Available online at www.sciencedirect.com

ScienceDirect

Procedia - Social and Behavioral Sciences 00 (2011) 000–000

Procedia Social and Behavioral Sciences

www.elsevier.com/locate/procedia

15th edition of the European Working Group on Transportation

Transportation Greenhouse Gas Emissions and its Relationship with Urban Form, Transit Accessibility and Emerging Green Technologies: A Montreal case study

Seyed Amir H. Zahabi[a*], Luis Miranda-Moreno[a], Zachary Patterson[b], Philippe Barla[c], Chris Harding[b]

[a]*Department of Civil Engineering and Applied Mechanics, McGill University, Montreal, Canada*
[b]*Department of Geography, Planning and Environment, Concordia University, Montreal, Canada*
[c]*Centre for Data and Analysis in Transportation (CDAT), Université Laval, Quebec city, Canada*

Abstract

This research aims at 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 to the impact of the introduction of emerging green technologies. Using a large and representative sample of household diaries, trip-level GHG emissions are estimated by combining different sources of data (origin-destination (OD) survey data, vehicle fleet characteristics, transit ridership data, etc.) and by using modelling tools (traffic assignment and GHGs models). Moreover, UF and TA indicators are developed and combined to generate neighbourhood typologies. A simultaneous equation modelling framework is then implemented to investigate the link between UF, TA, socio-demographics, and travel GHGs, taking into account the well known “self-selection” issue. The potential impact of land use and transit supply strategies with emerging green technological scenarios is then compared. This is evaluated through the modification of current fuel consumption rates with those provided by new technologies such as hybrid transit buses and continuous improvement of vehicle fuel consumption rates. Our findings are consistent with the literature, more specifically we have found that the built environment (BE) attributes are statistically significant (10% increase in density, transit accessibility and land-use mix, results in 3.5 %, 5.8% and 2.5% reduction in GHG respectively), number of workers and retirees at the household level play an important role in the contribution to GHG emissions (102% *increase* by adding one worker and 51% *decrease* by adding a retiree to the household). Moreover, neighbourhood types represented by the combined effects of UF and TS have important effects on GHGs. Also it is found that by replacing transit fleet by electric trains and hybrid buses, the share of transit GHGs would decrease by 32%. With respect to the private motor-vehicle fleet, if current trends persist, the constant improvement of car fuel consumption economy would reduce car GHGs by 7%. 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; Land-use; self-selection; Transit accessibility.

* Corresponding author. Tel.: +1-514-649-4579.
E-mail address: seyed.zahabi@mail.mcgill.ca

1. Introduction

Transportation is responsible for approximately 30% of greenhouse gas (GHG) emissions in North America with private vehicles accounting for more than half (IEA, 2002). Given the importance of hydropower, the proportion of private vehicle emissions is even larger in the province of Québec where they presently account for over 22% of total emissions, up from 19.5% in 1990. In order to limit climate change, local and worldwide policy makers are therefore looking for strategies to reduce vehicular emissions. For instance, the Quebec government is still aiming for a reduction of GHGs of 20% for 2020 with respect to 1990 levels.

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 (Badoe and Miller 2000; Bento et al. 2005). 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 (Cervero and Kockelman, 1997; Chen et al 2008; Potoglou 2008; Bhat et al. 2009). While useful, only few studies have directly estimated the overall effects of urban policies on GHG emissions (e.g., Barla, et al. 2011). 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 neighbourhoods 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:

1. Develop and apply a methodology to estimate GHG emissions using completely disaggregate trip data and taking into account all emitting modes;
2. Estimate the impact of UF & TS factors on household level GHG emissions using an econometric approach that takes into account residential self-selection;
3. Estimate the potential impact of emerging green technologies (introduction of hybrid buses, electric commuter trains, and fuel efficient cars) and compare their impact with those related to UF&TS initiatives.

More specifically, our analysis will be carried out by combining a rich set of databases (origin/destination survey data, vehicle fleet characteristics, land use data, etc) as well as modeling tools developed for the region of Montréal. These objectives are linked in such a way that we can compare technological approaches with UF&TS strategies and see their individual and simultaneous effectiveness. This is expected in the decision making process when trying to make sustainable regional wide transportation planning decisions.

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, proposed scenarios and their relative GHG reduction potential. The final chapter will conclude with policy implications.

