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A DISAGGREGATED EMPIRICAL ANALYSIS OF THE DETERMINANTS OF URBAN TRAVEL GHG EMISSIONS

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A disaggregated empirical analysis of the determinants of urban travel GHG emissions

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ABSTRACT

This paper proposes a disaggregate approach for estimating travel-related greenhouse gas emissions (GHG) at the individual level, using an in-depth multiday activity-based survey. We then estimate a random-effect model in order to quantify the impact on emissions of individual and household socio-economic characteristics as well as urban form and transit supply indicators. The model results are obtained in terms of total individual emissions and by trip-end activity purpose such as work, leisure, and shopping. According to our results, female respondents produced, on the average, emissions that were 22% lower than those of males. Interestingly, we find evidence of economies of scale within household in the production of travel GHG emission. A couple would only produce 64% more emissions than a single. We find that both urban form and transit supply around the residence have a significant impact on GHG emissions, though this impact is relatively limited, implying that drastic land-use changes would be required to significantly cut travel emissions. For example, a 10% increase over the mean in residential or job density would lower emissions by less than 2%. This result is consistent with recent studies examining the relationship between travel and land-use.

RÉSUMÉ

Dans cet article, nous évaluons les émissions de gaz à effet de serre (GES) produites par les individus dans leurs déplacements quotidiens à partir des résultats d'une enquête détaillée sur les activités. Nous estimons ensuite un modèle économétrique à effet aléatoire afin de quantifier l'impact sur les émissions des caractéristiques socio-économiques, de la forme urbaine et l'offre de transport en commun. Le modèle est estimé en utilisant le niveau total des émissions produites par un

répondant et le niveau des émissions par type d'activités (p. ex. travail, loisir, magasinage). Selon cette analyse, nous montrons que les femmes produisent en moyenne 22% moins d'émissions de GES que les hommes. Nous montrons aussi qu'il existe des économies d'échelle significatives au sein des ménages dans le niveau des émissions de GES. Par exemple, nous montrons qu'un couple ne produirait que 64% plus d'émissions qu'une personne seule, toutes autres choses étant égales par ailleurs. La forme urbaine et l'offre de transport en commun ont aussi un effet statistiquement significatif sur le bilan des émissions. Par contre, ces effets sont assez marginaux, ce qui implique que des changements majeurs dans le tissu urbain sont nécessaires si on veut vraiment réduire les émissions. Par exemple, nous montrons qu'un accroissement de 10% de la densité résidentielle ou d'emploi dans un quartier ne diminuerait au mieux que de moins de 2% les émissions liées aux déplacements. Ces conclusions sont conformes avec celles obtenus par d'autres études récentes sur les liens entre choix de transport et forme urbaine.

1. INTRODUCTION

Transportation activities are responsible for about 30% of greenhouse gas (GHG) emissions in North America with private road vehicles accounting for more than half (1). Public policy makers are therefore looking for strategies to decrease automobile dependencies as one of the ways to limit changes to our climate. The "Smart Growth" movement argues that it is possible to reduce automobile addiction, and thus, emissions, by developing dense, diverse, and well-designed neighborhoods offering efficient public transportation options. In recent years, a large and quickly growing literature is evaluating the impact of urban form (UF hereafter) and transit supply (TS) on various aspects of individual or household travel behaviors [for a review, see Badoe and Miller (2), Ewing and Cervero (3) and (23)]. Some studies evaluate the impact of these determinants on the number or type of vehicles owned (4, 5, 6, 7), the distance traveled (4, 8, 9) or the modal choice (4, 10, 11, 12). Most studies find that UF and TS attributes have a significant impact on travel behavior; however, in several studies, the magnitude of this impact is quite limited (4, 7, 13). The results of these studies provide some indications on how UF and TS may affect GHG emissions, but the quantitative impact on emissions is at times difficult to infer from these studies as most of them focus only on a subset of transportation measures which determine emissions[1] . Moreover, studies sometimes report conflicting impacts. For example, Bhat et al. (9) report that households living in suburban neighborhoods own larger cars but that they are more likely to be recent models. The net effect on vehicle fuel efficiency is therefore uncertain.

In this paper, we address this issue by directly estimating the effects of UF and TS indicators on the level of GHG transportation emissions produced by individuals. To our knowledge, this is the first time this empirical strategy is being adopted. For this study, the first wave of an in-depth activity-based longitudinal survey in Quebec City is used. Specifically, our contribution is twofold:

[1] Another issue is the lack of multi-day and multi-period surveys. To quantify emissions, one needs detailed data not only on car ownership characteristics but also on daily travel for different periods (multi-day/multi-period data). Traditional survey methods such as origin-destination have a lack of detailed data.

- To propose an approach to evaluating transportation GHG emissions using disaggregated data on individual activities and travel during a seven-day period. The amount of emissions depends upon the travel mode, the vehicle used (make, model, and year), the distance travelled, the number of passengers, and the estimated peak and off-peak speed. It is estimated on a sample of about 400 individuals belonging to over 240 households in the Quebec City region (Canada) in 2002 and 2003.
- To estimate a model designed to highlight the main factors explaining variations in the individual emission levels. These factors include UF and TS indicators as well as individual and household socio-economic characteristics. This analysis allows us, for example, to evaluate the extent of emissions economies of scale within households or the impact of education, age, sex, and income.

