In fact, the construction of a traffic assignment model is one step in the process of establishing just such a platform for the Montreal region.

The road networks in many cities throughout the world, including Montreal, have been modeled according to the framework just described. The present research, therefore, is not breaking new ground in this respect but one or two departures from the norm are worth noting. First of all, the majority of large-scale traffic models use the EMME/2 software. The model described in this paper uses TransCAD. Secondly, while most models use greatly simplified networks containing only highways and major streets, the present model contains *all* streets in the region. Such detail is possible due to the integration of Geographic Information Systems (GIS) with conventional transportation planning tools.

GIS is a powerful tool for several reasons. First and foremost, it can be used to efficiently link travel behaviour patterns and socio-economic data within a spatial framework. Secondly, it incorporates geographic details which are essential in the construction of realistic links and nodes as well as in the discretization of space. Thirdly, it requires little formal programming although such capabilities are available for complex projects. And finally, GIS generates visual output of the analysis results which are invaluable in both the application and validation of the model.

It should be emphasized that while the eventual goal of this research is to construct a new and superior traffic assignment model, the first step in this process is to obtain a functional, detailed and representative transportation *network* for the Montreal region. Modern computing power is such that no limits need be placed upon the number of links and nodes in a network describing an urban region. Any contemporary desktop computer can handle the number of intersection and street segments contained in the world's largest cities. Similarly, there need be no restriction on the detail of the algorithm itself. Current technology allows for distribution and monitoring of millions of trip makers moving in real-time. The difference between micro-simulation and macro-simulation, however, lies not in required computing power, but rather in available data.

At present, there is no way to validate the predicted movements of millions of trip makers without resorting to aggregate measures (such as roadside counts) which defeat the purpose of a micro-level model. Therefore, any improvements in accuracy derived from such an approach cannot be measured. On the other hand, extensive data on the precise location and geometry of network infrastructure *is* available and can be applied to large-scale static models. The simplification of networks into collections of straight lines connected by identical nodes is no longer necessary.

The retention of local streets and detailed network geometry may bestow only small benefits on a static model of automobile traffic, especially if the assignment method remains aggregated to a system of zones. But these details become essential in accurate models of transit where the precise location of bus stops and their corresponding intersections is necessary to measure walking distances, transfer times, accessibility and overall performance of the transit system. The importance of geographic detail is even greater if a completely disaggregate modeling approach is the ultimate goal. It is hoped that the construction of a static traffic assignment model will facilitate the calibration and validation of a road network to be used as the basis for detailed economic models of a large-scale urban system.

What follows is a description of the construction of an automobile traffic assignment model for the greater metropolitan Montreal area. The region is delineated based upon the Agence métropolitaine de transport (AMT) O-D survey (AMT, 2001a) and the census zones defined by Statistics Canada. The first phase of the model covers the morning peak period defined as the hours between 6 am and 9 am. Only automobiles are modeled. The network and associated output will form the basis for future work in transit development and land-use changes.

This thesis is structured into seven chapters. Following the introduction, Chapter 2 provides a review of current practice in urban transportation modeling. Chapter 3 describes the data and Chapter 4 discusses the software tools used in the construction of the Montreal model. Chapter 5 outlines the methodology employed, Chapter 6 presents the preliminary results of the modeling effort and Chapter 7 draws some conclusions and suggests directions for future research.

2. REVIEW OF CURRENT PRACTICE

Many different traffic assignment algorithms have been proposed over the years. The simplest is the all-or-nothing approach which assigns all the traffic between origin-destination pairs over the links that make up the shortest path between the two nodes. This method is applicable to transit networks or uncongested road networks but not to congested networks where travel costs are dependent upon traffic flows. Probabilistic methods using logit models (Dial, 1971) were devised in an attempt to model route choice, although this methodology is not entirely suitable for dense urban networks (Easa, 1991). The dynamic methods first developed by Merchant and Nemhauser (1978a, 1978b) have been extensively researched and developed into complex mathematical formulations of travel behaviour. These models, however, remain somewhat unworkable outside the theoretical setting (Peeta and Ziliaskopoulos, 2001). Until the problems of tractability and applicability which surround dynamic models are resolved, the method most often used in large-scale transportation planning remains the deterministic user-equilibrium static model.

User-equilibrium is based upon two methods of assigning flows between origin-destination pairs to links. The simpler method is all-or-nothing assignment, where the entire travel demand between any O-D pair is assigned to the minimum cost path. The second method incorporates the idea of capacity restraint which says that the travel cost on a link will increase with the flow over that link. The rate of cost increase accelerates as the volume of travel demand approaches the capacity of the link.

Wardrop (1952) proposed two fundamental principles which form the basis of the static traffic model. The first principle is that of user optimization, where each trip-maker chooses the path that minimizes their individual trip cost. The optimization process includes the concept of equilibrium, which says that the system will tend toward a stable state where no individual traveler can reduce their travel cost by changing paths. According to the second principal of system optimization, trips are assigned in such a way as to minimize the overall cost to the system as a whole. The latter approach, while practical in some applications, is not usually realistic when applied to the highway network due to the selfish behaviour of individual drivers.

Wardrop's first principal was later described mathematically by Beckman et al (1956). LeBlanc (1973) applied the method of minimizing the non-linear objective function under linear constraints devised by Frank and Wolfe (1956) as summarized below.

The goal is to find the flow x_a on link a that minimizes the objective cost function z. The objective function is the sum of flow-dependent travel costs over all network links. Expressed mathematically:

$$\min z(x) = \sum_a \int_0^{x_a} C_a(u)du$$

where $C_a(u)$ is the travel cost function for link a.

The optimization problem is subject to two constraints. First, the conservation of flow:

$$D(j,s) + \sum_i x_{ij}^s = \sum_k x_{jk}^s$$

where $D(j,s)$ is the flow originating from zone j destined to zone s and x_{ij}^s is the flow destined to node s along the link connecting node i to node j. This constraint means that no flow can be lost between links. The second constraint is the non-negativity of flows:

$$x_{ij}^s > 0$$

The problem can be solved iteratively based on the following expression:

$$\min z[x^n + a(y^n - x^n)]$$

where x^n is a feasible flow vector satisfying the two constraints at iteration n and y^n is the feasible solution vector. The vector y^n is found by performing all or nothing assignment of trips based on the link travel times generated by flow vector x^n. The parameter *a* exists on [0,1] and is chosen such that z is minimized. It determines the amount by which x^n will change between successive iterations.

The process begins with an all or nothing assignment between origin-destination pairs based upon the minimal free-flow travel time yielding vector x^n. Next, the link travel times are updated to reflect the presence of traffic flow. Third, all-or-nothing assignment is performed again based upon the new link costs. The result is vector y^n. Fourth, *a* is found such that the objective function *z* is minimized. The fifth step is the setting of link flows to the values obtained through the minimization of *z* at iteration *n* and the progression to iteration *n+1*. That is to say

$$x_{ij}^{n+1} = x_{io}^{n} + a\,(y_{ij}^{n} - x_{ij}^{n})$$

Finally, the flow vectors between successive iterations (x_{ij}^{n+1} and x_{io}^{n}) are compared. If the difference between them is less than the convergence criterion, the process ends. Otherwise, the process is repeated beginning from step 2, the updating of link travel times according to flow vector x^n.

Auto travel costs are most frequently expressed in terms of travel time over a network link and, furthermore, the travel time is known to increase with traffic volumes. This relationship can be captured by a volume delay function devised by the Bureau of Public Roads (BPR), shown below.

$$t_i = t_{i0}\left(1 + a\left(\frac{V_i}{C_i}\right)^{b}\right)$$

This formula generates congested travel time on link *i* given the free-flow travel time (t_{i0}), the link volume (V_i), the link capacity (C_i) and two parameters specified according to link type and characteristics of traffic behaviour on the link (*a* and *ß*).

Most of the recent research in traffic modeling describes theoretical formulations of dynamic modeling that are ever more adept at capturing the temporal distribution of choices and activities. Static models, meanwhile, are rightly criticized for poorly representing utility-maximization theory and being unable to handle situations where demand exceeds capacity or where congestion is not continuous

(Verhoef, 1997). While dynamic models are undoubtedly better at applying the theory, there are usually no direct comparisons of results with static models when used in planning practice (Wu et al., 2001; Nagel et al., 1998; Boyce and Bar Gera, 2003). Researchers are encouraged to pursue investigations into dynamic, micro-level modeling due to the ever-increasing computing power made available. The difficulty, however, lies not with insufficient computational capabilities, but rather with insufficient data. Many large jurisdictions, such as Toronto and Montreal, have the benefit of detailed and reliable O-D surveys but other big cities – like Vancouver - do not. Global Positioning Systems (GPS) and various Intelligent Transportation Systems (ITS) tools can be used to generate enormous amounts of data on individual vehicle movement, but no efficient method of using this information as either as source data or as a validation tool has yet been found.

Modelers likely face the law of diminishing returns whereby enormous additional investment in spatial-temporal complexity will generate only marginal improvements in model quality. This is especially true when the model is used to forecast several years into the future. The fact that most transportation planners working both inside and outside academia continue to use static model frameworks such as EMME/2 is evidence of their persistent relevance (Florian, 1999; JPINT, 1998; Tremblay, 2004; Krajczar, 1998).

If static models continue to represent the norm in large-scale transportation modeling, methods of improving the static framework are of natural interest. One of the significant events in this regard is the advent of Geographic Information Systems (GIS). Since the early 1990s, enormous progress has been made in the development of GIS which offer solutions to problems inherent in the transport modeling process, including the modifiable areal unit problem (MAUP), boundary problems and spatial sampling, spatial dependency and spatial heterogeneity (Miller, 1999). Spiekermann and Wegener (2000) provide a good example of how GIS can be used to mitigate the problems inherent in the use of zone systems for transportation analysis. Furthermore, GIS allows for greater flexibility in managing data sources, can be used to construct highly detailed transportation networks and generates easily-decipherable visual output (Arampatzis et al., 2004). Also, the general user-friendliness of a GIS interface can greatly reduce the costs, in terms of both time and money, incurred in the construction of a transportation planning module (Souleyrette and Anderson, 1998; Johnston and de la Barra, 2000). Finally, as the modeling practice becomes more and more concerned with spatial and temporal disaggregation, GIS plays an increasingly important role (Frihida et al., 2002).

The importance of GIS and spatial analysis in general is most obviously apparent during the first phase of the transportation modeling process: the definition of space. The classical four-stage model requires the discretization of the study area into a set of zones. This is usually done by government agencies who define census zones based upon political and jurisdictional criteria and the resulting system is often adopted by transportation modelers to render the models compatible with census data. Some general guidelines for the construction of traffic analysis zones can be found in Ortuzar and Willumsen (1994) and Caliper Corp. (2002). Bennion and O'Neill (1994) presented nine criteria for zone system development derived from the literature. These are:

1. Zones should be homogeneous
2. Interaction between zones should be maximized
3. Zones should not have irregular shapes
4. Zones within zones should be avoided
5. The zone system should respect census boundaries
6. Political, historical and physical boundaries may be used
7. Only adjacent zones should ever be aggregated
8. Roughly equal numbers of trips should be generated and attracted between all zones
9. A maximum number of trips generated per zone should be established

In addition to these criteria, network detail should also be considered. A greatly simplified network containing only freeways, for example, will not benefit from zones defined by city blocks. Entire cities as individual zones would be better suited to a freeway network. Similarly, a very detailed network containing every street in the city would be greatly undermined by a discretization of space into large zones. GIS now permits the construction of detailed networks and the accurate spatial distribution of data, but only two studies have been done which measure the benefits of a detailed, disaggregate approach in static models. Jansen and Bovy (1982), whose work pre-dates modern GIS by nearly a decade, found that increasing network detail and decreasing zone size do indeed generate superior results, although the marginal improvement declines with increasing network detail and decreasing zone size. Tamin et al (2001) found that the zone system resolution is more important than network detail due the increase in intra-zonal trips as a result of larger zones. Intra-zonal trips are not assigned to the network and, since they do not contribute to link flows, will negatively affect the model's accuracy.

The two most important inputs for traffic assignment are link costs and capacities. Since there are no toll roads in the Montreal area, time is the only cost considered in the present model. Usual practice dictates the computation of free-flow travel times based upon the link length divided by the free flow traffic speed which can be taken as the legislated speed limit. The Highway Capacity Manual outlines procedures for determining link capacity based upon a large number of factors including the speed limit, road geometry, presence of on-street parking, lane width, intersection types, road types and traffic types. Horowitz (1991) describes a procedure for integrating the method described in the Highway Capacity Manual with the BPR function parameters.

While the procedures for calculating travel times and capacities are straightforward, modelers are often constrained by a lack of reliable data. A city of several million people will have thousands of links and intersections. Speed limits are legislated differently from district to district, each signalized intersection has a unique set of phases and cycle times, and parking regulations can vary from block to block. Simplifying assumptions are made based solely upon the type of street: freeway, collector, arterial and local. Rural highways and freeways have high speed limits, no intersections and no parking. These roads therefore are assigned the highest capacity, usually around 2000 passenger cars per hour lane (pcphpl). Collector roads feed the highways and are characterized by limited parking, few intersections and lower speed limits than freeways, all of which result in reduced capacity. Arterials are main urban thoroughfares and often have many intersections and frequent traffic signals. The capacity on arterials is therefore lower than collectors. Local roads have the lowest capacity of all due to their geometry, high intersection frequency and abundance of parking spaces. In large scale models, the local roads are usually omitted from the analysis entirely and replaced by dummy links called centroid connectors. These links are substitutes for streets that do not normally experience congestion, and are therefore assigned very high capacities to produce travel times that do not change significantly with volume. There are several precedents for determining link characteristics based upon functional class (JPINT, 1998; Horowitz, 1991; Theriault et al, 1999).

Centroid connectors are necessary due to the discretization of space required by the classical four stage model. Full sample individual data are never available, so the characteristics of the population must be aggregated into zones. Furthermore, the distribution and assignment stages are most easily accomplished using origin-destination matrices which are most efficient at a high level of aggregation. For these reasons, modelers typically develop a system of traffic analysis zones (TAZs) which form the foundation of the modeling framework.

The ultimate goal of urban transportation modeling is the completely disaggregate, dynamic framework and hundreds of papers have been published detailing new formulae and algorithms that can best represent the individual traveler’s conception of space and time. But this research remains almost entirely theoretical. While computers sufficiently powerful to implement the theory do exist, no jurisdiction has yet devised a method of collecting the detailed personal information required from millions of citizens. Meanwhile, there are only a few papers which outline, in detail, the practical considerations involved in building a traffic assignment model based upon available data.

Eames (1991) published a practical guide for the construction of a traffic assignment model. In it, he outlines important considerations such as the optimal level of detail in network representation and the prohibition of illogical movements. Eames’ work is especially valuable for its description of the numerous problems encountered during the modeling process and how they can be dealt with during the validation and calibration stages. Alan Horowitz produced a good description of the theoretical underpinnings of model traffic networks in the user manual that accompanies the GNE/QRSII software package (Horowitz, 2000). The US Department of Transportation's Travel Model Improvement Program (TMIP, 2001) provides useful procedures for validating traffic model output. This document also provides quantifiable benchmarks for acceptable model performance such as a minimum correlation between observed and forecast flows. In a similar vein, Livshits (1997) describes the type of questions that need to be asked and answered in the preparation of traffic assignment models in EMME/2.

The EMME/2 software appears frequently in the literature because of its widespread popularity among researchers and planners around the world, yet it is just one of many possible platforms for the assignment algorithm. Examples in include QRSII, Cube, ptv, SATURN and TransCAD. Of all these applications, TransCAD is unique in that it is the only one equipped with GIS capabilities which can greatly simplify the process of adding network attributes and defining zone systems. When necessary, special procedures can be coded using the GISDK language on which TransCAD operates. Researchers at Laval University were able to run a disaggregate all-or-nothing assignment model using GISDK (Theriault et al., 1999). Eventually, a similar approach could be applied to the model of Montreal roads with the addition of parameters necessary for capacity restraint and user-equilibrium.

This completes the section on the general state of current practice. The following chapters will focus on the practical issues surrounding the construction of a large-scale traffic assignment model.

3. DATA

3.1. *Census Tracts and Enumeration Areas for the Greater Montreal Area from the 1996 Census (Statistics Canada)*

The first step in any analysis of travel behaviour is to define the study area and decide how the geography it covers will be represented. The study area for the traffic assignment model was defined as the three census metropolitan areas (CMAs) of Montreal, St-Jean-sur-Richelieu and Salaberry-de-Valleyfield. Statistics Canada has many levels of spatial aggregation. The most disaggregate units are enumeration areas. An enumeration area usually has a population of no more than a few hundred people. Census tracts are made up of several enumeration areas. For the Montreal CMA, census tracts were chosen as the level of spatial aggregation. In the CMAs of Saint-Jean-Iberville and Salaberry-de-Valleyfield, no census tracts were defined and so enumeration areas had to be used. Neither census tracts nor enumeration areas make ideal traffic analysis zones and so the zone boundaries were modified during the course of the analysis to produce the system zones ultimately employed in the traffic assignment model (see Section 5.4).

3.2. *Origin-Destination Survey – Agence Métropolitaine de Transport (AMT)*

The travel behaviour data used in the Montreal traffic assignment model was taken from an origin-destination survey conducted in the fall of 1998. The survey is sufficiently detailed that the first three stages of the 4-stage model (trip generation, trip distribution and mode split) are not required.

The Montreal survey was designed by Groupe MADITUC at the University of Montreal's Ecole Polytechnique but is administered by the regional transportation authority, the Agence Metropolitaine de Transport (AMT) and the Quebec Ministry of Transport (MTQ). Undertaken during the fall of 1998, the survey contacted 65000 households which constitute a five percent sample of the greater metropolitan region. These households contained 164000 people making nearly 385000 trips. A representative from each household was asked the age and sex of each household member as well as details concerning every trip that each household member made the previous day. A trip was defined as a single individual traveling for a single purpose. Each individual trip record contains the trip purpose, a geocoded origin and destination, the time of departure and up to six modes of transport used during the trip. Appendix 1 contains all database fields and their descriptions. If multiple modes were used the respondent was asked to identify the junction point (AMT, 2001b; AMT, 2001c).

The survey is structured as a table which contains one record for each trip. Each trip is tied to an individual trip maker who is assigned a personal expansion factor based upon age and sex. Recall that each trip is defined as one person traveling for a single purpose. The expansion factor is a number that corresponds to the proportion of the population each individual represents. Because the O-D survey is a 5% sample of the population, each person could be considered to represent twenty people and the entire population would thereby appear in the survey. Due to the distributions of age and sex cohorts however, a person could represent more than twenty people or less than twenty people depending on the cohort to which they belong. By multiplying each trip record by its individual expansion factor, the same total population is achieved but with much greater representative accuracy.

The O-D survey yields information on the spatial and temporal distribution of travel behaviour in the Montreal region even before it is applied to a model. When the survey data are aggregated to the zones system, a prism map displaying the destination densities for trips made by car during the AM peak reveals that the Montreal region is polycentric (Figure 1). There are numerous zones in the central city with high trip densities, but there are some zones with extremely high trip densities in the surrounding regions as well. These zones often contain a single building or institution that generates a large number of trips and they are represented on the prism map as dark, slender columns.

When the absolute number of trips attracted is used to make the prism map, the downtown becomes indistinguishable (Figure 2). All the zones which generate large numbers of trips are located outside the central city. This does not mean that a very large proportion of trips are destined to areas outside the downtown. It simply means that some of the outlying zones attract high numbers of trips due to their large geographic area. Central city zones have been subdivided in such a way that they all generate roughly the same number of trips (see Section 5.4). This difference in trip attraction patterns between the downtown and the outlying regions is an example of the modifiable areal unit problem.

Figure 3 shows the temporal distribution of AM peak trips according to the departure time, as stated by the respondent. The chart shows that most people state their time of departure as being a multiple of 5 minutes past the hour. Most frequently, the time of departure is given on the half hour. The single most commonly stated departure time was 8 am. The temporal distribution has implications for the construction of origin-destination matrices (Section 5.6) and the validation of the model (Section 5.8).

3.3. CanMap Route Logistics – DMTI Spatial Ltd.

In addition to trip data, the assignment model also requires a mathematical representation of the transportation network. Typically, graph theory is used to build a system of nodes connected by directional links. Each link and node has variable and fixed costs associated with its use, such as travel times, tolls, intersection delays, or transfer penalties. As a basis for the network, DMTI Spatial Ltd. supplied a digital route logistics map for the province of Quebec. This detailed and geometrically accurate map displayed every street in the province, as well as other rights-of-way such as ferry routes, walking paths, cycling trails and some alleys. The tabular record associated with each link contained, among other attributes, the road segment length, the legislated speed, the street name and the street's functional class (see Appendix 2 for a complete list and description of fields). A travel time field was also included and contained values computed based upon the link's length and legislated speed. Finally, the database specified whether or not the segment was two-way (DMTI Spatial Ltd., 2002).

The functional class of each road was based more on jurisdiction than on physical attributes of the road or its surroundings. The field is not in fact designated as the functional class but is called, rather, Carto which is short for cartography. Each road segment falls into one of the following categories: freeways, primary provincial highways, secondary provincial highways, major urban streets and local roads. There are other types of segments as well. Ferry routes receive a separate classification, as do non-vehicular routes such as pedestrian and cycling paths or alley ways. All links of a given classification had common speed limits and travel times

Another important component of the route logistics data was a table listing prohibited turns. Almost all of the movements in the table are physically impossible since they represented overpasses, bridges and tunnels. No records corresponded to movements prohibited by law.

The Greater Montreal Area was excised from the provincial database. The excised region roughly corresponds to the area covered by the OD survey as well as by the Statistics Canada definition of the Montreal CMA. This street network map contained 134954 non-directional (one- or two-way) links. The distribution of links by functional class is shown in Table 2.

3.4. Number of lanes – Ministere des transports de Quebec (MTQ)

The DMTI database contained no information on road capacity. The capacity per lane could be roughly estimated using the link functional class, but the number of lanes on each link was obtained from a map of the MTQs EMME/2 network. Only actual network links were provided. Centroid connectors, centroids and all other nodes were removed from the file. EMME/2 is not a GIS program and therefore the MTQ map gives only a rough approximation of the network geography. There are no local roads in the network and the links that do appear are represented as straight lines. This network representation covered the same geographic region as the excised DMTI map and contained 26137 directional links.

A comparison of the levels of detail of the EMME/2 network and the DMTI network can be seen in Figure 4.

3.5. Observed flows on major streets – Ministère des transports de Québec (MTQ)

Validation of the assignment model requires a comparison of predicted traffic levels to observed counts. A database of Montreal-area counts for the fall of 1998 was provided by the MTQ which measured flows of class 1 vehicles (automobiles and light trucks) at 197 locations in half hour intervals during the morning rush hour. The first interval begins at 6 am and the last interval begins at 9 am.

This discussion of the various datasets to be employed in the traffic assignment model is followed in Chapter 4 by an overview of the primary software used to integrate the data.

4. SOFTWARE

4.1. Overview

TransCAD was the principal tool used to build the model. It was chosen because a functional model can be built without the use of a coding language but also, more importantly, TransCAD is a GIS program which allows the import and modification of geographic and tabular data from a wide variety of sources. GIS is advantageous because it can produce output in the form of maps and such displays are often more informative than columns of numbers or text. Furthermore, a map produced on a GIS platform is linked, by definition, to a database of attributes of map features. Each feature has one corresponding record (row) in the table, and each attribute has a field (column) in the table. This setup greatly facilitates the modification of link and node properties. Finally, TransCAD is able to process information provided by other programs such as MapInfo or Excel.

With respect to the four-stage model, TransCAD's matrix capabilities facilitate several elements of the analysis. Trip data from the O-D survey can be quickly imported into an empty matrix. External trip data can be calculated using vector multiplication in combination with conventional matrix operations. No other conventional GIS program offers these features.

MapInfo was used for parts of the analysis because of its Structured Query Language (SQL). This module allows for data aggregation independent of geography. In the O-D survey, MapInfo was useful for generating frequency tables of features such as stated departure times and number of modes used per trip.

Excel was found to be the best tool for displaying non-geographic output, such as validation tables and statistics.

The three platforms can be easily integrated. TransCAD can open unmodified Excel tables and MapInfo maps. TransCAD tables can be saved in DBF format which is compatible with Excel and MapInfo. TransCAD maps can be exported to MapInfo format as well.

4.2. Description of TransCAD and the GIS platform

A defining property of GIS is that all features represented by digital geography have modifiable attributes stored in a data table. Linked maps and tables are known as layers. Each layer, therefore, will have at least two files associated with it: one file containing geographic information, and another file for the attribute database.

There are two main types of GIS data. Raster data assign values of a single attribute to individual pixels in order to approximate continuous surfaces. Examples of raster data would include maps of ground elevations, or precipitation levels. Vector data makes use of geometry and topology to define spatial features independent of mathematical resolution. Vector data conforms to the usual conception of a map where land masses are represented by discrete areas, places are represented by points and rights-of-way are represented by lines. Interpolation methods can be used to generate raster data based upon a single attribute of a set of area vector data. For example, the population density of census zones can be converted into a continuous density surface in raster format. The elements of the traffic model were based on vector data. Occasionally, raster representation was used to generate graphical output of certain analyses in MapInfo. TransCAD cannot produce raster data from vector data.

