Mobility's Footprint: Household Travel, Greenhouse Gas Emissions, and the Built Environment in Santiago de Chile

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Abstract

Changing urban growth patterns and the form and design of cities (i.e., the built environment) may be an important element to reducing transportation's global and local emissions footprint. In this paper we attempt to empirically assess the relationship between the built environment and local and global emissions produced by household travel in Santiago using data from the 2001 travel survey. Specifically, we incorporate local built environment variables – measured by a range of different spatial approaches – into vehicle ownership and total household travel-related tailpipe emissions models. The results suggest that income dominates vehicle ownership and greenhouse gas emissions, but that relative location, relative transportation levels of service, distance to Metro stations, and several local built environment measures related to street network design, residential density, and land use mix also play a role. In combination, these factors roughly equal the income effect. Nonetheless, some tradeoffs emerge, particularly with respect to emissions of respirable particulates.

Key Words: built environment, greenhouse gas emissions, local pollutants, household travel

Word Count: 6059 Words (including abstract and references), 5 Figures, 6 Tables

1 Introduction

Much of the developing world's residents suffer from a lack of quality accessibility – the ability to reach the daily needs and wants necessary to survive and thrive. Mobility – the movement from place to place – plays a critical role in enhancing accessibility. Some form of mobility is very often necessary to work, learn, socialize, receive health care, etc. Fundamentally, growing mobility reflects a desire to increase accessibility and, thus, human development. Human development, in turn, leads to higher demands for accessibility – accessibility is a "superior good" – which then may drive further increases in mobility.

So, globally we can expect increasing income and development to fuel increases in demand for accessibility and, thus, mobility. Other key inter-related drivers of mobility demand worldwide include labour force participation, demand for space, demographics, infrastructure investments, and urban decentralisation (i.e., suburbanisation). The basic global trends point towards more trips, longer trips, and more trips by private motorized transport modes (Schäfer, 2000).

Without doubt, considerable variation exists within this broad-brushed global dynamic. Cultural factors and legacy systems (e.g., built urban form and densities, public transport systems), for example, influence mode choices. Under "business-as-usual," however, we can expect to see an important increase in the demand for private motorized travel, especially in the developing countries. The International Energy Agency (IEA, 2004) estimates that over the next 50 years per capita light duty vehicle distances travelled in the OECD countries will increase in the range of 0.2 to 0.8 percent per year, as compared to nearly 6 percent in China, 5 percent in India, and almost 3 percent in Latin America.

Much of this increased travel demand will be urban since the overwhelming share of developing countries' population growth will occur in urban areas (UN, 2009). A simple back-of-the-envelope calculation provides perspective. Between the period 2005-2030, ninety percent of *net* population growth on the planet – approximately 1.6 billion *additional* residents – will occur in developing country urban areas (UN, 2009). Assuming modest private car use per capita and reasonably conservative estimates of effective fuel economy, the marginal fuel demand of just these *additional* developing world urban inhabitants implies on the order of 450 million tonnes of carbon dioxide emissions annually[1] due to automobile travel alone, or almost exactly the total road-based transportation emissions for the entire Latin America and Caribbean region in 2008 (IEA, 2010).

These trends frame the fundamental sustainable mobility challenge: how can we maintain the systems' capabilities to provide non-declining accessibility over time (Zegras, 2005)? In other words, how can we increase society's overall accessibility levels, thereby increasing human development potentials, while reducing or eliminating the wide-ranging negative impacts, short- and long-term, that modern mobility systems impose on us, our ecosystems, and future generations? The latter include: local air pollution, death and injuries from traffic accidents, settlement disruption and other negative effects from large-scale transportation infrastructures, destructive effects associated with fuel and other resource extraction/production/distribution, and greenhouse gas (GHG) emissions and climate change risks due to transportation energy use.

Here we look at the prospects for sustainable urban mobility from the climate change risk perspective, exploring the links between transportation GHG emissions, local pollutant emissions and urban form. Specifically, we look at household travel-related local and global emissions and their potential association with patterns of urban development within a single, rapidly growing metropolitan area: Santiago de Chile. We aim to see whether empirical evidence supports the notion that we might mitigate urban transportation's contribution to climate change risk and local pollution problems by changing the forms and patterns of urban growth.

Following this introduction, the second section of this paper provides a brief background to transportation and GHG emissions, the potential role of the built urban environment, and theoretical and practical challenges to identifying the links. The third section introduces the empirical setting, Santiago de Chile. The fourth section presents the evidence, based on models of household vehicle ownership and total transportation energy use and emissions in 2001. The final section discusses implications and offers some conclusions.

[1] This is a conservative lower-bound estimate, based on: an average 2000 private car kilometers per capita (*1990* averages in samples of cities from: US, 11115; Australia, 6571; Canada, 6551, Western Europe, 4529; "wealthy" Asia, 1487; "developing" Asia 1848; Kenworthy and Laube, 1999) and 6 L/100 km average fuel economy (equivalent to the Japanese fleet average fuel consumption *target* for 2015; Eads, 2011).

2 Background: Transportation GHGs and the Built Environment (BE)

Globally, the transportation sector accounted for about 22% of energy-related greenhouse gas emissions in 2008, with road transportation responsible for about 75% of the sector's total (IEA, 2010). At the country level, income alone explains more than 80% of the variation in road transportation carbon dioxide (CO_2) emissions, exhibiting a relationship that implies a long-term income elasticity of about 0.9. In other words, every 1% increase in GDP per capita means a 0.9% increase in road transport greenhouse gas emissions per capita. Despite income's predominance in determining national road transport CO_2 emissions, other national-level factors also play a modest role – urbanization rate, gasoline price, per-capita paved road transport network, and national density explain another 10% of the variation across countries.[2]

This international sketch leads to the basic global transportation challenge: "decoupling" transportation growth and its energy use and greenhouse gas emissions from economic growth (e.g., Banister and Stead, 2002). As discussed in the introduction, income drives demand for accessibility which increases demand for mobility, typically with higher levels of speed, privacy, convenience, and comfort – all of which tend to also increase energy use (e.g., Schäfer, et al., 2009). Technology may moderate some of the future growth in road transport's energy use and emissions, although meeting ambitious goals for GHG emissions reductions from the sector will almost certainly require a combination of aggressive vehicle efficiency gains, low-carbon fuels and electricity, and reductions in travel demand (Kromer et al, 2009). The rapid urbanization and urban transformation underway in much of the developing world, leads to a logical question: can patterns of urban growth be altered to enhance *accessibility* while reducing demands for mobility, both for current residents and the 21st Century's billions of new urban residents?