The paper is organized into three sections following this introduction. In section 2, the data and methods of emissions estimation are presented. Section 3 describes the empirical model and its results. The paper is concluded in section 4 with a discussion of a future research agenda.

2. DATA AND GHG ESTIMATIONS

The main data source is an activity-based longitudinal panel survey on household activities and travel carried out as part of a major research program of the Canadian research network PROCESSUS to improve the behavioral foundations of integrated land-use, transportation, and environment (ILUTE) models. Three waves of these surveys, mostly in intervals of one year for a given household, were completed by early 2006. An effort was made to interview households during the same season in each wave. Different combinations of methods were used, drawing from in-home interviews, self-administered diaries of activity planning and execution, and telephone interviews. Seven days of data on executed activity and travel were collected in the first wave while two days worth were collected for each of the second and third waves. For an overview of this panel survey see Lee-Gosselin (14). For this paper, only Wave 1 data was used as it covers an entire week and has been extensively validated. During these seven days, all household members aged 16 and up had to complete a diary of their activities and travel. The target population is a sample of households in the Quebec City region. Initial contact by phone and mail were used to enroll participants, which led to a 10% respond rate. The resulting sample was established by a quota based on the household's stage in life, location, and number of vehicles owned. The sample included 249 households, involving 451 potential individual respondents; however, 51 potential respondents did not complete the diary because, although living under the same roof, they did not interact significantly with the heads of the households recruited. This criterion was necessary because the study included decision-making at the household level. Evidently, it is important to note that the size of the sample has a bearing on how the results should be interpreted. [2]

[2] The sample structure was compared with a larger dataset (>27 000 households) produced by the ministère des Transports du Québec (an origin-destination survey implemented in 2001, OD2001) covering about the same region. While there are some minor differences, the sample structure of the panel survey is quite close to that of OD2001 in terms of household size, age distribution, sex, and number of cars owned. It should be noted that the panel survey data, while having a smaller sample than OD2001, provides more detailed information on trips made as well as household, individual, and car ownership characteristics.

The seven-day activity and travel diary was completed by each adult, and validated in a subsequent interview with the possibility of correction. Respondents thereby provided information for each trip on the origin, destination, mode, time of departure, time of arrival, number of passengers, and the nature of the activity at each destination. The focus of the survey was on activities and trips within the urban region. The involvement of households was intentionally scheduled to avoid periods when any of the adults was expected to be travelling outside the region. Two GHG emission-producing modes are distinguished, namely private vehicles and public transit (bus). The private vehicle mode includes trips with the household vehicles (car, light duty vehicle, or motorcycle), other vehicles, and taxis. Geocoding of the origins and destinations was performed for 10,829 trips, corresponding to 94.3% of all recorded trips. The rate of trips with an unknown origin or destination, however, varies quite a bit among respondents, ranging from 0% to 61%. To control for this under-reporting problem without eliminating individuals, this rate was included as one of the explanatory variables in Section 3.

Accounting for the motor vehicle characteristics, travel speed, and vehicle occupancy, the GHG emissions at the trip level are estimated as follows:

$$GHG_{i,t} = \frac{FCR_{i,t}\ x\ SC_t\ x\ (D_t/100)\ x\ EF_{i,t}}{NP_{i,t}}$$

with:

$\boldsymbol{GHG_{i,t}}$: level of GHG emissions produced by respondent i on a trip t expressed in equivalent grams of CO_2.

$\boldsymbol{FCR_{i,t}}$: 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 respondent used a vehicle that is comparable to those he or she owns. For respondents that did not own a car, it was assumed that their automobile trips were made with a car with average fuel efficiency.[3]

$\boldsymbol{SC_t}$: 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 things other than vehicle speed. To take into account this detail, each trip was associated with an average speed which depended on the origin and destination as well as whether the trip occurred in a peak or off-peak period. While the information included in the diary could allow one to deduce an average speed for a given trip, the information in the trip duration was not reliable. Instead, the average speeds in peak and off-peak periods were estimated by the MOTREM model used by the ministère des Transports du Québec (MTQ) – see Tremblay (15). The Quebec City region is 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

[3] 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).

MTQ. These factors were developed by comparing actual versus average fuel consumption by speed for a sample of vehicles (16). [4]

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

$EF_{i,t}$: 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. The emissions factors reported by Environment Canada (17) were used.

$NP_{i,t}$: number of passengers in the vehicle excluding the household children aged less than 16. 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 in the count as they are not respondents (i.e. their trips are not reported in our data). In other words, their emissions are attributed to the adults in the car.

For transit bus trips, the GHG emissions are estimated as:

$$GHG_{i,t} = \frac{FCRB \times D_t \times EFB}{AC}$$

with:

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

D_t : estimated distance. This was calculated using simulations with ArcGIS and the local bus network.

