Household Activity Spaces and Neighborhood Typologies:

A spatial and temporal comparative analysis of the effects of clustered land use indicators on the travel behaviour of households in three Quebec cities

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Abstract

As the number of urban dwellers worldwide increases and as governments struggle to meet the pressure a concurrent rise in personal travel places on cities, the importance in understanding travel demand becomes vital. Traditional approaches to understanding the interaction between built form and travel have focused on individual indicators such as population density or land use mix, while measuring outputs such as vehicle kilometers travelled or mode share. Activity spaces, in contrast, are a relatively new and underexplored measure of travel demand which looks at the distribution of trips throughout space. These activity spaces are the focus of the following manuscript.

A variety of land use and accessibility measures are described and calculated, the goal being to discern their effect on activity spaces in the Montreal, Sherbrooke and Quebec metropolitan regions. Clustering is used to find representative combinations of urban form indicator values, or neighborhoods, after which statistical analysis is employed to quantify the relationships between these clusters and the travel patterns of the households living in them. The primary data sources for mobility are origin-destination surveys conducted 5 years apart in each city; three such surveys were used for Montreal, two for Quebec and one for Sherbrooke.

Results indicate that neighborhood type has a significant effect on the dispersion of travel, even after controlling for household size and type, number of trips and other demographic characteristics. Another key finding is that average activity space size is correlated with overall city size. Finally, the geometry of trip distribution is related to propensity for using specific transportation modes.

Dedication

À Francine and Larry

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Chapter 1 Introduction

In 1989, Newman and Kenworthy published a ground-breaking book, Cities and Automobile Dependence. In it, they conclude a definite link exists between urban density and fuel consumption (Newman & Kenworthy, 1989). This is one of many important works published in the last few decades to look at the relationship between urban form (UF) and travel behaviour. Despite various responses over the years which called into question the *undeniable* nature of the relationship the authors describe, or the methods of analysis employed in order to draw this conclusion (Gomez-Ibanez, 1991) (Pund, 2001) (Mindali, Raveh, & Salomon, 2004), Newman and Kenworthy's work has had a significant and lasting impact by popularizing the idea that raising density is good for the environment. This also provided the basis for policies and plans to address automobile dependence. By simplifying a complex problem and making it possible to wrap one's head around the phenomenon of increased automobile use, Newman and Kenworthy opened the field to a new generation of scholars.

As urban population rises and evidence accumulates linking increases in carbon emissions to climate change, the fact that transportation accounts for 26% of Canadian greenhouse gas (GHG) emissions (Environment Canada, 2007) makes it, if only for environmental reasons, a clear focal point for research. In addition, land development increasingly encroaches upon what were previously agricultural lands, and reports link increases in vehicle use with respiratory illnesses and traffic related accidents, among other ills (Frumkin, 2002) (Rooney, et al., 2012). It is therefore imperative to investigate the links between urban form and travel demand, as a clear understanding of the effects of land use on travel demand are crucial to improving the future health of urban dwellers, as well the planet's ecosystem as a whole.

The cities we live in have evolved dramatically over the past 60 years, as each new wave of development has redefined what the *city* really is and where its limits are set. What was once a clear spatial unit with a market center, port area and town square, has morphed into something much more complex. This changing definition of what a city is has only naturally come to affect the ways in which we move about space, with impacts on the location of our homes and activities. Whether one calls modern suburban development sprawl or progress, it would appear to be associated with increased personal vehicle use. Part of this increase in travel may be attributed to increases in per-capita wealth, but through the spreading out of development, the goal of which being presumably to offer every citizen his or her own backyard oasis within an (ideally) short commute of the metropolitan center, some would argue that we've bought in to a conception of the city where the only means by which one can achieve accessibility is by making use of automobility. This drastically breaks from our traditional mobility patterns as well as conception of space, a break the consequences of which are not yet fully understood.

The following thesis will not attempt to unpack and explain every complex social and economic issue underpinning automobile dependence, but rather will explore the relationships that appear to exist between the cities we choose to build and the ways people move about and interact with them. This thesis should provide the reader with an understanding of what the current literature regarding land use and transportation has uncovered about urban form and transportation linkages. In addition, the concept of what neighborhood typologies are and how they can be employed to better represent landscapes is a major component of the work.

Bringing a new perspective to the topic, the thesis will more specifically investigate a currently underutilized descriptor of travel demand, household activity spaces. These spaces allow one to represent the travel behaviour of households in two-dimensional space, or the dispersal of trips throughout a region. Activity spaces allow one to represent the areas people interact with, as well as better understand why they do. Analysis of the complex set of relationships embodied within these spaces will add a conceptual tool which planners can use to model the behaviour of households, and thus better plan for the sustainable development or redevelopment of communities. The ultimate goal of this work is to gain a better understanding of which interventions can increase the efficiency of cities while reducing travel patterns deemed unproductive or otherwise detrimental to the community as a whole.

The three articles included in this manuscript combine a study of household activity spaces with a clustered approach to defining neighborhood typologies in three cities (Montreal, Quebec City and Sherbrooke) as a means by which to more thoroughly understand total travel demand as a response to local and regional urban form characteristics. By typifying areas based on clusters of land use variables and exploring activity spaces generated using extensive origin-destination (OD) surveys, the thesis seeks to explain the relationship that exists between the type of neighborhood one lives in and the travel behaviour of the residents found within. Having data which not only covers different landscapes within a city, but which can also be utilized to compare one city to the next and one survey period with the next (three different OD surveys for Montreal, two for Quebec City and one for Sherbrooke) provided multiple avenues for exploration. These OD surveys also being quite comprehensive, consisting of approximately 60,000 households per year in the Montreal metropolitan region (Agence Métropolitaine de Transport, 1998, 2003 and 2008), 30,000 households per year for Quebec City (Transports Québec, 2001 and 2006) and over 8,500 for Sherbrooke, the research was able to explore specific micro-geographical effects as well as trends over time.

As shall be indicated in introductory sections preceding the reproduced articles, my role in each case was that of lead author. It should also be noted that since each article contains its own fairly comprehensive literature review and methodology section, and that the three articles follow in a logical order whereby analysis gains in complexity and sophistication as we progress from Chapters 6 through 8, the literature review and objectives sections that follow will be kept brief.

Chapter 2 Literature Review

The scholarship described in the following section provides an overview of the multitude of ways in which urban form and public transit accessibility can be defined and measured, and describe how their impacts can be assessed with respect to travel demand measures. A focus is placed on describing activity spaces more specifically.

The following topics will broadly divide the chapter:

- excessive travel demand?
- travel behaviour and explanatory variables
- design and use of neighborhood typologies
- activity spaces, a relatively unexplored travel demand measure

The Need to Reduce Sub-Optimal Travel Behaviour

If we were to compare the automobile use of North Americans to that of other industrialized nations, we would be faced with rather alarming facts. “The average U.S. city uses nearly double the per capita gasoline consumed by Australian cities, a little less the double the gas used in Toronto [and] four times the gas consumed in the average European city” (Newman & Kenworthy, 1989, p. 28); although Canadians aren’t the *most* voracious fuel consumers in the world, such statistics indicate that mobility here is very much dependent upon automobility. Case in point, the transportation sector accounted for 32% of Canada’s emissions growth over the 1990 to 2005 period (Environment Canada, 2007, p. 77).

Such was not always the case however, and the trend towards increased automobile ownership and use, described in Greenwood & Stock (1990) or Newman & Kenworthy (1989) isn’t a product of coincidence, unrelated to the cities from which data is obtained. Rather, it can be seen to result from the increases in wealth that provided widespread access to private automobiles, yes, but also, and this is the main point of the research undertaken here, as a response to the forms of development promoted over the last 60 years.

Mitigating automobile dependence and providing alternatives that enable individuals to shift from personal vehicles to public transit or active modes of transportation has advantages in many respects. As such, critics of automobile dependence can be found not only in the fields of urban planning, where one can discuss the impact such development has on the costs of infrastructure and the quality of architecture, but also in sociology, decrying the death of community (Putnam, 2000), health, where researchers have tied increases in motorization to a bevy of problems ranging from air quality to road mortalities (Marshall, McKone, Deakin, & Nazaroff, 2005), to economics, where congestion is evaluated at over 1.4 billion dollars a year for the Montreal metropolitan region alone (Les Conseillers ADEC inc., 2009)).

As outlined in Frumkin (2002), Kelley-Schwartz et al. (2004), and Ross et al. (2007), sprawling city forms and their resulting automobile dependence carry negative externalities. A shift toward car dependence, or hypermobility as John Adams (2001) so aptly put it, is a shift towards more sedentary lifestyles, which can lead to increased cases of obesity and overweight (Ross, Tremblay, Khan, Crouse, Tremblay, & Berthelot, 2007), as well as social exclusion, water quality and even mental health issues (Frumkin, 2002).

The environmental and economic imperatives to decreasing automobile dependence and excessive travel demand are also many. With respect to the environment, automobile-dependent, or sprawling, development can be linked to higher vehicle kilometers traveled (VKT) that in turn produce additional greenhouse gas (GHG) emissions and accelerate the process of global warming and climate change (Freund & Martin, 2007). Economically, the production of car-dependent landscapes can be said to lead to high expenditure on personal mobility (Kamruzzaman & Hine, 2012), in addition to high municipal and other governmental expenditure on infrastructure and public works (Calthorpe, 1993). More compact environments like New Urbanist developments, characterized by higher residential densities among other descriptors (Boarnet & Sarmiento, 1998), have been described as leading to lower costs for provision of water, sewage and electric power (Calthorpe, 1993).

Knowing all this, the question becomes: how did we as a society get to the point where our cities no longer work for us? As alluded to in the previous paragraphs, planning matters. The way in which we lay out our cities is intuitively, but also increasingly proven, to be correlated with the ways in which we move about these cities. As it is so succinctly stated at the outset of Driving and the Built Environment, "both logic and empirical evidence suggest that developing at higher population and employment densities results in closer trip origins and destinations, on average, and thus in shorter trip lengths, on average" (Transportation Research Board and Board on Energy and Environmental Systems, 2009, p. 3). How exactly one is to address the issue of expanding urban populations and preferences, be they perceived or real, for larger lot homes are issues planners and politicians need to address.

If one looks at cities like Montreal or Quebec City, which have grown over centuries and whose individual neighborhoods' urban form reflect this gradual development, it is obvious that shifts in planning paradigms greatly affect the forms development takes. These different eras of development lead to urban forms which produce dissimilar travel demand patterns – effects which can be quantified.

Utopian city models like Ebenezer Howard's Garden Cities or Le Corbusier's Ville Radieuse are ideas that were thought up as means by which to organize urban life in bold new ways, ways conjured up by the imaginations of visionaries that reflected the values upheld at the time at which they were dreamt up. Throughout history, the ever-changing qualities espoused by planners have been either access to green space for its curative properties, segregated transportation systems for their efficiency and safety, building form either ostentatiously ornate or markedly unpretentious, etc. This history led to different types of development within the landscape of cities like Montreal and Quebec, where a historic core can be found on the same map as dense inner ring gridded suburbs, cookie-cutter cul-de-sac sprawl and twenty storey apartment towers. Such a mix of neighborhoods affects the ways in which we interact with our cities. They also, through their heterogeneity, provide excellent canvasses upon which to test models of land use and transportation linkages.

Defining and Measuring the Factors that Influence Travel Behaviour

Predictors of travel demand are usually divided into categories for individual, household, and built form characteristics. Commonly used individual variables include gender, age, income (Bento, Cropper, Mobarak, & Vinha, 2005) and education (Boarnet & Sarmiento, 1998), whereas the household variables, or indicators, commonly used are number of persons or children in the household (the latter also standing in as a proxy for stage in the life-cycle) (Lin and Long, 2008), income and number of vehicles owned (Shay & Khattak, 2007). Built form characteristics can in turn be divided into a few categories; Krizek (2003), for instance refers to using density and land use mix, two such descriptors of urban form.

There is consensus within the literature that the three Ds, proposed by Cervero and Kockelman, describe the basic categories of built form characteristics, notably density, diversity and design (Krizek, 2003) (Shay & Khattak, 2007) (Transportation Research Board and Board on Energy and Environmental Systems, 2009). One most often finds residential and employment densities defined as a simple measure of individuals per unit area (Riva, Apparicio, Gauvin, & Brodeur, 2008) or retail employment per area (Boarnet & Sarmiento, 1998). Diversity and design vary more, being characterized by entropy measures, jobs-housing balances, intersection densities, sidewalk provision, etc. (Ewing & Cervero, 2001). As for public transit accessibility, many sources outline the different ways to address the issue, dealing with it as proximity to stations or bus stops (Shay & Khattak, 2007), rail and bus line coverage (Bento, Cropper, Mobarak, & Vinha, 2005) or proximity-headways (Miranda-Moreno, Bettex, Zahabi, Kreider, & Barla, 2011) .

Describing all the methods used to operationalize urban form and public transit characteristics could qualify as a thesis in and of itself, but suffice it to say that variations exist across studies. To evaluate land use mix or diversity, Riva et al. (2008) for instance use the most common approach, that of an entropy index; in Ewing and Cervero's 2010 meta-analysis, out of 14 studies looked at, 10 used such an approach, the remaining 4 describing diversity in terms of jobs-housing balance. Operationalization of other indicators also vary greatly, both in the ways in which their basic spatial units are defined (grid cells, census tracts, traffic analysis zones, etc.), as well as in variations in the definition of the phenomenon of interest itself. Examples of such variation can be found in the use of specific types of services or amenities in measures of commercial accessibility (Manaugh & El-Geneidy, 2012), or use of road network buffers, relative travel time polygons or standard travel times to capture the accessibility of a given phenomenon (Sherman, Spencer, Preisser, Gesler, & Arcury, 2005). Employment accessibility is another example of an indicator that can be interpreted in many ways, as work by Cerda (2009) demonstrates. Cerda defines a series of location-based accessibility indicators, as well as measures of competitive accessibility to jobs in the Montreal region, exploring the many ways this concept can be viewed, be it from the perspective of the firm, individual or household (Cerda, 2009).

Within the planning profession, there is a growing consensus that urban form attributes affect travel behaviour, by altering the time-cost of travel for example. Where debate persists is on the nature of such a relationship, its strength, and potential means by which it can be quantified. Many scholars agree that as densities or diversity increase, automobile mode share and VKT decrease; the same relationship is generally accepted with respect to increases in accessibility to public transit and, to a lesser extent, decreasing distance to the Central Business District (CBD) and increasing street grid connectivity (Ewing & Cervero, 2001) (Ewing & Cervero, 2010) (Bento, Cropper, Mobarak, & Vinha, 2005) (Leck, 2006) (Tracy, Su, Sadek, & Wang, 2011) .

Looking to specific findings, residents of job rich zones have been found to generate shorter commutes (Levinson, 1998). Levinson and Krizek write “that a 1 percent increase in origin job accessibility (opportunities) … decreases commute durations by 0.22 percent” (Levinson & Krizek, 2008, p. 161). Given that work trips act as key structuring components of mobility patterns, it is important to properly take the location and density of jobs into account; work commutes may only represent a portion of all trips (a declining portion actually (Black, 2001) (Axhausen, 2007)), but they are most often repeated daily and they bear an important influence in the shopping behaviour of individuals (Manaugh et al, 2010).

“In the simple monocentric model (Muth, 1969) in which all employment is located in the CBD and the number of trips per worker is fixed, the number of miles a household travels is proportional to how far from the CBD it locates” (Bento, Cropper, Mobarak, & Vinha, 2005, p. 467). In fact, even when cities are polynucleated, distance to CBD is used as an explanatory variable to predict VKT. This is because the location of the historic core and the waves of development that followed have an important impact on travel behaviour. The growing dispersion of employment and industry in outlying employment centers and the changing dynamics of work however, toward more dual-earning households among other trends, call for a more complex analysis (Shearmur R. , 2006).

Making matters more complicated, access to employment centers cannot necessarily be treated as additive, given the specialized nature of employment found in each. Shearmur (2006) describes in his paper the effects of employment center specialisation, writing that commuting distance to employment centers as work locations should be larger than to other locations because of what he calls "milieu effects". These “milieu effects” are essentially positive worker innovation-and-productivity spin-offs resulting from having similar industries clustered together in an area; also discussed in (Porter, 2000) and (Florida, 2008). This makes them more competitive and as a result more attractive to employees working in the field. The increased competition for the jobs at the cutting edge in these “milieu” means a larger pool of applicants from farther away are likely to work in these centers (Shearmur R. , 2006).

Ewing and Cervero state in their 2001 meta-analysis of over 50 studies related to the effect of built form on travel outcomes, that the number of trips a household is likely to make is more a function of its socio-economic characteristics, but that the built environment is the main explanatory variable with respect to predicting trip length (Ewing & Cervero, 2001). In addition, this meta-analysis describes an interesting finding, that population density, long heralded as one of the most important components in predicting travel demand, may actually be more of a confounding variable. Badoe and Miller (2000) likewise find in a comprehensive review of the literature that the effect of employment density on travel behaviour, notably mode choice, is significant and greater than that of residential density. As the TRB’s Special Report Driving and the Built Environment so aptly puts it, there is no point in “increasing the density in the middle of nowhere to reduce VMT [-vehicle miles traveled-]” (69), a certain density of people and activities being simultaneously needed for travel demand to be affected in any considerable way.

Leck uses meta-analysis, assigning part-weights to research relating urban form to travel behaviour thus “attempting to settle the contradictory findings reported in single studies” (Leck, 2006, p. 37). His results, like those of Ewing and Cervero, confirm the validity of many land-use indicators in predicting VKT, mode split and trip generation, namely residential and employment densities, and land use mix.

Every piece of transportation and land use research does not however point in one clear and unified direction. Boarnet and Sarmiento (1998) for instance state in their article on land-use policy and its potential impact on non-work travel that among population density, retail employment density and service sector employment densities, only the latter proved to be a significant explanatory variable at the 95% confidence level (the dependent variable in this case being non-work trip generation). In this same article, the authors voice their concern that model results must be interpreted carefully and that issues of residential self-selection, among others, must be taken seriously so as not to overestimate the potential benefits predicted by regression analysis looking at development density (Boarnet & Sarmiento, 1998). Along these same lines, recent scholarship that looks at connectivity and design seems to be divided on whether or not factors such as porousness of the street grid truly lead to reductions in VMT (Gordon, Lee, Moore II, & Richardson, 2005) (Leck, 2006).

In conclusion, the works of Leck (2006), Transportation Research Board (2009), and Ewing and Cervero (2001 & 2010) do an excellent job of reviewing the different individual, household and urban form attributes that can be related to travel behaviour, but the elasticities found in these different studies point to very different levels of influence. The above concerns, as well as large variations in the estimation of variable coefficient elasticities, explain why different approaches are being explored outside the traditional path of defining indicators and using them in ordinary least squares (OLS) regression models.

For all the reasons expressed above, one can understand the desire to move away from studying the effects of individual indicators and instead look at representative combinations, or neighborhood types, as one potential solution.

Design and Use of Neighborhood Typologies

As mentioned above with respect to the traditional approach of using regression analysis to link individual urban form and public transit accessibility measures to travel outcomes such as vehicle hours traveled (VHT), VKT, mode share and trip generation, two main problems occur. First, there are issues of low or non-statistically significant elasticities, as described in Bento et al. (2005), Boarnet and Sarmiento (1998) and Ross et al. (2007). Second there are problems related to the variable endogeneity, or more specifically of distinguishing the influence of urban form from that of residential self-selection (Leck, 2006). Self-selection is aptly described by Miranda-Moreno et al. as a process whereby “neighborhoods chosen by households correspond with their lifestyle” (Miranda-Moreno, Bettex, Zahabi, Kreider, & Barla, 2011), creating a bias in the estimation of the effect of urban form on travel outcomes.

What neighborhood typologies enable is the possibility of dealing with urban form attributes as bundles or clusters (Shay & Khattak, 2007), (Riva, Apparicio, Gauvin, & Brodeur, 2008), (Lin & Long, 2008), (Gershoff, Pederson, & Aber, 2009), (Miranda-Moreno, Bettex, Zahabi, Kreider, & Barla, 2011). A multi-indicator clustering technique improves the classification of areas as it doesn't simply lump together all cells with high population density or all cells with high land use mix, but instead looks for representative combinations. As is explained in Bento et al. (2005), creating such typologies "allows us to examine the implications of moving sample households to cities [or neighborhoods] with different vectors of transit and sprawl characteristics" (Bento, Cropper, Mobarak, & Vinha, 2005, p. 467). "Individually, the effect of changing measures of urban form and transit supply is small, (...) [t]his, however, is not the case if measures of urban form and transit supply are considered jointly" (ibid, p.475). By creating a limited number of typologies for neighborhoods, which combine elements such as residential density, transit accessibility and intersection density (Lin & Long, 2008), what is obtained is a means by which to classify neighborhood units and see what effect these types of neighborhoods (which deal with UF and public transit (PT) variables jointly once again) have on travel behaviour (Bento, Cropper, Mobarak, & Vinha, 2005) (Miranda-Moreno, Bettex, Zahabi, Kreider, & Barla, 2011).

While results obtained by Bento et al. (2005), indicated a potential reduction to VMT on the order of 25% when *moving* a hypothetical household from one neighborhood type to another - sprawling Atlanta to denser Boston is the example referred to-, Miranda-Moreno et al. find that moving a household unit from one neighborhood type to another can reduce VMT by as much as 75% (factors such as land use mix and public transit accessibility enabling one not to own a car) (Miranda-Moreno, Bettex, Zahabi, Kreider, & Barla, 2011).

There are many ways to approach the task of developing neighborhood types through clustering, either by establishing a fixed number of desired types from the start, using the Calinski-Harabasz test to determine their optimal number (Dimitriadou, Dolnicar, & Weingessel, 2002), Davies-Bouldin and Dunn-Silhouette values (Vogel, Greiser, & Mattfield, 2011) or even trial and error. The latter approach can be effectively employed by comparing dissimilarities between clustering iterations on a visual display of the study area or with the use of tables of summary statistics (Lin & Long, 2008) (Riva, Apparicio, Gauvin, & Brodeur, 2008). Some authors use software packages like SPSS, R or STATA to apply algorithms like k-means or k-medians clustering to create the groups (Lin and Long, 2008) (Riva, Apparicio, Gauvin, & Brodeur, 2008). The aim of the research, as well as the scale and geographic context, determine which approach is most appropriate, but the end goal is always the same: cluster analysis groups together units in an attempt at minimizing intra-group differences while maximizing inter-group differences (Shay & Khattak, 2007).

The best way to ensure the pertinence of indicators included in the clustering exercise is to use those that have repeatedly proven significant in previous work. As such, this enables a researcher to look to the traditional literature and find interesting indicators as well as methods of measurement, and then to combine them for increased effectiveness. A review of Ewing and Cervero’s 2001 or 2010 “Travel and the Built Environment” for instance, provides ample references from which it is possible to mine examples of tried and tested variables for use in clustering.

For examples of how groups of indicators can be clustered or combined to find representative sets, see Gershoff, Pederson, & Aber (2009), Lin & Long (2008), Manaugh, Miranda-Moreno, & El-Geneidy (2010) and Shay & Khattak (2007).

The question of units of analysis is also worth clarifying, given the importance these units play in evaluating indicator levels; the following will describe some of their more important distinctions.

Basic units of analysis can significantly affect the outcome of variable measurement, and hence research results. This is referred to as the modifiable areal unit problem (Openshaw, 1984). Riva et al. (2008) make use of dissemination areas and census tracts as units for their study on social environments, while grids superimposed upon the study area can be found in (Manaugh, Miranda-Moreno, & El-Geneidy, 2010) (Miranda-Moreno, Bettex, Zahabi, Kreider, & Barla, 2011). Wineman et al. (2009), use grid cells also, but in a novel way, extracting rooks as their basic units (a rook being "a respondent block and the four blocks that surround it" (Wineman, Marans, Schultz, van der Westhuizen, Grant-Pierson, & Max, 2009). The availability of data can at times determine the realm of possibilities available to researchers, as units like census tracts carry socio-demographic and other information available through Statistics Canada, whereas ad-hoc units developed on a grid mean that information may need to be obtained via questionnaires or other means, limiting the volume which can be reasonably or conveniently compiled and collected. Other ways exist whereby units can be laid over geometries already containing demographic and other information, the weighted or non-weighted average then being taken for the data falling within this new unit. No matter which approach one chooses, it is simply important to keep in mind the potential biases one can inadvertently bring to measurements.

Once UF and other information are collected, a simultaneous equation model (SEM) is one possible means by which to deal with endogenous variables. Bento et al. (2005) aptly describe endogeneity with an example, wherein "the same variables that affect vehicle ownership are [said to be] likely to affect miles driven. [As such] it is reasonable to assume that the error term in the average-miles-person-vehicle equation, ε_i, will be correlated with [the unobserved component of the ownership utility function]" (p. 473). Vehicle ownership is also dealt with as an endogenous variable in Miranda-Moreno et al. (2011). Such SEM approaches lead to a better characterization of the interaction between urban form and travel behaviour, as the techniques are suited to address the correlation that exists between variables (Miranda-Moreno, Bettex, Zahabi, Kreider, & Barla, 2011), (Shay & Khattak, 2007), and (Manaugh, Miranda-Moreno, & El-Geneidy, 2010). If not addressed, this correlation between variables could inject bias into the estimation of coefficients, leading either to over or under-estimation, depending on the context.

Activity Space Literature

Activity spaces, a new dimension in the analysis of household travel demand, are used to measure the dispersal of activities throughout space, as well as understand the areas individuals interact with (Kestens, Lebel, Daniel, Thériault, & Pampalon, 2010). Interest in this measure is partly a result of the increased awareness of the effect of non-work trips on total travel demand (Buliung & Kanaroglou, 2006).

One of the simplest ways in which activity spaces can be mapped is to represent all the trip ends for individuals or members of a given household (using their XY coordinates for instance), then using some tool such as a standard deviational ellipse or minimum bounding geometry, draw a polygon around the points (see Figure 1: Example of Activity Space below).

