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Urban travel CO_2 emissions and land use

Philippe Barla
Centre for Data and Analysis in Transportation (CDAT)
Department of Economics
Université Laval
Phone: 418-656-7707
E-mail: philippe.barla@ecn.ulaval.ca

Luis F. Miranda-Moreno
Department of Civil Engineering and
Applied Mechanics
McGill University
Phone: 514-398-6589
E-mail: luis.miranda-moreno@mcgill.ca

Martin Lee-Gosselin
CRAD
Université Laval
Phone: 418-656-7558
E-mail: Martin,Lee-Gosselin@CRAD.ulaval,ca

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Abstract

In this paper, we empirically analyse the determinants of urban travel greenhouse gas (GHG) emissions. Specifically, we examine the impact of individual and household socio-economic characteristics as well as the effect of land use (LU) and transit supply (TS) characteristics around the residence and work place. The analysis is carried out using an activity-based longitudinal panel survey in the Quebec City region (Canada). We find that emissions considerably vary depending upon the respondent sex, professional status, age, family structure, income level and day of the week. Particularly, we find evidence of significant economies of scale within household in the production of GHG emissions. We also find major differences in emissions depending upon the type of neighbourhood. A respondent living in the city periphery would produce on average 70% more emissions that if he was located at the city center. LU and TS attributes are however also extremely different between these two locations. When estimating the elasticity of emissions with respect to LU and TS indicators such as residential density, we find that there are relatively small. In other words, drastic changes in urban pattern are required to curb urban travel GHG emissions.

1. Introduction

Worldwide, policy makers are looking for ways to reduce automobile dependency in urban areas. Automobiles are indeed responsible for several externalities such as congestion, noise and air pollution. They are also a significant source of greenhouse gas (GHG) emissions. The "Smart growth" movement advocates for the development of compact, transit-oriented and walkable neighbourhoods as a way to significantly reduce automobile use. A growing empirical literature (for reviews see Badoe and Miller, 2000, Ewing and Cervero, 2001, Transportation Research Board, 2009 or Barla et al. 2010) is examining if it is indeed possible to drastically affect travel decisions by changing the built environment.

In this paper, we contribute to this literature by estimating the impact of land use (LU) and transit supply (TS) attributes on the level of daily GHG emissions produced by Quebec City residents in their urban mobility. To our knowledge, this is one of the first attend to directly measure these relationships. Indeed, most existing works only focus on a subset of travel decisions affecting GHG emissions. For example, some studies analyse the impact of LU (e.g residential density) and TS indicators on the number and type of vehicle owned, others on mode choice or the distance driven. While indicative, these studies do not allow to precisely access the overall impact on GHG emissions.

Our analysis uses the results of a three waves longitudinal panel survey on households travels involving about 400 respondents belonging to 250 households and providing over 3800 observations on daily levels of GHG emissions. Emissions are computed taking into account each trip distance, mode choice, vehicle make-model-year, speed and number of passengers. We estimate a reduced-form model explaining the level of emissions as a function of individual and household characteristics (e.g. age, occupation, number of children), fixed effects for the day of the week and season, LU and TS attributes. LU is characterized by residential density around the respondent dwelling and by job density around his or her work place. The percentage of the respondent trips that are feasible by public transit and the bus-car relative travel time characterize TS.

We find that on average, Quebec residents produce 6.8 kg of CO_2e per day in their urban travel activities. Variability across respondent is quite important. Our empirical analysis shows that socio-economic characteristics play a critical role. For example, we find that women produce on average 20% less GHG emissions than men. Emissions begin to decline after 50 and drop sharply (-40%) after retirement. We also find significant evidence of economies of scale with the number of adults within the household. For example, a couple would only produce 55% more emissions than a single *ceteris paribus*. Income is positively associated with emissions. Emissions significantly increase during the week culminating on Friday (+ 22%). However, they are 24% lower on the weekend. Concerning the effect of LU, our results indicate that a respondent moving from the periphery to the city center could see his urban travel emissions be reduced by 70%. While this result could suggest that smart growth urban policies is effective, it is however very important to stress that the scenario under consideration actually corresponds to drastic changes in LU pattern. Indeed, a move from the periphery to the city center corresponds to an eight fold increase in residential density! In fact, the elasticity of emissions with respect to residential density is at best -0.18. Moreover, we find evidence that increasing density in a neighbourhood that is not close to the city center could have an even smaller impact.

The rest of this paper is organized as follows. In section 2, we present our empirical strategy and detail our contribution. Section 3 describes the data and the methodology to compute the level of GHG emissions. The empirical specifications, estimation procedures and results are discussed in section 4. Robustness analysis is presented in section 5. Finally, we conclude in section 6 with a discussion of policy implications.

2. Background

The level of daily GHG emissions caused by an individual *i* depends about a set of travel decisions as illustrated by the following factorization:

$$GHG_i = \left(\alpha_i^{PV} s_i^{PV} + \alpha^B s_i^B + 0\, s_i^{NM}\right) D_i$$

with :

α_i^{PV} : the average GHG emission factor of the private vehicles used by the respondent;

s_i^{PV} : the share of the daily travel distance made by private vehicles;

α^B : the emission factor of public bus;

s_i^B : the share of the daily travel distance made by public bus;

s_i^{NM} : the share of the daily travel distance using non-motorized modes (walk, bike);

D_i : the daily total distance travelled.

It highlights the role of the distance travelled, the modal shares and the emissions factor of the chosen modes. For this last aspect, the respondent has some control over the emission factor of the private vehicles he uses. It is affected by the type of fuel used by the vehicle, its fuel rating but also by the driving conditions especially the speed. Indeed, it is well known that actual fuel consumption varies considerably with speed.