2. Literature review:

Past literature on travel behavior indicates that urban form (UF) and transit accessibility are important factors in determining household travel behavior such as mode choice, neighborhood choice and travel distance (Cervero 2001 Handy et al 2005; Ewing and Cervero 2010; TRB report 2009). The vast literature over the past 2 decades consists of numerous studies that have analyzed travel behavior while controlling for measures of the BE and socio-economic variables. This vast literature has been summarized in some documents such as Badoe and Miller (2000), Ewing and Cervero (2010) and TRB report (2009).

Badoe and Miller (2000) 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) (2009) 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 (2010) 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 (2005) 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 behavior and addresses issues of self-selection. The literature review of Cao and colleagues (2008) 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 (2010) 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 (2006), Schafer et al. (2006) and Wee et al. (2005) who evaluate different vehicle technologies in North America and Europe. Similarly, Ally and Pryor (2007), Karman (2006) and Frey et al. (2007) 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 (Castella 2009; Chester 2010; Rozycki 2003). For cars, it ranges from 67% to 74% of the total life cycle emissions (Schafer 2006). 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 (Marin 2010a, 2010b) and it eliminates the combustion of fossil fuels (Smith 2003). 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 (Zamel 2006; Meegahawatte 2010).

Among other shortcoming in this vast literature, we can mention again that the impacts of BE & TS accessibility includes the fact that very few comprehensive studies on the comparison of UF and TS strategies and emerging green technologies. Moreover, some limitations in the approaches used for estimating GHG emissions. Most of the past studies have used aggregated and simple methods for estimating transportation GHG, not very exact and biased fuel consumption rates and correction for speed.
The impact of emerging green technologies has attracted a lot of attention in the last years, with few studies looking at the impact of technologies at the regional (city) level and comparing them with UF and TS strategies,

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 (Barla, et al 2009, Barla, et al 2011). 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 O-D survey, which provides 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, car occupancy, 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.

The following sections provide some details of each of these steps.

3.1. *Trip-level GHGs:*

For each trip in the 2003 Montreal household travel survey, two GHG emitting mode categories are distinguished, private motor vehicles and public transit. Some trips can involve one or more modes (e.g., commuter train and automobile in kiss & ride or park & ride trip).

<u>*For private motor vehicle trips*</u>: For trips involving motor-vehicle as a unique or combined mode (e.g., in “kiss and ride” and “park and ride” trips), 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 Barla, et al (2009) and Barla, et al (2011) and emissions for a given trip departing in a particular hour are estimated as:

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

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. As mentioned above, the O-D surveys do not include vehicle information. We therefore used an alternative dataset which provides the FCR of all registered private vehicles in the province of Québec. This dataset has been developed by Barla et al. 2007 and provides an average FCR at three-digit postal code level (Forward Sortation area, or FSA) considering the fleet characteristics (make, model and year). This was

generated using the motor-vehicle fleet inventory of the automobile insurance corporation of Quebec (SAAQ).
D_{ij} = Travel distance on segment (link network) *i* in 100km. For selecting trip paths, user equilibrium conditions are established for morning and afternoon rush hours. For out-of peak hours, free flow conditions are defined. Then, travel times and speeds at the link level are specified for peak hours (considering congestion) and out-of peak hours (without congestion). Finally, using the shortest time path algorithm, the trip path is defined according to the departure time (hour). The final outcome of this step is the speeds and distances for each link belonging to each trip path. Speeds and distances are estimated 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 (Babin, et al 2004). 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[†])

R_{Aj} = Number of passengers in trip j including driver. Obtained by summarizing for car trips done in the same household, at the same time, origin and destination.

<u>*For public transit trip:*</u> For uni-modal or multimodal trips involving public bus transit and/or commuter trains, 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:

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

Where:

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:

$$FC(S) = 257.8*(Bus\ speed)^{0.48} \tag{3}$$

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 (Chapleau 1992). Trips were simulated in collaboration with the *Agence Métropolitaine de Transport* (AMT).

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

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

R_{Bj} = Ridership for bus on trip j. To determine the proportion of transit-trip-level emissions that should be assigned to a given passenger, emissions are divided by the number of passengers thereby taking into account occupancy rates.

