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Residential Location, High Capacity Transportation Infrastructure and their Influences on Emissions and Travel Dispersal

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Abstract. There is a large literature on the link between transportation and the built environment. This literature has tended to concentrate on the effect of the built environment on a few transportation demand indicators. Recently, there has been some literature to look at the impact of the urban built environment on transport-related CO_2. It has tended to use relatively coarse calculations for transport-related CO_2 and the built environment. This paper uses an approach developed by Beckman, Golob and Zahavi (1983) to analyze the effect of proximity to high capacity transport infrastructure on activity spaces and extends it to include more types of infrastructure, as well as to analyze the effect of infrastructure access on transport-related CO_2. Data from the region of Montreal is used to generate activity spaces and transport-related CO_2 emissions for groups of households at different distances from the CBD close to different types of transport infrastructure. Results indicate that both activity spaces and CO_2 are related to transport infrastructure in predictable ways: emissions are on average higher for households living close to expressways, and activity spaces and emissions are smaller for those close to metros and commuter rail. We also find that emissions (and more weakly activity spaces) exhibit an inverted U-shape (for households near all infrastructure types apart from expressways) – at first increasing with distance from the CBD and then decreasing. We argue that this is related to households "falling out of the orbit" of the city.

Keywords. Residential location, CO2 emissions, transportation infrastructure, travel dispersal, built environment.

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Introduction

There is a large literature on the link between transportation and the built environment. This literature has tended to concentrate on the effect of the built environment on a few transportation demand indicators, such as vehicle kilometers travelled (VKT), mode share, number of trips, etc., and more recently on activity spaces. With increasing interest in the contribution to CO_2 emissions of the transport sector, there has been some literature to look at the impact of the urban built environment on transport-related CO_2. The literature that does exist has tended to use quite coarse calculations for transport-related CO_2 as well as of the built environment. Thanks to the availability of highly disaggregate data, a richer understanding of the relationship between the built environment and transport-related CO_2 emissions has been developing. One element intuitively (and previously) recognized to have an important impact on travel behavior, but which has not yet been explored with respect to transport-related CO_2 emissions, is proximity to high capacity transport infrastructure.

This is a question of interest for jurisdictions around the world examining transport investments and policies, at least partly aimed, at reducing transport-related CO_2 emissions. The question is of particular interest in the province of Quebec, Canada since it has set itself a goal of a 20% reduction in GHG emissions below 1990 levels by 2020. To reach this, transportation will have to play an important role since it produces 42% of total GHG emissions in the province (Ministère du Développement durable, de l'Environnement et des Parcs, 2011). As such, better understanding the links between land use, travel demand and emissions is crucial.

In this paper, we build upon the methodological work of Beckman, Golob and Zahavi (1983b) in which they look at the effect of infrastructure on travel dispersal. We extend their work by considering a larger array of infrastructure types and their effects, first on activity spaces, and then on transport-related CO_2 emissions.

Using descriptive statistics, visualization and regression modeling, we seek to understand what the effects of distance from core and access to transit or highways can have on overall dispersal of travel, as well as sustainability of travel (operationalized in this context as transport-related CO_2 emissions). In the regression portion of the analysis, we use land use indicators at the home locations for individuals sampled, distance from high capacity infrastructure and the city core, as well as household characteristics to estimate the effect of proximity to high capacity transport infrastructure on CO_2 emissions and dispersion. A specific point which we believe to be very important to look at with this work is the potential for there to be inflection points both for dispersion and GHGs, namely distances from the city core at which emissions peak and then fall, and distances after which activity space polygons, or travel probability fields cease to increase in area. Furthermore, if the inflection points occur at different distances for households with different high capacity transport infrastructure access, this would also reveal information on the pull of the city (that we have taken to refer to as the "orbit" of households relative to a city) under different infrastructure proximity scenarios. Finally, we use the estimated CO_2 model to visualize the effect of distance from the core and high capacity transport infrastructure by forecasting and mapping a transport-related CO_2 surface.

The paper is structured thus: the next section provides a review of the literature on travel and the built environment, activity spaces and urban GHG emissions. The following section describes the case study region, the data used and the methodological approach adopted. After this, the modeling results and transport-related CO_2 surface are explained with the last sections providing discussion and the overall conclusion of the paper.

Literature review

Transportation and Built Environment

The past two decades have seen an explosion of research in the field of transportation and land use. Of particular interest in this research has been the link between the built environment and transportation behavior, particularly, although not exclusively as it relates to the environmental sustainability of transportation. A main focus of the research in this field has sought to evaluate the degree to which the built environment influences various aspects of transportation demand.

The built environment has most commonly been quantified as the three (or five) Ds: namely density, diversity and design (the first three), and destination accessibility and distance to transit as the fourth and fifth (Krizek, 2003) (Transportation Research Board and Board on Energy and Environmental Systems, 2009). Density typically refer to population or employment densities. One can find residential and employment densities quantified as simple measures of individuals per unit area (Riva, Apparicio, Gauvin, & Brodeur, 2008) or retail employment per area (Boarnet & Sarmiento, 1998), but more elaborate methods are also employed. Diversity measures such as “entropy” (see e.g. Frank, 2005) quantify the degree of diversity in land uses. Design variables try to quantify urban form characteristics through variables such as intersection (Boarnet et al. 2004) or block densities (Bhat et al. 2009). Destination accessibility quantifies the ease with which destinations can be accessed, and has been measured in various ways - as simply as distance to downtown (Naess, 2005), or with more sophisticated estimates of the number of opportunities that can be reached from a given location (e.g. Cervero & Duncan, 2006). Accessibility to transit has been quantified in different ways including proximity to stations or bus stops (Shay & Khattak, 2007), rail and bus line coverage (Bento, Cropper, Mobarak, & Vinha, 2005), available transit headways (Miranda-Moreno, Bettex, Zahabi, & Kreider, 2011), etc.

Within this literature, these indicators have been used to test the degree to which the built environment has an impact on common measures of travel demand such as vehicle kilometers travelled (VKT), vehicle hours travelled (VHT), number of trips and mode choice. Some of the most widely cited papers summarizing this work are Ewing and Cervero’s review papers from 2001 and 2010, highlighting the links found between different indicators and travel behavior. They identify those for which the strongest correlations are observed as well as where the evidence of impact has been hard to quantify and difficult to establish statistically. On the whole, there is a growing consensus that the built environment affects. Debate continues, however on the nature of the relationships, their strength, and how the relationships ought to be quantified. Many researchers agree that automobile mode share and VKT decrease with both density and diversity; that these decrease as accessibility to transit increases is also typically found; the case for decreasing automobile mode share and VKT as distance to the Central Business District (CBD) decreases and as street grid connectivity increases are found, although not quite with such certainty as the variables mentioned previously (Ewing & Cervero, 2001) (Ewing & Cervero, 2010) (Tracy, Su, Sadek, & Wang, 2011) (Leck, 2006) (Bento, Cropper, Mobarak, & Vinha, 2005). While the vast majority of work linking the built environment to travel behavior has concentrated on these traditional demand indicators, the effect of the built environment on activity spaces has begun to be explored as well (Authors 2011, Authors forthcoming).