EFB : emission factor for bus transit. It is based on the information reported by Tecsult, Inc. (18).

AC : estimated bus capacity set at 60 passengers in order to derive a measure of emission per seat.[5] The part of bus emissions that should be attributed to each passenger is an issue. It could be argued that the emission generated by a passenger is close to zero since the marginal fuel consumption of an extra passenger is negligible. Yet, some bus line with very few passengers may not be justified from an environmental point of view. By using the emission per seat, we take an intermediate view on this issue. However, this solution should be viewed as a starting point that will be reexamined in future research.

[4] For example, at a speed of 30 km/h, the actual fuel consumption rate would be about 20% larger than the average rate.
[5] Note that the actual number of seats is 40 but the maximum number of passengers is 80, therefore the average value of 60 is used.

Table 1. Sample vs. Population characteristics

	CRAD survey	Quebec City Region
Number of individuals	559	682 757[1]
Number of households	249	295 105[1]
Number of individuals per household	2.2	2.3[1]
Number of car per household	1.3	1.4[2]
% female	52.8	51.9[1]
% with a university degree	32.9	24.8[1]
Age structure	%	%[1]
0-19	23.7	22.2
20-34	22.3	20.3
34-49	25.2	25.5
50-64	21.0	18.2
65 and more	7.8	13.7
% of household with	%	%[2]
0 vehicles	13.6	12.3
1 vehicle	54.4	46.8
2 vehicles	26.0	34.5
3 or more vehicles	6	6.4

(1) Canadian Census 2001
(2) Origin-Destination Survey 2001

These trip-level emissions are then summed at a respondent-level. Table 1 presents some of the characteristics from the sample and compares them with the Quebec City region population. The sample structure is usually close to the population except for a larger representation of individuals with a university degree and a smaller share of seniors.

TABLE 2 reports descriptive statistics on GHG emissions and travel behavior per respondent and per day. On average, a respondent produced about 6.7 kg of CO2 per day traveling. One can note a large variance in this figure with one respondent producing no GHG, while 12 respondents produced more than 20 kg.

This average is smaller but still comparable to the estimate of 7.5 kg as reported by Tecsult, Inc. (18), based on aggregate data on the quantity of fuel sold in the Quebec City area. This difference could be explained in two ways. First, the estimate used in this paper is for the years 2001 and 2002, while Tecsult's figure is for 2006. Second, long distance trips were excluded from this analysis. Interestingly, on average, close to 20% of a respondent's GHG emission were linked to leisure activities, and only 17.7% for trips to work. It should be noted, however, that, for the whole sample, trips to work accounted for 22.8% of total emissions while leisure trips only generated 17.9%. Respondents produced an average of 204 g of CO2 per km.

This rate takes into account all modes (including non-motorized modes which emit nothing), speed, and the number of passengers for automobile trips. TABLE 3 illustrates the difference in travelling behavior and its implications on emissions depending on the respondent neighborhood type. Households in the central area of Quebec City produced much less GHG: they travelled less, chose less polluting modes, and had more fuel efficient vehicles. At the other end of the spectrum, households living in the periphery of the city (other zones) produced more than double the amount of emissions produced by centrally-located households.

The UF characteristics might explain this difference but it could also result from differences in the household socio-economic characteristics. In the next section, a statistical model to highlight the relative contribution of each determinant will be estimated.

Table 2. Descriptive statistics on emissions and travel (average per respondent and per day)

Variable	Average	SD*	Min.	Max.
GES (g./day)	6,625	5,226	0	28,205
% of emissions linked to :				
Work trips (%)	17.9	17.1	0	82.8
Leisure trips (%)	19.9	15.3	0	77.3
Shopping trips (%)	15.1	14.1	0	100
Return trips (%)	36.7	11.7	0	75
Other trips (%)	10.2	12.1	0	68.1
Distance (km)	32.0	21.9	2.2	127.6
Number of trips	3.8	1.4	0.4	8.7
% of distance in peak period	29.6	19.8	0	85.2
Average speed (km/h)	48.7	16.1	5.4	94.0
Emission rate GHG, all modes included (g/km)	201.3	81.1	0	474.3
Average number of person per automobile-trips	1.4	0.3	1	4

* SD: Standard deviation

TABLE 3.
TRIP AND EMISSIONS CHARACTERISTICS BY ZONE OF RESIDENCE
(AVERAGE PER RESPONDENT AND PER DAY)

Zone of residence	Respondents	GHG (g/day)	Distance (km)	Car trips	Bus trips	Non-motorized trips	Average fuel rating of cars (l/100 km)	Average density of residence (number of residences per km^2)
Central zone	46	4,084	21	58%	8.7%	33.1%	9.7	4,643
Old suburbs	93	4,725	24	73%	5.8%	20%	10.3	2,102
New suburbs	148	6,400	30	86%	2.6%	11.4%	10.0	1,312
Other zones	113	9,518	45	94%	0.5%	5.1%	10.3	486

