Modeling spatio-temporal diffusion of carsharing membership in Québec City

Résumé/Abstract

During the last few years, carsharing has undergone significant growth, both in Canada and around the world. In this type of service, users share access to a fleet of vehicles, thereby giving them most of the advantages of an automobile, such as its temporal and spatial flexibility, without many of the constraints of ownership. This article studies the geographical and socio-economic factors that favour membership of a carsharing service in Québec City. We combined Cervero's and Kockelman's 5D model (density, diversity, design, distance to transit and destination accessibility) with Hägerstrand's concept of innovation diffusion so as to analyze the evolution of potential carsharing membership. Zero-inflated negative binomial (ZINB) regression was used to model the spatial diffusion of the number of carsharing members in Québec City from 1996 (two years after its inauguration) to 2008 at the local scale with an annual time step. Results indicate that the carsharing distribution did indeed follow Hägerstrand's innovation diffusion model and that, even though some of the 5D model significantly influenced membership, it was the socio-economic factors (education, non-motorization, and family structure) that most greatly affected the membership rate in the service area. The model is used to assess and discuss the market coverage potential in Québec City.

Keywords: carsharing, sustainable mobility, Hägerstrand's innovation diffusion model, 5D model, spatio-temporal modeling

1. Introduction

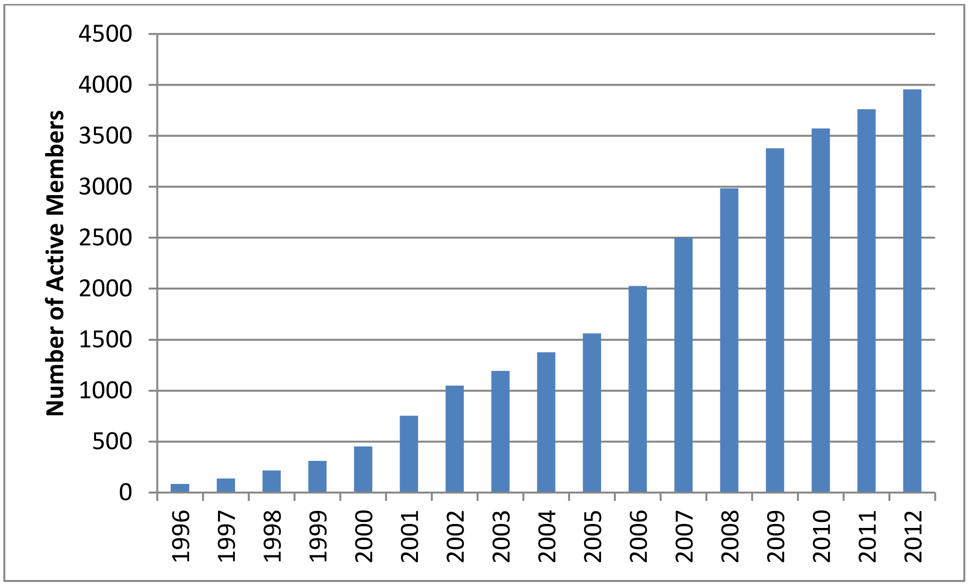
There have been numerous studies conducted on the consequences of developing cities around the automobile. The evolution of transportation methods in the Western world has converged toward what could be described as an automobile "monoculture" (Sperling and Gordon, 2009). This car-centered transportation has had all sorts of impacts, be they urbanistic, economic, social, or environmental. A common point in current discussions concerns the place of the car in urban environments. Despite the rise in popularity of alternative transportation methods, cars remain, in a society based on exchanges, the transportation method that best meets "an increasing need for transportation flexibility, both in terms of schedules and destinations" (Tecsult, 2006). Given the consequences of "everything for the car," the need has arisen to develop "more individualized" public transportation methods for today's society, such as carsharing (Asher, 2001). In other words, despite the evident disadvantages associated with it (Katzev, 2003) and because of a well-established culture of moving around in individual cars, it has become difficult in the current context to compete with the automobile paradigm: "The car can be integrated into the complex structures of contemporary lifestyles like no other mode of transportation" (Nobis, 2007: 35). It is argued that carsharing allows users to combine the advantages of a car, such as its temporal and spatial flexibility, without many of the constraints of ownership. It is an alternative model of car ownership, use, and access (Britton, 1999), analogous to carpooling but without the disadvantages of schedule and route incompatibility.

While there are several definitions of carsharing, the Transportation Research Board recommends the following: "A membership program intended to offer an alternative to car ownership under which persons or entities that become members are permitted to use vehicles from a fleet on an hourly basis" (Millard-Ball et al., 2005: 2-2). In other words, members of a carsharing service pay for costs related to kilometres driven and time of usage, which gives them access, generally upon reservation, to cars available in a "self-serve" mode in predetermined parking lots. The subscription, reservation, and payment system, the type of organization and means of operation all vary according to the company considered. But whatever the specific characteristics, the goal usually remains the same: to make car use more efficient, since owning a car, with the high ratio of fixed costs to marginal usage costs it entails, inevitably encourages its usage (Nobis, 2006). What is more, carsharing optimizes the usage time of cars, which in normal circumstances (when owned by an individual or family) is only used 2% of the time, as compared to 30 to 40% for shared cars (Scott et al., 2003).

Carsharing began in Zürich, Switzerland in 1948. At the time, a group of citizens decided to share cars through the creation of a cooperative, *Sefage*. This neighbourhood effort, which cannot be considered as a modern, car-sharing organization, ended in 1998 (Robert, 2005b). Switzerland, the Netherlands, Germany, Denmark, France, Ireland, Italy, Scotland, and Sweden were, in the early 1990s, the main countries with carsharing companies (Shaheen et al., 1998: 36). Since then, the service has grown considerably on the European continent as well as in North America, with 14 operators in Canada (39,664 members; 1,667 vehicles) and 19 operators in the United States (279,174 members and 5,838 vehicles) (Stillwater et al., 2009; Shaheen and Cohen, 2007; Shaheen et al., 2009). On a worldwide basis, we are seeing fast growth and increasing diversification of service (e.g. one-way rental, rental without reservation). As of October 2010, more than 1.25 million individuals were sharing over 31,660 cars (Shaheen, 2012).

The first North American organization to provide a regular service was *Auto-Com* in Québec City in 1994, years before *City CarShare* in San Francisco (Cervero et al., 2007). In 2000, *Auto-Com* became *Communauto*, which has, as of 2011, more than 24,000 members in seven cities across the Province of Québec (Québec City, Montréal, Sherbrooke, Gatineau, Laval, Longueuil, and Lévis), with more than 4,000 in Québec City and Levis (Figure 1). The travel behaviour of Montreal users was studied (Habib et al., 2012; Sioui et al., 2012), but the deployment process of service in the urban space is still to be investigated.

Figure 1. Evolution in membership of Communauto in Quebec City and Levis



Source: Communauto

Numerous authors have looked at this growing phenomenon, particularly since the first pilot projects in the United States. However, research into that field began in Europe, in particular with Biau (1991), who described a self-serve car service in Montpellier, France in the early 1970s. Shaheen et al. (1998) wrote up a history of carsharing around the world, highlighting the success of certain projects in Europe and the beginning of the phenomenon in North America. Studies on the impact of carsharing were conducted by Litman (2000) and Katzev (2003). They examined *Carsharing Portland*, the first company of its kind to be firmly established in the United States. In a report written in 1999 but published in 2004, Shaheen used theories of social marketing and learning to explain the process underlying the people of San Francisco's acceptance of transportation innovation in the form of the carsharing service *CarLink*, which was set up under her supervision. Cervero (2003) and Cervero and Tai (2004) took a look at the *City CarShare* program in California and observed the effects of travel behaviour after one and two years of service. Robert (2005) drew up the history of *Communauto* in Québec City. Lane (2005) analyzed the motivations of users of *PhillyCarShare* in Philadelphia and the impacts on their mobility. Shaheen et al. (2006) examined the increase in carsharing in North America and estimated its growth potential in large metropolitan regions at around 10% of people 21 and over. More recently, Shaheen et al. (2009) looked back at the last decade of carsharing in North America, identifying three phases in the development of North American organizations: market insertion, from 1994 to mid-2002; growth and diversification, from mid-2002 to 2007; and a larger scale offer, from the end of 2007 until today. Carsharing continues to be of interest to researchers, in particular from the angle of impact on motorization (Cervero et al., 2007; Martin et al., 2010), the multimodal aspect of the phenomenon (Nobis, 2006, 2007), its effects on the environment (Alexandre, 2010; Firnkorn and Müller, 2011), and user behaviour (Jemelin and Louvet, 2007; Morency et al., 2012; Costain et al., 2012) or its potential in Shanghai (Wang et al., 2012).

The present article examines the geographical and socio-economic factors underlying the deployment of the carsharing service in Québec City so as to determine their relative weight using a statistical model. In keeping with Stillwater et al. (2009), we hypothesized that carsharing potential is linked to urban form, being limited to high density neighbourhoods with good access to daily services and workplaces. We combined Cervero and Kockelman's (1997) 3D model – density, diversity, design – and Cervero et al.'s (2009) 5D model – in which distance to transit and destination access are added and which are regularly used to assess transportation demand potential – with Hägerstrand's (1967) concept of innovation diffusion. The goal of this study is to model the spatial diffusion of carsharing membership in Québec City from 1996 (two years after the service was launched) to 2008. The objective is not to understand the mobility rationale underlying a user's choice to join but rather to determine the built environment characteristics and the neighbourhood socio-economic attributes that favoured carsharing membership (market coverage), while considering the phenomenon's endogenous evolution. It is important to note the difference between membership and usage: we did not measure the frequency or likelihood of service utilization, but only the simple fact of being an active member (paid annual subscription) or not. To our knowledge, this is the first time that the spatial diffusion of carsharing is carried out at the city scale, thanks, among other things, to the duration of the service in Québec City. Moreover, the model developed here integrates and compares the effects of a large range of urban and socio-economic characteristics. The modeling approach simultaneously considers the growth of the service area (control of excess zeros) and the increase in membership using ZIP (zero-inflated Poisson) and ZINB (zero-inflated negative binomial) regressions so as to estimate growth with a capacity constraint (number of eligible drivers) at a large scale (hexagonal grid cells with a 250 m radius).