An interesting feature of this literature is that while accessibility to transit, and accessibility to destinations by different modes are routinely considered as important factors affecting travel, the effect of proximity to different kinds of transport infrastructure has rarely been examined. At the same time, the work of Beckman, Golob and Zahavi (1983a, 1983b) suggests that proximity to different types of transport infrastructure has an important impact on travel behavior. In the context of the analysis of travel dispersion through activity spaces, they provide a method to analyze, and demonstrate the importance of, the proximity to different types of high capacity transport infrastructure on travel behavior. In particular, they consider groups of individuals living along two different transportation corridors in Los Angeles. Their key findings were that; i) the major axis of the activity space formed by households tended toward the urban center; ii) ellipses were more elongated the further one got from the core; iii) travel probability fields (activity spaces) generated by car drivers were more elongated than those of transit riders; iv) the orientation of the ellipse is affected by the supply of transportation infrastructure (highways and bus routes in their case).

Built Environment and Transport-related CO2

Given the important contribution of transportation to GHG emissions in Quebec (again, accounting for 42% of the Province's GHG emissions (Ministère du Développement durable, de l'Environnement et des Parcs, 2011)), as well as the great deal of interest in the built environment and transportation more broadly, there has been surprisingly little research linking the built environment to transport-related CO_2 emissions. This is not to say, however, that there has been none. What appears in the academic literature has not generally been focused explicitly on transport-related GHGs, but rather on overall GHG emissions in different urban environments (e.g. Andrews, 2008; Glaeser and Kahn, 2010; Norman et al. 2006). There has also been interest in the grey literature, like Chapter 5 of the Transportation Research Board report *Driving and the Built Environment* (TRB, 2009) that forecasts the effect of different development patterns on VKT and CO_2 emissions in the US. While each of these is interesting in their own right, one thing that they have in common is that the estimates of transport-related GHGs (CO_2 really) are quite coarse. Andrews (2008) estimates regional transport-related CO_2 emissions based on National Household Transport Survey (NHTS) estimates of VKT at the census tract level that are then converted to CO_2 using national fuel efficiency averages. Norman et al. (2006) attribute regional level transport-related CO_2 emissions to "core" and "outer-suburbs" based on estimates of VKT attributed to the two urban sub-regions. The TRB (2009) uses national average household VMT, with households in compact forms of development traveling less than those in non-compact forms of development. National fuel economy averages are used to convert VMT to CO_2 emissions. Glaeser and Kahn (2010) estimate CO_2 emissions based on a regression of gasoline consumption by household drawn from the NHTS as a function of a few built environment (population density and distance to CBD) and household (income, size, age) variables. In general, this literature supports what most people would expect, namely that travel behaviour in more centrally located urban regions produces fewer CO_2 emissions than suburban regions. An interesting nuance to this is Andrews' (2008) finding of an "inverted U" shape for CO_2 emissions – that is while emissions increase in increasingly suburban regions, in very far off ex-urban regions, emissions begin to decrease.

Given the limited literature to look at the link between the built environment and transport-related CO_2 emissions, there is a potential to explore a large number of issues. At the same time, and as outlined previously, data on transport-related CO_2 emissions has tended to be quite coarse. Fortunately, in the case of Montreal, entirely disaggregate estimates of transport-related CO_2 emissions have recently been developed (Zahabi et al. 2012). The availability of such data has opened up the possibility much more fine-grained research into the links between the built environment and transport-related CO_2 emissions (e.g. Barla et al. 2011, Miranda-Moreno et al. 2012).

The goal of the research presented here then is to take advantage of disaggregate transport-related CO_2 data, and use it to examine a question having received relatively little attention in the transportation and land-use literature until now, namely: to what extent does proximity to different kinds of high capacity transport infrastructure influence transport-related CO_2 emissions? In order to do this, the approach developed by Beckman, Golob and Zahavi (1983 a;b) is extended to include additional types of transportation infrastructure, and adapted to include the analysis of transport-related CO_2 emissions.

Case Study Region

The region of Montreal, Canada was chosen as a case study because of the availability of extensive origin destination survey and transport-related CO_2 emissions (described in greater detail below) data. Montreal is the second largest city in Canada and had a population of 3.6 million inhabitants as of the 2006 census (Statistics Canada n.d.). For this research, data from 3 OD surveys for Montreal (1998, 2003 and 2008), in addition to a comprehensive dataset containing built form and land use characteristics for the entire census metropolitan area (CMA, analogous to an American MSA) were used. Another interesting feature of Montreal is that it has, within its metropolitan region, a mix of high mobility transportation alternatives (commuter rail, underground metro and expressways), allowing measurement of the impact of each of these forms of transportation on the dispersion and emissions of residents.

Methodology

To understand the impact of proximity to different types of transport infrastructure we proceeded in five steps. The first step was to create household groupings on which to base calculations of activity spaces and CO_2 emissions. The approach employed is based upon ideas described in Horton & Reynolds (1970), as well as Beckman, Golob and Zahavi (1983a and 1983b) and Axhausen (2007). They believed that travel dispersion would be influenced by the type of infrastructure to which people had access, as well as their distance from the urban core. As such, we selected groups of households that were found along major expressways and transit infrastructure at regular intervals from the CBD. Second, as did Beckman, Golob and Zahavi (1983) we calculated aggregate household activity spaces for households at each of the selected sites. We extended their approach by also calculating average transport-related CO_2 emissions. Third, we conducted graphical analyses of both aggregate activity spaces and average transport-related CO_2 emissions. Fourth, we estimated regression models of both activity space size and emissions. Finally, we used these regression models to estimate transport-related CO_2 emissions, using these estimate to create a transport-related CO_2 emissions surface for the entire region. The details of each of the steps are presented in the following sections.

