Across Region Comparison of Transportation Greenhouse Gas Emissions and its Relationship with Urban Form, Transit Accessibility and Emerging Green Technologies: Montréal Vs Québec City

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Abstract

This research focuses on estimating a GHG emission inventory at the household level using completely disaggregate trip data and taking into account all emitting modes. The impact of urban form (UF) and transit accessibility (TA) characteristics on household level GHG emissions is then quantified and compared across two major cities in Quebec, Canada (Montreal and Quebec City). A simultaneous equation modeling framework is then implemented to investigate the link between UF, TA, socio-demographics, and travel GHGs. Our findings are consistent with the literature. Moreover, neighborhood types have important effects on GHGs. According to our results, the two most efficient strategies to reduce GHGs at the regional and household level seem to be the continuous fuel-efficiency improvement of the private motor-vehicle fleet and the increase of transit accessibility.

Keywords: Greenhouse gas emissions; neighborhood typologies; Emerging green technologies; travel behavior; built environment characteristics

Résumé

Si l'article est en français, le résumé français sera le premier.

Mots clés : conférence, article, modèle, dix mots maximum

1. Introduction

In Canada, GHG emissions from transportation make up to 27% of Canada's total greenhouse gas (GHG) emissions [1]. In addition, GHGs linked to transportation have risen consistently, seeing an increase of nearly 25% between 1990 and 2005 [2]. In order to limit climate change, local and worldwide policy makers are looking for strategies to reduce vehicular emissions. For example, the Quebec government is aiming to reduce GHGs by 20% with respect to 1990 levels for the year 2020.

Numerous studies have proposed and evaluated different strategies and policy options to reduce GHG emissions. These include strategies falling under the umbrella of urban planning concepts such as 3-D's or 5-D's, which contend that it is possible to reduce automobile dependence by developing dense, diverse, and well-designed neighbourhoods' with efficient public transportation options. Many other studies have been looking at the impact of emerging green technologies such as hybrid, electric and fuel cell passenger cars and transit vehicles. Nevertheless, these different strategies might have vastly different costs and impacts depending of the context or urban area. Moreover, there is evidence and general believes that the simultaneous changes in several aspects of the UF, TS and technologies could lead to meaningful reduction in fuel dependence [3]- [4]. As such, the debate remains open and additional evidence is still required.

Despite the extensive literature several research gaps still exist. First, most studies empirically have assessed the impact of the UF and TS characteristics on only a subset of travel decisions affecting GHG emissions. For example, some studies evaluate the impact of UF and TS attributes on the number or type of vehicles owned, whereas others evaluate the impact on distance driven or on mode choice [5], [6]. While useful, only few studies have directly estimated the overall effects of urban policies on GHG emissions (e.g., [7]). Second, the bulk of evidence concerns US urban areas. Transferability of US evidence to the Québec context may not be adequate given socio-cultural, vehicle fleet, urban form and mobility pattern differences.

Third, the existing evidence is mostly based on cross-sectional analysis comparing mobility patterns across neighborhoods at a single point in time and without correcting for residential-self selection. As a result, estimated relationships between UF/TS and GHG emissions may only reflect spurious correlations (UF/TS and GHG are affected by the same underlying factors) rather than causality. Finally, few studies look simultaneously at the potential impacts of land use changes, transit supply strategies and emerging green technologies at the household and regional level. The GHGs reductions associated with green technologies and UF/TS strategies have rarely been investigated in the same context. Our research project makes a contribution by tackling these shortcomings.

The main objective of this research is to estimate GHG emissions at the household level and evaluate the impact of urban form (UF), transit supply (TS) and emerging green technologies. The specific objectives of this research are to:

a. Develop and apply a methodology to estimate GHG emissions using completely disaggregate trip data and taking into account all emitting modes;

b. Estimate the impact of UF & TS factors on household level GHG emissions using an econometric approach that takes into account residential self-selection;

c. Estimate the potential impact of emerging green technologies (introduction of hybrid buses and fuel efficient cars) and compare their impact with those related to UF&TS initiatives between cities.

More specifically, our analysis will be carried out by combining a rich set of databases (origin/destination survey data (O-Ds), vehicle fleet characteristics, land use data, etc) as well as modelling tools developed for the region of Montréal 2003 and Quebec City 2006 O-Ds in order to come up with strategies reducing GHG emissions across the region for both cities. This is expected in the decision making process when trying to make sustainable regional wide transportation planning policies.

This paper is structured as follows: in the following section, a literature review of past research is discussed. The third section is a description of the study area, the methods used to estimate GHG emissions at the trip level and methodology on how to determine neighborhood typologies. This is followed by a section on selected statistics and figures regarding the input data. The next section presents the empirical results of the statistical models and the impact of UF and TA and Green technologies on GHG reduction for each city and a comparison for the two cities. The final chapter will conclude with policy implications.

2. Literature review

Past literature on travel behaviour indicates that urban form (UF) and transit accessibility are important factors in determining household travel behaviour such as mode choice, neighborhood choice and travel distance [8], [9], [10] and [11]. The vast literature over the past 2 decades consists of numerous studies that have analysed travel behaviour while controlling for measures of the BE and socio-economic variables. This vast literature has been summarized in some documents such as [10], [11] and [12].

Badoe and Miller [12] summarize the empirical evidence concerning impacts of urban form on travel, but also look at mode use and studies of impacts of transit accessibility on urban form. They conclude that results are mixed; some studies conclude that urban densities, traditional neighborhood design schemes, and land-use mix have an impact on auto ownership and use. Other studies find the impact of such variables to be at best marginal. In quantitative terms, one of the studies they looked at concluded that 10% increase in density led to only less than 1% reduction in household automobile travel.

Another recent literature review by the Transportation Research Board (TRB) [11] reported elasticities of between -0.1 and -0.24 for car distance travelled with residential density (i.e. an increase of 10% in residential density causes a reduction of 1 to 2.4% in trip distance). Also elasticity for land use mix (entropy) is 0.5% for 10% increase in entropy. As for accessibility, they reported a 2% increase by 10% increase in accessibility.