In attempting to answer this question, we must maintain perspective. For example, individual and household travel is only one of many sources of total GHGs for a city or beyond. McGraw et al (2010) find that on-road transportation accounts for about 20% of the city of Chicago's GHG emissions in 2005, a figure only slightly higher than road transport's global share cited above. A study of 12 global metropolitan area's carbon footprints, estimates that transportation's share ranges from a low of 5% in Beijing to 66% in Delhi (Sovacool and Brown, 2010). For households themselves, transportation is of course only one GHG source. In Toronto, Canada, Norman et al (2006), estimate that transportation accounts for 40–60% of life-cycle GHG emissions (including building materials, and all sources of operational energy use) associated with residential developments' BE.

2.1 ASIF: An optic on the potential role of the built urban environment

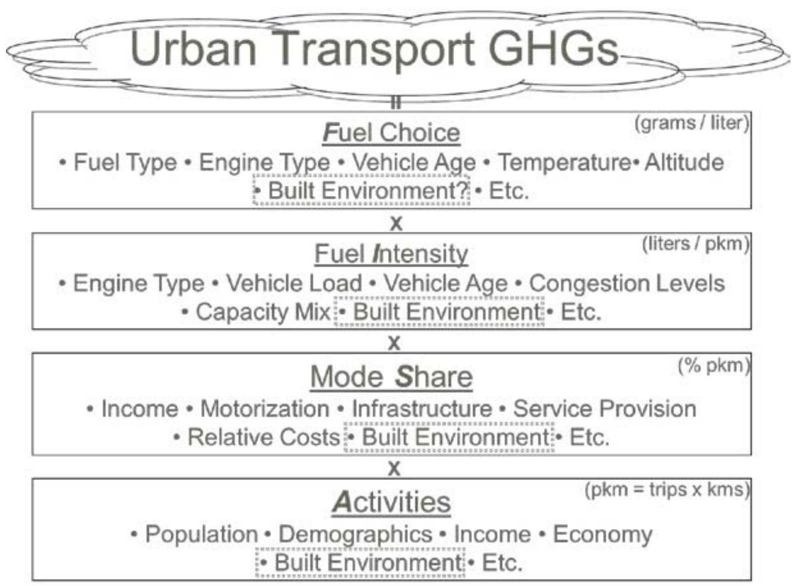
Contemporary Western notions of using urban form and city planning to influence travel behaviour towards some desired outcomes can be traced back to Howard's "garden city" of the beginning of the last Century, through the modernist heyday of LeCorbusier's "radiant city," the post-World War II "new community" movement, and up to contemporary movements related to "smart growth," "new urbanism," etc. (Zegras, 2010). Nonetheless, empirical and practical reality often collide with the visions – city planning and resulting urban forms and designs *might*

[2] Regression is: LN(Road Transport CO2/Capita) = 0.91*LN(GDP[PPP]/Capita) + 0.34*LN(Urbanization rate) - 0.39*LN(gasoline price) + 0.12*LN(Paved Roads/Capita) - 0.06*LN(Density). Robust t-statistics: GDP[PPP]/Capita (9.83), Urbanization rate (2.01), gasoline price (5.68), Paved Roads/Capita (2.06), Density (1.85). R-square=0.90; n=121 countries; data from IEA (2010); NationMaster, GTZ, World Bank – full data available upon request.

influence behaviour, but they cannot *dictate* behaviour. Theory itself does not offer an *a priori* certainty regarding the expected effects of the BE on total travel, and thus energy use and emissions.

Let's first examine, briefly, the various components of mobility that lead to transportation energy use and emissions and the possible role of the BE. Schipper et al. (2000) provide the "ASIF" identify, as a useful optic to illuminate transportation energy use as a function of total activity (A), mode share (S), fuel intensity (I), and fuel type (F) (thus, ASIF). Multiple factors influence each of the ASIF components (see Figure 1). In terms of household travel, the built urban environment can, in theory, influence: activities (A), by affecting the distribution of activities and total travel distances (e.g., Cameron et al., 2003); mode shares (S), since urban form (e.g., land use mixing) and design characteristics and local street patterns may influence mode choices (e.g., Rajamani et al., 2003); and fuel intensity (I), as urban design (e.g., street network type) may influence vehicle occupancy levels (e.g., Zhang, 2004). The BE may even influence fuel choice (F), since certain fuel technologies may be better suited for certain vehicle types which, in turn, may perform best in specific types of urban settings.

Figure 1. Activities, Mode Share, Fuel Intensity, and Fuel Choice: An ASIF View on the Built Environment and Travel GHGs



2.2 Theoretical and practical challenges

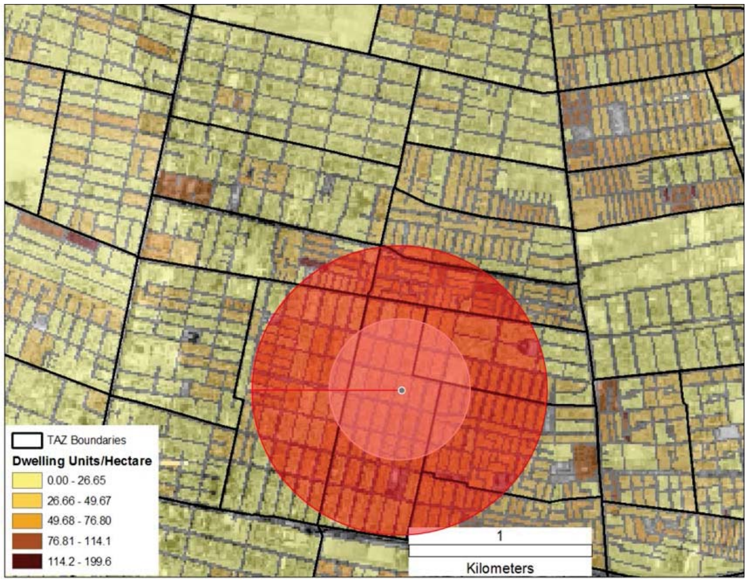
Despite the potential, as illuminated by ASIF, a main challenge to the argument that we can predictably use the BE to purposely influence transportation energy use is the theoretically ambiguous *a priori* net effects. Maat et al (2005) lay it out simply: the BE's potential influence on travel behavior is via effects on *net* utility—the utility of travel (e.g., number, quality, distribution of destinations) less its disutility (actual and perceived travel costs). As an example, imagine a specific attribute of the BE, a grid street network, reduces travel times. An effected individual may, then, choose to: (a) increase activity time (undertaken at a particular destination); (b) choose an alternative (more-preferred) destination; (c) schedule additional non-home activities. Deductively, the case of (b) and/or (c) would result in increased total travel and, thus, quite possibly increased energy use. This result is also consistent with the idea of constant travel time budgets (e.g., Schäfer, 2000).

Empirically, the argument also faces challenges. Regarding data, for example, travel or activity surveys carried out for a particular day may mask effects which accumulate over a week or month, across different spaces (all important from a GHG emissions perspective). Empirical analyses also face the classic causality challenge, associated with "self-selection" (Mokhtarian and Cao, 2008). In aiming to show whether the BE *produces* different household activity patterns and transportation energy use, at least two related forms of bias may be present: simultaneity bias (e.g., individuals who prefer a low GHG lifestyle choose to live in low GHG-oriented neighborhoods); and omitted variable bias (unobserved variables, like preferences for lower GHG emissions, produce the low-GHG travel outcome, but also correlate with the BE). In other words, the presumed exogenous causal variable, the BE, is actually *endogenous*, which can produce inconsistent and biased estimators.