For commuter train lines 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) 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 (Miranda-Moreno et al. 2011). 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 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. For instance, in the case of land use mix, the area of each land use for all nine cells are added and applied to the central grid. 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).

<u>Land use mix:</u> 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.

The entropy index was calculated using:

$$E_j = -\sum \frac{\left[\left(\frac{A_{ij}}{D_j}\right)\ln\left(\frac{A_{ij}}{D_j}\right)\right]}{\ln(n)} \qquad (4)$$

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.

Finally, n is the total number of different land uses which is 5 in this analysis.

Population density: Population was obtained at the census tract level from Statistics Canada (Statistics Canada 2001) 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 5).

$$PTaccess_j = \sum_{i=1}^{n} \frac{1}{(d_{ij} * h_i)} \quad (5)$$

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 by Lin and Long (2008), Riva, et al. (2008) and Miranda-Moreno (2011). By combining indicators, one can better describe activity density (Kamruzzaman et al 2009) and more clearly understand the effect that changing levels of urban form and public transit can have (Bento et al 2005).

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 (Fig 1. (a)) and ii) simultaneous equation model in which UF&TS attributes are combined and represented through neighborhood typologies (Fig 1. b).

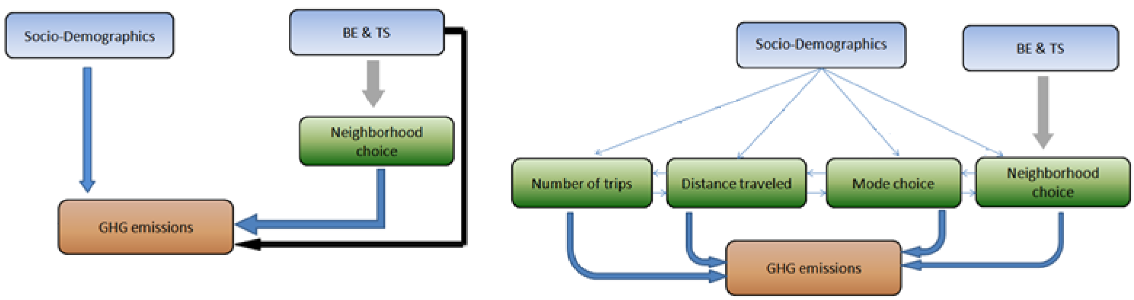

Fig.1 (a) Direct link between UF&TS and GHG; (b) Indirect link between UF&TS and GHG emissions

In the second approach, the choice of residential neighborhood is modeled as a simultaneous choice with the natural logarithm of GHGs as a continuous outcome. Different choices (neighborhood typologies) are set up using a clustering technique, each indicating the cluster (or neighborhood) chosen by the households as their residential location.

The modeling algorithm follows a maximum simulated likelihood formulation.

$$\ln(GHG_i) = \alpha x_i + \sum_{j=1}^{5} \mu_j k_{ij} + \sum_{j=1}^{5} \lambda_j l_{ij} + \varepsilon_i \tag{6}$$

$$N_{ij} = \beta_j z_i + \delta_j l_{ij} + \eta_{ij} \quad j = 1, \ldots, 10 \tag{7}$$

Where,
$\ln(GHG_i)$: is the natural logarithm of total transportation GHGs at the household level
N_{ij} : is the 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 (2006), which has been implemented in STATA. This estimation method models multinomial treatments on continuous outcomes using maximum simulated likelihood. The model considers the effect of endogenous variables (neighbourhood type and car ownership) on the GHG variable, conditional on two sets of independent variables. The model is estimated using maximum simulated likelihood and the simulator uses Halton sequences (Deb and Trivedi 2006).

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 OD survey for all trips and then aggregated at the household level. These attributes consist of number of motor-vehicles, number of persons, number of children, number of full-time and part time workers, number of retirees and students, number of adults. A summary statistics of socio-demographics is presented in Table 1.

4.1. *UF & Transit indicators*

Figures 2 (a)-(d) show population density, land use mix, transit accessibility and the resulting neighborhood typology clusters respectively, in Montreal for the year 2003. Also in table 1 some statistics for UF and transit accessibility are reported. For more detail on these indicators see section 3.2.

