DEVELOPING A DYNAMIC AGENT-BASED MULTIMODAL TRAFFIC ASSIGNMENT MODEL FOR TRANSPORTATION PLANNING AND SIMULATION: LESSONS AND METHODS FROM A CASE STUDY ON THE GREATER TORONTO AND HAMILTON AREA *

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Introduction

Traditional transportation planning approaches apply aggregate four-stage models to mimic individuals' travel choices within urban regions. Demand data is stored in matrices, with rows and columns referencing traffic analysis zones (TAZs). These widely deployed conventional models are primarily used to evaluate regional-scale infrastructure investments (such as highways), or to simulate long-term economic trends. However, it is cumbersome and difficult to use these models to effectively test complex policies (such as transit pricing policies), as they do not provide sufficient level of detail in their standard formulation. These complex policies instead require large cross-classification tables and many matrices to represent different classes of traveller if the standard approach is to be used. By contrast, agent-based models simulate each traveller in an urban region as a discrete object, defining dimensions of complexity as agent attributes (e.g., each agent has an occupation, age, gender, etc.). Complex population heterogeneity can be thus modelled as an endogenous aspect of the model: agent-based models simply define dimensions of the data at the individual level and then aggregate as required for analysis. As a result of this flexibility, there is significant interest in agent-based approaches

Historically, the four-stage model has been used by transportation planners to answer questions with respect to travel behaviour and the implications that potential policies will have on individuals' behaviour. This modelling procedure is limited by the use of trips as a unit of demand, which fails to understand the actual reasoning behind travel within the urban region, thereby limiting the applicability of such models for complex policy testing. Conversely, considering daily travel-activity chains or tours allows for representing travel behaviour more accurately when compared to modelling peak period trips only (Doughty et al, 2002). In activity-based models, trips are considered as a product of demand for activities, which gives a far better representation of the underlying reason for travel. When applied to a disaggregate framework, each agent defines their own schedule of activities, and the trips become the necessary linkage between activities in different locations. Hence, agents can make multiple trips throughout the day for work, shopping, leisure or other activities, forming a set of sequential trips or a trip-chain. This provides a more behaviorally realistic method of examining travel behavior relative to the standard four-stage approach. These daily activity-travel chains can be modeled as a chain of choices made by each trip maker for different travel decisions, such as trip departure time, mode of travel choice, destination choice, trip purpose choice, etc. Such chain of choices is then passed to a trip assignment tool in order to simulate individuals' route choices and thereby obtain trip level-of-service attributes for each trip during the course of day.

It is important to couple an activity-and-agent-based approach with a spatially disaggregate and temporally dynamic assignment procedure. In an activity model, schedules have a very fine grain quantization of time - as much as 15 minutes or as little as 1 second, and need to be able to estimate travel times to that level. This is at odds with static assignment approaches, whose assignment period is in the order of hours. Equally, spatial disaggregation is desirable for an agent-based model, since spatial heterogeneity (i.e., spatial distribution of activity locations) needs to be represented (Algers, Eliasson & Mattson, 2005). Such an integrated framework could be used to test and evaluate potential policy measures such as: changing pricing scenarios (e.g., congestion pricing and increasing transit fares), introducing new transit services, and improving station facilities (e.g., parking lots, ease of transfer, bike stands, etc.). These policies also highlight the need for a multimodal assignment system, which allow modellers to test the implications of different policies across a wide range of modes.

As of 2010, the MATSIM (Multi-Agent Transport Simulation) platform is a dynamic activity and agent-based software packages which includes modules for joint transit and automobile assignment. MATSIM's development has been facilitated by the advent of modern desktop computers and the ability to simulate a small percentage of traffic while still producing useable disaggregate results, making the assignment procedure more reasonable from a computational standpoint (Erath et al, 2012). In order to develop a fully functioning multimodal assignment tool using any software platform, transit schedule data is essential as it provides the details of not only where transit stops are located, but also when transit vehicles will visit these stops and in what order. As a further complication, in many larger urban areas, multiple transit agencies may operate, with many agencies using their own format for storing their transit schedules, which creates issues with respect to data processing. Fortunately, the development and wide spread adoption of General Transit Feed Specification (GTFS) data, a common format for transit agencies to publish their schedules for developers, solves the problem of divergent data sources. These features, coupled with an the wide spread use of planning level assignment networks as part of the assignment portion of the four stage model, prompted the exploration into the feasibility of developing a multimodal agent-based dynamic simulation using these data sources.