Questions remain about how to properly measure the BE. These relate to the modifiable areal unit problem (MAUP), which has two dimensions: scale, the fact that the scale of analysis can be changed via the aggregation of areal units; and unit definition (the "zonal effect"), the fact that a multiple number of possible areal units within which an area of analysis can be defined (Horner and Murray, 2002). The implications for understanding the BE's influence on travel behavior are fairly clear. Taking the typical transportation model spatial analysis unit (the traffic analysis zone or TAZ), we cannot know whether such a division of space adequately represents the way in which the BE is perceived and used by individuals (Figure 2). Zhang and Kukadia (2005) explored the MAUP as it relates to the relationship between the BE and travel behavior and find evidence of both a scale and unit definition effect. They suggest using behaviorally based scales and unit definitions - a theoretically attractive proposition, but with practical questions. Upon what sort of behavior should the areal unit be defined? A risk of tautology exists: if we define the basic areal unit based on households' average trip distances and we use that areal unit to then attempt to capture the influence of the BE on travel behavior, haven't we just defined the extent of the effect (Zegras, 2005)?

Finally, difficulties remain in capturing the effects of inter-relationships among relevant BE dimensions. One approach consists of "vector-izing" the BE, deriving quantitative measures of BE dimensions – such as density of uses, diversity of uses, and design of space – and entering the resulting variables directly into a behavioral model. Alternatively, one might take a "typological" approach – identifying "types" of neighborhoods (possibly via quantitative analysis) and examining behavioral differences among them. "Typologization" and "vectorization" could also be used together.

Figure 2. Block-level Dwelling Unit Densities, OD Survey Zone Boundaries, and Block-Centroid-Generated 400m and 900m Straight-Line Buffers (Santiago)



2.3 Empirical precedents

Many reviews of the BE-travel behavior research exist. Ewing and Cervero (2010) offer the most recent compilation, conducting a meta-analysis of more than 50 empirical studies (all but four apparently in North America), including 19 which attempt to control for "self-selection" in some way. Their analysis suggests an approximate elasticity of private vehicle kilometers traveled (VKT) with respect to the combination of population density, land use mix, and street configuration of about 0.25. Relative location (e.g., distance to jobs) has a similarly sized elasticity with respect to automobile VKT. They find roughly similar sized effects with respect to public transport use and walking. Regarding direct links to greenhouse gas emissions, a recent study commissioned by the US government reviewed much of the same evidence as Ewing and Cervero (2010) and also developed several scenarios regarding the potential role of future urban development in reducing passenger travel GHGs in US metropolitan areas (TRB, 2009). The study reveals two points of interest for our purpose. First, it immediately focuses on vehicle miles traveled (VMT), presumably private VMT, which the study virtually uses as a synonym for GHGs, which may not be as relevant for places with less total car dominance than the USA. Second, the scenarios suggest modest future effects of changing development patterns: somewhere between 1-8% potential reduction in CO_2 by 2030 versus business as usual, given an estimated 60 million new dwelling units developed at twice the prevailing development densities. This scenario likely has little relevance outside the USA – for example, doubling the prevailing densities in USA reflects extremely modest density by global standards.

In short, while an important body of work on the BE and travel behavior exists, with some attempts to link this to GHGs, the studies remain limited primarily to North America. Generalizing from such research to other contexts may be risky for a number of reasons and, in any case suffers from challenges relating to the scale of analysis, the type of BE measures used, the travel behavior data used, analytical approaches, and ultimately the outcomes measured (Zegras, 2010). In the Santiago context, at least two recent relevant analyses exist. Donoso et al

(2006) used an integrated simulation model, calibrated on the 2001 travel survey and land cadaster data, to model meso-level land use development patterns (concentrations of origins and destinations) that would reduce GHGs. Zegras (2010) estimated cross-sectional econometric models to examine the relationship between the BE and automobile ownership and use among Santiago's households, also using the 2001 data. Our paper builds directly on Zegras (2010).

3 Context: Santiago de Chile

Santiago de Chile, a metropolitan area of nearly 6 million people and 1.7 million households, has experienced rapid economic and physical growth over the past two decades, transforming the transport system. The motorisation rate (vehicles per 1000 persons) increased nearly 3% per year over the period 1991-2006 (although in 2006 it still stood at only 20% of the US level and just 30% of Western European levels), while private motorised travel demand increased even more rapidly. The overall trip rate increased at almost 3% per year, with a large growth in non-work, non-school trips as a share of total travel (Zegras, 2010). The government has embarked on major interventions in the sector over the past decade, including: aggressive expansion of roadway infrastructure, especially through Chile's highway concessions program (approx. 180 kms of new or upgraded highways in Santiago); urban heavy rail (Metro) expansion; and important reforms to Santiago's bus-based public transport.

Table 1. Transportation's Contribution to Santiago's Annual Transportation Emissions and Vehicle Kilometers Traveled (VKT)

Vehicle Type	PM_{10}	$PM_{2.5}$	CO	NO_x	VOCs	SO_x	CO_2e	VKT
Private autos	9.3%	0.0%	56.6%	28.8%	48.1%	27.0%	39.1%	52.7%
Taxis	1.2%	0.0%	2.4%	1.7%	2.8%	3.3%	4.9%	6.7%
Colectivos	0.9%	0.0%	1.9%	1.4%	1.8%	2.6%	4.0%	4.9%
Buses[a]	17.3%	20.2%	0.8%	20.0%	4.2%	19.3%	12.1%	3.7%
Commercial Vehicles[b]	23.2%	23.6%	34.5%	18.0%	29.0%	18.6%	20.6%	21.5%
Trucks	48.0%	56.1%	1.7%	29.9%	10.3%	28.9%	18.0%	9.3%
Motorcycles	0.1%	0.0%	2.1%	0.1%	3.7%	0.3%	0.3%	0.9%
Metro[c]	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	1.0%	0.3%
Transport Share of Total[d]	*31.2%*	*29.1%*	*87.8%*	*68.0%*	*18.7%*	*0.9%*	n.a.	n.r.

Sources: Derived primarily from DICTUC, 2007. Notes: PM_{10} includes tire wear and brake dust; VOCs include evaporative emissions; CO_2e includes N_2O and CH_4. (a) Include "rural" and "interurban." (b) Apparently include jeeps and private pickups, with unclear distinction of private or commercial use, and include school buses and private buses. (c) CO_2e based on kWh reported for 2005 in Metro (2007) and electricity emissions factors for Chile (USDOE, 2007); VKT is coach-kms. (d) Total emissions include point and area sources, off-road vehicles, but do not include fugitive dust. n.a. = not available (in case of criteria pollutants for Metro, those are not emitted within the Santiago are)a; CO_2 emissions were unavailable for non-mobile sources. Highway through traffic is not included in these data.

