Available online at www.sciencedirect.com
SCIENCE DIRECT®
Transportation Research Part D 10 (2005) 427–444
TRANSPORTATION RESEARCH PART D
www.elsevier.com/locate/trd

Correlation or causality between the built environment and travel behavior? Evidence from Northern California

Susan Handy [a,*], Xinyu Cao [b], Patricia Mokhtarian [b]

[a] *Department of Environmental Science and Policy, University of California, One Shields Avenue, Davis, CA 95616-8762, USA*
[b] *Department of Civil and Environmental Engineering, University of California, One Shields Avenue, Davis, CA 95616-8762, USA*

Abstract

The sprawling patterns of land development common to metropolitan areas of the US have been blamed for high levels of automobile travel, and thus for air quality problems. In response, smart growth programs—designed to counter sprawl—have gained popularity in the US. Studies show that, all else equal, residents of neighborhoods with higher levels of density, land-use mix, transit accessibility, and pedestrian friendliness drive less than residents of neighborhoods with lower levels of these characteristics. These studies have shed little light, however, on the underlying direction of causality—in particular, whether neighborhood design influences travel behavior or whether travel preferences influence the choice of neighborhood. The evidence thus leaves a key question largely unanswered: if cities use land use policies to bring residents closer to destinations and provide viable alternatives to driving, will people drive less and thereby reduce emissions? Here a quasi-longitudinal design is used to investigate the relationship between neighborhood characteristics and travel behavior while taking into account the role of travel preferences and neighborhood preferences in explaining this relationship. A multivariate analysis of cross-sectional data shows that differences in travel behavior between suburban and traditional neighborhoods are largely explained by attitudes. However, a quasi-longitudinal analysis of changes in travel behavior and changes in the built environment shows significant associations, even when attitudes have been accounted for, providing support for a causal relationship.

* Corresponding author. Tel.: +1 530 752 5878; fax: +1 530 752 3350.
E-mail address: slhandy@ucdavis.edu (S. Handy).

1361-9209/$ - see front matter
doi:10.1016/j.trd.2005.05.002

Keywords: Built environment; Travel behavior; Smart growth; Land-use

1. Introduction

Sprawling patterns of land development have been blamed for high levels of automobile travel, and thus for air quality problems. The defining characteristics of sprawl include: low-density development, unlimited outward expansion, and leap-frog development (Burchell et al., 2002). This low-density pattern of growth has two important effects on travel: longer trip distances and greater reliance on the car. In response to these travel effects and other impacts, smart growth programs designed to counter sprawl have gained popularity in the US. The American Planning Association (2002) defines smart growth as "the planning, design, development and revitalization of cities, towns, suburbs and rural areas to create and promote social equity, a sense of place and community, and to preserve natural as well as cultural resources". Specific land use policies used in smart growth programs include mixed-use zoning, infill development, brownfield development, and transit-oriented development, as well as bicycle and pedestrian infrastructure. The hope is that these strategies will bring residents closer to destinations and provide viable alternatives to driving, and thus help to reduce automobile use.

Recognizing this potential, the US Environmental Protection Agency (EPA) now accepts land-use policies as an effective tool for improving air quality and allows state and local communities to account for the air quality benefits of smart growth strategies in state air quality plans (EPA, 2001). However, the estimation of the emissions effects of land use policies is based on limited empirical evidence, and little is known about the sensitivity of air quality to changes in land use. Studies in the US show that, all else equal, residents of neighborhoods with higher levels of urban density, land-use mix, transit accessibility, and pedestrian friendliness (among other characteristics) drive less than residents of neighborhoods with lower levels of these characteristics. These studies have not established the underlying direction of causality, in particular, whether neighborhood design influences travel behavior or whether travel preferences influence the choice of neighborhood. The available evidence thus leaves a key question largely unanswered: If cities use land use policies to bring residents closer to destinations and provide viable alternatives to driving, will at least some people drive less, thereby reducing emissions?

This paper provides new evidence that helps to answer this question; it aims to provide a stronger basis for assessing the potential for land-use policies to reduce automobile travel, and thus vehicle emissions. The study uses a quasi-longitudinal design to investigate the relationship between neighborhood characteristics and travel behavior while taking into account the role of travel attitudes and neighborhood preferences in explaining this relationship.

2. Literature review

If cities use land use policies to bring residents closer to destinations and provide viable alternatives to driving, will people drive less, thereby reducing emissions? Existing research does not provide a clear answer. The idea that land use and design policies could be used to influence travel behavior was not widely explored until the 1980s. Early interest focused on the connection between density and transit use. The study by Pushkarev and Zupan (1977) suggests that transit use can be increased through polices that increase densities. A heated debate ensued in the early 1990s, over analysis by Newman and Kenworthy (1999) on the correlation between densities and gasoline consumption for a sample of international cities (Mindali et al., 2004). In response to the emergence of the smart growth movement and the concept of new urbanism, a number of recent studies have examined the effect of specific characteristics of the built environment on travel behavior at a disaggregate level in an effort to test the hypothesis that policies that shape the built environment can be used to reduce automobile travel.