A huge literature is analyzing the determinants of travel decisions. In many recent studies, special attention has been given to the impact of LU and TS. Generally, these studies find that LU and TS attributes do have a statistically significant impact on transportation decision however the magnitude of the effects is usually limited. For example, Bento *et al.* (2005) studies the impact of a city spatial structure (e.g. population centrality, residence/job mix) on the number of car owned, commute mode choice and the distance driving. The analysis is based on a cross section of 114 US cities. Most of the estimated LU and TS elasticities are below 0.1 in absolute values. Fang (2008) explore the impact of a neighbourhood residential density on car ownership and distance travel for a sample of Californian households. She finds that a 50% increase in residential density would only lead to a 200 km reduction in the annual distance driven by cars.

Brownstone and Golob (2009) estimates the impact of a neighbourhood residential density on the distance driven and fuel consumed also using a sample of Californian households. They find an elasticity of the fuel consumed with respect to residential density of -0.14. A recent literature review (Transportation Research Board, 2009) reports that the elasticity of distance driven with respect to residential density would be between -0.1 and -0.24. Reducing automobile dependency would therefore require drastic changes in the built environment. If the results of these studies provide some indications on the impact of the built environment on GHG emissions, they do not allow to precisely evaluating them. Indeed, each of them only studies a subset of the travel decisions determining emissions.

In this paper, we tackle this issue by directly estimating the impact of LU and TS attributes on the level of GHG emissions produced by individuals in their daily travel activities. In other words, we estimate a reduced-form model which provides the net effects of these variables on emissions. Barla *et al.* (2010) report preliminary results using this approach. We extend this analysis in several directions. First, we use a larger data set that comprises three waves of a longitudinal panel survey. Second, the analysis of GHG emissions produced by a respondent is carried out at the daily level which allows characterizing the weekly pattern of emissions. Third, we examine not only the impact of LU and TS around the respondent resident but also around its work place. Fourth, we use a variety of alternative estimation methods and specifications to access our results robustness.

Beside LU and TS indicators, our model also includes respondents and households characteristics. This is important in order to limit the risk of what is often referred in the literature as "residential sorting". Indeed, one major challenge in this type of analysis is making the distinction between associative correlation and causality (see Brownstone and Golob, 2009, Bhat and Guo, 2007 and Pinjari et al. 2007). This problem is due to the fact that a household's place of residence is the result of a choice that is based on the same determinants as its mobility profile. This means, for example, that even if it is observed that households living in dense neighbourhood are less dependent on automobiles, it cannot be necessarily concluded that this is the direct result of neighbourhood density. Indeed, these households may have characteristics (size, income) and attitudes (lifestyle, green mind-set) that make them prefer both living downtown and a form of mobility that is less automobile-dependent. Policies promoting dense neighbourhoods would only lead to changing the population's profile not residents' travel behaviour. Hopefully, some recent studies (Bhat and Guo, 2007, Brownstone and Golob, 2009) show that proper controlled for the respondent and household main socio-economic characteristics greatly limit this issue.

3. Data and GHG emissions computation

The main data source is an activity-based longitudinal panel survey on household activities and travel designed to improve the understanding of the relationships between land-use, transportation and the environment.[1] The panel includes three waves mostly at one year interval for a given household. Table 1 presents some characteristics of the panel. Different survey

[1] The survey was carried out as part of a research program of the Canadian research network PROCESSUS.

methods were used to gather a rich set of information while keeping a high response rate. They include in-home interviews, self-administrated diary of activities and travel and validation procedures by phone. For wave 1, one week of activities and travel were reported while for waves 2 and 3, two consecutive days of data were gathered. Each member of a household aged at least 16 years old had to provide detailed information activities and travel. The targeted population is the Quebec City region area. A letter was first sent to identify potential respondents. The first wage sample was then designed by quota to insure that it fit the area population profile in terms of age group, localization and number of cars owned. Figure 1 presents a map of the area and the localization of households in the first wave. The retention rate is over 65% between wave 1 and 3 which is quite high given the questionnaire complexity. For each trip, a respondent had to provide the precise origin and destination, the travel mode, time of departure and arrival, the number of passengers for private vehicle trips and the nature of the activity at destination. The survey was designed to characterize daily activities within the region. In other words, it intentionally avoids scheduling the survey during periods where one of the household members was expected to take a non-routine long-distance trip.

Obviously, the size of the sample is relatively limited. In Barla et al. (2010), we compare the sample structure with the region socio-economic characteristics provided by the Census. We also use an origin-destination survey to access the panel reliability.[2] While there are some differences, overall the panel is quite representative of the population structure and travel pattern.

For each trip reported (over 15 000), it is possible to evaluate the amount of GHG emission that is generated. The emissions depend upon the mode used namely private vehicle (PV), public bus (B) or non-motorized modes. The mode PV includes all trips made using one the household vehicles (motorcycle, cars, and light duty vehicles) or any other private vehicles including taxi. In the Quebec City area, buses are the only public transit mode. A trip occurs when there is a change of localization (the origin differs from the destination). Several trips are however eliminated either because there are not relevant for our analysis (i.e. non-routine long distance trips) or because missing geo-localization of the origin or destination (less than 5%).

For the PV mode, the emissions produced at the trip level are estimated as follows:

$$GHG_{i,t}^{PV} = \frac{FCR_{i,t} \; x \; SCF_t \; x \; EF_{i,t} \; x \; (D_{i,t} / 100)}{NP_{i,t}}$$

$GHG_{i,t}^{PV}$: the level of GHG emission produced by respondent *i* on trip *t* using a PV. It is expressed in gram of CO_2 equivalent.

