TRAVEL DEMAND MODELLING AND THE MODIFIABLE AREAL UNIT PROBLEM

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Introduction

The modifiable areal unit problem (MAUP) has been a topic of interest in the field of transportation for the past few decades. Much of the transportation-related MAUP research pays particular attention to determining ideal structure of traffic analysis zones (TAZs). Researchers have been able to conclude effects of MAUP on both the statistical results associated with travel demand models by aggregating or disaggregating zones of a particular analysis region.

For travel demand modelling purposes, understanding the impact of MAUP is very crucial to achieving more accurate trip forecasts. Travel demand forecasts are conducted in a spatial manner (i.e. in the form of TAZs), so investigating MAUP impacts on various zone structures can also lead researchers to determining the most suitable zone structure for analysis purposes.

Extremely limited literature exists on the impacts of MAUP on the mode split stage of the Urban Transportation Modelling System (UTMS). There are also few publications that discuss the zonal effect of MAUP, as much of the MAUP literature discusses the scale effect. This is especially the case in the MAUP-related travel demand modelling literature.

Based on these points, this paper intends to introduce new analyses of these impacts of MAUP which are not widely available in the literature, as well as to reveal how stable the effects are in diverse models. A review of the literature is conducted to provide an overview of MAUP, including the scale and zonal effect, as well as its recent applications in travel demand modelling and other subject areas. The scale and zonal effects are tested using census data and associated zone structures of the Greater Montreal Area (GMA). The results are summarized and discussed, and recommendations for further research are provided.

MAUP Defined and Applied

The MAUP is the result of the scalar or structural adjustment of a series of geographic units used for data collection and storage, often represented in the output statistics, originally defined as the scale problem and aggregation problem (Openshaw, 1977), and more recently as the scale effect and zonal effect[1] (Hunt and Boots, 1996; Zhang and Kukudia (2005). The scale of the spatial unit refers to "the number of areas into which the (sample) population is divided" (Tranmer and Steel, 2001, p.105), while the structure of a geographic unit is defined as "the arbitrary nature of the boundary division placed upon the data" (Manley et al., 2006, p.144).

Scale Problem of MAUP

The manner in which a geographic analysis area is divided can have an impact in output statistics, both in terms of the number of zones used and their respective sizes and shapes. This concept was first demonstrated by Gehkle and Biehl (1934) before the concept of MAUP existed. Since then, similar results have been found in subsequent studies since (see Robinson, 1950; Yule and Kendall

[1] Hunt and Boots (1996) use the term 'zon*ing* problem'.

1950; Blalock, 1964; Openshaw, 1977; Fotheringham and Wong, 1991).
It has been a common finding that more disaggregate zone structures, such as dissemination areas (DAs) or enumeration districts (EDs) used for census data, tend to yield more accurate and significant statistical results than aggregate zone structures, as has been supported by various goodness of fit tests and other significance tests (Ding, 1994; Horner and Murray, 2002; Binetti and Ciani, 2002). In traffic assignment, the main advantage of disaggregate zone systems is the reduction of intrazonal trips (those that begin and end in the same zone), which cannot be modelled in aggregate zone systems.

One traffic assignment study, found in Khatib et al. (2001) and Chang et al. (2002), revealed that good results do not always come from the most disaggregate zone system. Their Idaho based study looked at traffic network performance in 11 zone systems at three different scales: counties (most aggregate scale), census tracts and census blocks (most disaggregate scale). Their unique approach included 3-4 different zone systems at each scale using a different centroid based on either the geometric (physical) centre within the zone, the (largest) city within a zone, a weighting by population, or a weighting by household-density. Aside from common network performance measures[2], a ratio between the estimated volumes against recorded average annual daily traffic counts (AADT) provided by the Idaho Transportation Department (ITD), where a result of 0.8-1.2 would be considered satisfactory. Census blocks yielded better results of this index on all road types except urban minor arterials, where the census tracts performed better.

Zonal Effect of MAUP

"The zonal effect exists when a set of spatial units in a given scale is recombined into different zones and the recomposition generates

[2] The network performance measures included trip length (measured in minutes), number of intrazonal trips, and percent root-mean square error (RMSE%) – an index that measures the variance between the observed and forecasted traffic volumes.

variations in data values and measurement results" (Zhang and Kukudia, 2005, p.73). One of the first informal findings of this ideology came from Blalock (1964) who, while testing for scale effect, analyzed the impact of different zone delineations at the same scale. Other similar results were provided by Openshaw (1977), Fotheringham and Wong (1991) and Hunt and Boots (1996) using many more zonal reconfigurations.