Since the early 1990s, such studies have appeared with increasing frequency. Recent reviews document over 70 studies during the 1990s that explored and quantified these relationships (Handy, 1996; Boarnet and Crane, 2001; Ewing and Cervero, 2001). Sorting out the extent to which socio-economic characteristics and characteristics of the built environment impact travel behavior is a common challenge in these studies. Ewing and Cervero (2001), after one of the most thorough reviews of these studies, come to the conclusion that the built environment has a greater impact on trip lengths than trip frequencies and that mode choice depends as much on socio-economic characteristics as the built environment. Their analysis of the existing studies shows small but statistically significant effects of the built environment on vehicle miles of travel.

In the US, the debate over the link between neighborhood design and travel behavior now centers on the issue of causality (Transportation Research Board and Institute of Medicine, 2005). Scientific practice dictates four criteria for establishing causality between an independent variable (the cause) and a dependent variable (the effect): the cause and effect are statistically associated (association), the cause precedes the effect in time (time order), no third factor creates an accidental or spurious relationship between the variables (non-spuriousness), and the mechanism by which the cause influences the effect is known (causal mechanism) (Singleton and Straits, 1999). Most studies have met the first criterion but have not met the other three.

Almost all of the studies have used cross-sectional designs to establish a statistical association between the built environment and travel behavior. Cross-sectional designs do not establish whether the cause precedes the effect, however. Most studies have controlled for socio-demographic characteristics, thereby minimizing the possibility that income, for example, creates a spurious relationship between the built environment and travel behavior. But few have accounted for the effects of attitudes towards travel. By falling short on the criteria of time-order and non-spuriousness, these studies leave open the possibility of self-selection, in which individuals who would rather not drive choose to live in neighborhoods conducive to driving less. In this case, the characteristics of the built environment do not cause them to drive less; rather, their desire to drive less causes them to select a neighborhood with those characteristics. Understanding the role of self-selection is the key to understanding the causal relationship between the built environment and travel behavior.

A few studies have made efforts to address the self-selection issue by accounting for preferences and attitudes, although with cross-sectional data as well, thereby addressing the non-spurious criterion but not the time order criterion. Studies by Handy and Clifton (2001) and Bagley and Mokhtarian (2002) in fact suggest that the observed associations between travel behavior and neighborhood characteristics are largely explained by the self-selection of residents with certain attitudes into certain kinds of neighborhoods. On the other hand, Schwanen and Mokhtarian

(2005), also using cross-sectional data but a different methodology, found that neighborhood type does impact on travel behavior, even after attitudes are accounted for. Unfortunately for efforts to reduce car use, they found the effect to be more extreme in the suburbs (where residents who preferred higher-density neighborhoods drove to work about as often as those who liked their lower-density environment) than in the city (where residents who preferred lower-density neighborhoods drove to work more often than those who liked higher densities although not as much as those who lived in the suburbs). Cao et al. (2005) recently found that characteristics of the built environment influence walking behavior after accounting for a preference for neighborhoods conducive to walking.

The causal mechanism that might link the built environment to travel behavior has been given limited attention by researchers. Boarnet and Crane (2001) offer an economic explanation: the built environment influences the price of travel, through its impact on travel time and other qualities of travel, which then influences the consumption of travel. A similar idea is implicit in discrete choice models of travel behavior: the utility of a particular travel choice—what mode to take or which destination to choose—is influenced by travel time and other characteristics of the possible choices, that in turn are influenced by the built environment. But these explanations focus on the immediate and direct connection between the built environment and travel behavior and do not account for longer term decisions about residential location. It is possible that different causal mechanisms apply in different situations, depending on the combination of the preferences of the individual and the type of environment in which she chooses to live (Handy, 2005). It is also possible that the built environment has a less immediate and more indirect effect on travel behavior through its impact on attitudes over time. Not only has the existence of a causal relationship not yet been established, the nature of potential causal relationships is poorly understood.

3. Methodology

The objectives of the study presented here were, first, to confirm the role of attitudes and preferences in explaining the observed link between the built environment and travel behavior, and, second, to more directly test the general hypothesis that the built environment has a causal effect on travel behavior. Causal relationships are most validly established through experimental designs, in which individuals are randomized to treatment and control groups (thereby addressing non-spuriousness) and behavior is measured for both groups before and after the treatment of interest (thereby addressing time order) (Singleton and Straits, 1999). Neither randomization nor the application of a treatment is practical for studying the link between the built environment and travel behavior. Instead, in this study, the treatment is defined as a move from one neighborhood to another and the lack of randomization is addressed by accounting for preferences and attitudes that might influence the choice of neighborhood. The specific hypotheses addressed here are thus as follows:

1. Differences in the built environment are associated with differences in travel behavior, after accounting for socio-demographic characteristics and for attitudes and preferences. More specifically, environments where residents are closer to destinations and have viable alternatives to driving are in fact associated with less driving.

2. Changes in the built environment are associated with changes in travel behavior, after accounting for socio-demographic characteristics and for attitudes and preferences. More specifically, moves to environments where residents are closer to destinations and have viable alternatives to driving are associated with a decrease in driving.