$FCR_{i,t}$: the average fuel consumption rate of the motor vehicle used in liters per 100 km. This rate is based on the make, model, and year of the vehicle when the information is available (*i.e.* when the respondent identified the car used). These rates were provided by the *Energuide* produced by Natural Resources Canada. For cases where the vehicle was not identified (for example when the respondent used another vehicle or was a passenger), it was assumed that the

[2] The origin-destination is a large cross section survey of over 27 000 households. While much larger than the panel, it gather much less detailed information.

respondent used a vehicle that is comparable to those he or she owns.[3] For respondents who did not own a car, it was assumed that their automobile trips were made with an average fuel efficiency vehicle.[4]

SCF_t : the average speed correction factor. It is well known that the average fuel consumption rate reported by authorities most often underestimates actual fuel rating which depends on factors such as vehicle speed. To take this aspect into account, each trip was associated with an average speed which depended on the origin and destination as well as whether the trip occurred in peak or off-peak period. While the information included in the diary could allow us to deduce an average speed for a given trip, the information on trip duration turned out to be unreliable. Instead, the speeds were estimated by a traffic simulation model developed by the Quebec Ministry to Transport (see Tremblay 2007). The Quebec City region was divided into 799 traffic zones and free-flow as well as peak average speeds were simulated for each possible link. The fuel consumption correction factors were also provided by the Transport Ministry. These factors were developed by comparing actual versus average fuel consumption by speed for a sample of vehicles (Babin et al., 2004).[5]

D_t : the estimated distance (in km) between the trip origin and its destination. Distance was simulated using ArcGIS and the region route network. The chosen itinerary corresponds to the shortest time trip using posted speed limits. To compute emissions, we divide *D* by 100 since *FCR* is expressed in liters per 100 km.

$EF_{i,t}$: the emission factor. The level of emissions per liter of fuel consumed depends on the type of fuel (gasoline or diesel) as well as the age of the vehicle, which affects the type of pollution control equipment. We use the emissions factors reported by Environment Canada (2007).

$NP_{i,t}$: the number of passengers in the vehicle excluding the household children less than 16 years of age. The number of passengers is controlled in order to account for car sharing within as well as outside the household. For example, if a couple makes a trip together, each will report one trip, but the trip emission is only counted once (*i.e.* half for each observation). If the passenger is not a household member, only half of the emission is attributed to the respondent (and thus the sampled household). The household children were excluded from the count as they are not respondents (*i.e.* they did not complete a diary). In other words, their emissions are attributed to the adults in the car.

For public bus, the GHG emissions are estimated as:

$$GHG^{B}{}_{i,t} = \frac{FCRB\ x\ D_t\ x\ EFB}{ANP_t}$$

with:

$FCRB$: the average fuel consumption rate for public bus. Based on the local bus statistics, a fuel rating of 58.9 liters of diesel per 100 km was used.

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[3] If the household own several cars, we use the average fuel consumption rate.

[4] The average fuel consumption rate of the Quebec city fleet was used namely 9.29 liters per 100 km. For taxis, the average consumption rate of new compact and intermediate vehicles was used (8.53 liters per 100 km).

[5] For example, at a speed of 30 km/h, the actual fuel consumption rate would be about 20% greater than the average rate.

D_t: the estimated distance. This was calculated using the GIS software ArcGIS and the local bus network.

EFB: the emission factor for bus transit. It is based on the information reported by Tecsult, Inc. (2008).
ANP_t: the average number of passengers on board. We use data provided by the Quebec bus transit authority on the count of passengers for each departure, lines and between each stops. We estimate the weighted average number of passengers in peak and off-peak period. The average is taken over the whole network and weighted by the distance between stops. The average number in peak period is 14.9 passengers per bus while it is 11.8 in off-peak period.[6]

The trip-level emissions are then aggregated by day and per respondent. Table 2 reports some descriptive statistics on trips and emissions. Based on our estimations, respondent would produce on average about 6 835 g of CO2e with little differences across the waves (less than 10%) but significant variability across respondent and day. Our estimate is actually quite close to an estimation done by Tecsult inc (2008) for the city using different methodologies. Tecsult obtains a level of travel related emissions per capita and per day of 6453 g in 2004 and 6327 g in 2006.[7] Examining the main drivers of emissions, the average daily travelled distance is 32.8 km over about 4 different trips. On average 95% of the emissions produced by a respondent are due to PV. This reflects the large modal share of automobiles as well as the higher emission factor. About 30% of the travel distance is in peak period and the average speed is slightly less than 40 km/h. For trips in PV, the average number of persons in the vehicle is 1.46. On average the emission rate is at 211g of CO2e per km.

Table 3 shows how the average level of emissions varies with the respondent and household characteristics. We note significant variations. For example, female would produce 25% less emissions than male. Emissions appear to peak in the 35-49 age group with significant reductions after 65 years old. The average level of emissions per respondent also appears to increase with the size of the household, employment and income. The Quebec City area can be broadly divided in four zones based on the historical development of the city (see Vandermissen *et al.* 2004). The center corresponds to Quebec City center on the North shore of the Saint-Laurent River as well as the city center of Levis on the South shore. Old suburbs include neighbourhoods developed after World War II while new suburbs include those developed essentially after 1965 and the rest corresponds to the periphery. The average level of emissions per zone is quite different with households located at the periphery producing more than double the amount generated by those located in the city center. Obviously, these results are based on partial correlations that need to be validated using an econometric analysis.

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[6] Conceptually, it is not obvious to determine which part of the emissions produced by a bus to attribute to one specific passenger. The emissions could be divided by the number seats offered or, as we do it here, by the number of passengers. It could also be argued that the marginal contribution of one extra passenger is negligible. In this paper, we use the level of emission per passenger in order to be consistent with our computation of emissions for PV. In Barla et al. (2010), we do the analysis using the level of emissions per seat offered. The results are very similar to those reported here.
[7] The three methods used by Tecsult are based on: i) sales of fuel in the Quebec city region, ii) a model of traffic flow and iii) an adjustment of the emissions produced at the provincial level using the region share of vehicles.

4. Empirical specification and results

Our reduced form empirical model has the following overall structure:

$$GHG_{i,h,t} = \alpha + \beta X_{i,h,t} + \nu D_t + \eta LU_{i,h,t} + \lambda TS_{i,h,t} + \varepsilon_{i,h,t}$$

with:

i: an index identifying a respondent;
h: an index identifying a household;
t: an index representing the time.