Santiago has made important strides in improving its air quality since the early 1990s, although it still often violates standards for respirable particulates (PM_{10}), ozone, and carbon monoxide (CO) (DICTUC, 2007). As of 2005, transportation contributes an important share of criteria pollutants: 31% of PM_{10}, 90% of CO, and 70% of the oxides of nitrogen (NO_x), an ozone precursor. Cars are the majority transportation source of CO, trucks and commercial vehicles the main source of PM_{10}, while NO_x responsibility rests more evenly across cars, trucks, buses, and commercial vehicles (Table 1). Transportation emitted approximately 6.2 million tonnes of carbon dioxide-equivalents (CO_2e) in 2005, with private cars accounting for the largest share, almost 40%, followed by commercial vehicles, trucks and buses. Private cars account for a slight majority share of total estimated annual vehicle kilometres travelled (VKT).

3.1 Travel, energy, emissions, and built environment data

The last full household origin-destination (OD) survey, the basic data source for this paper, comes from 2001. Although a smaller survey is available for 2006, we use 2001 as our study year because of the size of the dataset (15,000 households) and the availability of contemporaneous BE measures. Furthermore, being before implementation of most of the Transantiago-related reforms and the massive highway building carried out over the past decade, 2001 offers a good baseline to assess effects of the system's evolution. Due to data limitations, our study area is limited to the 34 *comunas* traditionally defined as Greater Santaiago.

Travel distances, private vehicle and taxi occupancies, and other key travel attributes were derived from the 2001 OD survey. Trip distances for automobile, taxi, colectivo, school/institutional buses, motorcycle, walk and bike, were derived via shortest-path on the road network. Metro trip distances were based on reported station entry/exit; bus trip distances were estimated based on shortest path along the bus route network. If transfer coordinates were known for intermodal trips, trip distances for each mode were allocated thusly. If such coordinates were unknown, the distances were simply divided equally among the reported modes for each stage.

We only consider end-use energy and tailpipe emissions or close approximates. Energy use and emissions factors for motorized road transportation modes come from Univ. de Chile (2002) with speeds varying crudely based on peak-/off-peak trip time as reported in the survey. For Metro, we use total system-wide electricity use reported for 2001 (Metro, 2007) and average electricity emissions factors for Chile (USEIA, 2007). Energy/emissions for private car trips use occupancy rates as inferable from the survey (matching origin, destination, time, mode)[3]; taxi trips use occupancy based on the average observed during the specific trip period (DICTUC, 2003). For fixed-route-based public transport modes (colectivos, buses, and Metro), we take the estimated system-wide energy use for each mode (Univ. de Chile, 2002; Metro, 2007) and then allocate that energy use to each individual trip based on that trip's distance relative to total trip distances estimated for the mode. This approach attempts to account for the fact that a short trip on a public transport mode still benefits from the full extent of the public transport network, including the low-/no-occupancy trip to terminal.[4]

Since human-powered transportation (HPT) also uses energy and produces greenhouse gas emissions, we crudely attempt to account for these. We assume that, on average, each person should have a minimum amount of 20 minutes exercise per day and estimate the equivalent CO_2 emissions associated with those 20 minutes.[5] We then subtract those emissions from any

[3] Likely under-estimating actual automobile occupancy rates.

[4] In rigor, a similar approach should be used for taxis, since taxi passengers benefit from the time taxis spend cruising or responding to a call. We had inadequate information to apply this approach to taxis.

[5] Humans emit between .08 and .13 cubic meters per hour of CO_2 when performing "normal work", between .33 and .38 cubic meters doing "hard work," and .02 cubic meters when resting (http://www.engineeringtoolbox.com/co2-persons-d_691.html). Using "median" emission ranges, CO_2 rates are

individual's daily emissions associated with HPT – for an individual's HPT beyond 20 minutes, the associated CO_2 then get counted as transportation emissions. While imperfect – for example, not accounting for metabolic differences among ages or whether the individual "gets" her 20 minutes daily exercise elsewhere – we feel this represents a reasonable compromise. People need exercise, and HPT can satisfy exercise requirements; however, exercise, just like any other human activity, can have its environmental effect (and energy use/cost, which may be particularly acute for the poorest, calorie-poor groups).[6]

Measures of the BE come from various sources: property cadastres and tax records, land use coverage maps, the road network, etc. as detailed by Zegras (2010, 2005). Land uses (dwelling units, offices, etc.) were available as coordinates which were assigned to the closest adjacent census block. In order to account for the possible MAUP problem, we use three different spatial units to represent a household's BE (see Figure 2): the home OD survey zone (737 within study area), which simply aggregates all the blocks, street characteristics, etc. within its boundaries; and 400- and 900-meter radii straight-line buffers drawn from each household's block centroid (10,600 unique buffers), which aggregate all street characteristics within the area and spatially averages the contents of the blocks covered by the buffer.