Here an innovative approach is used to examine the causal relationship between the built environment and travel behavior while taking into account the role of attitudes, including attitudes with respect to travel and preferences with respect to neighborhood characteristics. The research design enables both cross-sectional and quasi-longitudinal analyses.

3.1. Survey and sampling

The data came from a self-administered 12 page survey mailed in two rounds in late 2003 to households in eight neighborhoods in Northern California. The neighborhoods were selected to vary systematically on three dimensions: neighborhood type, size of the metropolitan area, and region of the state. Neighborhood type was differentiated as traditional for areas built mostly in the pre-World II era, and suburban for areas built more recently. Although this design was intended to provide ample variation across neighborhood types, and these discrete indicators of neighborhood type are useful for descriptive comparisons, they are too simplistic for more detailed analyses. For the multivariate models presented in Section 4, we used a rich set of variables describing the neighborhoods along a variety of dimensions.

Using data from the US Census, we screened potential neighborhoods to ensure that average income and other characteristics were near the average for the region. Four neighborhoods in the San Francisco Bay Area—two in the Silicon Valley area and two in Santa Rosa—had been previously studied (Handy, 1992). Two neighborhoods from Sacramento and two from Modesto were selected to contrast with Bay Area neighborhoods (Fig. 1). The four traditional neighborhoods differ in visible ways from the four suburban neighborhoods—the layout of the street network, the age and style of the houses, and the location and design of commercial centers, as shown in Fig. 2 for Sacramento as an example.

For each neighborhood, two databases of residents were purchased from a commercial provider, New Neighbors Contact Service (www.nncs.com; this service maintains an overall database of names and addresses for residences throughout the US constructed from a variety of public records. The database is largely used for commercial advertisement mailings): a database of movers and a database of non-movers. The movers included all current residents of the neighborhood who had moved within the previous year. From this database, we drew a random sample of 500 residents for each neighborhood. The database of non-movers consisted of a random sample of 500 residents not included in the movers list for each neighborhood.

Survey questions were developed from surveys used in previous research projects by the authors and other researchers. The survey was pre-tested on UC Davis students and staff, then on a convenience sample of Davis residents. Participants were asked to first complete the survey, then to discuss the survey questions with the researchers, either in a group meeting or in one-on-one interviews. Based on these pretests, survey questions were modified and refined.

The survey was administered using a mail-out, mail-back approach. Surveys were mailed to households in the selected neighborhoods, and the cover letter asked for "any adult household

Fig. 1. Location of neighborhoods.

member who shares in the decision making... and who participated in selecting your current residence" to complete the survey. The initial survey was mailed out at the end of September 2003. Two weeks later, a reminder postcard was mailed to the entire sample using first-class mail. At the beginning of November, a second copy of the survey with a revised cover letter was sent to a shorter list that excluded incorrect addresses and individuals who had already responded to the survey. Two weeks later, a second reminder postcard was mailed to this list of residents. As an incentive to complete the survey, respondents were told they would be entered into a drawing to receive one of five $100 cash prizes; the winners were selected in December.

The original database consisted of 8000 addresses but only 6746 valid addresses. The number of responses totaled 1682, for a response rate of 24.5%. This is considered quite good for a survey of this length; the typical response rates for a survey administered to the general population are 10–40% (Sommer and Sommer, 1997). A comparison of sample characteristics to population characteristics (based on the 2000 US Census) shows that survey respondents tend to be older on average than residents of their neighborhood as a whole, and that households with children are underrepresented for most neighborhoods while home owners are overrepresented for all neighborhoods

Fig. 2. Comparison of traditional and suburban neighborhoods-Sacramento.

(Table 1). However, since the focus is on explaining the relationships of other variables to travel behavior rather than on describing travel behavior per se, these differences are not expected to materially affect the results (Babbie, 1998).

Table 1
Sample characteristics vs. population characteristics

	Traditional				Suburban				Traditional	Suburban
	Silicon Valley—Mountain View	Santa Rosa—Junior College	Modesto—Central	Sacramento—Midtown	Silicon Valley—Sunnyvale	Santa Rosa—Rincon Valley	Modesto—Suburban	Sacramento—Natomas		
Sample characteristics										
Number	228	215	184	271	217	165	220	182	898	784
Percent female	47.3	54.3	56.3	58.2	46.9	50.9	50.9	54.9	54.1	50.7
Average auto ownership	1.80	1.63	1.59	1.50	1.79	1.66	1.88	1.68	1.62	1.76*
Average age	43.3	47.0	51.3	43.4	47.1	54.7	53.2	45.6	45.1	48.9*
Average HH size	2.08	2.03	2.13	1.78	2.58	2.19	2.41	2.35	1.99	2.40*
Percent of HHs w/kids	21.1	18.6	21.7	8.9	42.4	24.8	25.5	31.9	16.9	31.5*
Average number of kids	1.60	0.16	1.83	1.58	1.65	1.59	1.98	1.64	1.65	1.71
Percent home owner	51.1	57.8	75.6	47.0	61.1	68.7	81.0	82.4	56.4	73.3*
Median HH income (k$)	98.7	55.5	45.5	64.2	95.0	49.5	55.5	55.3	68.5	55.5
Population characteristics[a]										
Population	5,493	9,886	13,295	7,259	14,973	13,617	19,045	13,295		
Average age	36.1	36.3	36.5	42.7	35.9	38.3	38.1	31.7		
Average HH size	2.08	2.21	2.46	1.79	2.66	2.48	2.51	2.57		
Percent of HHs w/kids	19.3	20.3	32.9	12.4	35.3	35.4	34.2	41.7		
Percent home owner	34.3	31.2	58.8	34.3	53.2	63.5	61.4	55.2		
Median HH income (k$)	74.3	40.2	42.5	43.8	88.4	49.6	40.2	46.2		
Percent of units built after 1960	54.3	37.2	21.4	22.7	79.9	90.3	94.6	97.6		