A layer of vector data can be either a point layer, a line layer, or an area layer. One of the more powerful features of a GIS program is its ability to overlay layers one on top of the other. For example, an area layer such as the jurisdictional boundaries of a city can be overlaid with a line layer of city streets. The overlaying process can then be used to compute aggregate statistics such as the road density in each zone, or the number of zones that lie within a given distance of a highway and so on. This type of spatial analysis was essential in the construction of the traffic model.

Another GIS tool that was frequently used to set up various model components was a process called “tagging”. The tagging procedure allows the attributes of one layer to be copied to an overlapping layer. The most common example is when features in a point layer are given attributes of the polygon (in an overlaid area layer) that contains them. Tagging can also be used to aggregate data to the polygon level. For example, the computer can count the number of features in a point layer that are contained within each polygon and attributes of the points can summed or averaged and the computed values assigned to the parent polygon.

Joining tabular databases is a third capability of GIS programs. Often, a geographic database has a corresponding set of non-geographic data. The census is a good example of this. The electronic versions of the census zone maps are separate from the enormous data files that describe the populations of those zones. Recall that a GIS map has an associated table with a record for each attribute. So as long as the table associated with the map of census zones has a field containing a unique identifier for each zone (such as a census tract name) and the data table uses the same identifiers, then the map table can be joined with the statistical database.

The overlay and tagging tools are common to all GIS platforms, but additional functions are needed for transportation systems analysis. In TransCAD, each line geographic file is automatically furnished with three fields. The first field is labeled “ID” contains an identification number that is unique for each line. The second field, “Length”, contains the length of each link in units specified by the user. The third field, “Dir”, describes the link direction. This field can have one of three possible values: -1, 0 or 1. A value of 0 indicates that the flow on the line can travel in either direction. A 1 indicates that the flow can only travel in the direction in which the link was drawn (the topological direction). A -1 indicates that the flow must travel in the reverse topological direction.

In TransCAD, layers are called geographic files and carry the .dbd extension. The data table associated with a geographic file is stored as fixed-format binary and carries the .bin extension. TransCAD will recognize tabular data of various formats. Line layers by default have a layer of endpoints associated with them and this endpoint layer has its own data table. Therefore a single line layer will have four principal files associated with it. In fact, several additional files are created by TransCAD so that a line layer geographic file will actually be a collection of ten or more files. With the rapid multiplication of file extensions, good data management is important.

Chapters 3 and 4 have summarized the software employed as well as the base data which were acquired in order to build the Montreal traffic assignment model. The next chapter will discuss how these data were integrated and elaborated in the modeling process.

5. METHODOLOGY

5.1. Overview

The traffic assignment model was built using an iterative improvement process. An initial version had to be constructed in order to test assumptions and to find errors. Common errors, as opposed to systematic errors inherent to the algorithm, were found in either in the road network or the zone system. The creation, detection and correction of network errors are described in Section 5.8. After a model was run, the output would be examined and the existence of errors investigated. Corrections would be made, a new model version would be compiled, and the process would be repeated (see Figure 5).

Each new version, therefore, had slightly different zone systems and network geometries and attributes. While the network construction and error detection processes are detailed at length, only the properties of the latest version are described below.

5.2. Defining Capacity

Volume-delay functions require link capacity and link free-flow travel time as input. The travel time was already provided in the DMTI data, but there was no information on capacity. The first step in imputing the capacity was to assign the correct number of lanes to each link and this information was available in the skeletal EMME/2 network provided by the MTQ.

Integration of the two data-sets presented a challenge. While the DMTI map was very precise and intricate, the EMME/2 network was only geographically approximate. The DMTI map contains a great deal more links - many of which are curved - and all the EMME/2 links are straight lines. A third discrepancy between the data sets was in the representation of one-way and two-way links. All links in EMME/2 are one-way and so a two-way street is shown as 2 parallel links flowing in opposite directions. The DMTI network, meanwhile, usually represents 2-way streets as single links flagged as being bi-directional. Boulevards are represented as pairs of anti-parallel links. As a result, the geographic correspondence between the two maps was poor and so no automated procedure could be used to append the lanes data to the DMTI table. The lanes data had to be added manually, link by link.

The EMME/2 map was segregated into different selections depending upon the number of lanes belonging to each link. The largest number of lanes on any link in the network was 5 and so four selection sets were made: one for each number of lanes from 5 down to 2. All remaining links were assumed to have single lanes either according to the MTQ's coding or by virtue of the fact that such streets are too small to be included in the MTQ's model. Each selection of links was overlaid with the DMTI network and the links were compared individually. EMME/2 links that were not selected were made invisible. All DMTI links that corresponded to the visible set of MTQ links were selected by hand. Once the corresponding links for a stretch of road had been the selected, they were assigned the appropriate number of lanes. In this manner each of the four lane categories were dealt with one by one. Links with 5 lanes were completed first, followed by the four-lane links and then the three-lane links and so on. Table 3 shows the links in the EMME/2 and DMTI network classified by number of lanes.

Often, single DMTI links would correspond to anti-parallel pairs of EMME/2 links and so the DMTI data table had to have a separate field for the number of lanes in each direction. The field containing the number of lanes for the topological direction was labeled Lanes_AB and the field containing the number of lanes in the reverse-topological direction was labeled Lanes_BA. The AB/BA designation is recognized by TransCAD as indicating pairs of directional fields.

Initially, MapInfo was used to assign lanes to the DMTI network but TransCAD was soon adopted as the preferential tool due to the latter's ability to display directions. TransCAD can draw arrows on links to show either the designated direction of flow or the topological direction. This feature was useful in deciding the field - BA or AB – to which the lane information would be assigned. The number of field records updated correspond to the number directional links in the network. In total, 18429 directional (one-way) links in the DMTI network were updated in this manner. The remaining 227209 directional links were assumed to be 1 lane in each direction and were updated automatically.

TransCAD was more ideally adaptable to this type of work than was MapInfo. Updating columns in MapInfo requires the user to click on the menu bar, choose the "Update column" option, specify the table and the selection of records to be modified and indicate the value or expression to be assigned to the records. TransCAD, by contrast, displays different selection sets in the same window. The user has only to select the set to be modified, right-click on the target column, select the "Fill" option and indicate the value to assign to the field of the selected records.

Once each link had been assigned the correct number of lanes, a lane capacity had to be determined. Lane capacity was measured in passenger cars per hour per lane (pcphpl) and was taken as being equal to the ultimate lane capacity corresponding to level-of-service E, as recommended by Horowitz (1991).

The method of assigning lane capacity was far from optimal. For the first version of the network, the capacities were assigned globally according to link functional class. A much better method would incorporate data specific to each road segment such as the existence of on-street parking, the lane width, the speed limit, road geometry, and intersection capacity as outlined in the Highway Capacity Manual. Intersection capacity alone requires a detailed database describing the signage or signal systems. Since none of this data were available for the entire Montreal region, a global method was adopted. Links were assigned an ultimate capacity based upon their functional class (see Table 4). The TTS network coding manual (JPINT, 1998) was used as a guideline.

DMTI's road classification system was based more upon jurisdiction than on the surrounding environment or physical characteristics of the road itself. For example, Sherbrooke and Saint-Denis streets both fall under provincial jurisdiction and are officially designated as highways. As such, they were assigned the cartographic code corresponding to provincial highways as well as the corresponding speed limit and capacity. On the island of Montreal however, neither of these streets have the functional characteristics of highways. They are regular urban arterials. Therefore, the link properties of these streets were adjusted accordingly and a new Carto code of 50 was used to identify them as provincial highways re-classified as urban arterials. Several streets in the region fell into this category. Some of these streets, such as the primary provincial highway Taschereau Blvd. on the South Shore, are difficult to assign to a single functional class. Taschereau Blvd. is a divided suburban road with fairly long intervals between signalized intersections. Along some stretches it resembles a suburban multi-lane highway and in other locations it resembles an arterial road. The Carto code of Taschereau Blvd was therefore varied with location. In some places it was assigned a 2, in others a 3 and so forth.

The maximum link capacity corresponding to level of service E is recommended for optimal performance of the BPR function (Horowitz, 1991). While this volume was estimated for most roads as described above, it could also be measured using the MTQ’s roadside counts on links with observation posts. The procedure was as follows:

First, the total flow for each hour in the AM peak period was calculated on all links for which data were available (199 directional links). An hour of flow was considered to be any two consecutive 30 minute periods. There were seven thirty minute observation periods in the dataset and therefore six observation hours (0600-0700, 0630-0730, 0700-0800, 0730-0830, 0800-0900 and 0830-0930). The highest hourly flow observed during these six hours was divided by the number of lanes on the segment to obtain the volume per lane. The 199 links were then sorted according to volume per lane, from highest to lowest. The 20 or so links with the highest observed volume per lane were assigned this value as their capacity.

For example, the link with the highest observed hourly flow rate was the inbound Jacques-Cartier Bridge over which passed 7838 vehicles during the period from 0730 to 0800. The inbound Jacques-Cartier Bridge has 3 lanes of traffic, resulting in an hourly flow rate per lane of 2613. Therefore, the ultimate operating capacity of the bridge must be at least 2613 veh/hr because this number of cars per lane was observed traveling over the bridge during a single hour. Furthermore, it is assumed that the capacity of given road segment is the same in both directions, so a value of 2600 vphpl was accorded to both the inbound and outbound lanes of bridge. The Jacques-Cartier Bridge caries a provincial highway and is located only a few kilometres from the downtown core. If its capacity were assigned solely according to functional class and location, a value around 1200 or 1500 vphpl would be used which is clearly incorrect. Such situations make clear the pitfalls of the global approach to assigning capacities.

The method applied to the Jacques-Cartier Bridge could be used on most other inbound bridge links because these links are likely operating at or near capacity. In fact, any link where an observed hourly flow was higher than the capacity designated according to the road functional class had its capacity increased to this observed value. While the observed rate of flow may not be the actual link capacity, it has to be a better estimate than the lower value. As such, the capacities were adjusted on a few arterial links where observed flows exceeded 900 vphpl.

The link capacity was never reduced according to values yielded by this empirical method, even if the link in question was known to be congested. For example, the eastbound Autoroute 40 in St-Laurent is known to be heavily congested, but the peak hourly flow observed was 1679 vphpl. It is possible that this is the actual capacity of the freeway in this region, but it is also likely that the demand exceeds capacity and the segment is operating under forced flow conditions at a flow rate much lower than the maximum. There is no way to be certain which scenario is the right one, so the link capacity remains the global value for a freeway which is 1900 vphpl.

5.3. Adding link directions

The DMTI street map came with a Oneway field identifying whether or not a street is one-way. The field contained a 0 if the street was two-way and a 1 if the street was one-way. A second field, called Road_dir, indicated which direction the traffic flows if the street is 1-way. The Road_dir field was in character format and could take one of two possible values: “FT” or “TF”. “FT” referred to “from-to” which indicated that the traffic flow was the same as the topological link direction. “TF” indicated flow in the reverse topological direction. These fields were integrated with TransCAD’s direction field by updating it according the values in the Oneway and Road_dir fields. Initially, it was found that all one-way streets in the DMTI network were labeled “FT” meaning they were one-way in the topological direction and would receive a 1 in the

Dir field. Over the course of the validation process, however, approximately 300 links were found to be incorrectly labeled.

5.4. Zone system development

Spatial definitions are an important component of any urban transportation model. For the present model, four criteria for the zone system were devised based upon the recommendations in the literature (Bennion and O'Neill, 1994; Ortuzar and Willumson, 1994; Caliper Corp., 2002):

1- The system must be mutually exclusive and collectively exhaustive. In other words, the zones must not overlap and must entirely cover the area under study.
2- The system must respect the boundaries of existing census tracts. This condition was imposed in order to facilitate linkages between model data and demographic data contained in the census.
3- Trips must be distributed evenly throughout zones. Zones generating or attracting exceptionally large numbers of trips will result in large assignment errors because trips whose ends are distributed throughout the zone will be aggregated to a single point.
4- The system must be optimally disaggregated. While the zones must be small enough to provide reasonable spatial resolution, they must not be so small that many thousands are required to cover the study area. A ten thousand zone region will generate a matrix of 100 million cells. Even if this matrix were to be filled with all the valid trip records in the O-D survey (the case of a 24 hour model), at most 385000 – only 0.4% of all cells – would be filled.

For the Montreal region, the study area was initially taken to be the consolidated metropolitan area (CMA) of Montreal as defined by Statistics Canada in the 1996 census. The AMT's O-D survey assigned trip ends to 1996 census tracts. Closer examination of the trip data revealed a large number of trip ends outside the boundaries of this region and so it was decided to include two additional CMAs: Saint-Jean-Iberville and Salaberry-de-Valleyfield. With the resulting zone system of 873 zones (see Figure 6), the first criterion was mostly satisfied although some trips in the O-D survey began or terminated outside these 3 CMAs.

The analysis of the trip end distribution was confined to destinations but included trips for the entire day, not just the morning peak period. This was done to ensure that the zone system could be applied to the simulation of any single hour during the 24 hour period. Furthermore, the inclusion of all trips meant that it would not matter whether origins or destinations were used as the trip ends since the origin-destination matrix is approximately symmetrical over 24 hours.

When destinations were aggregated to the zone level, some zones contained significantly more destinations than the average. Under the initial TAZ boundaries, the average number of trips attracted was 8935 trips per zone. The standard deviation of attracted trips was 7039. Therefore, the few zones that attracted no trips were just beyond one standard deviation from the mean. The largest recorded value however, was 55718 - more than six standard deviations from the mean. Such a distribution is problematic because it results in a very unrealistic assignment of traffic. The zone with the largest number of attracted trips was the central business district. Because few people live in this area, the census tract being used as a traffic analysis zone was quite large with an area of 0.82 square kilometers. As a result, trips that were meant to be spread out over this considerable expanse were all being drawn to a single centroid.

To tackle this problem, a clustering method was used. The x-y coordinates of each trip destination was used to map these destinations as visible points. TransCAD could then group these points into clusters according to their spatial distribution. The procedure was as follows: First, the original census tract layer was superimposed over the point layer of trip destinations. Second, a zone containing a large number of destinations was selected. The zones were sorted by the number of destinations they contained to ensure that zones attracting the largest numbers of trips were dealt with. Third, the destination points contained within the selected zone were isolated. A distance matrix was constructed based upon the Euclidean distance between all destinations in the zone. The clustering tool uses this matrix to group trip ends together into a user-specified number of clusters. Each group of points is assigned a colour. Based upon the visual display of the groupings, the user can draw new zone boundaries (see Figure 6). The new zones would correspond exactly to their parent census tract if merged.

Large point generators, such as shopping malls, universities, colleges and office towers were often identified with this method. They would appear as clusters of a single point, but would in fact be many trip destinations super-imposed on top of each other.

The CMA of Salaberry-de-Valleyfield was not subdivided into census tracts but rather into smaller enumeration areas. Since most enumeration areas were too small to generate a significant number of trips, some of them were merged in order to produce sufficiently large zones. The method of merging zones was ad hoc, but was done with due consideration for the distribution of trip ends and the layout of the road network.

The end result of this exercise was an improved distribution of trip ends. In the final zone setup, the mean number of trips attracted was 8417 and the standard deviation was 4549. The minimum number of trips attracted to a zone was still zero, but the maximum was 23839, roughly three standard deviations from the mean.

The final zone system contained 947 zones with a corresponding O-D matrix comprising 896809 cells. One-hour O-D matrices based on this system will be sparsely populated: if the simulation hour fills 10000 cells, about 1% of the matrix is not empty. This situation is inefficient but at least the spatial distribution of origins and destinations has been improved.

Once the zone system was finalized, each geocoded trip end and junction point was tagged with the ID number of its parent zone. A few trips either began or ended outside of the region defined by the three CMAs of Montreal, Saint-Jean-Iberville and Salaberry-de-Valleyfield. These trips were not included in the model (refer to Table 1).

5.5. Construction of the network

Traffic assignment models in TransCAD require the construction of network files. A network file is a digital representation of a line network as a series of nodes and directional links. The network file cannot be displayed but its functionality can be tested using a visual tool that displays the shortest path between any number of points selected by the user.

When a network file is built, the user is asked to provide a set of links in a line layer that will form the basis of the network file, as well as link attributes to be included in the network. For the term "shortest path" to have any meaning, each path must have defined costs to provide a basis for comparison between routes. Two obvious costs are segment length and travel time. Segment length is generated by TransCAD automatically in the Length field. Travel time must be calculated according to the speed on the segment. The DMTI road network contains both a speed and travel time field but due to the discrepancies in classification methods (see Section 5.2) as well as subsequent adjustments to speeds along certain links, travel time was recomputed as the length divided by the specified speed.

Capacity is the other vital link attribute in traffic assignment models. The process of assigning capacity to each link is described in Section 5.2.

Additional line layer attributes were incorporated into the network file. The BPR volume- delay function has two parameters, alpha and beta, which vary between segments according to the roads' functional class and free flow speed. The present model is based upon parameters estimated by Horowitz (1991) – see Table 5. Horowitz did not provide an estimate for global parameters on urban roads operating under interrupted flow conditions because factors other than the volume-to-capacity ratio – such as signals and intersection characteristics – affect the link performance. Nevertheless, global values were required and were estimated ad hoc: alpha was taken to 0.6 and beta was taken to be 2 based on the trends in parameter variation by road functional class (see Table 5).

The Carto field was also included in the network to allow the disabling of certain classes of links, such as trails or ferry routes. When links are disabled in the network file, they are not included in any calculation of shortest paths, and therefore are not considered in the assignment model.

Before the network file can be built, the line layer upon which it is based must be finalized. Any change to link geometry or connectivity, such as the addition of new links or nodes, requires the construction of a new network file. The DMTI network, in its original form, contained numerous small errors and inaccuracies. The largest and most obvious omission was the Ville-Marie tunnel which carries the Ville-Marie expressway underneath downtown. Two important features of the tunnel were missing. Firstly, the tunnel does not run in a straight line between its two portals but rather curves southward and then curves northward to return to its original axis (see Figure 6). Secondly, the tunnel is actually an underground interchange between the Ville-Marie expressway and the Bonaverture expressway. In the original DMTI network map many of the ramps connecting the two highways were either missing or had been classified as trails rather than functional roads. Most network errors however were not as obvious as this one. Missing links, improperly connected streets and streets with the wrong flow directions were much harder to detect.

Street geometry is one important element of the network. Another important element is turning restrictions. The DMTI map was accompanied by a .dbf table that listed prohibited turning movements. These prohibitions apply to specific intersections or nodes and are referred to as specific turn penalties. Global turn penalties - which apply to movements at all nodes not governed by a specific turn penalty - are discussed below. According to CanMap Route Logistics manual, the table includes both legislated restrictions and physical restrictions (DMTI, 2001). Although the database does contain a field indicating the time of day during which the restriction applied, no legislated restriction could be found among the records representing Greater Montreal. All the listed turn prohibitions in the region were due to the physical configuration of roads such as underpasses, tunnels, bridges and flyovers.

In order to apply these specific turn penalties to the TransCAD network, the table provided by DMTI had to be translated into a format recognizable by TransCAD. TransCAD reads turn penalties from a table that has a standard form. The table has three columns. The first column is labeled “From” and holds the link ID number from which the movement is made. The second column is labeled “To” and contains the ID of the destination link. The third column is labeled “Penalty” and contains a value that represents the movement penalty. A positive integer indicates the cost incurred for traveling from the origin link to the destination link. The penalty cost must have the same units as the cost that is to be minimized in the shortest path algorithm. For the traffic assignment model, the cost is in terms of minutes. A zero in the “Penalty” column means that there is no penalty. If the “Penalty” field is blank then the movement is prohibited.

The original DMTI table contained only movements that were physically impossible. Intersection delays, as opposed to prohibitions, need to be calculated based on signaling and traffic levels. The DMTI table had a field for each origin and destination link but the link IDs were those conceived by the cartographers at DMTI. These IDs were not the same as the ID numbers automatically assigned by TransCAD and only the TransCAD IDs would be recognized in the functional turn penalty table. A join was used to replace the DMTI IDs with TransCAD IDs. The original turn penalty table was joined to the table of road network segments based on the DMTI IDs. The TransCAD IDs were then copied into a new column in the original turn penalty table. This process was done twice: once for the origin links and again for the destination links.

In the absence of signal and signage data, the turning delays at intersections could only be estimated and applied globally. A penalty of 0.5 minutes (30 seconds) was applied to all left turns. Right turns received a global penalty of 0.2 minutes (12 seconds) and straight movements through intersections were assigned a delay of 0.05 minutes (3 seconds). U-turns were prohibited. These settings are improvisatory although there is at least one precedent for their global application (Theriault et al, 1999). It is preferable to have estimates of intersection delays rather than no delays at all. In addition, the absolute delay values are less important than their relative values. Very generally, it takes less time to make right turn than to make a left turn and a vehicle’s progress through an intersection will likely be fastest if it does not have to turn at all. U-turns, meanwhile, are usually illegal and even if they are permitted they are difficult to undertake in heavy traffic.

The next step in the network construction process is production of centroids and the dummy links that connect them to actual network. These dummy links are called centroid connectors. Centroids are points in the geometric centre of their parent zone. TransCAD can connect centroids to the network without first generating a geographic file of centroid points. The program will simply build centroid connectors from the zone’s geometric centre to the nearest network node if the user chooses to make centroid connectors using the automated procedure. Zones can also be connected manually. The manual method is undoubtedly superior since the automated process affords the user very little control over how centroids are connected. In the interests of saving time however, the centroid connectors in the Montreal model were built using the automated procedure. The user can specify the set of network nodes to which connections are to be made, the number of connections per centroid and the maximum connector length.

Centroid connectors are supposed to substitute for local roads. Therefore, they should not connect directly to highways or highway access ramps but rather to collector streets or local roads. TransCAD’s GIS capabilities were used to select those nodes that were not connected to highways or ramps. Only nodes in this set would be considered as candidates for connections to centroids. To reduce the likelihood of u-turns being required to enter or leave the road network, 2 connections per centroid were specified. The road density was sufficiently high that no limit needed to be set on centroid connector length.

Once constructed, the centroid connectors were assigned a Carto code of 100. The speed was set at 40 km/h – the same as for local streets. The travel time over the link was simply the length divided by the speed. Finally, each centroid connector was assigned a capacity of 99999 vehicles per hour since congestion delays should not occur on fictional links. It is also important that there be no through traffic over centroid connectors because the links do not exist in the real world. For this reason, the centroid points have to be identified as such in the network file. To do this, TransCAD asks the user to specify a selection of nodes as centroids.

After the connectors have been built, it is important to check that the connections are logical. The most likely type of error in this regard is the connection of island centroids to mainland streets. One other example is that of Dorval airport which, because of the high number of trips it generates, is a zone unto itself. There is only one road that can be used to reach the airport, but the automated connection procedure built a link to an arterial road several hundred metres distant. Errors such as these must be corrected.

Finally, before any shortest path model can be run, non-functional links must be de-activated. These links are selected based on their Carto field values. Recall that the Carto field was included as a network attribute. This selection of links was disabled.

5.6. Construction of origin-destination matrices

In TransCAD, a matrix must be constructed based upon a geographic file. In this case, the geographic file is the set of trip generating nodes (centroids and external trip generators). The row and column index numbers must have the IDs of the trip generating nodes.

The matrix is empty when initially built and has to be filled with trip data. This was done by extracting the relevant trips from the origin destination survey. For an AM peak car traffic model, only trips made by car whose departure time was given as being after 5:59am and before 9 am were extracted. These trips were in turn separated, based on the stated departure time, into the three hours that make up the AM peak period: 6:00-6:59, 7:00-7:59 and 8:00 to 8:59. A separate O-D matrix was used for each hour.

Recall that the O-D survey defines a trip as an origin-destination pair completed by one person traveling for a single purpose. Therefore, a trip could consist of multiple modes. Six numerical fields exist in the survey to describe the sequence of modes used. If the trip contained multiple modes and one of these modes was public transit, one of the mode fields would contain the number 17 which designates a geocoded junction point. For example, a trip initially made by auto-drive (mode code 1) and completed by commuter train (mode code 8) would have the first mode field filled with a 1, the second mode field filled with 17 and the third mode field filled with an 8.

The six numerical mode columns in the survey were merged and converted to a single string field which served to enumerate the mode sequence for each trip. The above example would yield a "mode string" coded as follows: " 1 17 8 0 0 0 "[1]. All trips whose mode string contained a " 1 " but did not contain a " 17 " were imported into the O-D matrix with their origin and destination zone fields corresponding,

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[1] The spaces before and after each number are essential in order to differentiate 1 (auto-drive) from other mode codes that start with 1 (like junction points: code 17).

respectively, to row and column index numbers. If the trip mode string contained a " 1 " followed by a " 17 ", the origin zone ID would be the row index and the junction zone ID would be the column index. Similarly, if the mode string contained a " 17 " followed by " 1 ", the junction zone ID would be the row index and the destination zone ID would be the column index. There were no trips where the junction code was separated from the auto-drive mode by an intermediate mode.

An obvious problem with this methodology is the aggregation of junction points to zone centroids. Junction points are usually metro stations, commuter train stations or regional bus terminals. There are roughly 100 such points in the Greater Montreal Area. Each junction point will eventually be its own zone but in the current version they have not yet been added to the zone system and corresponding matrix.