Ewing and Cervero [10] conducted a meta-analysis on the built environment-travel literature before 2009 for different travel outcomes (VMT, walking, and transit use). They reported weighted average elasticities for these studies in the literature. They found that a 10% increase in population density causes 0.4% reductions in VMT. Also by increasing Land use mix (entropy index) by 10%, the trip VMT goes down by 0.9%. For accessibility by transit, they reported an average weighted elasticity of -0.05. In other words a 10% increase in accessibility causes a 0.5% reduction in VMT.

Handy [9] summarizes evidence for the hypothesis that new urban design strategies will reduce VMT. She discusses how well studies have sorted out the relative importance of BE and socioeconomic characteristics in explaining travel behaviour and addresses issues of self-selection. The literature review of Cao and colleagues [13] is primarily focused on the issue of self-selection to determine whether the effect of BE is statistically significant for those approaches controlling for socioeconomic characteristics and preferences and, if true, what is the magnitude of the causality. More recently, Barla et al [7] used a simple linear regression model to predict GHG emissions at the individual level as a function of socioeconomic, LU, and TS indicators. Concurrent with previous studies, they found that there was a statistically significant negative impact of LU and TS on GHG emissions; however, the individual impact of each LU and TS variable was small. They reported that a 10% higher residential density would result in 2% decrease in GHG emissions from transportation. From this literature, we can say that in general, the elasticities of population density varies between 0.4% and 2.4% elasticities for land use mix varies from 0.5% to 0.9% and transit accessibility from 0.5% and 2% (when each attribute is increased by 10%). In a similar way, the impacts for the penetration of green technologies have been estimated in several studies. These impacts are evaluated in terms of energy savings and GHG emission reductions. This includes the impact of the introduction of new motor vehicle technologies, such as more fuel efficient, electric and hybrid vehicles and in public transit, the use of biodiesel, electric or hybrid buses and electric trains. Among other studies, we can refer to Zamel and Li [14], Schafer et al. [15] and Wee et al. [16] who evaluate different vehicle technologies in North America and Europe. Similarly, Ally and Pryor [17], Karman [18] and Frey et al. [19] investigate the impact of bus technologies in Australia, China, Portugal and the United States. Based on the technologies these studies found reduction in transit GHG emissions ranging from 10 to 35 percent. For most transportation modes, operation is responsible for the largest portion of life cycle GHGs [20], [21], [22]. For cars, it ranges from 67% to 74% of the total life cycle emissions [15]. Despite the large capital investments for electrification of trains, it is one of the most efficient transportation systems as it transfers more than 85% of the electricity input to the wheels [23], [24] and it eliminates the combustion of fossil fuels [25]. The use of renewable resources such as hydropower, solar energy, wind and geothermal energy for electricity production would greatly affect the overall emissions as they are assumed to have zero emissions [14], [26].

3. Methodology

The methodology proposed for this research builds on previous research dealing with a disaggregated analysis of the determinants of urban travel GHG emissions [7]-[27]. For this work, several sources of data are necessary including trip-level data from a household survey, motor-vehicle fleet characteristics, land use data, etc. In this empirical analysis, the main source of trip data is the Montreal and Quebec City O-D surveys, which provide urban travel information for a very large sample of the region under analysis – 5% of the households in Montreal. To collect data, interviewed households were asked to provide details for all trips made during one day by members aged over 4 years. The information collected for each trip includes: origin and destination x-y coordinates, transportation mode(s), purpose, transit lines used, time of departure, etc. Socio-demographic information at the individual and household level includes gender, age, work status, family structure, number of vehicles at home and household income. Since O-D survey data do not include information on the make, model, or year of vehicles owned by each household, we overcame this problem by using the motor-vehicle fleet inventory of the Quebec automobile insurance corporation - SAAQ.

For this research the following steps were implemented:

a. Calculation of GHGs at the trip level: This considers different trip-level attributes such as speeds at the link level, vehicle fleet characteristics, vehicle occupancy and travel distance.

b. Definition of the UF&TS indicators: The three main factors studied are residential density, land use mix and transit accessibility. These are the factors often reported in the literature. Based on these three measurements, neighborhood typologies were generated.

c. Estimating the impact of UF&TS on GHGs: For this an econometric approach is adopted accounting for the residential self selection problem.

d. Estimating the potential impact of emerging green technologies: The potential reduction in GHGs for the introduction of green sources of energy is investigated and compared with the potential impact of UF&TS strategies.

3.1. Trip-level GHGs:

For each trip in the household travel surveys, two GHG emitting mode categories are distinguished, private motor vehicles and public transit. Some trips can involve one or more modes.

For private motor vehicle trips: For trips involving motor-vehicle as a unique or combined mode, the emissions are estimated using distance and average speed at the link level, vehicle fuel consumption rate (FCR) and GHGs emission factors. This procedure is based upon [7]-[27] and emissions for a given trip departing in a particular hour are estimated as:

$$GHG_{Aj} = \sum_{i=1}^{N} \frac{FC_{Aj} \times EF_A \times [\, D_{Aij} \times SP_{ij} \,]}{R_{Aj}} \qquad (1)$$

Where:
GHG_{AJ} = GHGs for the automobile portion of trip j (kg of CO_2),

FC_{Aj} = Average fuel consumption rate (FCR) in litres of gasoline/100km for the vehicle used in trip j. This was generated using the motor-vehicle fleet inventory of the automobile insurance corporation of Quebec (SAAQ) by Barla et al. [28] and provides an average FCR at three-digit postal code level (FSA).

D_{ij} = Travel distance on segment (link network) *i* in 100km. For selecting trip paths, user equilibrium conditions are established using a traffic assignment platform implemented in the modeling software (EMME/3) which has been developed and calibrated by the Quebec Transportation Ministry.