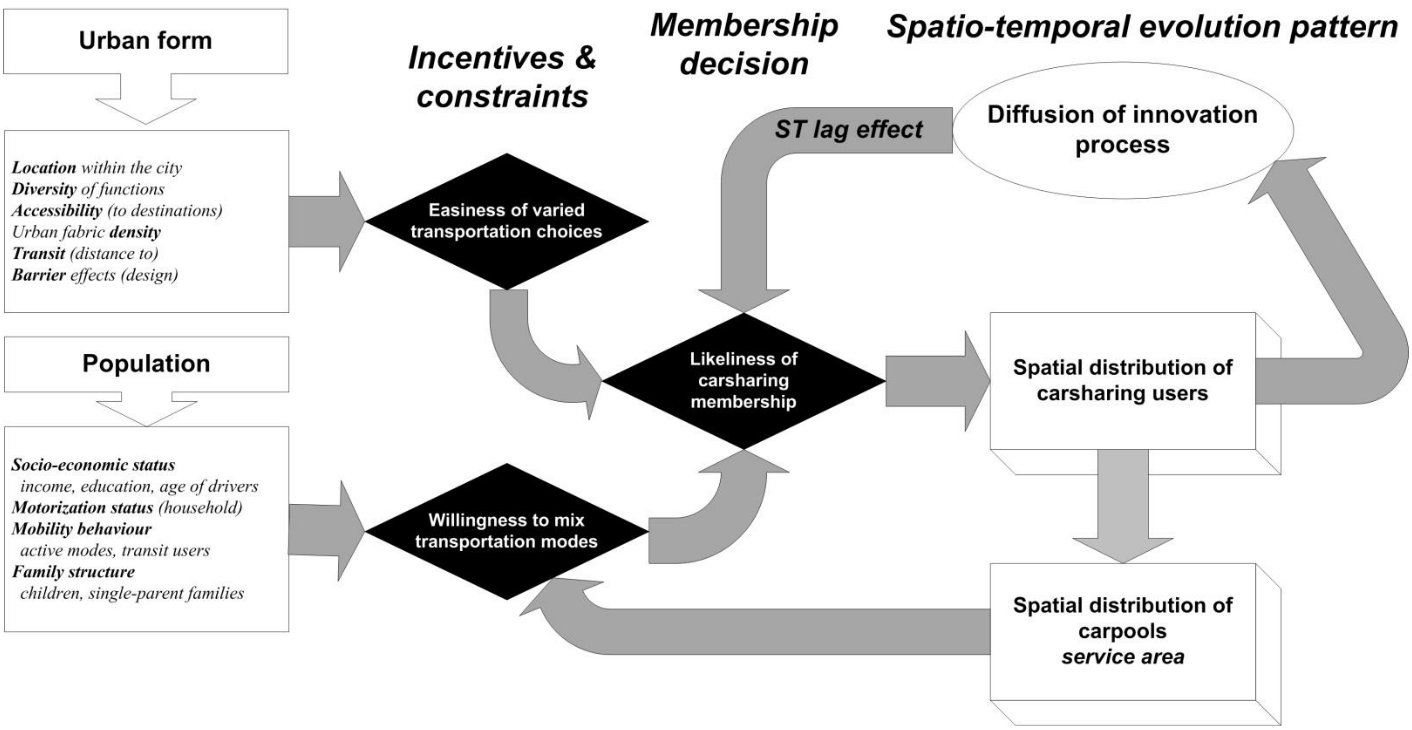
The rest of the article is structured as follows: Section 2 comprises the conceptual framework and the research hypotheses; Section 3 expands on the membership data, the characterization of urban areas, and the analysis methods; Section 4 shows the regression results; Section 5 presents and discusses findings; and the conclusion discusses the implications of the empirical results and suggests avenues for future research.

2. Conceptual framework

The theoretical framework of this research is built on three principles (Figure 2): 1) at the local level, carsharing membership rates (market coverage) should normally be related to motorization, mobility behaviour, socio-economic status and neighbourhood attributes; 2) neighbourhood effects can be summarized using Cervero's 5D: density, diversity, design, destination accessibility and distance to transit; 3) carsharing membership is an emergent behaviour that can be modelled as an innovation diffusion process using Hägerstrand's model (spatio-temporal lag effect).

After a start-up phase that generally occurs for unspecified reasons, but in a suitable place, the number of carsharing subscribers grows more rapidly in places where socio-economic conditions and the urban form offer the best environment to compete with car ownership. From this point on, the phenomenon spreads step by step through an imitation process generating waves of innovation. In order for carsharing to reach maturity, a city must provide basic conditions: 1) prevalent urban sprawl leading to overall car dependency for most citizens (whereby cars are needed to reach remote locations with specialized services); 2) a fairly good public transit system (that can be used to travel on a regular basis); 3) availability of many services and workplaces that can be reached by foot or transit (enabling diversified modal choice); 4) neighbourhoods with suitable density in order to justify parking lots for shared cars (and/or on-street parking constraints for car owners); 5) a population that sometimes needs to travel by car, but that is also willing to mix transportation modes for economical or ideological reasons; and last but not the least 6) enthusiastic people to start and operate the service (or business incentives). These preconditions lead to identification of the neighbourhood and socio-economic factors that result in motorization being replaced by carsharing at the individual and household levels, and that also generate a pool of potential subscribers at the neighbourhood level. The questions that then arise are: What is the extent of the neighbourhood effect? Is it different in the initial stages? How does it eventually expand and develop with membership growth? Is it a continuous or discontinuous diffusion process? At each step, what is the effect of the location of the parking lots (or previous stage membership) on the probability of increasing membership in a given area?

Figure 2. Conceptual framework



2.1 Characteristics of the target population

A portrait of carsharing users has been drawn up in several studies from Europe (Biau, 1991; Green, 2001; Flamm, 2008; Nobis, 2006), the United States (Cervero, 2003, 2004; Katzev, 2003; Shaheen et al., 2000, 2006, 2009; Shaheen and Meyn, 2002), and Québec (Robert, 1996; Tecsult, 2006; El Fasi, 2009; Grasset, 2009). The standard profile of North American carsharing users was depicted through a survey of North American carsharing organizations (Burkhardt and Millard-Ball, 2006) (Table 1).

Table 1 Characteristics of North American carsharing users

CHARACTERISTIC	ALL RESPONDENTS (CANADIANS AND AMERICANS)	CANADIAN RESPONDENTS ONLY
Age	• 37.7 yrs (mean) • 35 yrs (median)	• Higher representation of the 25-34 age bracket
Revenue	• More than $60,000 (for 50% of respondents)	• $20,000-$60,000 bracket strongly represented
Education	• Majority had a high level of education (bachelors or more) • Less than 2% did not have a community college diploma	• Majority had a high level of education (bachelors or more) • Less than 2% did not have a community college diploma
Gender	• A few more women (57 vs. 43 %)	• A few more men (52% vs. 48%)
Size of household	• 64% of people lived with at least one other person • Average household size of 2.02 people	• 71% of people lived with at least one other person
Car ownership	• 72 % of households did not own a car	• 87% of households did not own a car

Generally speaking, a typical carsharing user is in his or her 30s, has a high level of education (university), and does not, for the most part, have a car. The development potential of carsharing in a neighbourhood would thus seem to be inversely proportional to the motorization rate of households. As mentioned by Burkhardt and Millard-Ball (2006), the geographical and socio-demographic markets are undeniably linked. In other words, there are certain common user characteristics associated with the place of residence. They list, among others, the number of people per household (a high proportion of single people often fosters service growth) and the transportation method used to get to work: a neighbourhood where people go to work on foot has a higher growth potential than a neighbourhood where people go to work alone in a car (Millard-Ball et al., 2005).

2.2 Automobile use by carsharing members

The relationship between carsharing and automobile use is not entirely clear. On the one hand, some people argue that most users do not initially own a car and that it is the service which increases car accessibility and usage which would not otherwise have occurred. On the other hand, the alternative viewpoint says that the carsharing's billing format increases the awareness of the real costs involved in car use, which thereby limits its usage and the desire to buy one's own car. One year after *PhillyCarShar*e was founded, Lane (2005) measured a monthly increase of 29.9 vehicle miles traveled (VMT) for members who did not have access to a car before the service began, whereas the VMT of members who gave up their car decreased by several hundred miles. Cervero's work with *City CarShare* (2003, 2004) likewise tended to show that, in the long term, there is a reduction in the kilometres carsharing members travel by car (Cervero and Tsai, 2004: 126). Jemelin and Louvet (2007) measured a one-half reduction in monthly distance traveled (from 1040 km to just under 500 km, including carsharing). A comparative study of travel methods among a sample of carsharing members and car owners in Québec City confirmed that the members' choice of transportation was much more diversified and that they only used the car sporadically. In Québec City, nearly 50% of the members use shared cars less than twice a month and the modal share of cars for commuting is below 2.5% (Alexandre, 2010).

As concerns car ownership, Martin et al. (2010) showed that carsharing significantly reduced the rate of ownership by users. According to the estimations of these authors, who analyzed the answers from a North-American survey, a self-service car replaced from 9 to 13 conventionally-used cars, and this despite the fact that the majority of the carsharing members did not own a car before becoming a member. After one year of service, each *PhillyCarShare* vehicle had replaced approximately 22.8 cars on the road (Lane, 2005). In their report to the Transportation Research Board of National Academies, Millard-Ball et al. (2005) likewise identified a motorization rate that was lower than average in neighbourhoods that were most receptive to the carsharing programs. Finally, in Paris, 91% of households with carsharing membership did not own an automobile, compared to 59% before becoming members (Jemelin and Louvet, 2007).

For carsharing users, a lower investment in car ownership probably leads to a more diversified set of modes of transportation to get to activity locations. The low fixed costs motivate them to compare various combinations of destinations and transportation modes when planning to go to activities (e.g. walking to a nearby shop, riding a bus to a shopping centre or driving to a big box). In contrast, car owners likely overuse their vehicle because they want to absorb fixed costs and to take advantage of a car they have already paid for. These peculiarities in cost structures likely imply differences in behaviour between car owners and carsharing users, leading, in theory, to a higher use of public and active transportation modes among the latter, thus encouraging greater interest on the part of planners and policy makers in this emergent behaviour.

2.3 Urban form and carsharing

The urban form of a city and its neighbourhoods and the transportation habits of the resident populations are undeniably linked. The goal of several schools in modern urbanism, such as *new urbanism* or *transit-oriented development*, is to counter the "automobilization" of our societies by modifying the density, diversity, and design parameters of urban environments (Cervero and Kockelman, 1997: 199; Handy et al., 2005: 427). This is the famous 3-D model (density, diversity, design) proposed by Cervero and Kockelman (1997). The main objectives are for mobility to become less motorized and for car travel to occur over shorter distances with more people per vehicle. In the long term, carsharing supporters also hope to raise efficiency of car use.

This article takes particular interest in the link between carsharing and urban density, which is, in the North American context, often a characteristic of central, more populated neighbourhoods. Cervero and Kockelman (1997: 217) also determined that there was a link between urban design elements and trips not related to work: in places where the streets are aligned in a grid system typical of dense, central neighbourhoods, there are less solo trips by car. Often related to population density, diverse urban services (restaurants, grocery stores, etc.) also have a tendency to reduce the number of kilometres traveled in a car (Cervero and Kockelman, 1997: 202). It is in this type of environment that carsharing progresses best, since it provides a sufficiently large number of potential users in neighbourhoods where car ownership rates are low (Tecsult, 2006). In the same vein, Millard-Ball et al. (2005) suggested that a density of five living units per acre (or 10 units per hectare) is a minimum for the successful establishment and growth of a carsharing organization.