* Differences between traditional and suburban significant at 1% level.
[a] Source: 2000 U.S. Census of Population and Housing.

3.2. Variables

Travel behavior was variously measured through a series of questions on commute trips, non-work trips, and walking trips. In addition, respondents were asked to list vehicles currently available to the household, and to estimate how many miles they drive in a typical week. Although it is unlikely that respondents know exactly how many miles they drive in a week, these estimates should provide a reasonably accurate indicator of their level of driving. Reported vehicle miles driven (VMD) per week is used as the dependent variable in cross-sectional models. Change in travel behavior from either just before the move (for the movers) or from 1 year ago (for the non-movers) was measured using 5-point scales; for example, respondents were asked to indicate whether they drive "a lot less now", "a little less now", "about the same", "a little more now", or "a lot more now".

Table 2
Factors for neighborhood characteristics

Factor	Statement	Loading[a]
Accessibility	Easy access to a regional shopping mall	0.854
	Easy access to downtown	0.830
	Other amenities such as a community center available nearby	0.667
	Shopping areas within walking distance	0.652
	Easy access to the freeway	0.528
	Good public transit service (bus or rail)	0.437
Physical activity options	Bike routes beyond the neighborhood	0.882
	Sidewalks throughout the neighborhood	0.707
	Parks and open spaces nearby	0.637
	Good public transit service (bus or rail)	0.353
Safety	Quiet neighborhood	0.780
	Low crime rate within neighborhood	0.759
	Low level of car traffic on neighborhood streets	0.752
	Safe neighborhood for walking	0.741
	Safe neighborhood for kids to play outdoors	0.634
	Good street lighting	0.571
Socializing	Diverse neighbors in terms of ethnicity, race, and age	0.789
	Lots of people out and about within the neighborhood	0.785
	Lots of interaction among neighbors	0.614
	Economic level of neighbors similar to my level	0.476
Outdoor spaciousness	Large back yards	0.876
	Large front yards	0.858
	Lots of off-street parking (garages or driveways)	0.562
Attractiveness	Attractive appearance of neighborhood	0.780
	High level of upkeep in neighborhood	0.723
	Variety in housing styles	0.680
	Big street trees	0.451

[a] Represents the degree of association between the statement and the factor.

Table 3
Factors for travel preferences

Factor	Statement	Loading[a]
Pro-bike/walk	I like riding a bike	0.880
	I prefer to bike rather than drive whenever possible	0.865
	Biking can sometimes be easier for me than driving	0.818
	I prefer to walk rather than drive whenever possible	0.461
	I like walking	0.400
	Walking can sometimes be easier for me than driving	0.339
Pro-travel	The trip to/from work is a useful transition between home and work	0.683
	Travel time is generally wasted time	−0.681
	I use my trip to/from work productively	0.616
	The only good thing about traveling is arriving at your destination	−0.563
	I like driving	0.479
Travel minimizing	Fuel efficiency is an important factor for me in choosing a vehicle	0.679
	I prefer to organize my errands so that I make as few trips as possible	0.617
	I often use the telephone or the Internet to avoid having to travel somewhere	0.514
	The price of gasoline affects the choices I make about my daily travel	0.513
	I try to limit my driving to help improve air quality	0.458
	Vehicles should be taxed on the basis of the amount of pollution they produce	0.426
	When I need to buy something, I usually prefer to get it at the closest store possible	0.332
Pro-transit	I like taking transit	0.778
	I prefer to take transit rather than drive whenever possible	0.771
	Public transit can sometimes be easier for me than driving	0.757
	Walking can sometimes be easier for me than driving	0.344
	I prefer to walk rather than drive whenever possible	0.363
Safety of car	Traveling by car is safer overall than walking	0.753
	Traveling by car is safer overall than taking transit	0.633
	Traveling by car is safer overall than riding a bicycle	0.489
	The region needs to build more highways to reduce traffic congestion	0.444
Car dependent	I need a car to do many of the things I like to do	0.612
	Getting to work without a car is a hassle	0.524
	We could manage pretty well with one fewer car than we have (or with no car)	−0.418
	Traveling by car is safer overall than riding a bicycle	0.402
	I like driving	0.356

[a] Represents the degree of association between the statement and the factor.