SP_{ij} = Speed correction factor for segment *i* of trip *j*. Since fuel consumption also depends upon speed, speed correction factors developed by the MTQ were also used [29].These factors were produced after a calibration for the local condition in MOBILE6.

EF_A = Emission factor for gasoline (2.289 kg of CO2/ liter of gasoline[1])

R_{Aj} = Number of passengers in trip j including driver.

For public transit trip: It's worth mentioning that the public transit modes involved in Montreal consist of commuter train, bus and metro, whereas in Quebec City this is limited to buses only. For uni-modal or multimodal trips involving public bus transit and/or commuter trains (in the case of Montreal), GHGs are estimated in a similar fashion. In this case, however, average speeds are used. For the bus portion, GHGs are calculated using the following equation:

[1] National Inventory Report 1990-2009 (2011 submission), Environment Canada. (http://www.ec.gc.ca/ges-ghg/default.asp?lang=En&n=AC2B7641-1)

$$GHG_{Bj} = \frac{FC(S)_{Bj} \times D_{Bj} \times EF_B}{R_{Bj}} \quad (2)$$

GHG_{Bj} = GHGs for bus portion of transit trip *j* (kg of CO2)

$FC(S)_B$ = Average fuel consumption as a function of operating speeds *(S)* in liters of diesel/100km).
Fuel consumption rates for the typical fuel bus technology operating in real conditions were obtained from a local recent field study done by the local transit agency, Société de transport de Montréal (STM). The fuel consumption curve according to this study is given by *FC(S)* = 257.8*(*Bus speed*) $^{-0.48}$. Since similar buses are used in Quebec City, the same curve is used for that city.

D_{Bj} = Distance traveled by bus in transit trip j (km). For each trip involving transit (bus, metro and commuter trains) in the Montréal region, distances are obtained using the public transit software, MADIGAS [30]. Trips were simulated in collaboration with the *Agence Métropolitaine de Transport* (AMT). Since this database wasn't available for Quebec City, the bus network was modeled in ArcGIS. Using the shortest path algorithm and data available from the OD survey (origin-destination transit joints), the traveled distance on bus was then estimated for Quebec City bus trips.

EF_B= Emission factor for diesel (2.663 kg CO2/ liter of diesel).

R_{Bj}= Ridership for bus on trip j (average daily ridership for each bus line).

For commuter train lines in Montreal, using diesel or diesel-electric locomotives, average fuel consumption for passenger-km (FC/PK) were directly estimated by the local commuter train agency (Agence métropolitaine de transport - AMT). This was done by dividing the annual fuel consumption (lit of diesel) by their respective annual passenger kilometers traveled.
Travel distance by rail (DR) is then estimated for each trip (km). By multiplying (DR) by the fuel consumption rate per passenger km (FC/PK), liters of fuel consumed for the train segment are estimated. To get the kg of CO2 for each trip, the resulting liters of fuel for each trip is multiplied by the emission factor for CO2 obtained from Environment Canada. This is equal to 2.663 kg of CO2 for each liter of diesel fuel combusted in trains. It's worth mentioning that the GHG from metro (subway system) in Montreal is assumed to be close to zero. This is due to the fact that the metro runs on hydro-electric power and therefore this would be a reasonable assumption.
Finally, GHGs are estimated for each unimodal and multimodal trip in the O-D survey. Trip level emissions are then aggregated at the individual and household level.

3.2. UF&TS attributes and neighborhood typologies

To generate the UF&TS characteristics in the vicinity of each household involved in this analysis, a nine-cell grid approach was undertaken [31]. This is done in order to keep the benefits of a region-wide grid but partly overcome the inaccuracies in a normal grid method. The approach involves creating a grid for the Montreal and Quebec City census metropolitan area (CMA), with cells in this case having 500 meter sides. Each nine cell is represented by the central cell, for which the attributes of the eight surrounding cells are also considered equally and applied to this central cell. In defining a grid cell at 500 meters, the nine-cell grid method creates an area that approximates a buffer with an approximately 900 m radius (the minimum "radius" is 750 m, and the maximum is 1061 m). The primary benefit of using the nine-cell grid method over simply using large grids with 1.5 km sides is that it defines a central grid to which the observation will belong, and therefore constrains the absolute minimum and maximum distances of an observation to the outer edge of the nine cells (these distances are 500 m and 1.4 km, respectively).

Land use mix: Using the nine-cell grid approach, land use mix was calculated using the entropy index. The land uses considered, as defined by Desktop Mapping Technologies Inc. (DMTI), were residential, commercial, institutional and governmental, resource and industrial, and park and recreation, with water and open area not being considered in the equation.

$$E_j = -\sum \frac{\left[\left(\frac{A_{ij}}{D_j}\right)\ln\left(\frac{A_{ij}}{D_j}\right)\right]}{\ln(n)} \qquad (3)$$

In this equation, *A* is the area of land use *i* in the nine-cell grid *j*. D_j represents the total area of nine-cell grid *j*, without taking into account water and open area and *n* is the total number of different land uses (5 in this paper).

Population density: Population was obtained at the census tract level from Statistics Canada [32] for the Montreal CMA. Land use data from DMTI Spatial was then used to more accurately allocate population within each census tract, which then allowed for the calculation of approximate population per grid cell. There are particular ways in which incomplete cells near bodies of water or the boundaries of the study were dealt with, in addition to the weighing of cells that intersected partial land use tracts, but it is beyond the scope of this paper to describe these.

Transit accessibility: The grid approach was also used to calculate the accessibility to transit by finding the nearest bus, metro and rail line stops to each cell and summing each line's closest stop's contribution to a transit accessibility index; a stop closer to a cell centroid or with a smaller headway (calculated using AM peak) would mean a larger contribution to transit accessibility (See equation 4).

$$PTaccess_j = \sum_{i=1}^{n} \frac{1}{(d_{ij} * h_i)} \qquad (4)$$

Where:

$PTaccess_j$: accessibility to public transit at cell *j*

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

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

Neighborhood types: In order to generate neighborhood typologies based on the previously defined UF&TS indicators, a k-means clustering technique was used following a similar approach to the one proposed [31], [33] and [34]. By combining indicators, one can better describe activity density [35] and more clearly understand the effect that changing levels of urban form and public transit can have [4].