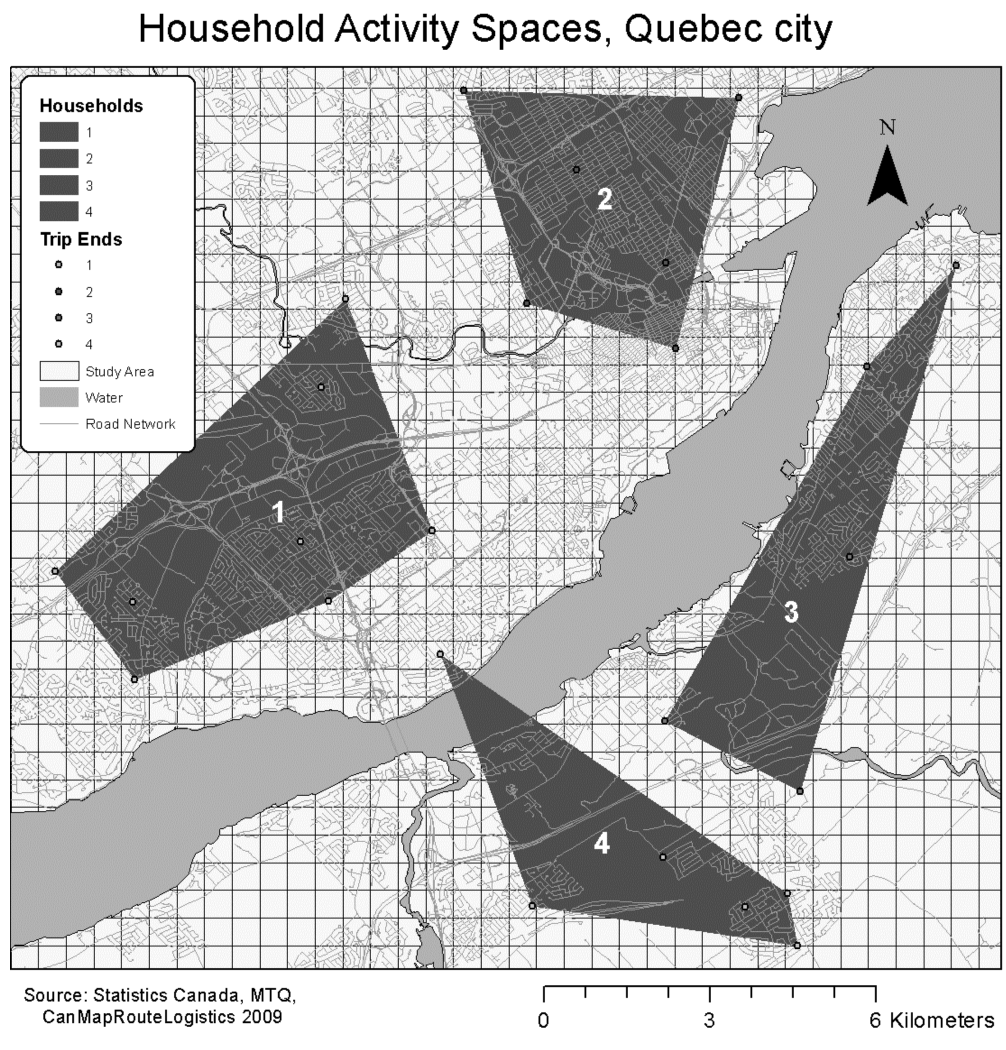


Figure 1: Example of Activity Space

Land use policies can have a significant impact on the accessibility of households to employment, leisure, and products and services, by bringing residential and other land uses closer together. A typical way activity spaces are used is to measure this accessibility by overlaying them on plots of specific amenities or services (like hospitals or food stores) to then determine the presence and concentration of said activities within an individual or household's habitual travel space (Vallée, Cadot, Grillo, Parizot, & Chauvin, 2010).

Activity spaces have been explored by academics working in a variety of fields, ranging from criminology (LeBeau, 1987), to transit planning (Kamruzzaman M. , Hine, Gunay, & Blair, 2009), to healthcare accessibility (Sherman, Spencer, Preisser, Gesler, & Arcury, 2005) and food security (Kestens, Lebel, Daniel, Thériault, & Pampalon, 2010). Because of the added dimension brought about by being able to generate a surface and locate it in space, travel behaviour can be analysed in a whole new way. No longer taking the numeric value (area of the space in this case) as an end in and of itself, as with travel outputs such as VKT and mode share, it can serve as a starting point from which it is possible to evaluate the spread of activities, determine which types of trip purpose stretch out a household's polygon and what activity sites a person or household travels through or around but does not visit, etc. These polygons also enable planners to better understand "how boundaries and transportation networks influence activity space" (Sherman, Spencer, Preisser, Gesler, & Arcury, 2005, p. 3).

In addition to the many applications this travel behaviour output can be used for, there exist multiple techniques by which activity spaces can be produced. Buliung and Kanaroglou (2006) and Rai et al. (2007) offer a comprehensive overview of these, describing minimum bounding geometries, standard deviational ellipses, road network buffers and others still. As with the choice of a basic spatial unit, the activity space type chosen is subject to the availability of different types of data, but also the purpose the space will serve in the end. Examples of different geometries are shown below in Figure 2.

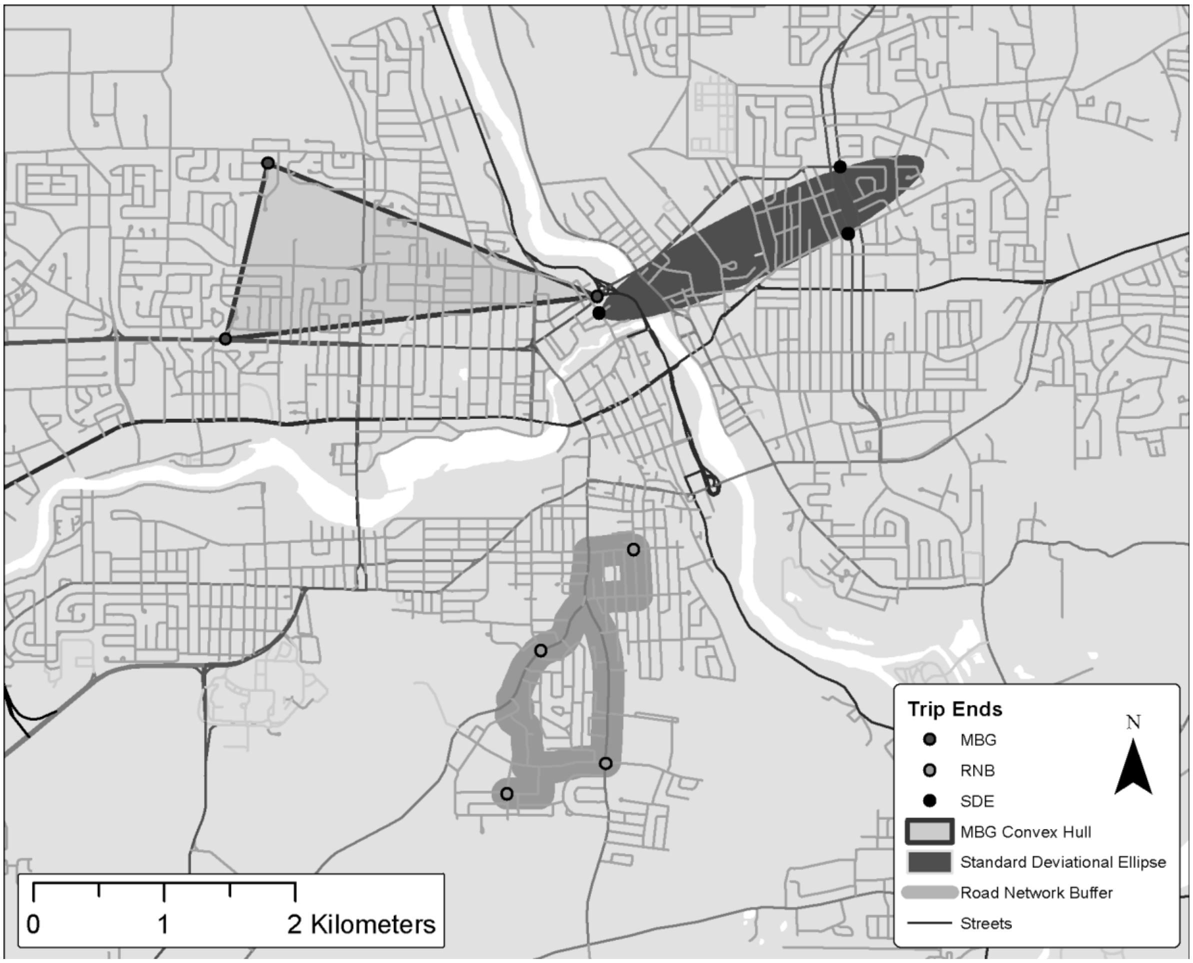


Figure 2 - Different geometries one can use to represent activity spaces: Minimum Bounding Geometry (Convey Hull Polygon), Road Network Buffer, and Standard Deviational Ellipse

Activity spaces can be generated from a variety of sources, ranging from interviews, to travel diaries, locations of members of one's formal or informal social network, etc. (Kamruzzaman M. , Hine, Gunay, & Blair, 2009) (Schonfelder & Axhausen, 2003) (Axhausen, 2007).

Past studies have linked higher values for individual land use indicators such as density and accessibility with smaller activity spaces (Fan & Khattak, 2008) (Lee-Gosselin, Miranda-Moreno, Thériault, & Kreider, 2009). These smaller activity spaces, or household footprints, are in turn commonly understood to also be associated with less detrimental travel behaviour, such as decreases in VKT and increases in active mode shares (Manaugh & El-Geneidy, 2012). These increases are in turn understood to lead to positive health outcomes (Frumkin, 2002) (Marshall, McKone, Deakin, & Nazaroff, 2005) and lower per capita infrastructure investments (Calthorpe, 1993).

Within the social sphere however, smaller spaces are not necessarily correlated with positive outcomes. Notably, researchers have tried to understand whether small activity spaces or low VKT may be a result, for some economically or otherwise disadvantaged populations, of mismatch between provided infrastructure (large arterials which enable high mobility for the owners of personal vehicles) and actual infrastructure needs, such as public transit and porous networks. The topics often discussed in this stream of literature, although not explicitly focused on activity spaces, are forced car ownership, whereby individuals and households are left with little choice but to acquire or rent a vehicle in order to participate in community and economic life, and its corollary, social exclusion (Kamruzzaman & Hine, 2012) (Currie, et al., 2010).

In dealing with activity spaces as a measure of area, one problem that arises is that their geometry accounts simultaneously for compactness (how circular or rounded a space or polygon is) and spread (in km^2 or hectares) of a phenomenon, thus generating similar values for dissimilar polygons. In Figure 3, presented below, we see 4 different types of activity space, combining 2 levels area and compactness. The first, low area, high compactness polygon could be the result of walking to a few nearby locations for instance, while the third, low compactness, low area polygon, while still having a small area, is produced by traveling to trip ends that are further apart, or along a corridor. The figure shows a few examples which are easy to distinguish one from the other, but reality is more complicated and not all levels of area or compactness can be turned into simple binary descriptors. Manaugh and El-Geneidy have begun work on an adapted area measure of activity spaces called the Local Travel Index in an attempt to resolve this problem (Manaugh & El-Geneidy, 2012), but work along these lines remains experimental at the moment.

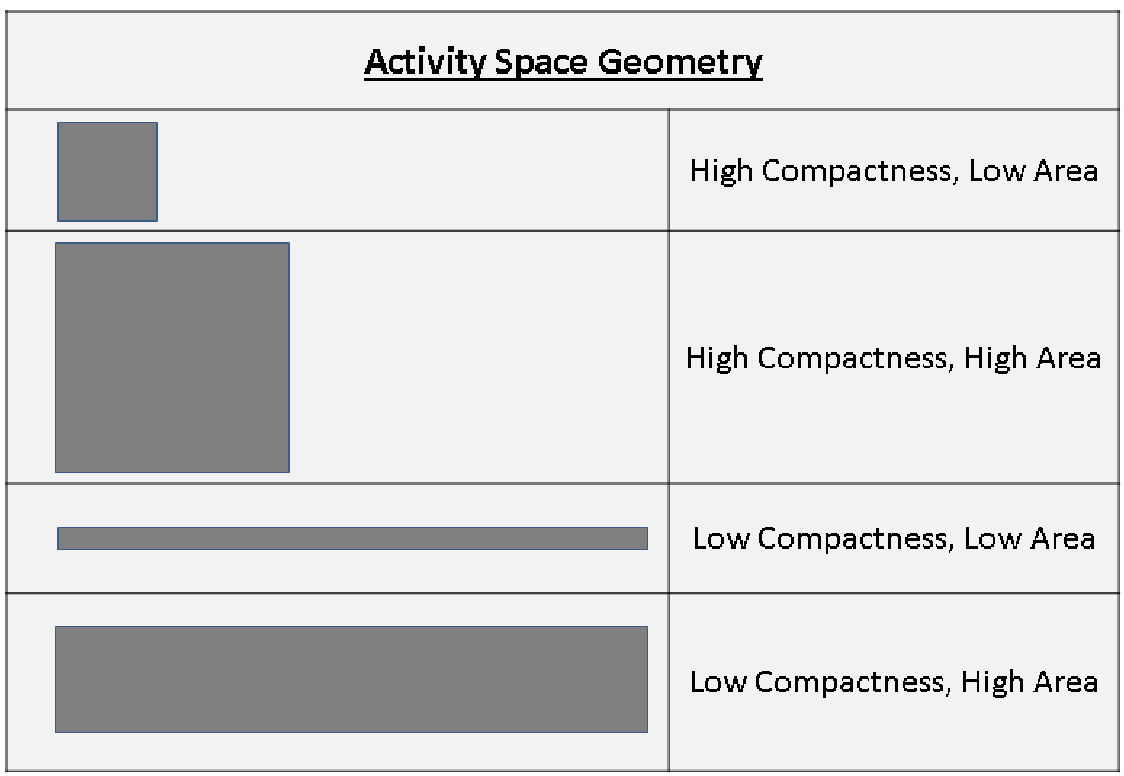


Figure 3 - Activity space geometry affects area

Studies such as those referred to above would indicate that a better understanding of household activity spaces would be beneficial to planners, enabling them to increase the efficiency and sustainability of cities, as well as ensure equitable access to employment and amenities. Translating measures of activity space, which remains a somewhat theoretical construct at the moment, into measures of spatial efficiency or something more tangible, are key areas for future research.

Conclusion

Many scholars have investigated the links between individual land use indicators and traditional travel outcomes such as VKT, VHT and mode share, but while some work has been done linking clustered indicators to traditional outputs, the relationship between clustered land uses and trip dispersal has yet to be explored using a metropolitan-scale, comprehensive origin-destination survey.

Having access to such data for three cities of different size and structure, the following thesis will attempt to add to the current knowledge regarding the effect of certain types of built form, but also metropolitan area, employment center access, and other variables, on trip dispersion. Trip dispersion itself will also be looked at to see what potential effect it may have on mode shares.

Chapter 3 Articles in brief and research objectives

After carefully reading the available literature on built form and travel demand linkages, I chose to focus my research efforts on neighborhood types and activity spaces, as there was potential for a contribution to be made to the field, given the data to which I had access (land use, transportation networks and OD data). The papers included in this manuscript will deal with these topics explicitly, investigating the effects of neighborhood, region, demographics, vehicle ownership and time on activity dispersion. This is done with the goal of helping enable planners to develop or redevelop cities more efficiently, equitably and sustainably.

The main objectives of the work carried out during my master's and summarized in this thesis directly built upon the scholarship presented in the previous section. These objectives are to better understand the effects of built form and demographics on activity spaces, as well as see how the spaces themselves could be better understood.

To address these questions in a logical and coherent way, the papers reproduced here (Chapters 6-8, also printed in the order in which they were written), provide the reader first with a basic understanding of what activity spaces and neighborhood types are (Chapter 6), after which similar methods are employed to analyse data on multiple census metropolitan areas (CMAs) over multiple years; this validates the approach in different geographical settings and allows for comparison between cities and over time (Chapter 7). Chapter 8 then makes use of GIS techniques and statistical analysis to see how the geometry of the spaces themselves can influence mode choice.

A city-wide typology generation with somewhere between 5 and 10 clusters was outlined as a starting point for investigation, as such a number should prove effective for transposition to policy when used in both the Montreal and Quebec city contexts – the first cities investigated. This approach should make it possible to quickly evaluate which broad combinations of urban form and public transit characteristics lead to favourable outcomes with respect to curbing excessive travel demand. Keeping the number of types to a small number (as was done in Gershoff et al. (2009)) should not only guarantee legibility of results, but increase the number of cases found in each type of environment, thus avoiding potential problems related to sample size.

Chapter 4 Study Areas

The Montreal, Sherbrooke and Quebec study areas

In order to ensure comparable data were found for each city, and to maximize the use of local knowledge in interpretation of results, the cities of Montreal, Sherbrooke and Quebec, all in the province of Quebec, were chosen as case studies. Data on the demographics and mobility of residents of the respective CMAs are available through OD surveys, as mentioned in the introduction, as are data relative to land use and transit service provision.

Montreal is host to a truly heterogeneous mix of neighborhoods. It has high density areas both in terms of population and employment, while also housing sprawling suburbs and suburban office parks. It has an underground heavy rail system which began operations in 1966 (Clairoux, 2003), as well as extensive bus coverage and commuter rail lines. This public transit infrastructure is complemented by a fairly extensive highway system that branches out from the city's core and reaches its far-flung suburbs. Its transportation amenities and mix of neighborhoods, which are a result of its long history (Montreal was founded in 1833 (City of Montreal, 2005)), combined with the Montreal CMA's population of over 3.6 million as of the 2006 census, make it a perfect candidate for cluster analysis; it presents a varied landscape which is not simply the reflection of a monocentric city with decreasing density as one moves further away from the historic core or CBD. Based on 2006 population and land figures, the overall CMA population density is 8.54 persons per hectare (StatsCan, Community profile 2006).

Quebec City, although not home to as varied a public transit offering or population, is also a city with a heterogeneous mix of neighborhoods resulting from its equally long history (Quebec was founded in 1608 (Aéroport de Québec, 2011)). As the political capital of the province but not its economic center, Quebec has a very different socio-economic makeup than Montreal. It also has less than one fifth the population of Montreal (StatsCan, Community profile 2006), no rail networks (commuter or otherwise) and a much more sprawled urban form. Based on 2006 population and land figures, the overall CMA population density is 2.18 persons per hectare (StatsCan, Community profile 2006).

Finally, Sherbrooke is smaller still, with a population of less than 200,000 (Statistics Canada, 2006). It has a strong history of manufacturing, but with the decline of the sector overall in North America, it is now better characterized by its large post-secondary student population. Based on 2006 population and land figures, the overall CMA population density is 1.52 persons per hectare (StatsCan, Community profile 2006).

All these factors come into play when analysing travel behaviour, and as such, the opportunity to compare one city to the next should prove enlightening.