It is moreover in these high density sectors that the efficient development of public transportation most often occurs. Cervero et al. (2009) thus added two dimensions (distance to transit and destination accessibility) to make a 5D model. The complementary nature of carsharing and public transportation services is, according to several authors, an essential element in the establishment of the former (Robert, 2005; Nobis, 2006) and its diffusion (Millard-Ball et al. 2005). Carsharing also helps to keep the public transportation clientele from declining by making cars accessible, thereby reducing the need to buy a car by meeting less frequent demands. Indeed, a good public transit system decreases the need to use a car and, in turn, the need to own one. However, Stillwater et al. (2009) have called this relationship into question, stating that, since studies of carsharing have always implicitly linked density and the usage of alternative transportation methods by subscribers, they might have influenced *a priori* the choice of parking locations by carsharing organizations, creating a process of self-selection. These authors therefore studied the complementarity of carsharing use and public transportation possibilities by differentiating these possibilities. Their results indicated that there was a positive relationship between car sharing demand and the availability of light rail (bus and subway excluded), but that the relationship was negative between car sharing demand and the availability of regional rail, possibly because of a lack of carsharing parking lots close to train stations. They thus concluded that carsharing and local public transportation are complementary but that carsharing and regional trains are substitutes for each other.

Lastly, destination accessibility represents the degree of accessibility to activities outside of the neighbourhood through other transportation methods than the car, such as travelling to one's workplace by bus. It is nonetheless important to take people's attitudes into account. In a quasi-longitudinal study in which attitudes concerning transportation and demographic factors were taken into account, Handy et al. (2005) succeeded in demonstrating that there was a causal relationship between the built environment and transportation behaviour: better accessibility to destinations would seem to be related to less automobile use. According to Nobis (2007), studying carsharing necessarily entails examining multimodality and intermodality. Since it is able to interact with most other means of collective and active transportation, carsharing might be able to play a central role in a cocktail of urban transportation (Britton, 1999).

2.4 Hägerstrand's innovation diffusion model

Being a carsharing participant can be considered as an emerging behaviour that can be modeled through Hägerstrand's (1967) innovation diffusion model. In the 1930s, Hägerstrand observed a clear proximity effect in the spatio-temporal pattern of adoption of subsidized grazing improvement and other cases of innovation in agricultural management by Swedish farmers. He found that communication within the local farming community was a more powerful agent of diffusion than public announcements which disseminated information in a dispersed pattern across rural space. Hägerstrand's innovation diffusion model has since been re-examined, most notably in the retail sector (Allaway et al., 2003), multi-agent simulations (Daudé, 2004), political geography (Erlingsson, 2008), and the diffusion of sustainable farming innovations to produce non-market goods and ecosystem services (van der Horst, 2011).

Hägerstrand's innovation diffusion model is based on an object requiring diffusion (in our case, carsharing membership), which spreads out from propagation sites to potential receivers, as well as through interaction mechanisms between transmitters and receivers (Pumain and St-Julien, 2001). In our study of carsharing, the strength of transmission sites is approximated by the number of members, with the receivers corresponding to people with driver's licenses (drivers) 21 years old and over.[1] When these contacts are stable and persistent over time and space, it is possible to correctly describe all diffusion in the geographical space, whether it be at the macro scale where the hierarchy of places had the greatest influence on diffusion, or at the micro scale where spatial contiguity has priority. According to Hägerstrand's model (1967: 134), there are three stages in innovation diffusion:

I. Local concentrations of initial acceptances
II. Radial dissemination outward from the initial agglomeration, accompanied with the rise of secondary agglomerations, while the original centers simultaneously continue to condense
III. Cessation of growth

In the present case, we might assume that early adopters of carsharing were already open to the idea of using alternative transportation methods (Scott and Brooks, 2003). Hägerstrand (1967: 138) noted that "the distribution of information is synonymous with the distribution of informed persons; the cultural element in question cannot be found where information does not exist; and the existence of information about innovation does not in itself guarantee acceptance". Nobis (2006: 96), who studied the attitudes and perceptions concerning carsharing in Germany, tended to agree with Hägerstrand, stating that there is a large distinction between knowledge of a service, open-mindedness about it, subscribing to it and using it.

The modeling of the innovation diffusion process is generally based on a probability function that describes population growth in a space with limited resources (potential adopters) and on basic principles of spatial interaction (effect of mass, distance, barriers, etc.), with the time of the process being categorized into discrete units (Pumain and St-Julien, 2001). In this paper, we use Poisson and negative binomial regressions to model the spatial diffusion of carsharing membership in Québec City, to test for significant relationships with the urban form and socio-economic attributes of potential users, and to assess its potential for further development. What is the diffusion potential? Is it highly dependent on the urban form, restricting deployment only to higher density neighbourhoods with good accessibility to services and workplaces? Moreover, since access to car pools implies walking (or riding) to fixed-locations, should we expect somewhat of an "oil stain" diffusion process on membership because cars are allocated on a proportional basis (e.g. 1 car per 20 members living around a pool)?

Hypotheses are: 1) various features of the urban form enhance or impede the deployment of carsharing services; 2) carsharing occupies a niche market and is attractive only for specific segments of the population; and 3) the evolution of carsharing follows innovation wave principles established by Hägerstrand.

There are several advantages to testing hypotheses about the relationship between urban form and the spatial diffusion of carsharing memberships in Québec City: 1) It is the oldest city in Canada having still a large European-style centre built before the introduction of cars (high-density,

[1] At *Communauto*, the carsharing membership contract states that the enrolling member must be at least 21 years old.

urban fabric with narrow streets and mixed land use); older neighbourhoods developed during car diffusion (1920-1960, mid-density with large streets and mixed land use); and new suburbs which are the result of urban sprawl following car domination (post-1960, low density with a sprawling expressway network and segregated land use). Nineteen years after its opening, *Communauto* is well established in the first two types of neighbourhoods and is now extending its services into the suburbs. 2) Its historic centre aside, Québec City is a rather typical Canadian city, thus providing a relevant test region for assessing potential of carsharing development in Canada. 3) An efficient bus service is operated by a public transit company (RTC). During the study period, it included two rapid-transit bus routes called "Metrobus", which use bus-and-taxi-only lanes and have a 5-15 minute frequency[2]. 4) Finally, there is a strong demand for greater knowledge about the relationship between mobility strategies and urban planning for sustainable development, as Québec City presented its mobility plan in 2010 to guide the sustainable development of urbanization and transportation for the next 20 years.

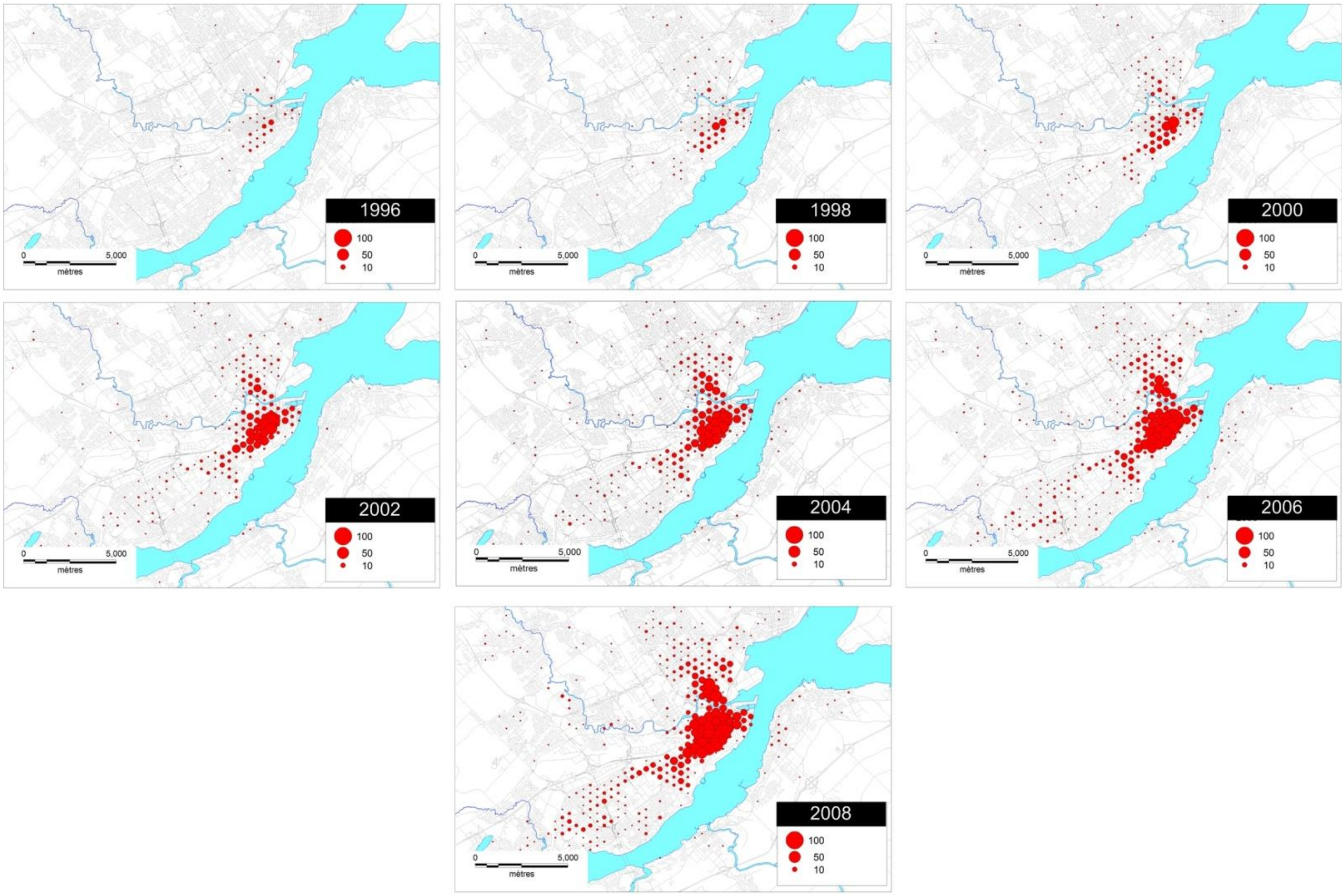
3. Carsharing diffusion and modeling approach: material and methods

A GIS was used to manage a comprehensive spatio-temporal database that was needed for mapping diffusion processes and for handling urban form and time-varying socio-economic indicators. For modeling diffusion, we controlled for spatial constraints (access to the carsharing service) and imitation (increasing visibility), as well as for the socio-economic determinants of the decision to join (see Appendix for the data sources used).