The explanatory variables are classified into:

Neighborhood characteristics and neighborhood preferences: Respondents were asked to indicate how true 34 characteristics are for their current and previous (only for movers) neighborhood, on a four-point scale from 1 ("not at all true") to 4 ("entirely true"). The characteristics of these neighborhoods as perceived by survey respondents reflect fundamental differences in neighborhood design. The importance of these items to respondents when/if they were looking for a new place to live was also measured on a four-point scale from 1 ("not at all important") to 4 ("extremely important"). The comparison of individuals' perceived neighborhood characteristics for their current residence and their preferences for neighborhood characteristics indicates how well their current neighborhoods meet their preferences. Since some of these characteristics measure similar dimensions of the built environment and are highly correlated, we conducted a factor

Table 4
Vehicle miles driven and explanatory variables by neighborhood type

	Average for traditional	Average for suburban	*p*-value[c] traditional vs. suburban	*p*-value[c] traditional only	*p*-value[c] suburban only
Vehicle miles driven per week[a]	148	175	0.00	0.66	0.64
Perceived neighborhood characteristics[b]					
Accessibility	0.15	−0.18	0.00	0.00	0.00
Physical activity options	0.01	−0.01	0.45	0.00	0.05
Safety	−0.14	0.16	0.00	0.00	0.00
Socializing	0.09	−0.12	0.00	0.00	0.00
Outdoor spaciousness	0.00	−0.01	0.82	0.00	0.00
Attractiveness	0.28	−0.33	0.00	0.00	0.00
Selected accessibility measures					
# business types within 400 m	2.6	0.8	0.00	0.00	0.09
# eat-out places within 400 m	0.7	0.2	0.00	0.00	0.44
Meters to nearest eat-out place	526	789	0.00	0.00	0.00
Preferences for neighborhood characteristics[b]					
Accessibility	0.03	−0.04	0.14	0.00	0.00
Physical activity options	0.01	−0.02	0.60	0.00	0.00
Safety	−0.18	0.21	0.00	0.00	0.48
Socializing	0.05	−0.05	0.05	0.00	0.00
Outdoor spaciousness	−0.05	0.06	0.02	0.00	0.03
Attractiveness	0.04	−0.05	0.04	0.00	0.00
Travel attitudes[b]					
Pro-bike/walk	0.20	−0.23	0.00	0.00	0.00
Pro-travel	−0.03	0.03	0.27	0.03	0.01
Travel-minimizing	0.01	−0.01	0.69	0.23	0.02
Pro-transit	0.15	−0.17	0.00	0.00	0.00
Safety of car	−0.27	0.31	0.00	0.00	0.00
Car dependent	−0.06	0.07	0.01	0.03	0.00

[a] Six respondents reported over 1000 miles per week; these values were treated as outliers and recoded to 1000.
[b] Scores normalized to a mean value of 0 and variance of 1.
[c] *p*-values for *F*-statistics from analysis of variance (ANOVA).

analysis to identify underlying constructs of perceived and preferred neighborhood characteristics. Through this analysis, these items were reduced to six factors (some items were dropped due to their poor conceptual interpretability): accessibility, physical activity options, safety, socializing, outdoor spaciousness, and attractiveness (Table 2).

Objective measures of accessibility were estimated for each respondent, based on distance along the street network from home to a variety of destinations classified as institutional (bank, church, library, and post office), maintenance (grocery store and pharmacy), eating-out (bakery, pizza, ice cream, and take-out), and leisure (health club, bookstore, bar, theater, and video rental). Accessibility measures included the number of different types of businesses within specified distances, the distance to the nearest establishment of each type, and the number of establishments of each business type within specified distances. Commercial establishments were identified using on-line yellow pages, and ArcGIS was used to calculate network distances between addresses for survey respondents and commercial establishments.

Travel attitude: To measure attitudes regarding travel, the survey asked respondents whether they agreed or disagreed with a series of 32 statements on a 5-point scale from 1 (''strongly disagree'') to 5 (''strongly agree''). Factor analysis was then used to extract the fundamental dimensions spanned by these 32 items, for reasons similar to those for neighborhood characteristics. As shown in Table 3, six underlying dimensions were identified: pro-bike/walk, pro-travel, travel minimizing, pro-transit, safety of car, and car dependent.

Socio-demographics: The survey also contained a list of socio-demographic variables that may help to explain travel behavior. These variables include gender, age, employment status, educational background, household income, household size, the number of children in the household, mobility constraints, residential tenure, and so on. Some changeable socio-demographics such as household structure and income were measured currently as well as before moving for movers and from 1 year ago for non-movers.