$GHG_{i,h,t}$: level of daily GHG emission produced by respondent *i* belonging to household *h* and for time *t*.
$X_{i,h,t}$: the respondent and household socio-economic characteristics. Note that not all respondent characteristics vary with *i*, *h* and *t*. In fact, many of them are fixed over time (*e.g.* gender). There are however some characteristics which may vary with *t* (*e.g.* the work status). The same remark holds true for the other variables categories.
D_t : time varying variables.
$LU_{i,h,t}$: land-use characteristics around the residence and job location.
$TS_{i,h,t}$: transit supply characteristics.
$\varepsilon_{i,m,t}$: idiosyncratic error term.
$\alpha, \beta, \gamma, \nu, \eta, \lambda$: parameters to be estimated.

Table 4 describes the explanatory variables included in the model and provides some descriptive statistics. Obviously, several alternative specifications have been analyzed. We only report in this section the ones that are the most revealing. We discuss the results robustness in the next section. The respondent and household characteristics are: driving licence status, gender, university diploma, professional status (student, part-time, retired, full-time worker), the age group, the household structure (number of additional adults beside the respondent and children), homeownership and income class. Note that income class is not provided by households but rather it is estimated by the interviewer during the first home visit. In order to control for underreporting, we also include, for each respondent, the percentage of trips with unknown origins or destinations. Indeed, while overall 95% of the trips in our dataset have been geolocalized, for some respondents that percentage is much lower. Travel activities are likely to vary over the days of the week. We thus include dummies for each weekday and one indicator for the weekend. Dummies are also included for each season.[8] The LU and TS variables will be described below. The model is linear so that coefficients can be directly interpreted as changes in grams of CO_2e. The model is estimated by OLS but the standard errors for the parameters are robust to clustering amongst household members.[9] Table 5 reports the estimated coefficients

[8] Note however that very few observations were collected during the winter time (3%).
[9] In other words, only error terms from different households are assumed independent.

and corresponding elasticities for three specifications corresponding to different LU and TS attributes. We first discuss the impact of the socio-economic and time-specific determinants before turning to the effects of the built environment.

Without surprise, respondents that do not have a driving licence produce on average 40% less GHG emissions. The lower level of emissions for female is confirmed as we find females producing 20% less emissions than men all else being equal. Being "head of the family" or having a university diploma does not seem to have any significant impact. Professional status is affecting emissions with students, part-time workers, respondents without job and retired producing much less emissions. The magnitude of the impact may be quite considerable with retired respondents producing as much as 50% less GHG emissions than average. For the impact of age, we find that emissions start to decline around 50 (-20%). The effect of the variable AGE65 is positive but not statistically significant. The effect of this variable should however be interpreted in conjunction with the variable RETIRED as over 92% of the respondents over 65 are also retired. The percentage of reported trips for which the origin or destination cannot be located is without surprised associated with a lower level of emissions. The impact seems however limited as the elasticity is very low at 0.02. It is well known that underreporting often involves short distance trips that are not part of a routine. Each additional adult in the household leads to reduction in the respondent level of emissions of about 20%. This result contrasts with the positive link between a household size and emissions in Table 3. In fact, a couple would only produce about 60% more emissions than a single *ceteris paribus*. Economies of scale within the family and car-sharing likely explain this result. Each additional child increases by less than 10% a respondent level of emission. A high income (above 60 000$ per year) is linked to a higher level of emissions (around +20%). Emissions are higher as the work week ends with a maximum on Friday (+25% compared to Monday). Emissions are 15% to 20% lower on weekends. We do not find any significant seasonal effects however recall that our sample is not necessarily representative on that aspect as only 3% of the observations are in the winter time.

Next, we examine the impact of LU and TS attributes. In the long run, transit supply is certainly endogenous and very much dependant upon LU characteristics particularly density (see Small 2008). Specifications (1) and (2) therefore only include LU indicators so as to capture the full long term impact. Specification (3) controls for both LU and TS indicators. In specification (1), LU at the respondent place of residence is characterized by the broad division of the city in four areas introduced earlier. This approach has the advantage of being simple and provides easily interpretable results. The central zone is the reference. We find significant and important differences depending upon the respondent house localization. On average, a resident of old suburbs would produce 19% more emissions than if he or she was located in the city center. For new suburbs and the periphery, we note a 27% and 70% increase respectively. These are major differences. It should however be stressed that the land use pattern is also quite different between these four zones. For example, the average residential density is 4351 residences per km^2 in the center, 2082 in old suburbs, 1307 in new suburbs and only 506 in the periphery. In other words, drastic differences in LU are indeed associated with large variations in emissions. Within each zone, LU pattern may also vary quite a bit. Thus in specification (2), we replace the city division by a measure of residential density measured around each respondent dwelling. Specifically, the density is measured in a 500m buffer zone around the residence. The buffer size corresponds to a distance that can be easily walked. Density is one of the most common and basic indicators used in the literature because it is readily available but also because it often determines other urban aspects such as commercial and transit viability. In fact, LU and TS attributes are often very highly correlated making it difficult to disentangle the precise impact of each of them. In specification 2, we also characterize LU around the respondent work place. In this case, we use the density of jobs in a 500m buffer zone.[10] Both these measures have a negative and statistically significant impact on the level of emissions. The elasticities are however not very large at -0.18 and -0.11 respectively. A 10% increase in residential density would therefore be associated with a reduction of less than 2% in the level of emissions. Our results are in fact quite consistent with existing evidence on the impact of LU on the travel decisions as reviewed in section 2.