We were given access to a full listing of Communauto's membership from 1994 to 2008, which provided the following data for 4,764 current and previous members living in Québec City: joining date, age, gender, residential postal code and, when applicable, withdrawal date. Using Canadian postal codes, the members' houses were located to the nearest urban block using geocoding. Using a tessellation made of regular grid cells (2,040 hexagons with a 250 metre radius), we computed the total number of active members (before a possible withdrawal) on a yearly basis (December 31). The Communauto members, who were more concentrated in the central neighbourhoods where the phenomenon was born, have progressively moved out across the city, following the evolution of the spatial distribution of the parking lots, of which there were 85 in 2010 (Figure 3). There was thus a consolidation of the main membership zones as well as diffusion into the neighbouring sectors, which implies that diffusion is still in the second stage as defined by Hägerstrand.

[2] There are now four Metrobus lines.

Figure 3. Evolution of carsharing membership in Québec City, 1996-2008



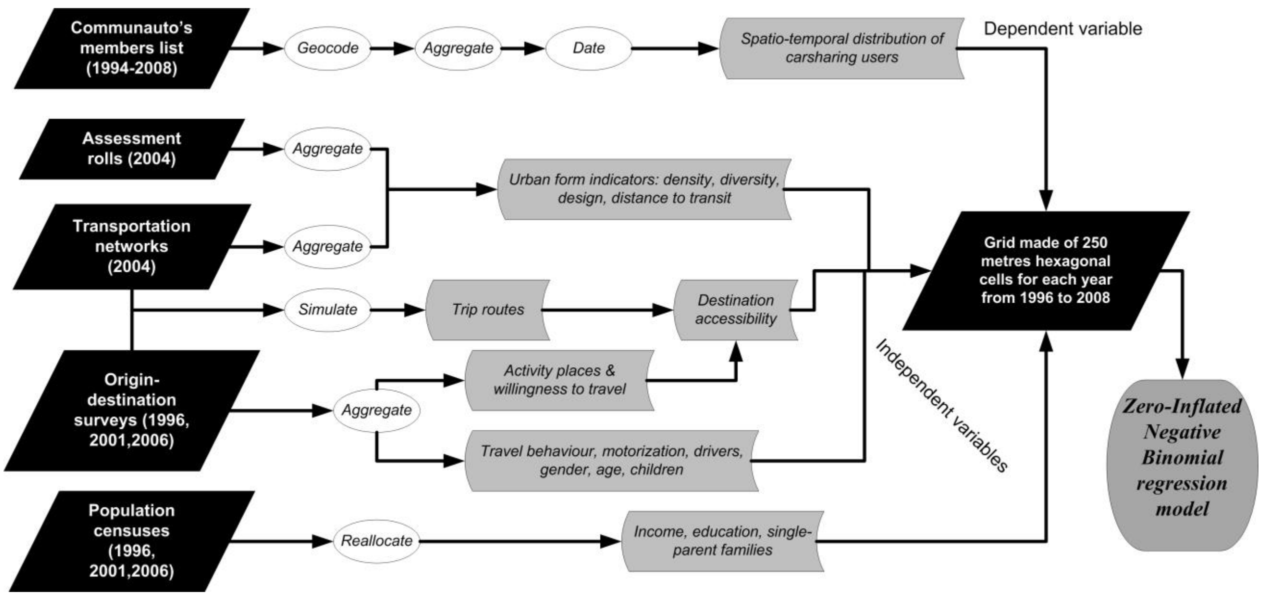
However, relying on aggregation into a grid tessellation has its drawbacks that should be mentioned. The first issue is known as the modifiable area unit problem (MAUP), originally identified by Openshaw and Taylor (1979; 1981). Any partition of land into discrete area units introduces bias potentially leading to instability of correlation coefficients based on the appropriateness of tessellation and scale. Thus, appropriate care should be taken when choosing the size and shape of land units. Census units have been a natural choice. But these units are highly variable in size and shape, leading to significant problems with regards to measuring proximity relationships; units are smaller at the center and grow further away. For this study, while being not perfect, hexagonal grid cells offer the best compromise because they are relatively insensitive to grid orientation (shape is close to circle) and they allow easy computation of incremental diffusion rates around any point in space. The second issue is related to what is called “ecological fallacy” (Robinson, 1950), meaning that relationships found using aggregated data could lead to false interpretation if inappropriately transferred at the level of individuals. Due care should be taken when drawing conclusion from aggregated models. In this study, we examine the deployment of carsharing from the point of view of urban planning, which implies measuring the neighbourhood effects rather than potential members’ attributes. The choice was made for a 250 meter radius because it provides an appropriate scale to handle variations of socio-economic attributes, accessibility and proximity over the urban space, while allowing for measuring the local shape of the innovation waves.

Using spatial interaction relationships (adjacency and proximity) among neighbouring cells, we estimated the incidence rate of membership (carsharing members per 10,000 driving licence holders 21 years old and over) for successive rings (0-500; 500-1,000; 1,000-1,500; and 1,500-2,000 metres). Then each tuple of the year-grid cell was associated with the carsharing membership of the previous year in the neighbouring cells, in keeping with the area of influence of Hägerstrand's innovation diffusion model. This provided data to do regression analysis of the spatial diffusion of the number of carsharing members in each cell (count data), taking into account potential members at time *t* (exposure) and membership rates in neighbouring cells at time *t-1*. However, that implies a multicollinearity issue among radiuses linked to spatial autocorrelation (SA) inherent to innovation waves when incidence is measured in absolute terms. Thus, we combined one incidence rate (scale effect) with three gradients (slope or shape effects) removing SA from the data. For this case, the most efficient combination was to keep incidence rate in the remote ring (1,500-2,000 meters) and to compute slopes between successive inner rings (0-500 versus 500-1,000; 500-1,000 versus 1,000-1,500; 1,000-1,500 versus 1,500-2,000). Moreover, this scale-slope strategy lowers multicollinearity.

Poisson and negative binomial models are appropriate when counts are skewed (rare event), which corresponds to carsharing membership. We conducted regressions to model the number of carsharing subscribers using the Poisson distribution, allowing the intensity parameter μ (Poisson) or μ and α (negative binomial) to depend on covariates (Cameron and Trivedi, 2008). The Poisson regression model is $y_i \sim Poisson(\mu_i)$ where $\mu_i = \exp(x_i\beta + offset_i)$ for observed counts y_i with covariates x_i for the *i*th observation (Cameron and Triverdi, 2008). The most common implementation of the negative binomial model is called mean-dispersion model in which individual outcomes are Poisson distributed, but there is an omitted variable v_i, such that $exp(v^i)$ follows a gamma distribution with mean 1 and variance α so that $\mu_i = \exp(x_i\beta + offset_i + v_i)$ and $exp(v^i) \sim \text{Gamma}(1/_{\alpha}, \alpha)$. The regression models were adjusted using Stata SE release 12. When appropriate, the goodness-of-fit (GOF) chi-square test confirmed the quality of adjustment. The Vuong (1989) test was carried out in order to check for model over-dispersion, leading eventually to selection of ZIP (zero-inflated Poisson) and ZINB (zero-inflated negative binomial) specifications (Cameron and Triverdi, 2008) to account for the excess zeros. Two kinds of zeros existed in our data, "true zeros," the cells without members but in which the carsharing service was available, and "excess zeros," the cells without members for which there was no nearby service. The ZIP and ZINB models estimate two equations simultaneously, one for the count model and one for the excess zeros. The inflated part specifies a list of variables that determines whether the observed count is zero, which can be interpreted as the probability of being located, at a given date, outside of a service zone. This avoided the bias that would be created if all the cells were considered to have equal service access. Finally, the Akaike (1974) information criterion (AIC) and Schwartz (1978) Bayesian information criterion (BIC), are used to provide a measure of the goodness-of-fit of a statistical model, with the model having the minimum AIC and BIC being the best (Davidson and MacKinnon, 2004).

Census data, municipal assessment rolls, topological transportation networks, and indicators of urban form computed using Origin Destination (OD) surveys (1996, 2001 and 2006) were included for each cell in order to assess the effects of 5D, travel behaviour indicators, and socio-economic factors on the marginal probability of increasing the number of carsharing subscribers at each location in space and time. Socio-economic covariates need to be estimated on a yearly basis because they evolve rapidly; other covariates (e.g. accessibility, urban form indicators) evolve very slowly (from decade to decade) and it was sufficient to estimate a mid-period value for each grid cell. Multicollinearity tests (variance inflation factors) were conducted in order to select lowly correlated covariates. In the final models, only two correlations are higher than 0.5. At the end, we were able to estimate data for 23,103 year-grid cells with estimates for car drivers 21 years old and over obtained from expanded OD surveys. Some cells were excluded because they were unpopulated or the average household income was missing from Census data. Figure 4 describes data bases and their integration in the spatio-temporal modeling procedure. The Appendix shows the main data sources.

Figure 4. GIS data modeling procedure



OD surveys relied on large samples of households (about 10% of the population) and were conducted by the MTQ (Ministry of Transportation of the Province of Québec) and the RTC (Réseau de Transport de la Capitale, Québec City's public transportation network) every five years. They describe trips made, transportation resources (driver's license, car ownership), home location (postal codes), household structure (age of members), and activity sites. OD surveys help to create indicators like proportion of non-motorized households and partially-motorized (cars < drivers) ones and mobility behaviour. In short, the peripheral sectors of Québec City were often characterized by considerable motorization and, as a corollary, by a higher rate of automobile use.

Topological transportation networks were used to model car, pedestrian and bus routes in 2001 using impedance and turn penalties in TransCAD (free traffic flow modeling) and to calculate accessibility indexes. These "standardized" accessibility indexes (between 0 and 1) compared, for each residential location, the service opportunities located within acceptable travel times; acceptability thresholds were estimated from the likelihood of traveling around the city (by type of person/household) and by considering the distribution of activity places in the city (Thériault et al., 2005). Their computation involves a four-step procedure done separately for each combination of trip purpose and transportation mode: 1) aggregate the expanded number of actual trips attracted by any destination cell in order to estimate attractiveness (potential model); 2) analyze the actual distribution of trip durations for each combination in order to estimate actual willingness to travel of people using the median and the 90th percentile to set suitability thresholds; 3) for each residential cell, aggregate attractiveness of destination cells considering suitability thresholds (fuzzy logic: 1 if below median distance; 0 if above 90th percentile; interpolation in between); 4) compare each cell result to the best regional score and rank between 1 (best) and 0 (null) accordingly. Since the distribution of service opportunities and the configuration of transportation networks evolve very slowly and the modeling procedure is computation intensive, it was considered sufficient to model accessibility at mid-period (2001).

Municipal assessment rolls from the Communauté métropolitaine de Québec (CMQ, metropolitan community of Québec City) described all real estate properties in 2004, showing land use, housing units, building values and land area. Examples of such 5D indicators were residential density, accessibility to work and commercial places using cars, buses or active transportation modes, the ratio of commercial versus residential land uses (or building values), design (estimated by distance to major, controlled-access highways) and distance to transit. Finally, socio-economic factors extracted from Canadian population censuses (Statistics Canada) were controlled for using indicators such as household income, family structure, university diploma proportion, etc.