Literature Review

The development of a multimodal assignment model requires a number of different components, including a software platform, the individual sub-algorithms within the software and transportation supply and demand information. The literature review presented here will present a number of the issues that are inherent in many if not all conventional software packages and data sources, and will frame the discussion of how to improve both the software and the data available to modellers and planners.

Dynamic Multimodal Assignment

Dynamic traffic assignment is an essential tool for understanding and modelling complex and indirect problems such as travel demand management tools like flexible work hours or road pricing. The vast majority of these models use the standard TAZ system, allowing for conventional OD matrices that fit within traditional four stage models to be utilized. These approaches continue to have problems in terms of spatial and temporal aggregation, and many of the software packages utilized for this do not as of yet support multimodal assignment. To compensate for the unimodal nature of many conventional approaches, techniques that attempt to replicate the impact of mixed mode traffic are utilized. One such approach involved using dynamic capacities along roads to mirror the impact of pedestrian and cycling activities on auto travel times for a sub section of Beijing (Ben-Akiva et al., 2012). Other possibilities include using a factor of automobile travel time to determine transit travel time for the same origin and destination (Rieser, Grether, & Nagel, 2009). While reasonable for more aggregate assumptions, the explicit modelling of multiple modes will provide a more detailed picture of how they potentially interact. As such, the limitations inherent with conventional approaches were instrumental in framing the selection of a modelling framework; a platform, which could support mixed mode assignment dynamically, while also providing temporal and spatial disaggregation; namely the MATSIM platform.

The MATSIM platform is a modular dynamic platform, which allows for large-scale agent-based transportation simulations. Each module within the MATSIM framework is independent, which allows for stand-alone utilization or combination with some or all of the other modules. Of particular interest to the development of multimodal MATSIM networks is route assignment for both transit and private automobiles simultaneously. Applications that utilize both of these modules include projects in Zurich, Singapore, South Africa (Rieser,

2010) (Erath et al., 2012) (Wevell, 2011) as well as preliminary investigations for Toronto. The preliminary work for the Toronto network investigated pure auto assignment (Gao, Balmer & Miller, 2008), the possibility of using MATSIM for multimodal assignment within a North American context (Kucirek, 2012) (the MATSIM platform was developed with a European transit system in mind) and a preliminary investigation into modifying existing planning level networks to reach the level of detail required for mesoscopic multimodal assignment (Weiss et. al. 2013). With these works completed, the development of a proper assignment model for the region could be undertaken. Unfortunately a challenge with the transit routing procedure utilized by the MATSIM software was identified.

Transit Routing

The transit routing procedure outlined by Reiser (2010) for the MATSIM framework was developed as an initial routing procedure with more emphasis placed on achieving a working transit routing procedure rather than routing efficiency or accuracy. This is an improvement on the earlier work done by Rieser, Grether, & Nagel (2009), which simply modeled transit by proxy (transit travel was a function of auto travel).

Of particular note with the Reiser approach is the concept of a transit routing network, which connects stops together by either transit vehicle links or transfer walk links. Because this network is only used for routing, it is important to differentiate between the physical stop infrastructure and an actual stop along a route. The same physical transit stop may in fact serve multiple routes, resulting in a large number of route stops located at the same physical location. This results in the number of "*route-stops*", which represent nodes in the physical network being higher than the actual number of physical transit stops. Within this framework the transit vehicle links are simply copies of the actual road network, whereas the transfer links are created during the routing network generation. A buffer around each route stop is created and a transfer link is created between the central route stop and all other route stops that fall within that buffer. This approach results in a functional routing network that allows for all reasonable connections to be made, but is severely limited in terms of its efficiency, resulting in excessively long routing times on large interconnected transit networks. As such, it is reasonable that this approach is a barrier to the adoption of the MATSIM framework for multimodal assignment and a reasonable solution to this barrier is proposed in section 4.