The existing matrix index numbers are the ID numbers of centroid nodes in the network map. The trip origins and destinations are indicated according to the zone ID numbers. A correspondence therefore had to be made between the centroid IDs and the zone IDs. This was done by adding a second indexing system to the O-D matrix. Since the matrix is based on the node geographic file, a new field was added to the node table and each centroid node was tagged with the ID of the zone it represents. TransCAD can construct new row and column indices for the matrix once the node IDs and zone IDs both exist in the base table. After the zone ID indexing system is in place, it becomes possible to import the survey data into the matrix.

Once each trip had been assigned an origin and destination zone (see Section 5.4), it was a simple matter to import the appropriate trip records into the matrix file and sum the expansion factor of each into the appropriate cell to get a representative O-D matrix.

An important component of the transportation demand is not captured by the origin-destination survey. Because the survey collects data from residents of the Greater Montreal Area, external trips – which originate and/or terminate outside the region – are neglected. Yet the effect of these trips on traffic flow in the city cannot be ignored. External trips add to the congestion on the road network and therefore will influence shortest path routings. Some means of estimating these trips was essential and the method employed here involved using roadside counts at observation posts provided by the MTQ. Among the sites included in the database were locations at the regional periphery along the freeways and important provincial highways that radiate out of Montreal. There were 34 such sites in total. Each of the observation posts measures directional traffic volumes and for all posts, the direction of flow was labeled either as “inbound” or “outbound”. The “inbound” label applied to flows heading toward downtown Montreal and the “outbound” label applied to flows heading away from downtown. For each observation link, a node connected to that link was selected as a trip generator. If the link in question was flowing inbound, the node would produce trips. If the link flowed outbound, the node would attract trips. In the inbound case, nodes upstream of the counting stations were used while nodes downstream of counting stations were used to generate outbound traffic. These generator nodes were already connected to the highway or free links and therefore no connecting dummy links were required.

Nodes that produced trips to be injected into the network (inbound) were assigned a number of trip origins equal to the volume of traffic observed by the MTQ at the observation post just downstream. Similarly, generators that attracted trips out of the region (outbound) were assigned a number of trip destinations equal to the flow of traffic at the observation post just upstream. The number of inbound trips was the volume observed during the hour being modeled – 6:00 to 7:00, for example. The number of outbound trips was taken as the volume observed during an hour-long period beginning 30 minutes after the model hour. So for the 6:00 to 7:00 model, the volumes would be tallied for the period from 6:30 to 7:30. This arrangement is to account for the fact that inbound trips are entering the study region at the time they are observed passing the inbound counting station. Meanwhile, outbound trip makers have already been traveling on the network for some time, and should reach the regional periphery only after an appropriate time lag.

These external trip generating nodes were included with centroid nodes as the geographic basis for the O-D matrices, resulting in a 981x981 matrix. The next step was to fill the cells corresponding to each generator with trip data. Therefore, all trips originating at an inbound trip generator had to be assigned destination nodes and all trips terminating at an outbound generator had to be assigned origin nodes. Two different methods were used to accomplish this.

In the case of both methods, the inbound and outbound trips were assumed to originate and terminate, respectively, somewhere within the study region. The number of through trips made by car during the AM peak is assumed to be negligible although this assumption has not been verified. In the first method, missing trip ends were assigned based on the distribution of travel demand in the O-D survey. For each inbound trip generator, the destination trip ends were assigned to zone centroids proportionally. If, for example, a centroid attracted 0.02% of all trips made during the hour captured by the O-D matrix, then the same centroid would attract 0.02% of all trips injected into the network by each generator.

The second approach used the same basic principle, but employed a gravity model to account for the declining probability of travel demand between nodes increasingly far apart. The gravity mode took the following form:

$$T_{ij} = \frac{O_i D_j f_{i \to j}}{\sum_{j=1}^{n} D_j f_{i \to j}} \quad \text{(5.1 – for distributing destinations)}$$

or

$$T_{ij} = \frac{O_i D_j f_{i \to j}}{\sum_{i=1}^{n} O_i f_{i \to j}} \quad \text{(5.2 – for distributing origins)}$$

where

$$f_{i \to j} = \exp\left[-0.5 \left(\frac{t_{ij}}{t_{\max}} \right) \right]$$

t_{ij} is the travel time (in minutes) between zone i and zone j.

t_{max} is the threshold travel time beyond which travel demand is unlikely (calibrated)

O_i is the number of trips originating in zone i

D_j is the number of trips destined to zone j.
T_{ij} is the number trips traveling between zone i and zone j.

When inbound trips are being generated, equation 1 is used to distribute the trips to destinations throughout the region. Only *centroid* nodes are included as being possible destinations. Other generator nodes are not considered. Similarly, equation 2 is used for outbound trips which are distributed among centroid origins. This was done to avoid an iterative distribution algorithm but it means that through-trips must be neglected.

This particular impedance function, developed by Guy (1983) to measure transit accessibility, was later found to have a very good correlation with observed trip lengths (Spurr, 2004). The incorporation of a threshold travel time is derived from the theory that the length of most trips on the network does not exceed a maximum value. This value, which varies from city to city, is difficult to quantify but is based on the assumption that most trips are less than 45 minutes in length. A value of 30 minutes was used for t_{max} for outbound trips and a value of 15 minutes was used for inbound trips. Different values may produce better results. The calibration process in ongoing.

The gravity model approach generated flows that fit slightly better with observed values compared to the proportional distribution method, but further calibration will be necessary. TransCAD's matrix-handling abilities were found to be especially efficient in this regard. Data can be easily transferred from tables to matrices and back again. In addition, the matrix indexing tools allow regions of the matrix to be isolated. In this way, the peripheral rows and columns which represent external trips can be modified without changing the survey data in the rest of the matrix.

5.7. The traffic assignment model

The user-equilibrium traffic assignment model requires several inputs. First, the line geographic file representing Montreal-area streets must be open. Secondly, the network file that is based on this line layer must be active. Third, the network must have all the appropriate settings applied, such as turn penalties and centroid nodes marked as such. Fourth, the network must contain the appropriate attributes of capacity, free flow travel times, and alpha and beta parameters according to link type. Finally, an O-D matrix for one hour of the AM peak period with the index numbers corresponding to centroid or generator node IDs must also be open.

The present model uses the deterministic user-equilibrium method with the standard BPR function to describe the relationship between link volumes and travel times. The algorithm is iterative and approaches the optimal solution incrementally. The incremental change is expressed as a percentage of the value of the objective function from the previous iteration. This percentage is called the relative gap. Since the optimal solution is approached, but never actually achieved, the user must specify a maximum value of the relative gap that will represent convergence. In this case, the convergence criterion was specified at 1%. In addition, the user can specify a maximum number of iterations, after which the algorithm will stop regardless of whether or not convergence is achieved.

Using a Pentium 4 processor, each iteration takes 4 to 5 minutes and the number of iterations required to reach convergence varied between 5 and 12, depending on the travel demand during the hour in question. Interestingly, the hour with the lowest travel demand, between 6 and 7 am, ran for 8 iterations. The third hour, where interzonal travel demand was about 70% higher, ran for only 5 iterations. This is due to the fact that trips in the first hour were longer on average and made greater use of high-capacity routes which were more likely to be congested.

The model generates text output and fixed-format binary output. The text output is displayed in Notepad and describes the performance of the model. The relative gap at the end of each iteration is listed as well as the maximum flow change and the root mean squared error (RMSE). Also included are the name and location of all the input and output files, the network fields used in the assignment model, the number of non-zero origin-destination pairs and the total travel demand. The notepad output from the three assignment models is included in Appendix 3.

The fixed-format binary output is a table with one record for each link in the line layer. In addition to the link ID numbers, the table has fields describing the traffic flow, the traffic speed, and the volume-capacity ratio (see Table 6 for description). This table can be joined to the line geographic file to create a thematic flow map displaying traffic volumes and the level of congestion represented by the volume-to-capacity ratio (see Figure 8). Records can be extracted from this table to allow comparisons between predicted flows and observed flows.

5.8. Validation and adjustment of the model

Overall model performance is evaluated based upon comparisons between predicted and observed flow on those links for which there are observation data. The observed flow data provided by the MTQ contained 197 observation posts, each one corresponding to a single directional link. In order to make efficient comparisons and rapidly generate performance statistics, a template table had to be constructed.

The first step was to select links in the line layer that corresponded to observation posts. Some of these links were bi-directional, and had to be flagged as such. A column was added to the MTQ observation post database indicating the ID number of the corresponding link. A second field indicated whether the forecast flow was in the AB or BA direction. A third field – left blank for the time being – was created to hold the forecasted directional flow along the link. A fourth field was created and filled with the observed flows for the given hour. Two additional fields were added to flag links as either bridges or freeways. These designations would prove useful in subsequent error checking procedures. The expanded data table served as a template for the validation of each trial run.

The numbers used for the observed flows were the sum of volumes for two consecutive half-hours, the first one beginning 30 minutes after the start of the hour described by the O-D matrix. For example, flows generated by the 6:00 am to 6:59 am matrix were compared to counts observed between 6:30 am and 7:30 am. This time lag was necessary to account for the period between the stated departure time, and the time when the trip maker crosses the link in question. While this is not an ideal way to deal with the temporal dimension of travel demand, trials revealed that the correlations between predicted and observed flows are consistently higher when the time lag is accounted for.

For each modeling attempt, the template table of observed flows was joined to the table of model output according to the link ID numbers. Those records with flow in the BA direction were selected and the observed flow field for these records was filled with the values BA_Flow field. Then the remaining records have their observed flow field filled with the values in the AB_Flow field.

Once the validation table was filled with the requisite data, several statistics could be computed. The first is the percentage error which is simply the difference between observed and predicted counts divided by the observed counts. In general, the predicted flows were expected to be lower than the observed flows, especially when aggregated over all the observation posts. While it is possible for the O-D survey to under-represent the population, it in unlikely that it is over-representative in the aggregate. The detailed nature of the street network was expected to provide many alternate paths and thereby reduce flows over some routes.

The next statistic that can be computed to measure performance is the percent root mean squared error (% RMSE). It is expressed as follows:

$$\%RMSE = \frac{\sum_j \frac{(x_j - y_j)^2}{\sqrt{n-1}}}{\frac{\sum_j y_j}{n}} * 100$$

Where x_j is the forecast flow at j

y_j is the observed flow at j

n is the number of observations

This is an aggregate statistic which measures the performance of the model as a whole, comparing forecast flows to observed counts. The U.S. Department of Transportation's Travel Model Improvement program recommends a %RMSE of less than 30 (TMIP, 2001).

Finally, a linear regression model was employed to measure the correlation between forecasts and counts. Ideally, the intercept of the linear function should be zero and the slope of the line should approach 1. The USDOT recommends a region-wide R-squared of at least 88% (TMIP, 2001.).

After the level of performance had been assessed using the above statistics, an error investigation began. One major potential source of error lies with the O-D matrix and its validity was checked immediately following a trial run using visual inspection and the text output of the assignment procedure. The matrix should display an expected level of travel demand and this demand should be equal to the total demand expressed by the appropriate records in the tabular survey data.

The first level of assignment error-checking was accomplished using the flow map built from the data in the fixed-format binary output. The flow map is a combination of two thematic map types: a colour theme, and a scaled symbol theme. Each link is assigned a colour based upon its volume-capacity ratio and a width based upon its hourly volume (see Figure 7). Serious network problems were apprehended by looking at this map. For example, a link on a major highway may have had no colour and only a hairline width, indicating that there was no traffic on that link. Such occurrences suggested either there is no access to this link due to an error in digital representation, or the link had faulty attributes that rendered alternative paths less costly.

The flow map also displayed illegal traffic movements. These were especially common on bridges and freeways where access was limited. If traffic was jumping onto overpasses instead of using ramps, it would usually be apparent in the flow map. These problems could be corrected by adding turn prohibitions to the turn penalty table. TransCAD provides a tool for doing this.

Another method of error detection involved looking at a scatter plot of forecasted vs. observed traffic volumes. Data points that were especially far from a line traced from the origin with a slope of 45 degrees represented locations where the model was performing poorly and these were investigated. Determining the root cause of these inaccuracies, however, was difficult if not impossible at this stage, especially if the link in question is a controlled urban road.

The Montreal region affords a natural benefit to modelers because of its geography. The city of Montreal is located on a large island. Just to the north is the city of Laval which occupies the somewhat smaller Ile-Jesus. Both of these islands are accessible by 22 bridges, 21 of which hosted MTQ observation posts. Obviously, there is no other way for a vehicle to enter these two islands, so this setup allows for a very efficient screen-line and cordon analysis.

As mentioned above, bridge links were flagged in the validation table. The corresponding table records were exported into an Excel spreadsheet and aggregated by region (see Figure 9, Tables 11 through 14). The directional flow was classified as being either inbound (toward downtown Montreal) or outbound (away from downtown Montreal). It was hoped that, even if predicted flows on individual bridge links did not match the observed flows, the forecasts for each region taken as a whole would be a good fit with observations. If this was in fact the case then the characteristics of individual bridges could be modified so that the flow was properly distributed.

The bridges also provided a convenient platform for critical link analysis. TransCAD performs critical link analysis by displaying a map of traffic flows composed only of travelers that used a particular bridge. If a bridge was found to be performing poorly, the paths of all vehicles crossing that bridge (in one direction) are displayed on the screen. All other traffic is not displayed (see Figure 10).

A similar approach was taken with autoroute links. In an interrupted flow regime, it is usually the signaling and signage that determines the road capacity. The performance of arterial, collector and local roads was not expected to be very good due to the complete absence of intersection data in the model. The capacity of freeways, on the other hand, depends mostly upon the free-flow speed and the number of lanes, both of which had been estimated for all freeway segments. Therefore, it was expected that the performance of freeway links would be good indicators of the validity of the network and the model in general. As with the bridge links, traffic flow on freeways was categorized as being either inbound or outbound and observation posts were aggregated by autoroute number. Freeway links were of interest in the validation process because, since most of the region’s large bridges carry freeways, the performance of freeways has a direct effect on the performance of bridges. Also, freeway nodes often served as injection points for external trips and freeway links are used in the distribution of these trips.

Yet another validation procedure involved comparisons between the straight-line distance of trip ends and the network distance. The straight line distance was calculated by substituting the coordinates of each trip end into the Euclidean distance formula. The network distance of each trip was computed using the route system tool in TransCAD. Although its intended use is in building transit networks, the route system tool allows for successive shortest-path searches between origin-destination pairs to be read from a list. Theriault et al. (1999) wrote their own code to accomplish the same ends but encountered difficulties caused by excessive memory usage in the computer processor. The route system method, while time consuming, did not cause memory errors or result in a system crash. Trips from the O-D survey were fed into the route system procedure in blocks of 50,000 at a time until all 385,000 trip records had been routed on the network. Each of these blocks consumed roughly 2 hours of processing time.

A very large discrepancy between straight-line and network distances might be indicative of an unrealistic routing. However, the regional geography is such that many trips are significantly longer than the straight line distance, occasionally dozens of kilometers longer. This is not implausible in an area made up of islands and divided by two large rivers. In only a handful of cases were the detours due to network errors.

None of the methods outlined so far were especially efficient at identifying flaws in the model. As it turns out, most network errors were discovered during the construction of the public transit network for the amalgamated city of Montreal and this process is described in the next section.

5.9. Transit network development

The development of a transit network was undertaken for the construction of a transit assignment model to run parallel to the traffic assignment model. While the interactions between road traffic and public transit parameters were recognized from the outset, the extent to which the construction of a transit network would benefit the performance of the road network was not immediately obvious. Much of the work described below was performed by Emma Hamilton, an undergraduate civil engineering student at McGill University.

Transit network models are much more complicated than road network models. In road networks, a simplified representation of links and nodes - each having specific characteristics – is all that is required to satisfy the theory of large-scale vehicle flow in a static model. The link and node geometry can be easily verified through aerial photos and digitized maps such as those developed by DMTI. By contrast, the links and nodes in a transit network consist of fixed routes, stops and stations. Some of these stops and stations (transit nodes) correspond to street network nodes, but many do not. Furthermore, digital copies of transit routes and stop locations are not readily available, especially in the case of bus services. And aerial photos cannot be used at all.

Additional complications arise from the fact that transit consists of multiple modes such as buses, streetcars, LRTs, metros and commuter trains and the connections between modes are made on foot. Each mode corresponds to a different link type with different characteristics and, because multiple routes and modes may be involved in a single trip, variable transfer times must be computed. Finally, travel cost for the user is no longer influenced by volume, but depends entirely upon vehicle capacities and headways. Vehicle headway data in a manageable format may be difficult to obtain. For all these reasons then, travel network construction presents a formidable challenge.

The methodology behind the development of the Montreal network is summarized here. More detailed accounts are available in Hamilton, 2004(a) and 2004(b). The entire project was made possible by the provision of GIS maps displaying the location of all bus stops and routes on the island of Montreal. The island of Montreal is served almost exclusively by a single transit authority – the Société de Transport de Montréal (STM) – who provided the data.

The GIS maps were not ideal for several reasons. First of all, the stops were not connected to the bus routes but were positioned adjacent to them to better represent their actual location at the side of the road. Also, neither the point layer of stops nor the line layer of routes was connected to the existing road network. Both of these facts presented obstacles because of the way in which TransCAD builds transit networks. TransCAD requires a functional street network file (.net file) in order to calculate the lengths and travel times of transit routes. Based upon this file and a set of route stops, given in sequence, TransCAD will generate a “route system”. A route system is a visual representation of transit routes and has an associated table of route attributes with one record for each directional route (see Figure 10). Finally, based on this route system, a transit network (another .net file) can be generated and used to calculate shortest paths and run assignment models. It was therefore decided to either assign bus stops to nearby existing nodes in the street network or to create new nodes in the street network, and use the line layer of the STM’s GIS map purely for validation purposes.

The automatic tagging procedure was used, but this approach resulted in many stops being improperly located. Numerous manual adjustments had to be made. The next task was to build a sequential list of stops for all 150 bus routes that operate during the AM peak period. This was accomplished by copying bus schedules off the STM website into an Excel table. This table would contain three fields: the route number, the route direction, the bus stop address or intersection and a field called TELBUS. The TELBUS field is five-digit number that travelers can type into their phones to find out when the next bus will arrive. It played a crucial role in the construction of the transit network because it was the only field that was common to both the TransCAD geographic file of bus stops and the Excel table containing the sequential stop list. This common field allowed the two databases to be joined thereby linking the nodes in the street network to the bus schedules.

The resulting table now contained all the elements necessary to generate a route system. It was an ordered list of stops for all routes in both directions with a network node for each stop. The route system was generated using the latest version of the network file being used in the traffic assignment model. Once the route system was displayed, the path generated by TransCAD could be verified using the bus route map provided by the STM.

The first route system that was produced from this table had 666 errors, but this output was invaluable because many of the errors were in the street network. Furthermore, these errors would likely never have been detected without the route system since there was no way to check whether individual drivers were following the correct path. Comparisons of predicted bus paths with their actual paths were possible because the transit route system was checked against the map of actual routes.

5.10. Types of errors and methods of correction

Network errors: The most prevalent type of error was inaccuracies in the DMTI digital network. These included missing links, links improperly connected, links not connected at all, links with the wrong functional class, links improperly directed and extra links that do not exist in reality. The effect of these errors on model performance depended upon the importance of the streets and intersections involved. Improperly connected local roads usually had no appreciable impact due to the small amounts of flow they carry. Errors on freeways had a greater effect on model performance. All these errors were corrected by direct edits to the geographic file, usually done with the aid of published street maps.

Turn penalty errors: Another common error was that of missing turn penalties. The DMTI network map comes with a .dbf table listing prohibited movements but some movements were not in the original list and had to be added subsequently. The most common example of a turn penalty error occurred at overpasses when the flow map revealed traffic “jumping down” from the overpass to the street below. In these cases, a toolbox application is used to point and click on pair of links between which movement is impossible, thereby adding a record to the turn penalty table. As with network errors, the effect of missing turn penalties on model performance depended upon the importance of the links involved.

Capacity errors: Due to the aggregate manner by which lane capacity was assigned, inaccuracies were common. One example, already described, is that of provincial highways traveling through dense urban environments where they are, for all intents and purposes, urban arterials. This problem was initially addressed using a similarly aggregate approach whereby all provincial highways within 40 kilometres of downtown were assigned the same capacity as urban arterials. However, the urban fabric does not extend an equal distance in all directions. With successive versions of the model, provincial highway capacities were readjusted according to the surrounding built environment. The built environment was assessed by visual inspection of the street map. If a provincial highway passed through a region where the surrounding street network was dense, then its capacity would be adjusted down to the level of an arterial road. Due consideration was also given to the frequency of intersections along the highway segment in question.

Procedural errors: This type of error arises from the implementation of traffic assignment theory and there are several examples.

One set of errors is due to the zone system - how it is defined and how it is connected to the network. Zones that generate exceptionally large numbers of trips will display an obvious aggregation bias, with huge flows assigned to only one or two streets leading toward the centroid. These errors were corrected using the zone balancing procedure described in Section 5.4.

Alternatively, zones that are improperly connected may not be able to generate any trips at all or they may result in illogical flow patterns. An example of these latter errors was found on Boucherville Island in the middle of the St. Lawrence River. Each centroid was connected to the network by 2 dummy links. The centroid on Boucherville Island had one connection linking it directly to a street on the South Shore, and the second connection was attached to a road segment isolated from the network due to the functional class of the surrounding links (see Figure 12). Illogical connections had to be detected by visual inspection and so close attention was paid to island zones to ensure that they were not connected to the mainland by a dummy link. Isolated connections were harder to identify but if a centroid were completely cut-off from the network, an error message would appear at the end of the traffic assignment procedure indicating that there was no path to or from that centroid.

Another set of procedural errors relates to the parameters of the volume-delay function, alpha and beta. Ideally, each road segment should have its own empirically determined values. However, as with road capacity, such empirical data are not available and so the parameters were applied globally according to link functional class.

The values suggested by Horowitz (1991) were useful in this regard. Changes to the alpha and beta values were found to have a very important effect on flow patterns. They are important calibration tools and will continue to be adjusted to improve model performance.

This chapter described the construction of the network, the zone system, origin-destination matrices as well as the development of a validation framework for the model as a whole. The end results of this work will be described in the next chapter.

6. RESULTS

6.1. Overall Performance

The results of the latest version of the Montreal-area model are encouraging although much work remains to be done. The US Department of Transportation's Transportation Model Improvement Program recommends a correlation coefficient of at least 88% and %RMSE of less than 30% between observed and predicted link flows. For the three hours modeled, the performance statistics are displayed in Table 7.

The bottom line in Table 7 corresponds to the AM peak taken as a whole. This is not a separate simulation, but rather just the sum of the forecast flows for the three hours and the sum of the observed flows over the same three hours. The goodness-of-fit statistics are computed using the 199 points generated by the MTQ's observation posts. These results show that the Montreal network model is approaching the standards for "good" model performance. The r-squared for the three hours taken together is above 88% (see Figure 13) and the %RMSE is 31.6.

The goodness-of-fit statistics are aggregate measures of performance. More detailed measures, however, provide a more accurate assessment. The two columns at the far right of Table 7 indicate the number of bridge and autoroute links whose forecast flows were within 5% of the observed flows. Highway and bridge links are discussed in detail in Section 6.2. A caveat must be added to the column displaying autoroutes. Thirty four observation posts corresponding to external trip generators were used to simulate external trips and are therefore "fitted" points (see Section 5.6). Since these posts lie along the periphery of the region, the forecast flow over these links from nearby generator nodes was set equal to the observed flow. Twenty-two of these posts were on autoroutes. A further 12 were also fitted along primary provincial highways.

Results with the 34 fitted points removed appear in Table 8. This table shows that the r-squared for all 3 hours falls slightly to 0.8759, but so does the %RMSE to 30.3. Overall, the model is still approaching the minimum TMIP performance standard.

In addition to the %RMSE and the r-squared, the %error can also be used to evaluate model performance. As can be seen in Table 7, the % error varies from hour to hour. The first hour of the AM peak generates traffic flows 15% below observed levels. In the second hour, forecast flows are nearly 6% above observations. In the third hour, flows are roughly 4% too low. It is difficult to explain the “missing” traffic in the first hour based solely upon the aggregate performance measures. However, the “excess” traffic forecasted between 0700 and 0800 may be due to the inability of the static model to deal with queues. During this hour, many Montreal arteries experience demand well above capacity resulting in queue formation upstream of the link and forced flow on the link itself. The static model cannot deal with either of these phenomena and so flow continues to appear on links even though absolute capacity has been reached. The fact that the static model performs well when all three hours are taken together is evidence of this phenomenon. By 9 am, most of the queues on the region’s roads have cleared and so, over the three hour AM peak, total demand has been met and the total percent error is close to 0.

Three additional aggregate measures were used to test the model’s validity. Average trip length, average trip time and average trip speed were calculated based upon output generated by TransCAD in the traffic assignment procedure. Average trip length was computed by dividing the number of vehicle-kilometres traveled by the interzonal travel demand. Average trip time was obtained by dividing total vehicle-minutes traveled by interzonal travel demand. Finally, average speed can be computed by dividing average trip length by average trip time. The results are enlightening (see Table 9).