Before the results are presented, a few methodological precisions should be made. First, we excluded the first two years of carsharing in Québec City (1994 and 1995) from the model, because the phenomenon had not yet reached the size of a public service and its organization depended primarily on the social contacts of its founder. Second, the model had a scale variable, the number of drivers 21 and over, which represented its capacity constraint. Given that we had the number of members for every year from 1996 to 2008 (dependent variable) and that we only had the number of drivers for 1996, 2001 and 2006 (OD survey years), we employed a linear adjustment in each cell to smooth out the number of drivers 21 and over for every year from 1996 to 2008, based on the OD survey data for 1996, 2001, and 2006. Third, for the socio-economic variables coming from the OD survey and from the Statistics Canada census (motorization, modal split, gender, age, household structure, education), we tested two assignments options: 1) apply the 1996 data to the years 1997 and 1998, the 2001 data to the years 1999, 2000, 2002, and 2003, and the 2006 data to the years 2004, 2005, 2007, and 2008 (5-year step assignment); 2) for each cell linear interpolation of values for years in between census and OD survey years. The mean household revenue variable (weighted according to the number of households) was estimated in constant 2002 Canadian dollars (which corresponds to the mid-period) for every year beginning with the 1996 census data and Statistics Canada's Consumer Price Index (CPI). Finally, all the data coming from OD survey samples were corrected with expansion factors based on the structure and location of the city's population as measured by the Canadian census.

Table 2 describes the model variables and their expected effects on the dependent variable (number of members for each year from 1996 to 2008). The table concludes with variables that take into account the non-availability of the service (i.e., zero-inflated model variables). These are the variables that estimate the phenomenon's maximum extent at a given date.

Table 2 Description of variables and expected effects on dependent variable (carsharing members among drivers 21+)

Variable groups	Variable name	Description	Expected effect [a]	Mean value/ *Frequency*[b]	Standard deviation [b]
Carsharing diffusion process (year before)	Gradient Yb < 500 m vs. 500-1,000 m	Gradient for membership rates for < 500 m vs. 500-1,000 m	(+)	0.251	0.751
	Gradient Yb 500-1,000 m vs. 1,000-1,500 m	Gradient for membership rates for 500-1,000 m vs. 1,000-1,500 m	(+)	0.345	0.860
	Gradient 1,000-1,500 m vs. 1,500-2,000 m	Gradient for membership rates for 1,000-1,500 m vs. 1,500-2,000 m	(+)	0.437	0.922
	Membership rate Yb 1,500-2,000 m	Membership rates for preceding year in neighbouring cells 1,500 to 2,000 m away	(+)	11.254	36.073
Density	Street length / residential area	Street length per hectare of residential land (km/ha)	(+)	0.354	0.904
Diversity	Residential land (ratio)	Proportion of land developed for residential purposes (0..1)	(+)	0.775	0.277
	Land use diversity	Ratio of commercial value to residential value	(+)	0.259	3.255
Accessibility to destinations	Workplaces by bus	Accessibility to jobs by bus (0..1)	(+)	0.389	0.351
	Workplaces by foot	Accessibility to jobs by foot (0..1)	(+)	0.087	0.147
	Shopping by foot	Accessibility to stores by foot (0..1)	(+)	0.118	0.128
Design – barrier effect	Controlled-access highway 0-250 m	Located less than 250 m from a major highway (dummy)	(-)	***4579***	
	Controlled-access highway 250-500 m	Located between 250 m and 500 m from a major highway (dummy)	(-)	***2486***	
Distance to rapid transit bus (RTB)	Metrobus 0-250 m	Located less than 250 m from a rapid transit bus (dummy)	(+)	***2397***	
	Metrobus 250-500 m	Located between 250 m and 500 m from a rapid transit bus (dummy)	(+)	***2160***	
Socio-economic status	Household income ($000)	Annual mean household revenue in 000's of constant 2002 dollars	(-)	60.98	19.70
	University diploma (ratio)	Percentage of people 20 and over with a university degree	(+)	0.243	0.140
	Drivers 31-60 (ratio)	Proportion of drivers 21 and over who are from 31 to 60 years old	(+)	0.672	0.224

	Drivers 61 + (ratio)	Proportion of drivers 21 and over who are 61 or over	(-)	0.163	0.195
	Female drivers (ratio)	Proportion of drivers 21 and over who are female	(-)	0.489	0.122
Family structure	Families with children (ratio)	Proportion of households with children	(-)	0.139	0.188
	Single-parent families (ratio)	Proportion of single-parent families	(+)	0.142	0.078
Motorization	Non-motorized households	Proportion of non-motorized households	(+)	0.08	0.142
	One-driver households	Proportion of households with only one driver	(+)	0.260	0.232
	More drivers than cars	Proportion of households with a motorization deficit (drivers > cars and cars > 0)	(+)	0.277	0.224
Mobility behaviour of drivers 21+	Active modal share	Modal share of active transportation (trips by drivers 21 and over)	(+)	0.049	0.089
	Public transportation share	Modal share of bus (trips by drivers 21 and over)	(+)	0.032	0.062
Year of membership	Yr1997…2008	Year of membership (dummies)	(+)	***1396*** ***1743*** ***2040***	Yr1996-98 Yr1999-03 Yr2004-08
Zero-inflated model variables	Membership rate Yb < 2 km	Membership rate for the preceding year in neighbouring cells (< 2 km)		11.154	38.483
	Bus service	Bus service within walking distance, < 500 m (dummy)		***13654***	
	Accessibility to work by car	Accessibility to work by car (0..1)		0.546	0.270
	Bus pass rate Dr21+	Proportion of bus passes among drivers 21 and over (0..1)		0.040	0.068
	Dwelling unit density	Number of dwelling units per residential zoning surface area (ha)		27.063	33.027
	Coefficient variation income	Coefficient of variation in household income (ratio)		1.327	0.488

[a] Expected effect on the dependent variable (+ increase; - decrease the probability of becoming a member)
[b] Calculated at the hexagonal cell scale
Yb: Year before

4. Results and model adjustment

While Poisson, ZIP and ZINB regressions were adjusted, ZINB specification yielded better results. For the Poisson regression, the goodness-of-fit test indicates a good adjustment of the model to data (pseudo R^2 = 0.7428; BIC = 17532). However, the Vuong tests (zero-inflated versus standard) clearly indicate over-dispersion (11.68; $p < 0.001$), highlighting the importance of going to a zero-inflated specification, which was done using both the ZIP and the ZINB specifications. Finally, both the AIC and the BIC criteria indicate that the ZINB specification is better than ZIP (AIC of 15936 versus 16398; BIC of 16314 versus 16768), which is confirmed by the likelihood-ratio test of alpha. Therefore, ZINB specification was retained and Table 3 presents results. While the number of parameters appears high, one should remember that several coefficients belong to mutually-independent categories (dummies) of a unique variable: distance to transit, age of drivers, family structure, motorization, year yielding fixed effects, without risk of collinearity.

Table 3. Odds ratios of carsharing membership, Québec City, 1996-2008 – Zero-inflated negative binomial (ZINB) models using interpolated socio-economic data – dependent: number of members; exposure: car drivers 21 years and over

Variables	ZINB	Sig.
Carsharing diffusion process		
Gradient Yb < 500 m vs. 500-1,000 m	1.0544	**
Gradient Yb 500-1,000 m vs. 1,000-1,500 m	1.0336	
Gradient Yb 1,000-1,500 m vs. 1,500-2,000 m	1.1007	***
Membership rate Yb 1,500-2,000 m	1.0029	***
Urban form factors		
Density		
Street length / residential area	.9816	
Diversity		
Residential land (ratio)	1.3153	***
Land use diversity	.9783	
Accessibility to destinations		
Workplace by bus	2.4406	***
Workplace by foot	2.0855	***
Shopping by foot	.7314	*
Design (barriers)		
Controlled-access highway 0-250 m	.7005	***
Controlled-access highway 250-500 m	.8223	***
Distance to transit		
Rapid transit 0-250 m	1.5295	***
Rapid transit 250-500 m	1.2529	***
Socio-economic factors		
Socio-economic status		
Household income ($000)	.9844	***
University diploma (ratio)	20.5830	***
Drivers 31-60 (ratio)	2.0136	***
Drivers 61 + (ratio)	.7441	
Female drivers (ratio)	.8080	

Family structure		
Family with children (ratio)	3.2104	***
Single-parent families (ratio)	5.9015	***
Motorization		
Non-motorized households	7.5767	***
One-driver households	2.4821	***
More drivers than cars	1.4504	
Mobility behavior of drivers 21+		
Active modal share	2.9933	***
Public transportation share	.5752	
Time (fixed effect) - year		
1996 - Reference	1.0000	
1997	1.6046	**
1998	2.4105	***
1999	3.3701	***
2000	4.9839	***
2001	8.0658	***
2002	9.3436	***
2003	9.1623	***
2004	9.4302	***
2005	9.9209	***
2006	11.6692	***
2007	13.1836	***
2008	14.2680	***
Constant	.0000145	***
Zero-inflated		
Membership rate Yb < 2 km	.9257	***
Bus service	.6135	**
Accessibility to work by car	2.4517	*
Bus pass rate Dr21+	.0105	***
Dwelling unit density	.9827	***
Coefficient variation income	.5986	**
Constant	6.611255	***
Ln alpha constant	.1205704	***
Statistics		
N (grid cells-years)	23081	
Goodness-of-fit test		
LL (log-likelihood)	-7921.070	
AIC (Aikake Criterion)	15936	
BIC (Schwartz Criterion)	16314	
Pseudo R^2		
Vuong test zero-inflated versus standard	8.68	***
Likelihood-ratio test of alpha = 0	463.54	***

Legend: * P<0.05, ** P<0.01, *** P<0.001 ; n.s.: non significant

Table 4. Comparison of carsharing membership models using 5-year step versus interpolated socio-economic factors (23,081 grid cells-years)

	Log-likelihood	AIC	BIC
5-year step assignment			
Poisson	-8600	17278	17592
Zero-inflated Poisson	-8173	16437	16807
Zero-inflated negative binomial	-7935	15964	16342
Linear interpolation (yearly)			
Poisson	-8570	17218	17532
Zero-inflated Poisson	-8153	16398	16768
Zero-inflated negative binomial	-7921	15936	16314

While Table 3 presents results for the linear-interpolation of socio-economic covariates, 5-year step assignment was also considered, but was somewhat less efficient (Table 4). The specification of a model on a yearly basis was necessary to efficiently model spatial diffusion. However, in order to assure that interpolation does not jeopardize coefficients estimation, we compared the full model (1996-2008) with a model restricted to census years only. Results are shown in Table 5. As we can see, all coefficients of the yearly ZINB model falls within the 95% confidence interval of the census years ZINB model and all significant variables of the latter remain significant in the former. Moreover, it is also clear that the yearly ZINB is far more efficient to handle spatial and temporal covariates, which provides better adjustment of other covariates through narrowing confidence intervals.