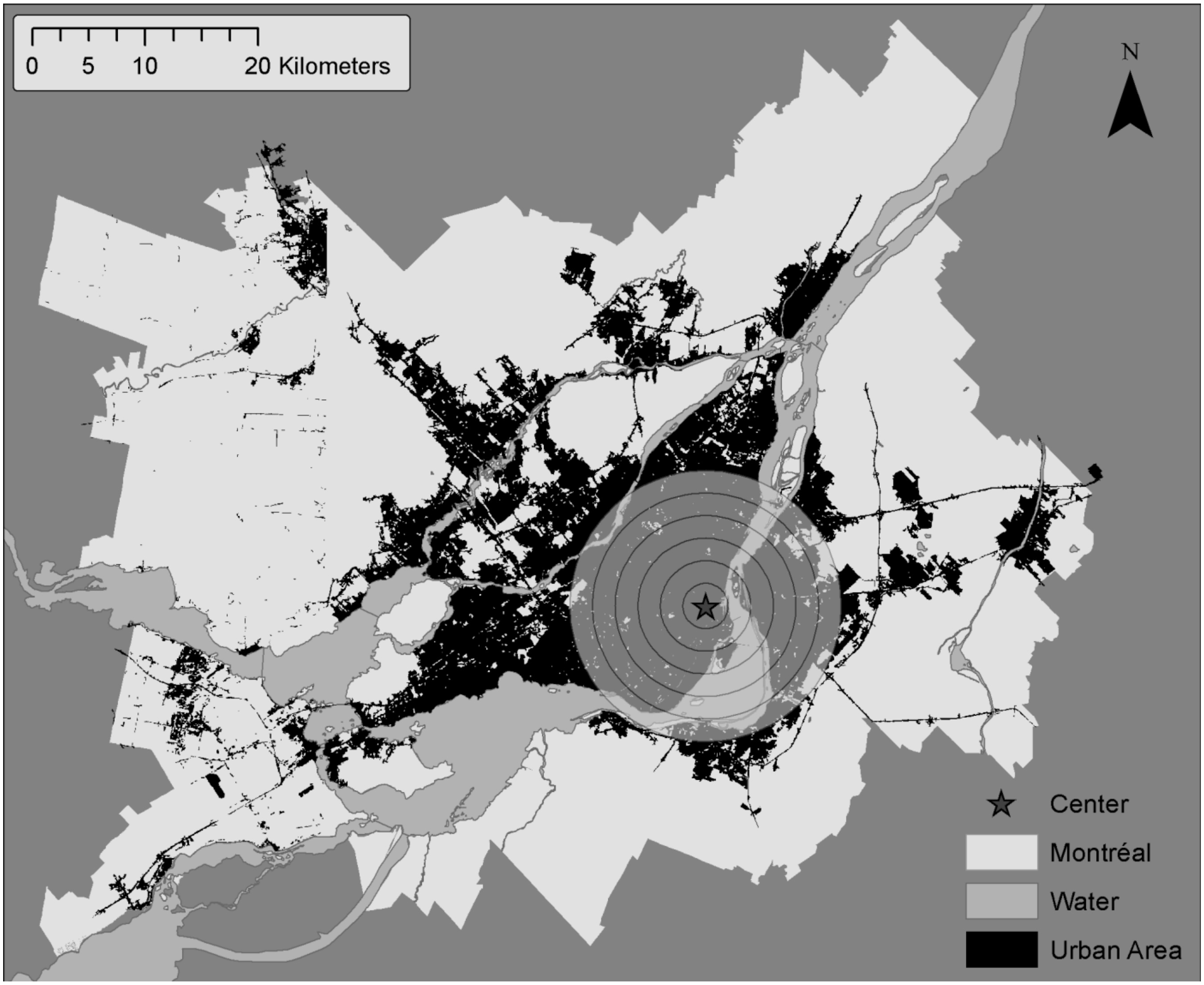


Figure 4 - Montreal CMA. Source for urban area: GEOBASE

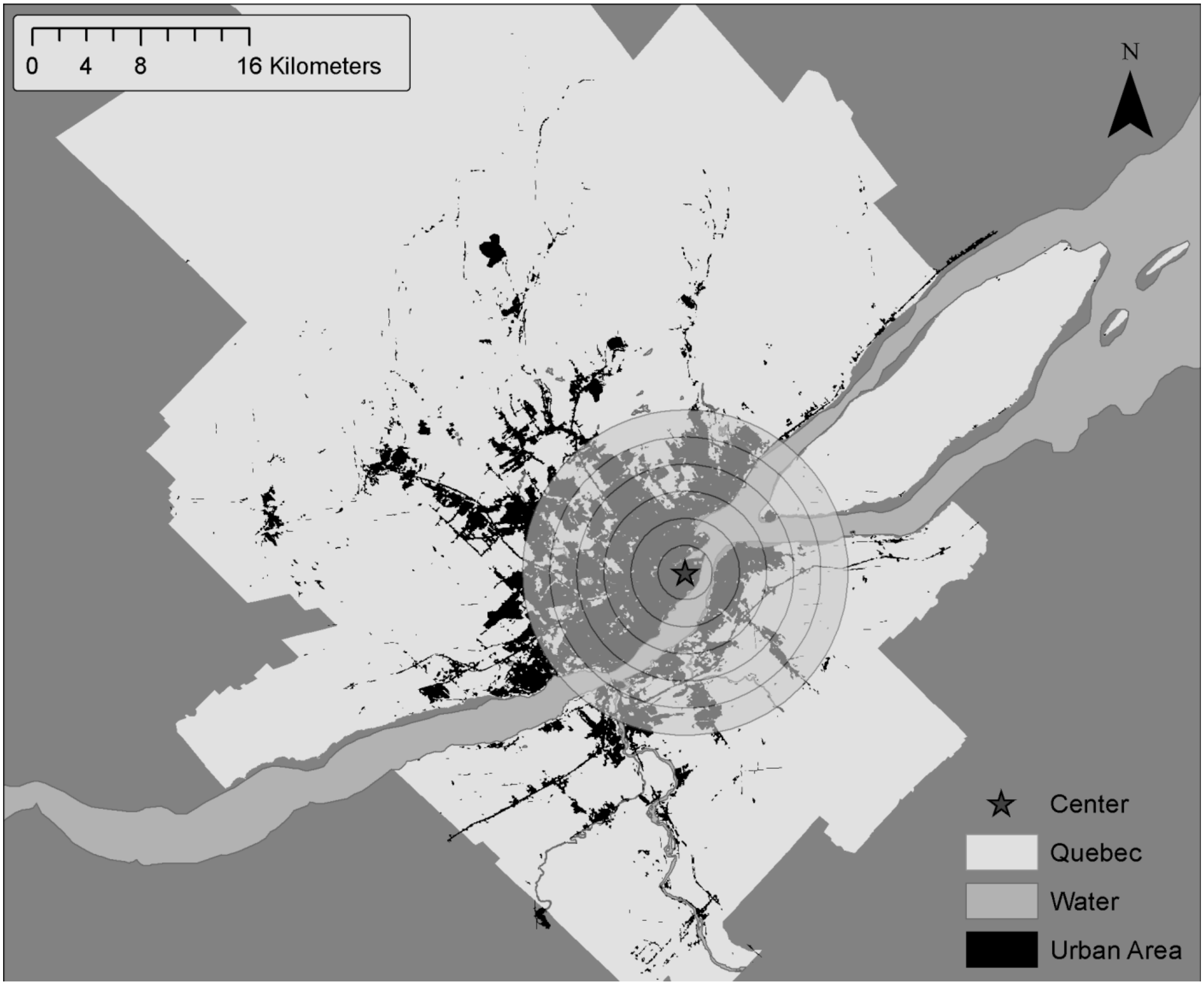


Figure 5 - Quebec CMA. Source for urban area: GEOBASE

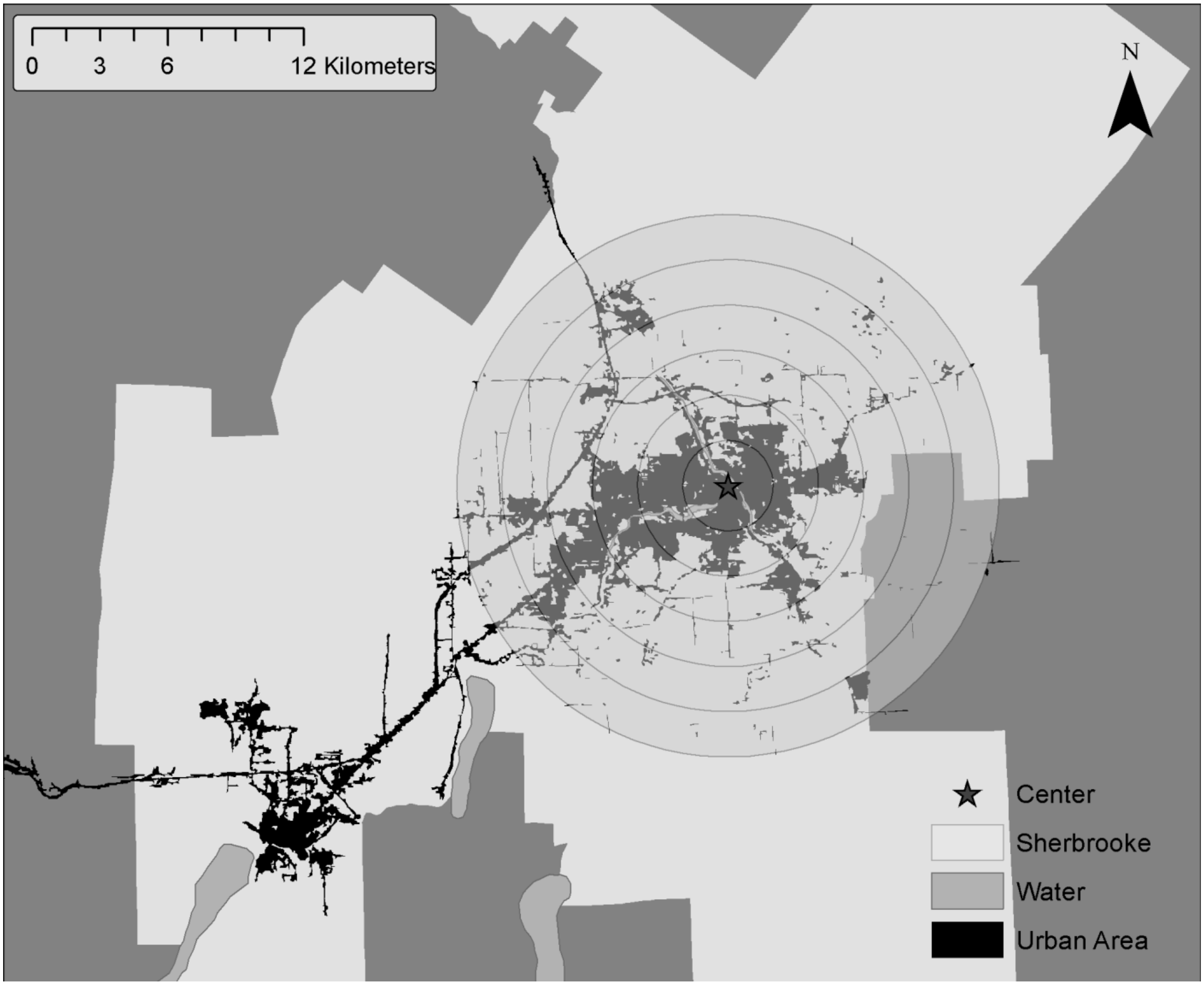


Figure 6 - Sherbrooke CMA. Source for urban area: GEOBASE

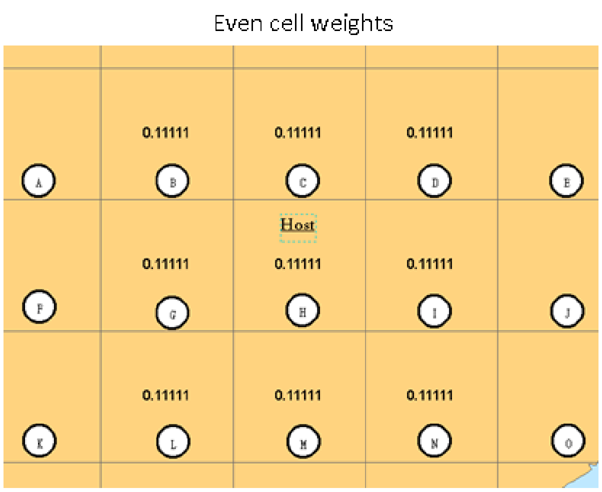
Chapter 5 Methods of Analysis

Building upon decades of research into modeling the effects of urban form on the travel behaviour of individuals and households, this thesis will take the approach of creating neighborhood typologies based on land use and public transit accessibility indicators, and use regression analysis to then investigate what effects certain combinations of indicators can have on household activity spaces. The following paragraphs will not however explain the process by which activity spaces are generated, not most other aspects of the work necessary to writing the papers that are reproduced in chapters 6 through 8; this is because those papers contain detailed methodology sections themselves. The points which will be mentioned here are those that are not covered in the papers, notably the way in which cell weights are calculated and the reasons behind choosing the 4 indicators used for cluster analysis.

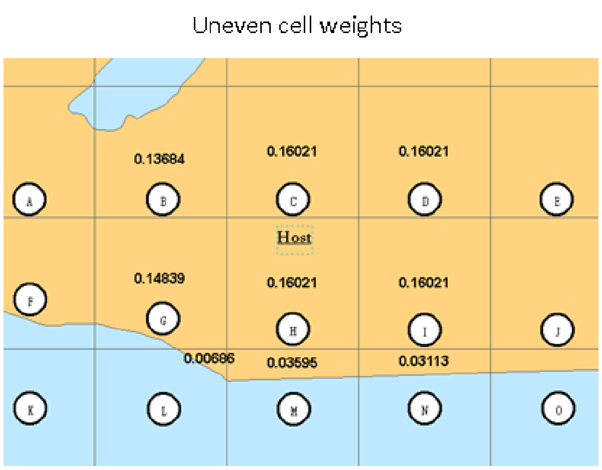
Indicator generation

All indicators will be defined at the grid cell level to provide a more disaggregate picture of their distributions. This technique has been used in various studies to circumvent problems associated with scale and modifiable areal unit problems, whereby different size basic spatial units (such as census tracts of varying sizes covering a CMA for instance) would lead to distorted results (Yeh & Li, 2001). Multiple techniques exist by which to create grids; one of the simplest, which was employed here, is to use the Fishnet tool available in ArcGIS 10.

The use of the grid to capture information about urban form attributes is explained in Chapter 6, but to demonstrate the way weights were used to average cell values and obtain indicator averages from surrounding cells, Figure 7 is shown below; the top and bottom screenshots being examples of even and uneven cell weights, respectively. Using weighted averages for indicator values avoided issues around the borders of the study area as well as water bodies, and avoided peaks in the data.



FID	ID1	ID2	AreaID2	AreaSumHost	Weight
...	...	...	...	...	...
50	G	M	250,000	2,250,000	0.1111
51	H	B	250,000	2,250,000	0.1111
52	H	C	250,000	2,250,000	0.1111
53	H	D	250,000	2,250,000	0.1111
54	H	G	250,000	2,250,000	0.1111
55	H	H	250,000	2,250,000	0.1111
56	H	I	250,000	2,250,000	0.1111
57	H	L	250,000	2,250,000	0.1111
58	H	M	250,000	2,250,000	0.1111
59	H	N	250,000	2,250,000	0.1111
60	I	C	250,000	2,250,000	0.1111
62	...	...	...	...	...



FID	ID1	ID2	AreaID2	AreaSumHost	Weight
...	...	...	...	...	...
50	G	M	250,000	2,250,000	0.1111
51	H	B	213,526	1,560,461	0.1368
52	H	C	250,000	1,560,461	0.1602
53	H	D	250,000	1,560,461	0.1602
54	H	G	231,553	1,560,461	0.1484
55	H	H	250,000	1,560,461	0.1602
56	H	I	250,000	1,560,461	0.1602
57	H	L	10,700	1,560,461	0.0069
58	H	M	56,097	1,560,461	0.0359
59	H	N	48,585	1,560,461	0.0311
60	I	C	250,000	2,250,000	0.1111
61	I	D	250,000	2,250,000	0.1111
62	...	...	...	...	...

Figure 7: Cell weights in grid

How it functions is that a system of weights was defined to indicate how much each cell would influence the mean value of indicators in surrounding cells. To do this, the net or occupied area of every cell was calculated after having been clipped to the study area (water bodies removed). Cell occupancies (how much of a cell falls on land within the study area) is then summed using the Summarize feature in ArcGIS to establish the total area occupied by a host cell and its adjacent cells (hereby referred to as slaves). With this information, a cell weight can be established for each slave with respect to its host, $SlaveWeight = \frac{SlaveArea}{HostTotalArea}$.

As one can see, cells that represent small areas because they are mostly located in waterways such as the St-Lawrence or because they are on the fringes of the study area carry less weight in the calculation of a given indicator. This avoids bias in the cells near these areas and permits a more representative evaluation of a phenomenon.

Cluster indicator choice

Most of the methodological aspects of the clustering work are covered in the articles, and as such I will not repeat them here, but one element which is not discussed is the different cluster configurations attempted. The number of clusters chosen for analysis is justified using visual examination, a need for results to be legible and intuitive to planners, and finally Calinski-Harabasz values (a means by why to find optimal numbers of clusters (Milligan & Cooper, 1985)), but the different combinations of indicators attempted are not shown. The figure below shows 4 different indicator combinations used in cluster analysis; five neighborhood types are defined and reclassified to range from rural to urban for each indicator combination (tests were run using anywhere from 4 to 10 clusters, results were similar across tests).

CNORM = population and employment densities, land use mix, and public transit accessibility (this is the **NORM**al configuration used for both the TRR and EPB papers)

CPOP = same as CNORM, but without employment density (only **POP**ulation density)

CREG = same as CNORM, but public transit accessibility is broken into two categories, one for local service and another category for **REG**ional service (commuter rail, peak-hour express buses, etc.)

CECAC = same as CNORM, but with **e**mployment **c**enter **ac**cessibility added (**ECAC**cess)

CNORM	NBPER	Ppl_HH	pop_ha	jobs_ha	lu_mix	PT_access_	localPT	regionalPT	Ecacc	PTpassBIN	AUTO_bin	ACTIVEbin	TRANSITbin	teen_bin	child_bin	AvValid	ActSpKm^2
1	10,777	2.89	7.02	1.27	5%	5.52	4.6	1.74	6,893	7%	99%	13%	30%	16%	29%	80%	38.18
2	23,566	2.69	21.1	5.61	12%	27.6	22.93	4.54	11,463	17%	96%	19%	30%	16%	24%	79%	21.55
3	14,698	2.35	35.92	14.7	20%	79.28	77.41	3.78	13,269	18%	86%	28%	29%	12%	17%	72%	14.15
4	5,552	2.15	45.14	32.67	26%	162.58	152.66	6.88	15,192	19%	79%	40%	30%	10%	13%	72%	9.36
5	2,521	1.85	62.49	83.88	31%	306.89	323.11	22.39	17,207	23%	61%	55%	34%	6%	8%	65%	6.93
CPOP	**NBPER**	**Ppl_HH**	**pop_ha**	**jobs_ha**	**lu_mix**	**PT_access_**	**localPT**	**regionalPT**	**Ecacc**	**PTpassBIN**	**AUTO_bin**	**ACTIVEbin**	**TRANSITbin**	**teen_bin**	**child_bin**	**AvValid**	**ActSpKm^2**
1	15,726	2.92	10.2	1.72	6%	8.18	6.15	2.77	7,623	9%	99%	15%	31%	17%	31%	81%	34.88
2	19,966	2.6	22.74	6.52	13%	32.45	27.41	4.34	12,057	18%	95%	19%	29%	15%	21%	77%	19.5
3	13,368	2.35	36.21	15.18	20%	81.76	80.71	3.81	13,271	18%	86%	28%	30%	12%	17%	73%	14.21
4	5,533	2.15	45.23	32.76	26%	162.71	152.6	6.9	15,218	19%	79%	40%	30%	10%	13%	72%	9.33
5	2,521	1.85	62.49	83.88	31%	306.89	323.11	22.39	17,207	23%	61%	55%	34%	6%	8%	65%	6.93
CREG	**NBPER**	**Ppl_HH**	**pop_ha**	**jobs_ha**	**lu_mix**	**PT_access_**	**localPT**	**regionalPT**	**Ecacc**	**PTpassBIN**	**AUTO_bin**	**ACTIVEbin**	**TRANSITbin**	**teen_bin**	**child_bin**	**AvValid**	**ActSpKm^2**
1	14,892	2.88	9.93	1.81	6%	8.64	4.88	2.66	7,972	10%	99%	14%	31%	16%	29%	81%	33.96
2	23,308	2.6	24.06	7.62	14%	36.9	28.71	4.06	12,007	17%	94%	21%	30%	15%	22%	77%	19.95
3	12,319	2.31	36.45	18.18	21%	94.7	90.23	4.83	13,654	19%	84%	30%	30%	12%	16%	73%	13.19
4	4,915	2.11	47.66	41.25	25%	189.45	176.89	8.84	14,807	18%	76%	41%	29%	9%	13%	70%	9.83
5	1,680	1.88	72.68	82.8	30%	307.75	404.53	24.29	17,491	25%	60%	56%	37%	7%	10%	66%	6.7
CECAC	**NBPER**	**Ppl_HH**	**pop_ha**	**jobs_ha**	**lu_mix**	**PT_access_**	**localPT**	**regionalPT**	**Ecacc**	**PTpassBIN**	**AUTO_bin**	**ACTIVEbin**	**TRANSITbin**	**teen_bin**	**child_bin**	**AvValid**	**ActSpKm^2**
1	4,398	2.72	11.63	4.69	10%	49.1	48.33	0.01	4,631	2%	96%	19%	25%	15%	26%	77%	32.99
2	7,928	2.93	10.01	1.55	6%	24.45	26.67	1.75	6,582	7%	98%	15%	31%	16%	30%	81%	34.65
3	15,397	2.82	18.12	3.59	10%	30.34	28.27	4.34	9,019	15%	98%	18%	32%	18%	27%	82%	25.56
4	11,502	2.55	23.07	8.69	14%	54.85	46.82	5.46	12,434	19%	95%	20%	29%	14%	19%	79%	17.46
5	17,889	2.13	46.31	32.68	25%	123.75	121.76	7.77	16,821	21%	77%	36%	30%	10%	13%	68%	9.99
TOTAL	57,114	2.52	28.09	15.19	16%	70.39	67.77	5.21	11,979	16%	90%	25%	30%	14%	21%	76%	20.4

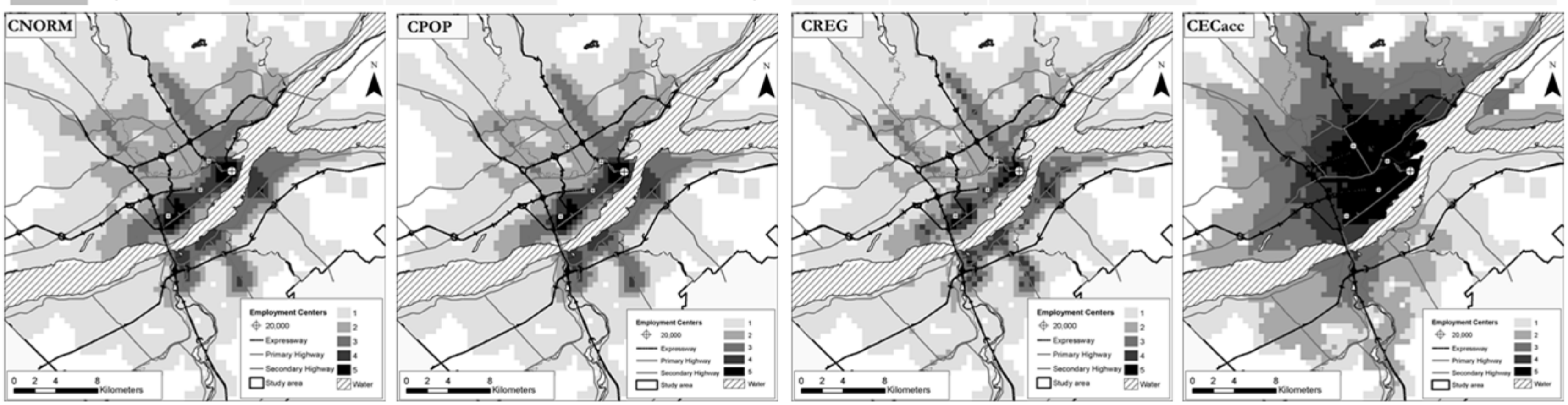


Figure 8: Different cluster configurations, variables in dark grey included in clustering

As one can see in Figure 8, which shows data for Quebec City, the cluster indicator that was most different from the 4 indicator-approach used in Chapters 6 and 7 (CNORM) is CECAC. The other two indicator combinations gave similar results to the 4 indicator approach used, but CNORM was chosen for a few reasons. First, given the data that we had at our disposal, generating an employment density indicator was not much additional work compared to CPOP, which had one indicator less and produced clusters with less variation in activity space. This variation was very important since the focus of the work was on isolating urban form effects on travel dispersal. In addition to this, the literature review and previous work I had done led me to believe that employment density (since it is a proxy for services and amenities in a way) would have a large effect on activity space generation – the larger variation in activity spaces across clusters once again confirms this, if only superficially.

Another reason CNORM was chosen was that the CECAC combination led to results which were dominated by the employment center accessibility variable. As such, results looked much more like distance to CBD than neighborhood types (especially in Quebec which does not have employment centers as significant outside the core). Finally, the CREG combination that divided transit offering into local and regional led to incompatible results for analysis of activity spaces. By this I mean that suburban locations far from the core were lumped in with more urban-type clusters and thus pulled the average activity space of these clustered households up significantly, while no longer representing a uniform type of environment.

For these reasons, CNORM was chosen as the indicator combination of choice.

Chapter 6 Modeling the effect of land use on activity spaces

Context

An earlier version of the following paper was presented at the Transportation Research Board's (TRB) annual meeting in January of 2012. Minor modifications were subsequently brought to it before it was submitted and accepted for publication in the Transportation Research Record (TRR). My role was that of lead author.

- Harding, C., Patterson, Z., Miranda-Moreno, L. F., & Zahabi, S. A. (2012) Modeling the Effect of Land Use on Activity Spaces. *Transportation Research Record: Journal of the Transportation Research Board. 2323, p. 67-74*

In the paper, minimum convex polygons are generated from OD data to quantify the area of the activity spaces produced by households, and clustering is explored to generate neighbourhood types from UF and transit indicators measured in a grid. The effect of these clusters on trip dispersal is then investigated by estimating cluster and other variable coefficients using multiple regression analysis.

Modeling results indicate a statistically significant link exists between neighborhood type and travel behaviour, and more specifically that increases in urban-ness lead to decreases in activity space size. Another noteworthy finding is that results from clustering would seem to indicate that the effects of certain urban form variables on activity space size are non-linear, and as such not properly estimated by regression models that include these UF and transit accessibility variables as continuous linear explanatory variables. The approach of creating neighborhood types based on the landscapes found within a given metropolitan region also allows planners to evaluate the effect of interventions in their local context. Having this type of information tailored to a given region adds to the realism of assessments made.

Introduction

Research on the effects of land-use on transportation has historically concentrated on a few key indicators, notably mode choice, VMT and number of trips. The focus of such research has also overwhelmingly been concerned with the effects of individual land-use variables: e.g. what is the effect of public transit accessibility or residential density on distances travelled. Recent literature has, however, brought to light that when modeled using a clustered approach, which typifies areas based on combinations of land-use variables, as opposed to dealing with them individually, their combined influence on individual and household transportation behavior is less ambiguous in direction and greater in magnitude.

In line with such findings and using the Metropolitan region of Montreal as an application environment, this paper examines the effect of clusters of land-use indicators on activity spaces, an emerging but traditionally ignored, transportation behavior indicator.

The paper begins with a review of the literature on land use variables and travel behavior, followed by a summary of the work on clustering, and finally that which pertains to activity spaces. The data used for this paper is described, as well as the ways in which it was employed to quantify the impact of land use variables on activity spaces. Regression model results and data analysis follow, and the paper concludes with a summary of key findings and suggestions for future research.

Literature Review

The following literature review outlines the different approaches taken to measuring the effect of land use variables on transportation behavior, both individually and as clusters, and ends with the material related to activity spaces.

Traditional Land-use and Travel Behavior Literature

The traditional approach to linking land use variables to transportation behavior looks to the levels of either mix or density and links these to common measures of travel activity such as vehicle kilometers travelled (VKT), vehicle hours travelled (VHT), number of trips and mode choice. Ewing and Cervero's (Ewing & Cervero, 2001) (Ewing & Cervero, 2010) seminal works looked at this body of literature in both 2001 and 2010, highlighting the links found between different indicators and travel behavior. They point out those with the strongest correlation, but also highlight areas where links have proven either difficult to quantify or demonstrate as significant.

Travel behavior variables are usually broken down into categories for individual, household and built form characteristics. Commonly used individual variables include gender, age, income (Bento, Cropper, Mobarak, & Vinha, 2005) and education (Boarnet & Sarmiento, 1998), whereas household variables, or indicators, commonly used are number of persons or children per household (the latter acting as a proxy for stage in the life-cycle) (Lin & Long, 2008), income and number of vehicles owned (Shay & Khattak, 2007).

Built form characteristics can also be divided into a few categories. There is widespread agreement within the literature that the three Ds proposed by Cervero and

Kockelman act as the basic categories of urban form indicators, notably density, diversity and design (Krizek, 2003) (Shay & Khattak, 2007). One can find residential and employment densities quantified as simple measures of individuals per unit area (Riva, Apparicio, Gauvin, & Brodeur, 2008) or retail employment per area (Boarnet & Sarmiento, 1998), but more elaborate methods are also employed. Many papers outline different ways to address public transit accessibility, dealing with it as proximity to stations or bus stops (Shay & Khattak, 2007), rail and bus line coverage (Bento, Cropper, Mobarak, & Vinha, 2005), headway (Miranda-Moreno, Bettex, Zahabi, Kreider, & Barla, 2011), etc.

Literature on clustering of urban form and public transit variables

More recent literature in the field deals with the effect of multiple land-use variables on transportation behavior through clusters, or neighborhood typologies.

In the literature that links specific urban form characteristics to travel behavior, three distinct problems are encountered, namely that of biased elasticities (Bento, Cropper, Mobarak, & Vinha, 2005) (Boarnet & Sarmiento, 1998), results that are not statistically significant (Ross, Tremblay, Khan, Crouse, Tremblay, & Berthelot, 2007) (Shay & Khattak, 2007) and issues of causation or self-selection (Leck, 2006) (Miranda-Moreno, Bettex, Zahabi, Kreider, & Barla, 2011). Neighborhood typologies, combined with household-level control variables, enable researchers to deal with urban form attributes while circumventing issues of biased coefficients, statistical significance and causation (Shay & Khattak, 2007) (Lin & Long, 2008) (Riva, Apparicio, Gauvin, &

Brodeur, 2008) (Gershoff, Pederson, & Aber, 2009) (Miranda-Moreno, Bettex, Zahabi, Kreider, & Barla, 2011).

Measuring levels of the three Ds is a common approach to linking travel behavior to land use, however, authors such as Krizek have argued that interpreting such measures individually disregards the inherent relationships that exist between them (Krizek, 2003). By combining indicators, one can better describe activity density (Kamruzzaman M. , Hine, Gunay, & Blair, 2009) and more clearly understand the effect that changing levels of urban form and public transit can have (Bento, Cropper, Mobarak, & Vinha, 2005). Techniques such as k-means clustering (Manaugh, Miranda-Moreno, & El-Geneidy, 2010) can be employed to define these typologies and, when combined with control variables such as income or life-cycle characteristics, aid in building more accurate models for predicting travel demand.

These clusters and neighborhood typologies can be built in different ways, with or without the use of weights, and can include any indicator one finds pertinent, be it population or employment density, street grid connectivity, sidewalk provision, transit availability, etc. See Gershoff, Pederson, and Aber (2009), Lin and Long (2008), Manaugh, Miranda-Moreno, and El-Geneidy (2010) or Shay and Khattak (2007) for an overview of different techniques and indicators used.

Activity Space Literature

Activity spaces can be used to represent the areas individuals or households interact with as they travel (Kestens, Lebel, Daniel, Thériault, & Pampalon, 2010). They can be used to measure either access to certain resources or the spread of activities throughout space, bringing a new dimension to travel demand modeling. Created using standard deviational ellipses (SDE), minimum bounding geometry or other means (Buliung & Kanaroglou, 2006) (Rai, Balmer, Rieser, Vaze, Schonfelder, & Axhausen, 2007), these spaces have been employed in fields as varied as criminology (LeBeau, 1987), transit planning (Kamruzzaman M. , Hine, Gunay, & Blair, 2009), nutrition exposure (Kestens, Lebel, Daniel, Thériault, & Pampalon, 2010) and healthcare (Sherman, Spencer, Preisser, Gesler, & Arcury, 2005). Different types of data have also been used to generate them, some accounting only for routine activities based on interviews (Sherman, Spencer, Preisser, Gesler, & Arcury, 2005), others using travel diaries (Kamruzzaman M. , Hine, Gunay, & Blair, 2009).

Fan and Khattak for example used the indicators of building density, retail accessibility and street grid connectivity to quantify the impact of land use variables on individual spatial footprints and found that downtown residents generated smaller spaces than their suburban counterparts (Lee-Gosselin, Miranda-Moreno, Thériault, & Kreider, 2009) (Fan & Khattak, 2008). Smaller activity spaces are commonly viewed as beneficial from an energy and environmental perspective (Freund & Martin, 2007) (Manaugh & El-Geneidy, 2012); this is also true from a health (Frumkin, 2002) (Marshall, McKone, Deakin, & Nazaroff, 2005) and economic perspective (Calthorpe, 1993). Activity spaces can therefore aid in developing policy to guide cities towards more sustainable mobility futures.