In specification (3), we add indicators characterizing transit. Specifically, we include a variable measuring the percentage of the trips made by a respondent that cannot (easily) be made by public bus (% NO BUS). We use the total access distance to transit to determine if a trip can or cannot be made by bus. If the total access distance is above 2 km, we consider that transit is not a viable option for the trip. This measure is therefore respondent and time specific as it depends upon her daily trip diary. We also include the total travel time if a respondent use public transit for its daily trips divided by the total travel time if he or she uses an automobile instead (BUS/PV). Relative travel time has been shown to be a key determine of mode choice.[11] In this model, the elasticities with respect to density around the house and workplace are slightly reduced at -0.12 and 0.07 respectively. As the share of trips that cannot be made by transit increases so does the level of emissions (elasticity at 0.13). Relative time also affect the level of emissions with an elasticity at 0.27. This means that a 10% reduction in bus travel time would lead to a 2.7% reduction in emissions. This is not negligible but notes that the improvements in transit needed for such a reduction are also not minor. Indeed, it supposes a time reduction for all the trips made by the respondent. In other words, a 10% improvement in travel time for only one specific bus line would have a much more limited effect as it would only affect a subset of trips made by a respondent.[12] Finally, note that the R-square is at best 0.2 meaning that a large share of the variability in the level of emissions cannot be explained.[13] In the next section, we examine how these results are robust to estimation and specification changes.

5. Alternative specifications and estimation methods

Examining the impact of alternative estimation methods, we start by re-estimating specification 3 using feasible generalized least squares in order to account for the possibility that the variance differ across respondents. The results are reported in Table 6. Compared to the results in Table 5, we note that i) some effects become somewhat smaller (e.g. NO LICENCE, FEMALE) and ii)

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[10] This measure performed better than one based on residential density. Note that it is set to zero for respondents that do not work.

[11] Note that our measure suffers two main shortcomings due to data limitations. First, total travel time for bus only includes access and bus travel time. We do not have information on frequencies making in impossible to include waiting time. Second, bus speed is set at 20 km/h and do not vary over time or lines.

[12] Also, this variable may be picking up the effect of trip distance. Indeed, BUS/PV increases with the trip distance (correlation at 0.4).

[13] This is not unique to our study. For example Bento et al. (2005) reports a R-square of 11% when explaining the distance driven.

some determinants become statistically significant (e.g. UNIV, AGE34).[14] However, overall the results and the main conclusions especially those on the impact of LU and TS remain very similar.

For about 15% of the observations, the level of emission is zero. In the majority of cases (57%), this is due to the absence of trips during the observed day. For the rest, the respondent has only used non-emitting modes (walk or bike). These observations with zero emission may cause a problem and lead to bias estimations when using OLS (see Wooldridge, 2002). We therefore re-estimate specification 3 using a tobit model with random effects at the respondent level. Rather than reporting the estimated coefficients, we instead present in Table 6 the total marginal effect which can be compared to our other results. Once again, the overall results are quite comparable when using this estimation approach. The Tobit results also allow examining the impact of the determinants on the probability that the level of emissions be zero.[15] The signs of these effects usually match those concerning the level of emissions. For example, a female respondent has a probability 5% larger than a man of reporting zero emission during one day. Also residential density is associated with a very small increase in reporting zero emission.

It is likely that respondent and household specific unobservable factors are creating correlation across observations thereby potentially affecting inference. To examine this issue, we estimate a two nested level mixed model with random intercepts at both the household and at the respondent-within-household levels. Once again our main conclusions remain largely unaffected (see Table 6).

Next, we report the results obtained using alternative specifications. First, we tried to include fixed effects for each waves. These effects were never statistically significant. We have also tried to introduce gasoline price. This variable was never statistically significant probably because of a lack in variability. Alternative measures for LU and TS were also tried (*e.g.* number of bus stop, measure of land use mix). The overall main conclusions were unchanged.[16] We also examined the impact of changing the size of the buffer zone to compute the LU indicators. The elasticity of emissions with respect to DENS@HOME is respectively -0.13 and -0.2 for 1 km and 3 km buffer size and the elasticity of emissions with respect to DENS@WORK is respectively -0.08 and -0.04.

We also re-estimate the model with the distance between the respondent home and his or her work (D_WORK) as a control variable. Clearly, this variable is certainly the result of a decision made by the respondent (and the household) that is very likely influenced by the variables already included so far. Still, it is interesting to measure the impact of the various factors conditional on D_WORK being fixed. The results are reported in Table 7. We first note that the variables capturing the respondent work status become statistically not significant and that the R-square is somewhat improved. We find that a 1% increase in D_WORK leads to a 0.28 increase in the level of emissions. The impact of DENS@HOME and DENS@WORK and

[14] As reported by Beck and Katz (1995), in small samples, standard error estimates from FGLS may be “too optimistic”.
[15] These results are available upon request to the corresponding author.
[16] Note that as most other studies, we find that the various LU and TS attributes are highly correlated making it sometime difficult to disentangle the specific effects of each of them.

BUS/PV is somewhat reduced but remain significant indicating that these aspects plays a role beyond simply reducing commute distances.

The results on the impact of residential density suggest so far that a respondent moving from a low density neighbourhood in the periphery to a highly dense area in the city center would see her level of emissions significantly reduced. It is unclear however if these results can be used to predict the impact of increasing density in a specific neighbourhood. Indeed, density may be pickup the effect of proximity to the city center. We therefore re-estimate specification 3 with an additional variable controlling for the distance between the respondent residence and the city central business district (D_CBD). Results are presented in Table 7. The effect of DENS@HOME is much decreased and not longer statistically significant. The effect of D_CDB is significant with elasticity at 0.2. Clearly, these two variables are correlated (correlation at -0.56) which may explain that DENS@HOME is no longer significant. Still, these results show that increasing residential density in a neighbourhood that is far from the city center may not reduce the level of emission very much unless obviously an alternative city center is developed.

6. Conclusion and policy implications

Our analysis provides indications on the net effects of socio-economic characteristics, LU and TS attributes on the level of urban travel GHG emissions. Our results indicate that:

- Female, respondents without a driving licence and those without job produce much less emissions;
- Emissions appears to be increasing first and then decline with age with a maximum in the 35-49 age group;
- The structure of the household is also a significant determinant. If children lead to an increase in the level of emissions produced by adults, we also find that there exist economies of scale with respect to the number of adult in the households.
- A high income is associated with a higher level of emissions.