Table 5. Comparison of yearly versus census years zero-inflated negative binomial (ZINB) models

	Census years ZINB (1996, 2001, 2006)				**Yearly ZINB**	
Variables	Coefficient	Sig.	95% Conf. Interval		Coefficient	Sig.
Carsharing diffusion process						
Gradient Yb < 500 m vs. 500-1,000 m	.0396		-.0370	.1163	.0529	**
Gradient Yb 500-1,000 m vs. 1,000-1,500 m	-.0131		-.1024	.0761	.0330	
Gradient Yb 1,000-1,500 m vs. 1,500-2,000 m	.0803		-.0085	.1691	.0959	***
Membership rate Yb 1,500-2,000 m	.0032	***	.0020	.0045	.0029	***
Urban form factors						
Density						
Street length / residential area	.0006		-.1013	.1024	-.0185	
Diversity						
Residential land (ratio)	.3216	*	.0061	.6370	.2741	***
Land use diversity	-.0063		-.1538	.1411	-.0220	
Accessibility to destinations						
Workplace by bus	1.0146	***	.5693	1.4599	.8922	***
Workplace by foot	.9615	***	.4741	1.4490	.7350	***
Shopping by foot	-.4692		-1.1469	.2086	-.3128	*
Design (barriers)						
Controlled-access highway 0-250 m	-.3171	***	-.4726	-.1616	-.3559	***
Controlled-access highway 250-500 m	-.2034	*	-.3709	-.0359	-.1956	***

Distance to transit						
Rapid transit 0-250 m	.3205	**	.1313	.5098	.4249	***
Rapid transit 250-500 m	.0880		-.1119	.2878	.2255	***
Socio-economic factors						
Socio-economic status						
Household income ($000)	-.0158	***	-.0231	-.0086	-.0157	***
University diploma (ratio)	3.1372	***	2.3890	3.8854	3.0244	***
Drivers 31-60 (ratio)	.7383	*	.1361	1.3404	.6999	***
Drivers 61 + (ratio)	-.0039		-.6513	.6436	-.2956	
Female drivers (ratio)	.1548		-.7965	1.1061	-.2132	
Family structure						
Family with children (ratio)	1.2860	*	.2273	2.3448	1.1664	***
Single-parent families (ratio)	2.1519	***	1.1826	3.1212	1.7751	***
Motorization						
Non-motorized households	2.2726	***	1.5207	3.0245	2.0250	***
One-driver households	.9562	**	.2616	1.6508	.9091	***
More drivers than cars	.4712		-.4043	1.3468	.3718	
Mobility behavior of drivers 21+						
Active modal share	.6589		-.2544	1.5722	1.0964	***
Public transportation share	-.6079		-2.0549	.8391	-.5531	
Time (fixed effect) - year						
1996 - Reference	1.0000				1.0000	
1997					.4729	**
1998					.8798	***
1999					1.2150	***
2000					1.6062	***
2001	2.0805	***	1.7702	2.3909	2.0876	***
2002					2.2347	***
2003					2.2151	***
2004					2.2439	***
2005					2.2946	***
2006	2.4234	***	2.0650	2.7819	2.4570	***
2007					2.5790	***
2008					2.6580	***
Constant	-11.6228	***	-12.634	-10.610	-11.1435	***
Zero-inflated						
Membership rate Yb < 2 km	-.1001	***	-.1542	-.0459	-.0772	***
Bus service	-.6646		-1.3804	.0511	-.4885	**
Accessibility to work by car	1.0934		-.5938	2.7806	.8968	*
Bus pass rate Dr21+	-5.8373	*	-11.308	-.3659	-4.5600	***
Dwelling unit density	-.0150	*	-.0283	-.0017	-.0174	***
Coefficient variation income	-.5018		-1.4114	.4080	-.5131	**
Constant	1.7982	*	.3811	3.2154	1.8887	***
Ln alpha constant	-2.1472	***	-2.5799	-1.7146	-2.1155	***
Statistics						
N (grid cells-years)	5169				23081	
LL (log-likelihood)	-1641				-7921	

AIC (Aikake Criterion)	3356		15936	
BIC (Schwartz Criterion)	3598		16314	
Vuong test zero-inflated versus standard	3.87	***	8.68	***
Likelihood-ratio test of alpha=0	80.51	***	463.54	***

Legend: * P<0.05, ** P<0.01, *** P<0.001 ; n.s.: non significant

5. Main findings and discussion

Comments are based on the ZINB model, but also hold for the ZIP specification. One has to keep in mind that the model is based on aggregated data and that statements should only apply at the level of cells, leading to potential ecological fallacy issue if used to describe the membership decision process. Most of variables' coefficients were highly significant (p<0.001). With regard to carsharing diffusion, the incidence rate ratios of a given year were modeled using the incidence rates of neighbouring cells (up to 2,000 m) during the previous year. The incidence rate ratio of the current year for the target cell was positively linked to the membership gradients (incidence rate slope of the previous year of neighbouring cells). To be more specific, likelihood of recruiting increased by 5.4% when <500 m equals 500-1,000 m and rose by 10.1% between 1,000-1,500 m and 1,500-2,000 m. The odds ratios of the carsharing diffusion process describe a spatial innovation diffusion wave in two forms: first, from close to close, starting in already "contaminated" cells; second, in a "piggyback" or wave form. Nonetheless, the carsharing membership rate was influenced by the presence of members from the preceding year in a radius of 1,500 to 2,000 m from the actual cell. This would seem to represent the outer limit of the effect, but this should be verified with larger radii in order to set the threshold more precisely. Figure 5 shows simulation of the diffusion based on the hypothesis of a single starting point.

Figure 5. Spatial trend model

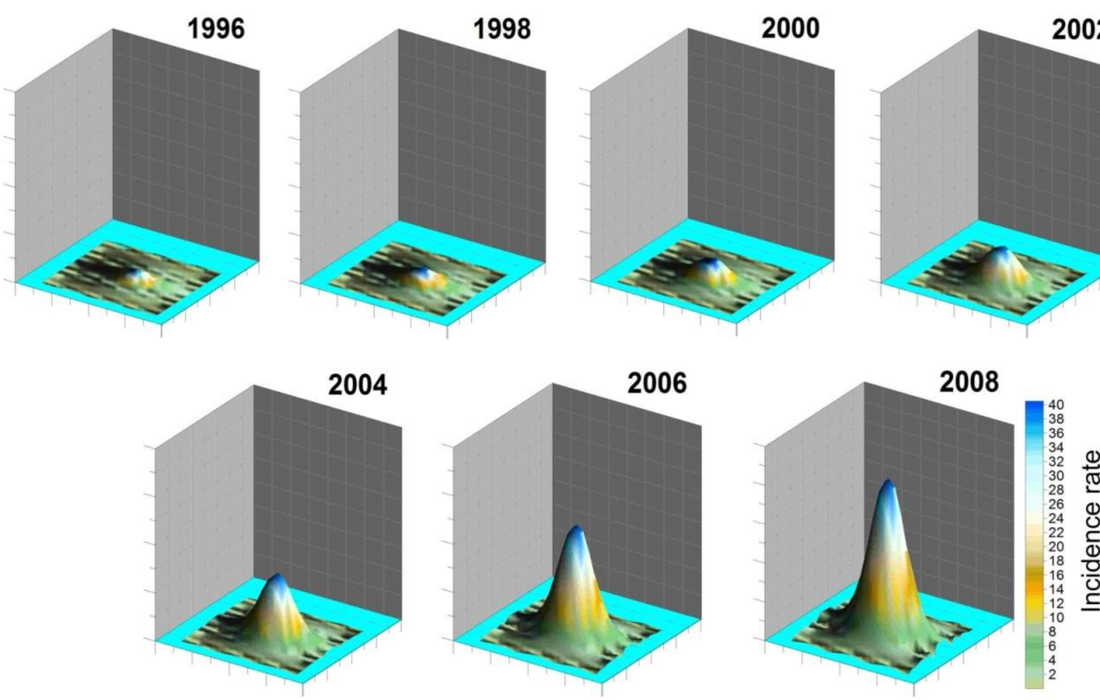
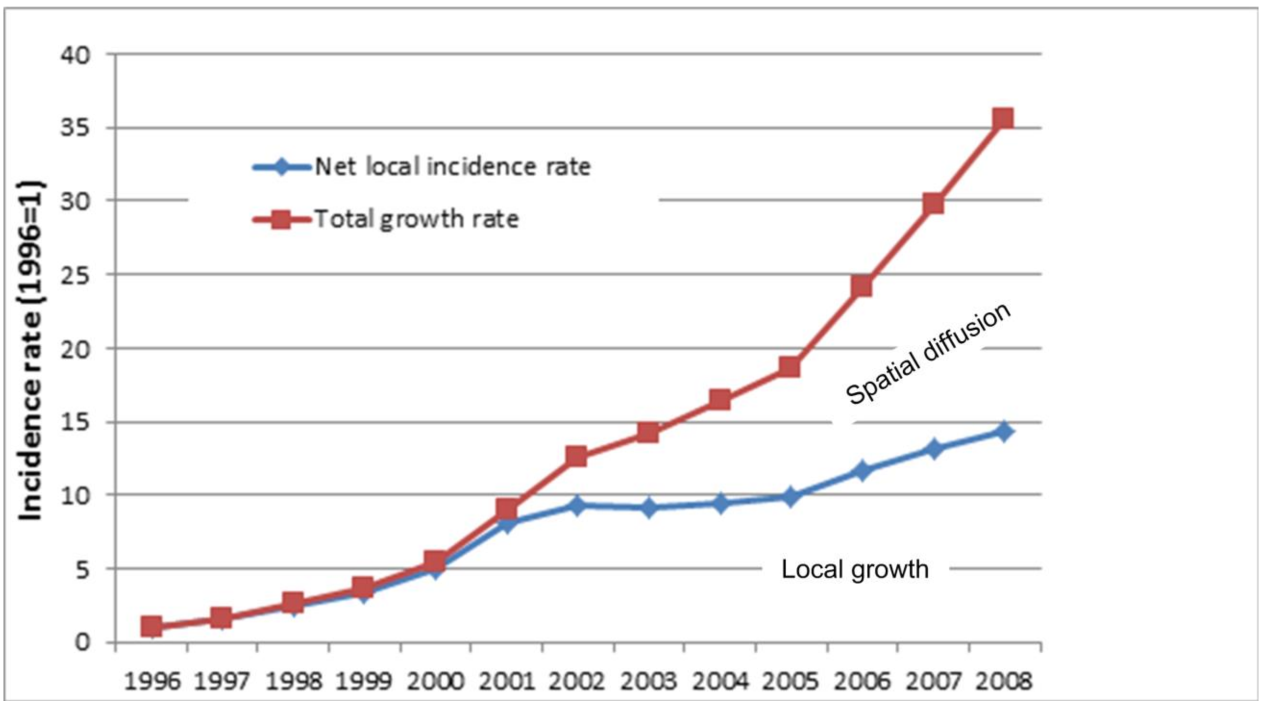


Figure 6 presents yearly local incidence rate after controlling for all the other model variables. These fixed effects depict average evolution of memberships within cells, showing significant increase of local incidence rates. The difference with the overall growth rate (regional level) could be attributed to spatial diffusion, which at the end of 2008, was still at its peak, meaning that the diffusion process was in phase II of Hägerstrand's diffusion model. Communauto was primarily linked to its founder's social network from 1996 to 1999 (mostly local growth in initial neighbourhood), but in the 2000s, its spatial diffusion began to pick up speed, with its first real acceleration occurring in 2001. This was followed by a fairly stable period from 2002 to 2005 (mostly spatial expansion), and then an acceleration beginning in 2006 (both local growth and spatial diffusion). This last year corresponded to the change in Communauto's subscription policy, namely the possibility of subscribing without becoming a member (without needing a $500 deposit).