The longest trips, both in terms of distance and time, occur in the first hour of the AM peak. This hour also contains the smallest percentage of intra-zonal trips (which are not assigned to the network), and the smallest travel demand. These findings are intuitively correct. People who must make longer trips must depart earlier if they wish to arrive on time. Also, since most stores and schools are still closed between 6 and 7 am, there are very few local trips being made. Furthermore, this hour displays the highest average vehicle speed which can be attributed to the relatively low level travel demand and therefore low congestion. Moreover, people making longer trips are more likely to use high-speed facilities like autoroutes.

During the second hour, between 0700 and 0800, average trip length is considerably shorter while average trip duration is only slightly shorter than in the previous hour. Travel demand has nearly doubled and the percentage of intra-zonal trips has increased. Once again, this situation seems to correspond well with reality. This is the hour during which most people leave for work or school and local trips become more prevalent as stores start to open. Travel demand reaches a peak. Therefore, roads are highly congested and average speed drops. Trips are shorter on average, but most of the time savings are cancelled out by the increased congestion.

During the final hour of the AM peak, demand drops off only slightly, but trips are noticeably shorter and the intra-zonal percentage is much higher. Average speed increases due to easing of congesting indicating that fewer trips are being made along high density corridors. This, in turn, suggests that trip purposes are more local and more "random". Many people are commuting to work and school, others are running errands, going to meetings or dropping off family members or colleagues.

The progressive diversification of trip purposes with each successive hour can be verified in the analysis of the O-D survey presented in Table 10. In the first hour, work trips comprise nearly 80% of the total. By the third hour, that share has decreased to 57% while the share of "other" trip purposes has risen to 36%. Also note the increase in the percentage of shopping trips from 0.4% in the first hour to 5.2% in the third. It seems, therefore, that the model is accurately representing these changes in travel patterns.

The speed and length measures also reveal problems with the model. U.S. census data for 2001 reveals that the average commute time stated by respondents in major American cities almost always falls between 25 and 30 minutes. The highest predicted average trip time predicted by the Montreal model is 22 minutes during hour 1. This value is probably too low considering that 80% of all trips are work commutes. Such results are in fact typical of deterministic user-equilibrium models due to their underlying assumptions. Because all trip makers are assumed to have perfect information and choose a route that minimizes their travel time, overall travel-times tend to be underestimated. In reality, drivers do not have perfect information and minimal travel time may not be the sole consideration in route choice (Dial, 1971, p.85).

On the other hand, an examination of trip length frequency distribution (TLFD) charts reveals that the tendency toward underestimation of travel times may not be a serious problem. Figures 14a through 14c show the distribution of trip lengths measured in kilometres. The dominant trend is the steady increase over the course of the AM peak in the proportion of trips less than 10 km long. In the first hour, these trips comprise 35% of all trips. By the third hour, they account for 63% of all trips. This trend can be attributed to the progressive diversification of trip purposes described above. When the trip lengths are measured in minutes (Figures 15a through c), a corresponding pattern is discernable. In the first hour (Figure 15a), trips between 20 and 30 minutes in length make up the largest single cohort at 22% of all trips. This finding is logical since most of the trips made during this hour are commute trips. For the remaining two hours, trips less than 10 minutes long dominate, comprising 27% of trips in hour 2 and 39% of trips in hour 3. These results correspond well to the trip distance distributions in Figure 14. In addition, the distribution curves become steeper with each successive hour, indicating a steady decrease in the proportion of longer trips.

In general, the TLFDs of distance (Figure 14) correlate well with the TLFDs of time (Figure 15) which suggests that the model is doing a good job of estimating trip duration. While the algorithm might underestimate trip times, it does not underestimate trip distances since travel costs measured in length do not vary with volume.

6.2. Performance by Link Type

After the aggregate measures of performance have been examined, model performance can be evaluated by link type. We look first at high-volume links because these are the elements of the model that are expected to perform the best. In the Montreal area, high-volume links are of two kinds: autoroutes and major bridges. Both types generally operate under uninterrupted flow conditions and so should be well-represented by the BPR function.

6.2.1. Autoroutes

The criterion used to determine whether a high-volume link was performing well was to see whether or not its forecasted volume was within 5% of the observed value. There were 66 observation posts that were set up on freeways, 44 of which were not fitted at the regional periphery for the purpose of generating external trips (see Section 5.6). The posts were further segregated based upon whether the traffic they were observing was flowing inbound or outbound with inbound being defined as heading towards downtown Montreal. In the 0700-0800 model for example, 8 unfitted links were within 5% of observations. Four of these were inbound and four of these were outbound. In the 0600-0700 model, 4 inbound links were within 5% of observed flows but only 2 outbound links were within 5%. For the 0800-0900 model, 3 inbound links and 2 outbound links were a good fit. For the AM peak period as a whole, 3 inbound links and 4 outbound links were within 5% of observations. A histogram of the %error on unfitted freeway links (Figure 16) indicates systematic overestimation. Although the distribution is mostly centered about zero there are 4 observations whose forecast flows greatly exceed observations. However, 62 of the 66 freeway links are within 50% error.

It is interesting to observe the performance of freeway links at ever-greater distances from their calibrated traffic generating nodes. Figures 14 and 15 show the deviations of predicted traffic levels from observed flows at successive stations along major freeways for all three hours of the AM peak. Observation posts on major bridges are excluded and are dealt with separately. This approach is derived from the assumption that all bridges act more as network bottlenecks than as high-capacity links. A practical expression of this phenomenon is the case of the Champlain Bridge which carries Autoroutes 10, 15 and 20 across the St.-Lawrence River although, with only three lanes in each direction, it acts as a single freeway.

As before, a separate analysis is performed for inbound and outbound flows. Taking the inbound case first (Figure 17), we can see that deviations tend to increase as we move further away from the first observation post which has been fitted to match observations (station 1). In most cases, the forecast flows tend to exceed observations by ever-greater amounts. This is the case with A-40 westbound, the A-35 northbound, the A-20 eastbound and the A-15 northbound. The A-15 south and the A-40 east remain within 20% of observed levels for all three observation posts. The A-10 westbound behaves especially poorly, with a huge spike in forecasted flows at the second observation post. This is difficult to attribute to queuing because the behaviour is apparent over the entire AM peak period. It may be related to problems with the A-35 north which joins the A-10 immediately upstream of this section. Just prior to this junction with the A-10, flows on the A-35 are forecasted to be 78% higher than observed levels. It is not clear what is causing these distortions – further investigation is required.

The seriousness of the A-35/A-10 problem is further emphasized by the examination of outbound flows (Figure 18). The same pattern exists here, with flows on the A-10 being forecasted 211% above observed levels. The A-35's outbound performance is more consistent with that of other freeways. The flows converge gradually toward the attractor node (station 3) and are always within 50% of observed traffic volumes.

6.2.2. Bridges

Most of the population of the Montreal region is clustered on or around two large islands. The larger of these contains the city of Montreal, the smaller hosts the city of Laval. These islands are connected to the mainland by 22 bridges. There were 21 MTQ observation posts set up on bridges. Route 125 over the Riviere-des-Milles-Iles did not have an observation post. This arrangement serves as an efficient series of screenlines around the city of Montreal and the city of Laval.

As with autoroutes, bridge flows were classified as being either inbound (toward downtown Montreal) or outbound (away from downtown Montreal). Trips heading toward downtown Laval were not considered inbound because the Montreal CBD is a far more important attractor of AM peak period trips (see Section 3.1). Forecasted volumes were compared to observed volumes for each of three hours and for the entire peak period as a whole. Bridge links were further classified based on the river they cross. Results could then be aggregated regionally to see if total forecast flows across a given river were approximately correct.

Five regions were delineated (see Figure 9). The St-Lawrence River separates the city of Montreal from the South Shore suburbs in Longueuil. Two bridges at the extreme East Island connect Montreal with suburban Repentigny and other small communities downstream. Two bridges on the extreme West Island carry westbound traffic toward Ottawa and Toronto and serve the suburbs of Ile-Perrot and Vaudreuil-Dorion. Bridges over the Riviere-des-Mille-Iles connect Montreal with Laval and the bridges over the Riviere-des-Prairies connect Laval with the cities of Ste-Therese, St-Jerome and Deux-Montanges.

The hour from 0600 to 0700 will be discussed first (see Table 11). Over all bridges in Greater Montreal, inbound forecasts were 2.7% too high and outbound forecasts were -31.9% too low. Taken as a whole, 4 of the 5 regions display inbound flows that are within 5% of observations. This is the convergence criterion for the two right-most columns. Total flows onto the East Island were 8% too high. This level of performance is quite acceptable. Outbound flows were another matter. No region displayed outbound flows anywhere near observed levels. Four regions were at least 20% under and the West Island region recorded a surplus of 18%. Only 2 individual bridge links were within 5% of the target – the inbound Médéric-Martin and the outbound Jacques-Cartier. The percentage error on the inbound bridges varied from +36.7% on the Legardeur bridge to -38.8% on the adjacent Charles-de-Gaulle. On outbound bridges, the error ranged between -97.4% on the Victoria to +68.0% on the Ile-aux-Tourtes. These results imply that, for inbound flows at least, total volumes are being accurately predicted but the distribution to individual bridges is far from optimal. It is difficult to account for the large amounts of flow that are missing from the outbound links.

The situation changes significantly in the second hour (see Table 12). The total inbound and outbound errors were 17.3% and 5.85% respectively. During this period, no region reports total inbound flows within 5% of counts. The inbound St-Laurent, Riviere-des-Prairies and East Island regions exceed observations by 16%, 25% and

32% respectively. Flow across the Riviere-des-Mille-Iles is 8.8% too high and West Island flow is 8.7% too low. Four individual inbound bridge links were within 5% and the error ranged from -32.3% on the Arthur-Sauvé to +106% on the Papineau. Clearly, these results are not very good but some of the error can be attributed to the fact that most of the bridges are experiencing demand well in excess of their capacity resulting in the formation of queues upstream. Queues cannot be modeled in the static framework and so excess flows appear on the saturated links. This argument is tempered by the fact that outbound links also perform poorly, although the results are acceptable at the regional level. Two regions report total outbound flows within 5% of counts and a third region is just over 5%. Two individual outbound links report volumes within 5% of the target and the error varies from -62.9% on the Victoria to +46.7% on the Jacques-Cartier.

The results improve during the third hour (see Table 13). Total inbound and outbound forecast volumes match observed volumes almost exactly. Four inbound regional aggregations and 2 outbound aggregations record total inbound flows within 5% of observations. Only the West Island and the outbound East Island have large errors. Three inbound and four outbound links are within target range. The inbound error ranges from -66.7% on the Legardeur to +43.5% on the Papineau. The outbound error is between -65.2% on the David and +45.7% on the Jacques-Cartier.

For the AM peak as a whole, inbound forecast flows are 7.4% too high and outbound flows are 7.0% too low (see Table 14). One inbound and two outbound regional aggregations display total flows within 5% of observations and those regions that are not within the 5% range are fairly close. The largest deviation is +15.9% on the East Island bridges. Furthermore, 6 inbound bridge links and 2 outbound bridge links are within 5% over the entire 3 hours. The extremes of the inbound error are -34.4% on the Arthur Sauvé and 56.8% on the Papineau. A distribution of the %error (Figure 19) shows that it is fairly well distributed about 0. The skewness is -0.48 and the kurtosis is 3.8, indicating a roughly normal distribution. All but 4 of the 42 bridge links are within 50% of observed levels.

Overall, the model's performance on bridges leaves something to be desired but two specific points are worth noting. First of all, outbound flows are more likely to be below observed levels than inbound flows. Part of this discrepancy may be attributable to the time lag between stated departure times and observation of vehicles on the network. This lag has been set at 30 minutes and the correlation between forecasts and counts is much improved over the case where there is no time lag at all. However, further testing is needed to determine whether a different time period would yield better performance. It is also possible that the time lag would be different for outbound and inbound trips. Outbound travelers are moving against the prevailing flow of traffic and therefore encounter less congestion. These trip makers are likely to take much less time to appear on the network and be counted at roadside stations. Further calibration of the time lag is in order.

The second point relates to highway links as well as bridges. The model displays a tendency to overload high capacity links. Flow on all posts taken together consistently fall below observed levels, but is often excessive on bridges and freeways. This is another characteristic of static models arising from the assumption that every traveler minimizes his/her travel time. All trip makers will gravitate toward high-capacity links even if they save only a fraction of a minute by doing so (Dial, 1971). An example of why this is problematic is made obvious in the critical link analysis of the inbound Champlain Bridge. Figure 19 shows the location of the origins of all trips heading into Montreal over the bridge. Figure 20 shows the location of all the destinations of these trips. It is clearly evident that all trips originate on the South Shore. But it is apparent that some of these trips *terminate* on the South Shore as well (Figure 20, lower-middle). Such an outcome is not unreasonable given the assumptions of the model. Visual inspection will confirm that a short cut between South Shore zones may be available by crossing on to the island of Montreal. Much of this trip would be made against the prevailing traffic flows and so travel time increases due to congestion may be quite small. In reality however, it is very unlikely that a traveler would take a “short-cut” like this. There is a large disutility associated with lining up to cross the Champlain Bridge onto Montreal Island, traveling the complex network of central city freeways and junctions and then using another major bridge to cross back to the South Shore. The disutility may not be measurable solely in terms of time. Possibly, the values of alpha and beta in the BPR function of bridge links could be adjusted to reflect this.

6.2.3. Other links

All links that were neither bridges nor autoroutes were assessed separately. These 75 links cannot be segregated as inbound or outbound because their direction of flow with respect to downtown Montreal was often ambiguous. Due to the influence of local factors which are not currently captured in the model due to data limitations, these links were expected to perform much worse than either bridges or highways and indeed this is the case. A histogram of the % error on "other" unfitted links over the entire AM peak (Figure 18) reveals a long right tail of segments whose forecast volumes are far above observed levels. Although the data is positively skewed, many links are consistently underestimating volumes, as evidenced by a median observation of -21%.

6.2.4. Functional class

Model performance can be further analyzed on the basis of link functional class. Table 15 shows the average link speeds weighted by link flow and the average link volume to capacity ratio weighted by link flow for each functional class of road and for each hour of the AM peak. The data reinforce some of the general trends outlined earlier.

Travel demand is lowest between 0600 and 0700. As such, the link volumes tend to be low and speeds are not much reduced from free-flow. However, the average volume to capacity (v-c) ratio already exceeds 0.5 for all classes except primary and secondary highways and arterial roads. This is due in part to the fact that freeways that extend to the edge of the study area are loaded by external trip-generator nodes. Provincial highways in urban environments serve as main arteries in areas where travel demand is high and so they carry significant volumes as well. Many secondary and tertiary highways in the outlying areas carry no flow whatsoever thereby depressing the average values.

As travel demand increases during the second hour of the AM peak, v-c ratios rise and speeds drop. Average speeds on most link classes appear reasonable although data to verify this are not currently available. The average speed on arterial roads may be too high but it does not account for global movement delays imposed at every node. All link types except for primary highways have volume-capacity ratios above 0.5. Former provincial highways converted to arterial roads have the highest average v-c ratio, followed closely be freeways. This is indicative of a concentration of traffic on high-capacity links. Arterials that were converted from provincial highways (Carto 50) have a higher v-c ratio than other arterials (Carto 4) because the former are located exclusively in high density city environments. Many regular arterials are dispersed throughout the surrounding hinterland as well as in the urban agglomerations and so their average ratio is lower.

During the final hour of the AM peak, v-c ratios drop to levels comparable to those observed in the first hour. This is as expected since total interzonal demand has eased and travel behaviour is more randomized (see section 6.2.2).

Pederson and Samdahl (1982) proposed some guidelines for assessing what size discrepancy between forecast and observed link volumes is acceptable. They suggested that a link which carries 8000 vehicles per hour should have a forecasted volume within 10% of observed levels. For a link carrying 2000 vehicles per hour, a 30% error is acceptable. Link volumes in between these two values may be interpolated linearly. When this approach is applied to the 165 unfitted observed links, 139 were found to be within acceptable ranges, over the AM peak as a whole.

6.3. Validation Process

The validation process involved repeated trials with modifications to the network, O-D matrix and zone system between successive runs. Once the network configuration had been finalized based upon the mapping of bus routes (see Section 5.9), and the zone system was completed based upon the clustering of trip ends (see Section 5.4), aggregate statistics were recorded for each trial. These appear in Table 15. A general improvement in model performance is apparent. In trial 1, the %RMSE was

49.5% and the r-squared was 0.82. By the 12th trial, the %RMSE had been reduced to 37.8% and the r-squared was at 0.88. Note that the size of the improvement increment varies significantly between trials.

Between trials 1 and 4, modifications consisted of the addition of a few external trip generator nodes and the correction of movement prohibitions at specific locations across the region. These changes had virtually no effect on performance. Between trials 4 and 5, however, the alpha and beta parameters were changed on freeways and rural highways. Initially all links had their alpha parameters set at 0.15 and beta values were set at 6 and 4 for freeways and other roads, respectively. After trial 4, freeways were assigned beta values of 0.83 and rural highways were assigned beta values of 2.1 and alphas of 0.71. All other streets retained their initial parameters. Also, all 34 external trip generating nodes were activated and the trips distributed proportionally (see Section 5.6). This set of changes resulted in a jump in the r-squared to 0.87 and the %RMSE dropped 12 points to 40%. The discrepancy between counts and observations was also reduced from -13.5% to -6.2%.

During trials 5 and 6, changes were made to the functional classification of some major streets, most notably Taschereau Blvd. on the South Shore. It was initially classified as a primary provincial highway and then was coarsely converted to an urban arterial (Carto 50) because it lies within 40 km of downtown Montreal (see Section 5.2). The functional class of Taschereau Blvd. changes depending on its location. Mostly it is a divided suburban arterial but as it approaches the Jacques-Cartier Bridge, it is essentially a freeway for 3 km. The road was re-classified and its capacity and BPR function parameters were changed to reflect this. These and similar changes on other roads resulted in a marginal improvement in model performance. Trial 6 was performed after the modification of the matrix to account for multi-modal trips. Before trial 6, all trips were assumed to be made by car from beginning to end, even if different modes, in addition to auto-drive, were utilized during the trip. The trip ends for these journeys were changed to include mode junction points in order to isolate the portions of multi-modal trips made by car (see Section 5.6). This change accounts for the significant negative increase in the %error.

Trial 7 was the first to run simulations for all three hours of the AM peak. The aggregate statistics indicated that the model performed worse for the final two hours than in the first hour. Overall, the forecasted flows were too high. This result implied that there were too many trips being injected onto the network by the external generators. In trial 8, therefore, the external trips were distributed according to a gravity model (see Section 5.6). The results of this trial showed that the volumes of outbound trips had decreased slightly, but inbound trip volumes had been unaffected. To address this, the impedance function for the distribution of inbound trips was increased in order to reduce the length of inbound trips and thereby reduce link flows across the region.

At this point, numerous streets had their capacities adjusted according to the maximum observed flow model described in Section 5.2. Alpha and beta parameters were also adjusted on several streets as well as globally according to link functional class. Local streets and arterials received alpha and beta values of 0.6 and 2, respectively (see Section 5.5). On secondary highways (Carto 3), alpha was set to 0.71 and beta to 2.1. And the freeway beta was reduced to 5.5 from 6. The effect of these changes worsened the overall performance of the model for the first hour in trial 9.

For trial 10, and the changes implemented after trial 8 were applied to all three hours of the peak period. Significant improvement was apparent, with the overall % error coming very close to 0, the % RMSE dropping to 35% and the r-squared rising to 0.88. Trial 11 employed the trip plan string method to isolate the auto-drive portion of multiple mode trips (Section 5.6) and resulted in a small improvement in the overall model. The final trial, number 12, incorporated a large correction to the BPR function parameters on urban arterials officially designated as provincial highways (Carto 50). At this late stage, these links still retained their original alpha and beta values of 0.15 and 4 respectively. This final change generated the latest – and best – results that have been described in this chapter.

The point of detailing the incremental improvements between trials is to illustrate which types of changes have the greatest impact. Clearly, the most important factors are the BPR parameters alpha and beta. The initial change from the default parameters led to an enormous improvement (trial 5). The second most important element was the addition of external trips and their distribution throughout the region.

This process reduced the %error in trials 5 and 6. The change in distribution methods from simple trip-end proportions to a gravity model served to increase the size of the %error for the first hour, but improved the accuracy of the other two hours and of the AM peak as a whole.

Individual link capacities were adjusted over the course of all 12 trials in combination to other model improvements. Therefore, it is difficult to gauge the impact on model performance of adjustments to link capacities alone.

After the modifications to delay function parameters, external trips and link capacities have been made, it is difficult to discern the importance of smaller measures such as the addition or elimination of erroneous turning restrictions. As described in Section 5.9 and 5.10, turn penalty errors were often found by chance and were scattered at random throughout the network. While the corrections had to be made for the sake of accuracy, it is unlikely they played a very large role in the overall performance although their combined effect was probably significant. The impact of *legislated* turn penalties may be greater because they are concentrated in heavily-traveled sections of the network. At this time, data on legislated turn penalties are not available.

Finally, it seems that model improvements become progressively more costly as performance levels increase. For example, trial 5 displayed a decrease in the %RMSE of over 10 percentage points from trial 4. A seven point decrease occurs between trials 7 and 8 and subsequent changes for all hours are no more than 2 or 3 points.

This completes the detailed summary of the model output. The next chapter will summarize the model’s applicability and evaluate the ultimate products of the research.

7. CONCLUSIONS AND FUTURE RESEARCH

7.1. Model performance

The goal of this research was to build a detailed model of the Montreal area street network. It was hoped that current GIS technology would allow this goal to be accomplished fairly easily without an enormous allocation of labour and monetary resources. Indeed the author, working over a 2-year period, has been able to construct a 240,000 link network that can reliably model current traffic flows. In fact, the present network performs sufficiently well that the next stages of the regional planning research can be contemplated, while the model itself is improved over time.

The current version of the model does not quite meet adequate standards. The model needs to be improved and there are many different ways in which improvement can be realized. The most immediate concern is the validation of network parameters based upon field data. These parameters include link capacity, free-flow speed, intersection capacity and the calibration parameters of the BPR function. Additional intersection capacity data will also facilitate the calculation of volume-dependent turning delays. Aerial photos and access to municipal transportation department databases can facilitate this process.

Numerous methodological concerns must be addressed as well. To begin with, the zone system is not optimal. Many zones still generate too many trips over too large an area and aggregation errors remain a concern. The zone system should retain the census tracts as a basis, but the tracts should be subdivided according to the distribution of travel-demand in the O-D survey. The use of enumeration areas as traffic analysis zones should be explored. The method of connecting traffic analysis zones to the network must also be changed. First of all, there is no need for the connections to be made to the geographic centre of a zone. The connection point should be determined based not purely upon geographic coordinates, but also based upon the land use patterns and the location of the transportation infrastructure within a zone. Secondly, the automatic construction of centroids increases the likelihood of unrealistic distribution of demand. The connections should be made manually, with due consideration for the connector length (which should be minimized) and the location of the connection node in the actual network. Thirdly, junction points between auto-drive modes and other modes (see Section 5.6) should have their own nodes and corresponding rows and columns in the O-D matrix.

Eventually, the goal is to do away with centroids and centroid connectors entirely and adopt a completely disaggregate approach. This process involves the elimination of the O-D matrix and the assignment of individual trips from a list, as has already been accomplished in TransCAD by Theriault et al. (1999). The elimination of the zone system and its associated matrix raises another interesting issue. The basic trip data will still be derived from the O-D survey which represents only a 5% sample. These records can be made demographically representative using personal expansion factors, but then one is faced with the question of how to distribute these expanded "people" across space. If the spatial distribution of the population is not considered, the result will be blocks of trips (perhaps more than 20, depending upon the survey sample size) moving from point to point.

The shortcomings of the BPR function must also be confronted. The capacity indicated in the BPR function is the absolute maximum flow that can pass over the link. Additional demand will result in forced flow below capacity. Yet there is nothing in the BPR function which prevents flow from being assigned to the link even after capacity has been exceeded. Traffic speed on the link declines, but link flow continues to increase. In the real world, unmet link demand results in queue formation upstream of the link. A method must be found to accurately represent traffic conditions when the demand exceeds the capacity of the link. This will undoubtedly involve the incorporation of dynamic methods (for an example, see Mahut et al, 2004).

Yet another issue is raised by external trips. For each hour, note the number of trips in the O-D survey that were not added to the matrix because one or both trip ends is outside the zone system (Table 1). These numbers match very well with the number of external trips generated artificially based upon roadside counts (see Section 5.6). The next step in the research would be to use the external trips in the survey to either calibrate or replace the gravity model. This process would involve extending the network since many of the external survey trips terminate at points beyond the current extent. These trips could then be assigned normally and perhaps that would solve the problem. Alternatively, the distribution of these trip ends could be used to compute a probability density function of trip length which could be applied to calibrate the gravity model.

In practical terms, model improvement should follow the methodology outlined in this dissertation. Efforts should initially be focused upon obtaining good results from the high-capacity links and then begin to investigate localized defects on roads operating under interrupted flow conditions. Outlier points on the scatter plots of counts vs. forecasts can highlight links that perform especially poorly. An initial improvement could be made by assigning link capacities which would differentiate between urban and suburban roads. Urban and suburban environments could be distinguished using census tract population density or quantitative measures of street network density. Additional validation data would be helpful, especially data describing the average speed of traffic which can be used to estimate the level of congestion.