Data Sources

The methods presented herein were created for the full development of a fully functioning dynamic multimodal assignment for a large urban region. Because of the specific requirements of the MATSIM platform, these methods were designed specifically to meet said requirements, however these techniques could likely be modified to fit other mesoscopic simulation platforms. These methods were designed to make use of existing and readily available resources that are commonly used by consultants and planning agencies. The resources that are required for these methods are:

1. A generic planning-level network, which is typically used for static traffic assignment using traffic zones as part of the assignment portion of the four-stage model. The planning level network must be converted to a MATSIM XML network file. Fortunately, there is support to convert planning level networks from a number of different software packages to be compatible with MATSIM framework.

2. Transit Schedule data in the generic form of GTFS for the region. Such datasets contain information about transit stops and routes. However, transit schedule data needs to be processed as it contains detailed information about every scheduled vehicle departure. This processing is outlined in the work of Kucirek (2012). These procedures organizes the GTFS data efficiently, extracting the relevant information for the MATSIM routing procedure, thereby minimizing the size of the MATSIM transit schedule file and map the transit data to the network.

3. Travel diary data to represent the travel demand, which will be used to create the demand for the assignment. Such travel information typically contains lists of activities performed by

each respondent, the activity locations, each activity end time, and the mode used to travel between activities. This information can be used to create the activity schedule for agents travelling during the course of the day. Within the MATSIM framework this schedule is stored in a “plans” file.

The combination of the first two data sources can often be challenging due to resolution mismatching. For a more detailed discussion of these issues and potential solutions please refer to Ordonez & Erath (2011) and Weiss et al (2013).

Transit Routing Network Improvements

In large networks with a highly integrated transit service, the MATSIM routing procedure is highly inefficient as the result of the large number of superfluous transfers generated in the routing network. Notable applications of MATSIM for multimodal assignment typically utilize transit networks with a limited number of routes and stops (High Speed trains and trams, which are more common in European cities), thereby reducing the number of transfers. Applications on larger networks with a larger number of transit routes (typical of many North American cities) result in excessive run times for the transit assignment when using the conventional MATSIM approach (Kucierk, 2012). As such, a method to accelerate the routing procedure was required. This is particularly important given the large population sample size needed to perform multimodal assignment in order to avoid the capacity scaling issues for transit vehicles outlined by Erath et al., 2012. The outcome of the large population sample is that more individual agents will needed to be routed, which will in turn increase the runtime of the assignment simulation. One potential improvement to the routing efficiency is to add intelligence to the transit routing network generation procedure through the removal of inefficient transfers. Other options that could potentially be investigated include reworking the transit routing algorithm developed by Rieser (2010) during the initial MATSIM transit implementation to address efficiency concerns, however this investigation fell outside the scope of this work and will potentially be investigated at a later date.

The procedure which was developed only permits transfers between two transit routes whose stops infrastructure were mapped to the same node during the map matching procedure. This simplification results in a number of longer distance walk transfers to be omitted from the automated router network generation procedure. Therefore a number of pre-coded transfer links must be added to the hybrid network at locations with high numbers of these longer distance transfers. These locations are typically located at interchange locations, resulting in a fairly simple identification procedure, however the network modeller requires some network familiarity in order to fully identify and include these transfers. To further reduce the number of transfers created in the router network, a procedure to identify sections along two routes with identical stop infrastructure sequences was established. These sections can be thought of as overlapping sections or stop sequences. The router network generation procedure only creates transfers between the first two route stops and the last two stops in the overlap section. This approach reduces the number of transfers created between transit routes serving the same stop infrastructure, only allowing riders to transfer as the paths diverge. Furthermore, this method allows for explicit identification of routes that overlap in the reverse direction. Previously, these reverse overlap stops were accounted for by not allowing transfers between two routes on the same line (e.g. routes traveling northbound and southbound). This method results in routes that have reverse overlap, but are part of different lines, to have unnecessary transfers created. This more explicit approach identifies other interline cases of overlap and does not allow transfers between them. Furthermore the explicit identification of overlap also allows for transfers between branches of routes in the same line that serve the same direction, which was not previously permitted when the no intra-line transfer rule was adopted.