The idea of moving from traditional transportation demand measures to activity spaces is supported by a growing recognition of the importance of non-commuting trips to the total travel of households (Buliung & Kanaroglou, 2006). The link between land use characteristics and distances travelled has already been investigated by many scholars, but a strong body of literature on the relationship between urban form, transit accessibility and activity spaces is not yet available. This paper will begin to fill that void by demonstrating the effect clustered indicators can have on activity spaces.

Study area and data used

The methods proposed in this paper are applied to the greater Montreal region of Quebec, Canada. Montreal is the second largest Census Metropolitan Area in Canada with a population of more than 3.6 million inhabitants in the latest (2006) census. It is an old city by North-American standards, characterized by an urban form built up over many phases. It also has a varied housing stock and a heterogeneous mix of transportation options, offering both heavy and commuter rail, and extensive bus service in addition to a well-developed highway network (see Figure 9). This heterogeneity in urban form and transit accessibility creates the landscape that makes Montreal a perfect case study for the effects of urban form on travel demand.

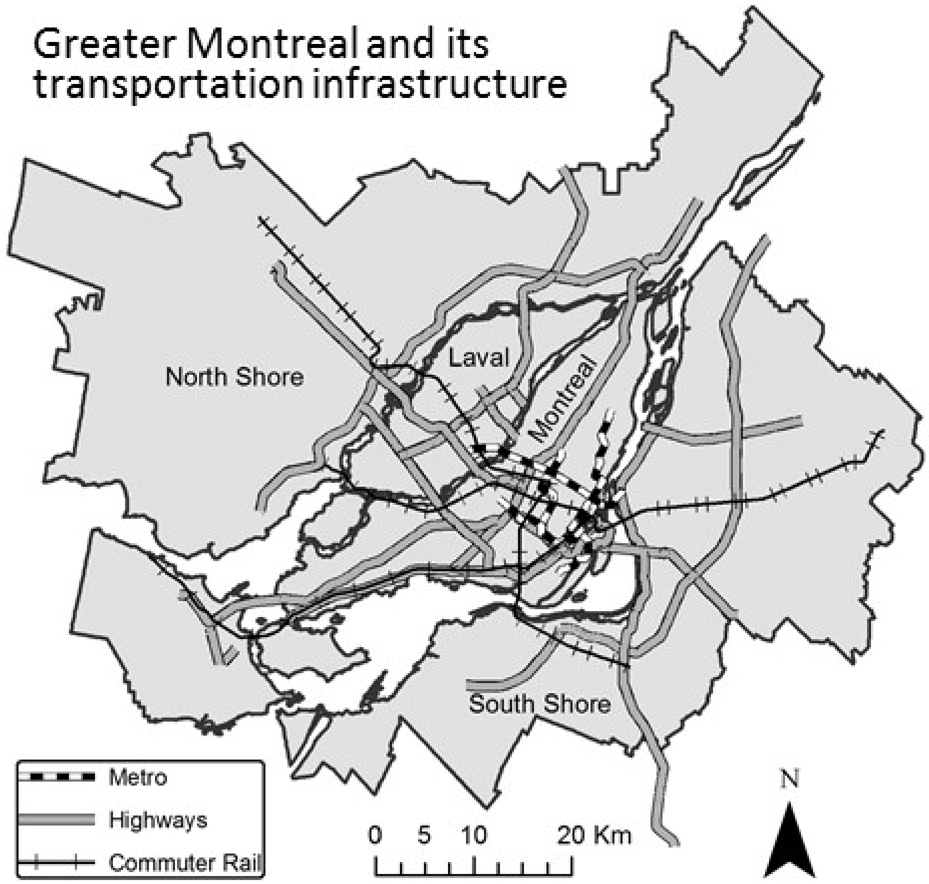


Figure 9: Study area, TRR

Seven different sources of data were required for this analysis, which builds upon the methodological approach of Miranda-Moreno et al. (Miranda-Moreno, Bettex, Zahabi, Kreider, & Barla, 2011): census tract (CT) population and employment counts, demographic characteristics, land use data, public transit data, personal and household mobility data, and finally CT shapefiles.

Land use shapefiles were obtained from Desktop Mapping Technologies Inc. (DMTI), a recognized GIS content provider. DMTI categorizes land use into seven categories, including water, open areas, residential, commercial, governmental and institutional, industrial and parks and recreation. Census tract shapefiles were in turn obtained from Statistics Canada's Census Tract Digital Boundary Files (Statistics Canada, 2006). These boundaries, as well as those for land use data, were used to delimit the study area.

With respect to public transit, geocoded transit lines and stops tagged with unique identifiers linking them to weekday AM-peak headways were used. The transit network used as the source for this information is a hybrid network. Its base comes from an existing TransCAD transit network of the Island of Montreal created in 2003 by Dr. Murtaza Haider of Ryerson University. The development of this digital network was supported by a grant from the National Sciences and Engineering Research Council (NSERC) as well as infrastructure provided by the Canada Foundation for Innovation (CFI). Transit lines off the island were added to the existing network in the summer of 2011. Both parts of the network were geocoded by hand since network information (property of five main transit operators) is not generally available outside of those institutions. That said, while the networks have changed over time, their main characteristics have remained similar. The principal difference between the 2003 and updated network was the addition of three metro stations in Laval, just North of Montreal Island on Jesus Island.

For household mobility data, the Montreal 2003 and 2008 Origin Destination surveys (OD), which are comprehensive travel demand surveys carried out every 5 years by the Agence Métropolitaine de Transport (AMT) – Greater Montreal's public transport planning agency- were used. Montreal's OD surveys contain data on approximately 5% of the households in the study area, collecting time, mode and motive specific travel descriptions, as well as origin and destination XY coordinates for all trips carried out by persons aged over 4 years. They also collect household and personal characteristics for the individuals in each surveyed household.

It should be noted that in 2003, household domicile coordinates were coded as the XY coordinates of the actual home, whereas in 2008, the domicile coordinates were instead entered as the XY coordinates of the dissemination area (census subdivision smaller than a CT) within which the household was found. To ensure compatibility between datasets, we recoded the 2003 home-based trips to indicate the dissemination area centroid as opposed to the domicile. Data concerning 56,965 households in 2003 and 66,124 in 2008 were used in this analysis (Agence Métropolitaine de Transport, 2003 and 2008).

A grid consisting of cells 500 meters wide, as well as a nine-cell grid encompassing the host and references to the eight surrounding cells was also used; the latter to average indicator values over a larger area, avoiding peaks.

Census level data was acquired via StatsCan's E-Stat website, which provides information at the CT level regarding both the socio-demographics of populations– including average income and education attainment, employment sector activity, etc.-, as well as built form – including building type, age, condition- and other variables (Statistics Canada, 2006) (Statistics Canada, 2001). Employment data was obtained through the 2001 and 2006 "Enquête sur le travail et le milieu de travail et les employés," produced by Statistics Canada (Statistics Canada, 2001) (Statistics Canada, 2006). This was provided by Statistics Canada as a 'special order' from a consortium of provincial government ministries and agencies. Statistics Canada uses census information to infer employment information (number of jobs by NAICS sector by CT).

Methodology

This section provides a description of the generation of clusters from the four selected indicators, the calculation of activity spaces and statistical methods employed to estimate the effect of land-use on activity space.

Whereas much of the research previously published has made use of aggregated data for their analyses, either at the transportation analysis zone or CT level, this paper uses highly disaggregate data for cluster analysis. For example, data such as population and employment may be obtained at the CT level, but by isolating land uses that could contain them and calculating their density after an adjustment to area, much more accurate information on the locations and densities of indicators is obtained.

Previous work on clusters has looked at population density, land use entropy, public transit accessibility (Miranda-Moreno, Bettex, Zahabi, Kreider, & Barla, 2011), urban design (Krizek, 2003) (Lin & Long, 2008) and other variables, and research by Leck (2006), Bento (2005) and Ewing and Cervero (2010) has demonstrated that employment density is an important predictor of travel demand. As such, clusters were designed to incorporate the following four indicators: population and employments densities, land use mix and public transit accessibility.

Densities

For all calculations involving residential density, only residential land use area was used, likewise for employment density, only commercial, government and institutional, and resource and industrial land use areas were used; to obtain the most accurate information 'net' and not 'gross' density was employed. These net-density employment and residential-only census tract polygons were then intersected with the grid previously described.

Land use mix

A similar process was used in the calculation for land use mix, also at the cell level, where an entropy index was devised based on that of Miranda-Moreno et al. (see Equation 1). The more land uses there are in a cell and the more evenly their areas are distributed, the higher the value; its range is 0 (no mix) to 1 (perfect heterogeneity).

Equation 1: Land Use Mix, TRR

$$E_j = -\sum_{i=1}^{n} \frac{\left[\left(\frac{A_{ij}}{D_j}\right) ln\left(\frac{A_{ij}}{D_j}\right)\right]}{\ln(n)}$$

Where:

Aij : area of land use i in cell j

Dj : area of cell (excluding water and open area)

n : total number of different land uses

Public transit accessibility

The grid approach was used to calculate the accessibility of cells to transit by finding the nearest bus, metro and rail line stops to each cell and summing each line's closest stop's contribution to a transit accessibility index; a stop closer to a cell centroid or a smaller headway (calculated using AM peak) would mean a larger contribution to transit accessibility (see Equation 2).

Equation 2: Public Transit Accessibility, TRR

$$PTaccess_j = \sum_{i=1}^{n} \frac{1}{(d_{ij} * h_i)}$$

Where:

PTaccessj : accessibility to public transit at cell j

dij : distance, in km, from cell centroid j to nearest bus stop of line i (minimum value of 0.1 km)

hi : average headway, in hours, of line i in AM peak (maximum value of 1 hour)

All four indicator values were averaged with those contained in the eight surrounding cells. There are particular ways in which incomplete cells near bodies of water or the boundaries of the study were dealt with, in addition to the weighing of cells that intersected partial land use tracts, but it is beyond the scope of this paper to describe these.

Neighborhood typology, or clustering

After compiling indicator values, k-means cluster analysis was employed to create the typology. Similar to the procedure outlined in Lin and Long, clusters were generated attempting to find a balance not only between predictive power and number of cases (households), but also using visual representations as a 'sanity' check (Lin & Long, 2008). Such a verification of face validity was also used later on in the regression stage, combined with a review of the correlation matrix, to aid in determining which independent variables to include in the model.

The four cell values, for population and employment densities, public transit accessibility and land use mix were input in STATA, and to increase the relevance of clusters, only cells that contained OD survey households and at least one non-null value were kept. Excluding cells that contained only null values removed 6,125 of 17,601 cells, or 35%, from the exercise, but only 1% of the valid OD households. Of the remaining cells, 3,007 contained the dissemination area centroids of valid OD households for 2003 and 3,168 for 2008. Since the goal was to predict activity spaces, assigning clusters to areas that were uninhabited was deemed unnecessary.

Although the densest cluster contains very few cells (and only 1.2% of the total number of households in a 7 cluster approach), the large size of the dataset ensures this remains a significant number of cases. See Table 1 for the mean of urban form and public transit characteristics, as well as counts and percentages, for each cluster.

Table 1 Summary statistics for clusters (valid households only)

2003 and 2008 Clusters	Obser-vations	Persons / Hectare	Employment / Hectare	Land Use Mix	PT Accessi-bility	House-hold Trips	Percent on Island of Montreal	Activity Space (km2)
1, Rural no Transit	44% / 18,210	19.66	4.70	21%	6.98	8.60	24%	68.79

2, Rural	11% / 4,685	29.78	8.90	30%	46.42	8.54	68%	40.57
3, Rural / Suburban	11% / 4,493	44.90	12.18	37%	109.54	8.20	100%	33.31
4, Outer Suburb	12% / 4,771	66.46	21.66	44%	171.75	7.82	99%	22.86
5, Inner Suburb	13% / 5,165	86.72	29.82	50%	247.95	7.53	100%	18.27
6, Urban Core	8% / 3,294	96.22	67.79	56%	362.37	7.16	100%	14.87
7, Downtown Core	1% / 499	86.38	250.55	59%	554.52	6.55	100%	11.41
Mean	41,116 Total	44.37	19.16	33%	107.19	8.18	62.5%	45.01

Clusters were reclassified to represent increasing levels of transit accessibility, land use mix and density. From cluster 1 to 2 and so on, the densities (measured in persons or jobs per hectare) increase rather significantly; cluster 7 has four times the mean population density and over 50 times the mean employment density as its transit-less rural counterpart, cluster 1 (see Table 1). Land use mix also increases significantly when one passes from the low value clusters (20% entropy value) to higher ones (60%), and transit increases almost exponentially, from 7 to 550 units. The transit indicator's values are unbounded, but in this case range from a low of 0, which indicates that no public transit stops are within a host cell's search radius, to a high of 775.

To be useful to planners, clusters must not only be significant in modeling travel demand, but must also provide clear and legible descriptions of the neighborhoods they represent. Based on the literature, limiting the generation to less than 10 clusters, was expected to produce a legible typology. The results and discussion sections describe two variations attempted and the problems encountered.

With mean population densities of 19 and 29 persons per hectare, clusters 1 and 2 (see Table 1) could be considered, as Newman and Kenworthy would call them, automobile-oriented outer suburbs (Newman & Kenworthy, 1999). Clusters 3 through 5, at 45 to 86 persons per hectare would be transit-oriented inner and middle suburbs, and clusters 6 and 7, at 86 to 96 persons per hectare, and much higher employment densities, would be pedestrian-oriented core suburbs (Newman & Kenworthy, 1999) (see Figure 10 for a visual representation of their distribution). Land use mix, transit supply and employment density also reflect the typical definitions of such neighborhoods.

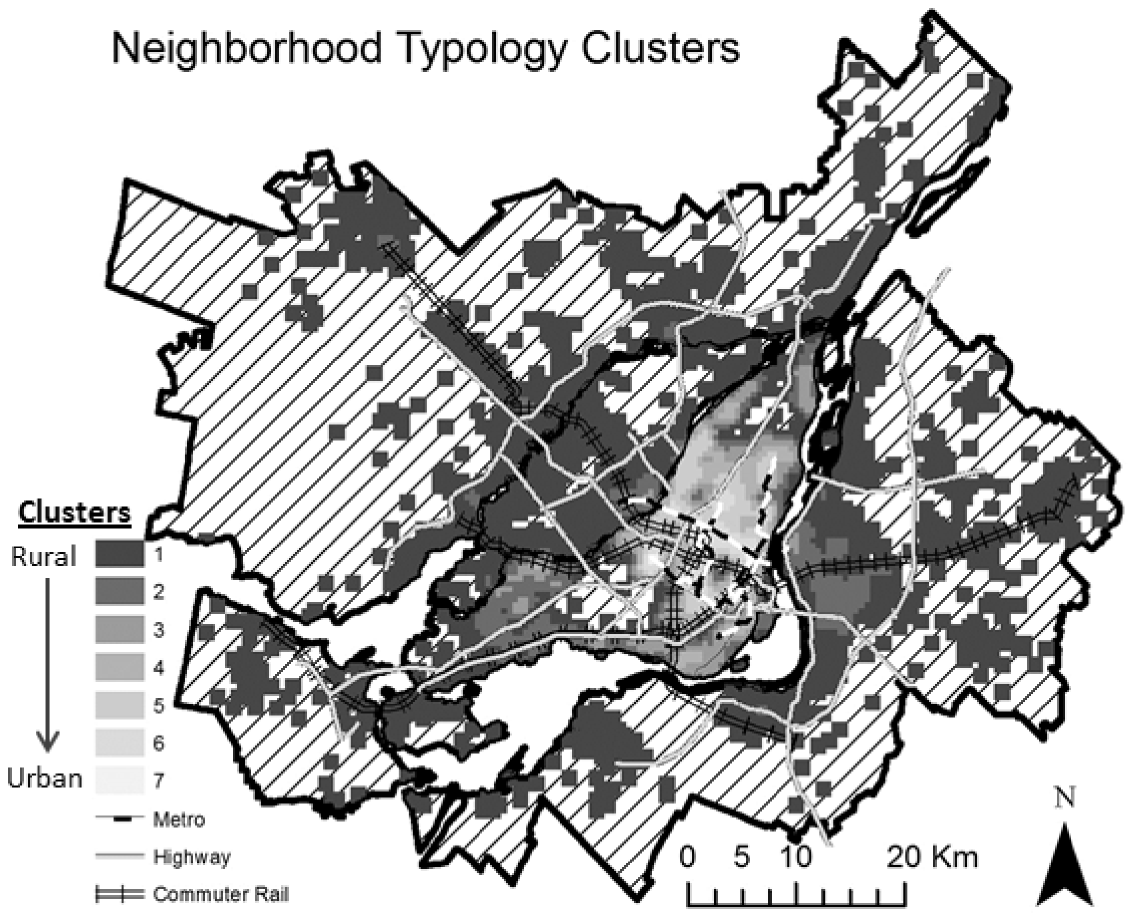


Figure 10 Neighborhood typology and the city's main transportation infrastructure.

Activity spaces

With respect to activity spaces, there exist many different tools that one can use to describe the travel behavior of households (Sherman, Spencer, Preisser, Gesler, & Arcury, 2005). Given the type of data available (daily travel surveys), the convex hull minimum bounded geometry (CVH) was however the best fit; regressions were also run on models using the standard deviational ellipse (SDE), but R^2 values were found to be higher using the CVH, which also ensured all trip locations were accounted for. Because of the joint constraints of the OD survey being a one-day travel diary, and that of activity spaces requiring 3 unique points, household activity spaces were chosen over individual activity spaces. Previous research supports such an approach, household characteristics having been demonstrated to effect travel behavior in previous models (Buliung & Kanaroglou, 2006).

The CVH polygons were generated using ArcMap 10. The first step was to isolate individuals whose trips were all performed within the study area, then to map their origins and destinations. Using the Minimum Bounding Geometry tool, convex hull polygons were generated around each household's origin and destination coordinates. Households whose trips only included one valid origin and destination pair were excluded from subsequent statistical analysis, having formed lines with no area as opposed to polygons. These were isolated by removing the CVH polygons with zero width (16,727 of 52,386 valid households in 2008 and 13,400 of 47,053 in 2003).

It should be noted that the prevalence of households with zero-width polygons was slightly higher in the dense urban clusters, where they account for 35% of cases, against 28% in the more sprawling suburban and rural clusters (2008 numbers). These polygons, however, also occur most often in smaller households (46% in households of 1 person and 41% in households with 2 persons, 2008 also), and these small households are more prevalent in dense urban clusters, where the mean household size is 2.27 as opposed to 3.22 in more rural clusters. Since the major influence is household, and not cluster,-based, it was determined results would be more accurate if the model were built without taking zero-width polygons into account.

Out of an awareness of the importance of household and life-cycle characteristics, over 25 different variables were run alongside clusters in the regression model; only the final set will be reported here. Since census tracts define areas that are "designed to be homogeneous with respect to population characteristics, economic status, and living conditions" (Lin & Long, 2008, p. 741) (Riva, Apparicio, Gauvin, & Brodeur, 2008), CT-level information was included by matching households to the census tracts in which they reside. This made up for the absence of socio-demographic information, such as income and employment, in the OD survey.

Distance to central business district (CBD) was considered, but as had been demonstrated in Shearmur (Shearmur R. , 2006), although the downtown core attracts high numbers of commuters, the concentrations of employment present in other centers, combined with the changing demographics of society (the increasing number of dual-income households for instance), would have required a much more elaborate model be devised.

Results

Looking at Table 2, one can see that all signs for the reported coefficients carry face validity and only variables with significance levels above 95% were kept. The model's dependent variable is the logarithm of the area occupied by the CVH polygons of households that had more than one unique OD XY coordinate pair and performed both mandatory as well as non-mandatory trips - such an approach was also taken in Manaugh and El-Geneidy (2012). This left us with 20,703 valid household polygons for analysis in 2008 and 20,413 in 2003.

Table 2 - Regression results, the logarithm of the activity space area is the dependent variable

	Number of observations		41,116
	R-squared		0.28
Variable	Coefficient	t-stat	95% Confidence Interval
Cluster 2, Rural	-0.25	-8.91	-0.31 to -0.2
Cluster 3, Rural/Suburban	-0.44	-15.17	-0.5 to -0.39
Cluster 4, Outer Suburb	-0.64	-21.54	-0.7 to -0.58
Cluster 5, Inner Suburb	-0.77	-25.55	-0.82 to -0.71
Cluster 6, Urban Core	-0.97	-26.57	-1.04 to -0.9
Cluster 7, Downtown Core	-1.52	-19.37	-1.67 to -1.36
FG workers per CT (%)	-1.07	-11.42	-1.25 to -0.88
# of Children	-0.32	-24.65	-0.35 to -0.3
# of Seniors	-0.27	-5.58	-0.37 to -0.18
# of Full-time Students	0.15	11.67	0.12 to 0.17
# of Full-time Workers	0.40	31.78	0.38 to 0.42
Licences per Household	0.32	25.94	0.3 to 0.34
# of Trips	0.10	34.79	0.09 to 0.1
Resident of Laval	0.15	5.47	0.09 to 0.2
Homemakers per CT (%)	2.95	18.29	2.63 to 3.27
OD 08 Household	-0.05	-3.03	-0.08 to -0.02
Constant	14.79	208.88	14.65 to 14.93

*Reference cluster is cluster 1, the most rural cluster

As the model demonstrates, more urban clusters lead to consistently smaller activity spaces; the absolute value of the coefficients for cluster dummy variables become larger as cluster values increase (see Table 2). In addition, not only are the cluster binary variables statistically significant, but the confidence intervals for these variable coefficients exhibit no overlap. This is a clear indication that, not only are these clusters significant in improving the predictive power of the model, but they are also statistically significantly different one from another.

For example, were we to build a sample household using the mean observed values for each individual model variable and then move this *typical* household across clusters, the predicted activity spaces produced would vary from a high of 67.11 km^2 in the base case (cluster 1, or low density transit-less rural), to 35.42 km^2 in cluster 4 (outer suburb), all the way to a low of 14.72 km^2 in cluster 7 (dense, downtown core). These differences in predicted activity space are the result not of changing household demographics or tract level properties, but merely moving a hypothetical *typical* household from one cluster to another. The values mentioned above are bias-corrected for logarithmic back transformation using the technique described by Newman (Newman M. C., 1993).

Model results indicate a significant link between clusters and activity space, and Figure 11 shows a 3D representation of this. In it, darker colors represent low cluster values and heights represent the average actual activity space at a given cell. The cells that appear flat on the map represent values for activity space below a certain threshold (for display purposes the heights are multiples of the square root of activity space). In contrast to the large dark peaks, many flat cells appear in the central portion of the island of Montreal and many low-height peaks are in white and light-grey (high-value clusters, or dense, highly mixed and well-served by transit areas).

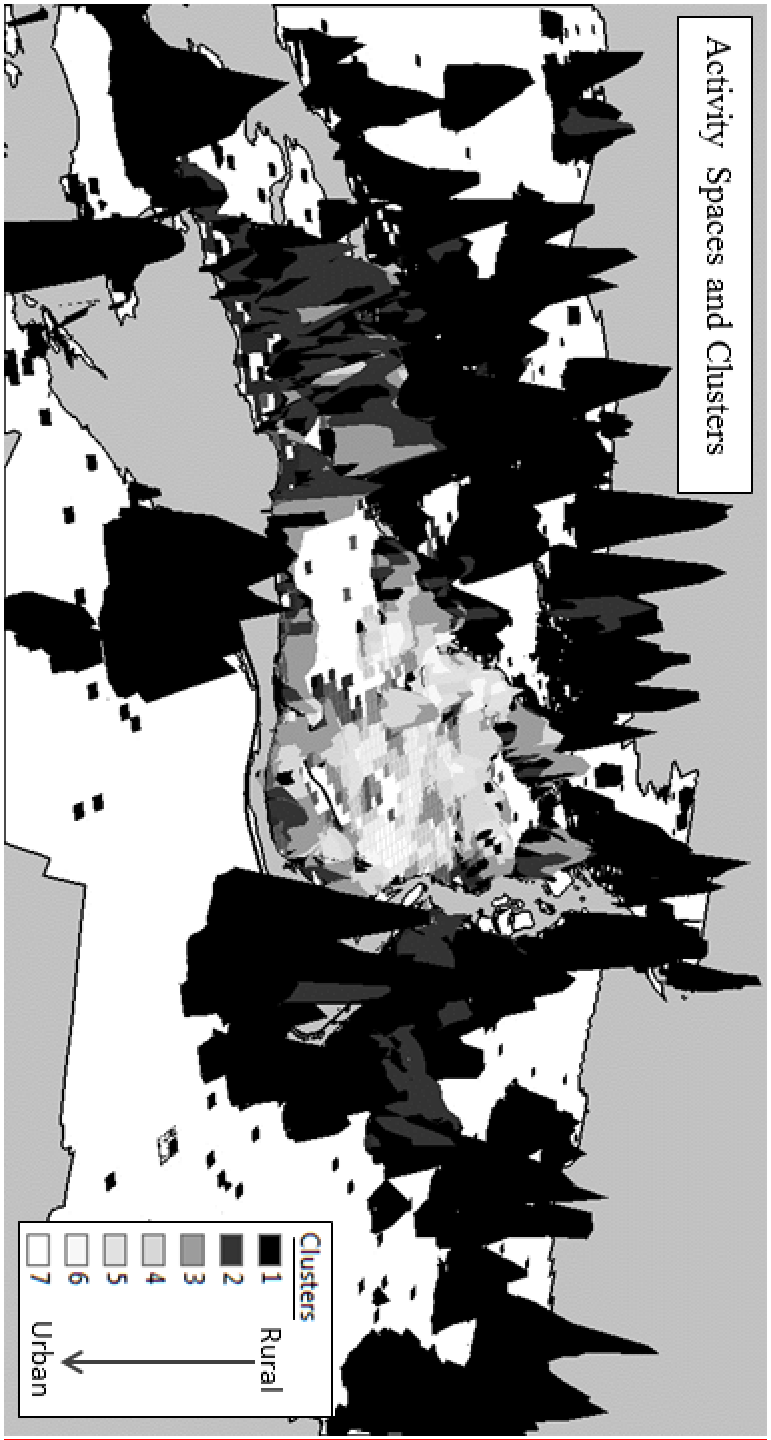


Figure 11: Clusters and activity spaces, 2008 data displayed – heights represent average activity space for all residents of a given cell.