Household Transport-related CO2 emissions

The emissions dataset prepared for Montreal at the household level by Zahabi et al. (2012), employed completely disaggregate OD trip data to produce household-level kg of transport-related CO_2, taking into account all CO_2 emitting modes. A detailed description of the methodology can be found in the Zahabi et al.'s (2012) paper (including formulas for fuel consumption curves and conversion factors for kg CO_2 equivalents). Suffice it to say that vehicle fleet characteristics, congested link speeds, passenger loadings and average vehicle fuel efficiencies were all taken into account, while for the metro network and parts of the commuter rail network running on hydro-electric power, trip legs including these segments were assigned zero emissions.

Table 1 - Summary statistics, neighborhood types

	Neighb Type	Kg CO_2 Eq	Pop dens (p/ha)	Empl dens (j/ha)	Land Use Mix (%)	Transit Access	Fam. with Kids	Single p. HHs	Auto Owner-ship	Active Modes	Transit Modes	Moto-rized Modes
Rural	1	16.06	16.12	2.91	0.10	12.05	0.37	0.14	0.96	0.13	0.16	0.90
Sprawl	2	10.38	30.65	10.56	0.33	50.29	0.26	0.24	0.88	0.18	0.24	0.80
↓	3	5.28	62.77	19.55	0.45	189.72	0.22	0.33	0.72	0.23	0.40	0.62
Dense	4	3.69	101.79	45.90	0.54	287.90	0.18	0.40	0.57	0.36	0.47	0.48
urban	5	2.50	86.30	306.56	0.62	507.50	0.08	0.53	0.42	0.50	0.36	0.31
	Av.	9.37	47.50	22.16	0.34	121.16	0.26	0.27	0.80	0.21	0.30	0.72

Information relative to the BE in the neighborhood of residence of individuals (population and employment densities, as well as public transit accessibility and land use mix) come from a dataset built at the grid cell level for the entire region in Authors (2012). Values for each indicator are captured at the cell level using information obtained through Statistics Canada (for population and employment counts), as well as land use information obtained from DMTI Spatial in their CanMaps Routelogistics dataset.

Once land use indicators were generated at the cell level and associated to households, based on residence coordinates recorded in the OD surveys, cluster analysis was conducted to group households by neighborhood type. Neighborhood types were coded according to their level of urbanity - broadly characterized by higher densities of transit, population and employment, and high land use mix. Table 1 shows the summary statistics of the variables characterizing the neighborhood types resulting from the cluster analysis.

Aggregate household activity spaces

Next, in order to group households by distance from the core and type of nearby infrastructure, we used Model Builder in ArcGIS 10 to create buffers rings at increasingly large intervals moving away from the core, ending in increments of 5 km from 15 to 45 km after which nearby highway corridors, commuter rail stations and metro stops, as well as cells away from both highways and mass transit, were found. Households within proximity to these points were queried, criteria being established to capture information on households within a reasonable distance from each identified site; 800 meters served as the catchment areas for transit, and 1500 meters for highways and sites unserved by transit or expressways.

This led to an initial selection of 344 sampling sites. Only sites with at least 100 households were included in the analysis, of which there were 218. For each of the sites, household trip ends were then selected for the next step in the process, while demographics and other characteristics were extracted from the OD survey to serve in future steps. Household types, persons per household, vehicle ownership, multimodal transportation emissions, and many other characteristics were aggregated to the level of the households sharing a sampling point. While sampling points were sought out as far as 65 kilometers from the core, no intersect point beyond 45 kilometers had the requisite 100 proximate households. The sampling points from which household travel data was extracted are shown in Figure 1.

Using the methods described above, information on 14,295 unique households was pooled, 34% of households being proximate to more than one sampling site. Households were pre-filtered to ensure those kept in the pool of candidates performed all their trips within the study area, as this was necessary in order to obtain precise trip coordinates from the OD survey.

The trip ends for all households associated to a given site were then plotted in GIS, and standard deviation ellipses (SDE) were generated to represent dispersal of travel for those specific households (see Figure 2 for examples of SDEs). Area and compactness values were also generated for each of the 218 valid sampling points' pooled household trips – the properties of the SDE.

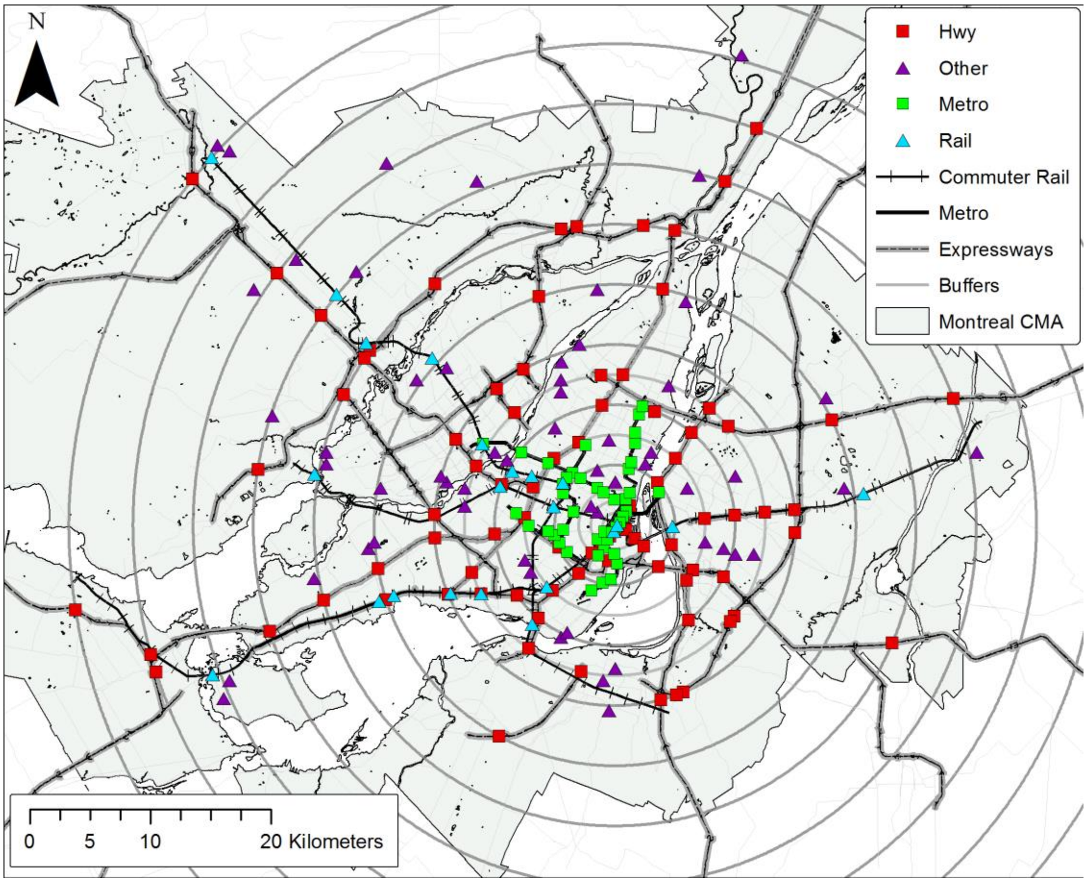


Figure 1 – Rings of proximity to CBD and nearby sampling sites

Results

The following section presents the results of analysis looking at aggregate SDEs and average transport-related CO_2 emissions of households near different types of infrastructure, at various distances from the core, i.e. the selection sites.