For the impact of LU and TS characteristics, we first note considerable variation in the average level of GHG emissions depending on the respondent localization. These variations remain important even after controlling for individual and household socio-economic characteristics. However, the urban pattern also considerably varies across localization. In fact, when estimating elasticities of GHG emissions with respect to LU and TS indicators we find that these are relatively small. For example, we find an elasticity of emission with respect to residential density around a respondent dwelling of at best -0.18. Moreover, some of our results suggest that this elasticity is very likely smaller when considering the impact of increasing residential density of a neighbourhood that is not close to the city center. Overall, we are able to explain only a small fraction of the variability in the level of GHG emissions.

We can draw the following policy implications from our results:

- Future changes in the population socio-demographic structure could have important consequences on the level of urban travel GHG emissions. As the population gets older, we may expect significant reduction in the level of emissions. However, if the number of adults living alone continues to growth this could have the opposite effect. Public policies favouring an increase in the number of adults per household (*e.g.* incentive for multi-generational housing) could potentially lead to GHG emission reductions.

- Substituting residential development at the city periphery by increasing residential density at the city center may indeed be a strategy that reduces GHG emissions. The overall contribution of this measure in curbing travel GHG emissions remains however to be evaluated.
- Public policies aiming at increasing residential density in the suburbs are very likely to have little impact on urban travel GHG emissions.

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Table 1. Structure of the panel survey

	Wave 1	Wave 2	Wave 3
Period	February 2002 - December 2003	June 2004 – March 2005	July 2005 – March 2006
Number of days surveyed	7	2	2
Number of households	247	198	167
Total number of trips	10 823	2 630	2 304
Modal shares (% of trips)			
PV	82.2	85	82.2
BUS	3.4	2.6	2.9
Number of respondents	392	305	248

Table 2. Descriptive statistics on trips and level of emission (average per day and respondent)

Variable	Mean	Standard-deviation	Min.	Max.
GHG (g/day)	6 835	7 319	0	63 228
Wave 1	6 725	7 164	0	60 361
Wave 2	7 281	8 192	0	63 228
Wave 3	6 889	7 013	0	44 220
Average share of GHG by PV (%)	94.5	21.0	0	100
Distance (km)	32.8	33.3	0	367
Number of trips	4	2.4	0	15
% of the distance in peak period	29.0	33.5	0	100
Average speed (km/h)	38.6	22.3	5	100
Emission rate (g/km)	211.3	112.2	0	929
Average number of persons for trips using PV	1.46	0.69	1	7

Tableau 3. Average daily level of GHG emissions per respondent for different subgroups

Variable	Average GHG emissions (g of CO_2e per respondent and per day)
Sex	
Male	7 895
Female	5 937
University Diploma	
No	6 629
Yes	7 123
Age Group	
Less than 35 years	6 032
35-49	8 726
50-64	6 018
65 and more	5 544
Household size	
1 person	5 736
2 persons	6 242
3 persons	6 300
4 persons or more	9 325
Employment status	
Retired or unemployed	5 088
Employed (including students)	7 563
Income group	
Less than 20 000$	4 601
20 000$ - 60 000$	6 493
60 000$ and more	8 554
Residential zone	
Center	4 324
Old suburbs	5 366
New suburbs	6 390
Periphery	9 662

Table 4. Description of the explanatory variables and descriptive statistics.

Variable	Description	Mean*	Min/Max
Socio-economic characteristics			
NO_LICENCE	Dummy set to one if the respondent has no driver's license	4.6%	0/1
FEMALE	Dummy set to one if female	54.1%	0/1
HEAD	Dummy set to one if respondent is head of the household	95%	0/1
UNIV	Dummy set to one if the respondent has a university diploma	41.6%	0/1
STUDENT	Dummy set to one if respondent is a student	7.1%	0/1
PART-TIME	Dummy set to one if respondent is employed part-time	6.4%	0/1
RETIRED	Dummy set to one if respondent is retired	19.4%	0/1
NO_WORK	Dummy set to one if respondent is unemployed	9.9%	0/1
AGE34	Dummy set to one if respondent is less than 35 years old.	23.2%	0/1
AGE35-49	Dummy set to one if respondent is between 35 and 49 years old.	33.0%	0/1
AGE50-64	Dummy set to one if respondent is between 50 and 64 years old.	31.0%	0/1
AGE65	Dummy set to one if respondent is 65 or older.	11.3%	0/1
% UNKOWN	Percentage of trips reported with unknown origin or destination	3.0%	0/61
D_WORK	Shortest distance in km between the respondent's residence and his/her work place	5.3	0/45
HOWNER	Dummy set to one for households owning their home	70%	0/1
N_ADULT	Number of adults (age 16 or over) in addition to the respondent.	0.74	0/2
N_CHILDREN	Number of children under 16 in the household	0.72	0/4
INCOME_LOW	Dummy set to one if the household income is evaluated as being less than 20k	18%	0/1
INCOME_MED	Dummy set to one if the household income is evaluated as being between 20 and 60k	48%	0/1
INCOME_HGH	Dummy set to one if the household income is evaluated as being higher than 60k	33%	0/1
Time specific variables			
MO, TU, WE, TH, FR	Dummy variables corresponding to each day of the week.	14%, 15%, 15%,14%,14%	0/1
WE	Dummy set to one for Saturday and Sunday.	27%	0/1
FALL,WINTER, SUMMER, SPRING	Dummy variables corresponding to each season.	37%, 3.6%, 40%, 18%	0/1
LU &TS variables			
CENTER	Dummy set to one if the respondent's resident is located in the city center	11.2%	
OLDSUB	Dummy set to one if the respondent's resident is located in the old suburbs of the city built after World War II.	23.9%	