3. EMPIRICAL MODEL AND RESULTS

The empirical strategy in this paper is to estimate a reduced-form model for highlighting the main determinants of travel GHG emissions at the individual level. Hence, instead of directly explaining the various choice-decision processes affecting an individual travel behavior, such as the choice of owning a car, the vehicle type, the mode, or the departure time, it is assumed that these various decisions are determined by individual and household characteristics. Given the research objective, the model is also conditioned on the UF and TS attributes around the residence. This assumes that the choice of residential location is predetermined (i.e. it is determined before any travelling decisions). This hypothesis is related to the widely debated issue of residential sorting – see, for example, Bhat et al., (9). Indeed, it is possible that travel behaviors are correlated with residential characteristics, as both travel and location are affected by common underlying factors or attitudes. In such a case, neighborhood attributes would not change travel behaviors, but rather affect the population pattern. It is now clearly established that controlling for the individuals and/or household socio-economic characteristics greatly limits this problem.[6] In fact, Bhat and Guo (19) and Browstone and Golob (13) show that it completely eliminates the residential selection bias.

Formally, the model has the following structure:

$$GHG_{i,j} = \alpha + \beta IC_{i,j} + \gamma HC_j + \omega UF \& TS_j + \sigma_j + \varepsilon_{i,j}$$

with:

$\boldsymbol{IC_{i,j}}$: characteristics of individual i belonging to household j

[6] A residential sorting bias may still be present if there are unobservable attributes that affect both travel and residential decisions.

$\boldsymbol{HC_j}$: characteristics of the respondent household

$\boldsymbol{UF \,\&\, TS_j}$: characteristics of the UF and TS around the household's dwelling

$\boldsymbol{\beta, \gamma, \omega}$: vectors of regression parameters

$\boldsymbol{\sigma_j}$: household specific error component

$\boldsymbol{\varepsilon_{i,j}}$: individual error term

TABLE 4 describes the explanatory variables included in the model and reports some basic statistics. Several alternative variables were tested, but only the "most preferred" specifications can be reported. The IC variables include driving license status, sex, role in the household, number of years in school, and professional status (worker, student, part-time or retired). The role of the respondent age was tested but no significant impact was found for the student or retired variables. As mentioned above, the model controlled for underreporting by controlling the percentage of trips with unknown origin or destination. A modeling issue is whether the model should include the home-to-work distance as one of the explanatory variables. Clearly, it should affect an individual level of emissions, but it is unclear if this variable can be assumed to be predetermined. This is why results are reported both with and without this variable.

The HC variables include ownership status of the residence, number of additional adults (beyond the respondent), number of children under 16, and household income class. The UF and TS attributes are the density of residence, job, and commerce in a buffer zone of 500 meters around the respondent's dwelling. The size of the buffer corresponds to a distance that can easily be walked and it has been used in several other studies (6, 20). Also included is a Mixed Density Index, see Cervero and Kockelman, (21) or Potoglou, (20) which is based on the residential, job, and commercial density (see Table 4 for details). Its value is zero for homogenous buffers (e.g. residential only) and its value increases with land-use diversity. TS is captured by the distance between the residence and the nearest bus stop. The number of different bus lines that cross the domicile buffer is also included. The impact of the distance to the nearest highway entrance is tested. We also allow the error term of respondents belonging to the same household to be correlated by using a random effect specification. [7]

The error terms and are assumed to be normally distributed so that the models can be estimated by maximum likelihood. It should also be noted that the models are linear, implying that coefficients may be directly interpreted as changes in grams of CO2.

One of the most challenging issues faced in estimating this model is the high level of correlation between the explanatory variables, especially between UF and TS indicators as illustrated in Table 5. This is a common problem in analyzing UF attributes which makes it difficult to precisely identify the effect of each attributes. Therefore, Table 6 presents the results of three different model specifications. Model (1) uses a broad typology of the respondent neighborhood distinguishing four types as illustrated in Figure 1.