Moreover, additional data are required as model input. Data on truck traffic, for example, could be used to pre-load the network and produce a more accurate picture of flow conditions. Even more valuable would be an intersection database from every municipality in the region containing information on the type of control (signs or signals) and the legislated movement prohibitions.

Finally, updating the model will require a constant effort. Every year, new roads are built, new signaling systems are installed, streets are renovated and facilities are upgraded. All of these changes must be recorded in the model. The zone system must also undergo continuous evolution to reflect the changing spatial distribution of the population and the travel demand.

7.2. Software Evaluation

The GIS platform provided by TransCAD and MapInfo greatly reduces the amount of time and effort required to build a detailed, functional traffic assignment model. GIS are time-saving tools primarily because they allow the rapid integration of data from diverse sources. Road network data from DMTI was easily overlaid with census geography data from Statistics Canada. Tabular data such as the O-D survey can be translated into geographic data through the use of a zone system. Geographic features can have attributes added to them using the join and tagging tools.

TransCAD was found to be an adequate platform for building and running traffic assignment models. The system's procedures for entering inputs are straightforward and user-friendly. Processing times are small: a 981x981 trip matrix can assigned to a 200,000 link network and reach a 0.01 convergence in about one hour using a Pentium 4 processor. So far, the software has not been used to its full capacity since changes to the volume-delay function and the assignment algorithm can be coded in GISDK language. MapInfo provides a complement to TransCAD during the data preparation and results analysis stage. MapInfo's structured query language (SQL) tool allows the modeler to examine the distribution of trip attributes and to compute aggregate statistics based on data classification. While data records can be segregated into selection sets in TransCAD, aggregating data by field values is more difficult than in MapInfo.

7.3. Future applications

Once the model is running at an acceptable level of accuracy, it will become a valuable resource for urban planners, economic modelers and engineers. The model portrays stable equilibrium conditions which are analogous to "typical" operating conditions given the current state of the infrastructure and the amount of travel demand. The effect of proposed network changes such as a new bridge or freeway can therefore be evaluated by changing the model network. Similarly, forecast travel demand can be adjusted based upon future projections. The projected regime, unfortunately, does not necessarily represent an equilibrium state, especially if there is a large amount of pent-up travel demand. If, for example, a new freeway is built to relieve congestion, travel costs will fall initially. Unless this cost reduction is offset by an increase in taxes or tolls levied on users, previously unmet demand will result in increased car traffic, increased congestion and the return travel costs to their equilibrium state. This phenomenon is well documented (see Kockelman, 2003, Lindsey and Verhoef, 2000). Network improvements have even been shown to increase total travel costs (Braess, 1968). Therefore, the interaction between the transportation system and the economic activities it serves cannot be ignored. Models of transport networks must be incorporated into models of development and land use.

7.3.1. Infrastructure evaluation

The most immediate and obvious application of a static traffic assignment model is the evaluation of existing and future infrastructure. The output flow maps facilitate the identification of high-congestion areas as well as the observation of changes in traffic patterns resulting from network modifications. This type of data can be used to inform policy decisions and avoid wasteful or counterproductive expenditures on large-scale infrastructure projects. The current model applies only to roads, but public transit as well. Indeed, work has already begun on a transit model for Montreal at McGill University (Hamilton, 2004a, 2004b).

7.3.2. Land Use Models

Location theory relies heavily upon the idea of the bid-rent curve. The bid-rent curve represents a situation where people choose where to live based upon a trade-off between transportation costs and shelter costs. Measures of travel costs, therefore, will play an important role in determining settlement and development patterns. In addition to travel-costs, another element of bid-rent theory is the idea of economic opportunity. In the simplest case, the greatest opportunity is assumed to be found in the Central Business District. Indeed, for most urban regions, the city centre does play host to the greatest concentration of employment, retail and entertainment activities. Increasingly, however, clusters of opportunity are beginning to appear outside of the downtown. This is especially true for employment (Pucher et al, 1998). A transportation model can be used to identify these sub-centres and compute the cost of travel between them with clear implications for land prices and development potential.

7.3.3. Urban performance indicators

With the high population growth of cities around the world and their central role in the health of the global economy and environment, there is growing interest in quantifying the performance of urban areas (Dahme et al, 2002; Kenworthy et al, 1997; Irwin et al, 1999). This can be attempted using any number of criteria but here we will deal with just two pairs of concepts: accessibility and equity, and energy consumption and air pollution.

Equity in transportation is concerned with providing equal access to opportunity for all members of society. Some measurement of access to opportunity is implied. There is a growing body of research investigating the question of whether or not transportation costs play a role in the persistent poverty of some urban neighbourhoods (Blumenberg and Waller, 2003; Grengs, 2001). Many of these studies make use of straight line distances and general proximity to employment centres. A more rigorous approach involves the distribution of opportunities across the study region and discounting them according to the travel costs that must be incurred to reach them. One example of such a study was done by Spurr (2004) where the performance of various accessibility measures proposed in the literature were compared based upon how well they explained urban phenomena such as mode split, average trip length, average income and average housing costs. The travel costs used to discount opportunities were derived from the network model described above.

Another set of major concerns in urban environments – and, indeed, the world in general – is air pollution and energy consumption. Urban transport consumes a very high percentage of the world’s total annual energy budget and contributes significantly to air pollution and greenhouse gas emissions. Both these effects have implications for the sustainability of human populations. A traffic model can be used to calculate total vehicle-kilometres-traveled which can serve as a basis for calculations of energy consumption. Total emissions can also be computed based upon forecast traffic volumes and speeds.

7.4. Final Remarks

This research has successfully produced a geographically detailed traffic assignment model by combining the GIS tools with conventional traffic assignment methods using TransCAD. A comparison of the output of the TransCAD model with those predicted by the MTQ’s existing EMME/2 model might provide some insights into the relative merits of two different modeling approaches. Such an analysis would depend upon the MTQ’s willingness to share measures of performance with external researchers at McGill.

In conclusion, the traffic model described here is approaching the conventional standards of good performance. The use of GIS has allowed for the low-cost construction of a detailed, geographically accurate road network of the Greater Montreal Area. Research can now proceed along the lines of improving the existing model and applying it to wide ranges of problems in urban transportation and land use planning. Given the current availability of data and transportation-GIS software, the prospects for significant advances in practical modeling techniques are good.

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9. TABLES

Table 1 – External trips in the O-D survey

O-D Matrix (AM Peak - Auto drive)		
	Records	Trips
0600-0659	9017	181556
0700-0759	17506	359874
0800-0859	16283	336692
External Trips - Not included in O-D matrix		
0600-0659	523	9908
0700-0759	967	18551
0800-0859	797	15433
External Trips added by generator nodes		
0600-0659		11922
0700-0759		18609
0800-0859		16049

Table 2 – Montreal network links by functional class before modifications

Carto value	Functional class	Count	Length	Speed limit
1	Freeway	5473	2148.15	100
2	Primary highway	4217	1089.84	80
3	Secondary highway	3567	1282.81	60
3	Ramps	48	6.81	50
4	Arterial road	14410	2673.37	60
4	Ramps	513	64.24	50
5	Local road	102189	20237.61	50
6	Trail	4496	1022.36	10
20	Ferry route	16	89.49	10
21	Ferry ramp	23	2.33	10
	TOTAL	134952	28617.01	

Table 3 – Comparison between EMME/2 and DMTI links classified by number of lanes.

	Number of lanes	Number of Directional Links
EMME/2 Map		
	1	16328
	2	6712
	3	2817
	4	277
	5	3
DMTI Map		
	1	227209
	2	13444
	3	4529
	4	443
	5	13

Table 4 – Modified DMTI links by functional class

Carto value	Functional class	Count	Length	Speed limit	Functional capacity per lane	Alpha	Beta
1	Freeway	3111	1568.84	100	1900	0.83	5.5
2	Primary highway	2190	812.15	80	1500	0.71	2.1
3	Secondary highway	4076	1360.91	60	1200	0.71	2.1
4	Arterial Roads	15111	2674.33	50	900	0.6	2
5	Local Roads	102964	20245.97	40	400	0.6	2
50	Arterial provincial highways (formerly Carto=2)	1294	157.76	50	900	0.6	2
51	Ramps	3358	704.52	50	1400	0.83	5.5
100	Centroid connectors	1894	319.28	40	n/a	n/a	n/a
	TOTAL	133998	27843.76				

Table 5 – Estimated BPR function parameters (Horowitz, 1991)

Coefficient	Freeways			Multilane		
	70 mph	60 mph	50 mph	70 mph	60 mph	50 mph
alpha	0.88	0.83	0.56	1.00	0.83	0.71
beta	9.80	5.50	3.60	5.40	2.70	2.10

Table 6 – Traffic assignment output table fields

Field Name	**Description**
ID	TransCAD link ID
AB_Flow	Forecast flow in the AB direction
BA_Flow	Forecast flow in the BA direction
TOT_Flow	Total flow in both directions
AB_Time	Forecast link travel time in AB direction
BA_Time	Forecast link travel time in BA direction
MAX_Time	Maximum directional travel time
AB_voc	Volume-capacity ratio in the AB direction
BA_voc	Volume-capacity ratio in the BA direction
MAX_voc	Maximum directional volume-capacity ratio
AB_speed	Average traffic speed in the AB direction
BA_speed	Average traffic speed in the BA direction

Table 7 – Performance of AM peak hour models including fitted points

Hour	R-squared	% RMSE	% Error	Bridge links within target range (out of 42)	Autoroute links within target range (out of 66)
0600-0700	0.8788	37.79538	-14.5924	2	27
0700-0800	0.8536	37.85626	5.879487	6	30
0800-0900	0.8414	41.14094	-4.39898	7	27
AM Peak (all 3 hours)	0.8891	31.6287	-3.33842	8	29

Table 8 – Performance of AM peak hour models; unfitted points only

Hour	R-squared	% RMSE	% Error	Bridge links within target range (out of 42)	Autoroute links within target range (out of 44)
0600-0700	0.8692	35.89391	-15.1613	2	6
0700-0800	0.8305	36.49927	6.222203	6	8
0800-0900	0.8201	35.31554	-2.54309	7	5
AM Peak (all 3 hours)	0.8759	30.34158	-3.27609	8	7

Table 9 – Performance of AM peak hour models; trip data

			Trip Lengths		
Hour	Total Demand	% Intra-zonal	Minutes	Kilometres	Avg. Speed
0600-0700	193559.47	7.75	22.44	21.07	56.33
0700-0800	378600.05	8.80	20.06	16.60	49.67
0800-0900	352772.96	11.36	14.17	13.52	57.21
AM Peak (all 3 hours)	924932.48	9.56	18.37	16.40	53.58

Table 10 – AM Peak auto-drive trips classified by purpose

	Work Trips	School Trips	Shopping Trips	Other
0600-0659	79.66633	1.633656	0.3913191	18.3882659
0700-0759	67.96934	4.385146	1.2195222	26.8132624
0800-0859	56.57752	4.329476	5.2275161	36.1289279

Table 11 – Bridge performance for the first hour of the AM peak (0600-0700)

Bridge	**0600-0700**							
	Forecasts		**Counts**		**Errors (%)**		**Convergence**	
	Inbound	**Outbound**	**Inbound**	**Outbound**	**Inbound**	**Outbound**	**Inbound**	**Outbound**
Champlain	5922	1271	5072	2335	16.76	-45.55	0	0
Victoria	2079	41	1623	1570	28.10	-97.41	0	0
Jacques Cartier	7007	1570	7761	1587	-9.71	-1.09	0	1
Mercier	4856	711	3971	1488	22.29	-52.20	0	0
Lafontaine Tunnel	4834	2816	5257	3233	-8.05	-12.90	0	0
Galipeault	2742	341	3122	473	-12.16	-27.92	0	0
Ile aux Tourtes	2428	739	1810	440	34.10	68.02	0	0
Louis-Bisson	7527	1089	6528	1577	15.31	-30.94	0	0
Lachapelle	3108	116	4077	339	-23.78	-65.89	0	0
Mederic-Martin	6093	1664	5835	2231	4.42	-25.43	1	0
Viau	2291	265	2559	382	-10.49	-30.64	0	0
Papineau-Leblanc	5124	712	4031	2025	27.11	-64.84	0	0
PieIX	4526	1331	5080	1688	-10.91	-21.17	0	0
Charles-de-Gaulle	6258	942	4509	1338	38.80	-29.61	0	0
Le Gardeur	1966	66	3105	249	-36.69	-73.43	0	0
Arthur Sauvé	884	309	1266	275	-30.18	12.52	0	0
Vachon	5037	1002	4593	1233	9.66	-18.72	0	0
Gédéon-Ouimet	5571	1723	5941	2112	-6.23	-18.43	0	0
Marius Dufresne	1142	240	1473	222	-22.50	8.22	0	0
David	1094	157	1198	320	-8.71	-51.07	0	0
Mathieu	4334	714	3790	1059	14.35	-32.55	0	0
TOTALS	84821.76	17818.5	82601.4	26176	2.69	-31.93	1	1
Regional Aggregations								
Fleuve St-Laurent	24699	6409	23684	10213	4.28	-37.25	1	0
West Island	5170	1080	4932	913	4.82	18.32	1	0
Riviere-des-Prairies	28668	5176	28110	8242	1.99	-37.20	1	0
East Island	8224	1008	7614	1587	8.02	-36.49	0	0
Riviere-des-Mille-Iles	18061	4145	18261	5221	-1.10	-20.60	1	0
TOTALS	84821.76	17818.5	82601.4	26176	2.69	-31.93	4	0

Table 12 – Bridge performance for the second hour of the AM peak (0700-0800)

Bridge	0700-0800							
	Forecasts		Counts		Errors (%)		Convergence	
	Inbound	Outbound	Inbound	Outbound	Inbound	Outbound	Inbound	Outbound
Champlain	6248	2508	4305	3027	45.12	-17.15	0	0
Victoria	2584	548	1538	1468	68.03	-62.68	0	0
Jacques Cartier	8354	3582	7838	2442	6.58	46.69	0	0
Mercier	4426	1088	3732	1486	18.61	-26.77	0	0
Lafontaine Tunnel	4999	5056	5434	3991	-8.00	26.68	0	0
Galipeault	3140	861	3020	718	3.98	19.92	1	0
Ile aux Tourtes	3241	1073	3967	939.2	-18.31	14.20	0	0
Louis-Bisson	7291	2210	6631	2226	9.95	-0.70	0	1
Lachapelle	4389	428	3046	787	44.08	-45.58	0	0
Mederic-Martin	7026	3703	6809	3258	3.18	13.66	1	0
Viau	3574	355	2510	709	42.37	-49.92	0	0
Papineau-Leblanc	6329	1667	3070	1262	106.14	32.10	0	0
PieIX	5438	2495	4993	2252	8.91	10.78	0	0
Charles-de-Gaulle	6236	1858	4654	1518	34.00	22.42	0	0
Le Gardeur	2112	138	1558	373	35.53	-62.89	0	0
Arthur Sauvé	724	445	1069	468	-32.30	-4.87	0	1
Vachon	4424	2127	3538	1629	25.03	30.57	0	0
Gédéon-Ouimet	5680	3677	5639	2863	0.73	28.44	1	0
Marius Dufresne	1566	526	1256	361	24.70	45.78	0	0
David	1284	289	880	439	45.90	-34.26	0	0
Mathieu	4405	1393	4231	1821	4.10	-23.48	1	0
TOTALS	93467	36029	79718	34037.2	17.25	5.85	4	2
Regional Aggregations								
Fleuve St-Laurent	26611	12782	22847	12414	16.48	2.97	0	1
West Island	6381	1934	6987	1657.2	-8.68	16.68	0	0
Riviere-des-Prairies	34045	10859	27059	10494	25.82	3.48	0	1
East Island	8348	1997	6212	1891	34.38	5.59	0	0
Riviere-des-Mille-Iles	18082	8458	16613	7581	8.84	11.56	0	0
TOTALS	93467	36029	79718	34037.2	17.25	5.85	0	2

Table 13 – Bridge performance for the third hour of the AM peak (0800-0900)

Bridge	**0800-0900**							
	Forecasts		**Counts**		**Errors (%)**		**Convergence**	
	Inbound	**Outbound**	**Inbound**	**Outbound**	**Inbound**	**Outbound**	**Inbound**	**Outbound**
Champlain	5051	2094	3572	2361	41.40	-11.31	0	0
Victoria	1660	182	1295	244	28.15	-25.32	0	0
Jacques Cartier	5102	2733	5610	1876	-9.06	45.67	0	0
Mercier	2445	1045	2711	1202	-9.83	-13.10	0	0
Lafontaine Tunnel	3304	3220	4003	3313	-17.45	-2.81	0	1
Galipeault	2013	630	1562	726	28.86	-13.24	0	0
Ile aux Tourtes	2192	963	3544.7	1202.1	-38.15	-19.87	0	0
Louis-Bisson	4945	1838	4458	1924	10.92	-4.49	0	1
Lachapelle	1627	815	2058	1036	-20.96	-21.36	0	0
Mederic-Martin	5235	3419	5410	2752	-3.24	24.24	1	0
Viau	1521	544	1438	589	5.79	-7.72	0	0
Papineau-Leblanc	3488	1346	2430	911	43.54	47.74	0	0
PieIX	2708	1349	2946	1626	-8.08	-17.02	0	0
Charles-de-Gaulle	3931	1304	3467	1335	13.39	-2.32	0	1
Le Gardeur	180	135	540	290	-66.67	-53.47	0	0
Arthur Sauvé	324	294	610	463	-46.82	-36.44	0	0
Vachon	2541	1364	2947	1122	-13.76	21.56	0	0
Gédéon-Ouimet	4390	2506	4463	2080	-1.63	20.50	1	0
Marius Dufresne	916	407	708	423	29.45	-3.76	0	1
David	623	119	595	341	4.73	-65.20	1	0
Mathieu	3165	1124	2767	1407	14.39	-20.10	0	0
TOTALS	57360.91	27430.49	57134.7	27223.1	0.40	0.76	3	4
Regional Aggregations								
Fleuve St-Laurent	17560.96	9273.73	17191	8996	2.15	3.09	1	1
West Island	4205.17	1593.1	5106.7	1928.1	-17.65	-17.37	0	0
Riviere-des-Prairies	19523.18	9310.18	18740	8838	4.18	5.34	1	0
East Island	4111.17	1439.01	4007	1625	2.60	-11.45	1	0
Riviere-des-Mille-Iles	11960.43	5814.47	12090	5836	-1.07	-0.37	1	1
TOTALS	57360.91	27430.49	57134.7	27223.1	0.40	0.76	4	2

Table 14 – Bridge performance for the entire AM peak (0600-0900)

Bridge	**0600-0900**							
	Forecasts		**Counts**		**Errors (%)**		**Convergence**	
	Inbound	**Outbound**	**Inbound**	**Outbound**	**Inbound**	**Outbound**	**Inbound**	**Outbound**
Champlain	17221	5873	12949	7723	32.99	-23.95	0	0
Victoria	6323	771	4456	3282	41.90	-76.52	0	0
Jacques Cartier	20463	7885	21209	5905	-3.52	33.53	1	0
Mercier	11727	2844	10414	4176	12.61	-31.89	0	0
Lafontaine Tunnel	13138	11092	14694	10537	-10.59	5.27	0	0
Galipeault	7895	1832	7704	1917	2.49	-4.44	1	1
Ile aux Tourtes	7861	2775	9322.1	2581.3	-15.68	7.51	0	0
Louis-Bisson	19763	5137	17617	5727	12.18	-10.30	0	0
Lachapelle	9123	1359	9181	2162	-0.63	-37.16	1	0
Mederic-Martin	18354	8786	18054	8241	1.66	6.61	1	0
Viau	7385	1164	6507	1680	13.50	-30.74	0	0
Papineau-Leblanc	14940	3725	9531	4198	56.76	-11.27	0	0
PieIX	12671	5175	13019	5566	-2.67	-7.03	1	0
Charles-de-Gaulle	16426	4104	12630	4191	30.05	-2.07	0	1
Le Gardeur	4257	340	5203	912	-18.17	-62.77	0	0
Arthur Sauvé	1932	1049	2945	1206	-34.40	-13.03	0	0
Vachon	12002	4493	11078	3984	8.34	12.78	0	0
Gédéon-Ouimet	15641	7906	16043	7055	-2.50	12.07	1	0
Marius Dufresne	3624	1174	3437	1006	5.45	16.66	0	0
David	3001	564	2673	1100	12.26	-48.74	0	0
Mathieu	11903	3232	10788	4287	10.34	-24.61	0	0
TOTALS	235649.7	81278.11	219454.1	87436.3	7.38	-7.04	6	2
Regional Aggregations								
Fleuve St-Laurent	68870.74	28464.97	63722	31623	8.08	-9.99	0	0
West Island	15756.19	4606.98	17026.1	4498.3	-7.46	2.42	0	1
Riviere-des-Prairies	82235.95	25344.77	73909	27574	11.27	-8.08	0	0
East Island	20683.36	4443.76	17833	5103	15.98	-12.92	0	0
Riviere-des-Mille-Iles	48103.44	18417.63	46964	18638	2.43	-1.18	1	1
TOTALS	235649.7	81278.11	219454.1	87436.3	7.38	-7.04	1	2

Table 15 – Link performance by functional class

				0600-0659		0700-0759		0800-0859	
Functional Class	Carto	Count	Length (km)	AB Speed by AB Flow	AB volume-capacity ratio	AB Speed by AB Flow	AB volume-capacity ratio	AB Speed by AB Flow	AB volume-capacity ratio
Freeway	1	3111	1568.84	82.29	0.62	76.28	0.73	87.51	0.56
Primary highway	2	2190	812.15	76.39	0.23	73.74	0.33	76.69	0.23
Secondary highway	3	4076	1360.91	51.21	0.41	49.00	0.51	53.67	0.32
Arterial Roads	4	15111	2674.33	45.87	0.34	42.07	0.53	44.78	0.40
Local Roads	5	102964	20245.97	34.10	0.51	32.35	0.63	33.69	0.54
Arterial provincial highways (formerly Carto=2)	50	1294	157.76	42.00	0.61	39.76	0.75	46.08	0.48
Ramps	51	3358	704.52	42.69	0.57	39.72	0.66	43.90	0.53
Centroid connectors	100	1894	319.28	40.00	0.00	40.00	0.00	40.00	0.00

Table 16 – Changes in model performance over successive trials

Trial	R-squared	% RMSE	% Error	Bridge links within target range (Out of 42)	Autoroute links within target range (Out of 66)
0600-0659					
1	0.8178	49.45086	-13.33778248	3	
2	0.8187	49.56457	-13.39477752	3	
3	0.8239	49.09624	-13.47378833	5	14
4	0.8094	52.07972	-13.50189539	6	9
5	0.8724	40.03511	-6.161721561	6	21
6	0.8728	38.5982	-8.762521381	2	19
7	0.8719	44.67398	-10.95417657	3	27
8	0.8753	37.85573	-9.285062388	4	24
9	0.8751	37.87904	-11.42500772	4	25
10	0.8755	38.52175	-11.1218334	5	24
11	0.871	38.82136	-13.68288967	4	25
12	0.8788	37.79538	-14.59235797	2	27
0700-0759					
7	0.822	49.65747	16.38989336	4	25
10	0.8443	43.18217	9.81551591	4	23
11	0.855	38.8192	7.193455699	6	25
12	0.8536	37.85626	5.87948652	6	30
0800-0859					
7	0.8241	46.9167	4.798220033	6	25
10	0.8323	38.70149	-2.277282943	9	27
11	0.8313	43.25576	-3.245693019	8	27
12	0.8414	41.14094	-4.398978766	7	27
AMPeak					
7	0.8689	38.22392	5.262295445	5	25
10	0.8813	35.2268	1.391053848	13	23
11	0.8855	32.79659	-2.198487263	11	28
12	0.8891	31.6287	-3.338416733	8	29

