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

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ABSTRACT

We empirically assess the relationship between the built environment and household travel local and global emissions in Santiago de Chile. We incorporate local built environment variables – measured by a range of different spatial approaches – into household vehicle ownership and travel-related tailpipe emissions models. The results suggest income dominates vehicle ownership and most emissions, but that relative location, transportation levels of service, distance to Metro stations, and several local built environment measures 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: greenhouse gas emissions, local pollutants, built environment, household travel, Santiago de Chile

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 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, where the overwhelming share of developing countries' population growth will occur (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 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

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 a 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' built environment.

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* influence behaviour, but they cannot *dictate* behaviour. Theory itself does not offer an *a priori*

[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.

certainty regarding the expected effects of the built environment (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) propose 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.

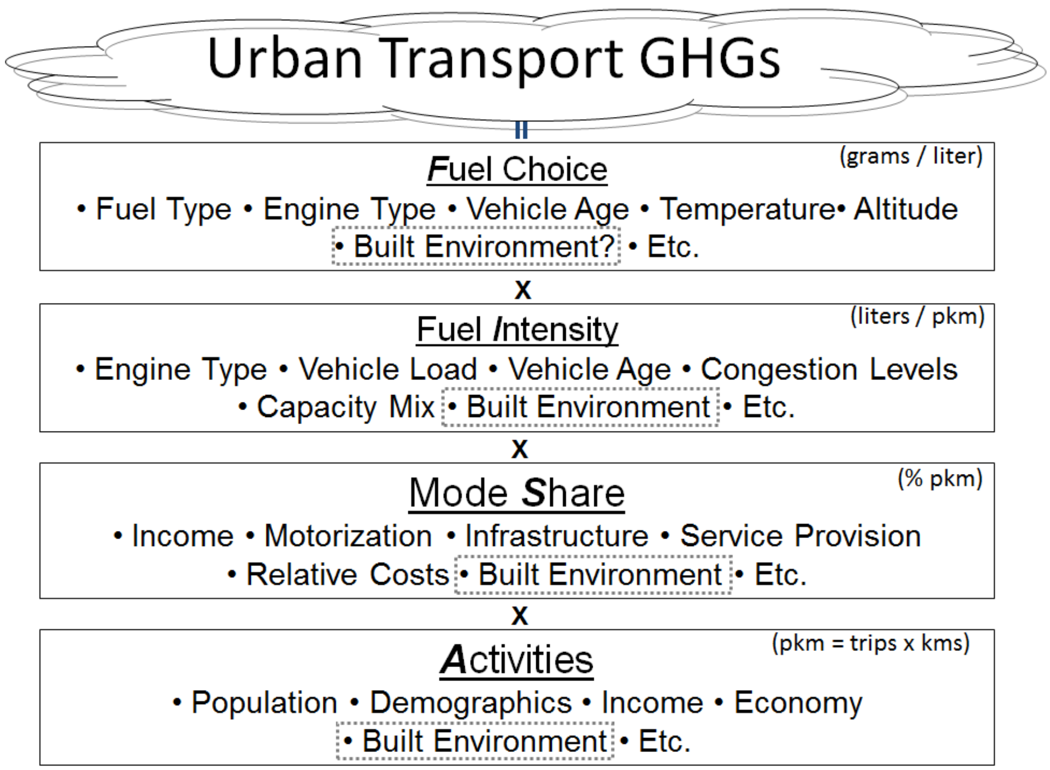

Figure 1. Activities, mode share, fuel intensity, and fuel choice: An ASIF view on the built environment and travel GHGs.

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 affected 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, 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.

In addition, the BE may well influence both vehicle ownership *and* travel use and emissions. Within the ownership and use decision, endogeneity bias may also be present. If one specifies a single ordinary least squares (OLS) model of household travel GHGs with the household's number of motor vehicles included as an explanatory variable, this choice variable may be correlated with unobserved variables (e.g., households with more energy-intensive travel lifestyles being more inclined to own private vehicles) and, thus, with the OLS error term. This violates a basic OLS assumption. One way to correct for this endogeneity bias is by developing an instrumental variable, the predicted number of motor vehicles (estimated from the vehicle choice model) and substituting this predicted value (as an instrument) in lieu of the actual number of vehicles in the household (Dubin and McFadden, 1984). Such an approach, in theory, 'purges' the independent choice variable (in this case, number of vehicles) of its correlation with the error term.

Questions remain about how to properly measure the BE. These partly 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? This introduces a tautological risk: 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)?