Table 1. Summary statistics of socio-demographics, UF and TS at the household level, Montreal OD 2003 (based on a sample of = 42,094 households)

Category	Variable	Mean	Std. Dev.	Min	Max
Socio-demo	Number of cars	1.266	0.914	0	18
	Number of persons	2.421	1.267	1	16
	Number of children	0.484	0.873	0	11
	Number of fulltime workers	1.064	0.844	0	10
	Number of part time workers	0.11	0.333	0	3
	Number of students	0.587	0.924	0	10
	Number of retirees	0.314	0.62	0	7
	Number of adults	1.936	0.833	1	11
UF & TS	Population density * (people per hectare)	47.04	34.36	0	148.65
	Transit accessibility *	120.87	126.44	0	747.37
	Land use mix (entropy)*	0.3438	0.1740	0	0.7578

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

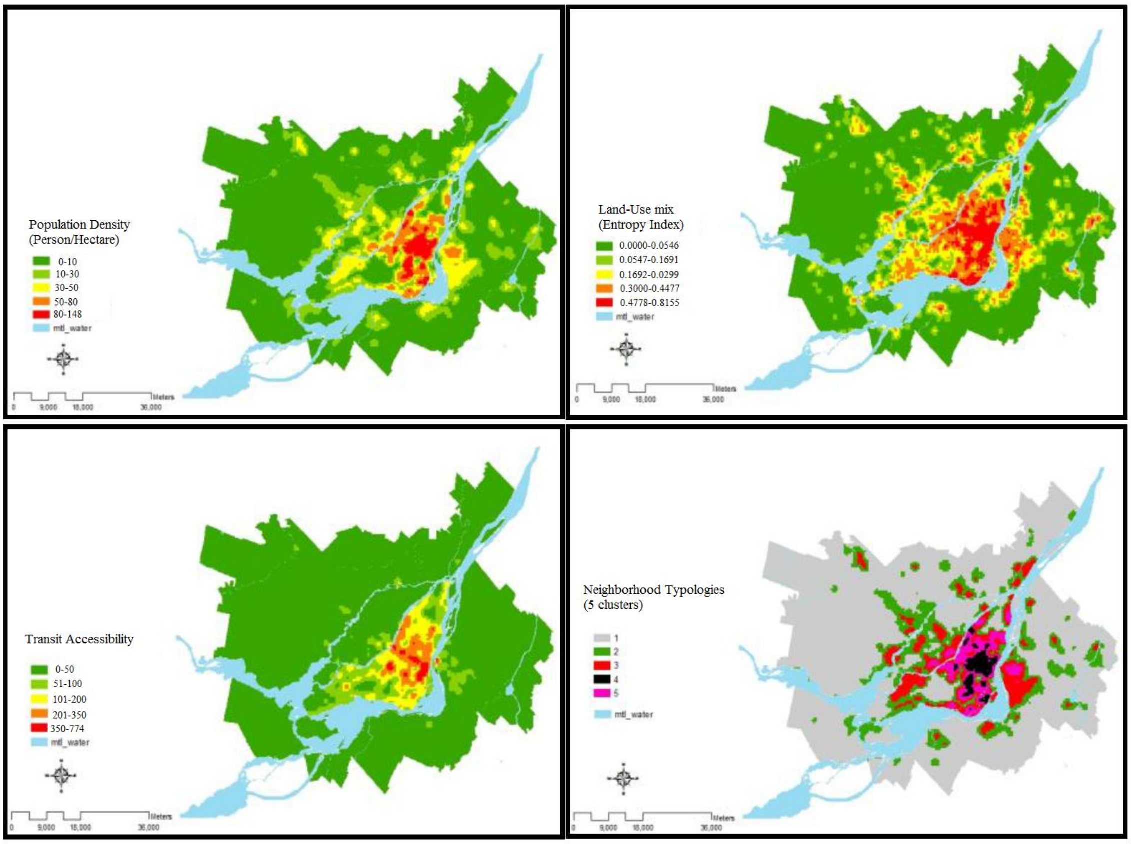

Fig.2 (a) Population density (person/Hectare) (top left); (b) Land-use mix (top right); (c) Transit accessibility (bottom left); (d) Neighborhood typologies (5 cluster setting for Montreal 2003) (bottom right).