10. FIGURES

Figure 1- O-D Survey 1998: Trip Densities: mode auto-drive, logarithmic scale

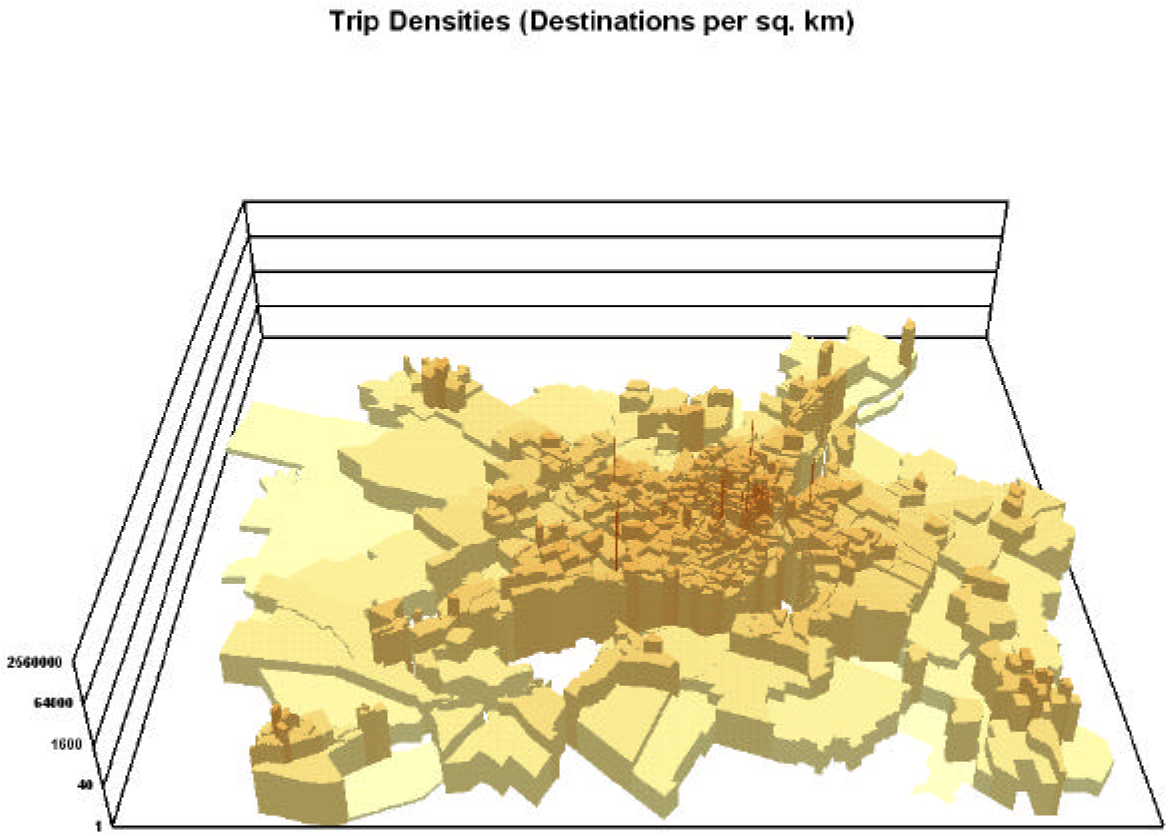


Figure 2- O-D Survey 1998: Number of trips attracted to each zone between 08:00 and 08:59

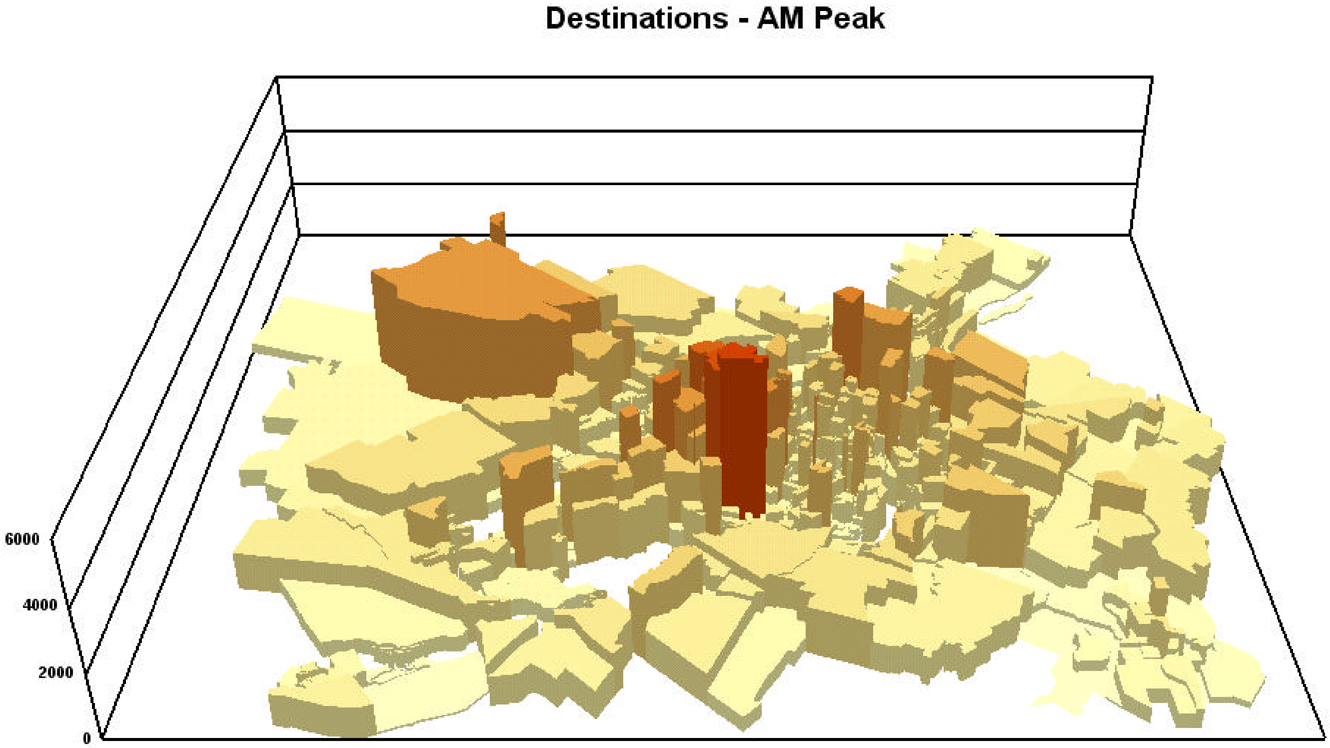


Figure 3- O-D Survey 1998 – Distribution of stated departure times for the am peak, auto-drive mode only.

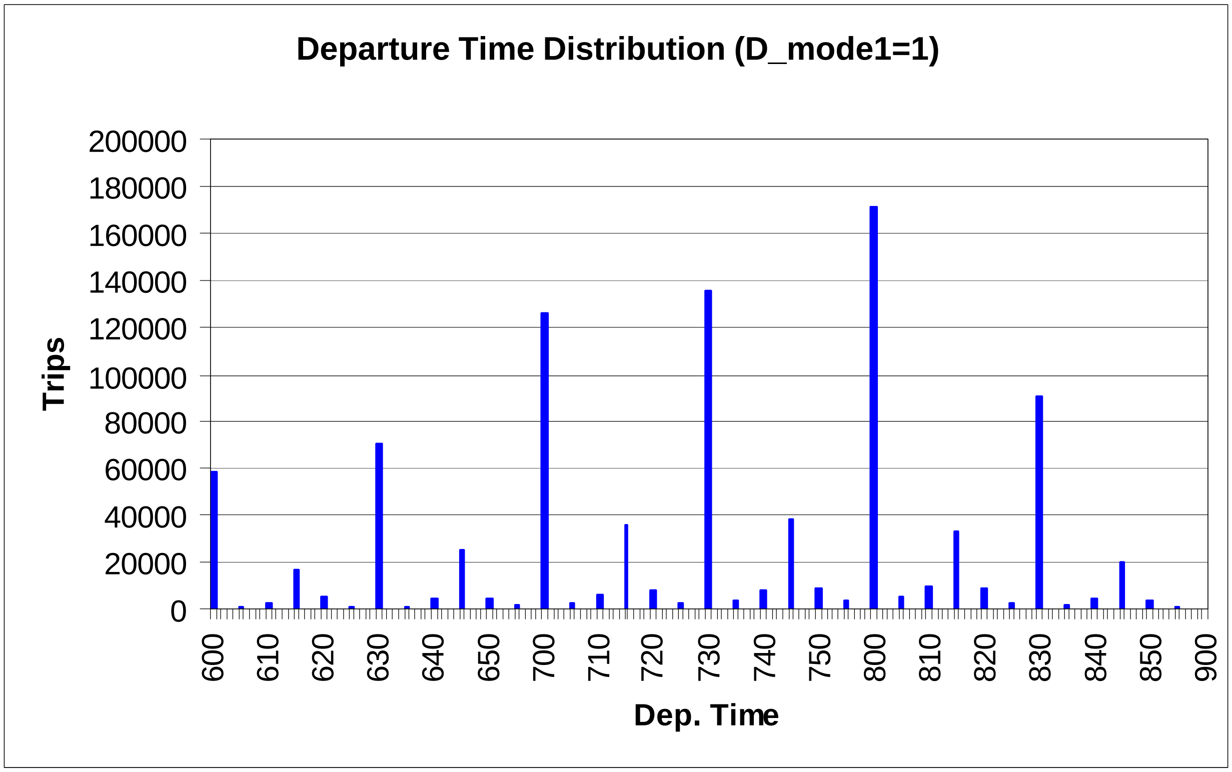
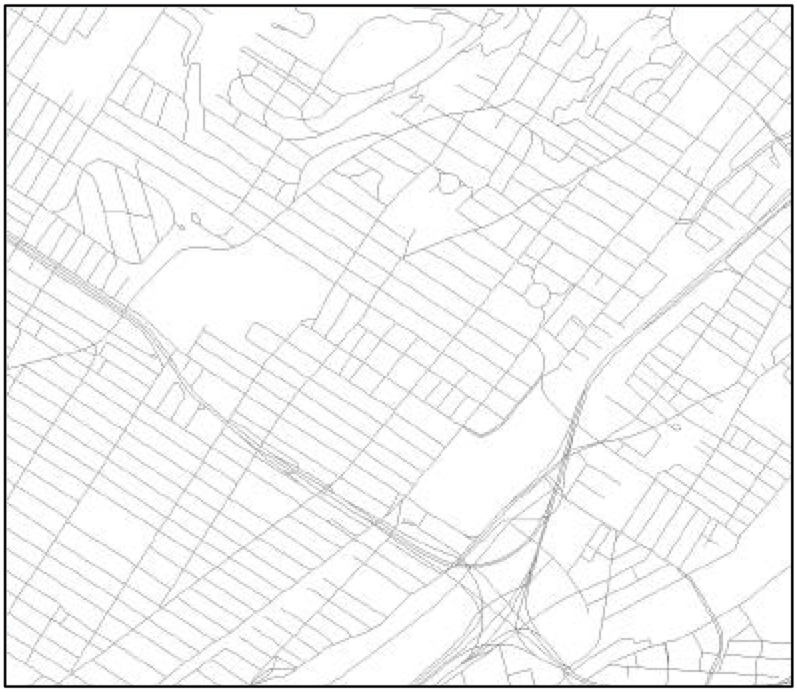


Figure 4- Comparison of network detail



a) DMTI Route Logistics street map.

(b) The MTQ's EMME/2 network map.

Figure 5- The model development process

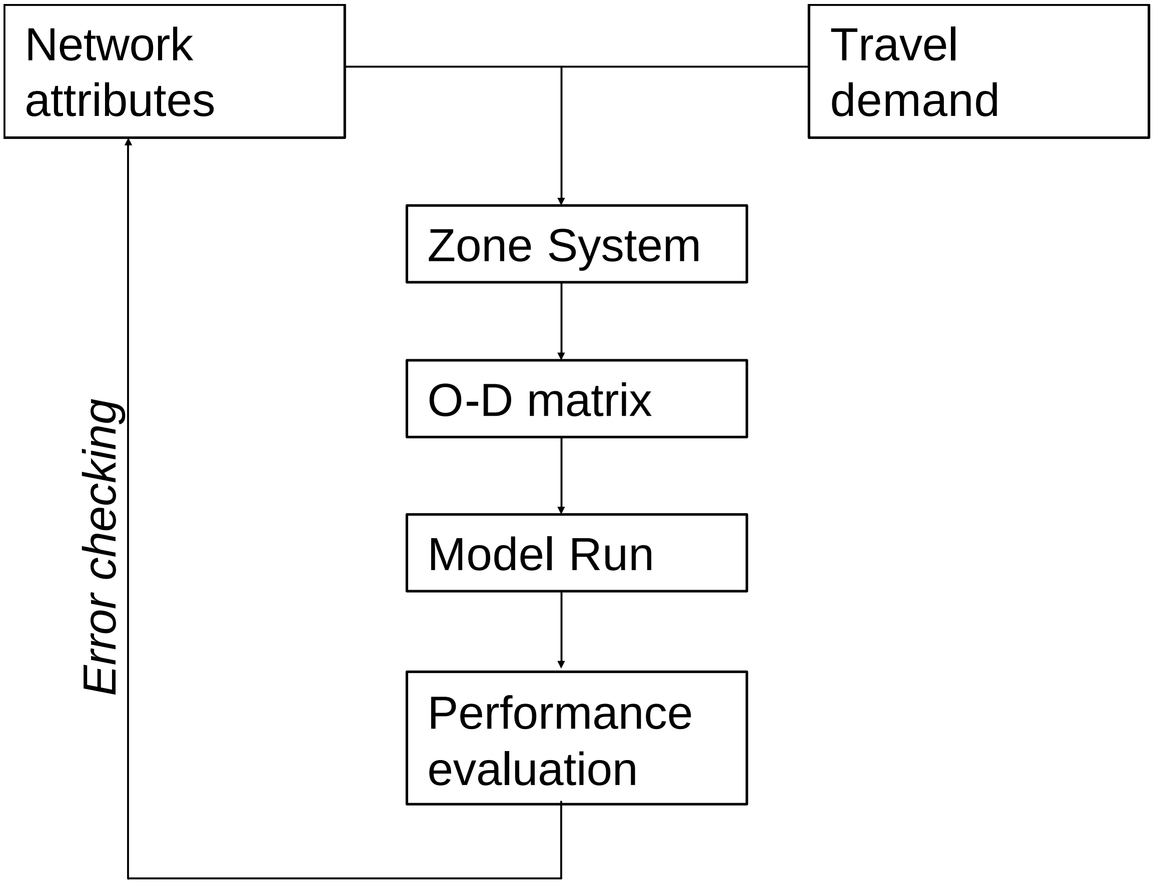


Figure 6- Destination clusters appear as different-shapes points. The original zone boundaries are thick lines. New zone boundaries (drawn by hand) are thin lines.

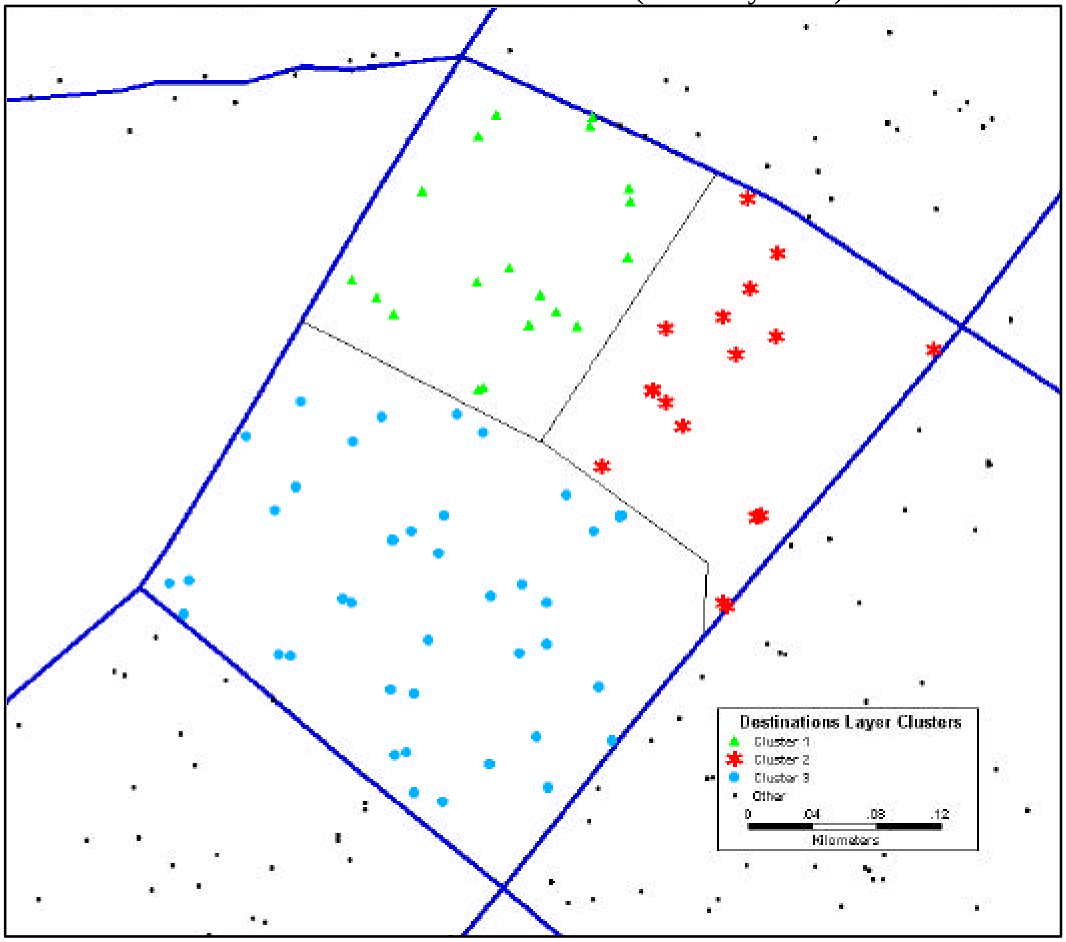


Figure 7- Ville-Marie expressway: original digitized configuration (left) and correct configuration (right).

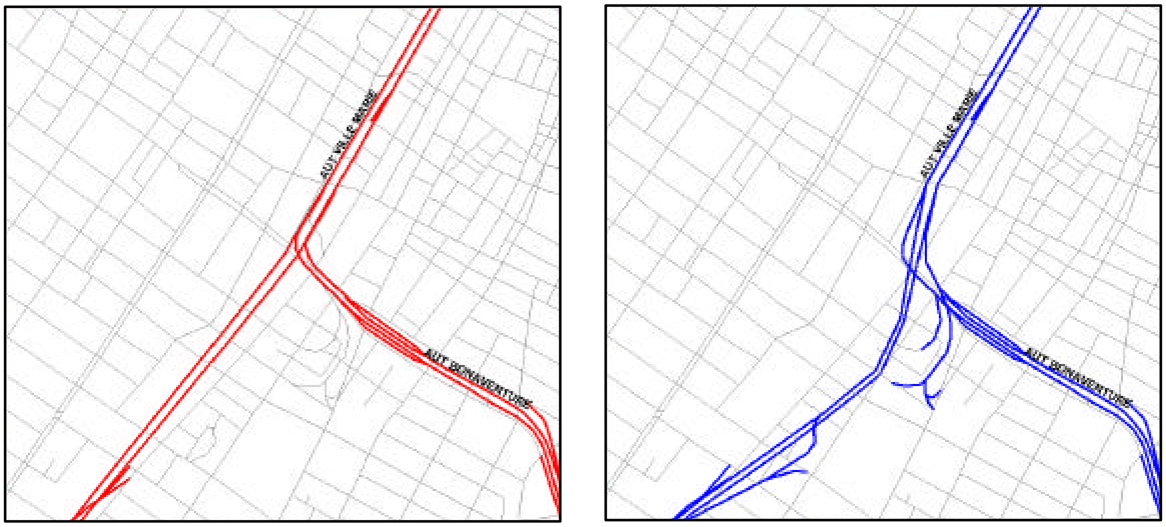


Figure 8- Traffic Assignment Model Output

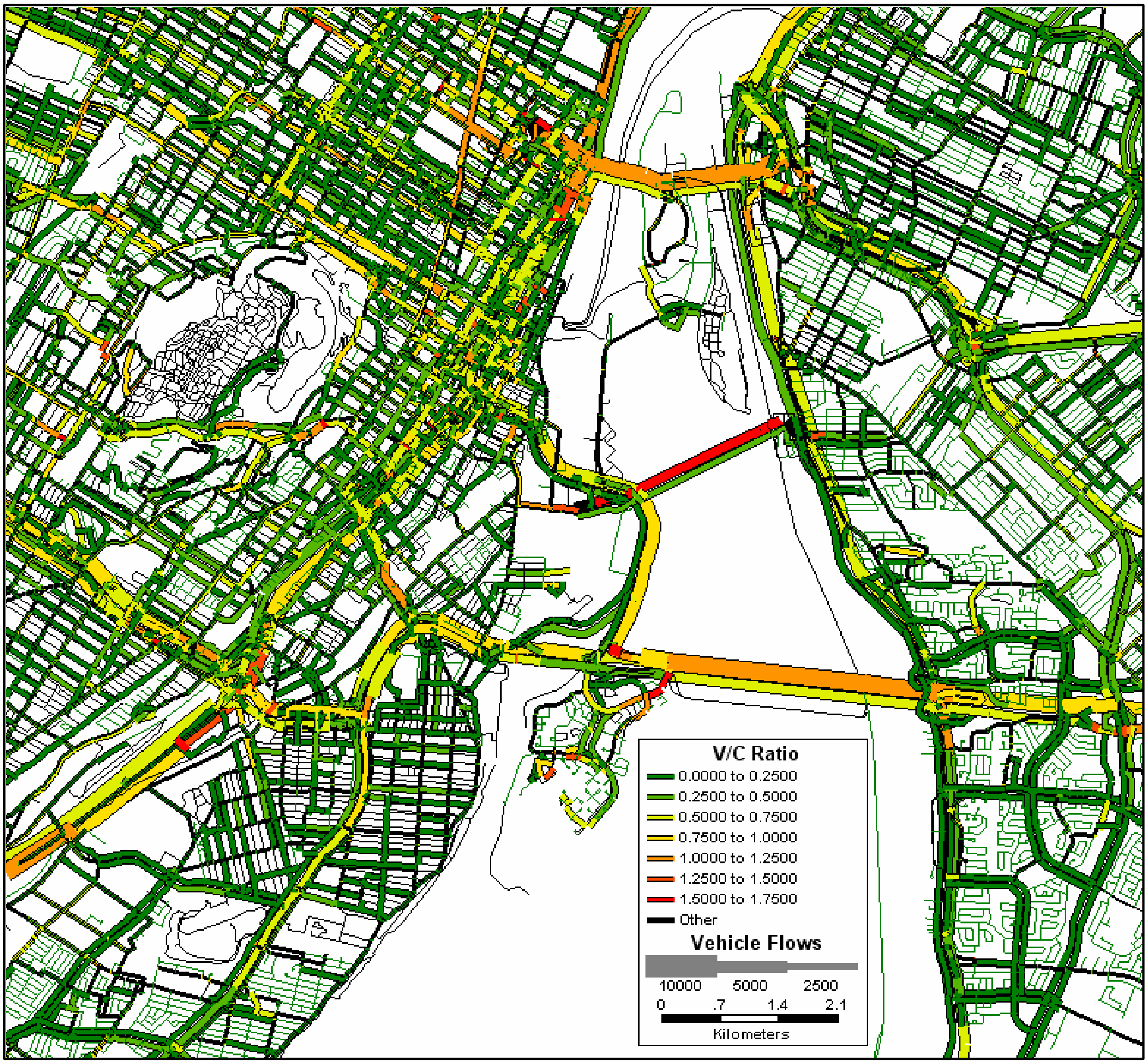
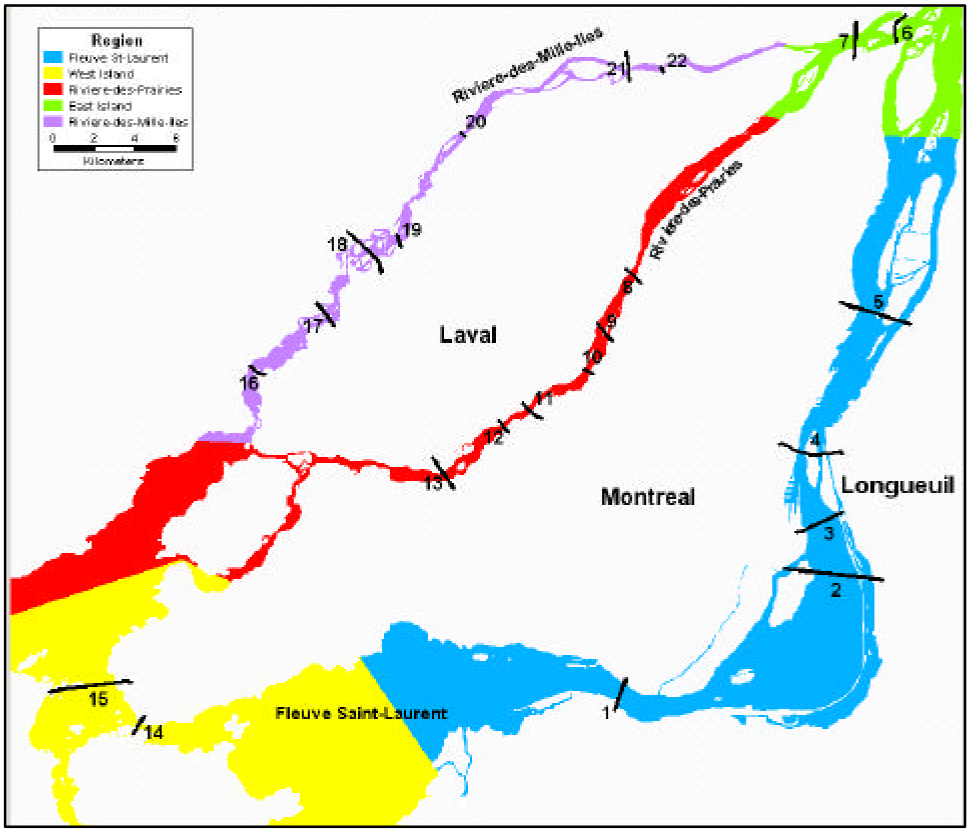


Figure 9- Montreal Area Bridges



1 – Mercier
2 – Champlain
3 – Victoria
4 – Jacques-Cartier
5 – Hippolyte-Lafontaine
6 – Legardeur
7 – Charles-de-Gaulle
8 – Pie-IX
9 – Papineau
10 – Viau
11 – Médéric-Martin
12 – Lachapelle
13 – Louis-Bisson
14 – Galipeault
15 – Ile-aux-Tourtes
16 – Arthur-Sauvé
17 – Vachon
18 – Gédéon-Ouimet
19 – Marius-Dufresne
20 – David
21 – Mathieu
22 – *Rte 125*

Figure 10- Critical link analysis. Bands show flow on links carrying traffic over the Gedeon-Ouimet Bridge (circled) outbound toward the top left of the figure. Points are centroids which are producing or attracting the trips. Larger centroids are generating more trips.