The one UTMS-related zonal effect study comes from Zhang and Kukudia (2005), who conducted an analysis of mode split in the Boston Metropolitan Area using 1990 U.S. census data and 1991 Trip Diary Survey data. Eight zone systems were created – three based on existing census geography (census block, block group and TAZ), and five arbitrary grid systems containing block sizes of 1⁄16, ¼, ½, 1, and 2 square miles respectively. In addition to testing for scale effect, the zonal effect was also tested on account that the ¼--mile grids were comparable in size with the census blocks, while the 1-mile and 2-mile grids were comparable with the other two census geographies zone systems. A multinomial logit model exploring the probability of a given travel mode[3] was calibrated for home-based work trips and home-based-non-work trips for each of the zone systems. Each of the output coefficients for the explanatory variables used in the logit models was diverse among the eight zone systems. With respect to zonal effect, this was also the case between the three pairs of "comparable" zone systems.

Rules of TAZ Design

The goal of TAZ design is to achieve a zone structure containing minimal intrazonal trips (those originating and terminating within the same zone), no doughnut shapes (a zone with a zone), and a homogenous distribution of demographic characteristics (such as population and income) and the number of trips produced and attracted (Baass, 1981; O'Neill, 1991; Choi and Kim, 1994; Ding, 1994; Binetti and Ciani, 2002; Martinez et al., 2007). It has also

[3] The options walking, biking, taking transit, carpooling or driving solo.

been common to maintain TAZ structures as similar to census data structures as possible (Baass, 1981; Ding, 1994; Chang et al., 2002), and thus the scale can be limited to the available census boundaries used, such as census tracts (aggregate) or dissemination/enumeration areas (disaggregate). Census data structures are usually delineated in a manner that is homogenous for population distribution and demographics, but such delineation does not account for point-specific data such as major trip attractors like employment centres (Downey, 2006).

With a common understanding of the impact of adjusting the scale or zonal boundaries of a TAZ, one must not delineate a TAZ structure in a completely random manner. Based on the identified criteria for appropriate TAZ design, zones should be delineated based on a series of specified constraints. However, constraint aggregation must be done carefully, as "the imposition of TAZ homogeneity for a specific variable (e.g. car ownership) and the number of zones established can have a deep impact in the modeling results, making the use of one specific data sample unfeasible in some studies" (Martinez et al., 2007, p.59).

There are means to automatically delineate zones by controlling for a particular variable (e.g. population) using computer software, such as the zonal design and aggregation procedure (ZODEAG) used by Baass (1981). The more recent trend in TAZ delineation has been to use geographic information systems (GIS) due to the spatial commonality of TAZs and related demographic characteristics used in travel demand modelling (O'Neill, 1991; Bennion and O'Neill, 1994; Choi and Kim, 1994; Ding, 1994; You et al., 1997; Binetti and Ciani, 2002; Cockings and Martin, 2004; Downey, 2006).

In certain cases, boundaries are manually designed as a result of organizational needs, such as jurisdictional boundaries, physical boundaries such as rivers, or transportation corridors for government analysis (O'Neill, 1991; Ding, 1994; Cockings and Martin, 2004). Grid systems are one form of arbitrary user-defined set of zones. Zhang and Kukudia (2005) concluded that their "grid approach to aggregating data produce(d) more tractable and stable results than the approach with statistical areal units (e.g., TAZ and [block group])" (p.78). Quite the opposite was concluded by Martinez et al. (2007) in their analysis of scale effect. After developing measures for statistical precision, geographical precision, and information loss between the local governmental TAZ system, an arbitrary grid system and newly delineated TAZs, they found that their grids produced better results than the existing TAZs, but that the newly delineated TAZs with more natural boundaries with additional constraints performed better than the grids.

Shortcomings in Research

Most of the travel demand modelling studies involving MAUP analysis did not investigate the typical outputs that one would look at when applying the UTMS process, including the common outputs of (logistic) regression analysis such as the coefficients, goodness of fit parameters and the like. Much of this literature evaluated the impact of MAUP through the analysis of the traffic assignment parameters.

One of the only analyses on MAUP and mode split was provided by Zhang and Kukudia (2005). However, their application of the grid structure in zonal effect analysis was inappropriate as it did not conform to the topology (especially with the presence of small islands, where two islands can be covered by a single grid depending on the specified area). While the zones were homogenous in size based on user-specifications, "the most important criteria for good aggregated zoning systems in transportation planning are the achievement of homogeneity of population inside the new zones and the conservation of the interaction between zones" (Baass, 1981, p.3). By artificially aggregating zones based on a specified area measurement, some of the new zones are subject to containing zero population, which can have a tremendous impact on the modelling and resulting statistical outputs.

Summary of Literature

The studies discussed in this literature review present the impact of MAUP on statistical outputs, both from a scale effect and zonal effect. Much of the travel demand modelling research related to MAUP focuses primarily on traffic assignment outputs. The general rules for TAZ design have been discussed in various studies, while they have been disregarded in others. There is thus a need to conduct a proper study of zonal effect on travel demand modelling, as well as to look at some of the impacts on basic statistical outputs from (logistic) regression models.