The inclusion of F and G categories of employment (percentage of persons per CT working in occupations in art, culture, recreation and sport, and sales and service occupations) as a CT-level variable was based upon trial and error, but also previous work that found that these sectors were consistently overrepresented outside of employment centers (Shearmur R. , 2006); i.e. more dispersed, leading to smaller distances traveled on average to access work locations. The lower level of specialization within these sectors, means local workforces are more likely to fill these positions.

A variable whose predictive power and significance proved very high was "homemakers". This CT-level variable indicated the percentage of women aged 15 and over in a CT spending more than 15 hours a week performing unpaid child care. When tracts with high homemaker values were displayed in ArcMap, a pattern emerged where most were rural CTs and the remainder high average-income CTs. Rural populations would intuitively have to travel long distances to reach activities, while high incomes would justify one partner's ability to stay home tending to children, while the other partner (most likely working in a specialized field or occupying a managerial position, would need to travel long distances to commute to his or her high income position).

Number of trips was included in the model despite higher trip generation in rural and suburban clusters because their numbers were found to be more closely tied to household size than urban form and transit indicators. Conversely, household sizes in the more rural and suburban clusters are on average larger, and as such it would be expected that their activity spaces be larger across the board, but these households also contain more children, who, as Shay and Khattak describe, lead to increases in household size without adding drivers (Shay & Khattak, 2007). As such they are unlikely to travel large distances for work or school, and by their influence on the time budget of adults, actually decrease average activity space (Manaugh, Miranda-Moreno, & El-Geneidy, 2010).

"From an economic perspective, distance to work is conceptualized as a cost, and greater travel distances are associated with higher earnings (and/or lower residential costs)" (Shearmur R. , 2006, p. 332), as such it was odd to find that the average income variable attempted in the model resulted in a very small coefficient. The aggregated nature of data may be one explanation, it having come from the CT as opposed to the household, but the fact that many high income tracts are found near the CBD is more likely the determinant factor.

High percentage of detached housing led to larger activity spaces and high rental-housing proportions led to smaller activity spaces, but these and many other CT-level variables were excluded from the model because they were not found to be statistically significant, possibly due to high collinearity. These housing indicators merely stand as poor proxies of urban form and transit characteristics, without taking into account the subtle variations that make the clusters more accurate.

Discussion

Data analysis had the objectives of quantifying the relationship between clusters and travel behavior, and in particular activity spaces.

The number of clusters to include in the final model was not only based on face validity when looking at the maps produced by assigning clusters to cells, nor was it determined purely on the basis of regression results. It is important in any study of the effect of urban form on travel behavior to bear in mind that the goal is to provide planners with easy to interpret and apply templates for neighborhoods, not merely to increase statistical significance.

As such, 7 clusters were generated, but a look at the Percent on-island Montreal (dummy variable) column of Table 1 reveals an important point related to scales of analysis; over 98% of the households represented by clusters 3 through 7 are on the island of Montreal (as can also be seen in Figure 10), this despite on-island observations representing only 62.5% of the valid household population. When 6 clusters were generated, this geographic difference was even more pronounced, with 92% of households represented by clusters 2 through 6 being Montreal households. In essence, the difference that exists between the landscapes of Montreal and its surrounding areas is so large that bringing their urban form and transit characteristics together to generate clusters leads to an almost complete disappearance of the subtleties present off-island. Clustering still leads to intuitively consistent predictions, but it does not leave much room for off-island tracts to learn from on-island ones; the differences in urban form and transit accessibility being so stark between the two that off-island municipalities aiming to emulate characteristics of denser Montreal clusters to reduce excessive travel demand would face landscape redesign challenges worthy of Haussman’s transformation of Paris. With respect to Montreal on the other hand, this reaffirms the vast differences that exist between geographically proximate, but dissimilar, neighborhood types.

An interesting notion to keep in mind when interpreting results is the concept of diminishing returns. As Krizek stated, once a certain level of service provision or density is exceeded, an increase in the number of businesses or transit stops may have negligible impact on travel behavior (Krizek, 2003). This is reflected in Table 1, wherein the population density actually decreases between clusters 6 and 7; a non-linear relationship case in point for using clustered land use indicators as opposed to individual ones.

Another important point is that the measure for transit could still be refined, as infrequent regional bus stops, as well as commuter rail stops, exhibit high spatial correlation with large activity spaces. Future research should thus try to separate local transit from regional and express transit, both of which by their very nature carry people over large distances while still creating an upward bias to cluster cells near them.

To reiterate, looking to the regression results in Table 2, one can see that the influence of clusters was high and all the included coefficients were intuitive and right-sided: household licences, high homemaker CTs, more trips, full time students and workers, and coming from Laval (an island just North of Montreal island, separated from it by bridges) increasing activity space, while high cluster values (which are associated with dense, mixed use and transit rich environments), service sector employment, and children and seniors decreased activity spaces. Finally, the OD 08 dummy variable produced a statistically significant, albeit slight, negative coefficient; this would indicate that activity spaces decreased somewhat from 2003 to 2008. Further analysis would be necessary however to confirm this as a trend.

Conclusion

In summary, this paper has demonstrated the pertinence of using a clustered approach to relate urban form and public transit to activity spaces in a context-sensitive way. Results point to a significant link between land use clusters and activity spaces, and imply that efforts to increase density, mix and transit accessibility are valid investments for cities seeking to reduce travel demand they deem excessive, environmentally detrimental or unproductive. Since household and CT characteristics were used as control variables, the regression results make a strong case for promoting densification, increased land use mix and better transit provision.

An approach that could bear fruit to improve model accuracy in the future may be to use latent-class linear regression, which would combine the land use clustering approach with a form of household clustering. Instead of using continuous household or even CT variables like income, number of cars, persons and children to predict activity spaces, these could instead be treated as subpopulations. Another improvement could be to endogenize household location choice to account for residential self-selection.

Future research aimed at developing land use and transportation policy could definitely make use of the clustered approach combined with activity spaces, but what this case study has demonstrated is that the scale and heterogeneity of the region studied must be carefully considered before undertaking such an endeavor. Smaller scales or an altered methodology would improve the likelihood of clear policy being written from these analyses. Cluster analysis provides an effective means by which the potential impacts of urban form and transit interventions can be assessed, and thus their costs and benefits properly evaluated.

Chapter 7 A spatial and temporal analysis of the effects of land use clusters on activity spaces in three Quebec Cities

Context

Building upon the work described in Chapter 6 Modeling the effect of land use on activity spaces), this chapter describes the results of broadening the cluster and activity space approach to multiple cities and explains the lessons that can be drawn from such comparative work.

To begin, the effect of neighborhood type estimated in Chapter 6 when looking at Montreal (increases in urban-ness leading to decreases in activity space) also comes through in model estimation for neighborhood types in Quebec and Sherbrooke. An equally if not more important finding in this paper however, is that of a clear city-size effect on travel dispersal; larger cities leading to larger activity spaces overall, seemingly irrespective of how dense or mixed the urban environment is. This has important implications for regional planning, especially in light of recent work by Florida and others that point to increases in the number of mega-cities worldwide in the coming decades (Florida, 2008).

This paper also broadened the methods of analysis employed by using a simultaneous equation model (SEM) in addition to an ordinary least squares multiple regression model (OLS). This was done in an attempt to deal with variable endogeneity. Contrary to previous work by colleagues at McGill (Miranda-Moreno, Bettex, Zahabi, Kreider, & Barla, 2011) however, statistical analysis did not reject the hypothesis of variable exogeneity; results are presented side by side to allow comparison of variable coefficients. Having these results side by side also allows one to see where coefficient estimates may be over-or-under estimated, providing guidance for isolating particular environments or concentrations of household types that may be skewing model estimation results.

As indicated in the paper's conclusion, were the model specification to change however, or even the statistical test used to compare the OLS to the SEM (BIC was used here), the hypothesis of variable exogeneity may yet have been rejected. This is something that, although not a reason to disregard any results, needs to be kept in mind. Given the investment of time required for additional testing, and that the primary purpose of the paper was to see what the effect of neighborhoods would be in different cities, this was not followed through on.

Finally, transposing the methods of indicator generation, clustering and regression analysis to Quebec and Sherbrooke CMAs served to demonstrate that the approach is not only valid in Montreal, but can be applied outside this context. The most complicated data source to obtain was perhaps the transit network, but given the growing use of GTFS data (like that which the STM and many other transit agencies already make available), such may not be the case for long.

The paper was presented in an earlier version at the 13th International Conference on Travel Behaviour Research, held in Toronto, Ontario; the annual meeting of the International Association for Travel Behaviour Research (IATBR), in July 2012. After the conference, Sherbrooke was added to the analysis and improvements made before the paper was submitted for a special issue of Environment and Planning: B. The final version was accepted April 21, 2013.

- Harding, C., Patterson, Z., Miranda-Moreno, L. F., & Zahabi, S. A. (in press) A spatial and temporal comparative analysis of the effects of land use clusters on activity spaces in three Quebec Cities. *Environment and Planning B, Special Issue on Activity Space Research from the 2012 IATBR- guest Editor: Harry Timmermans.*

Introduction

Scholars and planners alike have looked at the impact of various land use and accessibility measures, such as population density and land use mix, to investigate the links between travel behavior and where one lives or works. The relationships outlined through much of this research, however, have been plagued with inconsistent and often weak results (Boarnet & Sarmiento, 1998; Bento, Cropper, Mobarak, & Vinha, 2005; Ewing and Cervero, 2010; Pinjari, Pendyala, Bhat, & Waddell, 2011; Cao & Fan, 2012). To address these concerns, a new generation of transportation and land-use literature has emerged that investigates clusters of land use indicators, resulting in more consistent and stronger relationships between land-use and travel behavior (Shay & Khattak, 2007; Lin & Long, 2008; Manaugh et al., 2010) . These clusters, or neighborhood types, are thought to be more suitable descriptors of the built environment as they recognize interdependencies between indicators and identify representative combinations.

The dependent variables modeled in traditional travel demand literature have also most often been related to outcomes such as commuting distance or mode share. More recently, a growing desire to understand the non-work travel behavior of individuals and households has spawned interest in yet another dimension of mobility; activity spaces (Dijst, 1999; Schonfelder & Axhausen, 2003; Buliung and Kanaroglou, 2006; Fan & Khattak, 2008; Kamruzzaman & Hine, 2012; Manaugh & El-Geneidy, 2012). These spaces are a representation of the area covered by an individual or household during the course of their habitual travel.

Whereas outcomes like commuting distance or mode share were initially modeled to understand peak demand for road space or transit seats, activity spaces as a travel behavior indicator differ in that they represent the spaces where households interact with their cities, or where potential may exist for interaction. This allows researchers to better comprehend the interaction between travel over or around an activity site, and perception of the environment (Dijst, 1999). As Fan & Khattak (2008) describe, through knowledge of travel dispersion, we gain a better understanding of total travel demand, not simply at its peak, and given growing concern over greenhouse gas (GHG) emissions, knowing whether travel is progressively more spread about or concentrated in certain areas allows both emissions trends to be generated and palliative measure to be devised.

Combining a clustered approach to defining neighborhood types with an analysis of household activity spaces in the Montreal, Quebec and Sherbrooke census metropolitan areas (analogous to US MSAs), this paper investigates the influence of environmental factors on household activity spaces. Building upon previous work conducted using a subset of the land use variables and data for the Montreal region alone (Harding C. , Patterson, Miranda-Moreno, & Zahabi, 2012), traditional measures such as population and employment densities, land use mix and public transit accessibility are clustered to create a neighborhood typology for each of the cities. Activity space polygons are then generated from two distinct origin-destination surveys for Quebec, three for Montreal, and one for Sherbrooke. By creating typologies and linking households to them by residential location, one can establish links between the type of environment inhabited and the ways in which we move about. This provides a better understanding of which combinations of land use and transportation enable households to most efficiently satisfy their needs for accessibility, while curbing the ever-expanding growth in mobility.

Activity space area is analyzed using ordinary least squares (OLS) regression, but also simultaneous equation modeling (SEM) to account for potential joint residential location-and-vehicle ownership choice and the effect this may have on household trip dispersal. This is done to address concerns over residential self-selection biases (defined in section *Residential Self-Selection*, below).

The large sample size of the origin destination (OD) surveys (nearly 250,000 households when pooled together), combined with the element of evolution through time and over multiple landscapes provides new information to the field, combining neighborhood with regional-level analysis. Our results indicate that neighborhood types within cities have a statistically significant effect on trip dispersal, but that differences from one city to another bear the largest influence. This finding, while perhaps intuitive, appears to be downplayed in the literature on transportation and land use linkages. Other key findings are that where employment centers are fixed, activity spaces appear to be growing over time, and that comparison of SEM and OLS model estimation results does not provide conclusive evidence of residential self-selection.

Literature Review

Urban form and its effect on travel behavior

The transportation sector in Canada accounts for 26% of its GHG emissions (Environment Canada, 2007). With a growing concern over the effects of suburbanization on citizen health and that of our environment and economy, reassessing de-facto development patterns becomes imperative. The three (or five) Ds are the means by which urban form (UF) is traditionally quantified and classified; density, diversity and design, and destination accessibility and distance to transit (Krizek, 2003) (Transportation Research Board and Board on Energy and Environmental Systems, 2009). Work that looks at these variables in relation to travel demand usually links increases in density, diversity and destination accessibility to lower vehicle kilometers traveled, and improvements in the design of neighborhoods and reduction in the distance to transit with higher active and transit mode shares (e.g. Ewing & Cervero, 2001; Leck, 2006; Ewing & Cervero, 2010).

Such a view of the city and its dynamics is not without its critics however. Some question the validity of estimated coefficient elasticities, whether out of a belief that residential self-selection may be distorting the picture (Boarnet & Sarmiento, 1998; Cao & Fan, 2012) or that the variables chosen for analysis may be proxies for broader regional properties (Naess, 2012). Most academics agree that land use plays a key role in affecting travel behaviour, but where disagreement exists is in determining how much of this variation can be attributed to UF variables, which dimensions of UF affect which travel demand outputs (Leck, 2006; Pinjari, Pendyala, Bhat, & Waddell, 2011) and how best to capture the interactions between different urban form indicators (see following section).

Clustering for clarity

Whereas research on individual urban form indicators ignores the interactions that exist between different descriptors (i.e. high density *alongside* high land use mix, good street grid connectivity alongside high destination accessibility, etc.), clusters, or neighborhood types, group together observations based on similar combinations of indicator levels. This can be done through the use of principal component analysis to create indices of urbanity (Bagley, Mokhtarian, & Kitamura, 2002) or through statistical clustering of variables to create neighborhood types (Bento, Cropper, Mobarak, & Vinha, 2005; Shay & Khattak, 2007; Riva, Apparicio, Gauvin, & Brodeur, 2008; Gershoff, Pederson, & Aber, 2009). Given the nature of clusters, planning agencies or researchers can use the information gained regarding land use and travel demand linkages in a more holistic way, to both improve quality of life and maximize infrastructure expenditure utility. For example, if a high level of land use mix modeled alone does not prove to be a significant predictor of short trip distances, but areas with high population density that also have medium to high land use mix lead to a shift toward more local travel, planners can use this information to guide policy and concentrate efforts in certain locations, maximizing the impact of their work.

Residential Self-Selection

Another issue with relating UF to travel behavior is self-selection. At its simplest, self-selection occurs when "households or individuals who have a proclivity towards a certain lifestyle may choose or "self-select" to reside in neighborhoods that support their lifestyle preferences" (Eluru, Bhat, Pendyala, & Konduri, 2010, p. 604). Inferring from revealed travel that people residing in certain environments move about in a given way because of their exposure to that environment, as opposed to seeing their behavior as partly a function of their preferences for land-use or mode choice, may lead to unrealistic assessments of the impact of UF (Leck, 2006), or inflated coefficient estimates (Pinjari, Pendyala, Bhat, & Waddell, 2011; Cao & Fan, 2012).

To overcome this potential weakness, some authors have used matched pairs of observations (Cao & Fan, 2012), linked simultaneous equations together using common stochastic terms (correlated error terms) (Pinjari, Pendyala, Bhat, & Waddell, 2011) or modeled decisions related to household location and vehicle ownership jointly (Miranda-Moreno, Bettex, Zahabi, Kreider, & Barla, 2011).

Activity spaces

Early work on activity or action spaces grew out of the research carried out by Hägerstrand using space-time prisms. Combined with the idea of a cognitive space or mental map, when these prisms are transferred from the realm of potential travel to realized travel, what we obtain are activity spaces; 2 or 3 dimensional descriptions of the areas individuals interact with and acquire knowledge about through habitual travel (Dijst, 1999).

When measuring the activity spaces of people or households, what we obtain is an assessment of spread or dispersion. These measures can be generated using a variety of GIS tools and geometries, such as road network buffers (RNB), minimum convex polygons (MCP), standard deviational ellipses (SDE), etc. For an overview of these measures and their applications, see Buliung & Kanaroglou (2006) and Rai, Balmer, Rieser, Vaze, Schonfelder, & Axhausen (2007).

As Newsome, Walcott, & Smith (1998) explain, “the observed activity space may or may not represent the maximal area over which the traveller could engage in activities, but rather the area over which they are likely to regularly engage in those activities” (p. 361). Information added to a person’s mental map through exposure is what shapes future travel patterns, but a similar argument could be made regarding social networks; like our physical exposure to the world, these networks add to our awareness space, potentially leading to further travel. This is one of the reasons why one might seek to measure the influence of information and communications technologies (ICTs) on activity space (Axhausen, 2007).

Another motivation for the study of activity spaces is that the proportion of work trips is decreasing over time (Black, An unpopular essay on transportation, 2001) (Axhausen, 2007). As a result, priorities are shifting away from understanding peak demand to assessing safety of roads at off-peak periods, GHG emissions and potential for social exclusion. Regarding the latter, some researchers have investigated whether small spaces per se indicate transportation disadvantage or exclusion, but results remain inconclusive (Schönfelder & Axhausen, 2003). Although not explicitly measuring response to activity space and dispersal, one third of the low-income and high car ownership households in Currie et al.'s paper (2010) did "acknowledge that transport costs were a high proportion of their income and most adopted coping strategies to limit travel expenses" (p.294). Such an outcome is a prime example of what we should seek to avoid by better coordinating development in such a way that people are empowered to choose where to live, and not restricted in their options only to locations where car ownership is a prerequisite to participation in the community.

Study Areas & Data Used

In order to test the effect of clustered land use variables on activity spaces, both across time and in cities of different size and structure, we analyse data from the largest cities in

Quebec for which comparable data is available. Montreal, Quebec and Sherbrooke all have comprehensive OD surveys, and they are respectively the 1^{st}, 2^{nd} and 4^{th} largest census metropolitan areas (CMAs) in the province – the third being Ottawa/Gatineau, a CMA that was precluded from analysis because it crosses the Ontario/Quebec border. In addition to OD surveys, the selected CMAs share comparable employment and demographic, and land use and UF data.

Montreal is the cultural and economic hub of the province, with over half its population, while Quebec is the province's political and historic capital, characterized by a more sprawled UF, and lower density and transit offering. Sherbrooke, the only city in the sample not along the St-Lawrence seaway, was historically an industrial town, but is now home to the largest concentration of university students in the province. In 2006, their respective populations were 3,635,571 (Montreal), 715,515 (Quebec) and 186,952 (Sherbrooke) (Statistics Canada, 2006).

OD Data

Each city's OD surveys contain information on all the trips made by each household member aged 4 years or older, for the day prior to the interview. Trip information includes origin and destination coordinates, purpose, mode and time, while household demographics include information on every household member over 4 years of age (whether they make a trip or not); this includes vehicle ownership, driver's license, age, gender and occupation, and other variables. These surveys contain information on 4 to 10 percent of the households in each region.

Urban Form variables

The main sources of spatial data used in the creation of indicators are land use data obtained from DMTI Spatial, census tract (CT) boundaries and census socio-demographics obtained from Statistics Canada.

To characterize public transit accessibility, data was obtained from a variety of sources. The network for Montreal was composed of a base originally geocoded in TransCAD in 2003, to which off-island transit lines were added in the summer of 2011. Both parts of the network were geocoded by hand since network information (property of five main transit operators) is not generally available outside of those institutions.

For Quebec, the Réseau de Transport de la Capitale provided bus line stops and headways, while the Société de Transport de Lévis provided lines, from which stops were generated and headways approximated.

As for Sherbrooke, the Société de Transport de Sherbrooke supplied us with GTFS data (General Transit Feed Specification), as well as tables containing additional service which is run during university and CEGEP semesters.

Methodology

The methodology employed to generate clusters based on the following indicators is similar to that which is outlined in (Harding C. , Patterson, Miranda-Moreno, & Zahabi, 2012) and (Miranda-Moreno, Bettex, Zahabi, Kreider, & Barla, 2011).

Indicator Generation

Densities

Population and employment counts per CT were obtained from Statistics Canada for each of the census years nearest our OD surveys (1996, 2001 and 2006). We then assigned population figures to the portion of tracts occupied by residential land uses and jobs to commercial, industrial and institutional land uses, enabling us to calculate net densities.

To better understand the distribution within tracts, we intersected the land-use isolated tracts with a 500 meter grid, enabling generation of cell-level population and employment densities. Weights were applied to control for incomplete, and cell densities were averaged out with those of surrounding contiguous cells to avoid peaks.

Land use mix

Land use mix was also captured and averaged out at the grid cell level. Using DMTI Spatial's land use data, we calculated cell occupancy for each type of land use, and then applied an entropy formula (see below) to calculate relative mix.

Equation 3 - Entropy formula, TRR

$$E_j = -\sum_{i=1}^{n} \frac{\left[\left(\frac{A_{ij}}{D_j}\right) \ln\left(\frac{A_{ij}}{D_j}\right)\right]}{\ln(n)}$$

where:

E_j : land use mix of cell *j* (from 0 = no mix, to 1 = perfect mix)

A_{ij} : area occupied by land use *i* in cell *j*

D_j : area of cell *j* (excluding water and open area)

n : total number of different land uses

Public transit accessibility

To calculate transit accessibility, headways and distances between stops and cell centroids were used. Since there is theoretically no limit to how many transit lines can be near a cell centroid, the resulting value is unbounded.

Equation 4 - Public transit accessibility, TRR

$$PTaccess_j = \sum_{i=1}^{n} \frac{1}{(d_{ij} * h_i)}$$

where:

$PTaccess_j$: accessibility to public transit at cell j

d_{ij} : distance, in km, from cell centroid *j* to nearest bus stop of line *i* (minimum value of 0.1 km)

h_i : average headway, in hours, of line *i* (in AM peak with a maximum value of 1 hour for Montreal and all-day with a maximum value of 2 hours for Quebec and Sherbrooke)

Neighborhood typologies, or clusters

Once the indicator values were calculated, k-means cluster analysis was used to generate the typology for each city; the 'k' in k-means being the user-specified number of clusters, or neighborhood types, generated. To ensure that grid cells would be associated to the same cluster for the duration of the analysis, only the last year's cell-level indicator values were used. Also, as magnitudes affect clustering behavior (Song & Knaap, 2004), indicators were standardized.

To ensure a more objective choice for k (number of clusters), Calinski-Harabasz values were generated in STATA for each city, and for each k between 2 and 8 (see Table 3); the highest values indicate a statistically optimal number of clusters, or a number for which between-cluster sum of squares is maximized, while minimizing both within-cluster sum of squares and number of clusters (Milligan & Cooper, 1985). Milligan and Cooper (1985) tested 30 different stopping rules (or procedures) using synthetic data and found the Calinski-Harabasz to be the most consistent at correctly identifying clusters.

k	Montreal	Quebec	Sherbrooke
2	3562	1780	**902**
3	2973	1826	763
4	***4068***	**1901**	700
5	**3964**	1697	666
6	3685	1553	605
7	3577	1439	579
8	3283	1419	546

Table 3 - Calinski-Harabasz Values

This approach, combined with a visual evaluation of the clustering, resulted in the choice of 5 clusters for Montreal, 4 for Quebec and 2 for Sherbrooke – see Figure 12-Figure 14 below.