3.3. Impact of UF&TS on GHGs

To estimate the effect of UF and TS on GHGs, two approaches are adopted: i) simple OLS regression approach in which the three indicators (population density, land use mix and transit accessibility) are entered in the model directly and ii) simultaneous equation model in which UF&TS attributes are combined and represented through neighborhood typologies.

In the second approach, the choice of residential neighborhood-number of cars is modeled as a simultaneous choice with the natural logarithm of GHGs as a continuous outcome. The modeling algorithm follows a maximum simulated likelihood formulation.

$$\ln(GHG_i) = \alpha x_i + \sum_{j=1}^{5} \mu_j k_{ij} + \sum_{j=1}^{5} \lambda_j l_{ij} + \varepsilon_i \quad (5)$$

$$N_{ij} = \beta_j z_i + \delta_j l_{ij} + \eta_{ij} \quad j = 1, \dots, 10 \quad (6)$$

Where,
$ln(GHG_i)$: natural logarithm of total transportation GHGs at the household level
N_{ij} : indirect utility of neighborhood-number of cars choice of k_j for household i
x_i & z_i : socio-economic characteristics of household i
k_{ij}: dummy variables representing neighborhood cluster-number of car choice j for the household i
ε_i: random independent error (Normal distribution)
l_{ij}: latent explanatory variable of heterogeneity not observed by endogenous variables
n_{ij}: random independent error (Logistic distribution)
$\alpha, \beta, \delta, \lambda, \mu$: model parameters.
The model is estimated using the estimation method proposed by Deb and Trivedi [36], which has been implemented in STATA.

4. Input data: Socio-demographics, UF, TS and GHGs

4.1. Socio-Demographics

The socio-demographics of the household were obtained from the 2003 Montreal and 2006 Quebec City OD surveys for all trips and then aggregated at the household level. These attributes consist of the number of motor-vehicles, persons, children, full-time and part time workers, retirees, students and adults. In table 1 summary statistics for UF and transit accessibility are reported

Table 1. Summary of socio-demographics, UF and TS at the household level, Montreal OD 2003 & Quebec City OD 2006 (42,094 & 25,764 households respectively)

Category	Variable	Montreal 2003				Quebec City 2006			
		Mean	Std. Dev.	Min	Max	Mean	Std. Dev.	Min	Max
Socio-demo	Number of cars	1.266	0.914	0	18	1.504	0.805	0	9
	Number of persons	2.421	1.267	1	16	2.511	1.196	1	15
	Number of children	0.484	0.873	0	11	0.029	0.189	0	3
	Number of fulltime workers	1.064	0.844	0	10	0.994	0.774	0	6
	Number of part time workers	0.11	0.333	0	3	0.062	0.249	0	3
	Number of students	0.587	0.924	0	10	0.212	0.504	0	5
	Number of retirees	0.314	0.62	0	7	0.248	0.487	0	5
	Number of adults	1.936	0.833	1	11	1.562	0.704	1	7
UF & TS	Population density * (people per hectare)	47.04	34.36	0	148.65	25.102	19.29	0	98.5
	Transit accessibility *	120.87	126.44	0	747.37	63.304	72.156	0	394.8
	Land use mix (entropy)*	0.3438	0.1740	0	0.7578	0.139	0.096	0	0.4

**In the vicinity of each household (a buffer of nine-cell grids, 500m by 500m each)*

4.2. UF & Transit Indicators

Figures 1(a)-(d) show population density, land use mix, transit accessibility and the resulting neighborhood typology clusters respectively, in Montreal for the year 2003. Figure 2(a)-(d) shows the same attributes for Quebec City year 2006. K-means statistical cluster analysis is used to group grid cells into “k” homogenous clusters according to LU and PT characteristics. Then households are assigned to these clusters based on which grid cell the household is located. These neighborhood clusters are classified as: Cluster 1: Rural/Suburban: where all attributes are below the average with very low density, accessibility and entropy (1/30 to 1/5 of the average). Cluster 2: Outer suburb: where all attributes slightly below the average with UF indexes being half the average. Cluster 3: Inner suburb: this is the intermediate neighborhood type, with all UF values being equal or very close to the average. Cluster 4: downtown core: with very high density, accessibility and entropy (twice the average). Cluster 5: urban core: with high to medium density, accessibility and entropy (1.5 times the average).

4.3. Household Emission Inventory

The spatial distribution of GHGs at the household level is represented in **Fig. 3** for Montreal and **Fig.4** for Quebec City. The map represents the average emissions for total household travel GHG, for all households that fall inside it. From this figure it can be seen that the central neighborhoods emit less and as one goes towards the suburbs transport-related GHG emissions of the households increase. It’s interesting that this similar trend exists in both cities in the region of study. This can be explained by the relative increase in distance traveled by these households (suburban) and their predominant use of car.

5. Empirical results

5.1. OLS model with raw BE attributes

A log-linear regression, OLS, model is studied as the first model. In this first attempt, BE attributes (residential density, PT accessibility and land use mix represented by the entropy index) were directly entered in the GHGs model as explanatory variables. Again, the dependent variable is the natural logarithm of household travel GHG emissions. **Table 2** presents these results for the two cities. The first model is for Montreal; whereas the second model (model 2) is for Quebec City.

Interestingly, from **table 2** we can see that BE variables are statistically significant and negatively associated to household travel GHGs. From the elasticities we can observe that increasing population density and PT accessibility by 10% (one at a time) for Montreal (and Quebec) would cause 3.53% (1.50%) and 5.88% (0.47%) reduction in the households’ GHG, respectively. These results are in accordance with the literature, in terms of sign and significance; however the magnitude of these parameters in Montreal seems to be slightly greater than Quebec City and most of the past North American studies, in particular for transit accessibility. This may be linked to the fact that the Montreal region has a higher population density and better transit supply than Quebec City and many other US cities on which studies reported in the literature are based.