3.2 Basic Travel and Emissions Profile

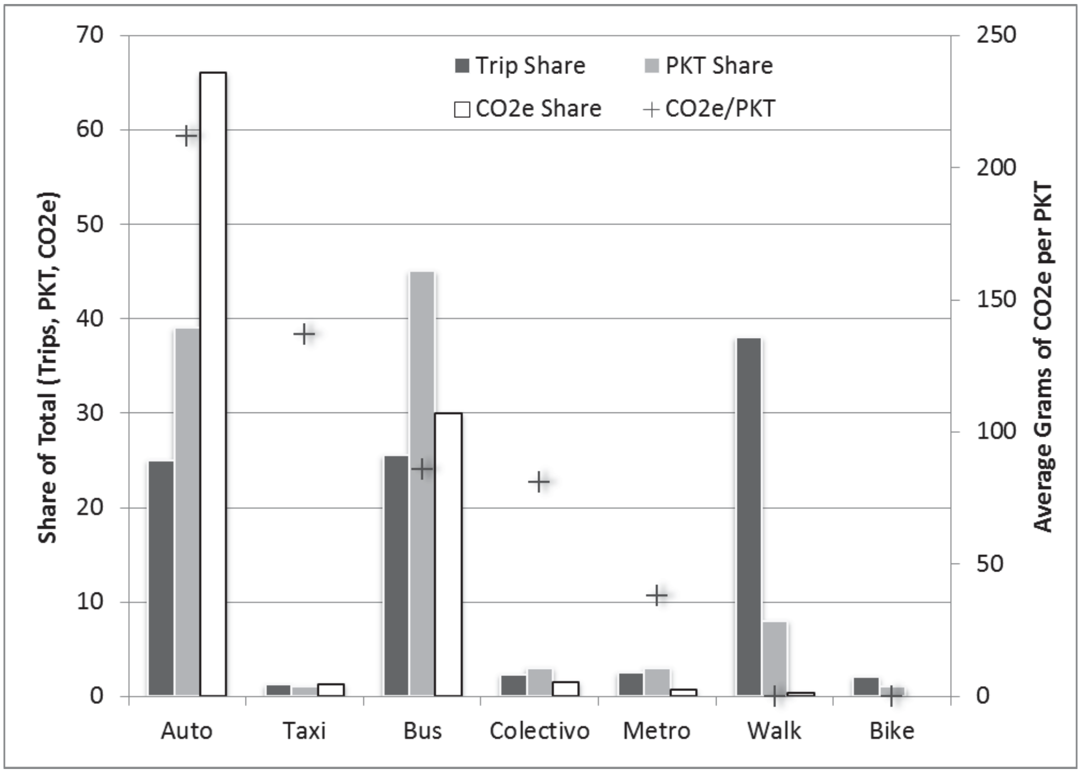
The average Santiago household emits about 7,000 grams of CO_2e per day, or about 2.56 tonnes per year, less than half of the estimated travel GHG emissions for Chicago households (about 6.71 CO_2e) (McGraw et al, 2010).[7] While auto and bus account for roughly the same mode share for all trips on average across all days, auto has more than double the share of total CO_2e among passenger transport modes (Figure 1) – this despite the greater share of total PKT in Santiago by bus, which shows that bus travelers in general, travel more than car travelers, possibly a result of relatively more distant locations of the poorer. On average, in 2001, the auto was the most GHG-intensive mode, followed by taxi. At 2001 occupancy levels, a bus used 40% of CO_2e per average PKT as an auto. Buses and colectivo were relatively comparable, although we must emphasize these are averages. The Metro used just 40% of the CO_2e per PKT than bus and colectivo and just 18% of auto. A striking picture emerges from the Figure: not only is walking the highest trip mode share, but the third highest total amount of PKT. Walking accounts for the majority of travel under 1.2 Kms (Figure 4).

$.355\frac{l}{hour} \times 1.977\frac{g}{l} = 701.835\frac{g}{hour}, 11.69725\frac{g}{min}$. Each person's human powered transport emissions "allowance" is 233.945g of CO_2.

[6] If cradle-to-grave emissions factors were used in this analysis, the carbon intensity of the food supply would also have to be accounted for.

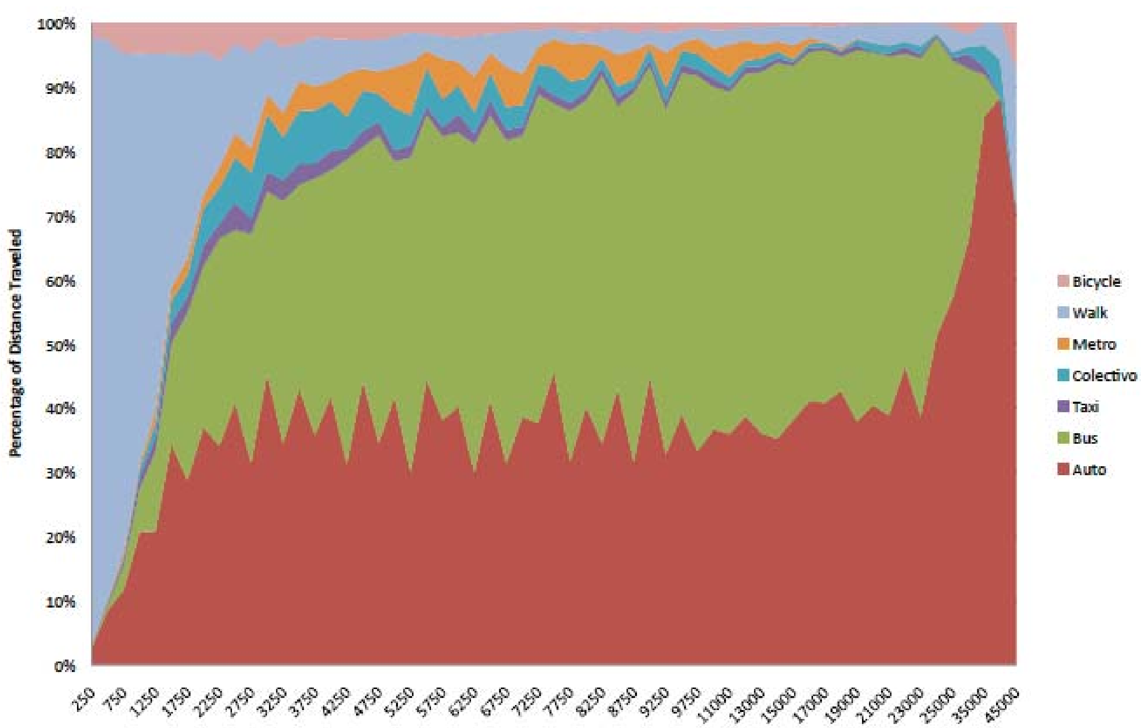
[7] Chicago estimate is based in part on vehicle odometer readings, so it may include out of city driving.

Figure 3. Primary Passenger Travel Modes in Santiago: Trip Share, PKT Share, CO2 Share



Note: Weekly averages.

Figure 4. Mode Share by Distance Traveled: Primary Modes



4 The role of the built environment

Following Zegras (2010), if a given household has chosen a location that maximizes, subject to budgetary and other constraints, its potential accessibility to daily wants and needs, then, *ceteris paribus*, we would prefer locations that produce less total GHG and other emissions. Focusing on total household emissions allows us to ignore underlying mechanisms (e.g., changes in relative costs) and intermediate outcomes (e.g., trip/mode substitutions) while gauging net effects on our outcome of interest. Further following Zegras (2010), we specify two inter-linked models: a household motor vehicle ownership model (multinomial logit), which incorporates BE variables, and a household total travel emissions model (ordinary least squares), which includes the predicted ownership category from the first model as an instrumental variable.[8] Table 2 presents the variables used.

[8] Unlike Zegras (2010) we use the predicted vehicle ownership category (0, 1, 2, 3+) instead of the expected number of motor vehicles (weighted probabilities of each choice from the MNL) as the latter was too highly correlated with income and it was too important to have income included explicitly in the emissions models.