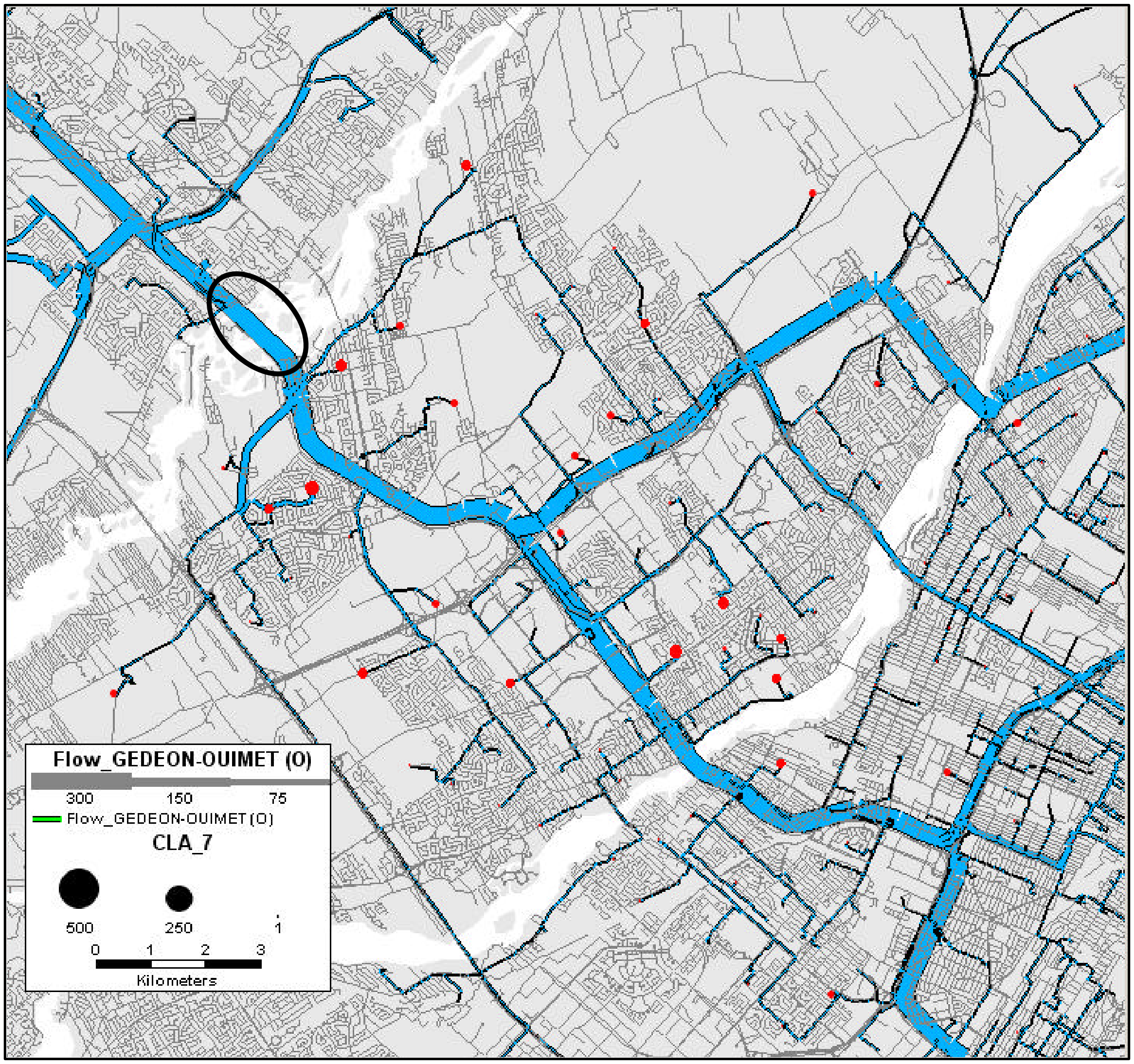


Figure 11- Route system in TransCAD showing STM bus and metro routes and stops.

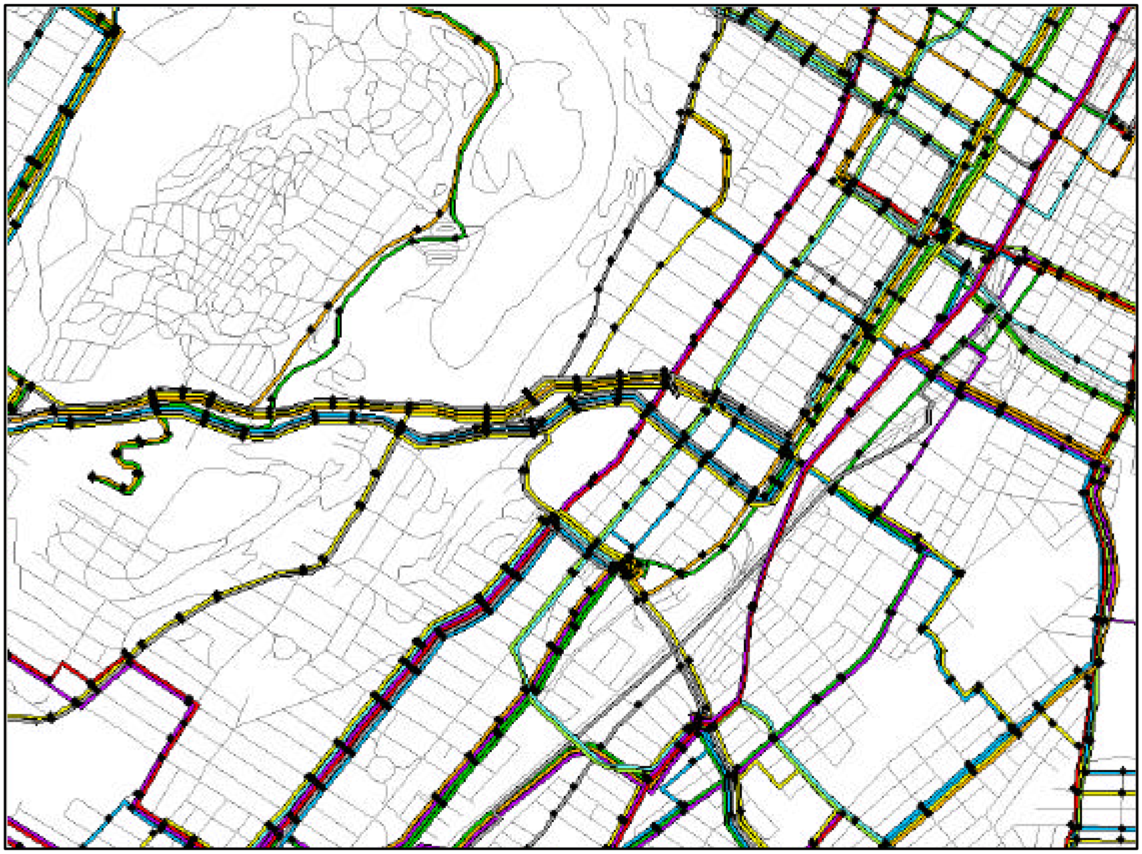


Figure 12- Example of improperly connected centroid, Boucherville Islands. Centroid connectors are the dark lines. The top connector is attached to the mainland and the bottom connector is attached to a link isolated from the rest of the network due to the functional class of connecting roads.

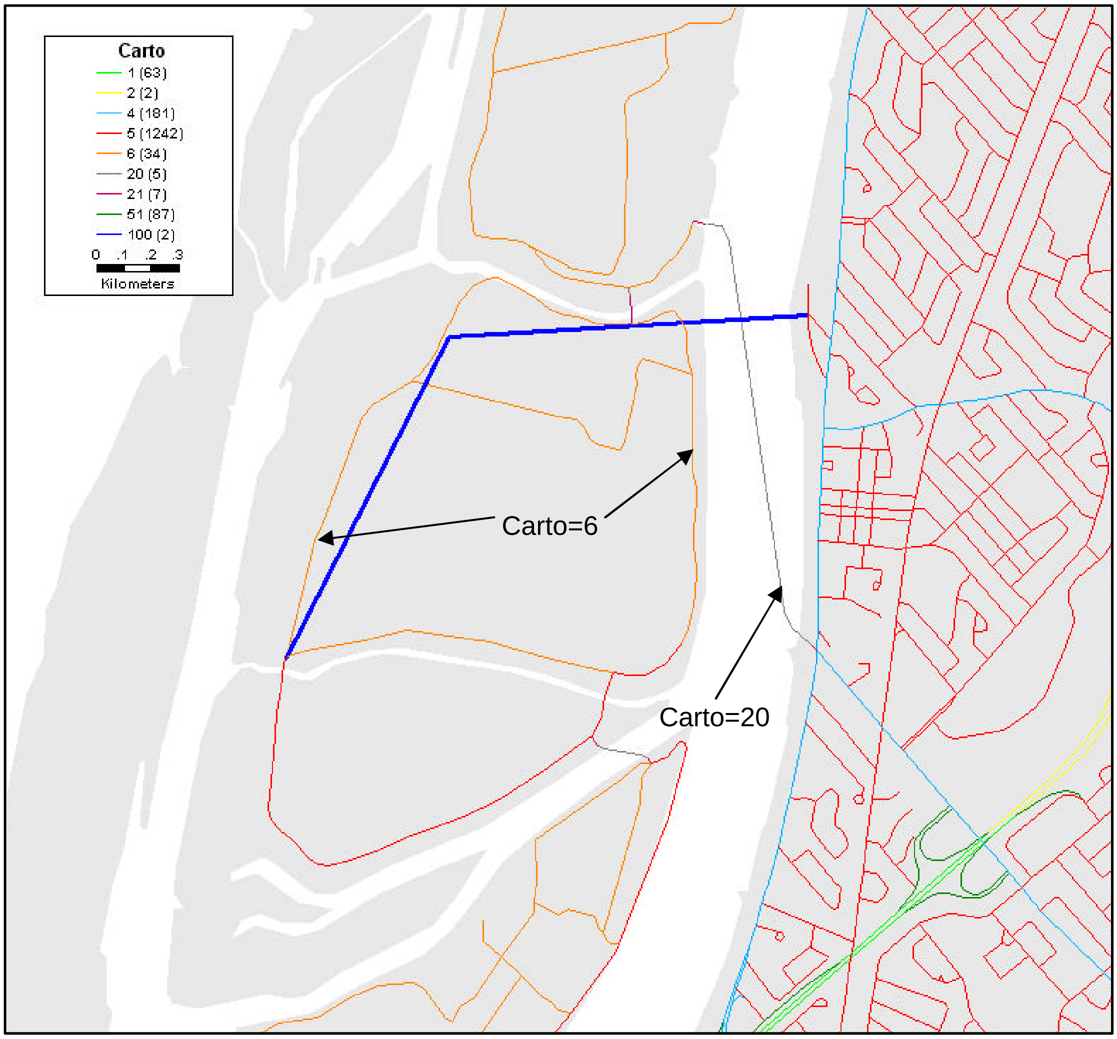


Figure 13- Scatter plot of counts vs. observations, entire AM peak, including fitted points.

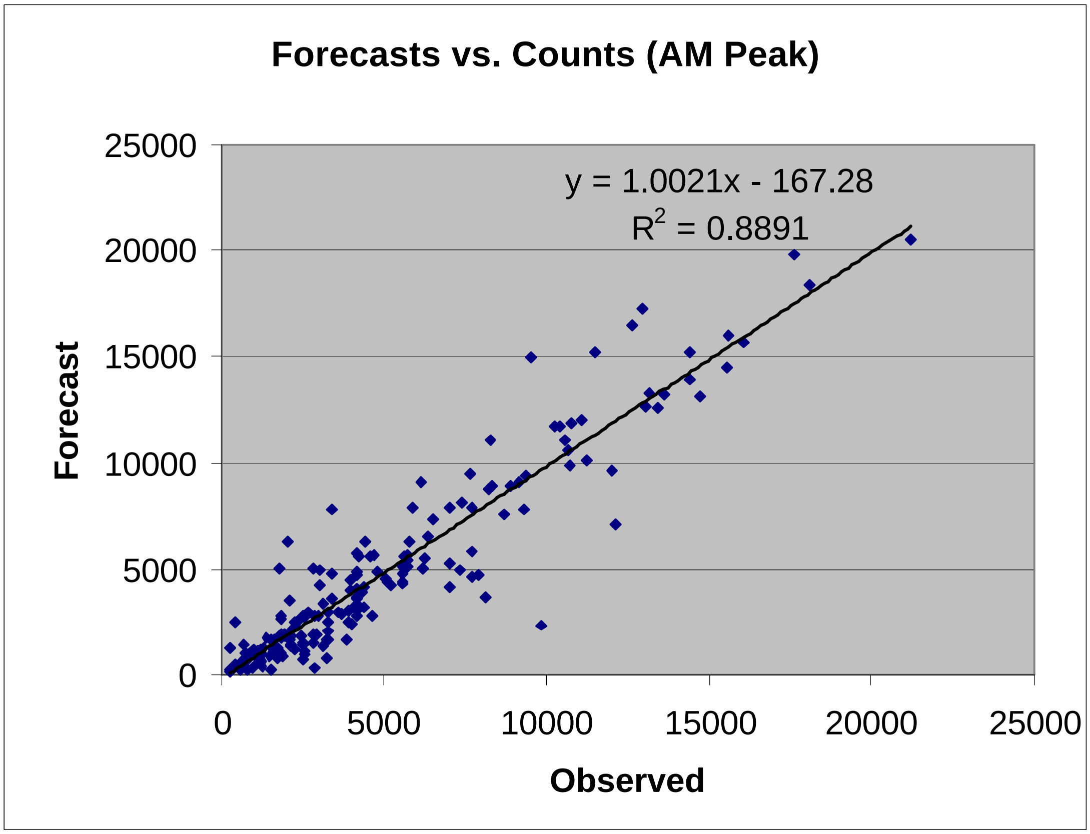
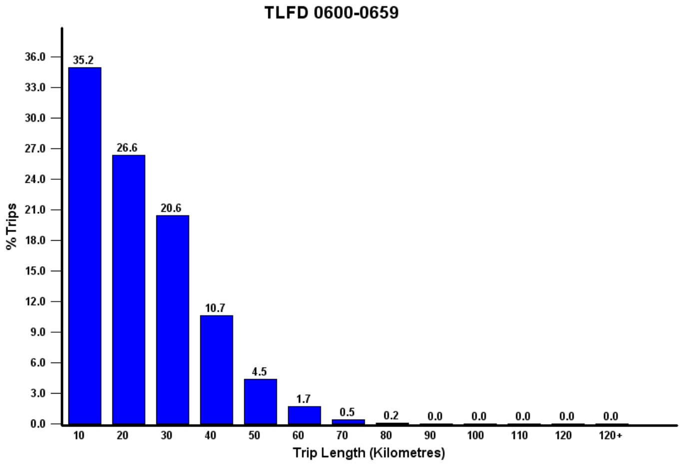
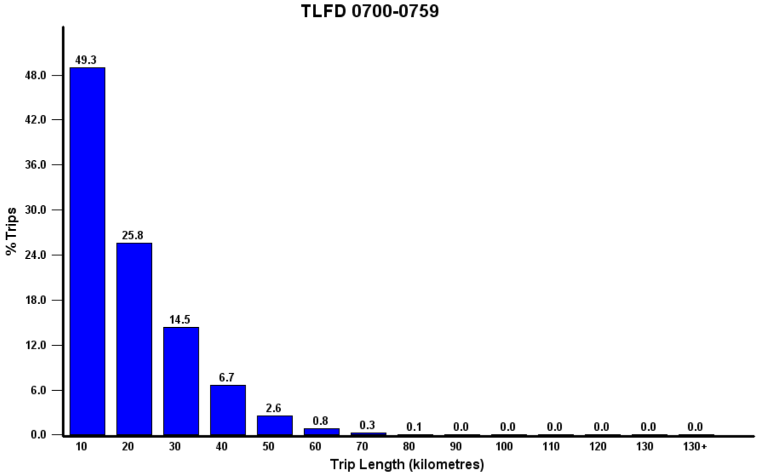


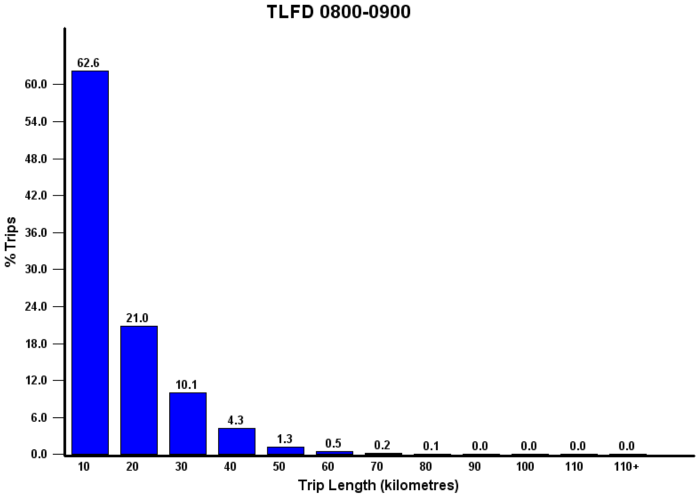
Figure 14- Example of trip length (in kilometres) frequency distributions.



a) First hour: 0600-0659

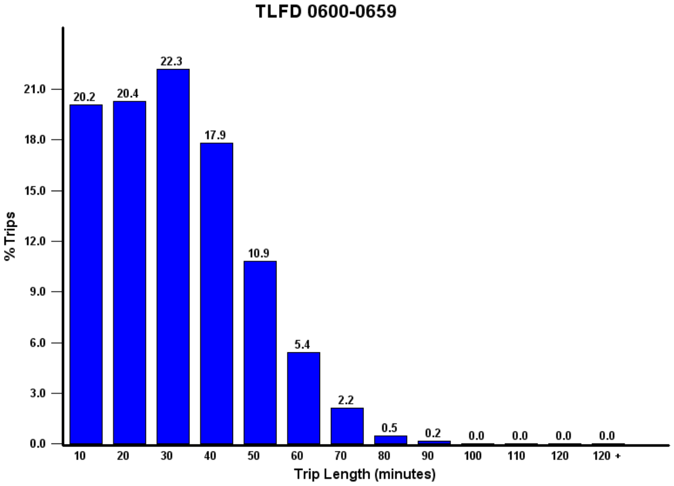


b) Second hour: 0700-0759

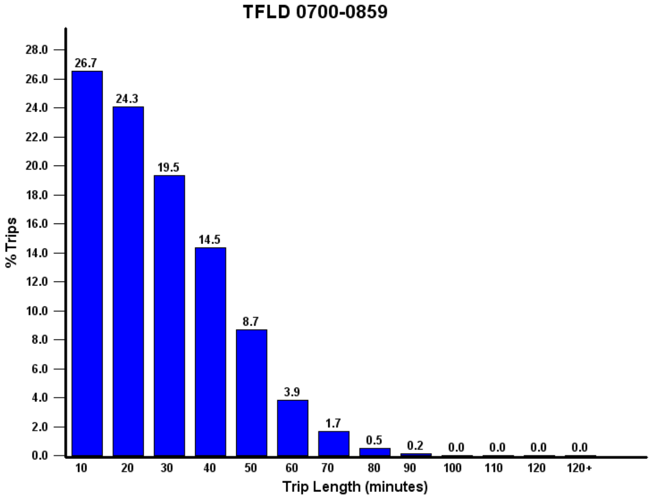


c) Third hour: 0800-0859

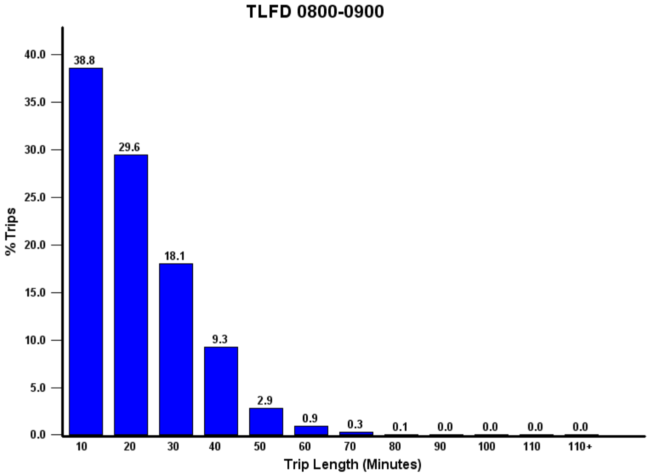
Figure 15- Example of trip length (minutes) frequency distributions.



a) First hour: 0600-0659



b) Second hour: 0700-0759



c) Third hour: 0800-0859

Figure 16- Error distribution on autoroute links

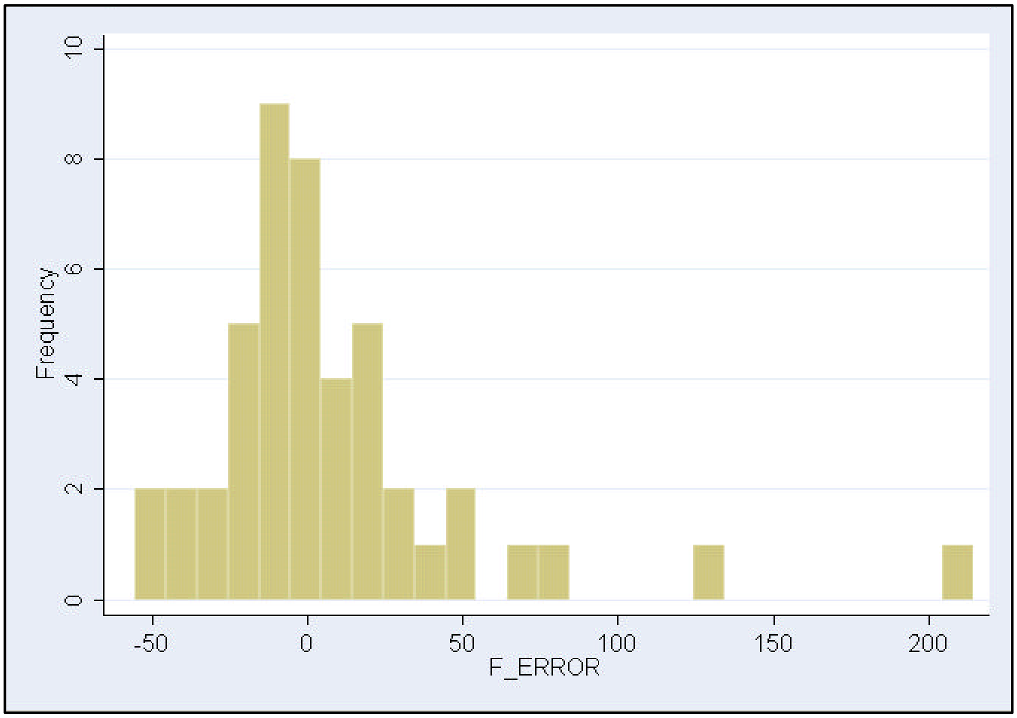


Figure 17- Deviations at successive autoroute observation posts (inbound)

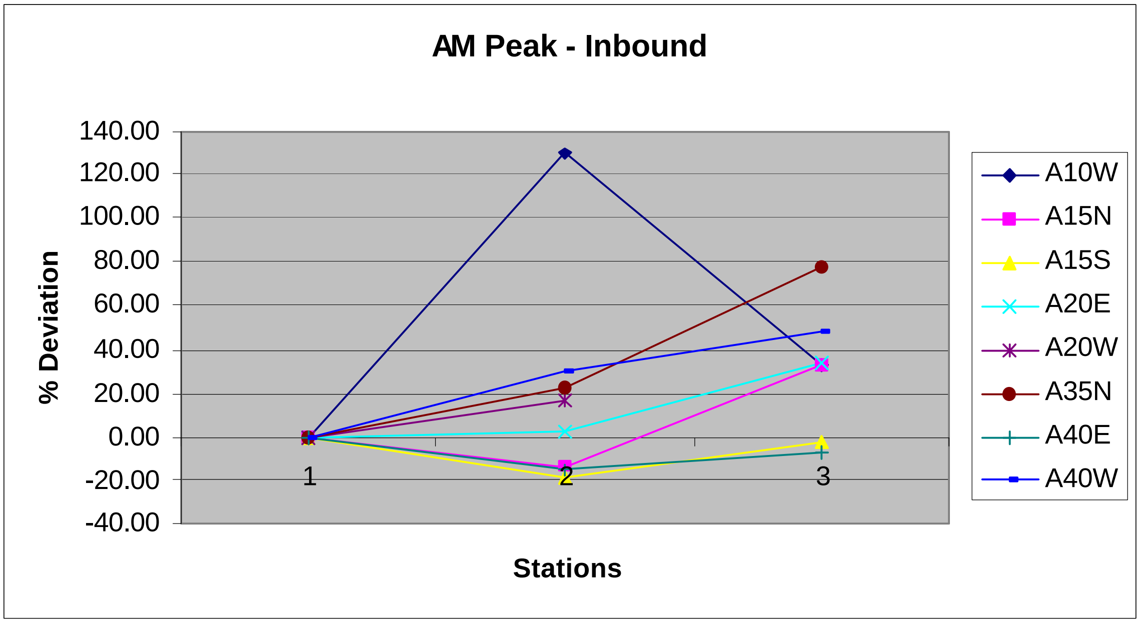


Figure 18- Deviations at successive autoroute observation posts (outbound)