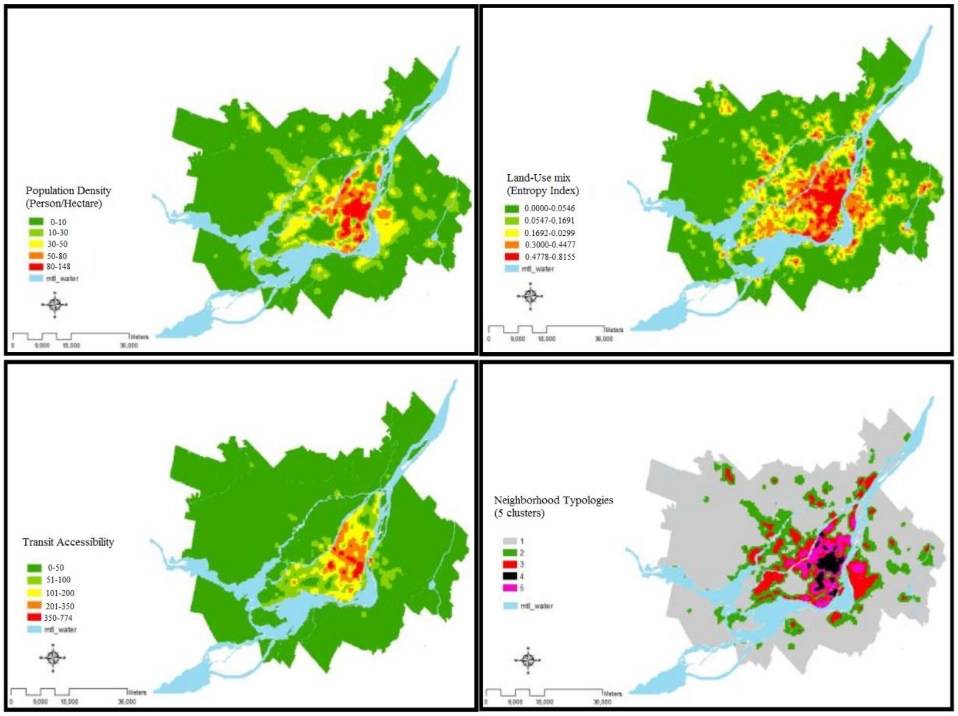

Fig.1 (a) Population density (person/Hectare) (top left); (b) Land-use mix (top right); (c) Transit accessibility (bottom left); (d) Neighborhood typologies (5 cluster setting for Montreal 2003) (bottom right).

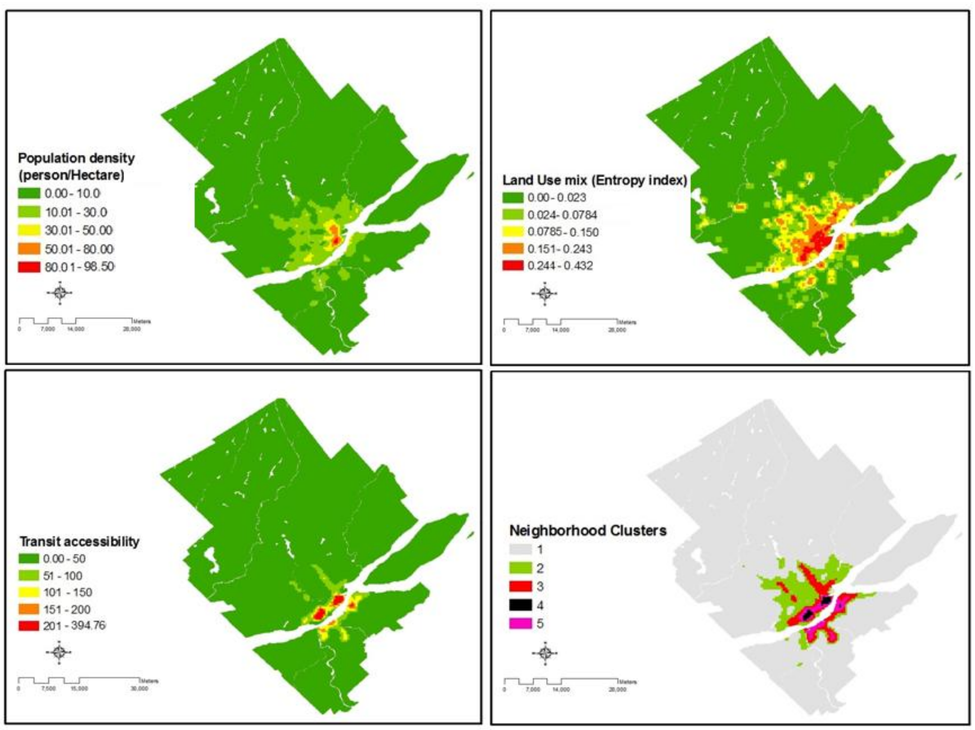

Fig.2 (a) Population density (person/Hectare) (top left); (b) Land-use mix (top right); (c) Transit accessibility (bottom left); (d) Neighborhood typologies (5 cluster setting for Quebec City 2006) (bottom right).