Figure 2 shows maps of aggregate SDEs for three different types of infrastructure (expressways, commuter rail and metro). In each example, the SDEs along one corridor are shown. As can be seen, for households near all types of infrastructure, the further one gets from the CBD, the more elongated the SDEs become (less compact or circular). This is consistent with prior expectations and literature (Beckman, Golob, & Zahavi, 1983b), since one would expect that farther out locations would have their residents' SDEs pulled toward the CBD as a result of commuting patterns.

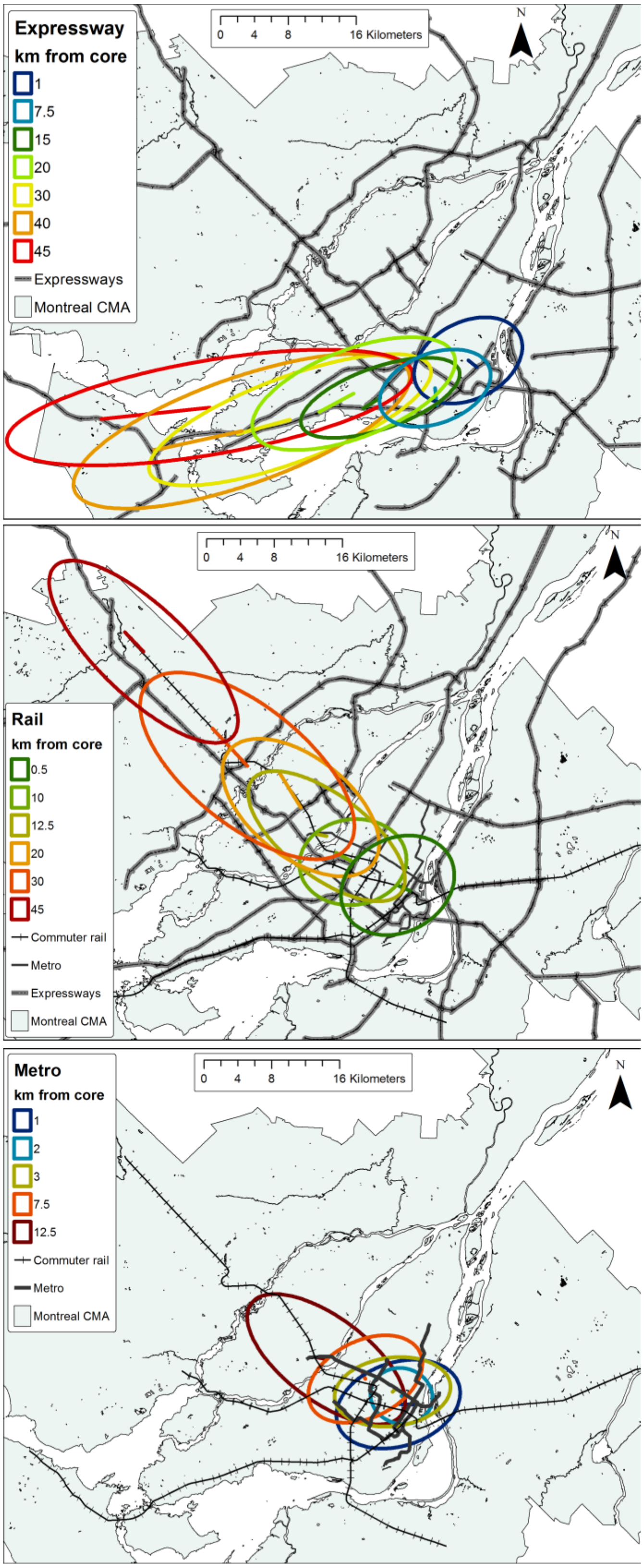


Figure 2 - Sample SDE activity spaces for households near expressways, commuter rail and metro stations

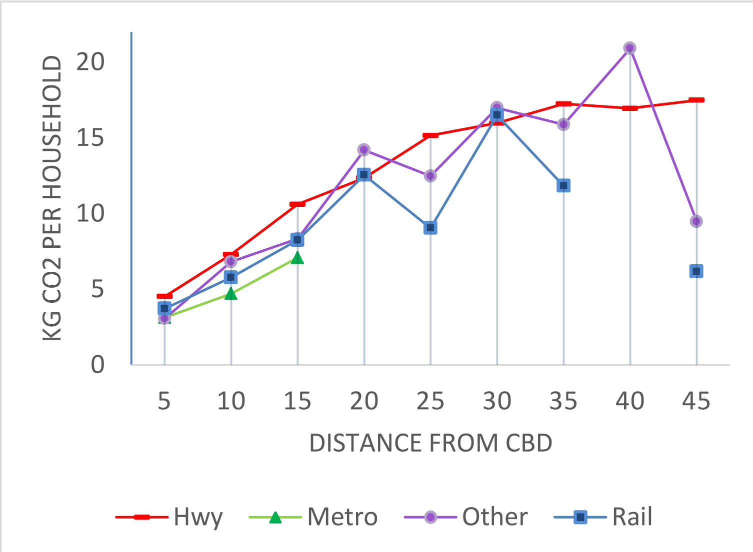


Figure 3 – Average household emissions and distance from the core, by infrastructure type

Figure 3 shows average transport-related CO_2 emissions for households associated with the different types of sites, at increasing distances from the CBD. There appears to be a strong, positive relationship distance from the CBD and household emissions. Differences between infrastructure types are surprisingly stark, this despite the fact that the same households can be included in both transit and highway in some cases, which should soften the distinction between the different lines. One can see that households nearest highways have the highest emissions per capita at almost every distance from the CBD, while households near the metro have the lowest. The fact that this comes through fairly clearly despite overlap in sampling locations is a clear sign that emissions are not only a matter of location within the CMA, but also to being immediately adjacent to infrastructure. Another interesting feature is the noticeable dip in emissions per capita at 45 kilometers for both rail and "other" (cells unserved by transit or highways), although not for highway.