Study Design and Methodology

To test the impact of MAUP on travel demand modelling, a case study of transit mode split in the Greater Montreal Area (GMA)[4] was conducted. The GMA was selected due to its population of approximately 3.5 million people (Statistics Canada [1], 2008) along with its geographic composition of two large islands and other small islands – all of which can create challenges for TAZ delineation.

Data from the 2001 census for the GMA was used in this study. The Canadian census is conducted by Statistics Canada every 5 years (Statistics Canada, 2006), and while 2006 was the most recent census taken, not enough detailed demographic data was available from the 2006 census at the time of the authoring of this paper.

This study was divided into two parts – testing scale effect and testing zonal effect. The scale effect analysis involved the review of statistical outputs from two established census zone structures at different scales, while the assessment of zonal effect included

[4] This is more commonly known as the Communauté métropolitaine de Montréal (CMM). Source: Communauté métropolitaine de Montréal (2007).

creating two zone systems with the same number of zones and different boundaries, as well as the comparison of statistical outputs of the two structures.

The Model

Since a mode split model was selected to test MAUP, the following binary logit model was applied to both parts of the study:

$$P_n = \frac{1}{1 + e^U}$$

where:

P = the probability of choosing alternative n;
n = mode of transportation (public transit);
e = exponential function (or 2.718281828)
U = utility of alternative $n = \alpha + \beta_k x_k$;
α = dependent variable coefficient (constant);
β = independent variable coefficient;
x = independent variables.
k = number of independent variables

An index for public transit ridership was developed from census data by taking the percentage of employed individuals who reported public transit as their mode of transportation out of the total employed labour force with a mode of transportation. The following independent variables were used in the initial models:

- households with children [hshld_child] – ratio of census families with children (including single parents) to total households;
- average income of population 15 years and over (measured in $10,000s) [inc15+avg];
- distance to central business district (CBD) [dist_CBD] – distance from the centroid (or geographic midpoint) of each

analysis zone to the centroid of the zone classified as the CBD, measured in kilometres.

The hypothesis was that less commuting made by public transit would occur from zones with a large proportion of households with children and higher average income, and those that were located further away from the CBD. Higher income is generally associated with a higher probability of vehicle ownership (Pucher and Renne, 2003). Trips involving children and their caregivers travelling together tend to involve trip-chains that may be too complex to accommodate by transit, such as dropping off the child(ren) to a daycare facility prior to going to the place of employment (Turner and Grieco, 2000; Jang, 2003; McGuckin et al., 2005; Lee and McNally, 2006). Due to the higher densities in a typical CBD of a major city, public transit service is usually more readily available and accessible in the CBD compared to its suburban counterparts, (Charney, 2005; Alshalalfah and Shalaby, 2007).

Explanatory variables to determine the effect of MAUP in all cases included goodness of fit tests (R^2 and adjusted R^2 – where a higher value equals a good fit), coefficients of the models' dependent and independent variables, and significance tests (student t-tests – where the variable is significant when $t \leq -1.65$ or ≥ 1.65).

Testing for Scale Effect

In order to demonstrate the scale effect of MAUP, the data used in this exercise were structured in two predetermined census zone formats: census tracts (CTs), which constituted 939 zones; and dissemination areas (DAs), made up of 5,966 zones. Statistics Canada defines a census tract as a small geographical unit containing a population of 2,500-8,000 and located in an urban centre with a population of at least 50,000 (Statistics Canada [2], 2008), while a dissemination area is referred to as a smaller unit with a population of 400-700 (Statistics Canada [3], 2008).

The goodness of fit between the dependent and independent variables was quite good, despite the different values of R^2 between the two scales (see **Figure 1**). Despite using fewer independent variables, the output coefficients still forced a hypothesis rejection on the impact of households with children on transit trips, while all other outputs supported the hypothesis (see **Figure 2**). Only average income and distance to CBD were significant in both zone structures, but their level of significance differed greatly between census agglomeration structures, as suggested by the t-tests.

Census Tract		**Dissemination Area**	
R^2	**Adjusted** R^2	R^2	**Adjusted** R^2
0.945	0.945	0.893	0.893

Figure 1 - Goodness of Fit Tests for Scale Effect Analysis

	Census Tract		**Dissemination Area**	
	Coefficient	**t-test**	**Coefficient**	**t-test**
CONSTANT	0.146	0.232	0.286	1.622
hshld_child	0.731	0.798	0.456	1.95
inc15+avg	-0.241	***-2.733***	-0.233	***-7.427***
dist_CBD	-0.092	***-7.334***	-0.091	***-18.681***

Figure 2 - Coefficients and t-tests for Scale Effect Analysis

The coefficients in Error! Reference source not found. reinforced the expectation that higher income and greater distance away from the CBD would have a negative impact on public transit ridership. It was surprising to see that larger households and households with children had a positive impact on transit trips, although a further review of the literature led to a study that reported similar findings (see Kim and Kim, 2004). However, almost all of the variables used in the logit model for the CT structure were insignificant as demonstrated by the t-tests, while the DA structure also had fewer insignificant variables.