Table 2. Variables, Definitions, Expectations and Descriptive Statistics

Variable	Description	Unit	Expected Correlation	Mean	Med.	S.D.	N
# Autos	No. Autos	HH	Dep.Var.	0.54	-	0.75	14,642
CO2e	Trav. CO_2e (g) on Day	HH	Dep. Var.	7,011	4,172	8,468	14,642
Inc/Pers	Inc/Person (pesos)	HH	(+) MVs,CO_2e	155,742	90,000	219,102	14,642
HH Inc	HH Income (pesos)	HH	(+) MVs,CO_2e	520,157	335,000	635,337	14,642
# Work	No. Workers	HH	(+) MVs,CO_2e	1.59	1.00	0.99	14,642
# Child	No. Children	HH	(+) MVs,CO_2e	1.11	1.00	1.20	14,642
# Pers	No. Persons	HH	(+) MVs,CO_2e	3.85	4.00	1.78	14,642
# Stud	No. Students	HH	(+) MVs,CO_2e	1.07	1.00	1.13	14,642
# 65+	No. persons Age 65+	HH	(-) MVs,CO_2e	0.33	-	0.62	14,642
Apt	In Apartment	HH	(-) MVs,CO_2e	0.19			14,642
HS Grad	$\geq$ 1 High Sch. Grad.	HH	(+) MVs,CO_2e	0.70			14,642
Univ Grad	$\geq$ 1 Univ. Grad.	HH	(+) MVs,CO_2e	0.21			14,642
Internet	Internet in HH	HH	(+) MVs,CO_2e	0.15			14,642
Renter	Renter	HH	(?) MVs,CO_2e	0.18			14,642
Summer	Summer day	HH	(-) MVs,CO_2e	0.20			14,642
Weekend	Weekend day	HH	(-) MVs,CO_2e	0.27			14,642
Topo	Residing in Foothills	OD	(+) MVs,CO_2e	0.09			737
CBD	Km-dist. to Plz de Armas	Blk	(+) MVs,CO_2e	10.09	9.49	4.82	10,600
0.5Metro	W/in 0.5 Km Metro	Blk	(-) MVs,CO_2e	0.06			10,600
1Metro	W/in 1 Km Metro	Blk	(-) MVs,CO_2e	0.13			10,600
Acc.	Auto:Bus Accessibility[(a)]	TAZ	(+) MVs,CO_2e	3.39	3.08	1.59	582
Res Dens	DU per m^2 Res. Land[(b)]	4/900	(-) MVs,CO_2e	0.01	0.01	0.00	10,600
Use Mix	Mix of activities[(a)]	400	(-) MVs,CO_2e	0.07	0.04	0.08	10,600
Off FAR	Office built m^2/km^2	OD	(-) MVs,CO_2e	17,404	925	85,094	737
Off Dens	Off. built m^2/m^2 Off. Land	400	(-) MVs,CO_2e	0.44	0.30	0.62	10,600
Rec %	Plaza+Park+Rec m^2/total m^2	900	(-) MVs,CO_2e	0.06	0.03	0.08	10,600
4-w Int.	4-way inters./road-Km	900	(-) MVs,CO_2e	0.00	0.00	0.25	10,600
Dd-end %	Dead-ends/intersections	900	(+) MVs,CO_2e	0.14	0.13	0.10	10,600
Alley %	Alley-Km/All road-Km	400	(-) MVs,CO_2e	0.30	0.30	0.20	10,600

Notes: (a) as calculated in Zegras (2010); (b) 400-meter measure used in ownership, 900-meter in emissions, but descriptives are marginally different.

4.1 Household Vehicle Ownership

We expect the BE to influence vehicle ownership because it may influence both the utility and disutility of having a car. We estimate a multinomial (MNL) logit model of vehicle ownership, including household, relative location, and BE variables. Table 3 presents the best model, as determined by the likelihood-ratio test, and testing BE measures in the various spatial units available. In general, and despite the different approach to incorporating spatial variables, the model results are similar to those of Zegras (2010). Noteworthy differences: the lack of significance of metro proximity; the lack of significance of auto to bus accessibility in all but the first vehicle choice; the lack of significance of land use mix in the choice of 3+ vehicles; the influence of 4-way intersection density on the one vehicle choice; and other detected street effects, particularly the positive effect of dead-ends on all choices, and the negative effect of alleyway share (presumably more difficult to find parking) on the 2- and 3-vehicle choices. These differences may arise from changes in the BE measures – in particular, a residential density measure that more explicitly accounts for space competition (dwelling units per area of residential land) – and the movement to the block-centric buffers to measure local BE in lieu of the OD survey zone. The ownership model indicates an income elasticity of demand for private cars of 1 (vehicles per capita with respect to income per capita).

Table 3. Multinomial Logit Model of Household Motor Vehicle Choice

Variable	1 Auto			2 Auto			3+ Autos		
	Beta	Z	P-value	Beta	Z	P-value	Beta	Z	P-value
Household Characteristics									
LN HH Inc	1.47	35.31	0.00	2.56	34.44	0.00	3.08	24.90	0.00
HS Grad	0.48	4.74	0.00	0.98	2.13	0.03	-1.33	-2.95	0.00
Univ Grad	0.79	6.64	0.00	1.49	3.18	0.00	-1.21	-2.58	0.01
Work1dum	0.35	7.87	0.00	0.35	7.87	0.00			
Work3dum	-0.55	-9.11	0.00	-0.41	-4.49	0.00			
Child2dum	0.27	5.62	0.00	0.42	4.71	0.00			
Child3dum							-0.94	-3.50	0.00
Child4dum	-0.06	-0.56	0.57	0.41	2.10	0.04	-0.78	-2.00	0.05
Intbroad	0.59	2.70	0.01	1.01	4.15	0.00	1.56	5.67	0.00
Transport Characteristics									
0.5Metro				-0.19	-1.08	0.28	-0.19	-1.08	0.28
Acc	0.04	2.36	0.02	0.00	0.10	0.92	0.05	1.31	0.19
Relative Location									
Topo							0.42	1.94	0.05
CBD	0.02	0.71	0.48	0.14	3.02	0.00	0.20	2.35	0.02
CBD-Sq.	0.00	-1.40	0.16	-0.01	-3.22	0.00	-0.01	-2.61	0.01
Local Built Environment									
Apt	-0.38	-6.11	0.00	-0.73	-6.11	0.00	-1.14	-4.86	0.00
ResDens (400)	-20.33	-4.74	0.00	-54.23	-4.52	0.00	-88.80	-3.03	0.00
Off FAR (OD)	0.09	1.62	0.11	0.18	1.98	0.05	-0.11	-0.65	0.52
Use Mix	-1.59	-3.79	0.00	-2.26	-3.30	0.00			
4-way Inters.	-110.02	-2.52	0.01	-235.96	-2.72	0.01	-250.29	-1.52	0.13
Dead-End%	0.86	2.54	0.01	2.41	4.39	0.00	3.36	3.76	0.00
Alley%	-0.05	-0.33	0.74	-0.68	-2.49	0.01	-1.25	-2.31	0.02
Rec%	0.17	0.67	0.50	0.78	1.70	0.09	1.24	1.76	0.08
Constant	-3.76	-15.89	0.00	-8.80	-14.08	0.00	-9.63	-10.86	0.00

N= 1462; referent = 0 vehicles; Log Likelihood= -10680.091; Wald chi2 (55) =3530.07; blank cells mean variable was left out of relevant utility function based on best model fit.