Figure 6. Yearly growth of carsharing membership, Québec City (1996-2008)



The proportion of residential land use significantly increased the likelihood of recruiting carsharing membership—by 32%. But contrary to our expectations, density and land use diversity have no significant positive effect. However, as we will see later, density had a strong effect on the delineation of the service zone. The probability of recruiting members grew as accessibility to workplaces by bus and foot increased. The accessibility index ranged from 0 (no accessibility) to 1 (optimal for the whole region); it was respectively multiplied by 2.44 and 2.09 in the two cells with the best accessibility to workplaces for these two modes. Everything else being equal, better access by foot to commercial amenities slightly decreased the relative interest in carsharing. In Québec City, this could be related to the prevalence of large shopping centers and power centers in low density areas. With regard to neighbourhood design, proximity of a major, controlled-access highway decreased the chances of recruiting members. This was due to the classic barrier effect of major highways, which limit the possibility of getting around on foot (or otherwise at the local scale) and which reduce the number of easily accessible carsharing parking lots. Finally, having a rapid transit bus nearby positively influenced the rate of carsharing members. The likelihood of recruiting increased by 53% in the first 250 m and by 25% between 250 and 500 m. These results clearly showed the significant effect of urban form factors on the carsharing membership rate.

Certain socio-economic factors likewise had an influence. For example, a university diploma ratio of 1 (100% of people) would have increased the odds of recruiting carsharing members in the grid cell by 20.6-fold, while higher income lowered the odds by a rate of -0.01572 (ln 0.9844) per thousand dollars of income. A higher level of education was typically associated with more central employment (civil service, head offices, postsecondary education), with an environmental consciousness, and with a certain ability in calculating the real costs associated with owning a car versus using it in carsharing mode. Carsharing members were also familiar with the Internet and various online operations (e.g., reserving a car). Two membership profiles stood out: on the one hand, educated people who were ready to adapt their lifestyle; and, on the other hand, people whose low incomes made it difficult to buy a car (e.g., students).

Neighbourhoods with high proportions of drivers aged 31 to 60 were more likely to increase carsharing members than those with concentration of drivers from 21 to 30. However, contrary to our expectations, gender ratios had no significant effect. If a cell were inhabited only by single-parent families, its probability of recruiting members would have increased by 5.9 times, which is greater than the effect of families with children (3.2). All other things being equal, it was somewhat surprising to discover that high proportion of children did not seem to reduce carsharing membership. This is most likely due to the availability of baby seats in many cars in the Communauto fleet. Not surprisingly, recruitment would have risen by 7.6 times in neighbourhoods with no motorized households, which means that the chances of recruitment went up as the proportion of non-motorized households increased, carsharing clearly becoming a substitute for car ownership. Even though high proportions of households with a single driver increase membership (2.5), motorization deficit in households (more drivers than automobiles) did not have a significant effect, contrary to our expectations. This might indicate that the decision to subscribe to carsharing occurred at the household level and not at that of drivers, who had partial access to a car in motorized households. This calls into question the theory that carsharing could be a substitute for buying a second car, even though this reasoning was mentioned in Communauto's satisfaction surveys. Despite the positive influence of accessibility to workplaces by bus, the modal share of the bus played no significant role in the carsharing membership rate, whereas a saturated modal share (100%) in active transportation increased the probability of subscribing to the service by 3. In other words, the probability of residents becoming members was clearly greater in neighbourhoods where they walked a lot (whatever the reason) and where workplaces were readily accessible by bus.

With regard to the variables that explained the non-availability of service (excess zeros: outside of the service zone), and that potentially limited the spatial expansion of carsharing in Québec City, the most important variable was very good access to the workplace by car. The probability at the best locations (highly dependent on the configuration of the expressway network) was 2.5 times greater than that of locations inside of the service zone. Conversely, a high rate of drivers

21 and over with bus passes, the presence of a bus service less than 500 m away, greater social diversity (high coefficient of variation of revenue), a high membership rate less than 2 km away in the preceding year, and a high density of residential units (Figure 7) decreased the probability in a zone with no carsharing service (excess zeros). Consequently, the carsharing territory reflected the competition between the use of individual cars in sectors where the density and efficiency (measured by the monthly bus pass holders rate) of the public transportation system made it possible. The odds ratio of being outside of a carsharing service area in relation to insufficient residential density dropped to 0.5 at 40 residential units per hectare and reached 0.17 at 100 units per hectare. These estimates of the required density are probably pessimistic, since the models were calibrated using all the years the service has existed, including the initial phase from 1996 to 2000.

Figure7. Odds ratio of being outside of carsharing service area versus residential density

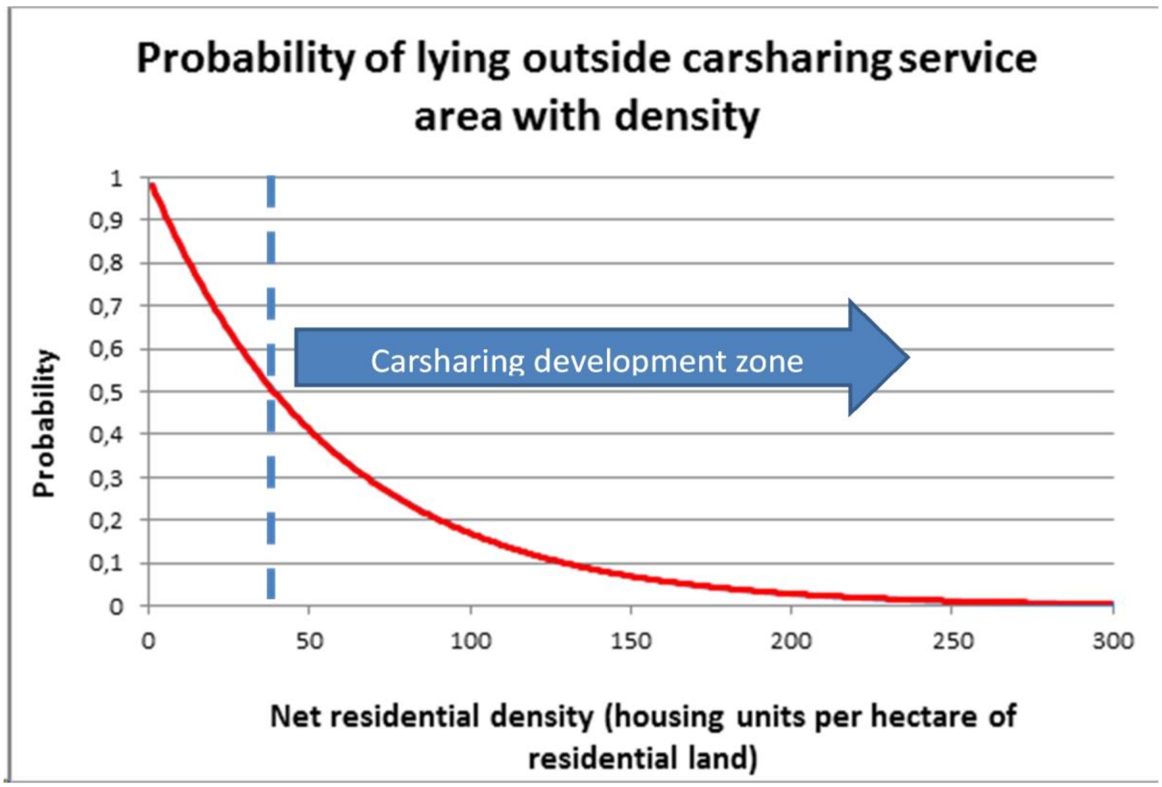
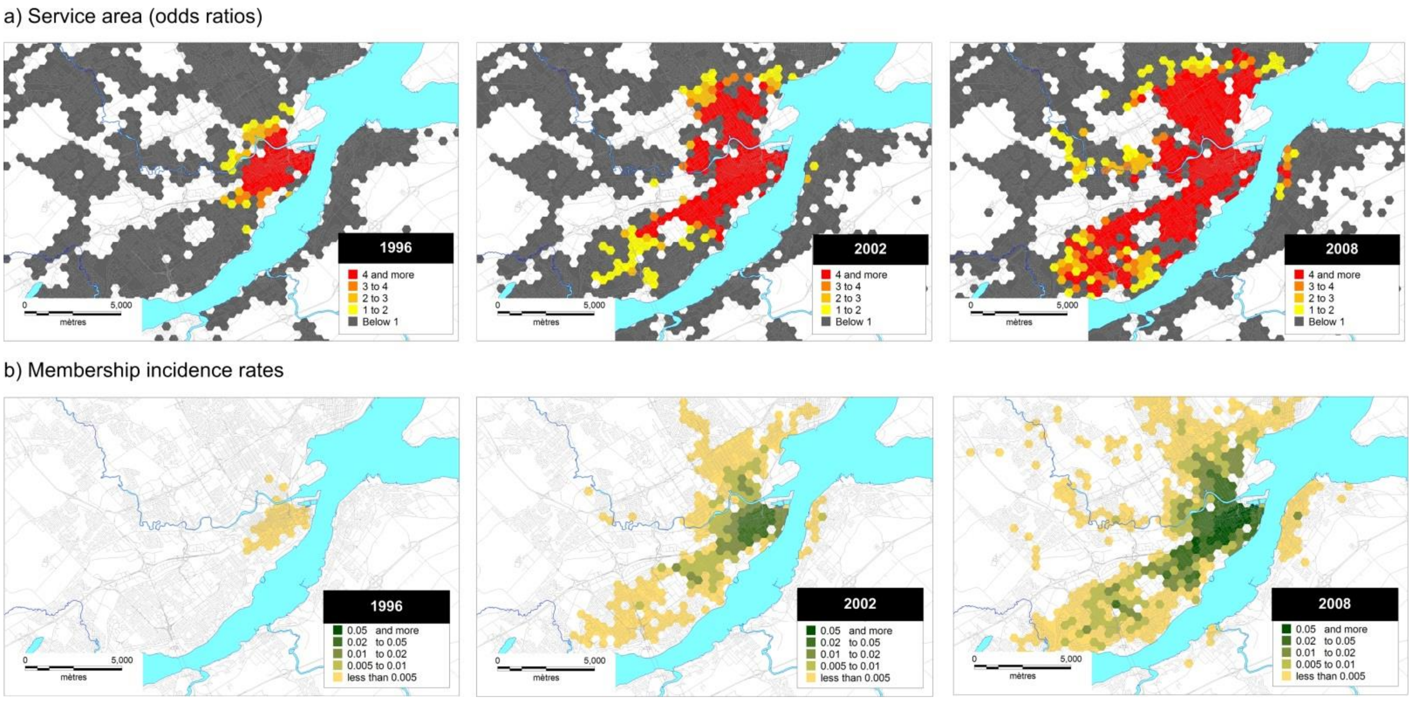


Figure 8 presents some examples of spatial structures predicted by the ZINB model. It shows, on the one hand, the growth of the service measured by the odds ratio and, on the other hand, the carsharing incidence rate (number of members/drivers 21 and over). In 2008, the incidence rate reached 0.1 in some cells located close to the very first (initial) cell; that is 10% of the potential members. Growth was still strong around the initial cell, thereby showing a growth potential that was not yet saturated, which is also true for the service area, which continued to spread from 2007 to 2008.