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The results from this section demonstrate the presence of scale effect in travel demand modelling. Significant differences in statistical outputs can be observed between aggregate and disaggregate scales. A more aggregate zone scale has been found to have a better goodness of fit, but the independent variables in the aggregate structure have been found to be less significant than in a more disaggregate scale. Further research is required on this topic with specific regard to appropriate scale of zones for travel demand models. Such zone structures should also have improved homogenous population distribution for travel demand modelling purposes, as the census agglomeration structures used in this analysis merely contained a specified population range rather than an absolutely defined population per zone.

Testing for Zonal Effect

A zonal effect analysis was carried out for the purposes of this paper due to limited research available on this topic. To carry out this analysis, two aggregate zone structures were created in a manner that avoided arbitrary delineation of zones (such as the application of a grid structure) and to improve homogeneity of population distribution between zones.

For modelling purposes, the two alternative zone structures were aggregating from the DA structure and weighted by the 2001 census population of the GMA. It was anticipated that aggregation bias would remain the same, and that two different spatial delineations would support this hypothesis, but also lead to the discovery of how statistical representation differs in different spatial delineations.

The 2001 census population of the GMA was 3.42 million, and summary statistics in census tract structure that each zone should have an average population distribution of 4,031. In order to accommodate this distribution, it was concluded that 850 zones would be required in a new zone structure.

Using a regional partitioning feature as described in Horn (1995), seed-zones were generated randomly though the specification of 850 clusters per structure. These zones were randomly selected in a manner that allowed them to be uniformly distributed across the land-mass of the GMA (thus excluding any body of water). The 2001 census population was used as the criteria for zone clustering. This process generated a zone system herein referred to as "Structure 1" and "Structure 2".

A binary logit model was run in each of the two new zone structures with transit mode split as the dependent variable and distance from CBD, households with children and average income as the independent variables. The same hypothesis tests from the revised scale effect models applied.

Many of the resulting outputs from the two new zone structures were similar to the model of the CT structure. As demonstrated in the scale effect analysis, aggregate zone structures yield higher goodness of fit results, as can be seen in the two new zone structures in **Figure 3**. However, the R^2 values differed between the two zonal structures by 0.01.

Structure 1		**Structure 2**	
R^2	**Adjusted** R^2	R^2	**Adjusted** R^2
0.955	0.955	0.954	0.954

Figure 3 - Goodness of Fit Tests of New Zone Structures

Once again, the hypothesis proved true for the impact on transit trip production of all independent variables except for households with children. In both zone structures, only average income and distance to CBD were significant as demonstrated by the t-tests (which was also the case for the CT model – see **Figure 2**). As seen in **Figure 4**, there were minor differences between the two models for level of significance of all variables (t-test values) and the numerical value of the coefficients. In addition, resulting coefficients and t-tests for the constant were also diverse among the two zone structures.

	Structure 1		**Structure 2**	
	Coefficient	**t-Test**	**Coefficient**	**t-Test**
CONSTANT	0.203	0.275	0.239	0.326
hshld_child	0.734	0.69	0.694	0.662
inc15+avg	-0.256	***-2.482***	-0.258	***-2.525***
dist_CBD	-0.093	***-6.957***	-0.093	***-6.97***

Figure 4 - Coefficients and t-Tests of New Zone Structures

The results from this section determine the existence of a zonal effect among two homogenous zone systems with different boundaries. Future research on this topic should include various zone delineations based on other multiple user-specified constraints.

Summary

This paper has attempted to fill a major gap in the research on MAUP and its impact on travel demand modelling. A thorough review of the literature provided for basic rules and parameters for travel demand modelling-related MAUP analysis. It was clear that most studies focussed on traffic assignment parameters rather than basic statistical outputs from (logistic) regression models. In a rare application of a mode split model in MAUP analysis, a study of transit mode-split in the GMA was conducted using a binary logit model. Scale effect was tested in two government census agglomerations at different scales, while two sets of homogenous zones were delineated were created to properly test the zonal effect.

The existence of scale effect was found between the two census agglomerations. While it was anticipated that a zonal effect would exist between the two new zone delineations, it was fundamentally important to test this possibility in non-arbitrary zone systems.

Future research will require scale effect analysis using more homogenous zone structures rather than predetermined census agglomeration structures. Much additional research will be required on zonal effect using other zone reconfigurations at the same scale.

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