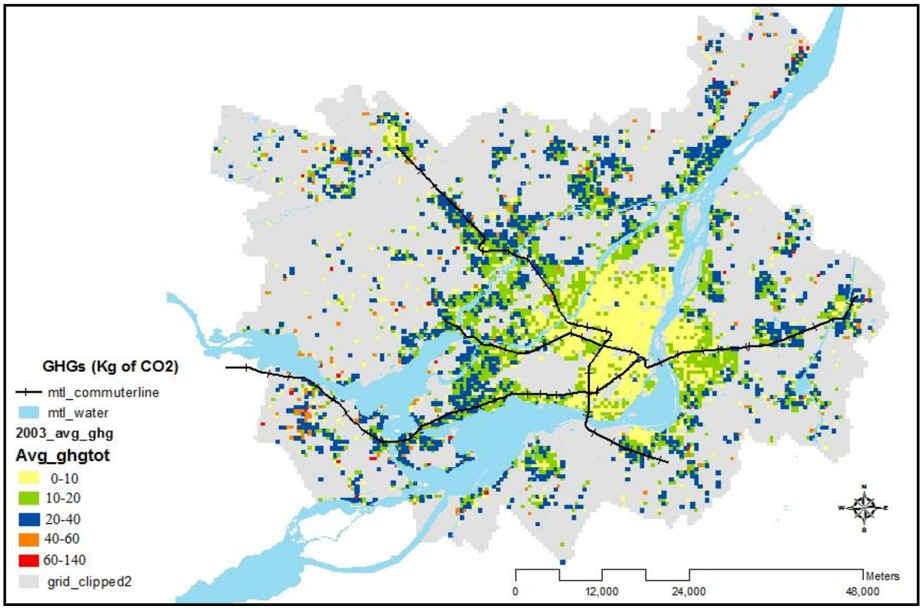

Fig.3 Montreal 2003 OD spatial distribution of household GHG inventory

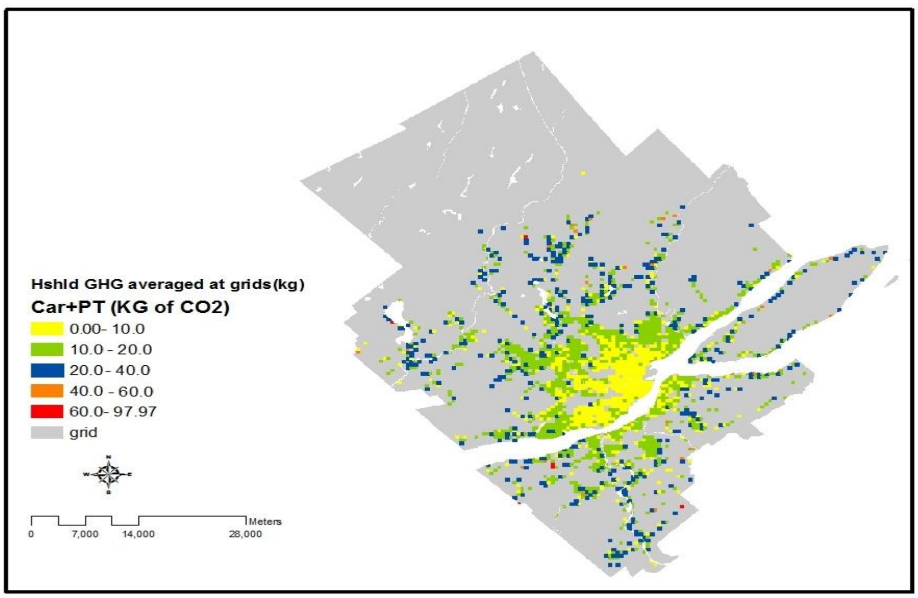

Fig.4 Quebec City 2006 OD spatial distribution of household GHG inventory

Table 2: OLS model of Ln (household total trips' GHG) with raw BE attributes

	Model 1 – *Montreal*			Model 2 – *Quebec City*		
Ln (Total Household GHG)	**Coef.**	**P>|t|**	**Elast %**	**Coef.**	**P>|t|**	**Elast %**
Residential density *	-0.007	0.00	-3.53	-0.005	0	-1.50
PT accessibility *	-0.004	0.00	-5.88	-0.0007	0	-0.47
Entropy *	-0.739	0.00	-2.53	-1.238	0	-1.73
Number of retirees **	-0.518	0.00	-51.85	-0.286	0	-28.62
Number of students **	0.219	0.00	21.97	0.394	0	39.45
Number of part time workers **	0.775	0.00	77.54	0.509	0	50.91
Number of fulltime workers **	1.021	0.00	102.18	0.612	0	61.22
Number of children **	-0.041	0.137	-4.14	-0.241	0	-24.11
Single adult family	-1.720	0.00	-82.11	-0.259	0	-22.87
Low income (less than 40k)	-1.425	0.00	-75.96	-0.280	0	-24.43
Medium income (40k to 80k)	-0.127	0.012	-12.00	-0.191	0	-17.43
High income (more than 80k)		Base case			Base case	
Constant	1.411	0.00	-	1.837	0	-

(10% increase for elasticity)
(1 unit increase for elasticity)

With respect to employment, different employment status variables are statistically significant. Increasing the number of full time or part time workers by one unit causes about *102*% (*61%*) and *77*% (51*%*) increase in the total household's trip GHG. This shows the important link between the labor force participation and transportation-related GHGs at the household level. On the contrary the number of retirees in the household tends to reduce GHG by *51*% (28*%*). This could be explained by the use of public transit by this group (retirees). The single adult family variable (household with only one member which is adult) is also found to be statistically significant. This type of household has a much smaller (82% less in model 1 and 22% in model 2) carbon footprint comparing to households with more than one member.

5.2. Simultaneous modeling:

To test for the presence of endogeneity, the simultaneous regression model (SEM) with car ownership and neighborhood types as endogenous choices is fitted to the data. Its outcome is then compared to the corresponding OLS regression model. Both outcomes are provided in Table 3. By running a likelihood ratio (LR) test, the significance of SEM is evident. The LR test of statistically significant and greater than zero indicates that the simultaneous model is a better option than the OLS - the null hypothesis of exogeneity is then rejected (LR=58 and P-value=0.000 in Montreal and LR=404 and P-value=0.000 in Quebec City). The OLS, however, only explains about 39% of variation in model 1 ($R^2 = 0.39$) and 45% in model 2 ($R^2 = 0.45$).
There are 10 categories (dummies) explaining the joint neighborhood type-car ownership choices (residing in one of 5 neighborhood types without a car or residing in one of these same 5 neighborhood types, but with at least one car). The reference case is cluster 3 with one or more cars. In the simultaneous model, all neighborhood type-number of car variables are statistically significant in explaining household GHG emissions in Quebec City and Montreal, except for cluster 5 with one or more cars for Montreal. Compared to the reference group (cluster 3 with at least one car), the two further-outlying neighborhood types (clusters 1 and 2 with at least one car) emit more, and the two more central clusters emit less. More precisely,

compared to the reference case, households of the periphery and suburban areas with at least one car (clusters 1&2 and car>=1) are expected to emit about 30% and 36% (69% and 11% in Quebec City) more on average. In contrast, residents of cluster 4 and with one or more cars (central neighborhoods) are likely to emit about 60% less GHGs. This highlights how policies targeting neighborhood location choices such as new developments in the suburban areas could affect the GHG emissions of households.

