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Distance traveled in three Canadian cities: Spatial analysis from the perspective of vulnerable population segments

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ABSTRACT

The objective of this paper is to investigate the factors that influence distance traveled by individuals in Canadian urban areas, with a particular focus on three population segments thought to face the risk of mobility challenges: the elderly, low-income people, and members of single-parent households. Data obtained for three large urban centers – Hamilton, Toronto, and Montreal – are analyzed using spatial expansion models, a technique used to obtain spatially-varying coefficients that help to tease out contextual person-location variations in travel behavior. Detailed geographical results help to enhance our understanding of the spatiality of travel behavior of the population segments of interest. Substantively, the results provide evidence of significant interactions between location, various demographic factors, and mobility tools. More specifically, the results evince patterns of mobility that are significantly different from the mainstream population, particularly in suburban settings, in ways that are indicative of mobility challenges.

1. Introduction

Demographic and socio-economic trends in many industrialized countries have in recent years called for renewed attention concerning the travel behavior of various population segments thought to be at risk of facing mobility challenges (Mohammadian and Bekhor, 2008). In an effort to understand the implications for transportation of, among other trends, demographic aging, globalization, immigration, and suburbanization of poverty, past research efforts have strived to clarify the current mobility situation, and how it will affect the accessibility expectations of some of these special interest groups. The mobility and accessibility trends of the elderly, for instance, have been acknowledged to pose a critical challenge to transportation systems (Pisarski, 2003), a situation that has prompted a body of scholarship on the subject (e.g. Alsnih and Hensher, 2003; Kanaroglou et al., 2008; Mercado and Páez, 2009; Newbold et al., 2005; Paez et al., 2007; Rosenbloom, 2001; Schmocker et al., 2008; Scott et al., 2009). The implications of accessibility disadvantages for low-income individuals have also been investigated, particularly from the perspective of employment outcomes (e.g. Blumenberg and Shiki, 2003; Gurley and Bruce, 2005; Hess, 2005; Sanchez, 1999). Other so-called special population groups have only recently begun to receive attention, including the very young, persons who experience disabilities, individuals in single-parent households, and recent immigrants (e.g. Blumenberg, 2008; Lovejoy and Handy, 2008; Mohammadian and Bekhor, 2008; Schmöcker, 2009; Sener and Bhat, 2007).

Interest in the accessibility status of these groups is traditionally motivated by system efficiency considerations. More recently, as well, interest is driven to a significant extent by a belief – in many cases still in need of empirical validation – that accessibility challenges can act to constrain and in some cases severely limit the facility with which individuals can partake of quotidian activities. This includes the ability to reach employment and training opportunities, as well as to avail oneself of services at food stores, financial, recreational, health, and other social facilities. Greater awareness of the potential implications of poor accessibility for the well-being of individuals, and the anticipation of larger trends that could further negatively impact accessibility-disadvantaged groups in society (e.g. demographic aging), has led to serious evaluations of policy responses in a number of countries (e.g. Social Exclusion Unit, 2003). From a Canadian perspective, an emerging concern is the ability of vulnerable individuals and families to access all the places associated with their daily needs, and the role that transportation may have in affecting this ability. In order to

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support policy analysis, a necessary first step is to develop a better understanding of the current mobility and accessibility situation of various population segments, something that requires us to clarify whether there are significant differences in the travel behavior of various population groups of interest.

Of the various aspects of travel behavior that are of interest, this paper is concerned specifically with distance traveled, which we conceive of as an important component of accessibility. The analysis of accessibility is multi-layered, and affected, on the one hand, by various aspects of mobility, and on the other, by the spatial distribution of opportunities or the opportunity landscape. Accessibility, for instance, is not defined for individuals who do not travel (Roorda et al., 2009), and so the generation of trips is a *sine qua non* condition for accessibility. For those individuals who do travel, accessibility is defined at the intersection between distance traveled and the distribution of opportunities across space (Naess, 2006; Páez et al., forthcoming). In particular, it is possible to think of distance traveled as a proxy for activity spaces, a concept that has previously been linked to social exclusion research (e.g. Schönfelder and Axhausen, 2003). For a given distribution of opportunities in space, more mobile individuals who travel longer distances can reach farther destinations, and potentially be in contact with a greater number of them. In contrast, individuals who travel only short distances will be more limited in the range of destinations they can reach. Distance traveled therefore constitutes a useful tool to understand spatial behavior.

The objective of this paper then is to investigate the factors that influence distance traveled, with a particular focus on population groups of special interest. An all-purpose indicator of the spaces of daily life is analyzed, namely mean trip distance centered on the place of residence during a one-day period. This measure gives an indication of typical trip length and therefore of general levels of mobility. Analysis is performed on geocoded micro-data from three major Canadian urban areas, Montreal, Toronto, and Hamilton. Spatial support of data at the level of the individual facilitates the adoption of a spatial modeling strategy, based on the estimation of spatial expansion models that result in spatially-varying regression coefficients (Casetti, 1972). This analytical tool assists in the estimation of differences in behavior based on personal attributes (the typical province of travel behavior analysis), and also facilitates the examination of the role of geographical context in influencing behavior (see Paez, 2006). The application provides a clear example of a situation where detailed spatial information can enhance our understanding of mobility, and illustrates the richness afforded by spatial modeling when applied to the analysis of urban systems (Miller, 1999; Morency, 2006; Paez, 2007; Páez and Scott, 2004). More substantively, our interest is in the travel behavior of three population segments: the elderly, low-income households, and individuals in single-parent households. The analysis seeks to expand on previous elderly-related researches that have yielded limited geographical insights due to data availability or other considerations (e.g. lack of individual geocodes in the case of Mercado and Páez, 2009; use of broad geographical classes in the case of Schmocker et al., 2005). The analysis also aims at expanding the knowledge-base for low-income individuals, and most particularly, for single-parent household members, a population segment that has not, to the best of our knowledge, been the specific focus of previous research.