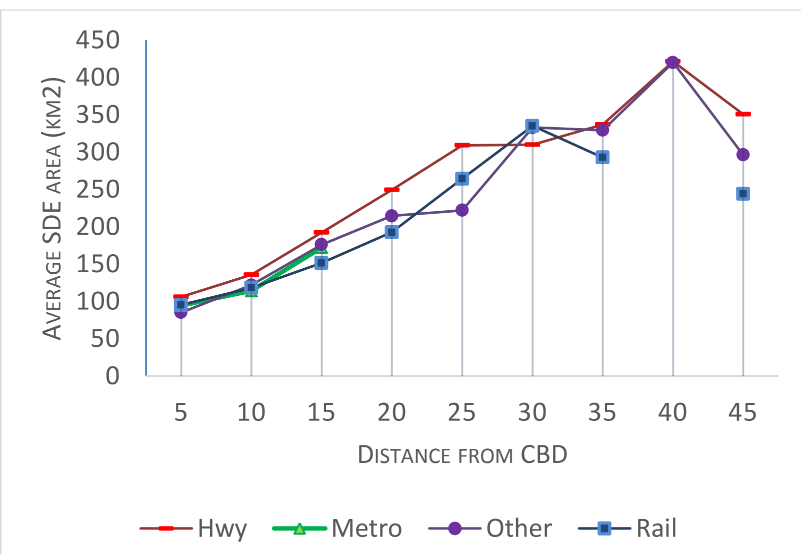


Figure 4 - Average SDE area per household by distance from core

Figure 4 is similar to Figure 3, but shows average household SDE area, as opposed to emissions. It also shows similar trends as Figure 4, with SDE area increasing with distance from the core. At the same time, the trends observed in emissions figure are not quite as distinct for SDE area as for emissions. For example, while sites close to highways almost always have the largest SDE, the metro and rail sites are not quite as obviously different from the other types of sites. Also of interest, whereas sites close to highways do not see a decrease of emissions at the farthest reaches of the region, SDE area for highway sites do decrease at the furthest point.

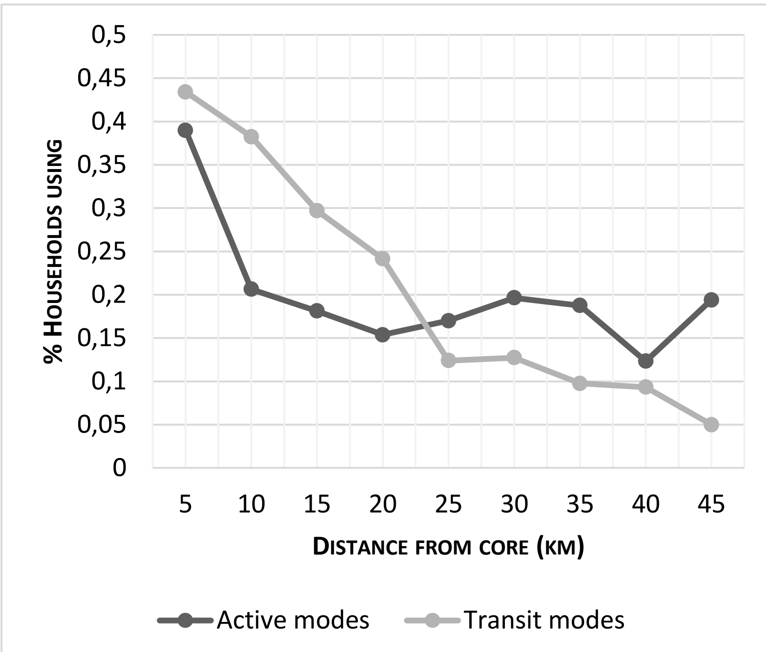


Figure 5 - Active and transit mode use by distance from CBD

Looking at the reason behind the large increases in CO2 emissions as one moves away from the core, we see in Figure 5 that active mode use falls rapidly from a high of 40% near the core to just below 20%, where it hovers starting around 10km from the CBD. This despite the fact that households increase in size as one moves away from the core and the number of children and teens (captive active-mode users) is also higher there.

As for transit, the peak in modal use is also found near the core, after which it falls rather drastically – the 10-15 km mark coincides with the point at which we leave the island of Montreal when looking to the north, and essentially leave the metro coverage zone. This has profound implications which can be seen in the emissions per household graph (Figure 3).

Regression analysis

To better understand the different factors affecting both emissions and activity spaces, we used the average household values for a variety of variables aggregated together at each of the 218 sampling points (sites) in a regression model. Variables for inclusion were chosen using a backward step-wise regression, attempting to capture non-linear effects through the transformation of values. Those values having a statistically and effect-wise significant coefficient estimate were kept when building the emissions model, then the same model specification was used with the SDE area as the dependent variable to see what the differences in coefficient estimates might be.

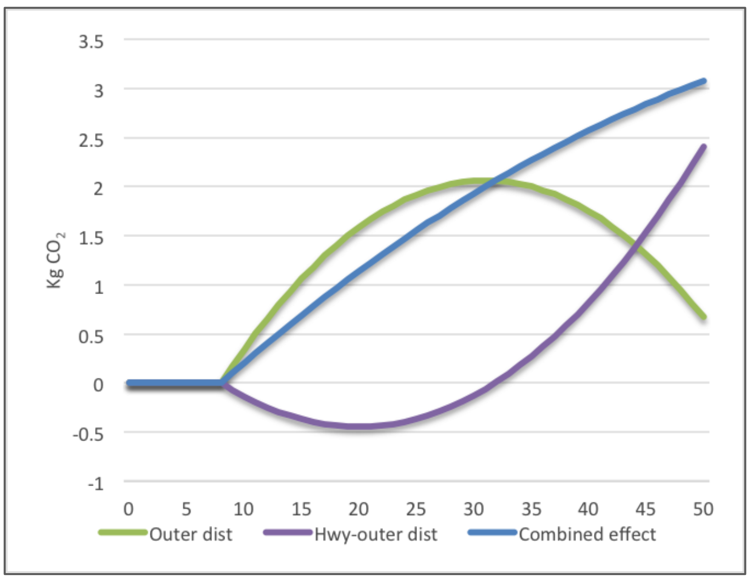
The first two variables are "outer distance" from the CBD and its square. This variable represents network distance to the CBD from the site. It takes on a value of 0 for the first 8 km (5 miles). This is to be consistent with Nasri and Zhang (2012), who used a similar cut-off point when investigating the effect of built environment variables at different scales, more specifically the effect of city center strength on vehicle miles traveled per household. The third and fourth variables in the model measure network distance to the closest train or metro station. Highway intersection "outer distance" represents the distance from the CBD of the closest intersection if the site is within 1,500 metres of an expressway. As with the "outer distance" variable, it has a value of 0 for the first 8 km. Following these are land use control variables. These include the logarithm of population density and the four neighbourhood cluster variables (exurban being the omitted category). After that are two household characteristic variables (average size and presence of children), and average household transport characteristics. These describe the proportion of households identified with the site making work trips, school trips, leisure trips, and trips to pick up or drop someone off (chauffeuring).