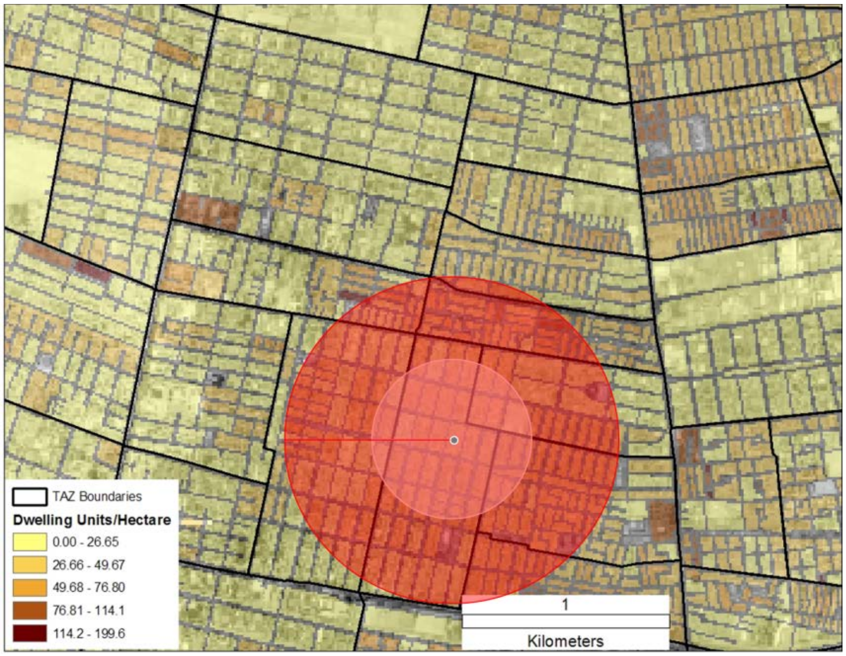

Figure 1. Block-level dwelling unit densities, origin-destination survey zone boundaries, and block-centroid-generated 400m and 900m straight-line buffers (Santiago).

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. We use the "vectorized" approach below.

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 comparable 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, possibly not 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 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 evidence 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 analysis 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.

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 (Table 1): 31% of PM_{10}, 88% of CO, and 68% 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. 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).

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 (USEIA, 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 area); CO_2 emissions unavailable for non-mobile sources; highway through traffic not included.

Travel, Energy, Emissions, and Built Environment Data

The last full household origin-destination (OD) survey, our basic data source, 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 against which future changes can be assessed. Due to data limitations, our study area is limited to the 34 *comunas* traditionally defined as Greater Santiago.

Appendix 1 provides details on the methods used to calculate travel distances, vehicle occupancies, emissions, and other key aspects. In summary, we use: only end-use energy and tailpipe emissions or close approximates; speed-based emissions factors for road-based modes, although speed only varies by peak/off-peak; survey-observable vehicle occupancies for auto trips and field survey reported occupancies for taxis; relative distance-weighted energy use/emissions for trips by each fixed route public transport mode (bus, Metro and shared fixed-route taxis or *colectivos*), allocating the system's daily energy use/emissions to each individual trip based on that trip's distance relative to total trip distances estimated for the mode; and, human-metabolic-based GHG emissions for walking and biking. Our treatment of public transport modes 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.[3] Our treatment of human-powered transportation (HPT) aims to reflect that using human energy for movement also has GHG implications. While people need exercise, and HPT can satisfy exercise requirements; human activity, can have its environmental effect (and

[3] 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.

energy use/cost, which may be particularly acute for the poorest, calorie-poor groups).[4] To roughly balance the "benefits" and "costs" of HPT, we assume that, on average, each person should have a minimum amount of 20 minutes exercise per day and count any HPT-based CO_2 emissions beyond those 20 minutes 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.

Measures related to 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. Appendix 2 provides details of our calculation of a diversity index, to measure relative mix of land uses, and automobile and bus accessibility measures, to account for relative transportation levels of service of the household's "home TAZ."

Basic Travel and Emissions Profile

Across three broad income categories, the largest share of household passenger kilometres travelled (PKT) occurs in the 6-7 km range, although, expectedly, more total PKT accumulates within shorter distances among lower income groups, while higher income groups have larger shares of longer distance PKT (i.e., "fatter tails") (Figures 3 and 4). Unsurprisingly, PKT by different modes varies notably by income and distances travelled (Figure 3). For low income households, walking accounts for the largest share of PKT up to about 2 kms, after which the bus takes over; overall the bus accounts for the majority of lower income PKT. For middle income households, walk dominates only under the first km; the bus still accounts for a large share, particularly in the 4-14 km range, yet the important role of the automobile emerges across a range of distances, including for short trips (under 3 km). Finally, for high income households, the automobile dominates across all trip distances. The bicycle only accounts for a noticeable PKT share for low income households – providing this group approximately the same share of PKT as *colectivos* for trips up to about 7 kms of travel distance.

Examining trip purposes (Figure 4), evidently low income households satisfy an important share of non-work travel locally, likely reflecting the income constraint on discretionary travel and a lack of "school choice" (i.e., being unable to send children to schools further away). The majority of all PKT happens within about a 7 km distance for low income households; the majority of PKT for each purpose other than work happens within this range. For work PKT, the majority accumulates beyond the 10 km range, indicating a relative low income location disadvantage vis-à-vis workplace opportunities. For middle and higher income households, the majority of PKT takes place within about a 9 km distance. High income households accumulate more longer distance PKT for work and school trips suggesting they: are no less isolated, on average, with respect to shopping and other activities, but tend to be farther from workplaces; and, have fewer constraints in sending children to relatively distant schools.

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[4] 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.