2. Background

2.1. Analysis of distance traveled

A number of authors have considered distance traveled in the past, and how this indicator of mobility is influenced by various demographic and socio-economic factors of interest. Khattak et al. (2000), for instance, examined the commuting patterns of low-income individuals, and found that, among people who work, residents of low-income urban neighborhoods commute longer and farther than residents of low-income suburban neighborhoods. Casas (2007), on the other hand, showed that being young, coming from a small household, possessing a driver's license, having a steady job, living in an urban setting, increases distance traveled and therefore the number of opportunities available to individuals. Naess (2006) found in his analysis of Copenhagen that females tend to travel shorter distances, trip lengths peaked for middle-aged individuals, higher-income associated with longer trips, whereas number of underage household members reduced the distance traveled. There has also been research reported for the Canadian context. Morency and Kestens (2007), for example, used travel survey data from the Montreal Area in recent research to observe how activity spaces of various population segments have evolved over a 5 years period (1998–2003). Using measures such as number of different places visited and scale of convex hull of activity locations, they observed that while the *size* of activity spaces has increased, the number of different locations visited during a typical day has tended to decline. This is consistent with time budget constraints: as people travel longer to reach various destinations, the time available to realize each becomes more limited. With respect to population segments, the study revealed that some population segments have wider activity spaces than others, namely people living further from the central parts of the city, males, people who own a car, and workers. Lack of access to a private vehicle in particular was noted to be the most important constraint to the size of activity spaces. Mercado and Páez (2009) report research for Hamilton that is concerned with the determinants of distance traveled with a particular focus on seniors, and the different modalities of travel. The results give evidence of a significant loss of mobility for seniors who use their private vehicles, and thus highlight the paradoxical situation of those who depend on a mode to maintain only very modest levels of mobility. The results regarding seniors are important since this population segment will become increasingly important in many societies including Canada. Access to different modes of transportation has in fact been identified as a key factor in affecting the mobility of seniors and, consequently, their quality of life (Banister and Bowling, 2004; Metz, 2003, 2004; Tacken, 1998). Finally, there has been research on gender and commuting distance (e.g. Turner and Niemeier, 1997), however, single-parent households do not appear to have been the focus of previous research.

2.2. Population segments of interest

The focus of the study is on three population segments perceived as being at risk of facing mobility challenges, namely the elderly, low-income people, and individuals in single-parent households. To provide some context, the situation of these groups in Canada is briefly discussed next.

2.2.1. Seniors

The elderly represent an important group of interest considering their significant increase in number as Canada's population continues to age, as documented in Newbold et al. (2005). In Central Ontario, it is reported that the proportion of population older than 65 years of age will grow from 12% to 25% in 2021, because of the decline in fertility to offset the large aging baby boom population, born in the years 1946 to 1965 (Bourne, 2003). While higher levels of education, health, technology access and auto dependence have characterized the aging baby boom generation (Bush, 2005), there are continued concerns about their mobility needs in the future, since many made the suburbs their place of residence at a time of cheap transportation, and many are expected to "age in place". The mobility implications of becoming a senior are ambiguous: on the one hand, it is conceivable that the reduction in mandatory activities (e.g. employment) at spatially fixed locations, will free time for more discretionary travel, thus increasing both the generation of trips, and their length. At the same time, older individuals may suffer from deteriorating skills that affect their basic motor skills, which may negatively impact their ability to move. The net effect is not evident. In particular, the ability to use different modes of transportation has been identified as a key factor in affecting the mobility of this vulnerable population segment, and while auto ownership appears to be a powerful mobility enabler, the challenges of driving cessation have also been clearly highlighted by recent research (Paez et al., 2007).

2.2.2. Single-parent households

Single-parent household members are another group of interest. Single-parent families represent a significant population group in urban centers of Canada, and one which according to the 2001 and 2006 Canadian censuses increased during this time period from 15.7% to 15.9% at the national level. The rates in fact tend to be higher in larger cities such as Toronto, a city where single-parent families represent a slightly larger share of all families (16.89%) and the increase from the 2001 rate (16.39%) was more pronounced. Moreover, the vast majority of all single-parent families in Toronto (83%) are headed by women, and economically, these families achieve much lower incomes than couple-headed families and even male-headed single-parent families. Statistics Canada, for instance, reports that 26% of female-headed single-parent families have after-tax family incomes below the low-income cut-off, nearly three times the rate of couple-headed families. From a mobility perspective, in addition to the limitations imposed by economic hardship, individuals in this population group also tend to carry the joint burden of generating employment income while maintaining household and child-care responsibilities. Clearly, time spent on household maintenance and child-care activities will reduce the amount of available time for the daily commute (Turner and Niemeier, 1997), a fact that makes it even more important to ensure equitable accessibility to employment for single-parent family household heads.

2.2.3. Low-income

While there is no official poverty line in Canada, a variety of measures are used to assess and track the rate and depth of poverty. The most widely used poverty measure is defined by Statistics Canada in terms of Low Income Cut-off (LICO) criteria which vary depending on household size and the population size of the area where people reside. As a rule of thumb, households that spend disproportionate amounts of their pre-tax income on food, clothing and shelter – 20% above the average family – are considered low income. Based on the LICO measure, Ontario has a lower proportion of low-income persons than Quebec. In 2005 Ontario had 14.5% in the LICO category while Quebec shows higher with 17% (Centre for the Study of Living Standards, 2007). Their respective metropolitan regions follow the same pattern. Toronto had 17% while Montreal posted even higher than the provincial estimate with 19.8%. Trend analysis, however, shows that over the period 2000–2005, poverty rate using the LICO measure in Quebec and Montreal had declined by about 11% and 17%, respectively. In contrast, during the same period, Ontario increased by 2.3% but a dimmer picture has been shown in the Toronto CMA where poverty rate has increased by about 13%. Low-income individuals are considered a vulnerable group since they are the most likely to lack the material means to realize the mobility potential.

3. Data and methods

3.1. Household travel surveys

Two sources of data are at the basis of this research: the Greater Toronto Transportation Tomorrow Survey (TTS; see http://www.jpint.utoronto.ca/ttshome/index.html) and Montreal's travel survey (see http://www.cimtu.qc.ca/EnqOD/Index.asp). These are two of the largest cross-sectional origin–destination (OD) travel survey programs in the world, and have been conducted every 5 years since 1986 in the Greater Toronto Area (GTA), including the City of Hamilton, and since 1970, approximately every 5 years, in the Greater Montreal Area (GMA). Analysis and models presented in this report are based on the latest set of data available for each metropolitan area: the 2001 TTS and the 2003 Montreal travel survey.

These large-scale repeated cross-section travel surveys provide unique sets of data on travel behavior for these areas. Among their characteristics we count:

- *Scale*: The survey gathers information about a sample of approximately 5% of all households residing in the survey area: around 70,000 households in the 2003 GMA survey and more than 135,000 households in the 2001 GTA survey.
- *Depth*: Details regarding the travel behavior of every person (5 years and older in GMA, 11 years and older in GTA) belonging to the surveyed household are gathered as well as attributes of households and people, using Computer Aided Telephone Interview tools;
- *Spatial resolution*: Every location visited by an individual (home, trip-ends) is geocoded with x–y coordinates using structured databases on addresses, intersection, trip generators. This allows for great flexibility in spatial analyses that can be conducted, either at the micro-data level or at any level of aggregation, using any type of mapping delimitation.
- *Itinerary*: Particular importance is given to the gathering of valid trip-related information; hence, transit trips are declared using routes and subway stations and, in the GMA, partial declaration of car routes is also added (highways and bridges).