Table 2 - Regression model estimates, OLS with kg CO2 as dependent variable

		Emissions (Kg CO_2 e)			SDE area (km_2)		
	Variable	Coef.	t-stat	p-value	Coef.	t-stat	p-value
Location	Dist. outer (km)	0.179	4.45	0.000	3.779	3.59	0.000
	Dist. outer^2	-0.004	-4.27	0.000	-0.036	-1.52	0.129
	Dist. nearest metro (km)	0.162	5.08	0.000	2.961	3.62	0.000
	Dist. Nearest rail (km)	0.076	4.58	0.000	1.382	3.26	0.001
	Hwy-prox. dist outer (km)	-0.075	-2.06	0.041	1.330	1.13	0.261
	Hwy-prox. dist outer^2	0.003	2.83	0.005	-0.013	-0.32	0.752
Neighborhood	ln(Pop density [p/ha])	-0.727	-4.14	0.000	-10.092	-2.25	0.026
	% cluster 2	-0.744	-1.67	0.097	-25.176	-2.20	0.029
	% cluster 3	-1.685	-2.89	0.004	-17.827	-1.19	0.234
	% cluster 4	-1.976	-2.76	0.006	-27.068	-1.47	0.143
	% cluster 5	-0.944	-1.28	0.203	20.496	1.08	0.281
Household and trip making	% Single person HH	-6.956	-3.89	0.000	-71.780	-1.57	0.119
	% Families with children	-4.293	-2.18	0.030	35.237	0.70	0.484
	% HHs making work trips	9.860	6.47	0.000	195.662	5.01	0.000
	% HHs making school trips	3.778	1.89	*0.060*	-158.247	-3.10	*0.002*
	% HHs making leisure trips	8.509	4.21	0.000	28.962	0.56	0.577
	% HHs chauffeuring	6.168	2.42	0.017	-172.741	-2.64	0.009
	Constant	*1.092*	*0.70*	*0.483*	107.032	2.69	*0.008*
	Nb Observations	218			218		
	R-Sq	0.936			0.873		
	Adj R-Sq	0.930			0.862		

To present the results, we will start with the emissions model and then use it compare with the SDE model afterwards. First off, the majority of the coefficients are statistically significant and right-sided and the model has a high goodness of fit, which is perhaps not surprising since these are aggregated data.

With respect to the coefficients themselves, the first thing to note is the variables of “outer distance” to the CBD and its square; these two variables suggest that as distance from the CBD increases, CO_2 emissions initially increase but towards the outskirts of the region, begin to decrease. This is consistent with Andrew’s (2008) finding of an inverted u-shape in GHG emissions along the urban-rural gradient. Distance to transit infrastructure increases CO_2 emissions as is to be expected – the further from metro or commuter rail stations, the higher the emissions. The “outer distance” from a highway intersection to the CBD, when a site is within 1.5 km of a highway, at first glance appears to be wrong-sided. I.e. it is negative, suggesting that as the variable increases, average CO_2 emissions decrease. At the same time, this variable needs to be seen in the context of its square (which is positive) and the “outer distance” variable itself. Its square implies a non-linear (u-shaped) relationship. Also, taken together with the two “outer distance” variables, the combined effect of distance from the CBD for sites located within 1.5 km of a highway is positive and increasing over the range examined (8-50 km). To illustrate this more



clearly, the interaction of these distance variables is shown in Figure 6.

Figure 6 - Combined effect of “outer distance” and Highway Intersection outer distance variables

We explain this decrease in emissions as households become very far from the city with an analogy from astronomy and in particular the notion of “orbit.” As a result of gravitational pull objects can be kept orbiting around each other (e.g. the moon around the earth). We see households’ whose emissions begin to decrease after a long distance from the core, as households that are falling “out of orbit” of the city core – their trips being less frequently drawn in to the centre of the city and instead being satisfied by more local trips, perhaps to smaller and nearer regional centres.

As expected, with respect to land use, CO_2 emissions decrease as the log of population density increases, and also when one moves from more suburban to urban clusters (the omitted cluster is exurban). That the most urban cluster (5) is insignificant with a coefficient value suggesting a reduction in emissions less than the other clusters has to do with the fact that cluster 5 locations are only found in the highest employment density cells immediately adjacent to the CDB, where a rents are very high and the demographics of the population are considerably different from that of the rest of the CMA. As can be read in Table 1, only 8% of the households living in cluster 5 cells are families with children, and so despite having lower vehicle ownership rates than households in other cells, the people who live there have the highest combined metro, rail and highway access in the CMA, while facing the least amount of travel time scheduling constraints. In addition to the demographic element, the impact of proximity to rail and metro modes appears to be explaining most of the low average emissions associated with cluster 5 sites.

Furthermore, as the proportion of households with one person increase, emissions decrease, which stands to reason. That as the proportion of households with children increases, emissions decrease can be explained with families spending more time at home, and in the reverse of what was described above for central city residents, they have the highest number of travel time budget considerations to balance and thus must better chain their trips spatially. As the proportion of families undertaking various types of trips (work, leisure, school and chauffeur) increases, so do emissions which also stands to reason.

With respect to the area of SDEs model, the contrasts with the emissions model are interesting. First, the SDE model has fewer significant coefficients and has a lower goodness of fit than the emissions model. With an adjusted R-square of 0.862, however, the model still explains a high proportion in variation of average SDE area. Whereas an inverted-u shape was found unambiguously in the emissions models, the inverted u-shape trend is not quite significant in the SDE model. The square of “outer distance”, however is close to being significant at the 10% level. As such, perhaps with more observations an inverted u shape would be found, but based on the evidence from this dataset, it is not quite as obvious as the case of emissions. SDE area also does not exhibit the same patterns as emissions with respect to proximity to highway infrastructure; whereas proximity to highways increases emissions, it does not have a significant impact on overall SDE area. As with emissions, population density decreases SDE area. With respect to the cluster variables, increasingly urban clusters are associated with smaller SDE area (except, again, cluster 5), even though only cluster 2 is significant. That cluster 5 is wrong sided (although insignificant) is likely related to the same issue highlighted above for emissions. With respect to household characteristics, as the proportion of single person households increases, SDE area decreases, although it is insignificant. This has the same sign as in the emissions model. The two variables describing household characteristics, are both insignificant. With respect to the proportions of households engaging in different kinds of trips increases, as the proportion of households engaging in work trips increases, so does SDE area. For the other trips, they either don’t appear to have an effect at all (e.g. leisure trips), or they decrease overall SDE. This is perhaps due to the fact non-work trips take place close to home for Montreal residents, and don’t extend that far out of the normal bounds of the SDEs.