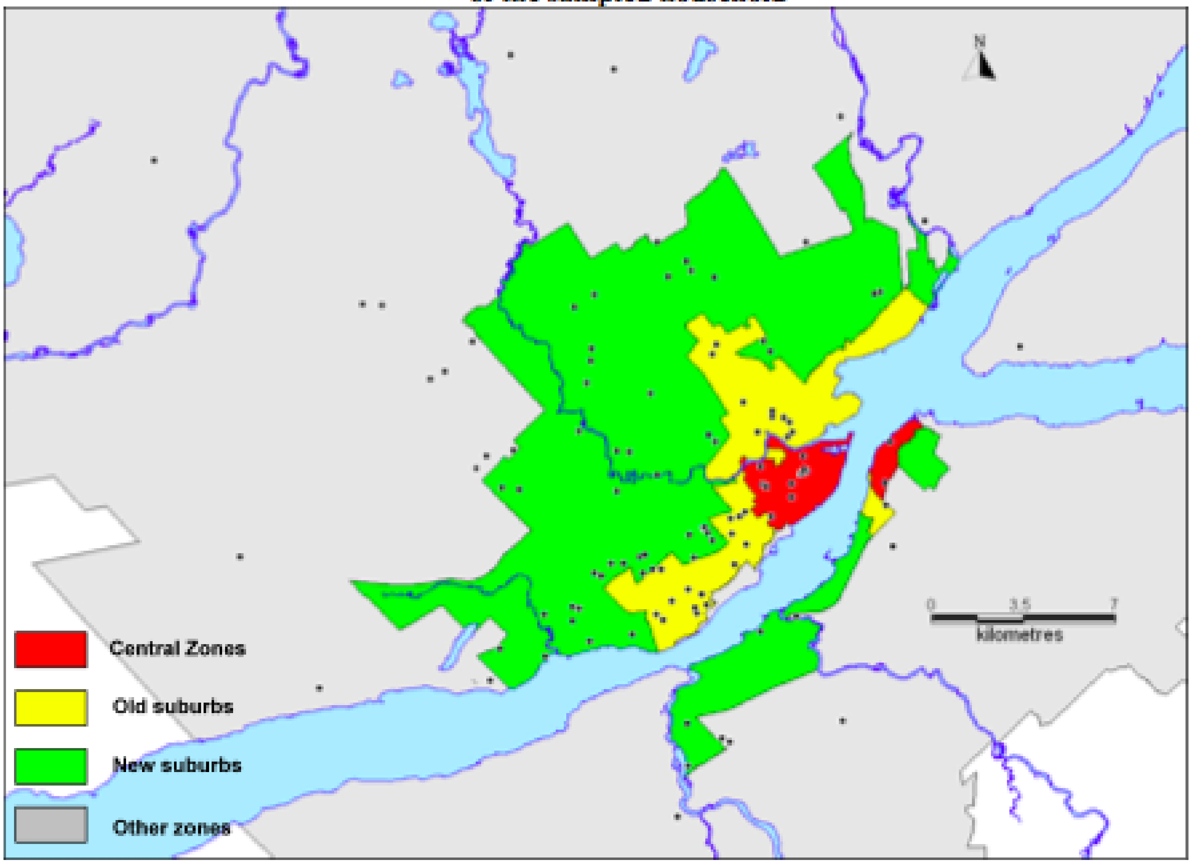
[7] Note however that the number of observations per household is quite limited varying from one to four with an average of about 1.6. Given this limitation, we have also estimated the model using a simple OLS. The results are quite comparable to those obtained reported here with the household specific random effect.

Table 4. Description of the variables

Variable	Description	Mean (SD)*	Min/Max
IC Variables			
NO_LICENCE	Dummy set to one if the respondent has no driving license	5%	0/1
FEMALE	Dummy set to one if female	53%	0/1
HEAD	Dummy set to one if respondent is head of the household	94%	0/1
SCHOOLING	Typical number of years in school for highest degree obtained	15 (3.4)	10/23
STUDENT	Dummy set to one if respondent is a student	7%	0/1
PART-TIME	Dummy set to one if respondent is employed part-time	7%	0/1
RETIRED	Dummy set to one if respondent is retired	17%	0/1
NO_WORK	Dummy set to one if respondent was unemployed	6.7%	0/1
% UNKOWN	Percentage of trips reported with unknown origin or destination	5.6%	0/61
D_WORK	Shortest distance in km to the respondent's job	5.9 (7.6)	0/51.7
HC variables			
HOWNER	Dummy set to one if the household owns its house	70%	0/1
N_ADULT	Number of adults (aged 16 or above) in addition to the respondent.	0.75 (0.45)	0/2
N_CHILDREN	Number of children less than 16 in the household	0.74 (1.0)	0/4
INCOME_LOW	Dummy set to one if the household income is evaluated as being less than 20k	19%	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	31%	0/1
UF&TS variables			
DEN_RES	Density of residence computed in a 500 meters buffer zone around the household location	1645 (1566)	22.9/7598
DEN_JOB	Number of jobs per km2 computed in a 500 meters buffer around the household location	1868 (3766)	0/20,979
DEN_COM	Number of commerces per km2 computed in a 500 meters buffer around the household location	36.4 (48.0)	0/253
MIXITY	Index of land use mix. It is the product of DEN_RES, DEN_JOB and DEN_COM divided by the sum of these terms.	63,307 (156,499)	0/762,146
D_BSTOP	Shortest distance in meters between the residence and a bus stop	998 (2594)	1.9/21372
N_BLINES	Number of different bus line in the buffer zone around the dwelling	7.6 (9.4)	0/47
D_HW	Shortest distance in meters between the residence and a highway entrance	2208 (1628)	39/12,805

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

Figure 1. Map of Quebec region area, neighborhood type and localization of the sampled household



This typology has been used in some previous works, e.g., see (22), and reflects the historical evolution and the elongated development of the city and transportation network on the north shore of the St. Lawrence River.[8] Model (2) only includes residential density around the residence and nearest distance to a bus stop for capturing impact of the UF and TS. Residential density is chosen as it is one of the most widely used measures in the literature and it is also the measure that improves the regression fit the most among our UF indicators. Model (3) includes the complete set of UF and TS variables around the residence. Results of the three model specification without a control of the distance to work are reported in Table 6a while the results with distance to work are presented in Table 6b.