4.2 Household Travel Emissions

We now model household total travel emissions on the survey day, estimated via ordinary least squares (OLS), using predicted vehicle ownership category from the MNL model (Table 3) and with other household-level, transportation and BE variables included as relevant (Table 4).

The results confirm, overall, our expectations and indicate some apparent tradeoffs between travel GHG emissions and local pollutants, as well as among local pollutants. Starting with household characteristics, we observe that wealth directly, and indirectly via automobile ownership, increases GHGs, VOCs, CO and NOx. PM_{10} emissions decline with income, as expected since these are directly associated with bus travel by households. More workers tend to increase emissions, as do students at home – reflecting the associated travel demands. More seniors (65+) reduce household travel emissions. Generally, higher education levels tend to increase emissions, not an entirely intuitive result, while internet access – possibly a proxy for more "modern" lifestyles – does not directly increase GHG emissions but does increase pollutants associated with automobile usage (consistent with the vehicle ownership model). Finally, renting lowers households travel emissions, suggesting possibly these households have chosen their relatively short-term location with more transport-efficiency in mind. Summertime is associated with less GHG-intensive travel while weekends reduce most pollutants.

Proximity to Metro is associated with lower GHGs, lower PM_{10}, and lower NOx emissions – suggesting overall that the Metro substitutes for other more GHG-intensive travel, although the neutral effects on VOCs and CO warrants further examination. Households further from the CBD have higher total travel GHGs, higher PM_{10} (reflecting the increased bus emissions associated with urban expansion) and higher NOx.

Turning to the local BE measures, we find that: residential density relates to lower household travel GHGs, VOCs, and CO, but *increased* PM_{10}, likely due to a relationship between density and bus use; local land use mix relates to lower GHGs, CO, and NO_x; increased density of 4-way intersections reduces GHGs, PM_{10} and NO_x; and, oddly, increased alleyway share is associated with increased GHGs, PM_{10}, and NO_x. Finally, in an attempt to detect a trade-off between land prices and travel energy use, we included average assessed land value (from cadaster) and do find a negative relationship with NOx and PM10 emissions.

Table 4. OLS Model of Household Survey Day Travel Emissions

Variable	CO_2e		VOCs		PM_{10}		CO		NO_x	
	Coef.	t	Coef.	t	Coef.	t	Coef.	t	Coef.	t
Household Characteristics										
LN HH Inc	2229	15.53*	2.79	9.61*	0.00	0.15	38.15	12.97*	5.53	13.29*
PV1[a]	2263	10.12*	3.62	8.00*	-0.15	-6.95*	50.01	10.91*	4.10	6.33*
PV2[a]	6226	12.56*	8.92	8.88*	-0.37	-7.65*	129.5	12.75*	12.17	8.46*
PV3[a]	10630	11.21*	13.55	7.06*	-0.50	-5.47*	204.9	10.55*	22.18	8.07*
Work1	191	0.73	0.20	0.38	0.15	6.02*	-2.97	-0.55	2.08	2.73*
Work2	736	2.53*	0.19	0.32	0.31	10.88*	-4.98	-0.84	4.89	5.80*
Work3	2136	6.40*	1.62	2.40**	0.60	18.60*	4.55	0.67	11.38	11.76*
65+_1	-549	-3.08*	-0.89	-2.45*	0.02	0.91	-11.26	-3.08*	-1.26	-2.44*
65+_2	-1375	-5.08*	-2.17	-3.96*	0.03	1.16	-27.44	-4.95*	-3.07	-3.92*
65+_3	-1961	-1.91	-3.40	-1.64	0.09	0.89	-43.65	-2.07**	-4.17	-1.40
Stud_1	609	3.81*	1.10	3.39*	0.11	7.17*	8.37	2.56*	2.44	5.26*
Stud_2	1306	7.56*	1.02	2.91*	0.16	9.63*	11.54	3.26*	4.57	9.12*
Stud_3	2486	11.17*	1.83	4.06*	0.35	16.11*	19.63	4.30*	9.19	14.24*
HS Grad	776	3.07*	0.95	1.87	0.18	7.45*	6.05	1.17	3.85	5.26*
UnivGrad	1444	4.47*	1.90	2.91*	0.16	5.06*	19.76	2.98*	5.28	5.63*
Internet	920	4.63	1.17	2.90*	-0.06	-3.29*	18.52	4.55*	1.64	2.85*
Renter	-936	-5.60*	-1.18	-3.48*	-0.02	-1.08	-15.76	-4.60*	-2.61	-5.40*
Day Characteristics										
Summer	-695	-4.28*	-0.27	-0.81	0.02	1.11	-5.94	-1.78	-0.45	-0.97
Weekend	-1460	-10.24*	-1.06	-3.67*	-0.02	-1.33	-13.98	-4.79*	-1.83	-4.42*
Transport and Relative Location Characteristics										
1Metro	-670	-2.89*	-0.79	-1.69	-0.16	-7.28*	-6.46	-1.36	-3.93	-5.84*
Acc.	0.50	1.28	0.00	1.90	0.00	-3.09*	0.02	2.63*	0.00	0.16
CBD	227	3.10*	0.14	0.93	0.02	2.45*	2.15	1.43	0.71	3.36*
CBD-Sq	-2.37	-0.79	0.00	-0.24	0.00	0.14	-0.03	-0.45	0.00	-0.46
Local Built Environment										
Res Dens	-60546	-2.89*	-123.4	-2.91*	12.35	6.11*	-1822	-4.25*	-10.84	-0.18
Use Mix	-2957	-2.07**	-5.17	-1.79	-0.07	-0.49	-60.42	-2.07**	-8.38	-2.03**
Off Dens	0.00	1.60	0.00	1.15	0.00	-1.30	0.00	1.78	0.00	1.00
Alley%	1771	4.12*	0.83	0.96	0.39	9.33*	3.96	0.45	8.08	6.48*
4-w Int	-1695	-2.73*	-1.49	-1.18	-0.12	-1.95**	-21.24	-1.67	-5.72	-3.18*
Avsqm	-0.77	-1.06	0.00	-0.53	0.00	-5.06*	0.00	0.03	-0.01	-2.70*
Constant	-1028	-1.66	-0.13	-0.10	-0.15	-2.45*	-4.76	-0.38	-4.32	-2.41*
R-Square	0.27		0.12		0.17		0.20		0.24	

N=13615; Notes: a. dummy=1 if predicted vehicle ownership (from MNL, Table 3) is 1, 2, 3+, respectively.
*p < 0.01; ** p < 0.05.