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 with these clusters based on which grid cell they fall in geographically. The goal of using this technique is to maximize the inter-cluster variation while minimizing intra-cluster variation. Only grid cells with at least one value in the three built environment measures were considered in the cluster analysis, meaning that cells with no land use mix, no public transit accessibility, and no population were eliminated from this stage of the analysis. Figure 2 (d) represents the generated neighborhood clusters. As it can be seen from Fig2 (d), the neighborhoods can be classified as followed:

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 average.

Cluster 3: Inner suburb: this is the intermediate neighborhood type, with all UF values being equal or very close to the average.

Cluster4: 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).

4.2. *Household emission inventory*

The spatial distribution of GHGs at the household level is represented in Fig. 3 (a) and (b). The map represents the average emissions for the total household travel GHG, for all households that fall inside it.

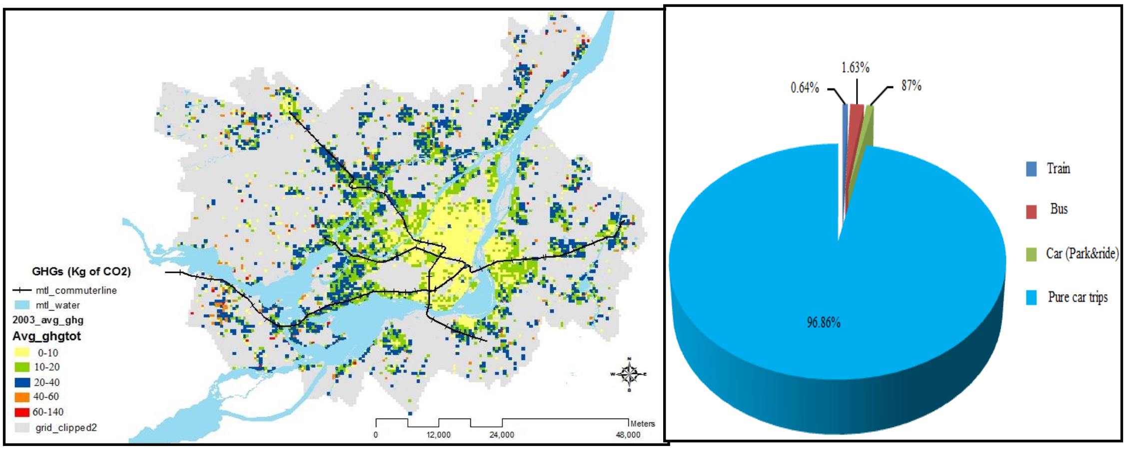

Fig.3 (a) Spatial distribution of household GHG inventory; (b) percent of total GHG by mode.

From this figure it can be seen that the central neighborhoods emit less and as one goes towards the suburbs the GHG footprint of the households increases. This can be explained by the relative increase in distance traveled by these households (suburban) and their predominant use of car.

Fig.3 (b) shows the GHG by mode. It’s clear that pure auto-vehicle trips have the highest contribution in household travel GHG. In comparison, the share for public transit sector is less than 4%.

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 two settings. The first model includes number of cars owned by the household; whereas the second model (model 2) does not use. The reasoning behind running two models is that the car ownership variable is usually reported in the literature as an endogenous variable with GHG. 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) would cause 2.49% (*3.53%*) and 5.17% (*5.88%*) 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 seems to be slightly greater than most of the past North American studies, in particular for transit accessibility (TS). This may be linked to the fact that the Montreal region has a higher population density and better transit supply than many US cities on which studies reported in the literature are based.

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

	Model 1 – with car ownership			**Model 2 - without car ownership**		
Ln (Total Household GHG)	**Coef.**	**P>|t|**	**Elast %**	**Coef.**	**P>|t|**	**Elast %**
Residential density *	-0.005311	0.00	-2.49	-0.007567	0.00	-3.53
PT accessibility *	-0.004309	0.00	-5.17	-0.0049088	0.00	-5.88
Entropy *	-0.261260	0.015	-0.89	-0.7390338	0.00	-2.53
Number of car **	1.198983	0.00	119.90	-	-	-
Number of retirees **	-0.857403	0.00	-85.74	-0.5184977	0.00	-51.85
Number of students **	-0.106384	0.00	-10.64	0.2196986	0.00	21.97
Number of part time workers **	0.346549	0.00	34.65	0.7754251	0.00	77.54
Number of fulltime workers **	0.738245	0.00	73.82	1.021828	0.00	102.18
Number of children **	-0.083305	0.005	-8.33	-0.0413944	0.137	-4.14
Single adult family	-1.33611	0.00	-73.71	-1.72077	0.00	-82.11
Low income (less than 40k)	-	-	-	-1.425569	0.00	-75.96
Medium income (40k to 80k)	-	-	-	-0.1278016	0.012	-12.00
High income (more than 80k)	-	-	-		Base case	
Constant	-2.40075	0.00	-	1.411356	0.00	-