By comparing results from Table 6a and 6b, it can first be seen that adding the resident to work distance improves the model fit. Moreover, the coefficient estimates and significance of some explanatory variables are affected by the inclusion of this

[8] The central zones (downtown) correspond to the oldest neighborhoods in the City. The old suburbs represent the developments established after the war. The new suburb zones group the neighbourhoods built predominantly after 1965 and reflect the building of an extensive freeway network.

Table 5. Correlation between urban form (UF) and transit supply (TS)

Variables	DEN_RES	DEN_JOB	DEN_COM	MIXITY	D_BSTOP	N_BLIGNES	D_HW
DEN_RES	1.00						
DEN_JOB	0.73	1.00					
DEN_COM	0.69	0.83	1.00				
MIXITY	0.80	0.95	0.78	1.00			
D_BSTOP	-0.28	-0.15	-0.21	-0.13	1.00		
N_BLIGNES	0.73	0.87	0.78	0.86	-0.24	1.00	
D_HW	-0.38	-0.28	-0.34	-0.24	0.50	-0.36	1.000

variable. The variables reflecting the respondent professional status (PART-TIME, RETIRED and NO_WORK) become statistically insignificant when D_WORK is included, and the impact of UF and TS attributes become somewhat smaller. This would suggest that the impact of these variables occurs, at least in part, through their effect on D_WORK. For example, if retired respondents produced about 1.6 kg less GHG emission than workers it is due to the fact that they do not have any work-related emissions (D_WORK=0). Secondly, comparing model (2) and (3), we note that the model fit improve only slightly when additional UF and TS variables are included.[9] In fact, when D_WORK is controlled for, the hypothesis that the coefficients on the additional UF and TS variables are jointly equal to zero cannot be rejected.[10] Also note that for all model specifications, we can reject the hypothesis that $\sigma_u = 0$, which means that there is correlation between the error terms for respondents belonging to the same household.

Next, we turn to the effect of the respondent characteristics. A respondent without a driving license produces between 2.2 and 2.9 kg less emission. Relative to the average emission level in the sample of 6.7 kg, this corresponds to a 37% difference. The coefficient on FEMALE is also systematically negative. Female respondents produce an average of 1.5 kg less emission per day than males which corresponds to a 22% variation. Being head of the household or the level of education do not appear to be significant determinants. As already mentioned, professional status affects the emission outcome only through the distance to work. In fact, each additional km in distance to work adds about 300 g of CO_2. At the sample average, this means that a 10% decline in D_WORK would reduce emissions by 2.6%. Finally, % UNKNOWN has the expected negative impact.

For the impact of household attributes, the home ownership status does not seem to have a significant effect. Interestingly, the number of additional adults in the household has negative impact,

[9] Note that the variance inflation factor confirms that multicollinearity may be an issue in this specification. This seems particularly problematic for the variables DEN_JOB and MIXITY which have factor well above 10

[10] Formally, we cannot reject the hypothesis that $\alpha_{DEN\_JOB} = \alpha_{DEN\_COM} = \alpha_{MIXITY} = \alpha_{N\_LIGNES} = \alpha_{D\_HGH} = 0$.

**Table 6a. Estimation results for total travel GHG emissions per respondent and per day
Models without distance to work**

Variables	(1)	(2)	(3)
Intercept	5599*** (1857)	8973*** (1785)	9722*** (1877)
NO_LICENCE	-2927*** (1016)	-2721*** (1026)	-2883*** (1025)
FEMALE	-1781*** (373)	-1827*** (374)	-1772*** (374)
HEAD	56.8 (1056)	240 (1057)	-266 (1052)
SCHOOLING	18.2 (68.3)	-3.9 (68.2)	-0.16 (68)
STUDENT	-1389 (935)	-1479 (942)	-1254 (941)
PART-TIME	-1343* (807)	-1388* (811)	-1382* (805)
RETIRED	-1372** (653)	-1678** (655)	-1717*** (649)
NO-WORK	-1444* (858)	-1400 (862)	-1520** (860)
% UNKNOWN	-44** (20.8)	-46.6** (21)	-46.3** (20)
HOWNER	454 (674)	369 (686)	253 (681)
N_ADULTS	-1504** (610)	-1411*** (614)	-1554** (613)
N_CHILDREN	886*** (273)	844*** (276)	782*** (273)
INCOME-MED	151 (742)	239 (734)	67.9 (743)
INCOME-HGH	1389 (916)	1310 (925)	1287 (927)
OLDSUB	1102 (915)	--	--
NEWSUB	1877** (875)	--	--
OTHER	4632*** (948)	--	--
DEN_RES	--	-0.68*** (0.18)	-0.78** (0.30)
DEN_JOB	--	--	-0.55** (0.26)
DEN_COM	--	--	-1.8 (10)
MIXITY	--	--	0.01** (0.006)
D_BSTOP	--	0.27** (0.10)	0.19 (0.12)
N_BLIGNES	--	--	-41.8 (59)
D_HW	--	--	0.07 (0.19)
Log likelihood	-3905	-3908	-3903
LR	Chi2(17)=126	Chi2(16)=120.5	Chi2(21)=129
LR test $\sigma_u = 0$	Chi2(1)=32.7	Chi2(1)=32.9	Chi2(1)=30

*Statistically significant at 10%; **Statistically significant at 5%; ***Statistically significant at 1%.