An advantage of working with these data sets is that there are minimal differences between the survey instruments (a 24-h trip survey), the survey procedure (telephone interview), the survey frequency (every 5 years) and the sampling rate (approximately 5% of all households) for these two data collection programs. This in turn allows for meaningful temporal and geographic comparisons. The content of both surveys includes socio-economic information about all household members. For a single fall weekday, individual trips by all modes of transportation, made by all household members greater than a specified minimum age are precisely documented in space and time. Contrary to often-used zoning systems for the coding of trip ends, origin and destination points for both surveys are geocoded at the x–y coordinate level using various types of identifiers such as trip generator, address or nearest intersection. Various spatial visualization tools using data from these surveys have been developed for data analysis or data dissemination (Buliung and Morency, 2009; Chapleau et al., 2008; Chapleau and Morency, 2005). Some differences need to be pointed out and addressed. These include:

- *Travel behaviors*: Since the Toronto and Hamilton surveys after 1986 gather travel information only for people aged 11 years or older, children under 11 years old are excluded from the analysis of trip characteristics for both regions. However, information for all household members is included in all socio-economic analyses.

- *Main occupation*: In the GMA, main occupation data were only collected in 1998 and 2003. Five mutually exclusive answers are possible: full-time worker, part-time worker, student, retired, others. Information collected in Toronto and Hamilton differs from that of the GMA. In Toronto and Hamilton, employment status and student status are collected separately, recognizing that a person can be both a student and maintain employment simultaneously. In Toronto and Hamilton, employment status is defined using the following categories: full-time worker, part-time worker, full-worker at home, part-time worker at home, and not employed. A common aggregated employment status variable was created to reflect a person's main occupation that included the categories: full-time worker (including full-time at-home workers and full-time workers that were also students), part-time worker (including part-time at-home workers and part-time workers that were also part-time students), student (including full-time students that were also part-time workers), other status (including not employed, and retired)
- *Income*: Income data are available in the 2003 GMA survey. The survey in Toronto, in contrast, does not collect income information. In order to address this limitation of the survey, household income data were obtained from the census. To better reflect income variations, average income for the census tract was stratified by household structure, and then imputed to individual households in the census tract based on comparable household structures (e.g., single, couples, couples with children, etc.)
- *Non-motorized trips*: In the GMA, non-motorized trips are gathered for all purposes. In Toronto and Hamilton bike trips are collected for all work and school trip purposes in 1986 and for all trips in 1996 and 2001. Walk trips are only collected for work and school trip purposes in all survey years.

3.2. Variables

Selection of variables for the analysis is based on a review of the literature and theoretical considerations. For a full discussion of the conceptual framework that animates the choice of variables, please see Páez et al. (2009a; particularly Chapter 1). The dependent variable is mean trip distance, defined as the ratio of the total distance traveled (in km) to the number of trips taken by an individual in the day reported. This variable was examined previously for the case of Hamilton by Mercado and Páez (2009). In order to ensure that estimated values of distance traveled are positive, analysis is performed on a transformation of the variable using the natural logarithm operation. Dependent variables describe various socio-economic and demographic factors, including age, income, household structure, and occupation. Mobility tool variables encompass factors associated with the ability to use various forms of transportation, including drivers license, vehicle ownership, and proximity to transit facilities. An urban form variable, population density, is also introduced.

In this study, age classifications have been constructed so as to reflect the differentiation in experiences between age groups. Previous studies have shown that increasing age is negatively related to trip length (Benekohal et al., 1994; Boarnet and Sarmiento, 1998; Chu, 1994; Rosenbloom, 1995; Schmocker et al., 2005) an effect that is particularly marked with respect to the use of car (Mercado and Páez, 2009). Occupation and household structure have also been shown to influence travel behavior. Vance and Iovanna (2007), for example, found a negative impact of employment status on the probability of car use and distance driven. In particular, employed persons drive 1.56 km less than their non-employed counterparts, on average. The effect of household structure influences travel behavior by altering the role of members in different household structures (for example, due to the need for social interactions at home in relation to the presence of children at home; Stradling et al., 2005), or by introducing interaction effects between travelers (Scott and Kanaroglou, 2002). Mobility tools such as license ownership, vehicle ownership, transit pass ownership or a combination of these have also been shown to influence travel behavior. Vance and Iovanna (2007) argued that there are close interrelationships between mode choice and distance traveled while Stradling et al. (2005) gave empirical evidence to show differences in factors affecting distance traveled by specific travel modes. Household income, on the other hand, has been found to have a significant positive effect on distance traveled (Limtanakool et al., 2006; Stradling et al., 2005).

3.3. Modeling approach

Our analysis of distance traveled is based on multivariate regression, a standard analysis technique, enhanced by means of spatially-expanded coefficients (Casetti, 1972) to more fully take advantage of the availability of geographically detailed information. The result is a model with spatially-varying coefficients that belongs to the class of local forms of spatial analysis discussed by Fotheringham and Brunsdon (1999). Selection of the expansion method as our modeling tool is conditioned to an important degree by the large sample sizes (tens of thousands of observations) and number of variables in the models (see below). This size implies non-trivial computational challenges for some of the alternatives (e.g. geographically weighted regression and Bayesian approaches; see Páez and Wheeler, 2009). The expansion method offers in this case a simple, efficient way of investigating person-location contextual effects, and implementation is feasible given the sample size, even if the approach may arguably miss more complex spatial variability (Fotheringham et al., 1998).

With regards to the use of multivariate regression models applied to the study of distance traveled, a number of applications has been previously reported in the literature. However, the degree of spatial resolution in the results has so far been limited. For instance, past research where detailed geocoded information was not available (e.g. Mercado and Páez, 2009) resorted to the use of multilevel models in order to account for the presence of spatial heterogeneity. In multilevel analysis, when spatial heterogeneity is detected, it is as a random component which by definition does not give indication of systematic spatial trends. In other research, analysis has introduced very broad geographical categories (e.g. inner and outer London; Schmocker et al., 2005) as opposed to detailed location information. The closest example that we are aware from in the literature, in terms of using spatial information, is the analysis performed by Naess (2006) of trip lengths, where he used location relative to the CBD as a variable in his models. As explained more fully below, spatially-expanded models go beyond this use of spatial variables by retrieving both between-person and between-location variations. In summary, the expansion method is capable of detecting systematic spatial trends, it can do so at a high degree of spatial resolution, and is able to identify person-location contextual variations.