(10% increase for elasticity)

****(1 unit increase for elasticity)***

With respect to employment, different employment status variables (retired, student, part time and full time) are statistically significant. Increasing the number of full time or part time workers by one unit causes about 73% (*102%*) and 34% (*77%*) 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 85% (*51%*). 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 (73% less in model 1 and 82% 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). The OLS, however, only explains about 39% of variation in the model (R^2 = 0.39).

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

	OLS			SEM		
Ln(Sum of hshld GHGs)	**Coef.**	**P>t**	**Elasticity %**	**Coef.**	**P>t**	**Elasticity %**
Cluster1 & car=0	-4.60	0.00	-99.00	-4.33	0.00	-98.68
Cluster1 & car>=1	0.46	0.00	58.97	0.27	0.00	30.97
Cluster2 & car=0	-4.96	0.00	-99.30	-4.77	0.00	-99.15
Cluster 2 & car>=1	0.34	0.00	39.88	0.31	0.00	36.2
Cluster3 & car=0	-4.29	0.00	-98.63	-4.04	0.00	-98.25
Cluster 3 & car>=1	Base case					
Cluster4 & car=0	-4.84	0.00	-99.21	-4.54	0.00	-98.93
Cluster 4 & car>=1	-1.02	0.00	-63.82	-0.91	0.00	-59.87
Cluster5 & car=0	-4.15	0.00	-98.42	-3.87	0.00	-97.91
Cluster 5 & car>=1	-0.38	0.00	-31.41	0.02	0.81	1.80
Number of retirees	-0.71	0.00	-70.61	-0.73	0.00	-73.13
Number of student	0.30	0.00	30.07	0.29	0.00	28.54
Number of part time workers	0.69	0.00	69.32	0.69	0.00	68.74
Number of fulltime workers	0.99	0.00	99.15	0.95	0.00	94.64
Number of children	-0.07	0.00	-7.16	-0.06	0.01	-6.77
Single adult family	-1.24	0.00	-71.03	-1.17	0.00	-68.89
Low income	-0.73	0.00	-51.6	-0.71	0.00	-51.2
Medium income	-0.08	0.08	-8.01	-0.09	0.05	-8.77
High income	Base case					
Constant	0.06	0.37	-	-0.35	0.00	-

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, except for cluster 5 with one or more cars

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% 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.

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). By adding a retired person to the household, total household GHG emission is reduced by 73% according to the SEM model. Also by increasing the number of fulltime or part-time workers by one person, the relative GHG emissions increase by 94% and 68%, respectively. Persons leaving alone (single person households) have a negative impact on GHG emissions. These households tend to generate about 68% 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%. This is due to the use of public transit and car sharing programs by these households for their daily trips and therefore a significant reduction in their GHG contribution. The income variables are also found to be statistically significant. 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% 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%.

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. More specifically, five scenarios are contrasted:

<u>*Scenario 1*</u>: 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).
<u>*Scenario 2*</u>: 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.
<u>*Scenario 3*</u>*:* 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 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.
<u>*Scenario 4*</u>: combination of scenarios 2 and 3. This scenario involves replacing current diesel trains by electric trains and for the bus fleet, hybrid buses replace normal diesel buses. The change in transit GHG per trip, comparing to the base case is then observed.
<u>*Scenario 5*</u>*:* projecting car fuel efficiency to the year 2010 using the current fuel consumption trends (from 2001 and 2008). 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 percentage reduction in car trip GHG is then estimated to see the difference.

The results of each scenario are presented in tables 4 and 5. 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). 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. This represents in general an 11% decrease in GHGs with respect to the status-quo scenario. 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 to fall to 0.387kg (20% reduction compared to the current state). Moreover if the two scenarios mentioned above were implemented simultaneously there would be a 32% reduction in transit sector GHG emissions.