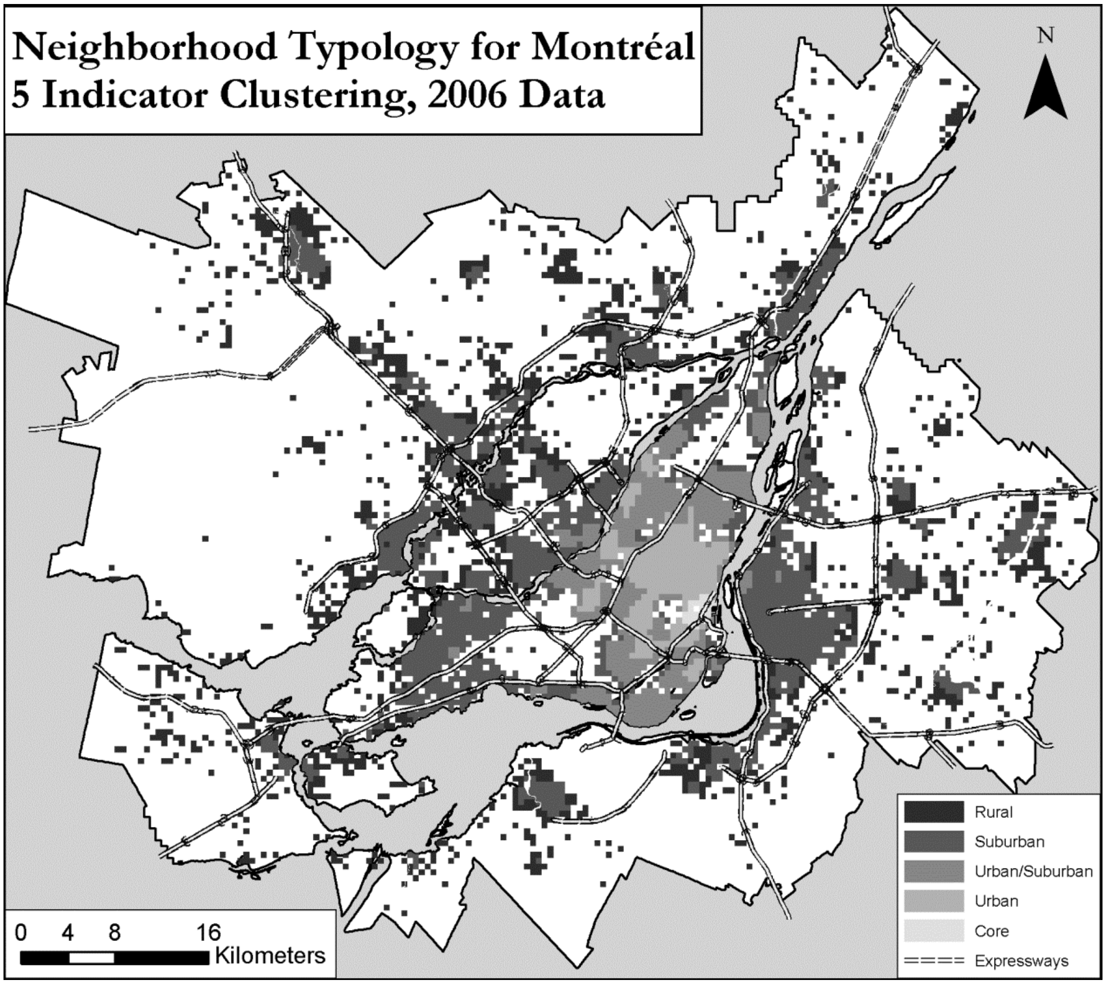


Figure 12 - Neighborhood typology, Montréal

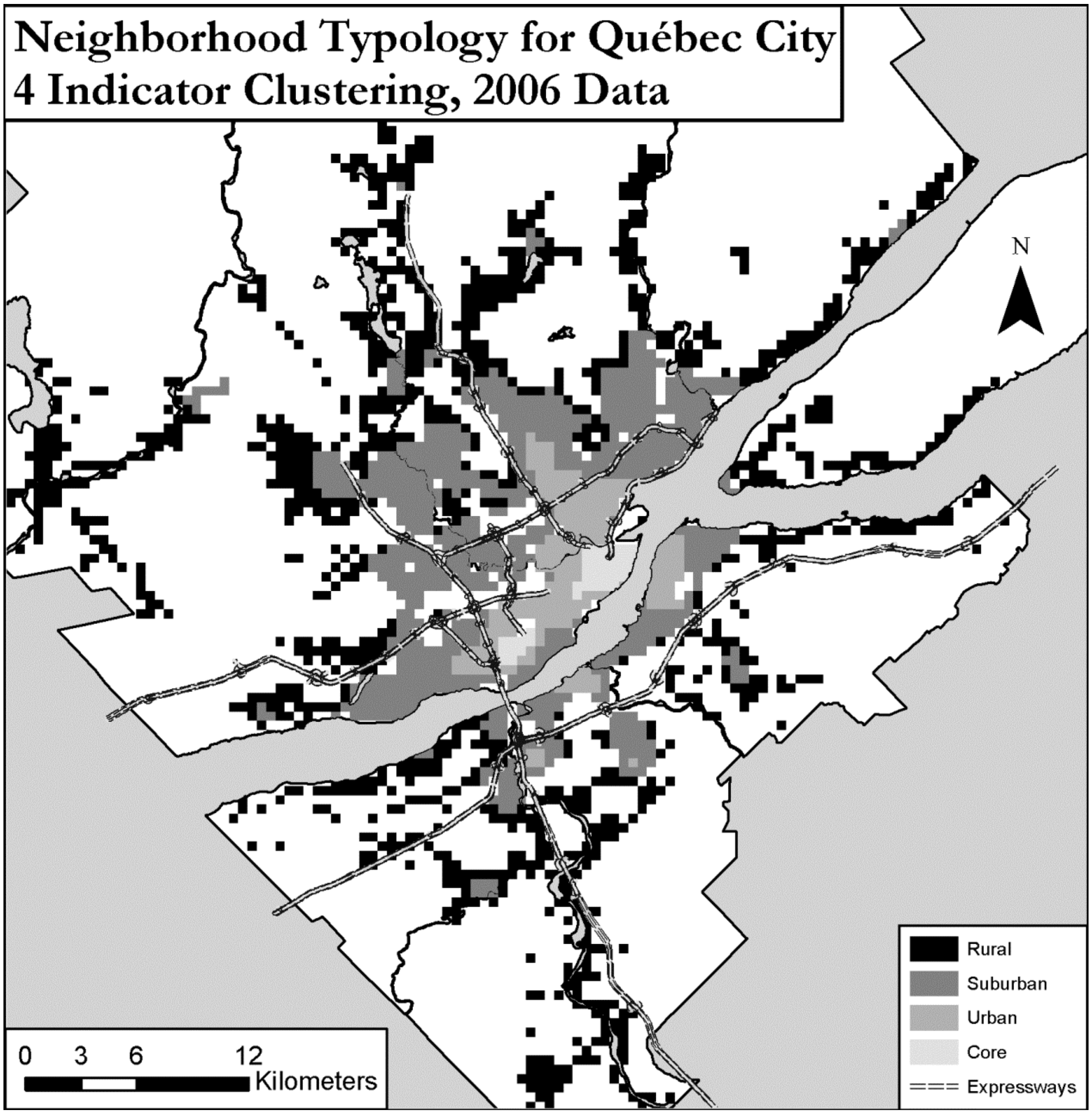


Figure 13 - Neighborhood typology, Quebec City

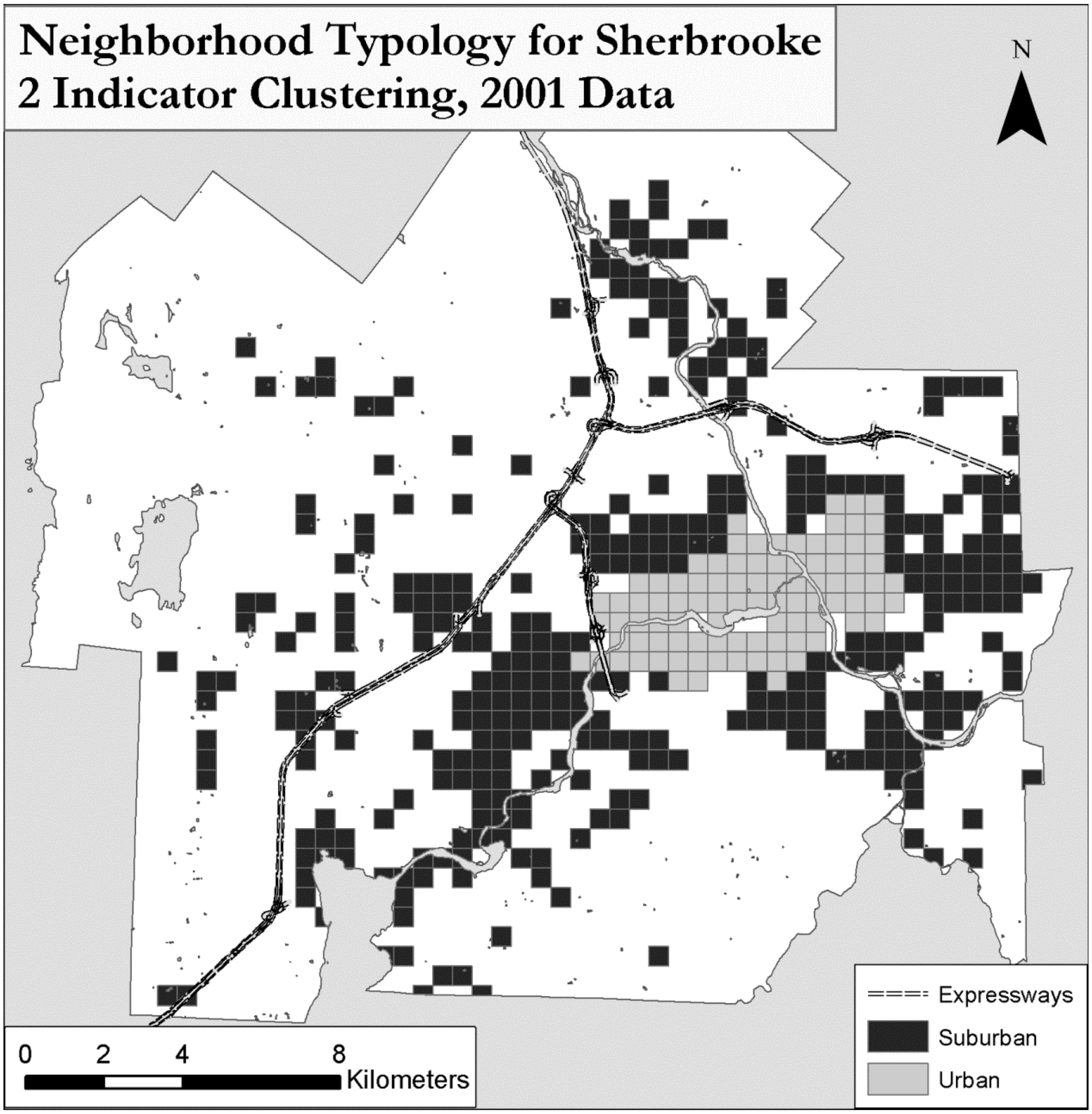


Figure 14 - Neighborhood typology, Sherbrooke

Activity spaces

Since we had access to single-day trip information for households through the OD surveys, the minimum convex polygon (MCP) was chosen as our activity space geometry. The MCP (see Figure 15) forms the smallest possible convex polygon around the locations visited by a person or household, and unlike standard deviation ellipses

(SDE) or standard distance circles (SDC), it does not have the tendency to exaggerate the space occupied when observations are low.

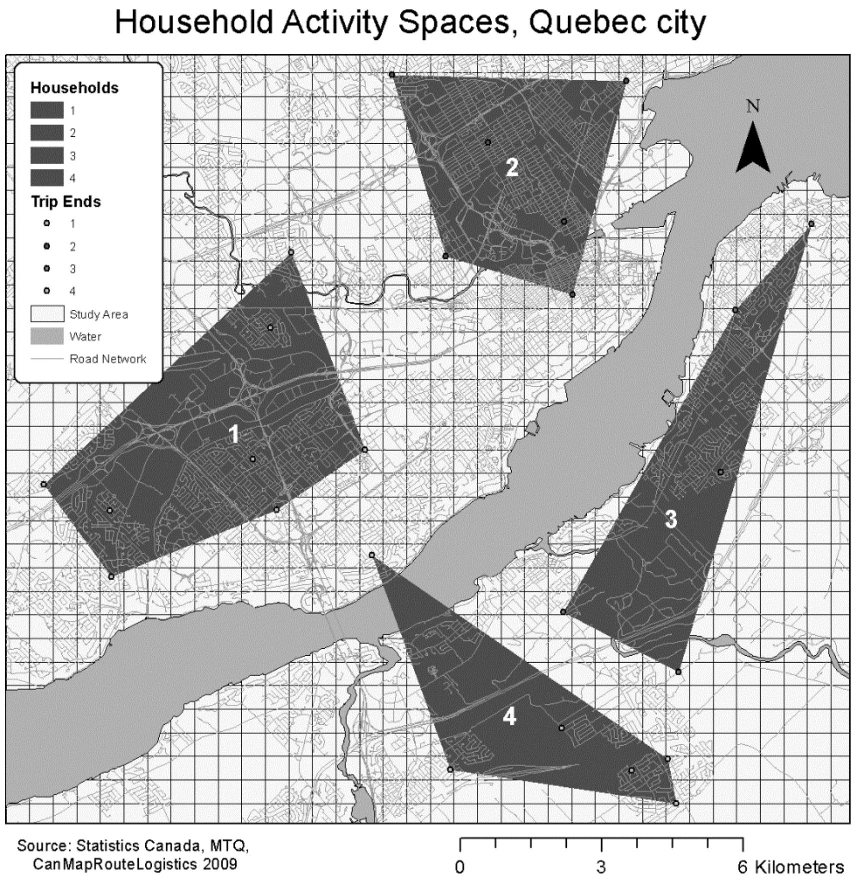


Figure 15 - Activity Space generation, synthetic example set in Quebec

Classification of trip purposes varies from study to study (Newsome, Walcott, & Smith, 1998; Manaugh & El-Geneidy, 2012), but generally accepted mandatory trips are those made for work or school, while non-mandatory trips are those carried out for shopping and leisure, or to meet friends and acquaintances. To get a better idea of typical total household travel, as opposed to simple AB-BA commutes, we isolated households that made both types.

Analysis

Much the same way that continuous built environment variables can be used to predict vehicle kilometers traveled (VKT), we use the neighborhood types generated above to estimate built environment effects on activity space size.

In order to make inferences about neighborhood effects, we must control for demographic differences in each neighborhood's households. In addition, the approach employed here controls for residential self-selection by simultaneously modeling the joint choice of vehicle ownership and residential location, with dispersion of travel (activity space size). This technique and its theoretical foundations are described in Miranda-Moreno et al. (2011). In our simultaneous equation model (SEM), residential location and vehicle ownership are framed as "cluster-car" alternatives, influenced by a series of exogenous household variables.

To test whether the SEM improves the predictive power of the model, thus describing self-selection bias, both an OLS regression model using the same potentially endogenous cluster-car variables, and a cluster-car ownership multinomial logit model (MNL) are run. With the results of these, we can compare model fit using Akaike Information Criterion (AIC) values and thus test the hypothesis of exogeneity, or presence of residential self-selection bias.

This investigation is carried out by comparing the Akaike Information Criterion (AIC) value produced by the SEM, with that of the OLS added to that of the multinomial logit (MNL) model whose dependent variable is the cluster-car choice; the MNL's independent variables are the same treatment variables included in the SEM. Lower AIC values suggest better fit (Congdon, 2003). If the SEM proved to be a better predictor of travel dispersal, it would imply that neighborhood of residence and auto ownership were endogenous, meaning that OLS coefficient estimates were biased.

$$\ln(ActSp_i) = \beta x_i + \sum_{j=1}^{n} \mu KC_{ij} + \sum_{j=1}^{n} \lambda_j l_{ij} + \epsilon_i$$

$$U_{ij} = \beta_j x_i + \delta_j l_{ij} + \eta_{ij} \qquad j = 1, \dots, n$$

where:
$ln(ActSp_i)$ = Area of activity space for household *i*;
x_i = socioeconomic characteristics of household *i*;
KC_{ij} = dummy variables representing neighborhood and vehicle ownership cluster *j* for household *i*;
ϵ_i = random independent error of activity space (normal distribution);
U_{ij} = utility of choice of KC*j* for household *i*, where
j = 1, . . . , n;
l_{ij} = latent explanatory variable of heterogeneity not observed by endogenous variables;
β_{ij} = random independent error of vehicle ownership (normal distribution);
and
β, δ, λ, and *μ* = model parameters.

The SEM was run using the mtreatreg plugin in STATA developed by Deb and Seck (2009).

We also chose to treat household composition as a series of binary variables as opposed to continuous variables. Results were thought to increase legibility for groups like families with children and singles, where one would suspect an intuitive preference for suburban or urban living. This echoes the methods used by Eluru et al. (2010).

Results and Discussion

The following section will present the main findings of our research. We begin by presenting the typology for each city accompanied by summary statistics for the most relevant variables, followed by results of the OLS regression presented alongside those of the SEM.

Summary Statistics

Neighbor-hood Type	Activity Space (km2)	House-hold Count	Persons per Household	Unique Locations Visited	Cars per Household	Carless Households	% Families with Children	Pop Density (per Hectare)	Job Density (per Hectare)	Land Use Mix	Public Transit Access
Rural	83.66	15,147	3.32	4.70	1.96	1%	59%	13	2	0.08	9
Suburban	54.49	25,596	3.16	4.70	1.73	3%	50%	27	8	0.30	38
Urban/ Suburban	27.09	13,700	2.94	4.47	1.31	13%	42%	55	17	0.43	165
Urban	18.70	13,505	2.62	4.31	0.95	28%	33%	96	44	0.53	286
Core	9.47	808	2.02	4.02	0.63	49%	16%	75	314	0.62	516
Total/ Average	47.90	68,756	3.03	4.57	1.53	10%	47%	44	19	0.32	111

Table 4- Summary statistics, Montreal

In Table 4, we see a few expected trends, such as smaller household sizes, less families with children and fewer cars per household in urban areas. The average activity space also decreases sharply as we move along the spectrum from rural to urban, outpacing changes in both household size and vehicle ownership. With respect to UF variables, the trend points to an increase in density, land use mix and public transit access as we move from the more rural to the more urban clusters, but we can also observe that population density does not increase in a linear way. This highlights why clustering is ideal when looking at UF effects on travel demand, as it captures non-linear effects.

Neighbor-hood Type	Activity Space (km2)	House-hold Count	Persons per Household	Unique Locations Visited	Cars per House-hold	Carless House-holds	% Families with Children	Pop Density (per Hectare)	Job Density (per Hectare)	Land Use Mix	Public Transit Access
Rural	42.12	10,664	3.19	5.14	1.84	1%	55%	14	2	0.06	20
Suburban	26.64	8,548	2.99	5.04	1.63	3%	44%	23	8	0.16	54
Urban	13.67	4,178	2.60	4.70	1.23	14%	32%	44	27	0.26	114
Core	10.42	1,641	2.23	4.53	0.90	30%	21%	72	86	0.30	276
Total/ Average	30.01	25,031	2.96	4.99	1.60	6%	45%	26	14	0.14	64

Table 5 - Summary statistics, Quebec

With respect to Quebec City (Table 5), similar trends to those for Montreal appear. Increases in urban-ness are associated with smaller activity space polygons, while densities and land use mix increase as we approach the core. Interesting to note first and foremost is the large difference in average activity space size between our two cities. Whereas Quebec City residents produce an average activity space polygon of around 30 km^2, in Montreal the average is 48 km^2, almost 60% larger. This is a surprising finding in many respects, notably because Quebec has a lower population density and more unique locations visited per household despite smaller household sizes and lower land use mix. It would seem therefore that the absolute size of the census metropolitan area has an impact on the travel behavior of residents, one even greater than neighborhood attributes.

Neighborhood Type	Activity Space (km2)	House-hold Count	Persons per House-hold	Unique Locations Visited	Cars per House-hold	% Families with Children	Pop Density (per Hectare)	Job Density (per Hectare)	Land Use Mix	Public Transit Access
Suburban Carless	3.08	40	2.30	3.78	0.00	10%	16	4	0.15	45
Suburban W-Car	20.97	1,515	3.09	4.91	1.79	38%	11	3	0.10	36
Urban Carless	2.92	148	1.91	3.90	0.00	5%	26	16	0.37	149
Urban W-Car	9.90	1,082	2.66	4.69	1.48	23%	24	15	0.37	128
Total	15.45	2,785	2.85	4.75	1.55	30%	17	8	0.22	78

Table 6 - Summary statistics, Sherbrooke

Sherbrooke being a much smaller CMA than Montreal or Quebec, it was interesting to bring it in to the analysis. As a result of there only being 2 clusters for the region and of the low number of observations for households with no car, it seemed interesting to present the table of summary statistics (Table 6) broken down into cluster-car combinations (as they are used in the regression models that follow).

Sherbrooke shows similar intra-city patterns with regards to the relationship between activity space size and neighborhood types, and further validates the finding relative to city size. Its households' average activity space is just over half that for Quebec City, and as was the case when comparing Quebec to Montreal, this precipitous drop in activity space size occurs despite a decrease in the density of population and employment. Land use mix is however higher in Sherbrooke than Quebec.

Regarding what factors might explain this disparity, the main difference would seem to be city size. Irrespective of how some employment is suburbanizing, all three CMAs still function as coherent wholes (commuting patterns being at the heart of their definition) and as such, if most or all of the specialized employment is found at the core, and if this core keeps getting further and further on average from where people live (as the CMA increases in size), then it is inevitable that people will travel greater distances to access these resources.

A complementary hypothesis would be that “the amount of travel is influenced to a greater extent by the location of the residence in relation to concentrations of facilities, rather than the distance to the closest single facility within a category” (Naess, 2012, p. 38), so that as cities grow, it does not necessarily matter that services are provided within close proximity to the home location, as households will prefer to patron the locations with high densities of a given amenity. The fact that leisure makes up an increasing portion of travel would also reinforce this trend toward larger activity spaces in larger cities, as coordination with others for joint-activities and novelty-seeking inevitably lead to locations further from the home as metropolitan size increases (Schönfelder, 2006).

Linear Regression and Simultaneous Equation Models

To further investigate the trends in travel dispersal within and between cities, OLS and SEM models were employed. The dependent variable in each model is the logarithm of the activity space.

To begin, using the AIC to test for endogeneity of variables, explained in section *Analysis* above, the hypothesis of endogeneity is rejected. The sum of the OLS’ and MNL’s AIC values (using the same explanatory variables as treatments in the SEM), was inferior to the AIC value of the SEM alone. The detailed results that follow do however exhibit certain interesting changes to coefficient values between the OLS and the SEM. These changes would tend to indicate that some travel behavior or some location-and-vehicle ownership choice may be explained in part by specific household predispositions.

Exogeneity as a whole however, or the validity of coefficient estimates obtained using an OLS approach, cannot be rejected.

	Variable	OLS Coeff.	OLS t-stat	SEM Coeff.	SEM t-stat
NO CAR	RURAL	-0.99	-6.67	-0.73	-4.57
	SUBURB	-1.23	-20.17	-1.36	-16.50
	URB/SUB	-1.15	-25.74	-1.18	-19.97
	URBAN	-1.52	-42.19	-1.58	-32.11
	CORE	-2.55	-29.36	-2.48	-24.66
CAR	RURAL	OMITTED		OMITTED	
	SUBURB	-0.36	-19.71	-0.38	-7.07
	URB/SUB	-0.74	-31.23	-0.76	-9.71
	URBAN	-1.02	-38.09	-1.08	-19.64
	CORE	-1.78	-20.97	-1.72	-18.75
	Laval	0.15	7.59	0.15	7.59
	Unique Locations	0.50	104.96	0.50	104.98
	FT Workers	0.27	28.15	0.27	28.00
	Students	-0.05	-5.43	-0.05	-5.43
	Licenses	0.20	19.40	0.19	16.22
	FG Empl.	-1.76	-10.81	-1.75	-10.80
	Homemakers	2.22	17.25	2.22	17.28
	Single Female*	-0.10	-2.64	-0.10	-2.66
	Single Male*	0.11	3.00	0.11	2.89
	Couple*	0.09	3.83	0.09	3.71
	SS Couple*	0.19	5.55	0.19	5.61
	Single Parent*	-0.30	-9.48	-0.30	-9.35
	Family with Kids*	-0.14	-6.10	-0.14	-6.18
	2003	0.09	5.80	0.09	5.81
	2008	0.12	8.00	0.12	8.01
	Constant	13.92	198.02	13.96	182.50

* indicates a variable included in the treatment logit (cluster-car)

Number of obs.		68,756		
R-squared		0.34		
Adj R-squared		0.34		
AIC		261,785	AIC	469,284
(AIC mlogit)		207,318		

Table 7 - Regression results, Montreal

All variable coefficients in the Montreal regression models (Table 7), are right-sided and significant. The omitted category is “Rural With Car” and all the other cluster-car binary variable coefficients make sense interpreted in relation to this (all other neighborhood types are estimated to produce smaller activity spaces, ceteris paribus). In addition, there is only one case for which the progression from Rural to Core does not decrease the value of the coefficient (which would indicate activity spaces are getting smaller as cluster cells become more urban); between clusters Suburban and Urban/Suburban. The Suburban-cluster households are in a unique situation, given the still-high level of transit service (see Table 4) allowing good connections to the core, accompanied by significantly higher vehicle ownership than the Urban cluster; the best of both worlds from a mobility perspective. These households also seem more active than suburbanites, as demonstrated by the higher ratio of unique locations visited per person. Overall the cluster-car portion of the model performs well.

The rest of the variable coefficients are also intuitive, with Laval (an island and important suburb just North of Montreal), number of unique locations, full time workers and licences all increasing the activity space size. As was the case in Harding et al. (2012), a CT variable found to be significant in predicting decreases in activity space size was FG (employment in sales, services and the arts). From an econometric perspective, “location choices are determined by the extent of spatial variation in wage rates and in housing price” (Madden, 1981, p. 183), meaning that households with lower wage elasticities for the industries in which they work will be expected to live closer to their job, or to choose their job more as a function of where they live. Employment in sales and services fits this description.

Mirroring results from Harding et al. (2012), 'Homemakers', a CT variable that represents the percent of women at home that perform 15 hours or more of unpaid child care, was positive and significant. Many of these high 'Homemakers'-value tracts are both affluent and some distance from employment centers.

Single parents also came out as a significant variable reducing the average activity space size. This is consistent with the literature on the effect of children on the time budget of single parents, a disproportionate share of whom are also women (MacDonald, 1999). Families with children produced a similar, albeit smaller, coefficient. Couple and SS Couple coefficients (two adults living together without children) complement this with positive values.

Finally, regarding evolution over time, significant, positive and increasing binary variable coefficients are found for '2003' and '2008' (1998 is the omitted category). The trend these coefficients imply regarding an increase in trip dispersal over time concords with the hypothesis that as households gain more time for leisure and improved access to ICTs, their social networks become increasingly disconnected from the location where they reside, resulting in larger activity spaces (Axhausen, 2007). This is also interesting as Harding et al. (2012), using an OLS model without controling for vehicle ownership, had found the opposite when looking at the 2003 and 2008 Montreal datasets. This highlights the significant impact controls and model specification can play. In Harding et al. (2012), the authors describe household composition using continuous variables, and number of licenses per household instead of vehicle ownership. The specification employed here leads to larger t-statistics on coefficient estimates for the year binary variables (indicating a clearer relationship) and better overall model fit is obtained (R^2 of 0.34 compared to 0.28).