While conceptually straight forward, an automated method to determine the overlapping or reverse overlapping sections or opposite is a non-trivial matter. To identify sections of overlap between all of the potential route pairs, the procedure is illustrated in figure 1:

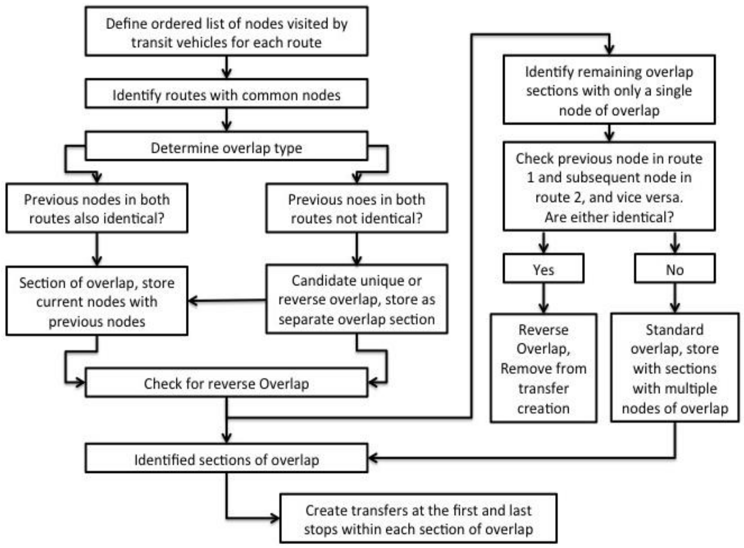

Figure 1: The Automated Router Network Generation Algorithm

With this procedure complete, an efficient routing network is now available for transit routing, speeding up the simulation. While this approach may require some minimal initial preparation, if multiple runs of assignment are to be performed, the savings in run time associated with this technique may be substantial.

In order to test the applicability of these methods, they were used on the Greater Toronto and Hamilton area, which had many of the prerequisite data sources for this method.

Case Study

The Greater Toronto and Hamilton area (GTHA) is situated to the north west of Lake Ontario in the province of Ontario, forming Canada's largest urban region. The GTHA's current population is over 6 million, with projected growth to approximately 8.6 million by 2031 (Metrolinx, 2008). The GTHA has eight local transit systems and a regional transit service operating under the administration of *Metrolinx,* a provincial government agency that was created to improve the coordination and integration of different modes of transportation in the region. Transportation planning agencies within the GTHA have identified a number of challenges facing the region as it continues to grow. The combination of population growth, auto-centric development, insufficient investment in transportation infrastructure and disconnected transit services are factors that contribute to the increase of reliance on cars, which in turn increase congestion levels. These issues are all indicators that an increase in transportation infrastructure and public transit spending are required so that the GTHA remains an economically competitive, attractive, vibrant and healthy region. The need for increased infrastructure in turn raises the question of where resources should be allocated such that they will have the most benefit. This question highlights the importance of transportation planning and modelling and in particular transit planning in order to understand the trade-offs between potential infrastructure improvements.

Data Sources

The data sources that were used mirror the more generic data inputs that are discussed in section 3. Each of the three inputs have their own unique characteristics that are outlined below.

EMME/MATSIM Auto Network

The existing MATSIM auto network was imported from a geocoded planning-level network developed for municipal planning departments (Travel Modelling Group, 2013) within the EMME traffic assignment software package. The EMME and the MATSIM networks consist of links and nodes, which are a virtual representation of the physical road infrastructure. Each node is associated with an identification number as well as a coordinate value and each link is associated with an identification number, a "from" node, a "to" node (representing the start and end nodes of each link), a length, a free flow speed, a capacity, and a list of modes which are permitted to use that link.

GTFS Data

In the case of the GTHA, GTFS datasets were obtained for the City of Toronto, the Region of York, the City of Mississauga, the City of

Brampton, the City of Hamilton and the GO Regional Transit Service, which is operated by Metrolinx. In cases where the transit authorities made their GTFS data publicly available, the GTFS data were retrieved from a GTFS database: *GTFS Data Exchange*. Otherwise the feeds were obtained by request from the transit agency in question. Three transit agencies that operate within the GTHA, did not have GTFS data available at the time of writing or were unwilling to provide said data and therefore these services were omitted from this study. Each of the agencies had their own identification tags, and agency specific prefixes were added to the IDs in order to distinguish between the agencies.