Given the interest in CO_2 emissions in this research, as well as the complex relationship between the various distance variables, it is easiest to understand impact of distance on emissions by visualizing it graphically. This is done by mapping a transport-related CO_2 emissions surface. To prepare such a surface, it was necessary to control for household, trip making and neighborhood characteristics, thus isolating the impact of access to certain types of high capacity urban transportation infrastructure, as well as distance from the core. This was done by first generating a synthetic “average” site and associating its characteristics to all cells in the CMA. CO_2 emissions for each cell were then estimated changing only the distance variables (outer distance to CBD, distance to metros, etc.) using the regression model coefficient estimates from the emissions model. The resulting CO_2 emissions surface can be seen in figure 7, below.

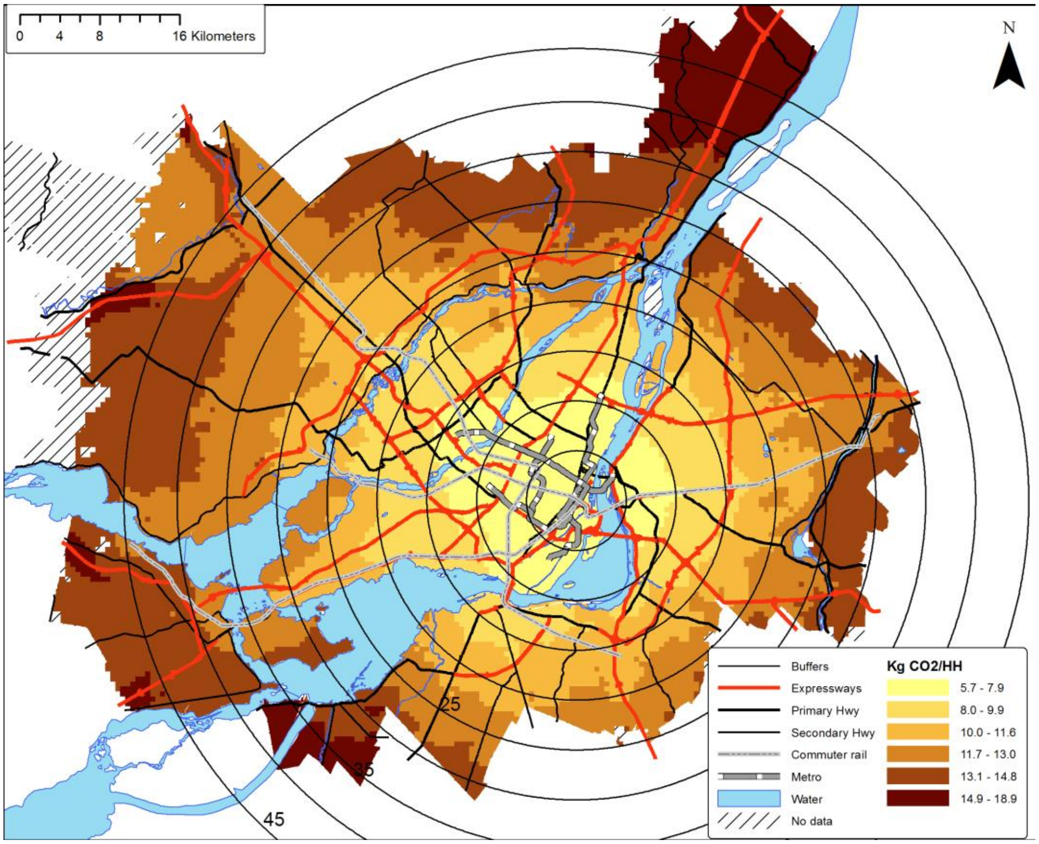


Figure 7 - Transport-related CO2 Surface

As can be seen, when controlling for household and neighborhood type, we obtain a somewhat smooth surface with very interesting particularities. To begin with, the non-linear effect of distance from the city core leads to a levelling off of emissions in the northwestern-most section of the map even in areas beyond 45 km from the CBD. Within this same region, we clearly see the effect that the presence of highways far from the core have on CO_2 emissions. The overall spread of average household emissions ranges from just below 6 kg CO_2 per household in the central parts of the region, to a high of 19 kg CO_2 in locations further afield. For cells nearest the highways further afield, the effect is as described in earlier sections, whereby the “orbit” of the city seems to be extended as a result to proximity to this type of high capacity infrastructure, inciting households to travel further afield as opposed to reorganising their activities around more accessible local activities. This property of proximity to highways at a significant distance from the core, which is clearly contrasted to nearby cells is important to understand if one is to develop a cohesive and realistic regional plan for development; understanding the effect of different types of infrastructure on the pull to a central or satellite city can help in better allocating resources to projects and not pitting one form of transportation against the other.

To better understand the influence of each component on transport-related CO_2 emissions of residential development at different locations in the city, the table of summary statistics and effect sizes below is also produced.

Table 3 - Effect size estimates, OLS with kg CO2 as dependent variable (* to better represent the effect of a 10% increase in density, the non-transformed mean was used as an input and converted to fit the model specification)