	Variable	OLS Coeff.	OLS t-stat	SEM Coeff.	SEM t-stat
NO CAR	RURAL	-0.73	-4.49	-0.87	-3.94
NO CAR	SUBURB	-1.11	-11.85	-1.30	-9.67
NO CAR	URB/SUB	-1.55	-23.40	-1.74	-15.42
NO CAR	URBAN	-2.10	-28.60	-2.25	-23.11
CAR	RURAL	OMITTED		OMITTED	
CAR	SUBURB	-0.28	-11.69	-0.30	-2.03
CAR	URB/SUB	-0.77	-20.91	-0.90	-9.48
CAR	URBAN	-1.09	-20.48	-1.17	-12.74
	Unique Locations	0.39	70.47	0.39	70.48
	Thurs/Fri	0.05	3.01	0.05	3.01
	Lévis	0.18	6.28	0.18	6.28
	Outer	0.18	6.85	0.18	6.84
	Homemakers	2.64	14.94	2.64	14.97
	FG Empl.	-0.42	-2.13	-0.42	-2.15
	FT Workers*	0.22	15.01	0.21	14.20
	Licenses*	0.16	11.15	0.14	9.34
	Children*	-0.12	-9.27	-0.13	-9.71
	Family with Kids*	0.08	2.88	0.07	2.50
	Couple2*	0.14	5.62	0.13	5.26
	Single Parent*	-0.13	-2.58	-0.14	-2.74
	2001	0.02	1.32	0.02	1.35
	Constant	13.44	179.94	13.54	143.75

* indicates a variable included in the treatment logit (cluster-car)

Number of obs.		25,031		
R-squared		0.40		
Adj R-squared		0.40		
AIC		87,595	AIC	151,658
(AIC mlogit)		63,960		

Table 8 - Regression results, Quebec

With respect to Quebec, the hypothesis of exogeneity is likewise not rejected, indicating OLS regression cannot be disregarded as a valid means by which to model the influence of UF and BE variables on activity spaces. In this case, the influence of clusters actually increases in the SEM, which would indicate that the OLS, if anything, is underestimating the influence of neighborhood type.

The trend in coefficients going from rural to urban clusters in Quebec is as expected (increases in urban-ness lead to smaller activity spaces), and once again all variables in the model are significant and right-sided.

The binary variable “Thursday / Friday”, indicating days where shops and service locations are open late, was found to have a statistically significant impact on activity spaces, causing an increase in their size. This is a variable not taken into account in traditional aggregate results, but echoes work on temporally constrained access to services (Neutens, Delafontaine, Scott, & De Maeyer, 2010), where store opening hours were found to make a significant impact on the travel patterns of individuals and households. Lévis and Outer, two variables that represent tracts further away from the historic core of the city or separated by a bridge, also have significant and positive effects, as do licenses and number of full time workers.

The coefficient for Families with Children in this case is positive, but given that number of children is also included as a discrete variable, this would seem merely to dampen the negative effect of children with respect to activity space size (more children decreasing the activity space, but not in a linear way). Finally, ‘2001’ was included and left in the model despite not being significant to indicate the potential influence of time (the omitted category is 2006). Its effect is weak, but would appear to indicate a slight decrease in activity space size over time. From previous work on the region, it is our hypothesis that suburbanization of employment may be the cause of this weak and negative trend. Additional data would be required to confirm this, but the implications would be significant if it were the case, implying that decentralization of employment might be an appropriate means by which to reduce travel demand.

		OLS		SEM	
	Variable	Coeff.	t-stat	Coeff.	t-stat
NO CAR	SUBURB	-0.95	-3.74	-0.69	-2.22
NO CAR	URBAN	-0.87	-5.43	-0.78	-3.75
CAR	SUBURB	OMITTED		OMITTED	
CAR	URBAN	-0.51	-6.90	-0.96	-4.31
	Unique Locations	0.41	25.34	0.41	25.36
	Homemakers	3.78	6.63	3.79	6.65
	Cars per Adult	0.33	3.58	0.32	3.57
	FT Workers*	0.24	5.09	0.23	4.82
	Only Students*	-0.48	-3.98	-0.44	-3.49
	65 plus*	-0.32	-2.62	-0.29	-2.35
	Single Parent*	-0.57	-4.80	-0.64	-5.21
	Family with Kids*	-0.17	-2.53	-0.21	-3.00
	Constant	12.61	69.94	12.79	63.02

* indicates a variable included in the treatment logit (cluster-car)

Number of obs.		2,785		
R-squared		0.34		
Adj R-squared		0.34		
AIC		10,092	AIC	14,793
(AIC mlogit)		4,691		

Table 9 - Regression results, Sherbrooke

Finally, when looking at Sherbrooke (for which the hypothesis of exogeneity of explanatory variables is once again not rejected), we see that clusters are also statistically significant predictors of activity space size. Car-owning suburbanites in either model are predicted to produce activity spaces significantly larger than any other cluster, but what is interesting are the coefficients for carless clusters: in the OLS, the suburban households are predicted to produce smaller activity spaces than their urban counterparts (which would be counter-intuitive given the lower destination accessibility in low-density suburban environments), while in the SEM, the estimated relationship between urban-ness and activity spaces is reversed. As for clusters with cars, in the OLS the coefficient for urban-with-car was smaller in magnitude than for carless clusters (as we would expect, since carless households in Montreal and Quebec have smaller activity spaces than their car-owning counterparts), but in the SEM, the coefficient for urban car-owning households is larger in magnitude than those for non-car-owning households of either cluster. This interesting set of reversals may result from the fact that so few observations exists for car-less households in the sample (see Table 6), but also because the study region as a whole is so much smaller than that of Quebec or Montreal. As one can see on Figure 14 - Neighborhood typology, Sherbrooke, a suburban household with or without car is never more than 8 or 10 km from the core, but 8 km can be a significant disincentive to travel when transit, the primary alternative to auto-mobility, is provided mainly during peak-periods. Given this particular setting, it would be interesting to see how carless households chain their trips, i.e. if they cluster them around school and work, around the home location, or if they make use of active modes to overcome the limitations of transit.

The results would also tend to indicate that the effect of neighborhood type, albeit significant in larger cities, is lessened when looked at in smaller cities. This further emphasizes the need to properly evaluate policy regarding the use of urban planning as a tool for achieving sustainable outcomes, to account for city size in conjunction with neighborhood design.

For the rest of the coefficients, intuitive, right-sided and significant relationships are observed. Each unique location visited, as well as each additional full time worker and car-per-adult adding to the activity space, while persons over the age of 65, households comprised only of students (included because of the large student population in Sherbrooke) and single parent households decrease the activity space.

Self-Selection bias and endogenous variables

As mentioned in section *Analysis* above, a mixed multinomial logit model was built using household composition types and additional household variables to evaluate the effect of possible cluster and vehicle-ownership endogenous variables. Unlike Miranda-Moreno et al. (2011) however, who used a similar cluster-car and SEM approach, our results do not lead to rejecting the hypothesis of exogeneity. One reason this may be the case is the availability of different types of neighborhoods in each city, making it possible for households to make residential location choices that do not lead to forced car ownership or spatial mismatch.

Conclusion

Previous research investigating the effects of land-use on transportation has focused on traditional indicators of transportation demand such as commuting distance, mode share, number of trips, etc. While there has been increasing interest in the use of activity spaces to understand travel behaviour through space, the effect of land-use on activity spaces is relatively unexplored. The work presented here investigated the influence of built form and temporal trends on activity spaces in three Quebec cities. This was done by estimating the effect on activity spaces (constructed by means of minimum convex polygons) of neighborhood types (defined as clusters of land use indicators) using OD data from cities of considerably different size, and spanning ten years. The effect of neighbourhood types on activity spaces was estimated through the use of regression analysis carried out using both traditional ordinary least squares (OLS) as well as simultaneous equation modeling (SEM) to test and account for residential self-selection, a topic currently generating considerable debate among travel demand modellers. This work allowed us to investigate whether travel is becoming more dispersed over time, and in what context this may occur. It also allowed us to explore what combinations of urban form indicator levels and what city sizes are most conducive to reigning in demand and improving sustainability.

Our results indicate that both local and regional descriptors of the built environment, neighborhood types and city size, can be used to predict the dispersal of travel through space. Neighborhood types are found to have a statistically significant effect on these spaces after accounting for household composition, vehicle ownership and CT properties, and results overall signal that efforts at affecting change to the travel behavior of households through the use of urban planning at both the neighborhood and regional scales are valid pathways to be explored.

A somewhat surprising finding, given that scholarship on land use and travel demand linkages focuses predominantly on neighborhood-scale determinants, is that a substantial city-size effect on travel dispersal was found, with larger cities leading to larger activity spaces irrespective of how dense or mixed their urban environment is.

With respect to temporal effects, results for Montreal seem to indicate a trend toward larger activity spaces over time, consistent with existing literature on the effect of ICTs and increased leisure trip-making, whereas the effect in Quebec remains inconclusive. The authors posit this may be due to the decentralization of employment in Quebec, but further research would be needed to validate this claim.

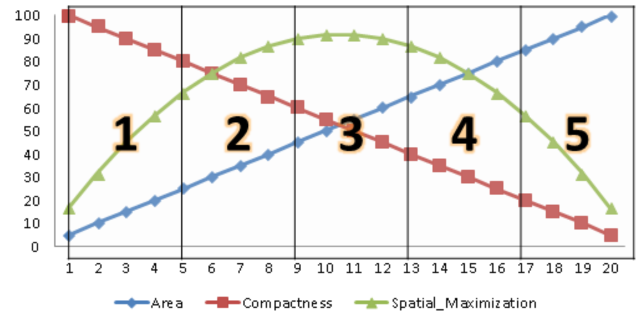
Finally, self-selection and variable endogeneity were tested by comparing SEM and OLS regression model results, but the hypothesis of exogeneity could not be rejected. As such, the results found in the OLS regression models linking urban form to activity spaces are not biased by residential self-selection effects.

Chapter 8 Activity space geometry and its effect on mode choice

The final paper in this manuscript was presented at the Transportation Research Board's Annual Meeting in January 2013. I thought it especially important to include this paper despite the fact that it will only appear as a conference proceeding because it is the most exploratory paper written over the course of my masters, as well as a clearer departure from current research. The first two papers (Chapters 6 and 7) made use of and altered existing methodologies, and employed them to gain a better understanding of an ill-explored phenomenon, while this paper was more experimental in nature. Both approaches to research are important in my view, and as a result I was keen on representing both perspectives in my thesis.

The impetus for this work was an idea that came to me when thinking about the concept of spatial efficiency (see Figure 16 below).

How to objectively define Efficient Travel or Spatial Maximization?



		1	2	3	4	5
Activity Space polygon properties	Area	low	Low-medium	medium	Medium-high	High
	Compactness	high	Medium-high	medium	Low-medium	Low
Travel Demand characteristics	Transit Use	?	?	?	?	?
	Active Mode Use	?	?	?	?	?
	Vehicle Ownership	?	?	?	?	?
Neighborhood Type	Mode	1-7	…	…	…	…
	Average	…	…	…	…	…

Figure 16: Efficient Travel, or Spatial Maximization

I had figured that there likely exists some optimal means by which to move about space, and that this could be derived using activity space geometry and size, all the while being expressed in terms of GHG emissions, energy, time, utility, etc. The idea of some optimal combination existing, being that you want people to have just the right amount of mobility and accessibility to enable them to do a great many things, but that neither requires they use a large amount of resources to gain this accessibility, nor that their environment restrict their mobility to an excessive degree. In other words, my desire was to make concrete an abstract idea of spatial efficiency using activity spaces in a novel way.

According to the figure above, which is a very simplified representation of my idea, one would try and fill in the question marks and ellipses by figuring out what combinations of area and geometry lead to either high or low transit use, high or low vehicle ownership, GHG emissions, etc. Then, when the geometries and their outcomes are better understood, use these in combination with built form descriptors of the home environment, work/school or other anchor points, and the metropolitan region more broadly, to define the conditions that lead to efficient travel.

I still believe there is scholarship to be done using such an approach, but once again given the time resources involved in investigating this concept fully, I chose instead to look at a more manageable portion of this relationship; activity space geometry and modal propensity.

Specifically, the paper that follows investigates the relationship between activity space geometry (expressed through compactness and area) and propensity to engage in different travel modes. The results of our analysis indicate that consistent with common understanding, active modes are preferred for travel that produces small areas with high compactness (small, circular polygons), and personal vehicles are chosen when travel leads to spaces that occupy large areas and are also rather circular or compact (i.e. very dispersed, as opposed to being along a corridor). Contrary to what one would expect however, public transit is not chosen predominantly by persons choosing to travel along a corridor, but rather that the distribution of their trips exhibits a broader range of shapes and sizes; the highest prevalence of transit use being found when Area to Compactness percentile Ratios (ACRs) are nearest 1, a relationship that is defined and tested on data from Montreal using a series of logit models.

This work did not answer every question regarding the relationship between activity space and mode share, but confirmed existing thoughts relative to the type of travel patterns that increase the likelihood of active or automobile trips being made, all the while bringing to light an unexpected finding regarding transit. Logit model results indicate that even when controlling for a variety of urban form, demographic and trip making characteristics, activity space geometry (expressed through area, compactness and ACR) still has a statistically significant impact on predicting the propensity to engage in travel using certain modes. Hypotheses as to why travel may look different than commonly understood are offered, and ideas for future research and real-world applications are presented.

As with the other papers in the thesis, my role was that of lead author.

- Harding, C., Patterson, Z., Miranda-Moreno, L. F. (2013). Activity Space Geometry and its Effect on Mode Choice. *Transportation Research Board.* Washington: 92nd International Conference of the Transportation Research Board (TBR)

Introduction

Much of the literature on urban form and travel demand has looked at the propensity of certain types of environments for generating outputs such as vehicle miles traveled (VMT) or mode share. The emphasis placed on smart growth and TOD for instance has been fueled by such interests in evaluating the potential for environments to reduce the negative impacts of our sprawling cities.

At the same time, the literature on activity spaces has drawn attention to how sprawling urban form has led to large activity spaces. These large spaces have been discussed as having negative consequences with respect to their effect on emissions, but also social equity. Whether the landscapes that increasingly define North American cities are detrimental to community, health and economic viability remains a hotly debated topic.

Where there exists a gap in the literature however is tying the geometry of these activity spaces to mode share. On the whole, small activity spaces are understood to be better from an economic and environmental perspective as they intuitively promote the use of active modes and the reduction in distances traveled, but looking at area alone is perhaps not the best way to link these concepts.

Inspired by the work of Manaugh and El-Geneidy, who asked the question “What makes travel local?”, and attempted to define local travel in a novel way using the measures of compactness and area of activity spaces in conjunction with network distance, this article concentrates on properties of activity spaces, but instead asks “What does green or sustainable travel *look* like?”. More specifically, as opposed to taking mode choice as a determinant of travel patterns, we look at the propensity for certain types of activity spaces (defined by combinations of area and compactness) for generating trips by either active, transit or personal vehicle modes.

Results of our analysis validate common thinking about small activity spaces being correlated with high active mode share and large activity spaces with high shares of personal vehicle use. An interesting and unexpected relationship however also appears to exist between the ratio of area to compactness and transit mode share. Given this finding, we delved deeper into the issue and tried to understand the reasoning behind transit patterns differing from the commonly accepted notion of occurring along corridors.

Using an exploratory framework, we try and explain the disparity between the taken for granted geometries of activity spaces (active modes being privileged for small areas and transit for travel along a corridor), and also seek to describe a concrete application to such analysis – something the current activity space literature lacks when compared to that of other outputs.

Literature Review

The literature on activity spaces falls into a finite set of categories. Broadly speaking, there are papers that describe the means by which spaces can be produced (Fan & Khattak, 2008) (Thériault, Claramunt, & Villeneuve, 1999), and there is work that links these activity spaces with issues of accessibility, health and equity (Kamruzzaman & Hine, 2012) (Schonfelder & Axhausen, 2003).

For brevity, this review will not explore all the possible interpretations of activity spaces, but rather focus on work relating built form to mode share and sustainability, and the interpretation of activity spaces in a transportation-related capacity. For work on built environment and travel demand linkages, see (Ewing & Cervero, 2001) (Ewing &

Cervero, 2010) (Badoe & Miller, 2000) (Leck, 2006) (Transportation Research Board and Board on Energy and Environmental Systems, 2009).

Activity spaces are characterized by three important components: home location, regular activities and travel between and around these pegs (Schonfelder & Axhausen, 2003). In turn, "the size of the area is an indicator for the dispersion of visited locations" (Schonfelder & Axhausen, 2003, p. 275), whereas "smaller activity spaces also indicate more uses of local opportunities and more neighborhood interactions, which may strengthen neighborhood attachment and foster social ties" (Fan & Khattak, 2008).

From the perspective of a regional or municipal planning body, whose mission it is to provide transportation infrastructure that enables people to reach activities efficiently, there is an incentive to reign in activity spaces to make better use of limited funds. However, because of an actual or perceived preference for large-lot single family homes and political incentive for responding with highways to cheap land at the fringe, cities tend to sprawl out irrespective of economic rationality.

Traditional literature on the built environment and travel demand looks to the local or regional properties of built form to predict demand for peak hour road space, parking or fuel consumption. A trend in the past few decades has been to link dense, mixed-use environments with low VMT and high transit and active mode shares, but the empirical work to back up such claims has not always been validated upon closer analysis; the impact of built form on travel behaviour is found to vary greatly depending on the source one looks at. Literature reviews and meta-analyses such as those performed by Leck (Leck, 2006) and Ewing and Cervero (Ewing & Cervero, 2001) (Ewing & Cervero, 2010) indicate there is a link between built form and travel demand, but the magnitude of response to changes in many variables remains uncertain and even contested (Crane, 2000).

What most agree on is that developing more densely is likely to reduce VMT by bringing locations closer together, but also by making active modes more of a viable option, as well as making investment in transit more feasible (Transportation Research Board and Board on Energy and Environmental Systems, 2009). This kind of combined impact is also investigated in works that look at neighborhood types, or clusters of variables, as opposed to individual indicators (Shay & Khattak, 2007) (Lin & Long, 2008) (Miranda-Moreno, Bettex, Zahabi, Kreider, & Barla, 2011).

Not all work is neighborhood-based however. Similar to the work of Derrible and Kennedy (Derrible & Kennedy, 2010), Bento et al. (Bento, Cropper, Mobarak, & Vinha, 2005), discuss the issue of mode share as a response to the built environment and spatial structure, looking at properties of cities at the macro scale and bringing in interesting tools to evaluate city shape and population centrality as complements to traditional measures such as local density and transit access. Their results indicate a statistically significant link between spatial structure, mode choice and VMT.

Finally, Manaugh and El-Geneidy (2012) sought to investigate the issues of sustainability and equity through activity spaces. Their work used a one-day travel survey to understand the effects of local and regional accessibility on the travel patterns of individuals. By defining local travel as that which occurs within the least spatially dispersed area while incurring the least distance along the road network, they highlighted some of the key issues in the interpretation of activity spaces. Notably, that combining different elements of traditional or emerging outputs (area, compactness and VKT in their case) provides a much clearer interpretation of the sustainability of travel than outputs interpreted individually.

The micro-scale analysis of what type of travel behaviour geometry is most conducive to the adoption of transit has however been left unevaluated. Establishing connections to the denser core of cities using a hub and spoke, or some similar approach, is more often than not taken for granted as leading to beneficial outcomes.

Geometry and Mode

In their analysis of activity spaces, Kamruzzaman and Hine (2012) find that "poor connectivity when coupled with the higher rate of public transport fare has forced low-income individuals to consume their activities along the main transport corridor" (Kamruzzaman & Hine, 2012, p. 115). This statement speaks both to the element of social equity considerations in designing networks, but also to the concept of maximized efficiency for transit when trips are made in a particular way; along a corridor in this case. This property of transit trips differentiates them from auto or even active modes because of the restrictive structure of line directness, fixed stops and transfer disutility. But does this common understanding of the nature of individual trips and chains hold true when daily activity space is looked at?

In describing the different forms of development that result from the pervasive influence of transportation infrastructure, Newman and Kenworthy explain that by the very nature of distance between stops and frequency of service, commuter rail lines lead to the formation of subcenters at stations, while trams lead to linear development along routes which they term corridors or main streets (Newman & Kenworthy, 1999). Pedestrian environments on the other hand have dense networks of organic interconnecting streets and automobile-oriented cities have hierarchical road networks that are not porous and favor low density built form.

Anas et al. confirm these development patterns when they state that transit oriented cities traditionally consisted of “a compact production core surrounded by an apron of residences concentrated around mass transport spokes” (Anas, Arnott, & Small, 1998, p. 1429). There is a certain history to the study of the geometry of development, as in Muth (Muth, 1985) who discussed the process of sectoring. As Muth himself states however, there are few studies that have explicitly looked at these geometric or radial patterns of development and their consequences on travel demand. Most often they are taken as a by-product of the mode, where car equals circular or dispersed travel, and transit equals travel along an axis or within a corridor.

As Badoe and Miller relate, many studies have also found that some households purposefully choose to locate near these transit corridors to reduce their reliance on personal vehicles (Badoe & Miller, 2000), a finding echoed in qualitative interviews, such as in Currie et al. (Currie, et al., 2010).

An interesting attempt to understand the impact of network design was done by Parthasarathi et al. (Parthasarathi, Hochmair, & Levinson, 2010), who argue its characteristics influence the perception of time and space in travel. Their analysis focused on the properties of the road network that fell within the activity space of households, which were in turn used to predict the size of the activity space formed.

One of the few actual applications of activity spaces as independent variables or tools comes from the work of Kamruzzaman et al. (Kamruzzaman M. , Hine, Gunay, & Blair, 2009). In their analysis of the commuting patterns of students, they look at the potential for using activity spaces to guide public transit development, wherein the provider can choose a demand responsive goal as opposed to a patronage goal by planning routes using the activity density surfaces produced by analysing students' activity spaces.

As opposed to trying here to define what sustainable urban form is, a task which has been tackled by many before (see (Williams, Burton, & Jenks, 2000) for a prime example), the following article instead tackles the issue of defining sustainable urban *mobility*. Building on the work of Manaugh and El-Geneidy, and Kamruzzaman et al., we will attempt to fill this gap in the literature by looking at the relationship between activity space geometry and mode choice in a broader sense.

Study Area and Data Used

To investigate the impact of activity space geometry and size on propensity to use certain modes, we used origin-destination surveys from Montreal and Quebec City.

Both these cities have extensive travel surveys which are carried out every 5 years with a significant portion of the region's households (5% for Montreal and 10% for Quebec, approximately). These surveys are detailed, in that they contain information on the households themselves (vehicle ownership, number of persons, ages for all members, employment status, etc.) as well as the XY coordinates for each trip conducted by any member of the household, and the XY coordinate for the household itself. For Montreal, as of 2008 the latter is coded as the centroid of the dissemination area within which the household resides, but because the other years for which we had data, and Quebec as a whole, were coded more finely, it was decided not to aggregate previous years' coordinates: tests run on this data indicate the offset did not distort the findings in any significant way. The mode used for each trip as well as the motive and time of departure are also coded in the origin-destination (OD) survey. (Agence Métropolitaine de Transport, 2003 and 2008) (Transports Québec, 2001 and 2006)

In addition to the demographics and travel demand information provided by the OD surveys, data describing the built form was also required for use as control variables in our exploration. To this end, land use data was obtained from DMTI Spatial, which characterized land into 7 categories and enabled the calculation of a land use mix indicator. Census information was also acquired in order to describe population and employment densities, as well as employment center accessibility: this was obtained from Statistics Canada. Finally, public transit information was obtained from a variety of sources. The network for Montreal was built up as a hybrid network, composed of a base originally geocoded in TransCAD by Dr. Murtaza Haider of Ryerson University in 2003, upon which were added additional lines to cover the extent of the CMA. The development of this base network was supported by a grant from the National Sciences and Engineering Research Council (NSERC) as well as infrastructure provided by the Canada Foundation for Innovation (CFI). Off-island transit lines were subsequently added by hand in the summer of 2011.

For Quebec, the Réseau de Transport de la Capitale supplied us with bus line stops and headways, while the Société de Transport de Lévis provided lines, from which stops were generated and headways approximated.

Methodology

Once the data were acquired, a few transformations were required before being able to evaluate the impact of activity space geometry on mode use. It should be noted that given the constraints of length, data for Quebec will be presented only in comparison to that for Montreal as opposed to providing an in-depth analysis of patterns for both cities.

Data Preparation

Activity Spaces

To generate activity space polygons, we isolated households from each survey if they comprised single person households, visited at least three unique locations, and made all their trips within the study area (defined as internal trips according to the agency that collected the data and corresponding roughly to the census metropolitan area for each city with a buffer of a few kilometers around). Three unique locations are also necessary in order to produce valid spaces as opposed to lines when using minimum convex polygons. Such a condition would not be necessary had we used standard deviational ellipses or road network buffers, but given that we wanted to get as precise as possible measurements for area and compactness without imposing a specific geometric form (Rai, Balmer, Rieser, Vaze, Schonfelder, & Axhausen, 2007) and thus creating bias, the minimum convex polygon (MCP) was chosen. *The formula used in quantifying compactness is presented at the end of the section.

The MCP was also deemed the most appropriate tool given the type of data used; single day travel surveys. Such surveys, unlike longer diaries used in some of the literature such as the six-week Mobidrive survey (Axhausen, 2007), offer only a glimpse at the total travel demand for any individual, but they do provide one with a good idea as to habitual daily travel patterns. When people choose to take transit to get to school, work or other activities, this is understood to be a choice that has lower variability over time than other decisions, such as the total number of trips made, or locations visited on any given day (Garling & Axhausen, 2003).

In other work describing the evolution of typical activity spaces over time, households that perform both mandatory and discretionary activities are often chosen to decrease the variability between observations and get a better understanding of typical weekday travel (Newsome, Walcott, & Smith, 1998) (Neutens, Delafontaine, Scott, & De Maeyer, 2010) (Manaugh & El-Geneidy, 2012). In our case, to maximize the number of observations, it was decided rather to include all single person households and to later include the presence of mandatory or discretionary activities as control variables.

Single person households were chosen as the population of interest as their movements in space are the simplest to analyse (less tradeoffs and interplay between decision-makers, only one work or school location as anchor point, no pick-ups or drop offs of dependents, etc.) As such single person households are an ideal starting point from which to analyse the difference in mode propensity as a result of activity space geometry.

The MCP activity spaces were generated in a GIS environment after displaying the XY coordinates for all locations visited by each respective household in the OD surveys. More specifically, the minimum bounding geometry tool in ArcGIS was used to create the smallest possible convex polygon that encompassed all the locations visited by a household. It should also be noted that only origins and destinations of trips were used to form the MCP, not junctions. This avoided the potential issue of distorting polygons when multimodal trips were made that did not include an activity at the junction.

The following formula describes the means by which compactness (or circularity) was calculated. For reference, a compactness value near 1 would indicate a MCP similar in shape to a circle, while a compactness value nearer 0 would indicate an elongated MCP, one more closely resembling a line.