Detailed descriptions of the expansion method can be found elsewhere in the literature (e.g. Fotheringham et al., 2000). In brief, the method operates on the principle of expanding the coefficients of an initial model, assumed to contain substantive knowledge of a process, as functions of expansion variables, which are meant to capture contextual variations. The principle can be rather simply illustrated using an example. Consider the following regression model with an initial specification that relates the variable y to a set of explanatory variables x, and random variation ε:

$$y_i = \sum_{k=1}^{K} x_{ki}\beta_k + \varepsilon_i \tag{1}$$

In this model, the set of variables x_k incorporates the substantive knowledge about the process being modeled (the value of variable x_{1i} is usually set to 1 for all i to give a constant term). In the terminology of the method, this is called the initial model. Some or all of the coefficients of this model can be further developed by means of a polynomial expansion of a suitable degree, using the coordinates (u_i, v_i) of location i to take into account the effect of location. To illustrate, consider the following linear expansion of a simple bivariate model (note the use of sub-index i in the expanded coefficients):

$$\begin{aligned} \beta_{1i} &= \beta_1^1 + \beta_1^2 u_i + \beta_1^3 v_i \\ \beta_{2i} &= \beta_2^1 + \beta_2^2 u_i + \beta_2^3 v_i \end{aligned} \tag{2}$$

The spatially-expanded coefficients lead to what, in the terminology of the method, is called a terminal model:

$$\begin{aligned} y_i &= \beta_{1i} + \beta_{2i} x_{2i} + \varepsilon_i \\ &= \beta_1^1 + \beta_1^2 u_i + \beta_1^3 v_i + \beta_2^1 + \beta_2^2 u_i + \beta_2^3 v_i x_{2i} + \varepsilon_i \end{aligned} \tag{3}$$

Compare to the initial, non-expanded model:

$$y_i = \beta_1^1 + \beta_2^1 x_{2i} + \varepsilon_i \tag{4}$$

It is important to remark that the use of spatially-expanded coefficients is *not* the same thing as the use of spatial variables (all variables in geocoded datasets are spatial after all!). The expansion method operates by considering between-person and between-location variations in travel behavior. Take as an instance a spatial variable that does not describe location, such as household income. A standard regression model would retrieve a coefficient describing the relationship between income and distance traveled, *without making reference to space* (see Eq. (4)). In other words, the model assumes that the relationship is location-invariant, which implies that, other things being equal, people with the same level of income behave in the same way in terms of distance traveled *regardless of where they are*. Spatially-expanded coefficients, on the other hand, represent in essence an interaction between an attribute and location (see Eq. (3)). A coefficient with significant expansion components would indicate that income and distance traveled do not relate in exactly the same way everywhere, but rather that there are contextual between-location variations in the relationship, again, other things being equal. Now consider a spatial variable that describes a location attribute, such as proximity to the CBD (see Naess, 2006). In a standard model the coefficient would indicate that the response varies with location, but is identical for all individuals at comparable locations, *regardless of who they are*. In a spatially-expanded model, the coefficients would be able to capture differential responses to location variables depending on the attributes of the individuals, or in other words, between-person contextual variations.

The coefficients of the terminal, spatially-expanded model, can be estimated using ordinary least squares approaches, and their significance can be tested in the usual way, by examining their t-scores or probability values. Furthermore, spatially-expanded coefficients can be mapped, and used to estimate the dependent variable locally, since the expanded coefficients map the effect of variable x_i on y_i at location (u_i, v_i). Judicious use of the explanatory variables allows the estimates to produce specific profiles to reflect the socio-demographic, economic, and other relevant attributes of various population segments. As a final remark, please note that higher order expansions (e.g. quadratic, cubic, etc.) and additional explanatory variables are straightforward to introduce.

4. Results

The results of estimating regression models for distance traveled are presented in Table 1 for the three case studies. Old age (65 or greater) and single-parent household status were expanded using the coordinates of the place of residence and distance to the CBD in all three cases studied. In addition, low-income status (income < $20,000) was expanded in Montreal, but not in Hamilton or Toronto because the income variable there is not truly a household level variable, but rather the average for the census tract. The quadratic surface used in the analysis for the expanded coefficients represents a compromise between a simpler linear surface and higher order expansions. Given that several components of the quadratic trend surface are already not significant, we are satisfied that this compromise, especially with respect to higher order surfaces, is reasonable. The goodness of fit of the models is conventionally assessed using the coefficient of determination, or R^2 statistic. This statistic, which ranges between 0.16 and 0.22 in the set of models reported, is interpreted as the proportion of the variance that is explained by the model. In other words, around 20% of the variability contained in the data is being captured by the models.

Regarding the interpretation of the models, in linear regression a coefficient is usually understood to represent the change in the dependent variable associated with a unit change of the corresponding explanatory variable. When the independent variable has been transformed using the natural logarithmic function, as in the present case, the interpretation instead is that the coefficients, when multiplied by 100, indicate the percentage change associated with a unit change in the explanatory variables. Consider for example the model for Montreal. In this city, being younger than 20 years old is associated with a 42% decrease in distance traveled, with respect to the reference age cohort. Couples with children tend to make trips that are 12% shorter compared to those of singles, and vehicle ownership confers almost a 17% increase in distance traveled. The results of the models can be easily converted back to the same metric of the dependent variable, to better understand the impact of various factors on distance traveled. This is done by selecting the coefficients that describe a desired individual profile, and introducing the corresponding variables in the calculation. Since most variables are dummies that take the value of 1 or 0, depending on whether an individual belongs to a given class or not, the effect for the most part is to switch on and off various combinations of coefficients. For instance, consider the profile of an individual in Montreal who is 36–50 years, with a household income of between 40 and 60 thousand dollars, and single. Assume that this person owns a vehicle, is in possession of a driver license, and is employed full time. In addition, we suppose that the individual lives exactly at the downtown location (in normalized coordinates $X = 0.64$ and $Y = 0.43$) where the density of population is about 3.8163 thousand people per square km. The estimate of distance traveled for a person fitting this profile would be calculated in the following way:

$$\begin{aligned} \log(\hat{d}) = {} & b_{CONST} + b_{INC_{40-60k}} INC_{40-60k} + b_{VEH} VEH + b_{DLIC} DLIC \\ & + b_{FTE} FTE + b_{PopDen} PopDen + b_{X^2} X^2 + b_X X + b_{XY} XY \\ & + b_Y Y + b_{Y^2} Y^2 \end{aligned} \tag{5}$$

Accordingly:

$$\hat{d} = e^{-2.1166-0.1889+0.3061+0.1699+0.5701-0.0218 PopDen-4.1085X^2+5.6710X-0.4131XY+4.8965Y-5.4665Y^2} \tag{6}$$

which gives a value of the average trip length $\hat{d}$ for this profile equal to 1.8216 km. In order to obtain estimates of distance traveled for the same individual profile at other locations, the corresponding

Table 1
Distance traveled models with spatial expansion.