Table 4: GHG for different transit technology scenarios

	Status Quo	**Hybrid bus**	**Electric train**	**Hybrid bus + Electric train**
***Average* per transit trip (*kg* of co2)**	0.4864	0.4314	0.3874	0.3327
Percent change from do nothing	-	-11%	-20%	-32%
Total for all transit trips in OD (*Tonnes* of CO2)	20.106	17.842	16.024	13.76

For scenario 5, GHG for pure car trips for status quo has a dominant effect in total GHG share (619,641 kg of CO2 for the pure car trips of all households in the 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. 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 of the carbon household 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 Montreal, 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. This is in accordance with the literature; however, these values are slightly greater than those obtained in past studies involving US & Canadian cities. 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 (up to 32% reduction when both hybrid bus and electric trains are introduced). 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% 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.

Acknowledgment

We would like to acknowledge the financial aid provided by FQRNT under the program “Recherche partenariat contribuant réduction et séquestration gaz effet de serre” and thank AMT and MTQ for providing us with the data necessary for this research.

References:

Ally, J.; Pryor, T. Life-cycle Assessment of Diesel, Natural Gas and Hydrogen Fuel Cell Bus Transportation Systems. Journal of Power Sources. 2007, 170, 401-411.

Babin, A., P. Fournier, and L. Gourvil (2004). “Modèle d’émission des polluants et des GES et modèle de consommation des carburants” pour MOTREM, Service de la modélisation des systèmes de transport, Ministère des Transports du Québec, 221.

Badoe, D., and E. Miller. 2000. Transportation—Land Use Interaction: Empirical Findings in North America, and their Implications for Modeling. Transportation Research Part D, Vol. 5, No. 4.

Barla, P.; Lamonde, B.; Miranda-Moreno, L.F. et N. Boucher (2009) , "Traveled Distance, Stock and Fuel Efficiency of Private Vehicles in Canada: Price Elasticities and Rebound Effect" , Transportation , vol. 36, no 4, pp. 367-467

Barla, P.; Miranda-Moreno, L.F. et M. Lee-Gosselin (2010) , "Urban Travel CO2 Emissions and Land Use: a Case Study for Quebec City" , Transportation Research Part D : Transport and Environment.

Bento, A. M., Cropper, M. L., Mobarak, A. M., & Vinha, K. (2005, August). The Effects of Urban Spatial Structure on Travel Demand in the United States. The Review of Economics and Statistics, 87(3), 466-478.

Bhat, C.R., Guo, J.Y., 2007. A comprehensive analysis of built environment characteristics on household residential choice and auto ownership levels. Transportation Research B 41, 506–526.

Cao, X., P. Mokhtarian, and S. Handy. 2008. *Examining the Impacts of Residential Self- Selection on Travel Behavior: Methodologies and Empirical Findings*. Research Report UCD-ITS-RR-08-25. Institute of Transportation Studies, University of California, Davis. http://pubs.its.ucdavis.edu/publication_detail.php?id=1194. Accessed on March 30, 2009.

Castella, P.S.; Blanc, I.; Ferrer, M.G.; Ecabert, B.; Wakeman, M.; Manson, J.-A.; Emery, D.; Han, S.-H.; Hong, J.; Jolliet, O. Integrating Life Cycle Costs and Environmental Impacts of Composite Rail Car-Bodies for a Korean Train. International Journal of Life Cycle Assessment. 2009, 14, 429-442.

Chapleau, R., La modélisation de la demande de transport urbain avec une approche totalement désagrégée. In Proceedings of the 6th World Conference on Transportation Research, Lyon, France, 1992

Chester, M.; Horvath, A. Life-Cycle Assessment of High-Speed Rail: The Case of California. Environmental Research Letters. 2010, 5(1), 1-8.

Crane, R. 2000. The Influence of Urban Form on Travel: An Interpretive Review. *Journal of Planning Literature*, Vol. 15, No. 1, pp. 3–23.

Deb, P. and Trivedi, P. K. Specification and simulated likelihood estimation of a non-normal treatment-outcome model with selection: Application to health care utilization. The Econometrics Journal, 2006 9: 307–331

Ewing, R., and R. Cervero. 2001. Travel and the Built Environment: A Synthesis. *Transportation Research Record* 1780, pp. 87–113.