	Variable	Mean	Coef.	Min	Max	Effect	Effect Type	*Max influence (Kg CO_2eq)*
Location	Dist. outer (km)	10.19	0.179	0	49.4	2.73%	outer + 1km	8.83
	Dist. outer^2	247.35	-0.004	0	2442	-0.04%	outer + 1km	-9.46
	Dist. nearest metro (km)	9.07	0.162	0	43.0	1.94%	mean + 1km	6.96
	Dist. Nearest rail (km)	5.20	0.076	0	44.4	0.91%	mean + 1km	3.36
	Hwy-prox. dist outer (km)	4.68	-0.075	0	45.6	-0.90%	mean + 1km	-3.43
	Hwy-prox. dist outer^2	106.91	0.003	0	2083	0.04%	mean + 1km	6.56
Neighborhood	ln(Pop density [p/ha])	3.55	-0.727	-2.41	4.831	-13.68%	mean + 10%	-3.51
	% cluster 2	0.30	-0.744	0	1	-0.89%	mean + 0.1	-0.74
	% cluster 3	0.20	-1.685	0	1	-2.02%	mean + 0.1	-1.68
	% cluster 4	0.16	-1.976	0	1	-2.37%	mean + 0.1	-1.98
	% cluster 5	0.10	-0.944	0	1	-1.13%	mean + 0.1	-0.94
Household and trip making	% Single person HH	0.27	-6.956	0.03	0.58	-8.33%	mean + 0.1	-4.03
	% Families with children	0.27	-4.293	0.03	0.58	-5.14%	mean + 0.1	-2.49
	% HHs making work trips	0.66	9.860	0.34	0.88	11.80%	mean + 0.1	8.68
	% HHs making school trips	0.32	3.778	0.07	0.57	4.52%	mean + 0.1	2.15
	% HHs making leisure trips	0.29	8.509	0.16	0.42	10.19%	mean + 0.1	3.57
	% HHs chauffeuring	0.17	6.168	0.05	0.41	7.38%	mean + 0.1	2.53
	Constant		1.092					
	Mean	8.35	Kg CO_2eq					
	Base	5.6474						

The relationships between distance from the core and proximity to highways having been described in Figure 6, here, we focus on the other infrastructure effects, as well as the control variables. With a maximum distance of approximately 35 km for both rail and metro, the respective impacts these variables have on emissions are maximum increase of ~6 and ~3 kg. More broadly, we see that the location within the CMA has a large effect, larger even than neighborhood type or density. This concords with much of the literature on the effects of TOD and other forms of sustainable suburban development, indicating that the effect of such development is greatly affected by location within the region. This is because only some trips can be replaced by local walking or cycling trips, while many still require travel outside the neighborhood to access specialized goods and services, or employment centers. This is not to say that neighborhood type does not matter however, as there can be a ~2 kg CO_2 reduction in average emissions for neighborhoods that have a high level of urbanity (cluster 4), household and location factors controlled for.

The fact that neighborhood type has a less important influence on the magnitude of emissions in comparison to location is noteworthy as well, as similar methods employed in a recent paper by Harding, Patterson, & Axhausen (2014), comparing trip dispersal in different metropolitan regions in Switzerland, found that neighborhood type had a larger influence on dispersal than distance from the CBD or proximity to employment centers – again, controlling for household type and trip making characteristics. This may be due to the differences in form of suburban and exurban development in Switzerland, the scale of cities in that sample (the largest being Zurich, a city of approximately 2 million inhabitants spread over a metropolitan area of 2,110 km^2, in contrast with Montreal which has a population of 3.6 million spread over 4,260 km^2 – a non-negligible difference) or perhaps simply an artefact of pooling households together as opposed to modeling the output for individual households. These differences in response when modeling trip dispersal or emissions are important to investigate, as the use of activity spaces in transportation research is rapidly evolving.

Discussion

The results presented in the previous section imply quite a few things. First, coefficients estimated for distance from the inner metropolitan area imply that development far away from the core of a city leads to less sustainable travel behaviour. Our results indicate that while an inflection point may exist, after which emissions begin to decrease, this point is found around 35 or 40 km from the core in the case of Montreal. Considering that development is already taking place at distances beyond that, this means that to reach emissions reduction targets for the region as a whole, policy must be reassessed, as building a few commuter rail stations is not enough to generate the significant reductions needed to meet provincial emissions reductions targets – not through land use alone at the very least. Luckily, while some development is occurring far away from the core, 80% of the CMA population and 88% of the total employment are found within the first 25 kilometers of the core, at which point only 40% of the CMAs total land area is included, 49% of which is still classified as open area.[1] Developing along strategic rail and metro corridors – and improving these same networks - in the central portion of the CMA is one possible approach to reigning in fringe development and improving development sustainability.

The significant figures obtained for increases in emissions when one gets further away from metro and rail stations, in conjunction with the increases in emissions associated with proximity to further out highway corridors also has profound implications for future development policy aimed at providing accessibility without increasing per capita emissions; to reduce emissions from transportation there needs to be a clear shift in priorities from congestion relief on highways to channeling development around transit nodes, as well as promoting redevelopment and infill around existing transit corridors. The combined effects of distance from transit and access to highways has the effect of increasing emissions in a significant way, even after controlling for neighborhood, household type and trip making characteristics.

The differences found between explanatory variables for SDE area and GHG emissions also clarifies part of the ambiguity in the literature regarding the relationship between these two travel demand measures. While there is a strong correlation between these dimensions (0.856), uni-dimensional measures of

[1] Authors’ calculations based on DMTI land use data.

dispersal do not properly represent sustainability - at least not from an environmental perspective - when they do not account for proximity to infrastructure or types of travel.

Aside from the points mentioned above, it seems appropriate to bring up the fact that results found here do not concord with findings from similar work done in Switzerland (Harding, Patterson, & Axhausen, 2014), which begs the question of what roles scale or network properties play in determining the orbit of a CBD. Our findings clearly indicate that highways increase the pull of a central city to beyond 40 kilometers given the current distribution of activities within the region. What role secondary centers, better transit feeder lines, or any other types of network changes can play in changing this dynamic is the question that should be explored in future work looking at regional planning and its effects on emissions.

Conclusion

The work presented here re-appropriates methods to investigate GHG emissions in a novel way, looking at the effect of distance from core, access to high capacity infrastructure, neighborhood type and finally the spatial distribution of activities. Results show that highways extend the orbit of a city, in addition to, or by association with, increasing average household emissions. Transit on the other hand allows long-distance travel while minimizing emissions. Additionally, the effect of distance is not linear, and associated findings are that when the orbit is escaped, both SDEs and emissions seem to mirror this by having inflection points in their evolutions.

The coefficient estimates generated in regression analysis could be used in conjunction with GIS and future development scenarios to assess the likely effect of new developments or new infrastructure on emissions for the region, adding another means by which to plan in conjunction with emissions reduction targets.

The question of a link between activity spaces and sustainability is also explored, and while it is found that, broadly speaking, increases in travel dispersal correlate with increases in emissions, interpreting these spaces without proper acknowledgment of the types of infrastructure present, and enabling this travel, leads to inaccurate assessments.

Future work

Two points which could be addressed in future work to remedy shortcomings of this research would be to gather data on the travel behaviour of residents in other CMAs in the province, to better understand the implications of regional development scale on emissions, as well as better understand where the inflection points may be found where high capacity infrastructure may be limited only to highways. As well future work using this approach should attempt to test for, and if necessary capture, spatial autocorrelation.

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