	Hamilton		Toronto		Montreal	
R^2	0.226		0.164		0.199	
s	0.988		0.887		1.099	
n	17,944		97,465		122,420	
Variable	Estimate	p-Value	Estimate	p-Value	Estimate	p-Value
Constant	2.5920	0.0000	−0.1771	0.0036	−2.1166	0.0000
Age						
Age < 20	−0.3943	0.0000	−0.5363	0.0000	−0.4165	0.0000
Age 20–35	0.1105	0.0000	0.0651	0.0000	0.0520	0.0000
Age 36–50	Reference		Reference		Reference	
Age 51–64	−0.0196	0.2140	−0.0196	0.0182	−0.0217	0.0144
Age 65+	0.4520	0.3696	0.7922	0.0000	0.6027	0.0529
Income						
Income (CT average)	0.0096	0.3454	0.0053	0.0000	–	
Income^2 (CT average)	−0.0015	0.1543	−0.0001	0.0016	–	
Inc. Refuse/do not know	–		–		−0.1730	0.0000
Income < 20 K	–		–		−0.9787	0.0080
Income 20–40 K	–		–		−0.2513	0.0000
Income 40–60 K	–		–		−0.1889	0.0000
Income 60–80 K	–		–		−0.1072	0.0000
Income 80–100 K	–		–		−0.0571	0.0001
Income > 100 K	–		–		Reference	
Household structure						
Single	Reference		Reference		Reference	
Couple	0.1451	0.0013	0.0011	0.4630	0.0105	0.1809
Couple W/children	0.0013	0.4896	−0.1477	0.0000	−0.1236	0.0000
Single-parent	−1.2507	0.3528	1.4205	0.0000	0.3073	0.3242
Other	0.1066	0.0140	−0.0227	0.0233	0.0429	0.0002
Mobility tools						
Driver license	0.2489	0.0000	0.1497	0.0000	0.3061	0.0000
Vehicle own	0.2180	0.0000	0.1068	0.0000	0.1699	0.0000
*Age 65+	−0.2099	0.0044	−0.1674	0.0000	−0.0036	0.4556
*Single-parent	−0.1247	0.1492	−0.0179	0.3151	−0.0410	0.2030
*Low-income	–		–		0.0159	0.2766
Transit within 500 m	0.1221	0.0563	0.0781	0.0000	−0.0826	0.0001
*Age 65+	−0.1986	0.1596	−0.0318	0.2567	−0.1679	0.0043
*Single-parent	−0.2718	0.2770	−0.2039	0.0053	−0.1284	0.1488
*Low-income	–		–		0.0925	0.0329
Occupation						
Full-time employment	0.4823	0.0000	0.4196	0.0000	0.5701	0.0000
*Age 65+	−0.1052	0.1462	−0.0048	0.4476	−0.0953	0.0262
*Single-parent	−0.2528	0.0065	−0.1393	0.0001	0.0073	0.4278
*Low-income	–		–		−0.0602	0.0106
Part-time employment	0.0484	0.0760	0.1407	0.0000	0.1674	0.0000
*Age 65+	0.1143	0.1654	0.2061	0.0000	0.0605	0.1878
*Single-parent	0.0959	0.2500	−0.0759	0.0829	0.0701	0.2369
*Low-income	–		–		0.1443	0.0006
Student	0.0286	0.1854	0.1337	0.0000	0.5323	0.0000
Free parking @ work	0.0740	0.0013	0.0401	0.0000	0.2271	0.0000
Urban form						
Population density	−0.1357	0.0000	0.0216	0.0000	−0.0218	0.0000
Spatial expansion						
Distance to CBD	1.5835	0.0000	3.5309	0.0000	4.3285	0.0000
*Age 65+	−1.1539	0.0624	−1.6627	0.0000	−0.5318	0.0334
*Single-parent	0.2147	0.4497	−2.4700	0.0000	−1.3899	0.0024
*Low-income	–		–		−0.2927	0.1597
X^2	1.0558	0.0655	−2.7749	0.0000	−4.1085	0.0000
*Age 65+	2.1021	0.1511	1.7473	0.0007	0.6009	0.1901
*Single-parent	−2.0120	0.3544	3.1426	0.0006	2.1477	0.0336
*Low income	–		–		−2.7450	0.0000
X	−2.2150	0.0093	3.1550	0.0000	5.6710	0.0000
*Age 65+	−1.2239	0.3314	−1.9455	0.0007	−1.0814	0.1337
*Single-parent	5.5993	0.2101	−3.7835	0.0002	−3.7316	0.0105
*Low-income	–		–		3.3953	0.0003
$X*Y$	1.6158	0.0435	−0.1097	0.2883	−0.4131	0.0009
*Age 65+	−5.6654	0.0283	−0.0697	0.4552	0.1262	0.3903
*Single-parent	−5.9308	0.2047	0.9103	0.1950	1.5921	0.0119
*Low-income	–		–		−0.4074	0.1887
Y	−4.2070	0.0000	0.1677	0.0506	4.8965	0.0000
*Age 65+	2.7084	0.1921	−0.2588	0.2159	−1.2045	0.0298
*Single-parent	−3.3423	0.3342	−1.4637	0.0046	−0.8996	0.2096

	Hamilton		Toronto		Montreal	
*Low-income	–		–		0.0420	0.4768
Y^2	4.2233	0.0000	−2.8158	0.0000	−5.4665	0.0000
*Age 65+	0.1608	0.4755	1.8595	0.0042	1.2649	0.0285
*Single-parent	8.3682	0.1060	3.3771	0.0029	1.7897	0.0611
*Low-income	–		–		−0.3942	0.2974

coordinates are substituted. Other socio-economic and demographic profiles can be explored, at the same or other locations. It is important to note, however, that without the spatially-expanded coefficients, the estimates for distance traveled for each individual profile would be constant throughout the region.

Some general findings can be outlined. With respect to the effect of age, the coefficients correspond for the most part to significant determinants of distance traveled, with the exception of the coefficients associated with the pre-retirement (51–64) and senior populations in Hamilton. Distance traveled peaks at age 20–35. Besides that, the estimates are lower for individuals who are younger than 20 years old, and also tend to decrease with increasing age after the peak, although this can only be appreciated for the elderly once the expanded coefficients are considered. In Montreal, lower income is associated with lower estimates of distance. Individuals in the second highest income group (80–100 thousand) for example have an estimate value of distance traveled that is about 5% smaller compared to the top income class. The difference is −25% for the 20–40 thousand class. The lowest income class also tends to make shorter trips on average, as becomes clear when the coefficients are mapped (see below). For the case of Toronto and Hamilton, distance was entered as a continuous variable. The results indicate that greater income values correlate with lengthier mean trip distance, up to a limit, as indicated by the squared term. The composition of the household also has some impact on distance traveled, although the results are less clear cut. With the exception of the "Other" category (a catch-all class for multi-person households without clear family connections), not a single household type is associated with a significant coefficient for all three cities. In the case of "Couple with Children" where the coefficients are significant, the signs agree, and indicate that members in this type of household make shorter trips on average in Toronto and Montreal. The effect of living in a single-parent household can only be assessed once the spatial trend has been calculated.