Table 6b. Estimation results for total travel GHG emissions per respondent and per day
Models with distance to work

Variables	(1)	(2)	(3)
Intercept	4138*** (1680)	6374*** (1616)	6783*** (1785)
NO_LICENCE	-2466*** (928)	-2262** (929)	-2422** (1026)
FEMALE	-1467*** (358)	-1485*** (359)	-1479*** (374)
HEAD	-578 (963)	-516 (958)	-447 (1057)
SCHOOLING	53.2 (62)	46 (61.4)	42 (68.2)
STUDENT	-990 (856)	-1071 (855)	-979 (942)
PART-TIME	-636 (751)	-638 (750)	-636 (811)
RETIRED	700 (631)	546 (628)	465 (655)
NO-WORK	917 (830)	1041 (826)	900 (862)
% UNKNOWN	-52*** (18.8)	-53.5*** (18)	-53.6*** (21)
D_WORK	305*** (32)	316*** (31)	308*** (31)
HOWNER	580 (582)	445 (582)	385 (686)
N_ADULTS	-1107** (530)	-1084** (525)	-1127** (614)
N_CHILDREN	853*** (232)	805*** (231)	774*** (276)
INCOME-MED	-287 (646)	-285 (637)	-309 (734)
INCOME-HGH	361 (795)	238 (238)	281 (925)
OLDSUB	729 (789)	--	--
NEWSUB	1195 (758)	--	--
OTHER	2793*** (837)	--	--
DEN_RES	--	-0.50*** (0.15)	-0.50* (0.18)
DEN_JOB	--	--	-0.33 (0.23)
DEN_COM	--	--	3.38 (8.7)
MIXITY	--	--	0.007 (0.005)
D_BSTOP	--	0.16* (0.09)	0.13 (0.10)
N_BLIGNES	--	--	-0.27 (50)
D_HW	--	--	0.001 (0.16)
Log likelihood	-3864	-3863	-3861
LR test	Chi2(18): 232	Chi2(22): 238.7	Chi2(22): 244.2
LR test $\sigma_u = 0$	Chi2(1)=15.6	Chi2(1)=14.1	Chi2(1)=14.3

*Statistically significant at 10%; **Statistically significant at 5%; ***Statistically significant at 1%.

which could be explained by car sharing as well as economies of scale in travelling activities within the household. Each additional adult reduces emissions by about 1.2 kg or about 18%. In other words, a couple would only be producing 64% more emissions than a single adult.[11] The presence of children less than 16 adds about 900 g to a respondent level of emissions (or +13%). Surprisingly, income is not a statistically significant determinant, while most studies find that income affects travel behaviors. It usually increases the probability of owning and using a car – see, for example, Bento et al., (4), and it also seems to favor larger vehicles (19). Browstone and Golob (13) also report a positive impact of income on annual fuel consumption. It can be found, however, that the income elasticities are usually small. Based on the results reported by Browstone and Golob (13), the elasticity of annual fuel consumption with respect to household income would be only 0.14. The lack of significance in this analysis could be due to the fact that the income classes are too large. It could also be due to measurement errors, as income is evaluated by interviewers rather than declared by the respondent. It may also be possible that the professional status variables capture most of the income variations.[12]

Finally, we turn to the interpretation of the UF and TS attributes. From model (1), we see that respondent living in old suburbs do not seem to produce more emissions than respondent living in the central part of the city. This may be explained by the fact that these old suburbs are close to the city center but also that they include their own center with shopping streets, commercial centers and other services. Residents of new suburbs produce about 1.8 kg more emissions than residents from the center. Note however that this supplement appears to be mainly caused by increased driving distance to work as the coefficient on NEWSUB becomes insignificant when D_WORK is included. Residents from the periphery produce 4.6 kg more emission when D_WORK is not controlled for and 2.7 kg more when D_WORK is assumed constant. Turning to the results from models (2) and (3), we find that higher residential density is systematically associated with a reduction in emissions. The magnitude of the effect is, however, quite limited since a 10% increase in residential density around the mean lowers emissions by about 170 grams (i.e. less than 2%). The distance to the nearest bus stop is linked to an increase in emissions but the elasticity is negligible at less than 0.04. For the other UF and TS indicators, job density also contributes to slightly reducing emissions when D_WORK is not included. A 10% increase in job density reduces emissions by 100 grams or about 1.5%. Commercial density does not appear to have any significant impact. Land use mix is associated with an increase in emissions. While this is somewhat surprising, as it is usually argued that it lowers automobile dependency, the impact of this variable is very small (elasticity at 0.09), and it becomes insignificant when D_WORK is introduced. Nevertheless, future research is required to understand this unexpected result. Finally, the distance to a highway entrance does not play a role in our models.