Ewing, R., and R. Cervero. 2010. "Travel and the Built Environment: A Meta-Analysis." Journal of the American Planning Association 76 (3): 265–94.

Frey, H.C.; Rouphail, N.M.; Zhai, H.; Farias, T.L.; Goncalves, G.A. Comparing Real-world Fuel Consumption for Diesel- and Hydrogen-fueled Transit Buses and Implication for Emissions. Transportation Research Part D. 2007, 12, 281-291.

Handy, S., Cao, X., Mokhtarian, P., 2005. Correlation or causality between the built environment and travel behavior? Evidence from Northern California. Transportation Research D 10, 427–444.

Handy, S. 2005. Smart Growth and the Transportation-Land Use Connection: What Does the Research Tell Us? *International Regional Science Review*, Vol. 28, No. 2, pp. 146–167.

Kamruzzaman, M., Hine, J., Gunay, B., & Blair, N. (2009). Using GIS to visualize and evaluate student travel behaviour. Journal of Transport Behaviour, 19, 13-32.

Karman, D. Life-Cycle Analysis of GHG Emissions for CNG and Diesel Buses in Beijing. EIC Climate Change Technology. 2006, 1, 248-253.

Lin, J., & Long, L. What neighborhood are you in? Empirical findings of relationships between household travel and neighborhood characteristics. [10.1007/s11116-008-9167-7]. Transportation, 35(6),2008, 739-758.

Manaugh, K., Miranda-Moreno, L. F., & El-Geneidy, A. M. (2010). Neighborhood travel behaviour: A factor and cluster analysis to understand travel behavior in the Montréal metropolitan region. Transportation, 37(4), 627-646.

Marin, G.D.; Naterer, G.F.; Gabriel, K. Rail Transportation by Hydrogen vs. Electrification – Case Study for Ontario Canada, I: Propulsion and Storage. International Journal of Hydrogen Energy. 2010a, 35, 6084-6096.

Marin, G.D.; Naterer, G.F.; Gabriel, K. Rail Transportation by Hydrogen vs. Electrification – Case Study for Ontario, Canada, II: Energy Supply and Distribution. International Journal of Hydrogen Energy. 2010b, 35(12), 6097-6107.

Meegahawatte, D.; Hillmansen, S.; Roberts, C.; Falco, M.; McGordon, A.; Jennings, P. Analysis of a Fuel Cell Hybrid Commuter Railway Vehicle. Journal of Power Sources. 2010, 195, 7829-7837.

Miranda-Moreno, L., Bettex, L., Zahabi A., Kreider, T., Barla P. A simultaneous modeling approach to evaluate the endogenous influence of urban form and public transit accessibility on distance traveled, Journal of Transportation Research Record (accepted), 2011.

Riva, M., Apparicio, P., Gauvin, L., & Brodeur, J.-M. Establishing the soundness of administrative spatial units for operationalising the active living potential of residential environments: An exemplar for designing optimal zones. International Journal of Health Geographics, 7(1), 2008, 43.

Schafer, A.; Heywood, J.B.; Weiss, M.A. Future Fuel Cell and Internal Combustion Engine Automobile Technologies: A 25-year Life Cycle and Fleet Impact Assessment. Energy. 2006, 31, 2064-2087.

Statistics Canada. (2001). 2001 Census of Population, Montréal (862 areas). E-STAT (distributor).

Smith, R.A. Railways: How They May Contribute to a Sustainable Future. Proceedings from the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit. 2003, 217, 243-248

TRB-Transportation Research Board (2009)."Driving and the Built Environment: The Effects of Compacat Development on Motorized Travel, Energy Use, and CO2 Emissions", Special Report 298, Washington DC, National Research Council

von Rozycki, C.; Koeser, H. ; Schwarz, H. Ecology Profile of the German High-Speed Rail Passenger Transport System, ICE. International Journal of Life Cycle Assessment. 2003, 8(2), 83-91.

Wee, B.V.; Janse, P.; Van Den Brink, R. Comparing Energy Use and Environmental Performance of Land Transport Modes. Transport Reviews. 2005, 25(1), 3-34.

Zamel, N.; Li, X. Life Cycle Analysis of Vehicles Powered by a Fuel Cell and by Internal Combustion Engine for Canada. Journal of Power Sources. 2006, 155, 297-310.