Being in possession of a drivers license and vehicle ownership are two factors that associate positively with distance traveled. In every case, the effect of auto ownership applies to the general population, but there are not differential effects from the perspective of single-parent households, or low-income individuals in Montreal. These groups do not appear to derive additional benefits from vehicle ownership in any of the three cities studied. Elderly travelers do not benefit more than the rest of the population from vehicle ownership in Montreal. In the case of Hamilton and Toronto, the net effect of vehicle ownership for the elderly is either very small (0.2180 − 0.2099 = 0.0081, or less than a 1% net increment in Hamilton) or even negative (0.1068 − 0.1674 = 0.0606, or a 6% decrease in Toronto). While a negative relation for seniors may appear counter-intuitive, it is borne by other evidence. As noted above, Mercado and Páez (2009) report that seniors who drive private vehicles tend to have much lower levels of distance traveled compared to seniors who do not drive. A possible explanation is that continued dependence on driving on the part of seniors leads to a detrimental effect on mobility as they become increasingly unsure of their ability to drive, while being unprepared to adopt other modes of transportation. Not owning a vehicle in the case of seniors could mean, for instance, a greater reliance on alternative mobility arrangements such as traveling as a passenger, a form of travel that does not have the negative correlation with distance travel (see Mercado and Páez, 2009, Fig. 1).

The results for proximity to transit nodes are mixed, since the coefficient is not significant for Hamilton, it associates positively with distance traveled in Toronto, but negatively in Montreal. The net effect for single-parent households in Toronto, however, is a reduction of about 13% in distance traveled with respect to the reference group. Neither group is different from the reference in this respect in the case of Hamilton. In Montreal, in contrast, proximity to transit tends to further reduce the distance traveled of seniors, while the net effect is a small 1% increment in distance traveled in the case of low-income individuals.

Full-time employment status associates with significant and substantial increases in distance traveled of between 42% (Toronto) and 57% (Montreal). Likewise, part-time employment tends to increase distance traveled, but not to the same extent, as the increments are only between 14% (Toronto) and 17% (Montreal), and not significant in the case of Hamilton. Seniors and low-income people who are full-time employed tend to travel shorter distances in Montreal, with respect to fully-employed members of the reference group. Single parents who are employed full-time also have smaller net increases in Hamilton and Toronto, but not in Montreal where the effect is not significant. In the case of part-time employment, the only segments that display different behavior are seniors in Toronto and low-income people in Montreal, two groups that tend to travel even longer distances than individuals in the reference group who are also employed part-time.

The effect of population density is significant but mixed across cities, as it tends to increase distance traveled in Toronto, but to decrease it in Hamilton and Montreal. In Toronto, this is likely also due the fact that short walk and bicycle trips to non-work non-school destinations are unreported, trips that are more likely to be observed in higher density areas. In this context, mean trip distance for such areas would only consider longer motorized trips. Since density is lower in Hamilton, the occurrence of non-motorized trips for non-work non-school destinations is lower and has less impact on the estimation of mean trip distance.

As previously described, spatially-expanded coefficients can be used to obtain estimates of distance traveled that are specific to an individual with a selected socio-economic and demographic profile, and a specific location in space. Mapping these results provides valuable insights regarding the spatial variation of distance traveled behaviors, and graphically demonstrates the differences between locations and population cohorts of interest. For each area, maps of estimated distance traveled are presented for the reference and special interest groups, and by vehicle ownership. The effect of proximity to transit nodes is localized by design (within 500 m of facility), which combined with a relatively small effect leads to barely distinguishable differences in the maps (the figures are available upon request). When producing these maps only coefficients with a 5% level of statistical significance or better were employed.

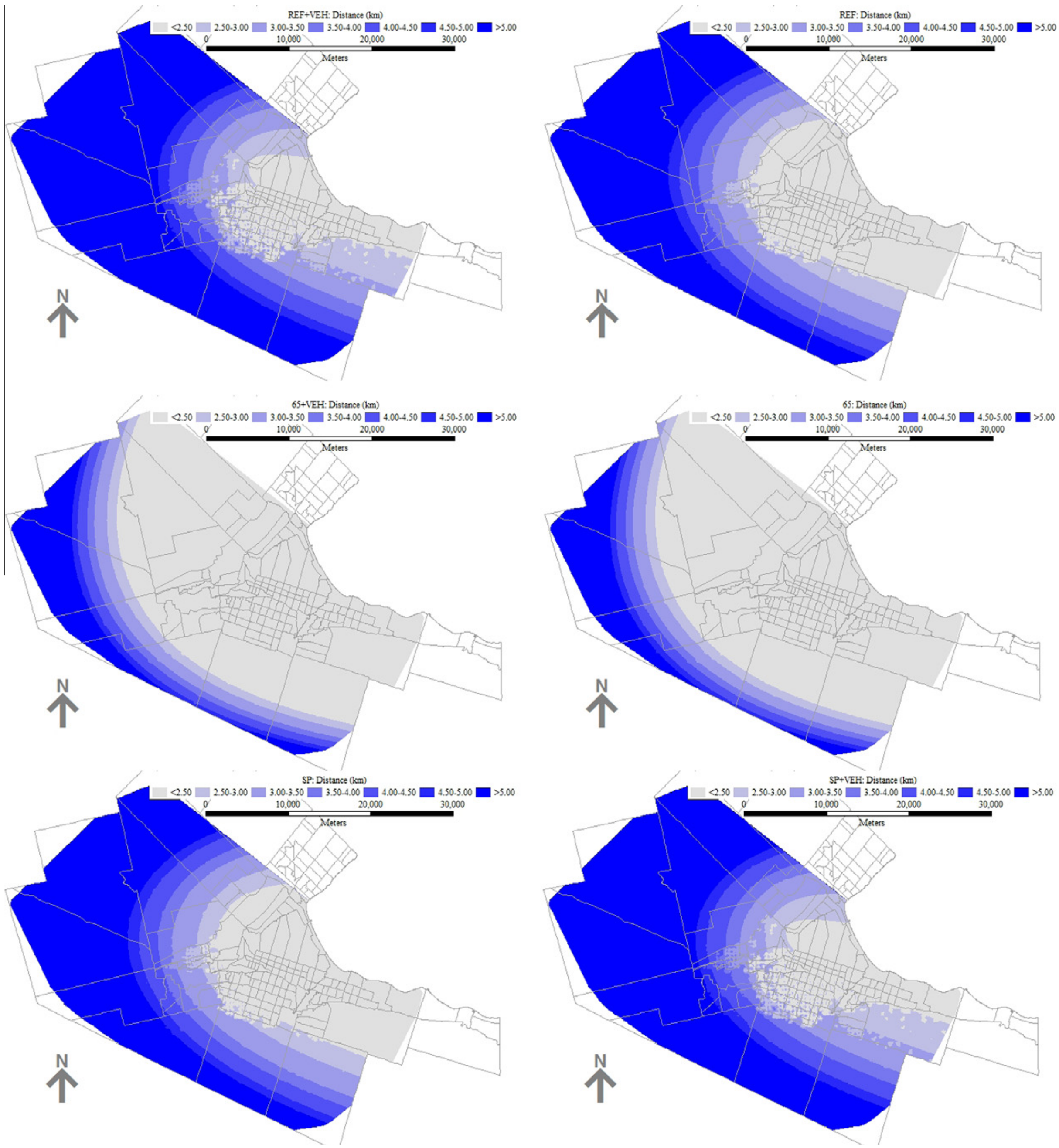

Fig. 1. Hamilton: estimates of distance traveled (in km) for reference (REF), the elderly (65), and single-parent household members (SP), with and without a vehicle.