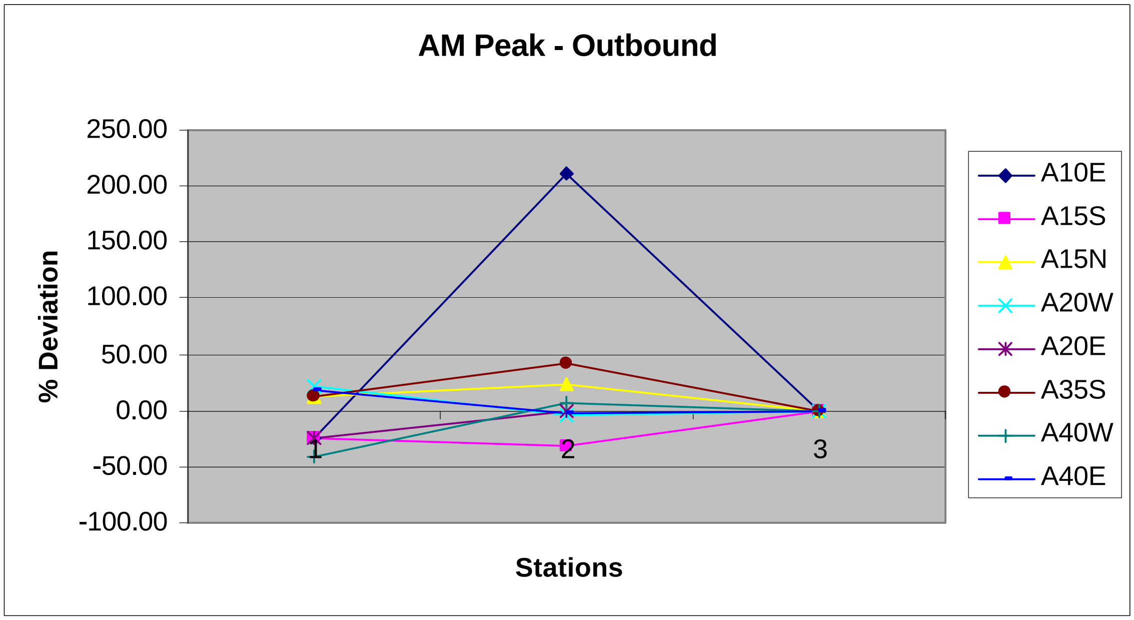


Figure 19- Error distribution on bridge links

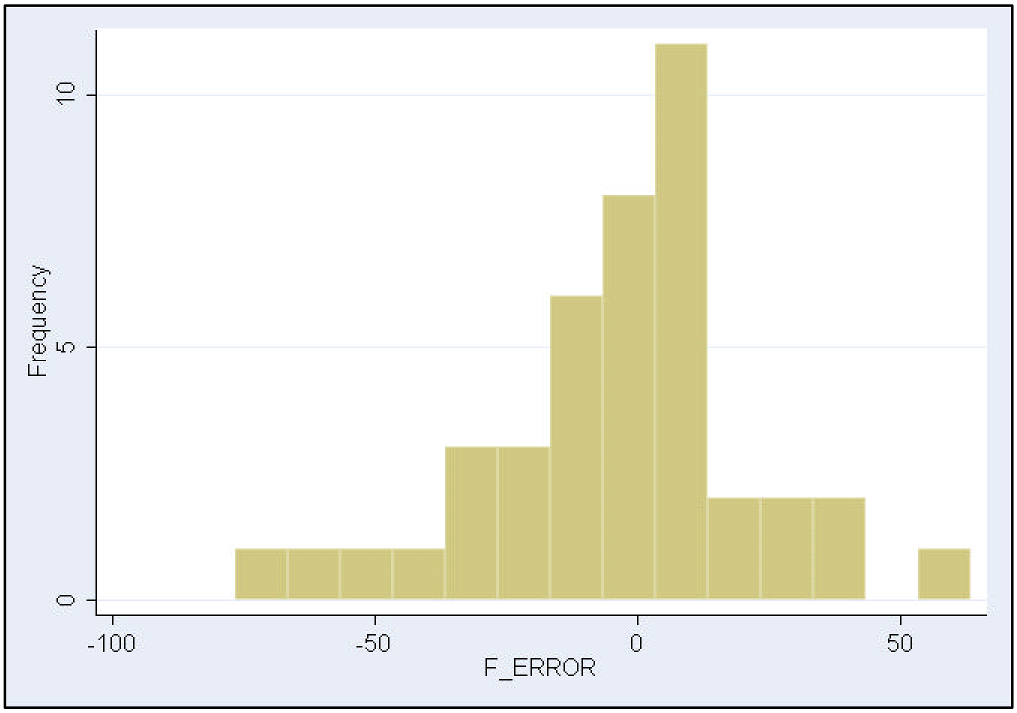


Figure 20- Number of trip origins – Champlain Bridge (Inbound)

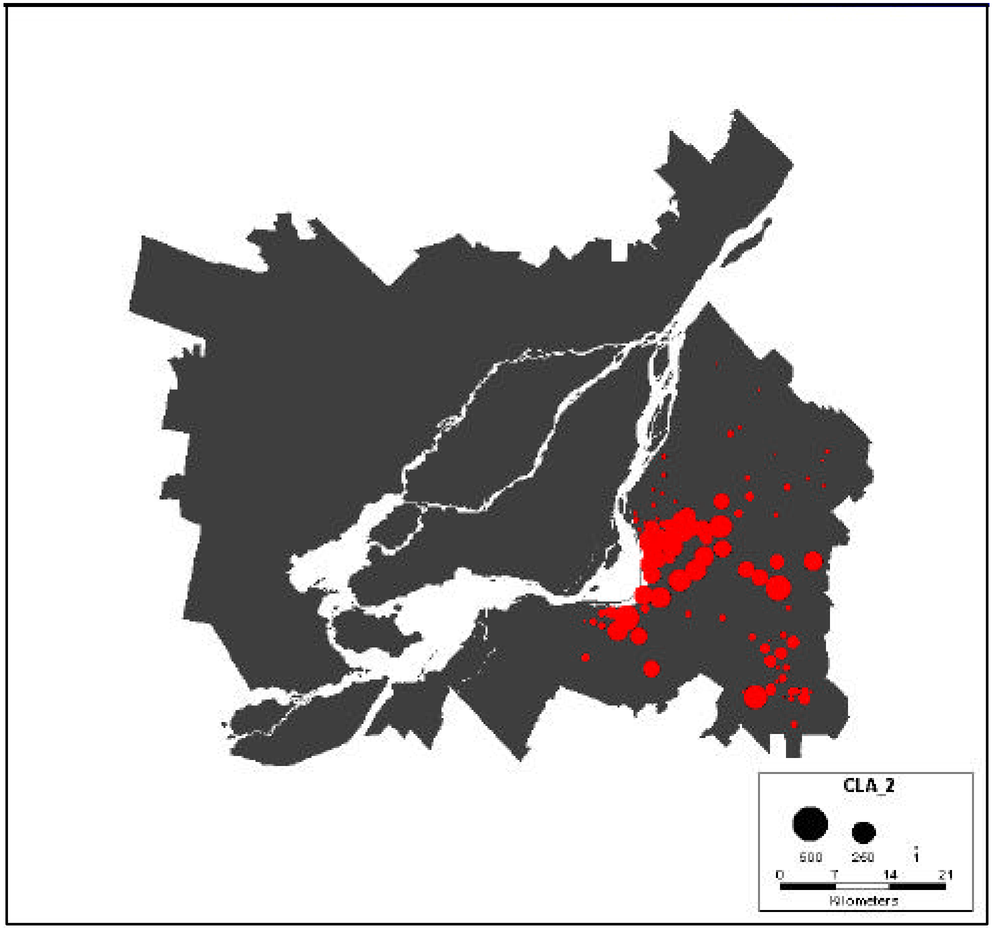
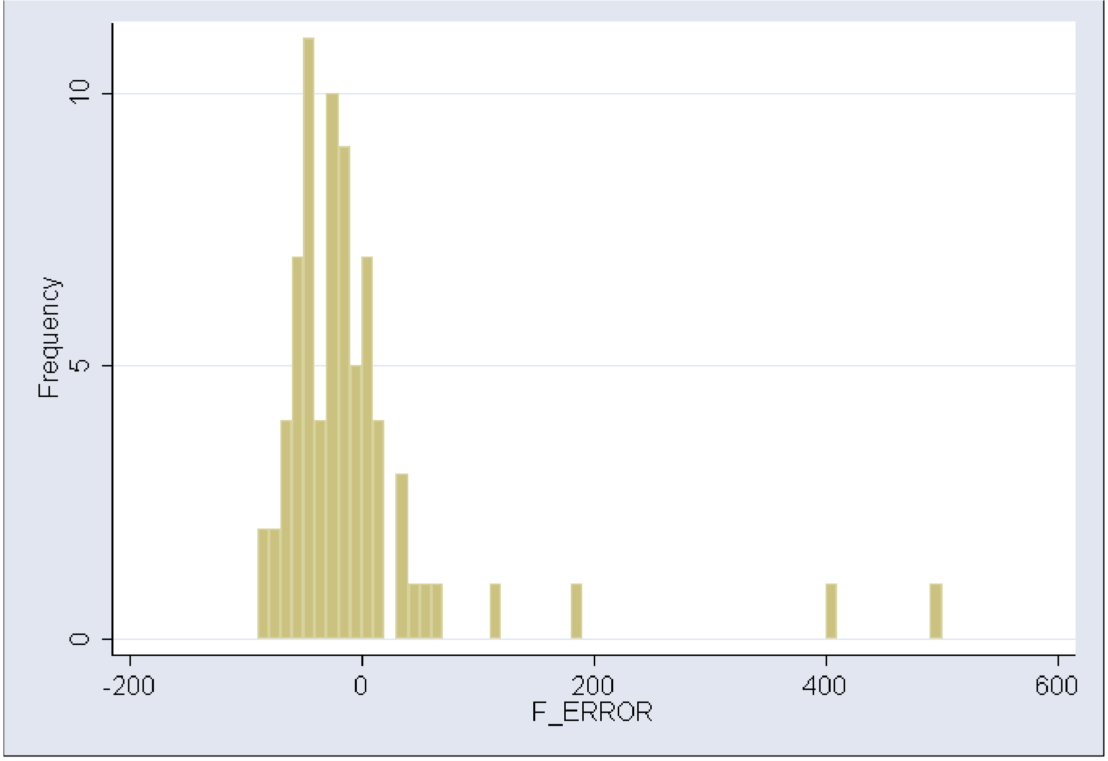


Figure 21- Number of trip destinations for the Champlain Bridge, inbound. Note the circled destinations on the South Shore.

Figure 22- Error distribution on non-bridge, non-autoroute links



APPENDIX 1 – Origin-destination survey fields (AMT, 2001)

MONTRÉAL O/D SURVEY 1998

File contains data for each sample week

Number of Records : 417950 comprising 65227 residences
164075 people (162594 utilized)
384945 trips (383176 utilized)

TYPE :
N Numeric
C Character

Name of field	Type	Length	Description
Ipere	N	6	Unique sequential number
m_numero	N	6	Trip number
m_debut	C	1	Head record associated with household : T : for the first occurrence blank : for susbsequent occurences
m_fexp	N	6.2	Expansion factor based on the number of residents by sector or census area as defined by Statistics Canada in the 1998 census. This weighting factor should only be used to estimate the characteristics of household.
m_auto	N	2	Number of vehicles in the household (0 to 14)
m_pers	N	2	Number of people in the household (1 to 14)
m_domrmr	N	3	Census Metropolitan Area code : 459, 462, 465
m_domsdr	N	5	Household 1996 census district (municipality)
m_domsr	N	6.2	Household 1996 census tract (none if outside CMA)
m_domsm	N	3	Household analysis sector (100 municipal sectors)
p_rang	N	2	Person number (1 to 14)
p_debut	C	1	Head record associated with the person : T : for the first occurence blank : for susbsequent occurences
p_fexp	N	6.2	Expansion factor based on age and sex groupings according to census regions as defined by Statistics Canada in the 1996 census. This expansion factor must be used to estimate the characteristics of individuals and their movements. Use FLAG=1 to save data only for persons incorporated in the survey and for whom the FACPER field is not blank.
p_valide	N	2	Code identifying if person was used in the expansion 1 : person was incorporated into the survey
p_sexe	N	2	Sex (1=male 2=female)
p_age	N	3	Age (1 à 99)
p_grage	N	2	Age group : 1 : 1 to 4 yrs 2 : 5 to 9 yrs 3 : 10 to 14 yrs 4 : 15 to 19 yrs 5 : 20 to 24 yrs 6 : 25 to 34 yrs 7 : 35 to 44 yrs 8 : 45 to 54 yrs 9 : 55 to 64 yrs 10 : 65 to 74 yrs 11 : 75 plus
p_statut	N	2	Occupation: 1 : Full-time worker 2 : Part-time worker 3 : Student 4 : Retired 5 : Other 6 : N/A : child les than 4 yrs old 7 : No response
p_permis	N	2	Possesses a driver's license : 1 : Yes 2 : No 3 : Doesn't know 4 : No response 5 : Not applicable (less than 16 yrs old)

MONTRÉAL O/D SURVEY 1998

File contains data for each sample week

Number of Records : 417950 comprising 65227 residences 164075 people (162594 utilized) 384945 trips (383176 utilized)	TYPE : N Numeric C Character

Name of field	Type	Length	Description
p_mobil	N	2	Person is mobile : 1 : Yes 2 : No, does not travel 3 : N/A : child less than 4 yrs old 4 : Doesn't know 5 : No response
d_deplac	N	2	Personal trip number
d_hrede	N	4	Departure time (hhmm = 0 à 2800) From 2401 to 2800, only trips required to return home are recorded.
d_grhre	N	2	Departure hour groups : 1 : 0h to 5h59 2 : 6h to 8h59 3 : 9h to 11h59 4 : 12h to 15h29 5 : 15h30 to 18h29 6 : 18h30 to 23h59 7 : 24h to 28h
d_motif	N	2	Reason for the journey : 1 : Work 2 : Business meeting 3 : On the road 4 : School 5 : Shopping 6 : Pleasure 7 : Visit to friends/ parents 8 : Health 9 : Driving someone else 10 : Looking for someone 11 : Returning home 12 : Other 13 : Undetermined / no response/ NSP
d_mode1	N	2	First mode taken : (can be blank) 1 : Car – driver 2 : Car – passenger 3 : Bus STCUM 4 : Métro 5 : Bus STRSM 6 : Bus STL 7 : Bus CIT 8 : TRAIN 9 : School bus 10 : Other bus 11 : Taxi 12 : Motorcycle 13 : Bicycle 14 : On foot 15 : Handicapped transport 16 : Interurban mode 17 : Junction point 18 : Undetermined
d_mode2	N	2	Second mode taken (idem mode1)
d_mode3	N	2	Third mode taken (idem mode1)
d_mode4	N	2	Fourth mode taken (idem mode1)
d_mode5	N	2	Fifth mode taken (idem mode1)
d_mode6	N	2	Sixth mode taken (idem mode1)

MONTRÉAL O/D SURVEY 1998

File contains data for each sample week

Number of Records : 417950 comprising 65227 residences
164075 people (162594 utilized)
384945 trips (383176 utilized)

TYPE :
N Numeric
C Character

Name of field	Type	Length	Description
d_jontyp	N	2	Junction type indicator : 1 : Private (car, motorcycle, taxi, bike), public (bus, métro, commuter train) 2 : Public (bus, métro, commuter train), private (car, motorcycle, taxi, bike) 3 : Private (car, motorcycle, taxi, bike), external (plane, bus, train, etc) 4 : External (plane, bus, train, etc), private (car, motorcycle, taxi, bike) 5 : Public (bus, métro, commuter train), external (plane, bus, train, etc) 6 : External (plane, bus, train, etc), public (bus, métro, commuter train) 7 : Other
d_orirmr	N	3	Origin Census Metropolitan Area code: 459, 462, 465
d_orism	N	3	Analysis sector of place of origin (1 to 101 : see annexe 1)
d_orisdr	N	5	1996 census district of origin (none if outside RMR)
d_orisr	N	6.2	1996 census tract of origin
d_desrmr	N	3	Destination Census Metropolitan Area code: 459, 462, 465
d_dessdr	N	5	1996 census district of destination
d_dessr	N	6.2	1996 census area of destination (none if outside RMR)
d_dessm	N	3	Municipal sector of destination (1 to 101 : see annexe 1)
d_jonrmr	N	3	Metropolitan region census code: 459, 462, 465
d_jonsdr	N	5	1996 census district of junction point
d_jonsr	N	6.2	1996 census area of junction point (none if outisde RMR)
d_jonsm	N	3	Municipal district of junction point (1 to 101 : see annexe 1)

APPENDIX 2 – DMTI Route Logistics field names in TransCAD (DMTI, 2001)

FIELD NAME	DESCRIPTION
ID	TransCAD ID
Length	in kilometres (from TransCAD)
Dir	TransCAD Direction
Street	Street Name
FromLeft	Address Range
ToLeft	Address Range
FromRight	Address Range
ToRight	Address Range
Predir	Prefix direction
Pretype	Prefix type
Street Name	Complete street name
SufType	Suffix type
SufDir	Suffix direction
Carto	Cartography or functional class
Left_mun	Municipality on left
Right_mun	Municipality on right
Left_fsa	Forward sortation area on left
Right_fsa	Forward sortation area on right
Left_prv	Province
Right_prv	Province
Uniqueid	DMTI Unique ID
Oneway	Street directions
Road_dir	Road direction by nodes
Fromnode	
Tonode	
Speedmiles	speed in miles
Rdlenmiles	road length in miles
Speedkm	speed in kms
Rdlenmetres	road length in metres
Traveltime	Free flow travel time

APPENDIX 3 – TransCAD output for the 3 traffic assignment models (one for each hour of the AM peak)

```
     Starting Procedure Traffic Assignment on January 25, 2005 (02:41 PM)
        Iteration              Step        Relative Gap     Max. Flow Change          RMSE    % RMSE
        -----------------------------------------------------------------------------------------------------
                1          0.301048           0.444851        3854.505328        125.74     205.76
                2          0.274194           0.099319        2176.129412         58.83      90.41
                3          0.125750           0.051019        1415.179116         25.40      39.18
                4          0.264403           0.022251        1407.081440         27.66      42.72
                5          0.098344           0.030668        1074.138285         16.94      26.30
                6          0.287544           0.010483         751.517967        20.19      31.35
                7          0.103610           0.021638         740.982490        14.71      22.96
                8          0.179444           0.008932         830.985046        13.65      21.29

        INPUT FILES
        ===========
        Network               : G:\MontrealRN\QCRoutes\TransCAD\Version 11_2\Network1.net
        Demand Table            : G:\MontrealRN\QCRoutes\TransCAD\Version 11_2\ODSurvey\AMPeak_2.mtx

        OUTPUT FILES
        ============
        Flow Table             : G:\MontrealRN\QCRoutes\TransCAD\Version 11_2\Traffic
Assignment\0600_0659_LinkFlow(13).bin

        LINK FIELDS
        ===========
        Cost                  : Traveltime
        Capacity              : Capacity*
        BPR-Alpha               : Alpha
        BPR-Beta               : Beta

        OD DEMAND
        =========
        OD Pairs               :             962361
        Non zero OD Pairs       :               36427
        Demand                 :          193559.47
        Intranodal Demand       :           14997.57

        PARAMETERS
        ==========
        Method                : User Equilibrium with Turn Penalties
        Maximum Iterations      :                 20
        Iterations             :                 9
        Conv. Criteria          :               0.01

        Running Results
        ===============
        Relative Gap           :               0.01
        RMSE                  :             13.65
        % RMSE                 :              21.29
        Max Flow Change         :              830.99
        Equilibrium reached      : Yes
        Total V-Time-T          :         4007417.57
        Total V-Dist-T          :         3762434.89
        Centroid V-Time-T       :           102947.34
        Centroid V-Dist-T       :           68631.56
        V-Time-T w/o Centroids   :          3904470.24
        V-Dist-T w/o Centroids   :         3693803.34


        Total Running Time 00:30:40.983.
     --------------------------------------------------------------------
     Starting Procedure Traffic Assignment on January 25, 2005 (03:21 PM)
        Iteration              Step        Relative Gap     Max. Flow Change          RMSE    % RMSE
        -----------------------------------------------------------------------------------------------------
                1          0.355912           0.752832        4733.243797        200.82     198.14
```

```
        2          0.243646          0.242097        2279.223902          87.11      80.38
        3          0.162305          0.097582        1603.404774          44.88      41.30
        4          0.181190          0.053786        1357.205467          39.11      36.12
        5          0.114809          0.037042         942.615535         23.37      21.60
        6          0.220646          0.023200        1070.656407          27.90      25.86
        7          0.081703          0.029898         671.186696         17.00      15.81
        8          0.260136          0.013632         725.519675         22.58      21.04
        9          0.090976          0.023250         632.278278         16.57      15.50
       10           0.152531          0.013927         684.154253          16.90      15.82
       11           0.068202          0.014500         492.406488          10.30       9.66
       12           0.178122          0.007934         583.826756          13.31      12.49

  INPUT FILES
  ===========
  Network              : G:\MontrealRN\QCRoutes\TransCAD\Version 11_2\Network1.net
  Demand Table            : G:\MontrealRN\QCRoutes\TransCAD\Version 11_2\ODSurvey\AMPeak_2.mtx

  OUTPUT FILES
  ============
  Flow Table             : G:\MontrealRN\QCRoutes\TransCAD\Version 11_2\Traffic
Assignment\0700_0759_LinkFlow(13).bin

  LINK FIELDS
  ===========
  Cost                 : Traveltime
  Capacity               : Capacity*
  BPR-Alpha               : Alpha
  BPR-Beta               : Beta

  OD DEMAND
  =========
  OD Pairs               :              962361
  Non zero OD Pairs       :               45214
  Demand                  :           378600.05
  Intranodal Demand       :            33307.30

  PARAMETERS
  ==========
  Method                 : User Equilibrium with Turn Penalties
  Maximum Iterations      :                 30
  Iterations              :                 13
  Conv. Criteria          :               0.01

  Running Results
  ===============
  Relative Gap            :               0.01
  RMSE                    :              13.31
  % RMSE                  :              12.49
  Max Flow Change         :             583.83
  Equilibrium reached     : Yes
  Total V-Time-T          :         6925070.75
  Total V-Dist-T          :         5733013.81
  Centroid V-Time-T       :          186899.70
  Centroid V-Dist-T       :          124599.80
  V-Time-T w/o Centroids   :          6738171.05
  V-Dist-T w/o Centroids   :          5608414.01


  Total Running Time 00:47:30.844.
-------------------------------------------------------------------
Starting Procedure Traffic Assignment on January 25, 2005 (04:26 PM)
   Iteration               Step        Relative Gap     Max. Flow Change          RMSE    % RMSE
  ---------------------------------------------------------------------------------------------------
        1          0.399687          0.311007        3630.431163         106.71     135.98
        2          0.321393          0.035351        1553.755571          43.85      54.45
        3          0.323955          0.013272         800.818298         26.38      32.90
        4          0.190399          0.010887         625.298045         16.19      20.25
        5          0.270731          0.006803         680.238368         15.78      19.77
```

```
        INPUT FILES
        ===========
        Network              : G:\MontrealRN\QCRoutes\TransCAD\Version 11_2\Network1.net
        Demand Table            : G:\MontrealRN\QCRoutes\TransCAD\Version 11_2\ODSurvey\AMPeak_2.mtx

        OUTPUT FILES
        ============
        Flow Table            : G:\MontrealRN\QCRoutes\TransCAD\Version 11_2\Traffic
Assignment\0800_0859_LinkFlow(13).bin

        LINK FIELDS
        ===========
        Cost                 : Traveltime
        Capacity             : Capacity*
        BPR-Alpha             : Alpha
        BPR-Beta              : Beta

        OD DEMAND
        =========
        OD Pairs              :            962361
        Non zero OD Pairs       :            43515
        Demand                :          352772.96
        Intranodal Demand       :          40085.82

        PARAMETERS
        ==========
        Method               : User Equilibrium with Turn Penalties
        Maximum Iterations      :              20
        Iterations            :              6
        Conv. Criteria          :              0.01

        Running Results
        ===============
        Relative Gap           :              0.01
        RMSE                  :             15.78
        % RMSE                 :             19.77
        Max Flow Change          :              680.24
        Equilibrium reached      : Yes
        Total V-Time-T          :         4432140.69
        Total V-Dist-T          :         4226269.40
        Centroid V-Time-T        :          152218.13
        Centroid V-Dist-T        :          101478.75
        V-Time-T w/o Centroids   :          4279922.56
        V-Dist-T w/o Centroids   :          4124790.65


        Total Running Time 00:22:29.530.
```