Table 5
Regression model for ln(VMD)

Variable	Coefficient	Standardized coefficient	*t*-statistic	*p*-value
Constant	3.646		11.317	0.000
Female	−0.282	−0.140	−5.650	0.000
Working	0.298	0.112	4.034	0.000
Age	−0.006	−0.094	−3.296	0.001
Driver's license	1.050	0.086	3.519	0.000
Cars per adult	0.170	0.069	2.852	0.004
Pro-bike/walk attitude	−0.055	−0.054	−1.973	0.049
Pro-transit attitude	−0.048	−0.046	−1.784	0.075
Safety of car attitude	0.060	0.058	2.255	0.024
Car dependent attitude	0.271	0.260	10.566	0.000
Outdoor spaciousness preference	0.054	0.052	2.110	0.035
N	1466			
R-square	0.160			
Adjusted *R*-square	0.154			

4. Findings

Vehicle miles driven by the respondent per week is 18% higher for residents of suburban neighborhoods than for residents of traditional neighborhoods (Table 4). This pattern holds true across individual neighborhoods: the highest level of driving for traditional neighborhoods (161 miles per week in Modesto Central) is still lower than the lowest level of driving for suburban neighborhoods (166 miles in Sunnyvale). The difference in total vehicle miles driven appears to come from differences in both work travel and non-work travel.

What explains these differences? According to an analysis of variance (ANOVA), traditional neighborhoods score significantly higher than suburban neighborhoods on factors for perceived accessibility, socializing, and attractiveness, but lower on safety; residents in these neighborhoods are also closer to more businesses. But traditional neighborhoods also score higher on factors for pro-bike/walk and pro-transit attitudes and lower on the safety of car attitude. To complicate matters, differences are often significant between neighborhoods of each type on both neighborhood characteristics and attitudinal factors; traditional neighborhoods are not all alike, nor are all suburban neighborhoods alike. To sort out the relative importance of neighborhood characteristics and attitudes and preferences in explaining levels of driving, multivariate models are estimated.

4.1. Cross-sectional analysis of vehicle miles driven

Most studies have used cross-sectional models of driving behavior to test the significance of built environment characteristics as explanatory variables. For comparison purposes, we also estimated a cross-sectional model, but unlike most previous studies we incorporated preferences for neighborhood characteristics and travel attitudes into the model to account for the possibility of self-selection. This tests the hypothesis that environments where residents are closer to destinations and have viable alternatives to driving are in fact associated with less driving, after accounting for attitudes and preferences as well as socio-demographic characteristics; lower levels of driving might result from shorter and/or fewer driving trips. Because of the skewed distribution of VMD, the natural log of VMD was used as the dependent variable and the model was estimated using ordinary least squares regression. Potential explanatory variables were entered into the model in groups, starting with socio-demographic factors, followed by travel attitudes and preferences for neighborhood characteristics, then perceived neighborhood characteristics and accessibility measures. At each step, insignificant variables were dropped and the model re-estimated before the next set of variables was entered.

The factor for car dependent attitude had the highest standardized coefficient (Table 5). This factor reflects a perceived need for a car, which may or may not reflect the actual availability of alternatives to driving. Other attitudes were also significant: pro-bike/walk and pro-transit attitudes were negatively associated with driving, and the safety of car attitude and a preference for outdoor spaciousness were positively associated with driving. With these attitudes accounted for, no measures of the actual built environment—neither accessibility measures nor perceived characteristics—were significant. As a result, it appears that observed correlations between neighborhood type and levels of driving are better explained by attitudes towards transportation than by the built environment. The model does not support the hypothesis that the built environment has a causal relationship with travel behavior and suggests that self-selection plays a significant role in explaining the observed correlations between the built environment and travel behavior. This finding differs from previous studies that found a significant relationship between the built environment and driving and demonstrates the importance of accounting for attitudes and preferences.

4.2. Quasi-longitudinal analysis of travel behavior

A stronger test of a causal relationship between the built environment and travel behavior involves an examination of the association between a change in the built environment and a change in driving. This approach addresses the time-order criterion for establishing causal validity: if the change in the built environment precedes the change in driving, then a causal relationship is more certain (Singleton and Straits, 1999). In the quasi-longitudinal approach used here, changes are measured for residents who have recently moved from before to after their move, and for non-movers from 1 year earlier to the present time. The model estimated from these data tests the hypothesis that moves to environments where residents are closer to destinations and have viable alternatives to driving are associated with a decrease in driving after accounting for neighborhood preferences and travel attitudes; decreases in driving might result from a decrease in driving distances and/or a decrease in driving trips.

The change in driving and the use of other modes is measured using a 5-point scale, from "a lot less now" to "a lot more now". For the sample of movers, changes in the built environment could be measured by taking the difference between perceived characteristics of the current and previous neighborhoods; the built environment was assumed unchanged for the sample of non-movers. A simple bivariate analysis of these variables for movers (Table 6) shows several significant associ-

Table 6
Percent of respondents by change in driving or walking vs. change in neighborhood characteristics[a]