4.1. Hamilton

For the case of Hamilton, estimates of distance traveled are significantly and substantially lower for seniors all across the city, as the maps in Fig. 1 show. In terms of the magnitude of the effect, there is somewhat less spatial variability in the travel behavior of the elderly. The trend for this population group indicates that the average trip distance is less than 2.5 km within an approximate 10 km radius from center of the city. Distance traveled tends to increase in the direction of the suburbs. The reference population shows a very similar pattern, with distance traveled generally increasing away from the central part of the region. This trend combines with more variability. With regards to mobility tools, owning a vehicle has in general a positive and significant impact on average trip distance, the effect of which can be appreciated in the figure. As noted before, being 65 or older essentially cancels the benefit of owning a vehicle, whereas individuals in single-parent households benefit, but not more nor less compared to the reference group. The differences in distance traveled are relatively minor between single-parent household members and the reference group. The differences between seniors and the reference group are especially pronounced in the suburban areas to the west and north of the city.

4.2. Toronto

Examination of the spatial coefficients for the case of Toronto also uncovers important geographical variations in distance traveled. The general structure of the surface indicates that the estimates of distance traveled tend to be lower near the center of

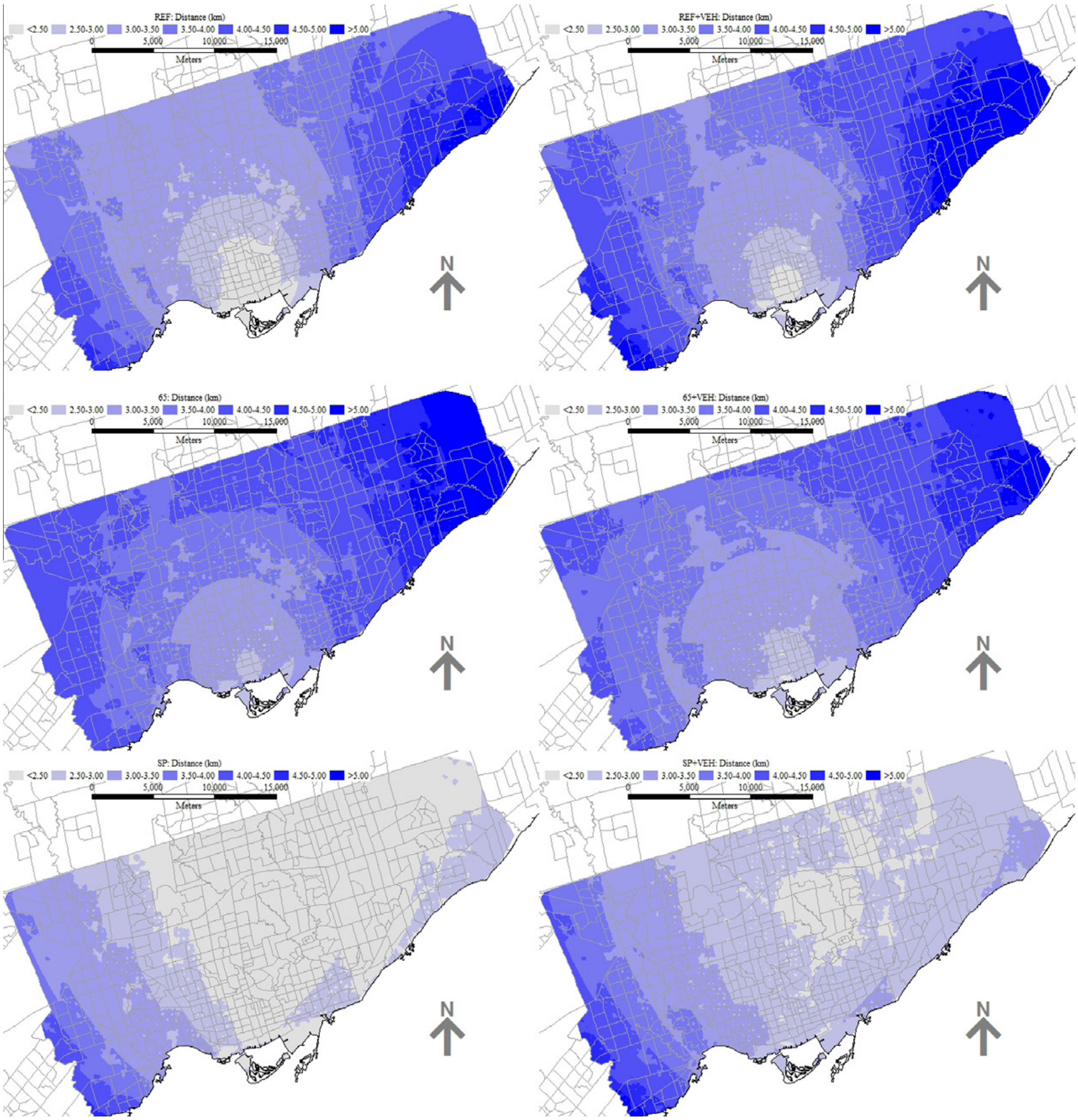

Fig. 2. Toronto: estimates of distance traveled (in km) for reference (REF), the elderly (65), and single-parent household members (SP), with and without a vehicle.

the city, and tend to increase and reach a maximum value in the north-eastern part of Toronto (Fig. 2). This general pattern can likewise be discerned for the case of seniors, who also tend to travel slightly longer distances compared to the reference. The pattern, in contrast, is different for individuals in single-parent households. In addition to having the lowest estimates of distance traveled, the pattern for this group places the lowest levels of mobility to the north and east of the center of the city, and increasing values from there, but particularly towards the west part of the region. With respect to mobility tools, owning a vehicle has a positive impact on distance traveled for people in the reference group and in single-parent households (no significant differences are observed between these two groups with respect to car ownership), but tends to decrease distance traveled of the elderly. As previously noted, this likely to be related to the fact that the TTS does not collect trip data for non-motorized trips for non-work non-study purposes.