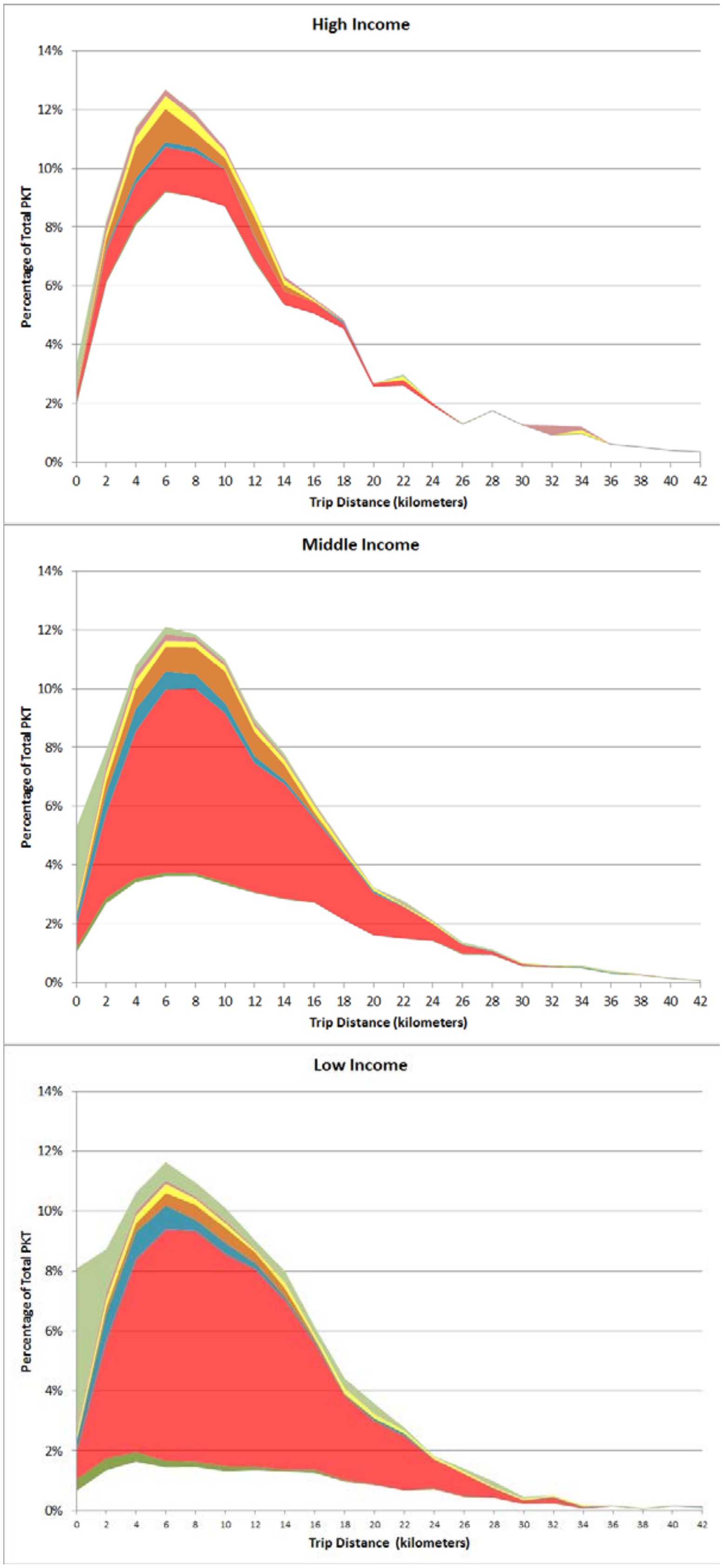

Figure 3. Passenger kilometers traveled (PKT) by distance traveled and mode: high, middle and low income households.
Note: Income category ranges and averages (in US$ converted at 2001 exchange rates): High, $30K-$156K, $50K; Middle, $5K-30K, 11K; Low, $200 – $5K, $3K.

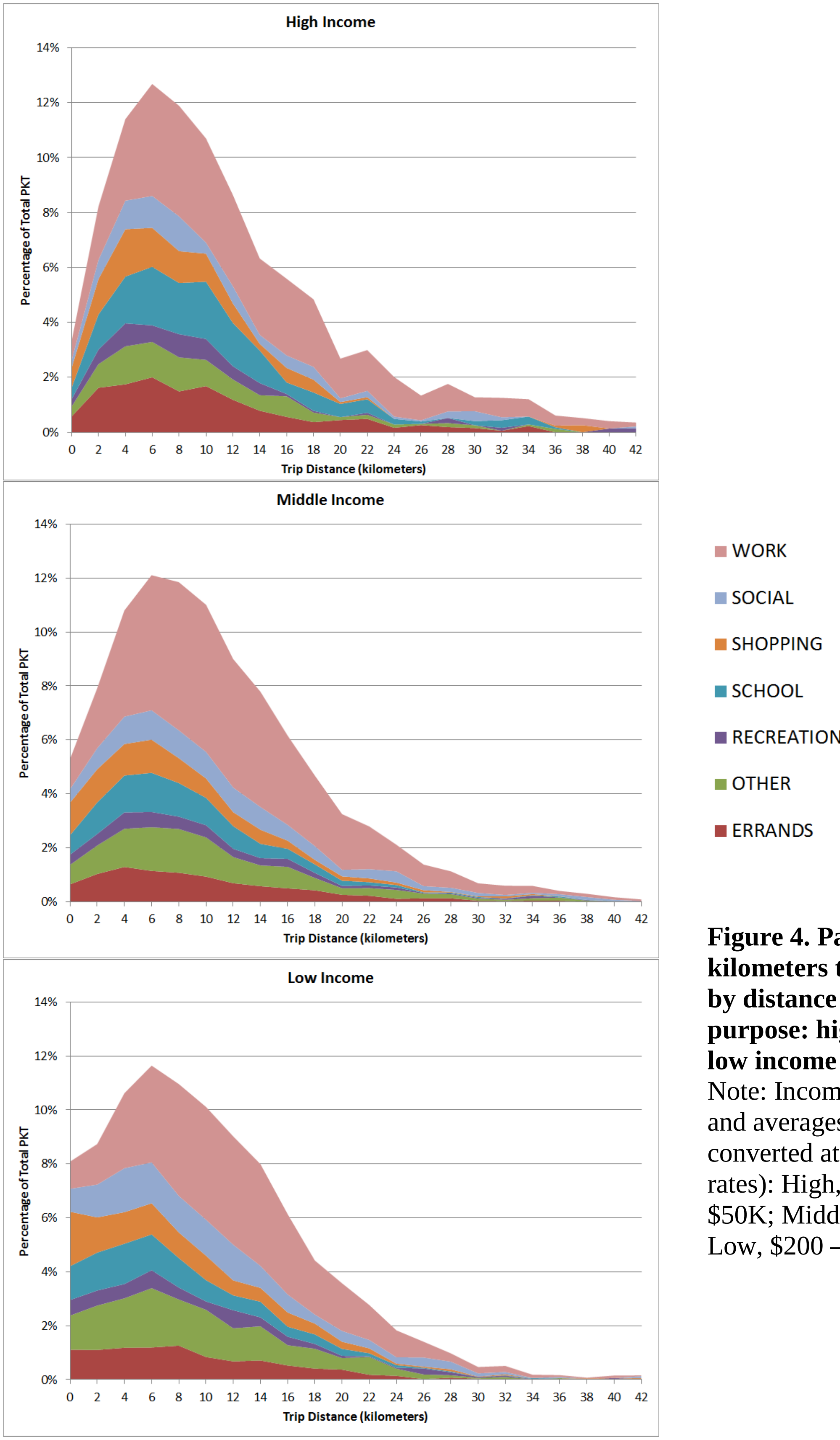

Figure 4. Passenger kilometers traveled (PKT) by distance traveled and purpose: high, middle and low income households. Note: Income category ranges and averages (in US$ converted at 2001 exchange rates): High, $30K-$156K, $50K; Middle, $5K-30K, 11K; Low, $200 – $5K, $3K.

Table 2. Santiago's household travel and emissions characteristics, annual (2001).

	Indicator		Income Category & Strata						Avg.
			High Income		Middle Income		Low Income		
			AB	C1	C2	C3	D	E	
Costs (US$2001)	% HH in each category		0.2%	4.6%	27.6%	23.1%	26.3%	18.2%	
	Average HH Income ('000)		122.9	49.3	15.3	7.0	4.1	1.7	9.7
	Out-of-pocket (OOP) $ per Km		0.05	0.08	0.06	0.05	0.05	0.04	0.05
	OOP $ per Trip		0.38	0.49	0.34	0.26	0.20	0.17	0.27
	OOP $ per Person		263	307	215	162	123	96	167
	OOP $ per Household (HH)		1338	1294	847	625	431	257	600
	OOP $ as % of HH Income		1.1%	2.6%	5.5%	9.0%	10.5%	14.9%	6.2%
	Motor Vehicle $ as % of HH Income		4.6%	9.6%	14.2%	15.7%	15.3%	15.6%	13.6%
	Transport Energy $ per KM		0.05	0.05	0.03	0.02	0.02	0.01	0.02
	Transport Energy $ per Trip		0.36	0.30	0.18	0.11	0.08	0.05	0.13
	Transport Energy $ per HH		1273	777	434	252	162	85	274
	Transport Energy $ as % of HH Income		1.0%	1.6%	2.8%	3.6%	3.9%	4.9%	2.8%
	Average Land $ (per m2) % of HH Inc.		0.05%	0.08%	0.12%	0.19%	0.27%	0.54%	0.2%
Trip-Making	Trips per person		1.9	1.7	1.7	1.7	1.7	1.6	1.7
	Kms per Day	per Person	13.7	10.7	9.8	8.5	7.3	5.9	8.4
		per HH	*69.5*	*45.3*	*38.5*	*32.8*	*25.7*	*15.8*	*30.0*
	Minutes per Day	per Person	51	77	92	86	76	63	82
		per HH	*260*	*325*	*361*	*332*	*267*	*170*	*293*
	Bus Share	of Trips	0.9%	10.2%	27.6%	34.4%	32.0%	28.7%	29.5%
		of PKT	*0.4%*	*10.1%*	*37.1%*	*54.6%*	*59.0%*	*56.9%*	*46.3%*
	Auto Share	of Trips	80.4%	67.2%	33.6%	16.3%	10.6%	7.4%	22.0%
		of PKT	*90.2%*	*74.2%*	*44.4%*	*24.5%*	*17.5%*	*13.9%*	*32.7%*
	Taxi/Colectivo Share	of Trips	0.3%	4.3%	5.3%	5.0%	4.0%	4.0%	4.7%
		of PKT	*0.3%*	*6.4%*	*4.6%*	*4.9%*	*4.5%*	*4.7%*	*4.7%*
	Human Powered Share	of Trips	9.9%	9.9%	24.5%	37.4%	48.4%	56.7%	37.1%
		of PKT	*2.1%*	*1.5%*	*4.0%*	*7.8%*	*12.0%*	*19.8%*	*8.1%*
	Metro Share	of Trips	4.1%	5.7%	6.1%	3.7%	2.2%	1.3%	3.9%
		of PKT	*3.0%*	*5.2%*	*7.3%*	*5.3%*	*3.6%*	*2.4%*	*5.3%*
Emissions (kgs)	CO_2e	per Person	1,343	1,404	905	561	421	281	639
		per HH	*6,832*	*5,918*	*3,565*	*2,169*	*1,472*	*754*	*2,294*
	PM_{10}	per Person	0.01	0.02	0.05	0.06	0.06	0.04	0.05
		per HH	*0.04*	*0.07*	*0.19*	*0.24*	*0.21*	*0.12*	*0.19*
	VOCs	per person	1.65	1.83	1.10	0.59	0.44	0.29	0.73
		per HH	*8.39*	*7.70*	*4.33*	*2.27*	*1.53*	*0.78*	*2.63*
	NO_x	per Person	*3.40*	*3.70*	*2.74*	*2.04*	*1.66*	*1.17*	*2.13*
		per HH	*17.30*	*15.61*	*10.78*	*7.90*	*5.80*	*3.14*	*7.65*

Sources: see Appendix1 for details on calculations.

On average, households spend about 6% of income on out-of-pocket operating costs (fuel, fares, calories), with lower income households shouldering a greater relative burden, in a pattern roughly matched when examining energy costs, including calories for HPT (Table 2). These households also live in *relatively* more expensive locations, when considering the average assessed *land* value as a share of household income. Using rough average annualized costs of vehicle ownership (updated from Zegras and Litman, 1994), annual household transportation costs average about 20% of income. The average *Santiaguino* travels 8 kms and 82 minutes per day, with distances going up and times going down with household income, reflecting high income use of higher speed (private motorized) modes (consistent with Schäfer, 2000). Tailpipe emissions also correlate strongly with income, with CO_2e, VOCs, and NOx generally increasing with income; PM_{10}, on the other hand, increases among lower income households, reflecting these households' dependency on bus transport. The average Santiago household emits about 2.3 tonnes of CO_2e for urban travel per year, less than half of the estimated average household tailpipe GHG emissions *from driving* in the Chicago (USA) metropolitan in 2001 (about 5.6 tonnes CO_2e) (Haas et al, 2010).[5]

Regarding relative modal productivity and CO_2e efficiency, 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 5) – this despite the greater share of total PKT in Santiago by bus, which shows that bus users, in general, travel more than car users, 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 the CO_2e per average PKT as an auto. Buses and *colectivos* 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.

[5] Haas et al (2010) do not account for household greenhouse gas emissions from non-automobile travel modes.

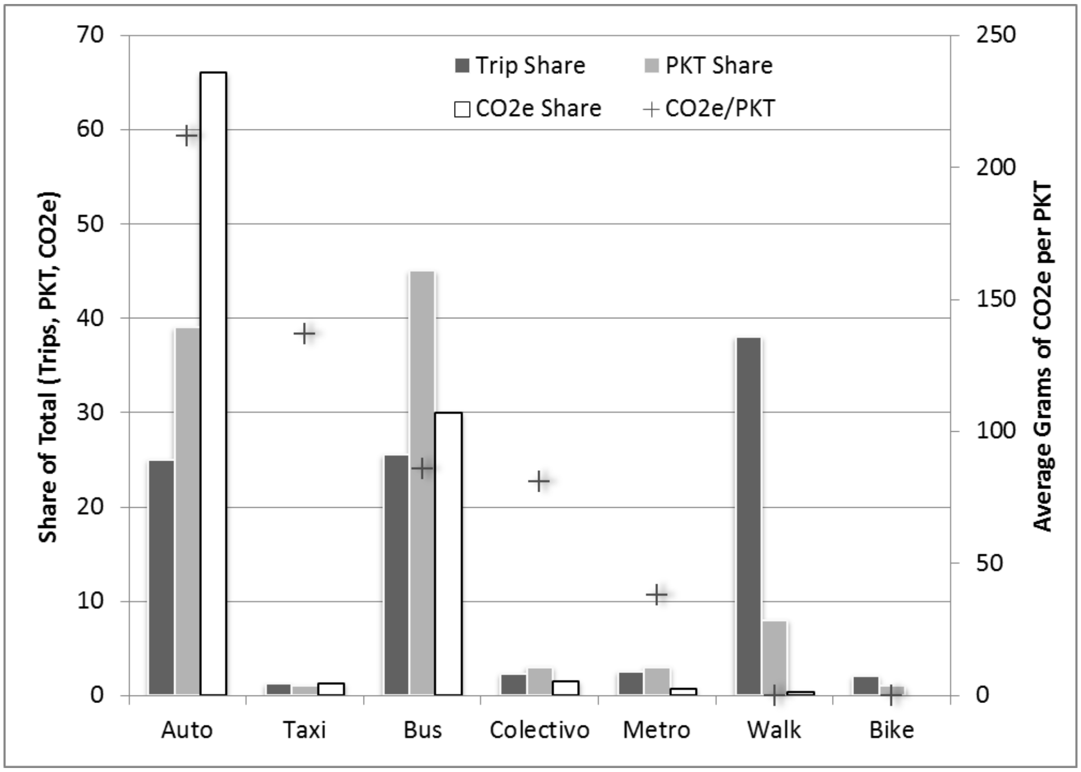

Figure 5. Primary passenger travel modes: Trip share, PKT share, CO2e share.
***Note*: Weekly averages.**

4. THE RELATIONSHIP WITH 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 household total travel emissions models (ordinary least squares, OLS), which include the predicted ownership category from the first model as an instrumental variable.[6] Table 3 presents the variables used, our expectations regarding correlations with emissions, and descriptive statistics.

[6] 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 3. 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) see Appendix; (b) 400-meter measure used in ownership, 900-meter in emissions, but descriptives are marginally different.

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 4 presents the best model, as determined by the likelihood-ratio test, and testing BE measures in the various spatial units available. That is, since we have no *a priori* expectation regarding which of the various spatial units (survey zone, 400-m buffer, 900-m buffer) available to incorporate in our models is "best," we allow the model estimation results to determine the most appropriate unit. 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).[7]

[7] Utilizing sample enumeration with a 1% change in income for all households.

Table 4. 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= 14620; 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.

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[8] (Table 4) and with other household-level, transportation and BE variables included as relevant (Table 5).

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 NO_x. 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 – 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 household travel emissions, possibly suggesting 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 significantly associated with lower GHGs, lower PM_{10}, and lower NO_x 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 farther from the CBD have higher total travel GHGs, higher PM_{10} (reflecting the increased bus emissions associated with urban expansion) and higher NO_x.

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 and do find a negative relationship with NO_x and PM_{10} emissions.

[8] For each household the probability of being in each ownership category was calculated based on its attributes and the parameter estimates from Table 4. Each household's ownership category was determined as:

$$veh_i = 1 \text{ if } \max(p[veh_0], p[veh_1], p[veh_2], p[veh_{3+}]) = veh_i,\ veh_i = 0 \text{ otherwise;}$$

where veh_i represents ownership category i, and $p[veh_0]$, $p[veh_1]$, $p[veh_2]$, $p[veh_{3+}]$ represent 0, 1, 2, and 3 or more vehicles, respectively.

Table 5. OLS model of household survey day travel emissions (grams).

Variable	CO2e		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 4) is 1, 2, 3+, respectively.
*p < 0.01; ** p < 0.05.

Combined Relative Effects of the BE

Finally, we estimate the combined elasticities of household travel pollutants with respect to various significant BE variables, and income (following Zegras, 2010). Briefly: for each household, vehicle ownership levels and emissions levels are estimated based on the model results (Tables 4 and 5); each variable of interest is changed by a small amount in the vehicle ownership model; the new ownership probabilities are used to calculate new emissions estimates (from the OLS model) which provides the *indirect* relationship betwen the variable and emissions due to vehicle ownership; subsequently, for variables also significant in the emissions models, the same change was made to calculate the *direct* relationship between the variable of interest and emissions. If a variable is only significant in the ownership (emissions) model, then only indirect (direct) elasticities are calculated (Table 6).

For GHGs and VOCs we see similar results in signs and, for the most part, in magnitudes: income dominates; VOCs increase a bit more strongly with distance to CBD than for GHGs; 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 higher (0.24) for VOCs. Metro proximity and public transport accessibility relative to the car combine for another 0.05, 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 6).

Table 6. Elasticities of household travel pollution with respect to several variables of interest.

Variable	**CO_2e**			**PM_{10}**			**VOCs**			**NO_x**		
	Indirect	**Direct**	**Both**	**Indirect**	**Direct**	**Both**	**Indirect**	**Direct**	**Both**	**Indirect**	**Direct**	**Both**
Income	0.164	0.321	0.486	-0.144	0.014	-0.130	0.220	0.357	0.577	0.087	0.243	0.330
Distance to CBD	0.001	0.206	0.207	-0.001	0.307	0.306	0.001	0.084	0.085	0.001	0.235	0.236
Distance to Metro		0.012	0.012		0.029	0.029		0.014	0.014		0.020	0.020
Auto:Bus Accessibility	0.013		0.013	-0.011	-0.003	-0.014	0.018		0.018	0.007		0.007
Residential Density	-0.003	-0.026	-0.029	0.002	0.067	0.069	-0.002	-0.048	-0.050	-0.002	0.001	-0.001
Land Use Diversity	-0.006	-0.048	-0.053	0.005	-0.044	-0.039	-0.008	-0.056	-0.065	-0.003	-0.046	-0.049
4-Way Inters. per meter	-0.013	-0.064	-0.078	0.011	0.112	0.123	-0.017	-0.059	-0.075	-0.007	-0.018	-0.025
% Dead End Intersection	0.036		0.036	-0.032		-0.032	0.047		0.047	0.019		0.019

Notes: elasticities calculated via simulation as described in text and based on significant variables in models from Tables 4 and 5; "Indirect" refers to relationship with emissions due to variable's significance in vehicle ownership (from model in Table 4) and subsequent relationship with emissions (via predicted vehicle ownership category in model from Table 5); "Direct" refers to variable's relationship with emissions directly (from model in Table 5).

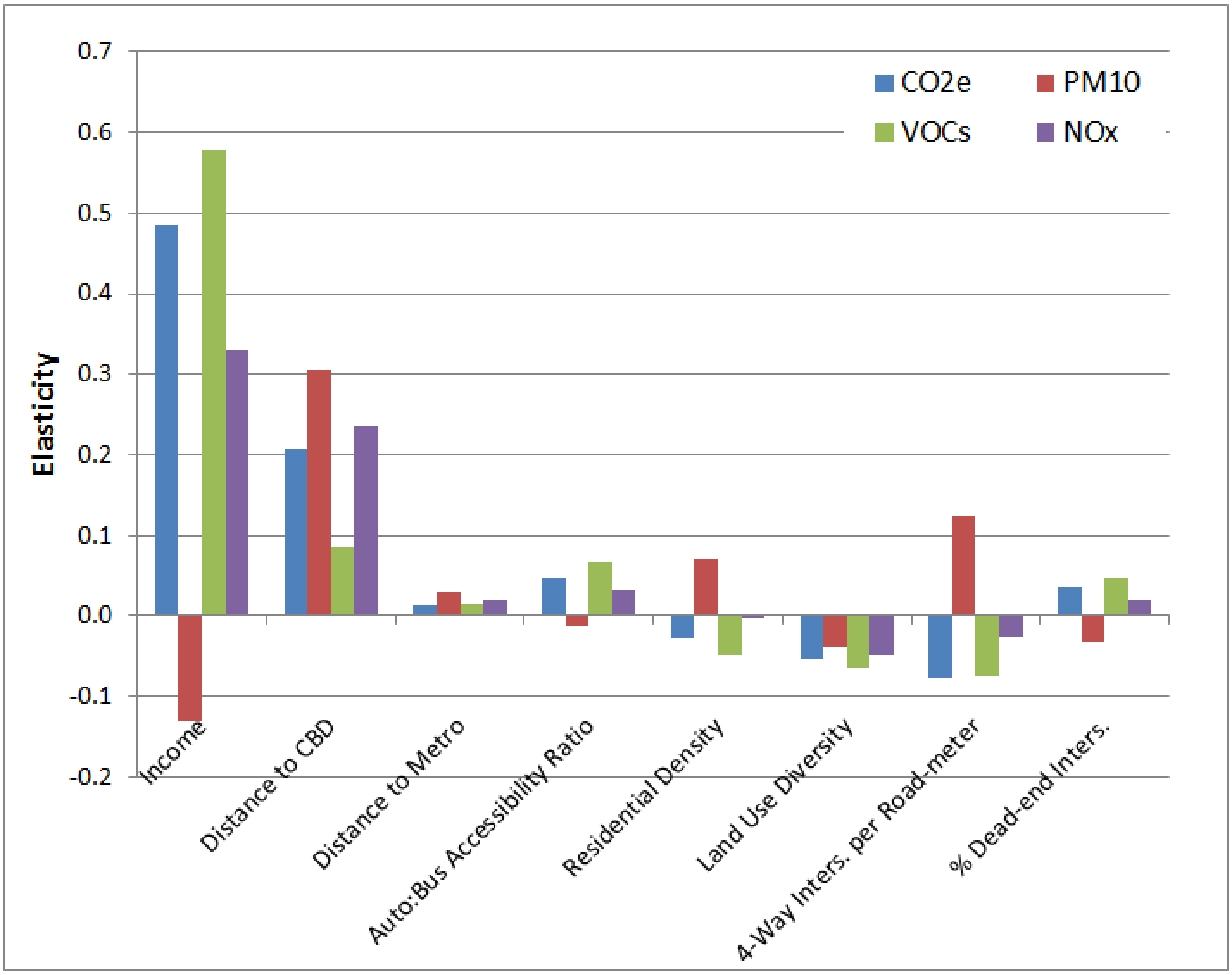

Figure 6. Combined (ownership and use) elasticities of household travel emissions with respect to income and various built environment and travel service measures.

5. CONCLUSIONS

We find modest support for the argument that the built environment measurably relates to household urban travel GHG and local emissions. In 2001, the average *Santiaguino* household emitted 2.3 tonnes of CO_2e annually, less than one-half the average Chicago household's automobile-related CO_2e per year in 2001. 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 nearly entirely offset by combined relative location and local BE characteristics. Perhaps we can partly build our way out of the urban 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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APPENDIX 1: TRAVEL MEASURE CALCULATIONS

Unless otherwise noted, household travel-related information come from the 2001 household travel survey conducted for Greater Santiago and provided to the authors by Chilean transportation planning authorities (SECTRA). The survey was based on a randomly generated sample of fifteen thousand households: 12,000 surveyed during the "normal season" and 3,000 during the summer time (in total, 1% of Greater Santiago's households). Ampt and Ortúzar (2004) provide information on the survey technique and results.

Trip Distances

Trip distances for automobile, taxi, *colectivo* (shared, fixed-route taxis), 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.

Travel Periods

Since average speeds and occupancy vary by time of day, we use the following travel periods: morning peak, 07:00 to 09:00; midday peak, 10:00 to 14:00, afternoon peak, 17:00 to 21:00 (DICTUC, 2003); all other periods, off-peak. For the purposes of metro subway frequency, the peak periods are defined as 07:00 to 08:59 and 18:00 and 19:59, Monday through Friday; all other hours are considered off peak.[9]

Vehicle Occupancies

For private automobile trips, members of the same household that share a common origin time, origin place, destination time and destination place are considered to share the

[9] http://www.transantiagoinforma.cl/tarifa.do (accessed November 6, 2010)

automobile.[10] Taxis occupancies are based on those observed during the respective time period (peak/off-peak) (DICTUC, 2003). For institutional buses, average number of occupants is assumed to be 28. This is based on 70% occupancy of a regular-sized bus (40 seats, DICTUC, 2003). For school buses (12-15 seat minivans in Santiago), average number of occupants is assumed to be 10. For fixed route public transport modes, see our treatment of occupancy-related issues in the following section.

Energy Use and Emissions Calculations

All on-road energy use and tailpipe emissions factors (for carbon monoxide [CO], volatile organic compounds [VOC], nitrogen oxides [NOx], nitrous oxide [N_2O], respirable particulate matter [PM_{10}] and methane [CH_4] are average speed-based factors for 2001 (Univ. de Chile, 2002) and for household autos account for whether the vehicle had a catalytic converter or not (as reported in the household survey). The average velocity was ascribed to each trip based on mode and peak status (as defined above). Energy consumption factors produce fuel consumption (FC) in grams which were converted to CO_2 based on:[11]

$$CO_2 = FC * 44/12 \quad \text{(A.1).}$$

CO_2e was estimated as:

$$CO_2e = CO_2 + (21*CH_4) + (310*N_2O) \quad \text{(A.2).}$$

For Metro, emissions per KWh (system-wide) were calculated for CO_2, CH_4, and N_2O based on average electricity emissions factors for Chile (USEIA, 2007).

For private vehicles and taxis, emissions factors per *passenger*-km traveled were derived using estimated occupancies as described above. 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 based on that trip's distance relative to total daily trip distances estimated for the mode (as estimated from the survey, using the survey expansion factors):

$$E_i^m = E^m * \frac{pkt_i^m}{\sum_{i=1}^{n} pkt_i^m} \quad \text{(A.3).}$$

E_i^m represents emissions for individual, *i*, in mode, *m*; pkt_i^m is passenger kilometers traveled by *i* in *m*, *n* is the total number of individuals using *m* on a given day, as expanded from the survey, and E^m is total daily emissions for each mode, based on the total estimated bus system daily distance traveled (Fernández and De Cea, 2003), total estimated *colectivo* system daily distance traveled (Univ. de Chile, 2002), total average daily Metro energy consumption (Metro, 2007) and relevant emissions factor. This approach allocates to a given individual her "share" of the mode's total energy consumption based on the individual's relative use of the system.

We calculate a "rate" of CO_2 emissions for human-powered transport (HPT, walking and biking) as the difference between emission levels for HPT and those emitted if resting. Humans

[10] Likely under-estimating actual automobile occupancy rates.
[11] http://www.epa.gov/OMS/climate/420f05001.htm#calculating (accessed November 6, 2010)

emit between 0.08 and 0.13 m^3 of CO_2 per hour when performing "normal work", between 0.33 and 0.38 m^3 of CO_2 per hour doing "hard work," and 0.02 m^3 of CO_2 per hour when resting.[12]

We assume each person, on average, should have 20 minutes "hard work" (exercise) per day for healthy living and that HPT can satisfy these exercise minutes. Thus for each individual, *i*, we estimate *i*'s net CO_2 emissions from HPT (using the median value from above, which equals approximately 10.6 grams/minute[13]) and subtract the CO_2 emissions associated with 20 minutes of hard work (212.8 g CO_2). If *i*'s daily emissions were below this, *i*'s HPT carbon emissions equals 0.

Out-of-Pocket Travel and Energy Costs

Our "out-of-pocket" travel costs only cover estimated costs for fuel, fares, and food (calories expended). We had insufficient information on parking costs to include them and we assume users don't consider maintenance-related costs as "out-of-pocket" at the time of journey. For calorie costs, the estimated *minimum* monthly household cost in Santiago of providing the national average daily caloric requirement in Chile is US$35 (Litchfield, 2001) in 2001 (based on 1998 pesos, inflated to 2001 and converted at prevailing 2001 exchange rates). Using average household size, the daily minimum calorie allowance and imputed cost of calories, we estimate the minimum energy cost for HPT. For motor vehicle energy costs, we used prevailing fuel costs (US$0.60 per liter of gasoline and US$0.38 per liter of diesel) and for Metro we used electricity costs reported in Metro (2007). For bus, *colectivo*, and metro trips, established fares (based on age, student-status, time of trip, etc.) per passenger were used. Taxi costs were calculated as US$0.25 for the flag down and US$0.63 per km. Energy and out of pocket costs were attributed to trips as per above for emissions.

APPENDIX 2: LAND USE-RELATED CALCULATOINS

Accessibility

We use a travel model run (matrix of travel times for 2001 for 582 zones) provided by SECTRA to develop bus and automobile accessibility measures:

$$A_i^m = \sum_{j \in L} w_j \, f_{ij} * 100 \qquad \text{(A.4),}$$

where: A_i^m is the accessibility measure for mode *m* in zone *i*; *L* is the set of all zones; w_j is zone *j*'s share of all *W*, where *W* consists of the total constructed area (m^2) of Commercial Services, Health Services, Manufacturing, Offices, Social Services, Public Administration, and Residences, Indoor Sports facilities, as well as the total land area for Parks and Outdoor Sports facilities; f_{ij} is exp($-bTT_{ij}^m$); TT_{ij}^m is the travel time (including in-vehicle time, waiting time, walking time) for mode *m* from zone *i* to zone *j*; and *b* is a parameter representing travel time sensitivity (in our case 0.46) (Zegras, 2010). We use the natural log of the ratio of auto accessibility to bus accessibility in our model, expecting that a higher ratio will indicate a more auto dependent location.

Land Use Diversity

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[12] http://www.engineeringtoolbox.com/co2-persons-d_691.html (accessed November 6, 2010)
[13] One tonne of CO_2 equals 556.2 m^3.

Following Rajamani et al (2003) we calculate land use mix as:

$$DI = 1 - \left[\frac{\left|\frac{r}{T} - \frac{1}{6}\right| + \left|\frac{c}{T} - \frac{1}{6}\right| + \left|\frac{h}{T} - \frac{1}{6}\right| + \left|\frac{o}{T} - \frac{1}{6}\right| + \left|\frac{p}{T} - \frac{1}{6}\right| + \left|\frac{s}{T} - \frac{1}{6}\right|}{\frac{5}{3}} \right] \quad (A.5),$$

where: r = m^2 of residential floor space; c = m^2 of commercial floor space; h = m^2 of health floor space; o = m^2 of office floor space; p = m^2 of public administration floor space; s = m^2 of social services floor space; and T = r + c + h + o + p + s.

A value of 0 for this index means that the land in the area has a single use and a value of 1 indicates perfect mixing among the six uses.

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