	Decrease in characteristic		Increase in characteristic		*p*-value
	Increase in driving or walking	Decrease in driving or walking	Increase in driving or walking	Decrease in driving or walking	
For driving					
Accessibility	31.0	28.3	23.9	47.6	0.00
PA options	28.3	38.3	24.7	44.2	0.34
Safety	30.3	41.0	23.2	42.6	0.11
Socializing	28.7	38.6	24.2	44.1	0.31
Spaciousness	24.4	44.6	27.4	39.6	0.42
Attractiveness	26.3	40.3	25.8	43.0	0.77
For walking					
Accessibility	37.4	27.8	55.9	16.7	0.00
PA options	35.4	28.8	58.9	15.1	0.00
Safety	44.8	28.0	54.2	14.9	0.00
Socializing	38.9	27.8	58.0	14.9	0.00
Spaciousness	50.6	22.4	50.4	17.7	0.21
Attractiveness	35.7	31.9	59.0	13.1	0.00

[a] Movers only; $n = 688$.

ations. In general, changes in neighborhood characteristics have the strongest association with changes in walking: for increases in all but one of the factors for neighborhood characteristics, a significantly higher share of respondents said that their walking levels had increased than said they had decreased. In contrast, only changes in the accessibility factor had a significant association with changes in driving: among respondents who reported that accessibility increased, a significantly higher share said that driving had decreased rather than increased. This finding is interesting given that accessibility may have two opposite effects on driving: 1. higher accessibility reduces the cost of driving and may increase levels of driving as a result; 2. higher accessibility reduces the cost of walking and may lead to a substitution of walking for driving. The results suggest that the latter effect outweighs the former, and that changes in neighborhood characteristics are more important in explaining changes in walking rather than driving (see also Handy et al., 2005).

The relationship between changes in the built environment and changes in driving while controlling for attitudes (and changes in socio-demographics) was estimated using an ordered probit model. This technique is appropriate for an ordinal dependent variable, and its model structure is parsimonious. The following sets of variables were tested: current socio-demographic characteristics, changes in socio-demographic characteristics, travel attitudes (assumed constant over this

Table 7
Ordered probit model for change in driving

	Coefficient	Standardized coefficient[a]	p-value
Constant[a]	1.508	1.147	0.000
Current age	−0.006	−0.084	0.014
Currently working	0.155	0.059	0.065
Current # kids <18 years	0.070	0.057	0.051
Limits on driving	−0.678	−0.074	0.000
Change in income	0.000	0.155	0.000
# groceries within 1600 m	−0.014	−0.066	0.048
# pharmacies within 1600 m	−0.028	−0.069	0.041
# theaters within 400 m	−0.703	−0.057	0.055
Change in accessibility factor	−0.269	−0.226	0.000
Change in safety factor	−0.088	−0.086	0.000
Car dependent	0.115	0.111	0.000
Pro-bike/walk	−0.070	−0.070	0.020
Threshold parameter—1	0.543	0.543	0.000
Threshold parameter—2	2.142	2.142	0.000
Threshold parameter—3	2.589	2.589	0.000
N	1490		
Log-likelihood at 0	−2378.038		
Log-likelihood at constant	−1954.785		
Log-likelihood at convergence	−1869.302		
Pseudo-R square	0.214		
Adjusted pseudo-R square	0.209		

[a] All independent variables standardized and model re-estimated; constant not standardized.

period), preferences for neighborhood characteristics (also assumed constant), objective accessibility measures for the current neighborhood, perceived neighborhood characteristics for the current neighborhood, and changes in perceived neighborhood characteristics. Non-movers were also included in the model, with changes in driving and socio-demographic characteristics measured from 1 year ago and changes in perceived neighborhood characteristics assumed to be zero. The resulting equation can be interpreted as representing the propensity of an individual to have a numerically larger change—either less of a decrease or more of an increase—in driving following the move. A statistically significant association between a change in the built environment and change in travel behavior provides evidence of a causal relationship.

Change in the accessibility factor was the most important factor in explaining changes in driving, as indicated by the standardized coefficients, with an increase in accessibility associated with either a smaller increase or a larger decrease in driving (Table 7). Change in the safety factor was also significant, with an increase in safety associated with either a smaller increase or a larger decrease in driving. Three objective measures were also significant: number of grocery stores and number of pharmacies within 1600 m and number of theaters within 400 m (why theaters is significant is not entirely clear, although theaters may be an indicator of a particular type of commercial district). Note that objective accessibility was measured for the current neighborhood only, rather than as the change in accessibility; however, a high current level of accessibility is more likely to be associated with an increase in accessibility than a decrease as a result of a move. In all of these cases, an increase in accessibility is associated with a higher propensity to drive less. Two travel attitudes were also significant: car dependent, with a positive effect on the propensity to drive more, and pro-bike/walk, with a negative effect on the propensity to drive more. These results support the hypothesis that changes in the built environment are associated with changes in driving and point to increases in accessibility as the factor having the greatest negative effect on driving.

5. Conclusions

One lesson that emerges here is that different types of analyses can yield different answers to the question: does the built environment have a causal relationship with travel behavior? A simple comparison of different neighborhood types shows significant variations in levels of driving. However, a multivariate analysis of cross-sectional data shows that these differences are largely explained by attitudes and that the effect of the built environment mostly disappears when attitudes and socio-demographic factors have been accounted for. But a quasi-longitudinal analysis of changes in driving and changes in the built environment shows significant associations, even when attitudes have been accounted for, providing support for a causal relationship. These results highlight the limitations of previous studies, that mostly rely on cross-sectional analyses and rarely account for attitudes and preferences—but also suggest that despite these limitations their conclusions are not entirely off the mark.