4.3. Montreal

In Montreal, distance to the central city exerts a stronger effect than it does in the other two cities. This effect is somewhat weaker for seniors and single-parent households, but does not differ significantly between low-income individuals and the reference group. Mean distance traveled typically tends to increase with distance from the Center of Montreal, the part of the region where activities are more abundant, before reaching a plateau in the suburbs. Fig. 3 shows that the estimates of distance traveled are similar (less than 2.5 km) for all population segments under examination in the central part of the city, within a radius of approximately 7 km of the Central Business District. As distance from that point increases, the differences between groups become more evident. Distance traveled estimates remain very low for individuals in single-parent households. Combined with findings concerning trip generation behavior (Roorda et al., 2009), this result suggests that while indi-

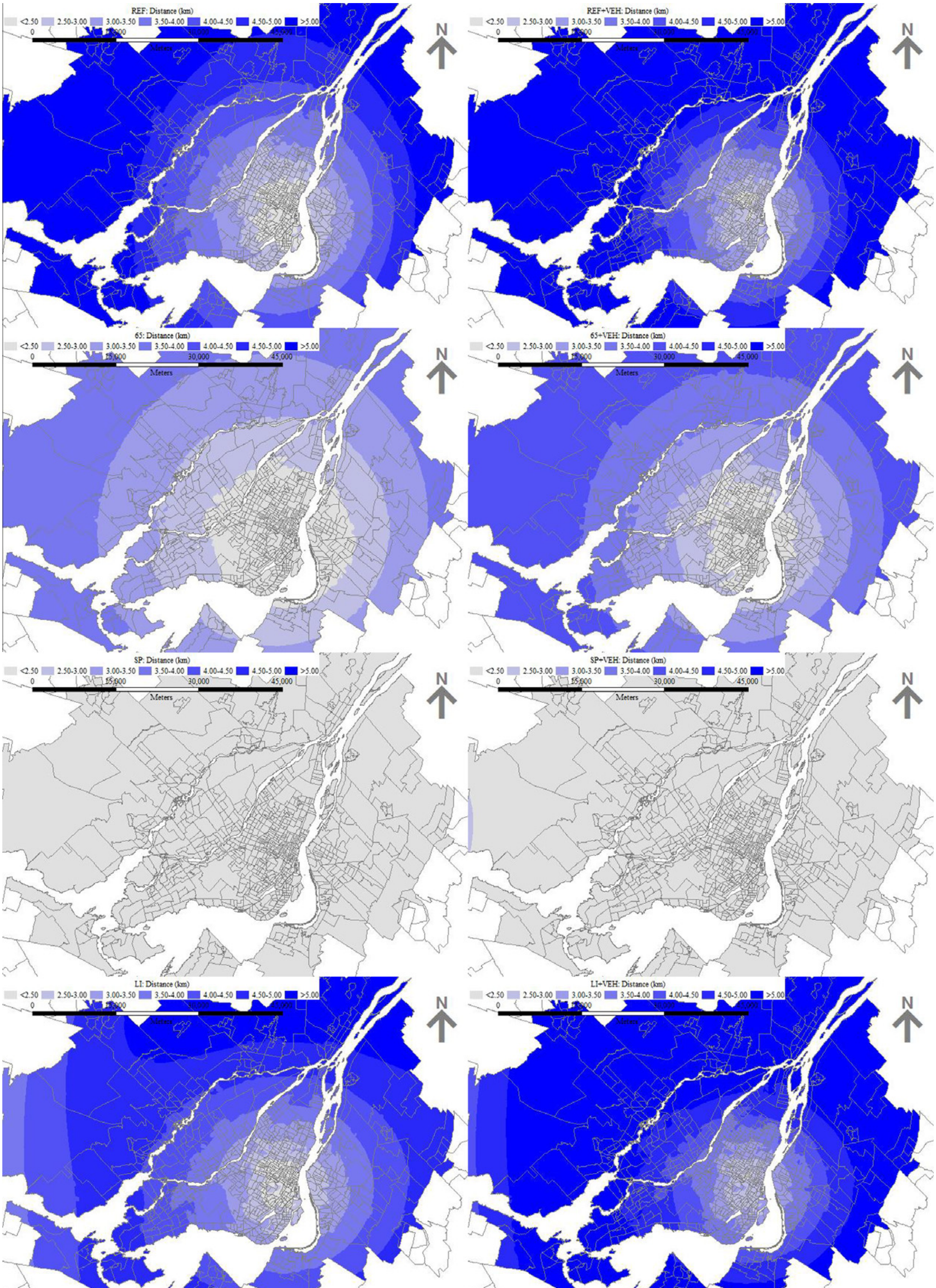

Fig. 3. Montreal: estimates of distance traveled (in km) for reference (REF), the elderly (65), single-parent household members (SP), and low-income (LI) with and without a vehicle.

viduals in single-parent households engage in trip making at levels comparable to the reference, they tend to remain geographically fairly circumscribed, even when controlling for age. A possible explanation for this could be linked that individuals in this class of household to local trips associated with children's activities. The surfaces indicate that mean distance traveled increases with access to a private vehicle for the reference group. This impact is not significantly different for seniors, individuals in low-income or single-parent households. The impact of car ownership is not significantly different for individuals in single-parent households, compared to the reference population.

5. Conclusion

The objective of this paper has been to investigate distance traveled from the perspective of various population segments of special interest. This was done by using multivariate linear regression with spatially-expanded coefficients, applied to geocoded micro-data from three major Canadian urban centers. The results provide evidence that travel behavior has an important spatial component, and do so at a level of resolution previously unavailable. The findings offer valuable insights regarding the effect of location, and in particular help to assess differences in distance traveled, as well as the variability of this indicator of mobility as a function of residential location.

The focus of the analysis was on the elderly, individuals in single-parent households, and low-income households (for the case of Montreal). The study of spatial trends in distance traveled provides important information about the parts of the study areas where vulnerable populations tend to experience more restricted mobility conditions that may affect their access to opportunities, and thus locations where interventions may be required to alleviate or compensate for poor mobility conditions. The findings suggest that individuals in the three at-risk groups examined tend to travel shorter distances, but not in every case studied, and neither in the same magnitude. For instance, seniors display the most limited mobility patterns in Hamilton, but in Toronto and Montreal, single-parent household members have the lowest levels of mobility. Seniors in Montreal tend to undertake shorter trips than the reference group, whereas in Toronto, they tend to travel slightly longer distances compared to the reference. The effect of vehicle ownership is to increase the level of mobility, with exceptions, such as the elderly in Toronto, a condition that essentially cancels the benefit of access to a private vehicle. In general, there are relatively small differences between groups in terms of the estimates of distance traveled near the central parts of the three cities. The differences tend to become more important away from central cities. In particular, mobility limitations tend to be seen for the most part in suburban locations.

It is important to note that distance traveled, by itself, does not equate accessibility. The findings regarding the spatiality of distance traveled are nonetheless relevant from the perspective of accessibility, because lower relative mobility in suburban settings, combined with lower density of opportunities, may lead to unfavourable accessibility outcomes. In this regards, as noted in the introductory remarks, distance traveled should be seen as a component of accessibility, with higher estimates of distance traveled indicating a wider range of potential destinations that can be reached, other things being equal. Analysis of accessibility proper would involve investigating whether more or less opportunities are effectively available in each case, something that depends on the specific opportunity landscape in each urban area. This question is the subject of companion research that proposes an approach to incorporate estimates of distance traveled (such as obtained in this paper) to develop relative accessibility deprivation indicators (e.g. Páez et al., forthcoming).

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