Equation 5: Compactness, TRB

$Compactness_i = Perimeter_{Circle\_i} / Perimeter_{MCP_i}$
Where:
$Compactness_i$: Compactness of the MCP of individual *i*
$Perimeter_{MCP\_i}$: Perimeter of the MCP of individual *i* (generated using "Calculate Geometry" in ArcGIS)
$Perimeter_{Circle\_i}$: Perimeter formed by a circle having the same area as the MCP of individual *i, or:*
$2 * \pi * \sqrt{\frac{Area_{MCPi}}{\pi}}$
Where:
$Area_{MCPi}$: Area of the MCP of individual i (generated using "Calculate Geometry" in ArcGIS)

Urban Form

To complement data on travel demand, we used a similar methodology as Miranda-Moreno et al. (Miranda-Moreno, Bettex, Zahabi, Kreider, & Barla, 2011) to generate indicator values for commonly used descriptors of urban form. The indicator values were captured using a 500m grid superimposed on the study areas. Values for population and employment density, public transit accessibility, land use mix and employment center accessibility (by personal vehicle) were all generated this way. The following formula indicates how the employment center accessibility values were calculated: (the process of identifying the centers themselves is similar to the approach described in Al-Shammari (Al-Shammari, 2007), but can be found described in full in (Harding C. , Création d'un indicateur d'accessibilité aux centres d'emplois, pour les années 2001 et 2006, pour les régions métropolitaines de Montréal et de Québec, 2011)).

Equation 6: Employment Center Accessibility, TRB

$$ECAccessibility_j = \sum_{i=1}^{n} \frac{Empl_i}{(Time_{ij})}$$
Where:
$ECAccessibility_j$: Employment centre accessibility at cell *j*
$Empl_i$: Number of jobs at employment center *i*
$Time_{ij}$: Network cost separating the centroid of cell *j* from employment center *i* (in minutes, with a minimum value of 5 minutes)
n : total number of employment centers

Next, land-use mix at the cell level is defined by the entropy formula below:

Equation 7: Land Use Mix, TRB

$$\boldsymbol{E_j = -\sum_{i=1}^{n} \frac{\left[\left(\frac{A_{ij}}{D_j}\right) ln\left(\frac{A_{ij}}{D_j}\right)\right]}{\ln(n)}}$$

Where:
Ej : land use mix of cell j (from 0 = no mix, to 1 = perfect mix)
Aij : area occupied by land use i in cell j
Dj : area of cell j (excluding water and open area)
n : total number of different land uses

And public transit accessibility values are calculated based on the combination of distance from stops and headways:

Equation 8: Public Transit Accessibility, TRB

$$\boldsymbol{PTaccess_j} = \sum_{i=1}^{n} \frac{\mathbf{1}}{(\boldsymbol{d_{ij}} * \boldsymbol{h_i})}$$

Where:
PTaccessj : accessibility to public transit at cell j
dij : distance, in km, from cell centroid j to nearest bus stop of line i (minimum value of 0.1 km)
hi : average headway, in hours, of line i (in AM peak with a maximum value of 1 hour for Montreal and all-day with a maximum value of 2 hours for Quebec)
n : total number of bus lines near cell j

Population and employment densities represent net densities calculated using land use data and census tract population and employment counts. Finally all cell level values are averaged with those of the cells surrounding them to avoid peaks in the data.

Methods of inquiry

Along the lines of the work done by Manaugh and El-Geneidy, we sought to better understand the impact of activity space geometry on environmentally friendly, or green, travel. Our hypothesis at the start was that certain combinations of area and compactness would lead to higher active or transit mode shares. Intuitively we believed that small activity spaces, especially when compact, would lead to high active mode share – as people would be better served by their own two legs than by transit or a car to cover short distances. We also believed that the linear nature of transit would discourage people from using such a mode to make dispersed trips in a small area, and likewise that parking availability, cost and inconvenience would be a disutility reducing the probability of using the car to make short, geometrically compact trips. Largely, our hypotheses proved to be correct – as one can see on Figure 1.

Next, with regards to automobile use, we expected this to be highest among individuals who generated large and dispersed activity spaces. The logic here being that large activity spaces are not conducive to active mode use, and that compact and large activity spaces in turn would reduce the likelihood of transit being chosen as the given mode, by the very nature of having to make transfers and wait. This hypothesis also proved true.

Where things became more interesting however, was in looking at transit mode use. As indicated above, in order to travel along more than one axis or corridor, transit trips, unlike car trips, involve wait times and transfer penalties or disutilities. As such, it was thought that much as the literature described when explaining the nature of city form and its evolution as a response to the emergence of different travel modes (see (Newman & Kenworthy, 1999)), transit would be chosen most often to make trips that occur along a corridor, i.e. trips with low compactness. In addition to being consistent with the ideas of minimizing transfers, and access and egress times and effort, such trips would also be consistent with the literature on awareness space– in that activity sites located along a given transit route would be more likely to be patroned by riders as they would be more aware of these locations than those that are outside the scene of the transit route. Transit routes are also more often than not direct as opposed to being circuitous, so if riders were to get on and off along a given route to access certain businesses, their activity space would maintain a low compactness.

All this would amount to an expectation that the activity spaces of transit riders would be characterized by low compactness, or would resemble what we traditionally describe as transit corridors. As Figure 17 demonstrates however, this is not the case.

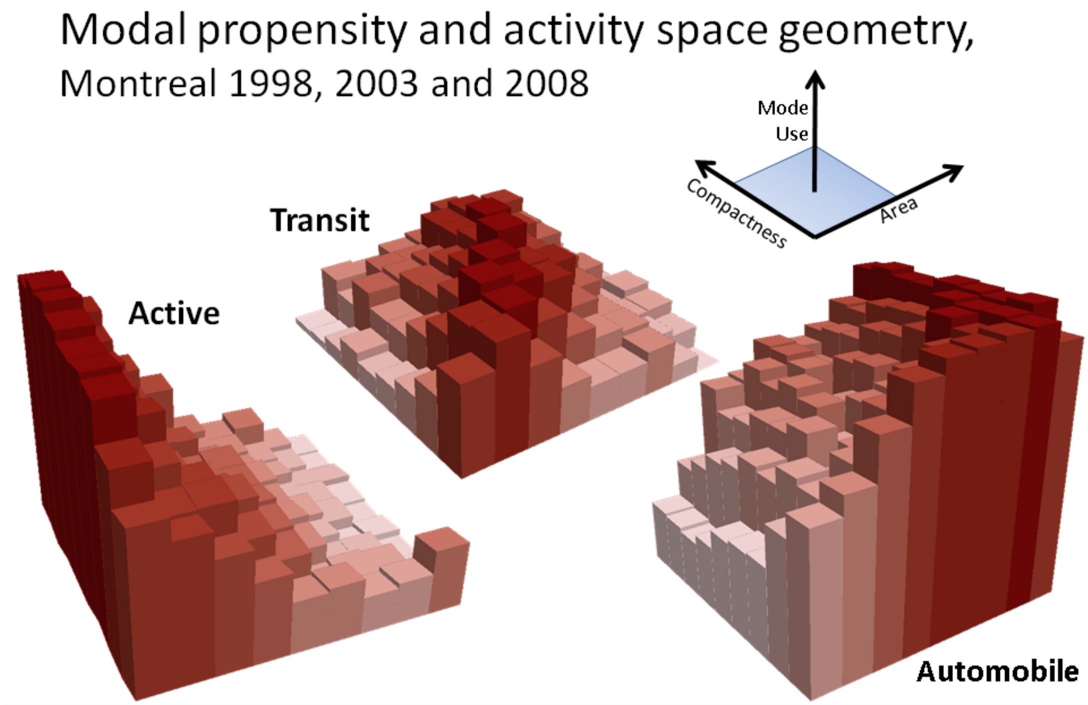


Figure 17 - Modal propensity based on the percentile of area and compactness for single person households in Montreal.

*The z-value indicates the percentage of households belonging to a cell that make at least one trip using the specified mode.

When we displayed the activity spaces of the individuals in our sample (13,561 observations), the pattern that emerged for transit riders was not as expected. Activity spaces that had compactness to area ratios closest to 1 were actually found to generate the highest transit ridership. When this finding emerged, we decided to investigate further in an attempt to better understand why transit trips followed such an unlikely pattern, given that most transit systems are designed essentially to connect farther out suburban locations with activity and employment centers (hub and spoke systems). The resulting trend was especially striking given the findings of Kamruzzaman and Hine (Kamruzzaman & Hine, 2012) that mobility-poor households (which would also make up traditionally understood captive riders) made the majority of their trips along a corridor to minimize time and monetary cost.

To better explain what is represented in Figure 17, the cells formed represent the area and compactness of the activity spaces of households in our sample, divided into bins based on the percentile value for each of the two properties. For example, if a household produced a MCP area at the 95th percentile and compactness at the 51st percentile, that household would be associated with cell 9(X)-5(Y). The percent use of each mode is then calculated by aggregating all households at the cell and representing their use of a given mode as a percentage with a z-value or *height*. This visual tool allowed us to observe in an intuitive and simple way the connection between activity space geometry and propensity for the use of certain modes. In interpreting the figure, one must remember that transit, car and active do not add to 1, but rather that any use of a given mode during the course of the day would lead to a value of 1 in the binary mode field for that individual.

The counter-intuitive trend for transit having emerged, we first sought to test whether Montreal had a macro-scale urban form that made it an outlier, be it the result of topography or other considerations. To do this, we applied the same methodology to the activity spaces produced by single-person households in Quebec and compared outputs.

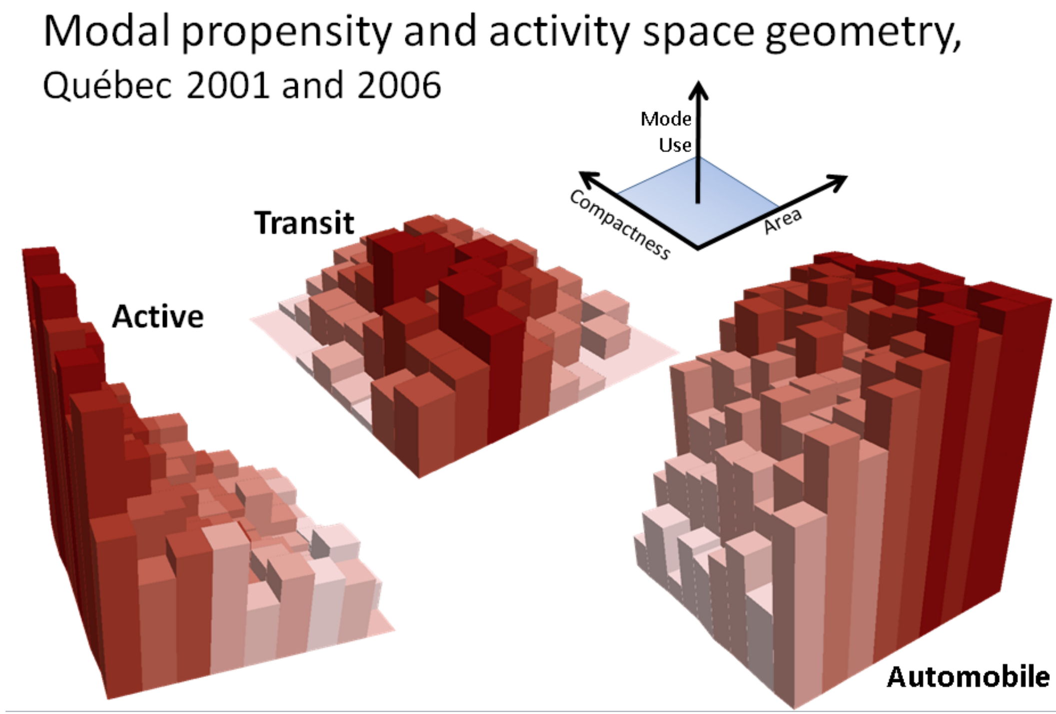


Figure 18 - Mode propensity for Quebec City

As one can see from Figure 18, the trends with respect to active mode use and car use are very similar to those in Montreal, and to a large extent so is the distribution of transit trips with regards to the activity spaces of the households that generated them. The strength of the ratio between compactness and area seemed slightly less pronounced, but still very much present.

The first thing that came to mind to explain this difference, given that it manifested itself as less transit trip generation toward the high end of the area spectrum, was that Quebec is a smaller city, characterized by simpler transit network (only buses, no commuter or heavy rail as in Montreal for instance); as such it would be very difficult to even produce a large activity space with high compactness in Quebec.

Another hypothesis for the difference between the two cities was the potential impact of multiple specialized employment centers. These are not present to the same extent in Quebec as in Montreal. An increase in employment distribution could hypothetically channel trips by transit from one regional employment center to another in Montreal, something unlikely in Quebec. It must be kept in mind that in addition to the smaller size of the transit network with respect to the overall city, transit mode shares are also considerably lower in Quebec, only accounting for roughly one in ten trips (McCray & Brais, 2007).

Looking to the literature to explain the unlikely pattern for both cities, we entertained the notion that transit use may differ from a corridor-shape partly because of novelty seeking behaviour (Axhausen, 2007), which encourages individuals to look outside their mandatory travel path to find new service and amenity locations. This novelty-seeking would apply across modes however, negating a specific effect on transit. It is also hard to see how rational individuals would make such choices en masse unless forced to do so by a lack of service offerings along main routes – a more plausible explanation.

The next step in our investigation was to see if there may be household or built environment independent variables that would account for this finding; if the high propensity for transit trips were actually due to built-form attributes, like public transit accessibility for instance, then high transit use would in fact be a function of this access, and not be related to activity space geometry. To test such a hypothesis, we built a logit model to predict transit mode use given the trip generating activities and demographics of households, as well as urban form variables captured at the household location.

Logit Model

Households were assigned a value of 1 in a field called transit if they used transit at all on the day of the OD survey; the same was done for car and active modes. The dependent variable in the logit model is thus 0 or 1 for each mode. To quantify the impact of the relationship observed in Figures 1 and 2, an Area-to-Compactness Ratio (ACR) was defined. Given the apparent trend of a high prevalence of transit trips when the ratio of area to compactness was closest to one, the ACR was expressed in the following form:

Equation 9: ACR, or Area to Compactness Ratio, TRB

$$ACR_i = {}^{1}\!/\!\left(|p_{area\,i} - p_{compact\,i}| + 1\right)$$

Where:
ACR_i: Area-to-Compactness Ratio of MCP *i*
| |: absolute value
$p_{area\ i}$: percentile of the area of MCP i
$p_{compact\ i}$: percentile of the compactness of MCP i

The ratio could just as easily have been called the Compactness-to-Area Ratio since the difference between the two is expressed in absolute terms, but given that it was associated with high transit use, we thought the *CAR* acronym may be somewhat misleading.

Results

Table 10: Logit Model Results for Montreal, the dependant variable is use or no use of a given transportation mode

MODE CHOICE AS A RESPONSE TO ACTIVITY SPACE, BUILT ENVIRONMENT AND DEMOGRAPHICS							
	13,561 Observations	**Transit**		**Car**		**Active**	
	Variable	Pseudo R2	0.36	Pseudo R2	0.52	Pseudo R2	0.37
		Coef.	P>z	Coef.	P>z	Coef.	P>z
Built Environment	Transit Access (cont)	**0.003**	**0.00**	**-0.003**	**0.00**	***0.001***	***0.06***
	Net Pop Dens (ppl/ha)	0.000	0.91	**-0.004**	**0.01**	**0.006**	**0.00**
	Net Empl Dens (ppl/ha)	**-0.005**	**0.00**	0.001	0.12	**0.002**	**0.00**
	Land Use Mix (%)	***0.592***	***0.06***	**-0.756**	**0.04**	**1.716**	**0.00**
	Empl.Cent.Acc. (cont/1,000)	**0.019**	**0.00**	**-0.008**	**0.01**	-0.001	0.63
Demographics	Male (binary)	**-0.203**	**0.00**	**-0.423**	**0.00**	**0.147**	**0.00**
	Median Income ($1,000)	-0.003	0.42	**0.015**	**0.00**	0.007	0.11
	Auto (binary)	**-3.103**	**0.00**	**3.428**	**0.00**	**-1.732**	**0.00**
	Age 75+ (binary)	-0.145	0.15	**0.405**	**0.00**	**-0.288**	**0.00**
	FT worker (binary)	**-0.279**	**0.00**	**0.328**	**0.00**	0.066	0.35
	Student (binary)	**0.271**	**0.02**	-0.058	0.66	***0.214***	***0.06***
Trip Making	Nb of Trips	**-0.122**	**0.00**	**0.230**	**0.00**	**0.547**	**0.00**
	AM peak trip (binary)	**0.492**	**0.00**	**-0.237**	**0.00**	-0.079	0.17
	Mandatory Trip (binary)	**0.624**	**0.00**	**-0.175**	**0.04**	-0.023	0.75
Activity Space	Percentile Area	**2.044**	**0.00**	**3.136**	**0.00**	**-4.141**	**0.00**
	Percentile Compactness	**-0.906**	**0.00**	**-0.945**	**0.00**	**-0.749**	**0.00**
	Area-to-Compactness Ratio	**3.267**	**0.00**	0.206	0.45	**-2.301**	**0.00**
	Constant	-3.837	0.00	-1.579	0.00	0.396	0.13

Describing all the variable coefficients included in the model across all modes would greatly exceed the space available here; suffice it to say that all but a few instances present urban form and demographic variable coefficient estimates that are intuitive, right-sided and statistically significant. Coefficients are also consistent with existing literature on the effect of built environment and household properties on mode choice;

transit accessibility increasing the likelihood of its use, population density decreasing the likelihood of using the personal vehicle, and land use mix increasing active mode share for instance.

With respect to transit coefficients specifically, transit accessibility, land use mix and employment center accessibility (all properties associated with development schemes such as Transit Oriented Development and New Urbanism) lead to increases in transit use, with “males” and vehicle ownership decreasing the propensity for transit use. Mandatory trips (work and school), students and AM-peak - all indicators of traditional captive transit markets because of the regular nature of the trips, the issue of income and finally the comparative advantage of transit in the AM peak- also exhibit strong positive effects on transit use, while number of trips decreases the likelihood of transit use. The latter makes sense intuitively, given the inflexible nature of transit, with disutilities for access and egress, as well as wait times. This also explains why an increase in the number of trips has a positive and statistically significant effect on both car use and active modes, for which these disutilities do not apply.

Full-time worker is the only variable for which the sign does not immediately concord with our prior hypothesis; a positive effect on likelihood of transit use. This may be due to the fact that AM peak and mandatory trip(s) were both accounted-for in the model. Together, these variables capture the effect of habitual, congestion-period travel; the two characteristics of a full-time worker that we would expect to increase the likelihood of transit use. The presence of many employment centers away from the central business district (CBD) may also play a role in explaining the negative coefficient, as many of these suburban employment centers are poorly connected to the transit network making the use of an automobile nearly a prerequisite for access.

Finally, the ACR still shows up as a significant variable in predicting high transit use despite the inclusion of the above described control variables, as well as percentile area (positive coefficient) and compactness (negative coefficient), both of which are also right-sided and statistically significant.

Planning Applications?

With a relationship isolated, the next question is to see how this information could be applied. Knowing that a particular type of activity space geometry leads to high transit ridership, it would follow that looking for areas within the city where such a geometry is prevalent could aid in planning for future transit network expansion. Planners with access to OD data for instance could isolate areas in the city where there are concentrations of households with low access to transit and low transit mode shares, but where spatially aggregated ACR values are high. Such areas would then, according to our model, be prone for a rapid response to transit investment – i.e. high impact investment areas. If properly defined, such a tool could serve as an aide to transit service providers, a means to complement the scheduler's rule for determining supply (Badoe & Miller, 2000).

Given the exploratory nature of such an endeavor and the lack of comparable previous work, there was no clear roadmap to follow with regards to understanding the scale at which such trends should be interpreted however. Efforts were made to visualize the trends spatially, but it remains unclear for the moment what the optimal scale should be.

Discussion and Conclusion

In conclusion, the portrait of green activity spaces would seem to be less simplistic than initially assumed.

In a sense, our findings give credence to the oft-cited "solution to scatter nodes across the suburban landscape, a compromise between monocentricity and sprawl which is depicted as a realistic method to elevate density and transit use" (Filion, Bunting, & Warriner, 1999, p. 1319). But whereas "massive transit investments in low-density areas have generally failed to alter … the heavy car reliance typical of suburban forms")(*ibid*), what we propose is a means by which to pretest whether the mobility patterns of individuals in a region are apt for mode shift through ACR values; an aide for decision-makers.

It also follows that transit provision in sprawling cities could be reassessed as serving a more complex function than previously understood. If transit systems are being used to connect individuals to unexpected locations, transit providers must adapt their offering if they seek to improve customer experience and gain market share, especially in suburban settings. Results indicate that there may be certain conditions under which mobility patterns, irrespective of underlying urban form attributes, make transit a viable option for riders. Adding cities to the comparison and looking for trends within them would be directions for future research.

If all transit trips from outer areas are designed uniquely to serve a population seeking to connect to the central city, our findings indicate we are missing a significant portion of the market.

Chapter 9 Overall Conclusion

The preceding papers looked at the interaction between neighborhood and city-level built form indicators, household demographics and activity spaces. The main contributions made through this manuscript are to highlight the significant relationships that exist between neighborhood types and travel demand, as well as the vast disparity in travel demand between cities of different scale. The large volume of observations included in analysis also provided the freedom and opportunity for interesting work looking at many different factors simultaneously without running into issues of low observations (with the notable exception of carless households in Sherbrooke, as mentioned in Chapter 7).

The research highlighted issues which are discussed in work by other authors, such as the potential for disadvantaged populations to be found in difficult situations as a response to changing urban forms. This is connected to the trends found in Chapter 7, whereby larger cities, which seem to be increasingly where the world's urbanites are choosing to settle for reasons of competition and a perpetual quest for innovation (Florida, 2008), are leading to more dispersed travel patterns for their residents. Although affordable access to public transit is one means by which to palliate the potential negative externalities caused by swollen metropolises, the potential for active modes to be promoted becomes less and less realistic as cities increase in size; Chapter 8 demonstrates this by highlighting the geometries of activity spaces conducive to increasing active mode use. This is unfortunate since, as Pucher and Buehler state in their book City Cycling, active travel is the most equitable, as well as environmentally benign form of transportation (Pucher & Buehler, 2012).

The introduction and papers also more broadly provided insight as to the appropriate methods to use in order to create built form and transit accessibility indicators, as well as group demographic variables into household types, and use any of the above indicators together by use of clustering algorithms. The section “Cluster indicator choice” also provided background and information regarding procedures to follow when clustering in order to maximize the effectiveness of the produced neighborhood types (or any other clustering output), while information on grids provided insight as to how such an approach can be taken to avoid issues relative to modifiable spatial unit problems.

With respect to the work presented in Chapter 8, novel methods were developed by which to present travel behaviour data (modal propensity cubes with percentile values for bins), and interesting findings emerged relative to the type of travel that is most often associated with transit use. As indicated however, further work needs to be done in order to take this finding from the stage of a mere observation to that of pertinent knowledge which can be applied by practitioners. The validation of prior knowledge with respect to travel distribution geometries that promote active or vehicle use, combined with the findings outlined in Chapter 7 A spatial and temporal analysis of the effects of land use clusters on activity spaces in three Quebec Cities, together indicate paths to follow if one is to seek to reduce reliance on personal vehicles through urban planning – be it for economic, health or environmental reasons.

Given the result outlined in Chapter 7, that TOD in a larger city still leads to more dispersed travel patterns than business as usual development in a smaller city, the logical question one must then ask is: if the same number of households were to move to a sprawling new development built in a smaller city where their travel patterns would be less dispersed, would their overall GHG emissions be higher or lower than if they were instead to live in a TOD/New Urbanist development built on the fringes of a larger city?

This question, which may seem obvious given the way it is framed above, is in reality far from simple to answer. If we take into account the different mode shares in each setting, as well as the different amounts of land converted for new development, the lower percentage of car-less households in less dense environments, the potential for forced car ownership in larger cities, etc., it is considerably less clear-cut which alternative truly is more sustainable. A comprehensive analysis and quantification of the carbon footprint of different urban development scenarios, making use of existing methodologies but also complemented by the techniques developed here would definitely be a welcome addition to the land use and travel demand linkages literature.

In conclusion, the work carried out during the course of my master's and presented here allowed me to gain a better understanding of urban form effects on travel demand, and this at various scales. This satisfied the main objectives I set out to complete, while additional relationships were also explored throughout the thesis, such as the potential impact of ICTs and time, regional effects, impact of household types, etc. Methodological approaches were also put to the test and refined, whether it be with respect to the clustering of urban form using grid cells in different CMA contexts, the representation of household activity spaces, or analysis of urban form and travel demand linkages.

Future Work

To explore the power of clustering techniques and potentially better define neighborhood types, in addition to the k-means cluster values generated here, future work could look at generating clusters through divisive hierarchical clustering. This could circumvent the issue of suburbs being lumped together when running cluster analysis on large CMAs, by attempting to differentiate the highly sprawled suburban areas mostly present off-island in Montreal and away from the historic core in Quebec. In the work conducted on Montreal, obtaining useful cluster values off-island was found to be one of the major difficulties when simultaneously trying to limit the number of classes; this is part of the motivation behind using hierarchical clustering, in that certain cluster-classes can subsequently be further divided to fit the needs of the modeler.

Another idea to be explored in future research would be to measure the activity density found within a given household's activity space (through overlays) and relate this to levels of urbanity at the home and work/school locations (anchors). Tests were run using cluster values as the captured phenomenon and household activity spaces to intersect the cells below; results were promising but there was insufficient time to follow through on these ideas.

Finally, the idea of spatial maximization described in Figure 16: Efficient Travel, or Spatial Maximization (p.104) would merit further investigation, perhaps using different means by which to group area and compactness into bin-combinations, as well as by integrating measures of GHG emissions or time. The work of Paul Tranter on "effective speed" (Pucher & Buehler, 2012) could be adapted to the concept of Spatial

Maximization or Efficient Travel, whereby access to certain activities using different modes and within different activity space geometries could replace the speed and cost inputs used in that context.

Fleshing out the ideas listed above was beyond the scope of my master's degree, but provided the opportunity I look forward to continuing the work.

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