Transportation Tomorrow Survey

The Transportation Tomorrow Survey (TTS) forms the basis of the travel demand to be used for the multimodal assignment simulation. The TTS is a retrospective telephone survey conducted in the GTHA once every 5 years. The survey collects approximately 5% of the households within the region. Along with household data, both person and trip data was also collected, which permitted the generation of activity chains. These activity chains could be used to create compatible agent plans for use within the MATSIM framework. The most recent TTS was conducted in 2011, but was still under review and not available at the time of writing. Therefore, demand data from 2006 was used.

Transit Routing Improvement Results

The transit routing network improvements resulted in a routing network with 278453 links relative to a routing network with 458165 links being created using the base approach and a buffer distance of 500 meters, which exists in the MATSIM core. The improvements in the routing procedure proportionally decrease the worst-case routing time of the Dijkstra algorithm; a 40% reduction in worst-case transit routing time (Fredman & Tarjan, 1987). These routing based improvements also result in an overall improvement in network realism as connections that fall outside of the 500-meter radius are now pre-coded into the network and by extension, the router network. This is particularly relevant if a smaller connection radius is used, which is the case in many applications as an attempt to decrease the runtime of the simulation.

Assignment Results and Discussion

This procedure made use of the route assignment functionality of the MATSIM platform, which typically requires between 30 and 50 iterations to reach convergence. The MATSIM multimodal run summarized here was performed on an Intel® Core™ i7-3770 CPU @ 3.40GHz with 16.0GB of RAM with a 64-bit operating system. 30 iterations of multimodal assignment were performed. This resulted in a run time of less than 24 hours, which is reasonable for the network complexity and population sample size used. The size of the population used for routing was over 750 000 travellers, each with a unique itinerary to be executed over a full 24 hour period.

The results were validated against recoded TTS trip distances, screenline traffic counts and transit agency boarding counts by mode and agency. Findings are discussed below while a more complete discussion can be found in the work of Weiss (2013). While within tolerable limits, there were some discrepancies between the simulated and recorded values that highlight a number of concerns associated with the existing assignment framework for the GTHA. Of particular note were issues regarding:

1) Fare amongst different transit agencies operating in the region.
    - Analysis of the simulation found that the more expensive regional transit services were being overused during the simulation. This was likely due to the simulation using a flat fare across all transit agencies. Individual fares and transfer rules across different agencies will be required for a more realistic simulation.
    - Further specific analysis of subway station boardings and alighting's found a significant under prediction of transfers between subway stations at major transfer points. This was likely the result of the transfer penalty on the pre-coded transfer links being higher than the penalty of transferring to a route stop that is located at the same node. The inclusion of intermodal transfer penalties (subway to streetcar, bus to

bus, etc.) would alleviate some of these issues. For instance, transferring from a bus to another bus in winter or summer is less appealing than transferring from a bus to a subway within a heated or air-conditioned transit station.

2) Installing road pricing on major freeways
   - Screenline analysis found an over prediction of travellers on specific stretches of highway with road pricing. Within the current implementation of the GTHA MATSIM no road pricing has yet been implemented, however support for this type of analysis exists within the MATSIM framework (Grether et al. 2008). Plans for future simulation of road pricing on tolled freeways as well as policy testing on other freeways is currently being investigated for the GTHA.

Conclusion

This paper examines the issues and challenges associated with the development of a dynamic agent based traffic assignment mode. The standard MATSIM transit routing procedure was addressed and improved by adding intelligence to the transit routing network generation procedure. These improvements required a small amount of network pre-processing and have the potential to significantly improve the runtime of the routing procedure for larger populations or highly interconnected complex transit networks. The initial assignment runtime for a case study of the GTHA was very reasonable for the size of the network that was used however further work is required to improve the validity of the overall assignment model. While these methods and improvements were established specifically for use with the MATSIM platform, these methods have broader applications and may be useful in a number of multimodal dynamic assignment procedures, which will be highly beneficial to researchers and practitioners alike as the need for more complex transportation planning tools continues to grow.

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