Figure 8. Values predicted by the ZINB model (service areas and incidence rate)



It is difficult to compare our results with those obtained in previous studies because on the one hand, we were interested in carsharing membership and not its use and, on the other hand, there are large variations in the way socio-economic factors and especially urban form are measured. Overall, however, our results confirmed that urban form characteristics influenced carsharing membership rates (Millard-Ball, 2005; Burkhardt and Millard-Ball, 2006; Stillwater, 2009).

Two points stood out with respect to the service area: 1) a density below 40 residential units per hectare – which corresponds to duplex housing – restricted service extension; 2) sectors that had excellent accessibility by car were also much more difficult for the carsharing service to colonize. The 5D approach proved to be relevant in modeling the diffusion of the phenomenon: 1) the effect of rapid transit bus accessibility to the workplace was considerably greater than that of density and diversity (non significant); 2) accessibility to the workplace by bus and by foot favoured carsharing membership; 3) the proximity of barriers (in this case major highways) decreased membership potential by 18 to 30%.

As for the influence of socio-economic characteristics on carsharing membership, particularly that of education, household size, and non-motorization, our results were in keeping with those obtained in surveys of the members of North American carsharing organizations, with some slight differences for the Canadian respondents concerning education (Burkhardt and Millard-Ball, 2006) and those from Philadelphia (Lane, 2005). The education level increased membership potential at a rate that compensated for the attrition exercised by revenue. This market was particularly attractive for the 31-to-60-year-old age group, its impact decreasing as the population aged. The carsharing attractiveness in places where proportion of single-parent families and those with children are higher is likely related to low levels of motorization. The data used here provided no evidence that people subscribed to the carsharing service instead of buying a second car, which remains to be verified with individual data. Finally, our results clearly showed that carsharing competed with car ownership, complemented public transportation, and likewise benefited active transportation in sectors where the urban layout made this possible.

Moreover, some of our results confounded our expectations about the meaning of certain variables' effects on the carsharing membership rate. These results were related in particular to the negative but non-significant effect of density, land use diversity and the modal share of bus travel. Density was found to restrict extension of the service area (below 40 units per hectare) and having little effect on growth of membership rate, meaning that, in Québec City, carsharing has a good potential in medium density suburbs. The non-significance of land use diversity was likely related to inadequateness of the ratio that could be replaced with a more comprehensive assessment based on entropy among a larger set of land uses. The negative relationship with the modal share of buses was more puzzling. Nonetheless, considering that the proportion of non-motorized households was likewise included in the model and generated a considerable rise in membership probability, we might propose that the decreasing tendency (not significant) of the modal share of public transportation corresponded to sectors where low motorization resulted from low financial means, which would have increased the use of public transportation regardless of carsharing membership. It is worth noting that, since the effect of revenue was included in the model, the resulting marginal relationship was particularly difficult to interpret in the linear regression because the complex transportation strategies were complementary.

Despite the above, our main hypotheses were confirmed: 1) our results indicated that various aspects of the urban form enhanced the deployment of carsharing services, specifically four of the 5D of Cervero: diversity (residential land), design, distance to transit, and destination accessibility (getting to workplaces by foot and bus, shopping by foot); 2) the results also indicated that carsharing occupied a niche market and was attractive only for specific segments of the population, namely, educated people who were ready to adapt their lifestyle and the people whose lower revenues made it difficult to buy a car but left them with enough money to occasionally use carsharing; 3) our results also confirmed that carsharing evolved in keeping with the innovation diffusion principles established by Hägerstrand, specifically in two forms: first from close to close, in and starting from already "contaminated" cells; second in a "piggyback" or wave form. As regards the niche market, our results indicated that it was potentially greater in Québec City (extension to inner suburbs) than what has been reported in the literature.

6. Conclusion

In this article, we looked at the geographical and socio-economic factors underlying carsharing membership in Québec City. We combined 5D factors for assessing carsharing demand potential, that is density, diversity, design, distance to transit, and destination accessibility, with Hägerstrand's diffusion of innovation concepts. We used a zero-inflated negative binomial regression to model the spatial-temporal diffusion of carsharing in Québec City, from 1996 (2 years after the start) to 2008. Results indicated that carsharing diffusion in Québec City was in keeping with Hägerstrand's innovation diffusion model and that, even though urban factors significantly influenced carsharing membership, it was socio-economic factors (education, non-motorization, and family structure) that had the greatest effect on membership in the service area.

Moreover, the results provided answers to the following questions:

1) *What is the diffusion potential of this emergent phenomenon?*

   Carsharing in Québec City, a highly motorized urban area where the automobile's modal share plainly dominates (74.7% of traveling in the city in 2006), clearly shows that this niche market was responding very well to the needs of certain population segments and that there was potential to extend into suburbs insofar as the latter had the necessary public transportation services and good pedestrian accessibility. The results presented in this article make it possible to foresee the likely extension of the service area based on previous development phases (the "inflated" part of the model). This is one of the original features of our work.

2) *Is carsharing development highly dependent on the urban form, restricting diffusion to higher density neighbourhoods with good accessibility to services and workplaces?*

   The membership potential depended above all on socio-economic factors such as motorization rate (negative effect), mix of transportation modes based on needs (positive), the presence of children (positive), especially in single-parent families (positive), level of education (positive), and income (negative). These results temper observations made by Burkhart and Millard-Ball (2006) about household size (predominance of single persons). Nonetheless, some of the urban form factors were also pertinent. Design, public transportation (distance to transit), and good accessibility to workplaces and stores were conditions that were just as necessary and that could partially compensate for a low residential density. Of all the factors tested, it was bus accessibility that provided the best potential for development, which confirms the complementary nature of carsharing and public transportation. This confirms and tempers the conclusion of Stillwater et al. (2009), by showing that the mean densities of some neighbourhoods likewise entail good potential when certain socioeconomic and environmental factors are brought together.

3) *Since access to car pools implies walking (or riding) to fixed-location parking lots, should we expect a sort of "oil stain" diffusion process on membership because cars are allocated on a proportional basis (e.g. 1 car per 20 members around a pool)?*

   The main form of growth has been to spread like an oil stain, even though the spatial-temporal diffusion model also had a piggy-back growth pattern, which made it possible to get round nearby obstacles. In Québec City, the main obstacles are the St. Lawrence River, industrial parks, institutional grounds (e.g., the campus of Laval University), and expressways. In our experience, the diffusion radius was at least 2 kilometres, which could be verified in a few years when the service has spread even more in Québec City, or in Montréal where the service will soon have been there long enough to apply the same model with more members in a bigger surface area.

To our knowledge, the modeling approach developed for this research (ZINB combined with urban form, socioeconomics, fixed growth effects, and a diffusion model) is quite unique. There were some limitations to its application, such as the linear interpolation used to estimate the data for each year in the model, and the radiuses used to model the membership gradients which remain to be confirmed, even though the 2 km radius produced satisfactory results. Furthermore, the choices made by households concerning their residence, motorization, and means of transportation are complex and multidimensional, mixed with endogenous effects. We did not assume that the factors in this model covered all the elements that might explain carsharing membership. Finally, the approach used here was based on cell aggregation and counting. Hexagonal cells were chosen over usual statistical areas so as to minimize the risk of directional bias. The 250 m radius represented a minimum for conducting OD surveys in an urban milieu to have a sufficient number of respondents. In Québec City, we were able to count on a sample size of 10% of the households. Despite all these precautions, modeling diffusion was subject to the MAUP and, since this was an aggregated study, we must be cautious before transposing our results to individuals and households, particularly due to the risks related to MAUP (Openshaw and Taylor, 1979 and 1981) and ecological fallacy (Robinson, 1950).

Our research benefited from the length of time that the service had been available in Québec City, making it possible to model the carsharing diffusion process at a weakly aggregated spatial scale. This, in turn, allowed comparison between effects of socioeconomic and urbanistic determinants on the spreading of the service alongside other transportation modes. Similar studies conducted elsewhere might validate or invalidate the results obtained in Québec City. If the relevant data is available, it would be very interesting to reproduce this type of model at the individual level by modeling the diffusion effect with spatial-temporal kernels that provide the number of members in a given radius the preceding month or year. In our study, we removed the members who withdrew from the service during the year. Interesting lessons could be learned by building spatial-temporal models for service withdrawal. Finally, it would be worthwhile to distinguish membership models from modal choice models. In Québec City, complementary studies (on an individual basis) concerning transportation choices as relates to greenhouse gas emissions of a small sample of carsharing members (available in French) helped to improve our interpretation of the membership model.

Appendix

Data description

Type of data	Source	Year	Description
Socio-demographic data	Statistics Canada	1996, 2001, 2006	Data from Statistics Canada's five-year survey grouped by diffusion area (a small region with 400 to 700 people and one or more islands).
Data on buildings	Municipal assessment rolls (Québec City)	2004	Quantitative and qualitative inventory of the buildings in the municipalities. Contains information on land use, building values, and surface area.
Trip data	Origin-Destination survey, (Québec Ministry of Transportation, Québec City's public transit company	1996, 2001, 2006	Telephone surveys jointly conducted by Québec's Ministry of Transportation and the transportation companies in the region (RTC, STL) used to draw a portrait of the population's local travel habits. Information included trips made during the day (at the individual level), possession of a drivers license, rate of household motorization, and so on.
Accessibility	Québec City public transit network), Québec City (roads)	2001	Topological network which, with TransCAD software, modeled trips by car, foot, and public transportation to various destinations. Accessibility indices for each cell were calculated for various transportation modes (Thériault et al., 2005).

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