These analyses are not definitive, nor do they clarify the nature of the causal relationship. More sophisticated analyses of these data, such as structural equations modeling, will help to establish the strength and direction of the relationships between attitudes, changes in the built environment, changes in travel behavior, and other factors. Even so, there are limits to what the quasi-longitudinal approach can do. For example, because it is not feasible to retrospectively measure attitudes, we have data on current attitudes only, and our interpretation of the results of the change model is predicated on the assumption that attitudes (those unmeasured as well as measured) remained constant over time and hence are controlled for. But we cannot rule out the competing hypothesis that an attitude change preceded and (partly) prompted the residential location change. To the extent that is true, the attitude change is confounded with the change in built environment and may account for some of the apparent effect of the built environment seen here.

Future studies that adopt research designs that more closely resemble a true experimental design will provide more definitive evidence yet. Two types of studies are possible: true panel studies of residents who move from one type of neighborhood to another (with measurements of attitudes as well as behavior before and after, and further exploration of the reasons behind the move), and natural experiments that examine the impact on driving in response to a change in the built environment, such as the implementation of a traffic calming program. Only with such evidence can we be sure that by increasing opportunities for driving less through land use policies, cities will help to reduce driving and thus emissions.

In the meantime, the results presented here provide some encouragement that land-use policies designed to put residents closer to destinations and provide them with viable alternatives to driving will actually lead to less driving. In particular, it appears that an increase in accessibility may lead to a decrease in driving, all else equal. Policies that could increase accessibility in new areas include mixed-use zoning that allows for retail and other commercial uses within close proximity to residential areas and street connectivity ordinances that ensure more direct routes between residential and commercial areas. Policies that could increase accessibility in existing areas include Main Street programs designed to enhance and revitalize traditional neighborhood shopping areas, incentives for infill development and redevelopment of underutilized shopping centers, and the like. Although this study does not definitively prove that land use policies can reduce driving, it provides evidence that supports the adoption of such policies.

Acknowledgements

This research was conducted under a project funded by the California Department of Transportation and was supported by grants from the Robert Wood Johnson Foundation and the University of California Transportation Center. Thanks to Ted Buehler, Gustavo Collantes, and Sam Shelton for their work on the implementation of the survey.

References

American Planning Association, 2002. Planning for Smart Growth: 2002 State of the States. Chicago, IL, February. Available at: http://www.planning.org/growingsmart/pdf/states2002.pdf. Accessed: 11/1/02.

Babbie, E., 1998. The Practice of Social Research, Eighth Ed. Wadsworth Publishing Company, Stamford, CT.

Bagley, M.N., Mokhtarian, P.L., 2002. The impact of residential neighborhood type on travel behavior: a structural equations modeling approach. Annals of Regional Science 36, 279–297.

Boarnet, M.G., Crane, R., 2001. Travel by Design: the Influence of Urban Form on Travel. Oxford University Press, New York.

Burchell, R.W., Lowenstein, G., Dolphin, W.R., Galley, C.C., Downs, A., Seskin, S., Gray Still, K., Moore, T., 2002. Costs of Sprawl 2000. TCRP Report 74, Transit Cooperative Research Program, Transportation Research Board, Washington, DC.

Cao, X., Handy, S., Mokhtarian, P.L., 2005. The Influences of the Built Environment and Residential Self-Selection on Pedestrian Behavior. Transportation. Forthcoming.

Environmental Protection Agency (EPA), 2001. EPA Guidance: Improving Air Quality Through Land Use Activities. EPA420-R-01-001, Transportation and Regional Programs Division, Office of Transportation and Air Quality, Washington, DC.

Ewing, R., Cervero, R., 2001. Travel and the built environment. Transportation Research Record 1780, 87–114.

Handy, S., 1992. Regional versus Local Accessibility: Variations in Suburban Form and the Effects on Nonwork Travel. University of California Berkeley, Unpublished dissertation.

Handy, S., 1996. Methodologies for exploring the link between urban form and travel behavior. Transportation Research D 1, 151–165.

Handy, S., 2005. Critical Assessment of the Literature on the Relationships among Transportation, Land Use, and Physical Activity. Prepared for the Transportation Research Board and Institute of Medicine Committee on Physical Activity, Health, Transportation, and Land Use. Washington, DC. January. Available at http://trb.org/downloads/sr282papers/sr282Handy.pdf.

Handy, S.L., Clifton, K.J., 2001. Local shopping as a strategy for reducing automobile travel. Transportation 28, 317–346.

Handy, S., Cao, X., Mokhtarian, P.L., 2005. Does Self-selection Explain the Relationship Between Built Environment and Walking Behavior? Empirical Evidence from Northern California. Journal of the American Planning Association, forthcoming.

Mindali, O., Raveh, A., