

**The Built Environment and Motor Vehicle Ownership & Use:  
Evidence from Santiago de Chile**

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## Abstract

This paper examines the relationships between the built environment (BE) – both “neighborhood” design characteristics and relative location – and motor vehicle ownership and use in a rapidly motorizing, developing city context: Santiago de Chile. The paper first attempts to answer the question, what role, if any, do factors such as dwelling unit density, land use mix, street design, and proximity to public transportation stations play in determining household motor vehicle ownership? A vehicle choice model suggests that income dominates the household vehicle ownership decision, but also detects a relationship between several built environment characteristics and a household’s likelihood of car ownership. The paper then turns to the question: what role does the built environment play on household automobile vehicle kilometers traveled (VKT)? A second model, directly linked to the ownership model to correct for selection bias and endogeneity, suggests a strong relationship with locational characteristics like distance to the central business district and Metro stations. Elasticities of VKT, calculated via the combined models, suggest that income plays the overall largest single role in determining VKT. In combination, however, a range of different design and relative location characteristics also display a relatively strong association with VKT.

## Introduction

Analyses of the influence of urban development patterns on travel behavior can be traced back to the very beginnings of modern transportation engineering. Boarnet and Crane (2001) suggest that the original “predictive” focus of such analyses – i.e., estimating travel demand and infrastructure requirements based on where land development might occur – eventually evolved to include an increasingly “prescriptive” purpose – i.e., modifying land development patterns to explicitly influence travel demand. In fact, efforts aimed at using urban design and planning to influence travel behavior can be seen in the original “Garden City” model of the early 20<sup>th</sup> Century (see, e.g., Lee and Ahn, 2003), the mid- 20<sup>th</sup> Century “new community” movement in the U.S. (e.g., Morris, 1969), and Dutch spatial planning policies begun in the 1960s (Maat, *et al.*, 2005). Evidence of a prescriptive analytical focus can be found in at least the early 1950s, when Carroll (1952) basically examines the jobs-housing balance in several U.S. cities, calling for “satellite” urban development patterns to reduce work travel. By the late 1960s, the advent of large scale modeling capabilities enabled crude forecasts of alternative urban structures on travel outcomes (e.g., Jamieson *et al.*, 1967). The global oil crises of the early and late 1970s spurred a number of relevant analyses (Gilbert and Dajani, 1974; Cheslow and Neels, 1980). The 1980s saw examinations of “wasteful” or “excess” commuting (e.g., Hamilton, 1982), related to concerns about the jobs-housing balance (ABAG, 1985). By the 1990s – paralleling increased interest in “new urbanism,” “transit-oriented development,” and “smart growth” more generally – the number of relevant analyses seemed to grow exponentially. The early 21<sup>st</sup> Century ushered in a growing number of analyses looking specifically at the built environment’s influence on human activity levels and public health (Brown *et al.*, 2008) and transportation greenhouse gas emissions (Ewing *et al.*, 2008).

Nonetheless, after more than 50 years of research and analyses, questions remain about the quantifiable influence of the built environment (BE) on travel behavior and active research in the area continues. Numerous reviews of this research exist (Hanson, 1982; Anderson *et al.*, 1996; Crane, 2000; Ewing *et al.*, 2008), as does at least one attempt to generalize the results in the form of elasticities of vehicle trips and vehicle distances traveled with respect to different built environment measures (Ewing and Cervero, 2001). Despite these efforts, generalizing from this research remains a challenge, due to variations in the:

- scale of analysis – that is, differentiating between relative location (“meso”-level) effects versus neighborhood (“micro”-level) effects;
- types of BE measures used (population density, dwelling unit density, entropy-based measures of land use mixes, etc.);

- areal scales of measurement and potential effects related to the Modifiable Areal Unit Problem (see Zhang and Kukadia, 2005);
- travel behavior data used (spatially aggregated versus disaggregate individual/household);
- analytical approaches and control variables employed; and,
- ultimate outcomes measured (trip frequencies, mode choices, distances traveled, etc.).

Moreover, inferring causality (i.e., the built environment causes the travel behavior outcome) from the typical research design and methodologies remains controversial, since rarely do the analyses control for the potentially confounding factor that residents may choose locations consistent with their travel predispositions (commonly referred to as “self-selection”; see Mokhtarian and Cao, 2008). In such a case, we would falsely attribute the BE as the cause of the observed travel behavior.

The great part of this continuously vigorous research base focuses on the industrialized world. Yet, cities in the developing world – undergoing massive increases in motorization and urbanization – may stand to gain the most from efforts to modify urban development patterns to change travel behavior. Rapid urban population increases, such as the 3 to 4 percent urban growth rates in China (see Yang and Gakenheimer, 2007), mean that new urban structures, forms, and designs will quickly emerge, potentially influencing travel patterns for large populations for decades to come. As such, empirical evidence of the influence of the BE on travel behavior in developing cities seems crucial to help provide meaningful planning guidance. Unfortunately, relevant research in such cities remains limited. In the face of rapid urban growth, and likely intensifying transportation-related problems like congestion and air pollution, what relative role might we expect the BE to play in influencing travel behavior?

This paper attempts to answer this question in the Latin American context, focusing on the Santiago de Chile case. Building on established analytical precedents, the paper examines the relationship between the BE and two related household behavioral outcomes: vehicle ownership, as measured by the number of vehicles in the home, and vehicle use, as measured by total household vehicle kilometers driven on a given day. The importance of motor vehicle ownership comes from the fact that the pace of motorization carries major implications for overall transportation system performance (e.g., Gakenheimer, 1999) and directly influences household vehicle use. Thus, we need to know the degree to which, *ceteris paribus*, the BE influences household vehicle ownership decisions. In turn, understanding the BE effects on vehicle distances traveled (e.g., vehicle kilometers traveled or VKT) – as opposed to trip frequencies, trip substitution rates, or mode choices – is important since automobile travel distance is often identified as an important overall indicator of system performance (e.g., Black *et al.*, 2001; McCormack *et al.*, 2001). Finally, explicitly linking ownership and use is important since the BE potentially influences automobile use both directly *and* indirectly (through its effects on vehicle ownership and subsequent effects on use). This paper explores these effects via econometrically linked models of household automobile ownership and use. The models utilize meso-level measures of relative location and micro-level measures of urban design together with disaggregate individual/household travel data from a 2001 household survey.

The remainder of this paper has five parts. The second section, following this introduction, provides the theoretical background and reviews research precedents and issues. The third section introduces the empirical case, Santiago de Chile, and discusses the data used for the analysis. The fourth section presents the specification and estimation of the motor vehicle choice model, including BE measures, while the fifth section presents the specification of the motor vehicle use model, again with BE measures and including the explicit link to the vehicle ownership model. A fifth section discusses the overall relative influence of the BE, as estimated via the combined effects on auto ownership and use. The final section offers conclusions, including limitations to the current analysis and areas for future research.

## **Theoretical Background, Research Precedents and Analytical Issues**

Settlement patterns provide the basic spatial context within which people make their travel decisions. In metropolitan areas, the BE’s potential influences on travel behavior, in general, play out at three different spatial scales: the metropolitan (structural) scale, since total city spatial size is apparently associated with

total motorized distances traveled (e.g., Cameron *et al.*, 2003); the intra-metropolitan scale (or relative location, “meso”-scale), since, for example, household distance to the city center apparently correlates with motor vehicle trip rates (e.g., Crane and Crepeau, 1998); and the local/neighborhood (“micro”- or “design”-) scale, since characteristics like dwelling unit density, block size and land use mix may influence vehicle and person distances traveled (e.g., Krizek, 2003).

Theoretically, the urban structure, relative location, and design effects represent different scales of, essentially, the same general forces of influence. The BE influences travel behavior by determining the total number and relative quality of potential activities (i.e., employment, shopping, entertainment, etc.) available; the relative distribution of those activities and, thus, travel distances; and the relative travel costs implicit in traversing those distances by various modes. Crane (1996) attempts to explicitly pull the relevant analyses into a microeconomic behavioral framework, whereby travelers assumedly maximize their utility subject to time and budget constraints and the BE influences trip-making through impacts on trip costs. In this framework, we can expect ambiguous ultimate effects, as lower trip costs (e.g., through shorter distances) may produce, for example, a higher trip rate, depending on the elasticity of trip demand with respect to cost (an empirical question which may depend upon trip type) (Crane, 1996).

Crane’s framework rests upon a trip-dependent utility function, where, for example, the number of trips by each mode for each purpose figures directly into utility. A more theoretically attractive framework would focus on the activity-realization benefit of travel. In other words, the trips by a given mode do not feed directly into an individual’s utility; instead, utility is derived by the activities that the trips facilitate (following from the idea transport as a derived demand). Maat *et al.* (2005) offer a theoretical framework along these lines. They suggest that most research on the influence of land use on travel behavior has taken (implicitly or explicitly) a cost-based perspective; in other words, the BE influences the cost of travel and thus behavior (Crane’s line of reasoning). Maat *et al.* (2005), however, note the need to include the benefit (utility) side of travel as well. In this sense, the BE influences net utility: i.e., activity realization – the positive utility – minus travel cost (including time) – the disutility. This perspective, extending beyond Crane’s, shows that the ultimate ambiguity of the BE’s influence on travel behavior may not only arise through the uncertain influence of trip costs (disutility) on travel, but also through influence on potential activity destinations (utility). For example, if land use changes reduce an individual’s travel time, that individual might invest that time in increased activity time (e.g., spending more time shopping), the substitution for more-preferred destinations (with no net change in travel time) or the scheduling of additional non-home activities. The latter two cases would result in increased total travel, consistent with the idea of constant travel time budgets (e.g., Schäfer, 2000). Unfortunately, typically available travel survey data (available for a household’s travel activity on a single day, with incomplete information on the specific type of activities realized at the trip end, etc.) make practical exploration of Maat *et al.*’s (2005) framework difficult.

By focusing empirically on total household motor vehicle use we can partly skirt these theoretical ambiguities. As discussed above, total VKT is often considered a primary indicator of transportation system performance (e.g., Chin *et al.*, 1999). Increases in VKT tend to drive increases in infrastructure costs, emissions, fuel consumption, accident risk, and so forth, although the actual impacts depend on technology-, time- and space-specific conditions. *All else equal*, we would prefer less total VKT. That is, assume that 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 a location that produces less household automobile VKT, assuming automobile VKT has greater negative impacts than distances traveled by other modes. Under these assumptions, the VKT focus enables us to ignore the underlying mechanisms (e.g., changes in relative costs) and intermediate outcomes (e.g., trip substitution, mode choice for different trip types, etc.) which may drive the ultimate outcome of interest (VKT). Differences in households’ BE conditions may have varying effects on, say, relative costs of different modes, but if we concern ourselves with total VKT we do not necessarily have to worry about the effects on other modes.<sup>1</sup> The VKT focus allows us to indirectly account for trip-chaining by automobile (which is enabled, in part, by the BE), but misses phenomena of possible local importance, such as the influence of cold starts on pollutant emissions or auto travel during the peak period on highly

congested streets. Furthermore, the data typically available from household travel surveys leave us with an incomplete picture of the full potential effects. For example, we cannot know if a household carries out relatively modest auto use during a given weekday, but more than compensates for that low use by intensive vehicle use on, say, a Saturday. Effectively accounting for such effects would likely require more detailed weekly (or even monthly) surveys of household travel activity.<sup>2</sup>

### **Empirical Precedents**

As for empirical analyses of auto ownership and distances traveled, many precedents exist. Beesley and Kain (1964), for example, using *aggregate* data from 45 U.S. cities in 1960, developed a regression model to predict automobile ownership as a function of median household income and gross city-wide population density. In 1980, Cheslow and Neels (1980) provide one of the first studies to explicitly recognize and attempt to quantify “neighborhood scale” (p. 77) effects (measured at the traffic analysis zone) together with meso-level effects (distance to CBD), using zonally aggregated data. They find significant effects of local-level densities as well as distance to CBD on automobile distances traveled. Miller and Ibrahim (1998), using zonally-aggregate data from Toronto, Canada, find distance from CBD to be the most important variable explaining VKT per worker. Holtzclaw *et al.* (2002) use aggregate data from three U.S. cities to claim an apparent universal influence of residential density (measured by households per acre) on vehicle ownership and use. The latter three analyses do not include household income effects.

Using *disaggregate*-level data to measure vehicle ownership, Cambridge Systematics (1997) find significant effects of population density in an ordered logit model of household vehicle availability for Philadelphia and find significant effects of dwelling unit densities in a multinomial logit model of vehicle availability in San Francisco (Cambridge Systematics, 2002). Hess and Ong (2002) find a significant effect of land use mix on household auto ownership in Portland Oregon. Kitamura *et al.* (2001) find some evidence of residential density influencing autos per household member in Southern California. Using the 1990 U.S. Nationwide Personal Transportation Survey, and city-wide measures of urban form and structure, Bento *et al.* (2004) find increased sprawl (developed as a Gini-coefficient, ranking census tracts by distance from CBD) to increase vehicle ownership trends, but confounding effects of density and land area. In terms of vehicle use, Cervero and Kockelman (1997), find that local BE measures (including street network characteristics, building type, land use mix, and block type) exhibit significant effects on non-work VKT, but to exert no measurable influence on total household VKT.

### **Analytical Issues**

In estimating econometric models, based on cross-sectional data, that attempt to show how the BE influences household vehicle ownership and use, several corrections may be required. If the ultimate purpose of examining the relationships between the BE and travel behavior is to determine *causality* (i.e., the degree to which the BE causes the behavioral outcome) then cross-sectional analysis with the typically available data faces the challenge generally referred to as “self-selection” (e.g., Mokhtarian and Cao, 2008). In fact, two forms of relevant bias exist, sample selection and endogeneity. In this case, endogeneity includes two possible biases: simultaneity bias, whereby residential location and travel behavior decisions influence each other, such as households not wanting (or able) to own a car choosing a neighborhood where car ownership is less necessary; and omitted variable bias, whereby unobserved variables, such as attitudes, produce the travel outcomes, but these attitudes also correlate with BE characteristics, producing incorrect associations. A sample selection problem may also exist since, in observing VKT as our ultimate outcome of interest, we can only observe the sub-sample which chooses to make automobile trips. This may introduce biases in our coefficient estimates. Mokhtarian and Cao (2008) provide a good review of the issues and possible analytical and research design solutions. The analysis presented below does not correct for this form of “self-selection.” The results, therefore, must be interpreted with caution. At best, we can infer association between the BE and travel behavior; we cannot, however, conclude anything about the causality of effects.

A similar set of problems exists within the system of models of household vehicle ownership (a discrete choice) and VKT (a continuous choice). Dubin and McFadden (1984) lay out the relevant theoretical framework, in the context of a household's choice for electric appliance ownership and electricity consumption. On the one hand, we face potential selection bias. Considering that we can only estimate the vehicle use model for households who choose to own a car, we may be estimating the vehicle use model on a sample that may be biased towards high usage households. This selectivity bias can be corrected in the ordinary least squares regression of vehicle use by incorporating for each household a selection bias correction factor directly derived from the vehicle ownership model. Dubin and McFadden (1984) show the approach to be consistent with utility maximization; Train (1986) and Mannering (1986) offer example applications; and Mannering and Hensher (1987) provide a broader review of applications in transport analysis. In specific examinations of the relationship between the BE and disaggregate household-level vehicle ownership and use, Kitamura *et al.* (2001) and Bento *et al.* (2004) employ the selectivity bias correction; Cervero and Kockelman (1997) do not. In addition, endogeneity bias may also be present, depending on the ultimate VKT modeling approach. If we specify a single ordinary least squares (OLS) model of household VKT with the household's number of motor vehicles included as an explanatory variable, this choice variable may be correlated with unobserved variables (and, thus, with the OLS error term), thereby violating 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. Such an approach, in theory, "purges" the independent choice variable (in this case, number of vehicles) of its correlation with the error term. The OLS model presented below ultimately employs corrections for both selection bias and endogeneity.

### **Empirical Case: Santiago de Chile**

Santiago, despite rapid economic growth over the past two decades, continues to exhibit motorization rates that, relative to the industrialized world, lean much closer to the dense Asian cities than Europe or North America. This comparatively low motorization rate seems to hold relative to Santiago's "peer" cities as well (see Table 1). In the latter case, it is not clear whether the apparently lower motorization comes from vehicle costs (due to, perhaps, stricter vehicle emission standards and/or restrictions on used vehicle imports), income distribution and relative purchasing power across all households (e.g., Gakenheimer, 1999), Santiago's built urban environment, and/or other factors (including inevitable data quality differences across different cities).

Santiago's economic growth, together with changing demographics and land use patterns have contributed to notable changes in basic travel behavior and related influencing factors (see Table 2). Auto mode share increased at a rapid pace between 1991 and 2001, virtually identical in rate to motorization (6.8% and 7% per year growth rates, respectively). This brought a concomitant decline in public transport mode share, although in total by only half the rate of auto use increase, suggesting that auto use increases total mobility – eating away at public transport mode share, but also inducing new travel, on average. Total trips by both bus and Metro continue to increase, but at a rate slower than population growth. In 2001, Santiago still enjoyed remarkably ubiquitous bus service, while for the Metro coverage was obviously more limited; not an insignificant fact, since for most periods of the day walking provides the primary means of Metro access and egress (Metro, 2001). The survey data reveal, somewhat surprisingly, a consistent increase in the share of walking trips. Some of this increase may derive from survey methodology differences, but could also result from other social and behavioral changes (e.g., increased comfort in public spaces), some of which might be attributable to changes in the BE. The data also reveal a clear increase in discretionary travel: while school and work trip rates remained nearly constant, the total trip rate increased, as we would expect given income growth.<sup>3</sup>

**Table 1.** Santiago's basic mobility characteristics relative to select "peer" cities

Characteristics	Riyadh	Buda- pest	Prague	Moscow	Kuala Lumpur	Bangkok	Johan- nesburg	Cape Town	Santiago
Population (mns)	3.1	1.9	1.2	8.7	3.8	6.7	2.5	2.9	5.7
Metro GDP <sup>a</sup> /capita (US\$1995)	5,939	5,679	9,145	5,103	6,991	6,316	5,137	4,243	5,500
Persons/Hectare	44	51	49	146	58	139	30	71	80
Autos per 1000	221	299	442	149	209	249	269	143	145
MCs <sup>b</sup> per 1000	0	7	48	7	175	205	6	8	3
Auto PKT <sup>c</sup> per Person	7,807	3,122	4,346	3,057	4,345	2,991	4,927	3,136	1,450
MC PKT per person	2	19	22	20	1,365	1,411	49	94	46
Public Transport PKT per Person	107	3,627	4,321	7,153	726	2,799	3,277	1,521	2,450
NMT <sup>d</sup> Mode Share	2	23	25	20	24	12	53	35	29-39 <sup>e</sup>
Daily Trips per Capita	2.2	2.5	4.6	2.7	2.7	2.6	2.1	1.4	2.4-2.8 <sup>e</sup>

Sources: Kenworthy and Laube, 2001; except for Santiago (SECTRA, 2002). Santiago data are from the 2001 household origin-destination survey; other cities' data are for circa mid-1990s. Notes: (a) metropolitan area Gross Domestic Product; (b) Motorcycles; (c) passenger kilometers traveled; (d) non-motorized transport; (e) the low end of the range is for trips over 200 meters by people over five years of age (typical to traditional travel surveys) and the high end is all trips in the public space made by all residents

Santiago has, historically and notoriously, suffered from among the worst air pollution problems in Latin American cities, due to high concentrations of total suspended particulates (TSP), respirable particulates (PM10), ozone (O3), and carbon monoxide (CO). The transportation sector accounts for 56% of PM10 and 87% of NOx, a precursor to ozone (transport is responsible for 31% of VOCs, the other ozone precursor) – the two most serious problems of air pollution in the capital city (CONAMA, 2003). Santiago has since the late 1980s employed a vehicle restriction program (*la restricción*), which during the high pollution season restricts vehicles without catalytic converters from operating on certain days of the week, based on the license plate number.

In the past decade, authorities have focused on reducing transportation air pollutant emissions primarily by improving fuel quality and strengthening vehicle emission standards, but also through the use of several system management measures put into place during periods of severe pollution risk (e.g., Díaz, 2004). In combination with interventions targeting fixed sources, the efforts have produced important improvements in pollutant concentrations as exhibited by declines in severe pollution days (CONAMA, 2003).<sup>4</sup> While early air quality management plans (e.g., CONAMA, 1997) explicitly mentioned "rationalizing" private auto use and reducing motorized trip demand as pollution control measures, such policies do not appear in more recent plan monitoring and updates (e.g., MINSEGEP, 2006).

**Table 2.** Evolution of basic socioeconomic & travel characteristics in Santiago

Category	Item	1977	1991	2001	AAGR (91-01)
<i>Socioeconomics</i>	Avg. HH Income (US\$ 2001)	n.a.	\$4,700	\$9,000	6.5%
<i>Demographics &amp; Motorization</i>	Households	649,820	1,162,845	1,484,903	2.4%
	Persons	3,483,084	4,502,099	5,325,193	1.7%
	Auto Fleet	208,263	414,798	748,007	5.9%
	Vehicles per 1000 Persons	60	94	140	4.2%
	Vehicles per Household	0.32	0.36	0.50	3.5%
<i>Trip Making</i>	Trips per Person	1.04	1.69	2.39	3.5%
	Work Share All Trips	n.a.	39%	27%	-3.7%
	School Share All Trips	n.a.	28%	19%	-3.5%
	"Other" Share All Trips	n.a.	1.3%	22%	28%
<i>Aggregate Mode Share</i>	Private Transport Mode Share	12%	20%	39%	6.8%
	Public Transport Mode Share	83%	71%	52%	-3.1%
	Other	5	10	9	-0.5%

*Sources:* Derived from SECTRA, 1992a,b; 2002; 2004. *Notes:* Only data for the jurisdictions common to the 1991 and 2001 surveys are used. Travel information is for comparable observations (i.e., trips over 200 m, by individuals over five years old) for the normal work week. AAGR: average annual growth rate; n.a: not available.

### Direct Research Precedents

For the case of Santiago, several relevant analyses into the influence of BE on travel behavior exist. As previously summarized (Zegras, 2004), aggregate, Municipal-level regression analyses using the 1991 survey data revealed little evidence of population density on Municipal mode share or walking trips, although the municipal-wide density measure is a gross BE proxy. An earlier analysis of the 1991 travel survey data followed the Boarnet & Crane (2001) approach to assess the influence of three gross measures of urban form on travel behavior in Santiago (Zegras, 2004). Specifically, controlling for socioeconomic and demographic factors and trip cost variables at the scale of the traffic analysis zone, that analysis looked at the influence of population density, relative share of commercial and service land uses, and relative share of vacant land on an individual's propensity to make home-based, non-work, non-school (HB NWNS) walking trips. The model results suggested that an increased share of commercial and service uses in the zone of trip origin increases the likelihood of making HB NWNS walk trips, while vacant land intensity decreased the probability. Somewhat surprisingly, population density in the zone of origin had no significant effect. Overall the models had little explanatory power, suggesting possible misspecification and/or poor measures of land use.

More recently, Donoso *et al.* (2006) carried out an analysis of the potential role for land use to influence travel behavior with the express purpose of reducing greenhouse gas (GHG) emissions in Santiago. The study utilized the 2001 travel survey as well as the 2001 land use cadastre in developing an integrated suite of models to simulate transportation and land use market equilibriums and to identify "optimum" land use patterns (with the goal of minimizing GHG emissions). The model focused primarily on meso-level, relative location effects. The analysis suggested several useful extensions, including: accounting for off-peak travel and weekend travel; assessing more thoroughly the degree to which *micro*-level urban design might influence travel behavior; and, developing a vehicle ownership model that also reflects sensitivities to land use variations.



### Travel Data

Travel data for this analysis come from the 2001 household origin-destination (OD) survey carried out for national 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). The urban area included 38 *comunas* (municipalities) and was broken down into 779 traffic analysis zone (TAZ), ranging in size from 17 to 19,000 hectares, with an average of 250 hectares. The survey included all trips in the public space taken by all household members (regardless of age), for 13 trip purposes, by 28 different travel modes (e.g., auto driver) or combination of modes (e.g., auto passenger-Metro). The survey contains information on individual educational level, job status, household income (actual reported or estimated), etc. The household information is geo-coded at the center of the census block (nearly 50,000 blocks, average size 1.5 hectares), while the trip origin and destination information is geo-coded at the nearest street corner (or, sometimes, census block). The time of trip departure and arrival is also included. Additional detail on the survey techniques and results can be found in Ampt and Ortúzar (2004).

### Land Uses and Measures of the BE

The land use data come from year 2001 national tax records and business and land use permits (as reported to Municipal governments) and include information (e.g., type of use, floor space constructed) for roughly 1.3 million residences and 400,000 non-residential land uses, geo-coded at the street address level or sometimes the census block level.<sup>5</sup> Land uses included 17 general categories (e.g., residential, manufacturing, public administration), for each registered activity, information included the constructed floor space and the relevant plot size. Additional measures, including street widths, intersection densities, block morphology, etc. were derived from digital block maps and street center-line maps. Other land use coverage data come from a map of open spaces, compiled originally by environmental authorities in 1998.<sup>6</sup> For this analysis, the data were aggregated to the TAZ, except for household relative location measures (distance to CBD and Metro stations), which was measured from the household’s census block centroid.

Most of the BE measures used are fairly straightforward. However, to measure local land use mix, a land use dissimilarity or diversity index is used, following Rajamani, *et al.* (2003). The measure aims to capture the mix of uses relative to a perfect distribution of uses. In this case, the index includes six different land uses, measured by built floor space:

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

where:

$r$  = square meters of residential floor space

$c$  = square meters of commercial floor space

$h$  = square meters of health floor space

$o$  = square meters of office floor space

$p$  = square meters of public administration floor space

$s$  = square meters 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.

## Household Motor Vehicle Choice

Theory suggests that the choice to own an automobile would be influenced by where we live: both micro-level design factors and meso-level locational relativity. In terms of relative location – the meso-level – the convenience of auto travel in the face of alternative modes might influence, for example, a household's auto ownership decision. At the micro level, factors such as parking hassle, the relative utility of having a vehicle (i.e., convenience of alternative travel options) would influence auto ownership choice. What role, if any, do these influences have in rapidly motorizing Santiago?

### Model Specification

To determine what influence the BE has on motor vehicle ownership, I estimated a multinomial logit model (Ben-Akiva and Lerman, 1985) of motor vehicle choice by household. The alternatives available to a given household are zero, one, two, or three (or more) motor vehicles.<sup>7</sup> An incremental model specification approach was taken. The basic model included only household socioeconomic and demographic characteristics, with transportation performance characteristics (zonal level accessibility; equation 2, below) then added, and, finally, meso- and micro-level BE characteristics included. Only variables that were significant at greater than 95% and that increased the model goodness of fit (as measured by the likelihood ratio test) were retained in the final model specification.

#### *Accessibility in the Motor Vehicle Choice Model*

Theoretically the relative convenience of alternative travel options may well influence the utility an individual or household derives from vehicle ownership. All else equal, a household that can more easily access other desired destinations without using an automobile will have less use for one. Therefore, that household's probability of auto ownership will be lower. Several different ways of measuring accessibility exist (see Geurs and van Wee (2004) for a good recent review). For the motor vehicle ownership model, I use a traditional, Hanson-type gravity measure whereby accessibility represents a theoretical measure of a household's potential access to all other relevant locations in the city:

$$A_i^m = \sum_{j \in L} w_j f_{ij} * 100 \quad (2),$$

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  $W$ ,

$W$  is the total square meters (constructed floor area) of commercial and services, health, manufacturing, offices, social and community services, public administration, indoor sports facilities, and housing; and, the total square meters (land area) of parks and outdoor sports facilities,

$f_{ij}$  is  $\exp(-bTT_{ij}^m)$ ,

$TT_{ij}^m$  is the travel time for mode  $m$  from zone  $i$  to zone  $j$ , and

$b$  is a parameter representing travel time sensitivity.

For this case, only travel times for automobile and bus were estimated. Inter-zonal travel times come from an ESTRAUS (Santiago's travel forecasting model) model run.<sup>8</sup> For bus, the travel time included in-vehicle time, access and egress time and wait time. In rigor, the  $b$  parameter should be empirically derived from a trip distribution model. In this case, a value of 0.4 was used (de Cea *et al.*, 2004). Within zone opportunities were not included in the accessibility metric due to the unavailability of relevant travel times. However, as several land use measures from the household's home zone were included in the model, these serve as proxies for local level accessibility.

### Model Estimation and Results

Table 3 presents the model results. The parameter estimates, in most cases (discussed further below), carry the expected signs and are highly statistically significant and the model displays a high goodness of fit as measured by the rho-square value. The parameter estimates (the “Beta” column for each vehicle choice) are not directly comparable within each choice bundle, but they are comparable across bundles. In other words, one cannot directly compare the influence of, for example, household income with dwelling unit density in the household probability of owning two vehicles by simply looking at the relevant “Betas.” One can, however, use the “Beta” values to compare the influence of the relevant variable across vehicle choice decisions (as clarified in the discussion below). To compare the influence of the different variables within each choice set decision, Table 1 also presents a statistic analogous to the standardized coefficient value from a traditional ordinary least squares regression (following Levine, 1998). The statistic is calculated by taking the absolute value of the product of the variable’s “Beta” value and the standard deviation of the variable within the choice set. This “relative importance” statistic indicates the relative contribution of the variable to the choice process since this contribution comes from the size of the “Beta” value and the variation of the relevant variable.

Starting with basic household socio-economic characteristics, we see the expected effect of household income<sup>9</sup>; the effect is positive and increasingly influential with the decision to own multiple vehicles (comparing across the “choice bundle” of number of motor vehicles to own). Looking at the relative importance of household income (columns labeled D in Table 3), this variable dwarfs all others across all choice sets. This confirms our expectation that income serves as the primary driver of household vehicle ownership. Household demographics reveal some interesting effects. Being a household with one worker increases the likelihood of owning one car, while a household with three workers lowers the likelihood of owning one or two cars. The latter may reflect the fact that, *all else equal*, as the household size increases the attractiveness of owning vehicles declines due to a something of a net income effect (i.e., more money is required to clothe, feed, etc. the household members, reducing possible vehicle expenditures). A similar effect seems evident when examining the influence of children in the home. Families with one, two, or three children (18 and under) have increased likelihood of owning one car and families with two or four children have an increase chance of owning 2 cars – in both of these cases, we see the utility of auto ownership for families with children (economizing on trips, etc.). However, and again *all else equal*, having children has a negative influence on the three vehicle ownership choice, once more perhaps reflecting the intra-household net income effect of having additional people to provide for.

Interestingly, the presence of a broadband internet connection in the household appears positively and significantly associated with household motor vehicle ownership, an effect with increasing influence as the choice of number of vehicles increases. Taken at face value, the result for this variable offers support for a complementary relationship between telecommunications and travel in the Santiago case (e.g., Mokhtarian, 2003). Nonetheless, the broadband access variable may also be a “lifestyle” proxy, perhaps correlated with other unobserved household characteristics associated with both broadband access and desire for auto ownership.

Turning to transportation characteristics and relative accessibility, we see a positive effect of the auto-to-bus accessibility ratio, an effect that does not vary across the choice sets. The modal accessibility variables were tested independently also (i.e., auto accessibility, bus accessibility), however (the log of) the ratio of the two variables (representing relative attractiveness of auto) proved to be the best model specification. We can interpret this result to mean that, when a household lives in a zone with poor bus accessibility relative to auto accessibility, the household’s probability of auto ownership increases.<sup>10</sup> This result is consistent with the recent anecdotal evidence suggesting that the initially very negative effects on bus service quality of Santiago’s recent introduction of radical reforms in the bus sector (*Transantiago*) is increasing auto ownership in the city. Also, if a household lives within 500 meters of a Metro (urban heavy rail) stop, the likelihood of owning two or three or more vehicles goes down, reflecting the reduced relative utility of auto ownership for a household that lives near the Metro.

**Table 3.** Multinomial logit model of household motor vehicle choice

Variables	0 Veh. (base)	1 Vehicle			2 Vehicle			3+ Vehicle		
		Beta	T-test	D	Beta	T-test	D	Beta	T-test	D
<i>Household Characteristics</i>										
HH Income (LNUS\$000s)		1.63	42.21	1.45	2.85	41.73	2.53	3.37	24.46	2.99
1 Wkr HH		0.43	9.91	0.21						
3+ Wkr HH		-0.59	-9.91	0.21	-0.64	-7.25	0.23			
1 Child HH		0.10	2.07	0.04				-0.37	-2.32	0.16
2 Child HH		0.30	5.66	0.12	0.28	3.13	0.12			
3 Child HH		0.174	2.52	0.07				-1.14	-4.21	0.47
4 Child HH					0.35	2.00	0.07	-1.05	-2.63	0.20
Broadband		0.70	3.01	0.11	1.25	4.71	0.19	1.78	6.18	0.28
<i>Transport Characteristics</i>										
LN Auto:Bus Acc. Ratio <sup>a</sup>		0.04	2.00	0.05	0.04	2.00	0.05	0.04	2.00	0.05
< 500 m Metro Station					-0.38	-2.21	0.09	-0.38	-2.21	0.09
<i>Meso- and Micro-Level Built Environment Characteristics</i>										
Live in Apartment <sup>b</sup>		-0.34	-6.05	0.13	-0.67	-6.11	0.26	-1.21	-5.08	0.47
Dwelling Unit Density <sup>c</sup>		-0.007	-4.53	0.10	-0.02	-4.95	0.23	-0.03	-4.4	0.46
Diversity Index <sup>d</sup>		-0.81	-2.72	0.07	-1.54	-3.1	0.14	-3.39	-3.89	0.31
4-way Int. per Km <sup>e</sup>					-0.21	-3.71	0.16	-0.27	-2.04	0.21
Distance to CBD (KM)		0.06	2.81	0.27	0.06	2.81	0.27	0.06	2.81	0.27
Dist. to CBD Squared		-0.003	-3.64	0.33	-0.003	-3.64	0.33	-0.003	-3.64	0.33
Constants		-3.94	-24.01		-7.67	-29.71		-9.9	-17.28	
Chosen Obs.	8632	4662			1135			300		
% Obs.	59%	32%			8%			2%		

Notes: all variables included significant at > 95%; t-test is robust; n=14729 (excluded households with no income reported); Null Log-Likelihood: -20418.7; Final Log-Likelihood: -10844.2; LR Test: 19148; Rho-Square: 0.469. A blank cell in the table means that variable was not included in the choice's relative utility function. When a parameter value is the same across choice sets (in the case of the auto to bus accessibility ratio and distance to CBD for 2 and 3+ vehicle choices), a single parameter was estimated for the relevant choices (this proved to be the best model specification). D represents a measure of relative importance, similar to a standardized coefficient, calculated as  $D_x = |\beta \times \sigma_x|$  - see text description. (a) Entered as Ln(auto accessibility/bus accessibility), with accessibility calculated from equation 2; (b) dummy variable = 1, if household lives in an apartment; (c) # of dwelling units per hectare of constructed area; (d) as calculated by equation 1; (e) the variable x 1000 is entered in the estimation.

Finally, looking at the BE characteristics, we see a range of effects across the household vehicle choice sets. Four variables that represent some aspect of the micro-level BE have an influence:

- apartment living negatively influences the likelihood of owning motor vehicles, with the strength of the negative impact increasing as the number of vehicles to own increases;
- dwelling unit density displays a similar pattern of effects – higher densities have a relatively modest negative effect on the decision to own one vehicle, an effect which increases in strength (by 4 times) at the decision to own 3 or more vehicles;
- the diversity index similarly has a negative effect, as households in zones with a high diversity of land uses have a lower probability of owning vehicles, again with the effect's strength increasing as the choice becomes owning more vehicles (the effect at 3 vehicles is almost 5 times stronger than at 1 vehicle);
- the local street network, measured by the number of 4-way intersections per roadway kilometer (a proxy for grid street layout), also influences the choice of two or three-plus vehicles – a more “gridded” street has a negative effect on ownership, again increasing with the number of vehicles chosen.

A household's relative meso-level location, measured by distance to the CBD, has somewhat countervailing effects. Households living further from the central business district have a higher likelihood of owning motor vehicles, the effect is constant across motor vehicle ownership categories. However, as the household moves further and further away, a negative influence on auto ownership takes over (indicated by the negative coefficient on squared distance to CBD), perhaps reflecting the presence of sub-centers on Santiago's periphery, essentially smaller cities like Puente Alto and San Bernardo, engulfed in Santiago's urban expansion.

Other BE variables, including block morphology, were also tested, but showed no statistically significant influence.

### *Discussion*

Overall, the model offers an interesting glimpse at the factors influencing the household vehicle ownership decision. As we might expect, household income dominates the choice process. Nonetheless, some role of the BE (as well as relative transport levels of service) can be detected, the strength of the effects tends to increase with a household's choice to own more motor vehicles. Let's compare the results with similar types of models estimated in the United States. Hess and Ong (2002), using an ordered logit model of the household decision to own no automobiles in Portland Oregon, find a significant and positive effect of TAZ land use mix (entered as a dummy variable for “good” land use mix). Cambridge Systematics (1997) reports significant effects of population density and a public transport-to-highway access ratio in an ordered logit model of household vehicle availability in Philadelphia. Using a multinomial logit model, Cambridge Systematics (2002) estimated a vehicle availability model for San Francisco, also finding significant effects of a public transport-to-auto accessibility ratio for two or and three or more vehicles, significant effects of dwelling unit density for all three vehicle choice options, and nearly significant effects for a “vitality index,” again for the two and three vehicle choice decision. Kitamura *et al.* (2001), on the other hand, while finding some evidence of residential density influencing autos per household member, find no significant influence of regional accessibility measures (transit or auto; they do not, however implement a relative accessibility ratio), leading them to conclude that in a highly motorized region like Southern California accessibility may have marginal, if any, effects.

That the model estimated for Santiago produces results somewhat similar to several models for households in US cities is interesting in itself; despite motorization rates at roughly 20% of US levels and much more rapid growth in the motor vehicle fleet, an effect of relative transportation levels of service and local- and meso-level land use characteristics can be detected. Apartment living, dwelling unit density, local land use mix, street layout, distance to CBD, and proximity to Metro (within 500 meters) all influence auto ownership, partly reflecting reduced needs for auto ownership (e.g., a high mix of local uses, represented by a high diversity index, means less need for automobiles) and also likely representing some degree of auto ownership hassle and cost. In the case of apartment dwelling, for example, the issue

of vehicle garaging likely plays a role. Dwelling unit density also reflects some amount of land scarcity for vehicle storage.

Leaving aside the uncertainty about causality, any indications for policy related to land use planning and urban design need to be taken cautiously. First, income still clearly dominates the ownership decision. Even at the choice of owning three motor vehicles, income effects are approximately 6 to 14 times stronger than the BE influences (judging by the standardized scores; relative effects on VKT are calculated via elasticities below). Second, certain factors, such as the effect of apartment living, are not necessarily land planning policy variables, per se. This is particularly the case if we consider that this model does not account for potential self-selection: some households may choose their location (e.g., apartment and/or area with a high diversity of land uses) because of a preference for not wanting to own more than one automobile. At the same time, the model results do suggest that the BE and relative accessibility should be incorporated into relevant aspects of travel forecasting for Santiago; something which currently (to the best of my knowledge) does not happen in the city. Planning authorities currently utilize a household type approach (i.e., cross-classification) for forecasting auto ownership categories; no spatial variation in ownership is apparently accounted for. Such an approach could bias forecasts and policy analysis in ways even as simple as regulations regarding parking requirements for residential developments. The results presented here suggest more resolution in analysis could be valuable.

## Household Vehicle Use

After household vehicle ownership is determined, how much automobile use will the vehicle-owning household undertake? Does the built environment have an influence on automobile use?

### Model Specification

To assess the influence of the BE on household motor vehicle use, I specify an ordinary least squares regression, predicting total automobile use per auto-owning household. The dependent variable in this case was derived based on all auto-driver trips undertaken by the household on the day of the survey. The trip distance was derived from the geo-coded trip origin and destination and the shortest path on the road network. Households that had at least one trip with no derivable distance (due to lack of a geo-coded origin and/or destination) were assigned a dummy variable which was used as one of the dependent variables, with the expectation that the presence of such trips in the household would exert a downward influence on total reported auto distances traveled.<sup>11</sup>

As discussed above, specifying and estimating such a model requires correction for possible selection bias and, perhaps, endogeneity. Testing of various different OLS specifications, ultimately led to a single OLS model – that is, a single equation, containing both the selectivity bias correction (SBC) factor and an instrumental variable, the household's expected number of motor vehicles, substituted for the household's chosen number of motor vehicles. Both the SBC and the expected number of vehicles are calculated from the vehicle choice model presented in the previous section. The SBC takes the basic form

of a ratio of the relevant multinomial logit choice probabilities:  $(1/K) \sum_{k \neq i}^K [P_k \ln P_k / (1 - P_k) + \ln P_i]$ , where

$K$  is the total number of alternatives and  $P_k$  is the predicted probability of choice  $k$  (Manning, 1986).<sup>12</sup> The household's expected number of motor vehicles is calculated as:  $(0 * P_0) + (1 * P_1) + (2 * P_2) + (3 * P_3 + \dots)$ , where  $P_n$  is the estimated probability of a household owning  $n$  number of vehicles. The SBC and expected number of vehicles enter as independent variables in the vehicle usage (continuous choice, ordinary least squares) model.

### Results

Overall, the model has fairly good explanatory power (R-square of 0.17), particularly considering the disaggregate nature of the data and the fact that only a single day's automobile use is predicted. Similar vehicle use models, estimated on data for cities in the U.S. have displayed R-squared values in the range of 0.04 to 0.17 (e.g., Kitamura *et al.*, 2001; Bento *et al.*, 2004; Cervero and Kockelman, 1997).

Ultimately, several BE variables, representing meso- and micro-scale influences proved to be significant explanatory variables (Table 4). The selectivity bias correction factor does not prove significant in the model.

#### *Vehicle-, Trip-, and Other Household-Related Variables*

Focusing, first, on the variables directly related to households and their trip-making and vehicle characteristics, we see both expected and interesting results. The expected number of vehicles in a household has a strong positive influence on total automobile kilometers traveled on the survey day. Based on the standardized coefficient, the expected size of the household motor vehicle fleet is the single largest factor influencing total motor vehicle use. Interestingly, whether a household has at least one vehicle not typically subject to Santiago's vehicle circulation restriction (vehicles with a catalyst are exempt from *la restricción*) increases vehicle travel.<sup>13</sup> In other words, the restriction does have a noticeable effect on household automobile VKT; although from the survey data we cannot know whether households compensate for this by increased auto use on days not subject to *la restricción*. Households with three or more workers also have more automobile usage, all else equal. Comparing this result with the negative effect of workers per household on auto ownership suggests that households with more working members own fewer cars, *ceteris paribus*, but they use their cars more.<sup>14</sup> Most interestingly, perhaps, household income does not figure significantly in the model – this suggests that household income influences a household's total auto use only via the impact on the number of vehicles expected in the home. Finally, the presence of broadband internet access in the home is positively associated with auto use. Similar to the auto ownership case, this might provide some evidence for the complementary relationship between telecommunications and travel; or broadband internet presence may simply represent other unobserved household characteristics that increase auto usage.

Several trip- and survey-related variables were tested in the model, to control for relevant effects. As discussed above, the number of auto trips with no recordable distance was included as a statistical control, but was not significant. In the end, only variables representing the survey day had a discernible effect. Households tend to record lower auto distances on non-summer Sundays and on summer Saturdays and Sundays. This is an interesting result, since according to the travel survey results, *Santiaguinos* tend to make more total auto trips (driver and passenger) on the weekends (SECTRA, 2004). The result suggests that the weekend auto trips are higher occupancy (more person-trips per auto, consistent with weekend socializing and shopping travel) and/or shorter distance.

#### *Meso- and Micro-Scale Built Environment Characteristics*

Looking at relative location, we see a fairly strong distance to CBD effect, lending some support to the structural idea of the compact city as a means for reducing auto VKT (e.g., Cameron et al., 2003). For each kilometer increase in distance from the CBD, we would expect a household's daily auto use to increase by 500 meters. Distance to metro stations also figures significantly into household auto use, suggesting an almost one-for-one increase in terms of household kilometers traveled with distance to the nearest Metro station. Compared to Metro effects on vehicle ownership – living within 500 meters of a Metro reduces car ownership (possibly reflecting vehicle ownership hassle/cost, plus reduced relative utility of car ownership) – the distance influence on use suggests the effect extends beyond a simple threshold (i.e., within 500 meters or not), suggesting a dampening effect of Metro on auto use, even for households with the same number of vehicles. Finally, a household's location in the Eastern foothills is also significantly associated with an increase in automobile use. In this case, the model results support the hypothesis that the hills make other travel modes less convenient and auto use more convenient. Nonetheless, as the variable enters the model as a dummy representing zones in the foothills, it may be capturing other unobserved effects associated with those parts of the city. Relative auto and bus accessibility levels were not significant.

Few micro-scale BE factors had a significant influence on auto use in this model. The variables that do play an apparent, albeit modest, role are the number of 3-way intersections per kilometer (a proxy for a more suburban street network and less neighborhood porosity), which was associated with increased

auto use. Zonal-level plaza density also significantly associates with a modest decrease in household auto use, suggesting that more greenspace reduces total auto travel, perhaps through total motorized trip reduction. A number of other micro-level design measures, including dwelling unit density, mix of land uses, 4-way intersections per km (proxy for street grid) were tested, but not significant. Finally, I examined potential “gated community effects” – under the supposition that such communities, typically with only one way in/out and a growing phenomenon in Santiago (Hidalgo, 2004) and elsewhere in Latin America, would increase automobile use among relevant households. A dummy variable indicating whether or not the household resides in a condominium was tested. No significant effect was detected.<sup>15</sup>

**Table 4.** OLS estimate of household total automobile kms on day of survey

Category	Variable	Beta	Standard Error	Standard Beta	T-Stat	Prob.
<i>Vehicles</i>	Dummy if at least one auto has catalyst	4.98	0.90	0.09	5.53	0.00
	Expected Number of Vehicles	12.28	1.76	0.26	6.96	0.00
<i>HHs</i>	3 worker HH	2.95	0.94	0.05	3.14	0.00
	Broadband	5.72	1.69	0.06	3.38	0.00
<i>Trips and Survey Day</i>	Normal Sunday	-7.58	1.17	-0.09	-6.48	0.00
	Summer Saturday	-4.50	2.29	-0.03	-1.97	0.05
	Summer Sunday	-8.69	2.47	-0.05	-3.51	0.00
<i>Urban Form &amp; Transport</i>	Dist to CBD	0.48	0.14	0.08	3.38	0.00
	Dist to Metro	0.96	0.21	0.11	4.64	0.00
	Foothills	3.87	1.48	0.04	2.62	0.01
<i>Urban Design</i>	3-Way Int. per KM <sup>a</sup>	0.68	0.23	0.05	3.03	0.00
	Plaza Density	-33.13	16.35	-0.03	-2.03	0.04
	Selectivity Bias Correction	-4.13	4.91	-0.03	-0.84	0.40
	Constant	2.66	2.95		0.90	0.37

*Notes:* the dependent variable is total auto distance traveled (in kilometers) by household on the day of the survey; R-square: 0.17; F-statistic 65.8 (Prob. 0.0); N=4,103; households with 0 income reported excluded from the analysis. (a) the variable x 1000 is entered in the estimation.

### Combined Effects: Overall Relative Influence of the BE

Finally, combining the vehicle ownership and use models enables the estimation of cascading influences, that is:

1. the relationship between the BE and automobile ownership levels, and
2. the relationship between the BE and automobile use, including the direct effects of the BE-VKT relationship and the indirect effects due to the BE’s relationship with vehicle ownership (1) and, then, ownership’s influence on use.



The relative influences can be estimated in the form of elasticities of VKT with respect to the different variables of interest. Table 5 presents such elasticities, calculated using the two models, combined, in simulations.<sup>16</sup> These elasticities confirm income as the most important factor influencing household VKT, although its effects, as discussed above, appear entirely through the vehicle ownership-to-vehicle use chain. Interestingly, however, the elasticities suggest fairly comparable influence for the meso-level BE indicator of distance to CBD, as well as proximity to metro stations. One micro-level urban design indicator, 3-way intersections per kilometer, the proxy for suburban roadway networks, also exerts a surprisingly strong apparent influence. The other micro-level BE indicators (dwelling unit density, grid streets, land use mix, and plaza density) exhibit fairly modest relative effects on VKT – representing a cumulative elasticity of about 0.10. In other words, if we could simultaneously double dwelling unit density, land use mix, 4-way intersections per kilometer, and plaza density, we would expect a 10 percent reduction in VKT.

**Table 5.** Elasticities of household VKT with respect to variables of interest

Variable	Elasticity of VKT Due to Variable's Effect on:		Combined (net) Elasticity
	Ownership	Use	
Income	0.253		0.253
Auto:Bus Accessibility	0.004		0.004
Distance to Metro	0.001	0.190	0.191
Distance to CBD	-0.024	0.252	0.228
Dwelling Unit Density	-0.039		-0.039
Diversity Index	-0.013		-0.013
4 Way Intersections	-0.020		-0.020
3 Way Intersections		0.151	0.151
Plaza Density		-0.027	-0.027

*Notes:* the elasticities were calculated via simulation; see details in note 16. Variables are defined as in Tables 3 and 4.

These elasticities should be viewed with some caution. Even if we assume that the underlying models are good, calculating static elasticities via these simplified simulations ignores the fact that, for example, changing the BE affects origins *and* destinations in a system of interactions (so that the entire system changes). Nonetheless, we can have some basic confidence in the model results, as summarized in the elasticities, by comparing them to values calculated elsewhere. The estimated elasticity of VKT with respect to income compares favorably to the value Train (1986) derives for California (0.29), but is just one-half the value (0.49) which Goodwin *et al.* (2004) derive from a review of a number of relevant studies since 1990. Note that the Santiago value represents an elasticity for urban travel only; we might expect a higher income elasticity if inter-urban auto travel were included, perhaps bringing the value closer in line with Goodwin *et al.* As for the various BE and related measures, the net effect of distance to CBD appears quite comparable to the “typical” elasticity of VKT with respect to “regional accessibility” estimated by Ewing and Cervero (2001): 0.20. Except for the surprisingly high value for the suburban street network proxy (3-way intersections), the other local-level “design” measures (dwelling unit density, diversity index, 4-way intersections, plaza density) together are comparable in their cumulative effects to the combined density, diversity and design effects also estimated by Ewing and Cervero: 0.13.

## Conclusions

This paper set out the goal of answering the question “What role might Santiago’s built environment play in household automobile ownership and use?” Via estimation of a multinomial logit model of household

vehicle choice, we saw – as might be expected in a city undergoing rapid economic growth and motorization – that at least one vehicle seems almost a certainty as soon as household income allows. Nonetheless, a number of meso- and micro-level location-related characteristics are also related to vehicle ownership, a relationship which in several cases increases in strength as the decision moves to choose additional vehicles. Increased local land use mixes, dwelling unit densities and proximity to the central business district are associated with a decreased probability of household vehicle ownership, as are improved bus levels of service relative to the auto. An association with the grid street network and Metro proximity is detected for the household choice to own two or three plus vehicles. In terms of transportation analysis, the lesson is clear: future transportation forecasting efforts should include built environment and transportation levels of service for projecting household auto ownership. If not, biased forecasts may result. For the purposes of urban planning and design, the findings offer, at least, some concrete evidence on the relationship between the BE and auto ownership and suggest areas worth further examination to detail the effects, including: dwelling unit densities and land use mixes, housing in proximity to Metro stations, and incentives to reduce urban expansion.

To gauge the cascading effects of vehicle ownership on household vehicle use, we turned to an ordinary least squares model predicting household automobile distances traveled on the day of the survey. The expected number of household vehicles shows the strongest relationship. Somewhat surprisingly, income does not display any independent association with vehicle use; income's effects on use come only indirectly via the influence on the vehicle ownership decision. Household distance to Metro stations and distance to CBD have relatively strong associations with vehicle use. As for associations with other BE measures, somewhat moderate effects are detected for a proxy for suburban street layouts and very moderate for plaza density. No apparent *direct* relationship between VKT and dwelling unit density or land use mix was found. The combined relative effects, estimated in the form of elasticities calculated from simulations, suggest that income plays the overall largest single role in determining VKT. In combination, however, a range of different meso- and micro-level BE characteristics play a strong role.

The largest shortcoming in this research comes from the inability to infer any true causality – and, in fact, the possibility to infer false associations – in terms of BE and travel behavior, due to the issue generally referred to as “self selection.” Both the decision to own vehicles and the decision to use them likely influence households' location decisions, so both of the models presented suffer from bias in this regard. Future research could target this problem by, for example, the development of a household residential choice model which could be used to instrument for the BE variables. Other research contributions could be made by exploring alternative areal units for analysis – to capture “neighborhood” effects that the TAZs may arbitrarily mask. Finally, research could extend beyond the VKT focus presented here, to examine more complete effects (e.g., use of all modes), for the purposes of estimating, for example, effects on total energy use.

Broader challenges remain in this field of research. One relates to the type of data typically used – trip-based household travel surveys for a single day (often a typical work week day). Such data make it difficult to assess broader travel impacts, including weekly shopping habits, recreational travel, and trip-chaining propensity. Such impacts have not been the focus of much research, in part because the data simply do not exist. Ultimately, the research presented here – showing some quantifiable relationship between BE and VKT – offers some evidence to support those who believe that urban planning and design can help improve the urban mobility situation in the rapidly developing world. It says nothing, however, about actually getting such planning and design done.

## Notes

<sup>1</sup> Again, this assumes that auto VKT has greater negative effects than kilometers traveled by other modes; furthermore, it ignores other possibly desirable travel outcomes, such as the potential for increased physical activity associated with walking and biking (e.g., Brown *et al.*, 2008).

<sup>2</sup> Furthermore, for some concerns, such as greenhouse gas emissions, a broader possible “rebound effect” exists: if individuals/households have roughly stable travel time and money budgets (e.g., Schäfer, 2000) and the built

environment enables lower average daily urban vehicle travel, this travel may be compensated by “investment” of the saved time/money in additional long distance travel.

<sup>3</sup> Some of the differences between the two survey years may also be attributable, at least in part, to differences in survey methodology.

<sup>4</sup> For example, since implementation of the pollution control plan of 1997, the city has experienced a 18-34% drop in average winter time PM10 concentrations measured at seven monitoring sites across the city (the city suffers from a thermal inversion in the winter months). Ozone concentrations have proven to be more tenacious, with the number of days exceeding the norm staying relatively constant (40-46 per year) over the six years from 1997-2003 (CONAMA, 2003).

<sup>5</sup> The database was provided to the author by SECTRA. Note, the geo-coding of the land use activity points (with each point representing a registered activity (residential or non-residential land use) was not 100% accurate. Since the data points were geo-coded based on street addresses and numbers, those activity points that could not “find” the proper address (the street map was from 1999; while the activity points were from 2001) remained “orphaned.” This phenomenon primarily occurred for points in the rapidly growing areas. Considerable effort was made to relocate those points based on the recorded street addresses and updated street maps, but room for error remains.

<sup>6</sup> This information, a database and polygons, was provided in a map and linked databases to the author by the Chilean Ministry of Housing and Urban Development (MINVU). This map provided a surprisingly good coverage of greenspaces (including parks, plazas, cemeteries, agricultural land, other greenspaces and sports facilities) within a larger land use map that included other zoned uses. The presence of the greenspaces in this MINVU map was corroborated via an orthophoto. The orthophoto provided (by the Transportation Planning Agency, SECTRA) was for the year 1997. The land use coverage information came from authorities’ field survey efforts to see the degree to which actual land uses matched zoned land uses (open spaces); multiple queries were carried out on the database to extract actual land uses, based on the recorded field survey observations contained therein. For example, only zoned open spaces that were surveyed to have some tree/grass coverage, not abandoned, were considered.

<sup>7</sup> In the decision to buy additional vehicles, the type of currently owned vehicle likely plays a role; the information necessary to model this possible influence was not available from the sample.

<sup>8</sup> The model run was provided by the transportation planning agency, SECTRA, for the year 2001, AM peak period.

<sup>9</sup> A “net” household income variable was constructed, which attempted to net out housing costs (reported rents or mortgage payments), but the variable did not improve model fit relative to income as simply reported in the survey.

<sup>10</sup> In reality, this accessibility provides a very imperfect measure of relative quality of service, since it ignores important attributes such as relative cost, travel time, security, comfort and reliability. Such data were not available for inclusion in the model.

<sup>11</sup> Whether the auto trip was “external” to the study area was also coded and included as an independent variable, but it had no significant explanatory power.

<sup>12</sup> The SBC utilized was simply for the binary case – whether a household owns a vehicle or not. This enabled specification and estimation of a single OLS model, which proved to be the best model specification.

<sup>13</sup> Average vehicle age in the household was also tested, but not significant.

<sup>14</sup> The number of children had no significant effect.

<sup>15</sup> It is not clear from the survey how accurately the “condominium” variable reflects the gated community setting – more research on this topic is warranted.

<sup>16</sup> The following procedure was used to calculate the elasticities of VKT with respect to the different variables. First a “baseline” total VKT estimate was generated for all households in the sample, utilizing the coefficient estimates from the OLS model (Table 4) and the relevant variables for the households (utilizing the expected number of motor vehicles in place of the actual number of motor vehicles). Then, for variables that figured significantly *only in the vehicle ownership model*: (1) a 10% change in the variable of interest was applied to each observation in the sample (n=14279; households with no income were excluded); (2) new vehicle ownership probabilities were estimated via sample enumeration and based on the 10% change; (3) the new ownership probabilities were used to estimate a new expected number of motor vehicles; (4) new VKT estimates were calculated for all households, using the OLS coefficients and the new expected number of motor vehicles. The elasticity was then calculated by:  $[(VKT_{baseline} - VKT_{new})/VKT_{baseline}]/(0.10)$ . For variables that figured significantly into *both the ownership and use models* (i.e., distance to metro and distance to CBD), the same four steps were followed. In step 4, the original variable, *not* the 10% changed variable was used in estimating  $VKT_{new}$  – this enabled an isolation of the vehicle ownership effect on VKT (presented in “Ownership” column in Table 5). Then, in an additional step (5),  $VKT_{new}$  was re-estimated by including the 10% changed variable directly in the VKT estimation model also. This  $VKT_{new2}$  was used to calculate a new elasticity, which appears in the “Combined (net) Elasticity” column in Table 5. For these two variables (metro

and CBD distance), the “Use” elasticity (that is the estimated isolated direct effect of the variable on use) is simply the difference between the “Combined” and “Ownership” elasticities. Finally, for variables that figured significantly *only in the vehicle use model*, the 10% changed variable of interest was incorporated directly in the VKT estimation model, with the elasticities calculated as per above. Note that distance to Metro entered the ownership model as a dummy for within 500 meters; when a 10% change in a household’s distance to Metro moved it within this 500 meters, the dummy was “triggered,” thus enabling a rough estimate of the distance to Metro effects on ownership and use.

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