Table 3: OLS and SEM model of Ln (household total trips' GHG) with cluster-car choice variables

	OLS						**SEM**					
	Montreal			***Quebec City***			***Montreal***			***Quebec City***		
Ln(Sum of hshld GHGs)	**Coef.**	**P>t**	**Elast. %**	**Coef.**	**P>t**	**Elast. %**	**Coef.**	**P>t**	**Elast. %**	**Coef.**	**P>t**	**Elast. %**
Cluster1 & car=0	-4.6	0	-99	-0.46	0	-36.6	-4.33	0	-98.68	-0.54	0	-41.55
Cluster1 & car>=1	0.46	0	58.97	0.341	0	40.6	0.27	0	30.97	0.526	0	69.14
Cluster2 & car=0	-4.96	0	-99.3	-0.82	0	-56.05	-4.77	0	-99.15	-0.84	0	-56.63
Cluster 2 & car>=1	0.34	0	39.88	0.073	0	7.53	0.31	0	36.2	0.13	0	11.72
Cluster3 & car=0	-4.29	0	-98.63	-1.02	0	-63.87	-4.04	0	-98.25	-0.98	0	-62.57
Cluster 3 & car>=1	Base case			Base case			Base case			Base case		
Cluster4 & car=0	-4.84	0	-99.21	-0.98	0	-62.47	-4.54	0	-98.93	-0.97	0	-62.24
Cluster 4 & car>=1	-1.02	0	-63.82	-0.03	0	-3.09	-0.91	0	-59.87	-0.02	0	-1.9
Cluster5 & car=0	-4.15	0	-98.42	-1.07	0	-65.72	-3.87	0	-97.91	-1.08	0	-65.9
Cluster 5 & car>=1	-0.38	0	-31.41	-0.08	0	-7.87	0.02	0.8	1.8	-0.02	0	-2.32
Number of retirees	-0.71	0	-70.61	-0.283	0	-28.28	-0.73	0	-73.13	-0.284	0	-28.42
Number of student	0.3	0	30.07	0.413	0	41.3	0.29	0	28.54	0.41	0	40.95
Number of part time workers	0.69	0	69.32	0.502	0	50.23	0.69	0	68.74	0.495	0	49.48
Number of fulltime workers	0.99	0	99.15	0.593	0	59.3	0.95	0	94.64	0.573	0	57.25
Number of children	-0.07	0	-7.16	-0.26	0	-25.47	-0.06	0	-6.77	-0.24	0	-24.11
Single adult family	-1.24	0	-71.03	-0.16	0	-14.66	-1.17	0	-68.89	-0.15	0	-14.08
Low income	-0.73	0	-51.6	-0.4	0	-32.88	-0.71	0	-51.2	-0.31	0	-26.82
Medium income	-0.08	0.1	-8.01	-0.29	0	-25.13	-0.09	0.1	-8.77	-0.24	0	-21.37
High income	Base case			Base case			Base case			Base case		
Constant	0.06	0.4	-	1.413	0	-	-0.35	0	-	1.341	0	-

In both models, OLS and SEM, the number of different occupations at the household level is found to be significant with respect to household GHG emissions (confirming the literature). Also by increasing the number of fulltime or part-time workers by one person, the relative GHG emissions increase by 94% and 68% in Montreal and 57% and 49% in Quebec City, respectively. Persons leaving alone (single person households) seem to have a smaller GHG footprint from transportation comparing to other households. These households tend to generate about 68% (in Montreal) and 14% (in Quebec) less GHG with respect to more than one person households.

The car ownership again plays an important part in contributing to GHG emissions. We can observe this by comparing the elasticity for cluster 3 and no car and the base case (same cluster but with at least one car). We see that living in the same neighborhood as the base case and not having a car reduces household GHG emissions by 98% in Montreal and 62% in Quebec City. This is due to the use of public transit, active transportation (biking and walking) and car sharing programs by these households for their daily trips and therefore a significant reduction in their GHG contribution.

Medium and low income households have a smaller GHG footprint than their high income counterparts. Low income households (less than 40,000$ per year) generate 51% (Montreal) and about 27% (Quebec City) less GHG emissions from their transportation trips when compared to high income households (more than 80,000$ per year). The medium income class (between 40,000$ and 80,000$ per year) also have a smaller GHG contribution than the wealthiest households, but only by approximately 9% (Montreal) and 21% (Quebec City).

5.3. GHG reducing technology scenarios:

This section explores the potential impact of the introduction of green technologies. For this purpose, some fleet technology improvements are considered and evaluated. In the case of Montreal five scenarios are contrasted, whereas in Quebec City, only one scenario has been studied (change in bus fleet technology to hybrid buses from normal diesel buses, scenario2):

Scenario 1: base case or status quo. In this scenario the GHG is calculated for the current data set, with respect to the current technology available (diesel buses, diesel trains except for one diesel electric line, fuel consumption rate for cars set to the 2003 mean value at the FSA level for Montreal, and for Quebec City, diesel buses and car fuel consumption rate set to year 2006).