NEWSUB	Dummy set to one if the respondent's resident is located in the new suburbs of the city built predominantly after 1965.	36.6%	
OTHER	Dummy set to one if the respondent's resident is located in city periphery.	28.1%	
DENS@HOME	Density of residences per km2 computed in a 500-meter buffer zone around the household location	1620	22/7598
DENS@WORK	Density of jobs per km2 computed in a 500-meter buffer around the respondent work place.	3411	0/21273
D_WORK	Shortest distance in km2 between the respondent's residence and his/her workplace.	5.7	0/45
% NO BUS	% of the respondent daily trips that cannot be made by bus because walking for 2 km or more is required.	28%	0/100
BUS/PV	Total trip time using the bus dividing the trip time using private vehicle. All the daily respondent trips are considered except: i) trips of less than 1 km and ii) trips that cannot be made by bus as they require walking for more than 2 km. The variable is censured at 4. The speeds for private vehicles are those used to compute GHG emissions. For bus, we assume an average speed of 20km/h for the bus segment and 5km/h for the waling segment to access the bus.	2.87	0.51/4

*: for dummy variables, we report the proportion (%) in the sample which is the mean multiplied by 100.

Table 5. Empirical results

Variables	Specification 1		Specification 2		Specification 3	
	Coef. (se)	Elasticity	Coef. (se)	Elasticity	Coef. (se)	Elasticity
NO LICENCE	**-3132 (584)**	**-45**	**-2771 (685)**	**-40**	**-2900 (657)**	**-42**
FEMALE	**-1671 (383)**	**-24**	**1626 (396)**	**-24**	**-1513 (389)**	**-22**
HEAD	-232 (1007)		-100 (1117)		-459 (966)	
UNIV	216 (502)		320 (484)		490 (485)	
FULL TIME	Reference		Reference		Reference	
STUDENT	**-1377 (784)**	**-20**	**-1285 (923)**	**-19**	**-1199 (740)**	**-18**
PART-TIME	**-1349 (803)**	**-19**	**-1841 (923)**	**-27**	**-2161 (994)**	**-32**
RETIRED	**-1979 (647)**	**-28**	**-3458 (706)**	**-50**	**-3409 (759)**	**-50**
NO JOB	-1028 (795)		**-1686 (839)**	**-25**	-1645 (873)	
AGE34	-116 (656)		-353 (672)		-529 (656)	
AGE35-49	Reference		Reference		Reference	
AGE50-64	**-1133 (655)**	**-19**	**-1553 (666)**	**-23**	**-1491 (644)**	**-22**
AGE65	1133 (986)		759 (908)		1165 (864)	
% UNKNOWN	**-38 (10)**	**-0.01**	**-47 (9)**	**-0.02**	**-48 (10)**	**-0.02**
OWNER	595 (621)		656 (598)		198 (564)	
N_ADULTS	**-1444 (539)**	**-21**	**-1503 (530)**	**-22**	**-1579 (521)**	**-23**
N_CHILDRENS	727 (318)		535 (327)		**538 (301)**	**+8**
INCOME_LOW	Reference		Reference		Reference	
INCOME_MED	453 (627)		574 (595)		264 (591)	
INCOME_HGH	**1555 (857)**	**+23**	**1835 (835)**	**+27**	**1420 (833)**	**+20**
MO	Reference		**Reference**		**Reference**	
TU	516 (323)		**574 (324)**	**+8**	476 (322)	
WE	573 (386)		584 (374)		**607 (365)**	**+9**
TH	**653 (371)**	**+9**	571 (362)		**670 (349)**	**+10**
FR	**1821 (458)**	**+27**	**1746 (440)**	**+25**	**1694 (432)**	**+24**
WEEKEND	**-1088 (379)**	**-16**	**-1124 (372)**	**-16**	**-1492 (371)**	**-22**
FALL	Reference		Reference		Reference	
WINTER	1495 (1177)		713 (1217)		1385 (1209)	
SPRING	574 (649)		-269 (622)		519 (628)	
SUMMER	388 (441)		59 (465)		435 (485)	
CENTER	Reference		--		--	
OLD SUBURBS	**1306 (673)**	**+19**	--		--	
NEW SUBURBS	**1893 (587)**	**+27**	--		--	
PERIPHERY	**4803 (741)**	**+70**	--		--	
DENS@HOME	--		**-0.79 (0.15)**	**-0.18**	**-0.53 (0.16)**	**-0.13**
DENS@WORK	--		**-0.22 (0.05)**	**-0.11**	**-0.15 (0.05)**	**-0.07**
% NO BUS	--		--		**33 (6.5)**	**+0.13**
BUS/PV	--		--		**644 (254)**	**+0.27**
CONSTANT	**5602 (1597)**		**10722 (1702)**		**7909 (1631)**	
R-SQUARE	0.17		0.17		0.20	
Nb. Obs.	3812		3812		3812	

The parameter standard errors are robust to correlation within households and heteroskedasticity across households. In bold, the parameters that are statistically significant at 10% or less. Elasticities are computed at the sample average values. For discrete variables, the elasticity corresponds to the percentage change in emissions associated with a one unit change in the discrete variable.