In Table 7, the results obtained using the level of emissions related to work, leisure, and shopping are reported, respectively. The regressions are estimated separately by activity purpose. For work-related emissions, the estimation is carried out on the subsample of respondents who have jobs. Note that for work-emission, we cannot reject the hypothesis that $\boldsymbol{\sigma_u = 0}$.

Respondents that are female produce less work- and leisure-related emissions. For shopping however, there is no significant difference with males.

[11] This figure does not take into account the FEMALE effect.
[12] The coefficients on the income variables are positive and significant when STUDENT, PART-TIME and RETIRED are excluded.

Table 7. Regression results for work, leisure, and shopping related emissions

Variable	Work emissions	Leisure emissions	Shopping emissions
Intercept	2087** (874)	2623*** (471)	139 (325)
NO_LICENCE	-719 (674)	-314 (266)	-383** (187)
FEMALE	-716*** (204)	-219** (93)	81.0 (76)
HEAD	-33.1 (446)	-1164** (270)	165 (193)
SCHOOLING	-21.2 (33.4)	26.3 (17)	15.2 (12.2)
STUDENT	-676 (436)	143 (243)	-22 (173)
PART-TIME	-979*** (370)	-63 (207)	91 (153)
RETIRED	--	198 (182)	269* (125)
NO-WORK	--	185 (230)	445*** (167)
% UNKNOWN	-5.2 (10)	-11.3** (5.4)	-11.4*** (3.7)
D_WORK	131*** (13)	21.8** (9.1)	20.9*** (6.1)
HOWNER	102 (273)	-72 (189)	245** (111)
N_ADULTS	-468* (257)	-454*** (170)	28 (101)
N_CHILDREN	217* (103)	-3 (77)	54 (43)
INCOME-MED	-170 (416)	-110 (204)	-0.8 (123)
INCOME-HGH	196 (471)	53 (258)	-164 (150)
DEN_RES	-0.08 (0.07)	-0.16*** (0.05)	-0.05** (0.02)
D_BSTOP	-0.01 (0.03)	0.000 (0.03)	0.02 (0.01)
Log-likelihood	-2539	-3375	-3221
LR test	Chi2(15): 141	Chi2(17): 56	Chi2(17): 73
LR test $\sigma_u = 0$	Chi2(1): 0	Chi2(1): 40	Chi2(1): 3.6
Number of obs.	287	400	400

*Statistically significant at 10%; **Statistically significant at 5%; ***Statistically significant at 1%.

Heads of household appear to produce somewhat less leisure-induced emissions. As expected, part-time workers also produce less work emissions. Retired respondents produce about 270 g more emissions than workers due to shopping activities. Non-workers produce 445 g. more shopping related emissions than workers. This is an increase of over 40% relative to the average level of shopping emissions in the sample. The distance to work positively affects not only the amount of work emissions but also leisure and shopping emissions. This could suggest that non-work activities may be occurring near the work place or that individuals that travel long distance to go to work are also more willing to travel more for non-work activities. Respondents belonging to households that own their home appear to emit more shopping GHG emissions. Residential density negatively affects emissions of leisure and shopping emissions but do not appear to have an effect on work emissions. In all cases, the magnitude of this variable is, however, quite limited. Indeed, if a 10% increase in residential density reduces leisure-related emissions by 26 g. or 1.9% and shopping emissions by 8.2 g. or less than 1%.

4. CONCLUSIONS AND FUTURE RESEARCH

This paper investigated the main determinants of an individual level of travel-related GHG emissions. It was shown that individual characteristics such as sex or distance to work have an impact on emissions. The importance of economies of scale in emission within household was also evaluated. Furthermore, it was found that UF and TS has a significant impact on emissions, though this impact is relatively limited, implying that drastic changes would be required to significantly cut travel emissions. This result is consistent with several recent researches e.g., see 4, 13, 23 and 24.

This analysis should be viewed as a first step to uncover the determinants of transportation GHG emissions. Several improvements could be considered in future research. It would be interesting to evaluate the impact of alternative estimation methods.

Similarly, it would be interesting to test and control for spatial correlation in the error terms. The regression of emissions by activity purpose could also be estimated as a system. Ideally, the model should be tour-based with a reasonable assignment of travel to purpose categories, eliminating return-home as a purpose. Cold-start emission factors could be also considered. In addition, the two subsequent waves should be incorporated to the analysis increasing temporal variability. The use of disaggregate panel data should be a better way to determine how changes in urban form and transit access can lead to reduction in GHG emissions. It would also be interesting to test the model with more recent data in order to test the temporal stability of the parameters. Indeed, increasing revenues, congestion and environmental awareness could potentially have an impact on the relationship we have uncovered.

However, it is probably quite unlikely that these changes have been so important over a period of less than ten years for our results to be irrelevant. In terms of specification, it would be worthwhile to test the effect of different buffer size. Finally, it could also be considered to adopt a more structural approach by estimating a system explaining not only the emission level but also its main determinants

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