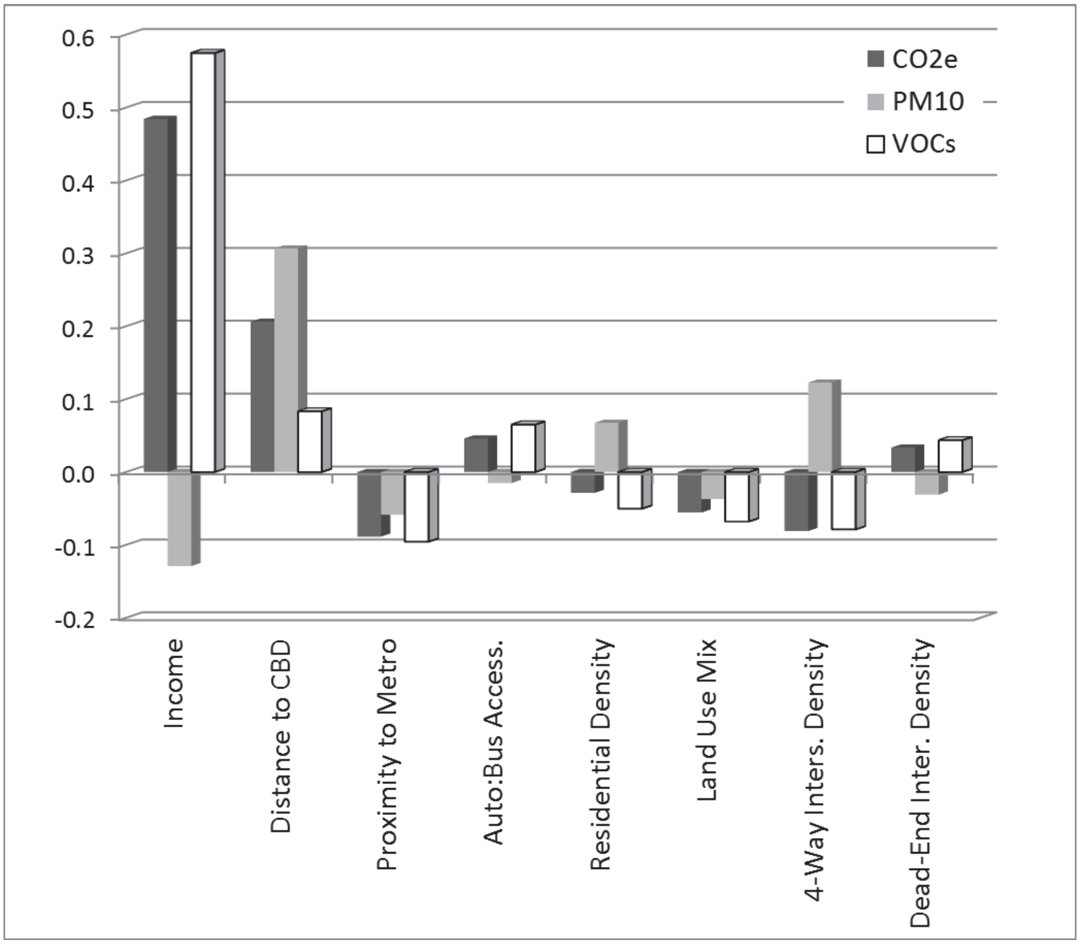
4.3 Combined Relative Effects of the BE

Again following Zegras (2010), we estimate the combined elasticities of household travel pollutants with respect to various BE variables, and income. These elasticities account for the significant relationships detected between the BE and household auto ownership and between BE and total household travel pollutants (Table 5). For GHGs and VOCs we see similar results in signs and, for the most part, in magnitudes: income dominates; GHGs increase more strongly with distance to CBD than for VOCs; otherwise, we see relatively modest effects associated with the BE: a combined elasticity of about 0.20 for GHGs with respect to density, land use mix and street layouts and slightly lower (0.14) for VOCs. Metro proximity and public transport accessibility relative to the car combine for another 0.14, approximately. For PM_{10} we see more nuanced effects. Income, for example, partly reduces PM_{10} due to increased car ownership, indicating bus substitution; however, holding constant vehicle ownership, PM_{10} modestly increases – indicating income's effect on travel demand, irrespective of mode. Overall, PM_{10} goes down as income increases. Except for the distance to Metro effect, the other transportation and local BE measures are not necessarily consistent in sign with GHGs and VOCs, showing that with current bus technologies some inevitable trade-offs exist regarding local and global pollutants and even among local pollutants (Figure 5).

Table 5. Elasticities of Household Travel Pollution with Respect to Several Variables of Interest

Variable	CO_2e			PM_{10}			VOCs		
	Own	Use	Both	Own	Use	Both	Own	Use	Both
Income	0.161	0.323	0.484	-0.152	0.023	-0.129	0.216	0.359	0.575
Distance to CBD	0.000	0.207	0.206	0.000	0.306	0.307	-0.001	0.084	0.083
Distance to Metro		-0.089	-0.089		-0.059	-0.059		-0.096	-0.096
Auto:Bus Accessibility	0.014	0.032	0.046	-0.014	-0.002	-0.015	0.020	0.045	0.065
Residential Density	-0.002	-0.027	-0.029	0.001	0.066	0.068	-0.001	-0.049	-0.050
Land Use Diversity	-0.008	-0.048	-0.056	0.008	-0.045	-0.037	-0.011	-0.057	-0.068
4-Way Inters. per meter	-0.009	-0.072	-0.081	0.008	0.114	0.123	-0.011	-0.067	-0.079
% Dead End Intersection	0.034		0.034	-0.031		-0.031	0.044		0.044

Figure 5. Combined (Ownership and Use) Elasticities of Household Travel Emissions



5 Conclusions

We find modest support for the argument that the built environment exerts a measurable effect on household urban travel GHG and local emissions. Overall, household income dominates, suggesting an income elasticity of household travel GHGs of about 0.5. This is almost exactly one-half the elasticity revealed by international cross-sectional regression, not an unlikely outcome given our elasticity is for *urban* and *passenger* travel only. Our model estimation process found that buffers drawn around the centroid of the block within which a household lives provide a better way of characterizing the BE, for the most part, although the changes detected relative to Zegras (2010) are modest. The research suggests important potential combined effects of the BE and relative location – for example, the combined elasticities suggest that household income growth's effects on travel GHGs could be offset by combined relative location and local BE characteristics. Perhaps we can partly build our way out of the travel GHG challenge. Nonetheless, several cautions are in order. First, tradeoffs exist – some BE measures that might reduce travel GHGs could have an adverse effect on local pollutant generation. Second, we should recognize that, due to failure to account for "self-selection" in this research, our estimates may be biased towards higher-than-actual reductions potential. Third, the comparative statics nature of the analysis fails to account for the fact that by changing, say, land use mix, one would implicitly be changing the characteristics of the whole city in ways these basic cross-sectional models do not capture. Finally, focusing on tailpipe emissions from travel, on a single survey day, fails to account for: the possibilities that households may substitute GHG-intensive travel across days or weeks, or from intra-urban to inter-urban travel; that less GHG-intensive travel may be compensated by other more GHG-intensive activities; and/or, the life-cycle emissions associated with the infrastructures and cities we build and use and the fuels (including calories) we consume in using them.

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