Table 6. Results for alternative estimation methods using specification 3

Variables	GLS		Tobit with RE		Mixed model	
	Coef. (se)	**Elasticity**	**Marginal effect (se)**	**Elasticity**	**Coef. (se)**	**Elasticity**
NO LICENCE	**-2122 (222)**	**-31**	**-2180 (750)**	**-32**	**-1889 (949)**	**-27**
FEMALE	**-1012 (143)**	**-14**	**1138 (393)**	**-17**	**-1640 (366)**	**-24**
HEAD	**-661 (313)**	**-9.6**	-581 (890)		-213 (988)	
UNIV	**409 (146)**	**5.9**	420 (406)		361 (457)	
FULL TIME	Reference		Reference		Reference	
STUDENT	**-1214 (273)**	**-17**	**-989 (699)**		**-1151 (803)**	**-17**
PART-TIME	**-1738 (284)**	**-25**	**-1550 (638)**	**-23**	-1065 (752)	
RETIRED	**-3288 (271)**	**-48**	**-3109 (539)**	**-45**	**-3086 (691)**	**-45**
NO JOB	**-2168 (262)**	**-31**	**-1878 (562)**	**-27**	**-1508 (674)**	**-22**
AGE34	**-834 (234)**	**-12**	-427 (533)		-294 (617)	
AGE35-49	Reference		Reference		Reference	
AGE50-64	**-1341 (191)**	**-19**	**-777 (393)**	**-11**	**-715 (459)**	**-10**
AGE65	**608 (312)**	**+9**	1077 (722)		1108 (772)	
% UNKNOWN	**-41 (6)**	**-0.01**	**-43 (7)**	**-0.01**	**-49 (8)**	**-0.02**
OWNER	82 (174)		-60 (358)		-240 (601)	
N_ADULTS	**-1046 (154)**	**-15**	**-719 (327)**	**-10**	**-981 (549)**	**-14**
N_CHILDRENS	**291 (88)**	**4.2**	306 (139)		**545 (242)**	**+8**
INCOME_LOW	Reference		Reference		Reference	
INCOME_MED	-84 (199)		-164 (389)		-17 (648)	
INCOME_HGH	**775 (269)**	**+11**	521 (492)		1093 (826)	
MO	Reference		**Reference**		**Reference**	
TU	**450 (222)**	**+6.5**	**406 (221)**	**+6**	481 (321)	
WE	**512 (225)**	**+7.5**	**476 (227)**	**+7**	**546 (328)**	**+8**
TH	**583 (227)**	**+8.5**	**459 (229)**	**+7**	**558 (332)**	**+8**
FR	**1153 (228)**	**+17**	**1208 (245)**	**+17**	**1570 (335)**	**+23**
WEEKEND	**-937 (196)**	**-14**	**-956 (187)**	**-14**	**-1631 (293)**	**-24**
FALL	Reference		Reference		Reference	
WINTER	**955 (330)**	**+14**	229 (444)		292 (668)	
SPRING	112 (189)		-234 (277)		38 (434)	
SUMMER	185 (150)		-87 (206)		-247 (326)	
DENS@HOME	**-0.43 (0.04)**	**-0.10**	**-0.35 (0.09)**	**-0.08**	**-0.39 (0.15)**	**-0.09**
DENS@WORK	**-0.14 (0.01)**	**-0.07**	**-0.08 (0.02)**	**-0.04**	**-0.09 (0.04)**	**-0.05**
% NO BUS	**28 (2.1)**	**+0.11**	**29 (2.5)**	**+0.11**	**52 (3.8)**	**+0.21**
BUS/PV	**921 (92)**	**+0.38**	**415 (108)**	**+0.18**	**641 (167)**	**+0.27**
CONSTANT	**6515 (562)**		**--**		**7039 (1592)**	
					$_i$=2984 (298)	
					$_i$ =2699 (230)	

The parameter standard errors are robust to correlation within households and heteroskedasticity across households. In bold, the parameters that are statistically significant at 10% or less. Elasticities are computed at the sample average values. For discrete variables, the elasticity corresponds to the percentage change in emissions associated with a one unit change in the discrete variable.

Table 7. Results for alternative specification

Variables	Model with D_work		Model with DC	
	Coef. (se)	**Elasticity**	**Coef. (se)**	**Elasticity**
NO LICENCE	**-2712 (619)**	**-39**	**-2919 (624)**	**-43**
FEMALE	**-1469 (354)**	**-21**	**1447 (385)**	**-21**
HEAD	-492 (891)		-462 (981)	
UNIV	**799 (432)**	**+12**	**895 (462)**	**+13**
FULL TIME	Reference		Reference	
STUDENT	-284 (737)		-905 (731)	
PART-TIME	-989 (875)		**-1883 (955)**	**-28**
RETIRED	-280 (771)		**-3319 (727)**	**-49**
NO JOB	1250 (889)		**-1963 (840)**	**-29**
AGE34	-218 (561)		-394 (647)	
AGE35-49	Reference		Reference	
AGE50-64	-600 (544)		**-1070 (623)**	**-16**
AGE65	**1679 (806)**	**+24**	**1796 (838)**	**+26**
% UNKNOWN	**-50 (10)**	**-0.02**	**-44 (10)**	**-0.02**
OWNER	-303 (495)		-69 (548)	
N_ADULTS	**-1147 (441)**	**-17**	**-1668 (519)**	**-24**
N_CHILDRENS	**649 (267)**	**+9.5**	436 (283)	
INCOME_LOW	Reference		Reference	
INCOME_MED	229 (556)		-144 (591)	
INCOME_HGH	1056 (768)		1322 (824)	
MO	Reference		**Reference**	
TU	413 (309)		413 (320)	
WE	541 (346)		562 (368)	
TH	**615 (333)**	**+9**	**658 (346)**	**+10**
FR	**1659 (413)**	**+24**	**1653 (423)**	**+24**
WEEKEND	**-1357 (351)**	**-20**	**-1447 (365)**	**-21**
FALL	Reference		Reference	
WINTER	1632 (1219)		1641 (1120)	
SPRING	871 (598)		-1037 (596)	
SUMMER	381 (428)		641 (453)	
DENS@HOME	**-0.38 (0.13)**	**-0.09**	**-0.20 (0.16)**	**-0.05**
DENS@WORK	**-0.09 (0.05)**	**-0.04**	**-0.14 (0.05)**	**-0.07**
% NO BUS	**27 (5.4)**	**+0.11**	**31 (6.3)**	**+0.13**
BUS/PV	337 (217)		**446 (248)**	**+0.19**
D_WORK	**340 (39)**		--	
DC	--		**223 (61)**	**+0.22**
CONSTANT	**4997 (1418)**		**6222 (1688)**	
R-square	**0.26**		**0.22**	

In bold, the coefficients that are statistically significant at 10% or less.

Figure 1. Map of the Quebec City area with neighbourhood type and location of the sampled households in wave 1.