Scenario 2: all transit buses are upgraded to hybrid buses. In this scenario, the fuel consumption calculation remains the same as the base case, except for the transit buses where the fuel consumption used follows another formula corresponding to hybrid buses. Relative transit GHG reduction is observed.

Scenario 3: all commuter trains are changed with electric trains. In this scenario, the emission for train is set to zero for all the diesel lines (92% of electricity in the province of Quebec is from hydroelectric dams), the GHG for the rest of the modes remains the same as the base. Relative change in transit GHG is estimated.

Scenario 4: combination of scenarios 2 and 3.

Scenario 5: projecting car fuel efficiency to the year 2020 using the current fuel consumption trends (from 2001 and 2008) for Montreal. For this scenario, the emission from car trips is calculated using the projection of the fuel consumption rate (FCR) to the 2020 and using the historical fuel consumption rates of the period 2001-2008. For all other emitting modes, their respective GHG remains the same as status quo.

The fuel consumption for hybrid bus relative to its speed is obtained from a technical report on hybrid technology prepared for the Société de Transport de Montréal (STM). Since similar buses are used in Quebec City, the same curve is also used for this city to calculate the hybrid bus fuel consumption.

The fuel consumption for better fuel economy is calculated by projecting year 2020's fuel consumption rates at the FSA level, using the data available on FCR from 2000 to 2008 at each FSA. A growth rate function was used for this purpose to predict 2020 fuel consumption rates (liters of gasoline/100km traveled at each FSA). The average FCR at year 2000 was 9.4 liters of gasoline/100km. For the future scenario FCR (year 2020), this is reduced to 8.77 liters of gasoline/100km.
By changing the current buses to hybrid technology, we can see that the mean fuel consumption per transit trip goes down to 0.431kg in Montreal and 0.907kg in Quebec City. This represents in general an 11% and 20% decrease in GHGs with respect to the status-quo scenario. The reason why the mean transit trip GHG is higher in Quebec City versus Montreal could be due to the fact that the only transit mode in Quebec city is the city bus, whereas in Montreal, three metro lines and five commuter rail lines exist which catch a great portion of transit trips, and since the emission attached to the electric metro systems is close to zero, this contributes in reducing transit GHG emissions per trip in Montreal.

If we enhance the commuter train efficiency by using electric trains, their relative GHG emissions would become close to zero (92% of electricity in Quebec is from hydroelectric dams). This would cause the new average GHG for each transit trip in Montreal to fall to 0.387kg (20% reduction compared to the current state). Moreover if the two scenarios mentioned above were implemented simultaneously (scenario 4) there would be a 32% reduction in transit sector GHG emissions in Montreal.

For scenario 5, GHG for pure car trips for status quo has a dominant effect in total GHG share (619,641 kg of CO_2 for the pure car trips of all households in the Montreal 2003 OD survey, Vs 639,720kg for the total transportation GHG). Regarding this huge share, the final scenario is targeting the fuel economy of passenger vehicle cars in Montreal. By using the 2020 projected fuel consumptions and re-calculating the total GHGs at the household level we see that the car GHG goes down to 578,485 kg for the car trips of the data set. This shows a 7% reduction in the relative car GHG emission for all the trips taking place in the OD survey.

It is important to notice that transit GHG is only a very small portion of total transportation GHGs for the household sample under analysis - less than 4%; therefore the relative reduction is very marginal when looking at the total transportation GHG level. Comparing with transit supply elasticity in Table 2, we can see that strategies such as increasing transit accessibility can play a more important role in reducing the carbon footprint than replacing transit units (fleets) with electric and hybrid vehicles. On the other hand, the improvement in the car fuel economy (scenario 5) is anticipated to have the greatest impact on household GHG reduction comparing to UF and TS strategies. In other words, and according to our results the two most efficient strategies to reduce the carbon footprint at the regional and household level seem to be the natural improvement of the car fuel efficiency and the increase of transit accessibility.

6. Discussion and conclusion

This research aims at investigating the potential impact of UF, TS and green technological improvements on GHGs at the household and regional level in the region of the province of Quebec, Canada; mainly in Montreal, and Quebec City which are among the large cities in Canada. These strategies are compared in terms of their GHG reduction effectiveness. Among other results, it was found that land use mix, population density and public transit accessibility have statistically significant and negative effects on the carbon footprint of daily travel in both cities. This is in accordance with the literature; however, the magnitude of these parameters in

Montreal seems to be slightly greater than Quebec City and most of the past North American studies, in particular for transit accessibility. Moreover, when looking at the combined effect of UF and TS indicators, through neighborhood typologies, it is observed that the effects are much greater.

Employment status and income are also significantly related to household trip GHG emissions; having more full-time and part time workers in the household and a higher income adds to the GHG contribution of that household. This is consistent with the literature and shows that a large share of trip GHGs are due to everyday commutes. Therefore, GHG reduction policies should target commuter trips and higher income households if they wish to maximize the effectiveness of their efforts.

With respect to the different GHG reduction scenarios, efficient green transit fleet is shown to lead to important reductions in the average trip emissions. However, transit GHG represents only a small fraction of overall household transportation GHGs (less than 5%). On the other hand, policies aimed towards more fuel efficient cars could be described as more effective. According to our results, the continuous replacement of the private motor-vehicle fleet by more fuel efficient vehicles is expected to have a very significant impact, if trends persist in the following years. A reduction of 6.4% on total passenger GHG is expected.

By comparing the emerging green technology scenarios with the UF & TS strategies, we observe that strategies such as increasing transit accessibility may be more effective in reducing “total” transportation GHGs than replacing transit fleets with electric trains and hybrid bus transit vehicles. Car GHG emissions do however maintain the largest share of total transportation GHG, therefore improvement in passenger vehicle fuel economy (scenario 5) has the greatest expected reductions in GHGs followed by the TSS strategy. In summary, the overall GHG reduction policy recommendation of this research comes down to two points: (i) continuous fuel-efficiency improvement of the private motor-vehicle fleet (with an expected reduction of 6.4% for year 2020) and (ii) the increase of transit accessibility.

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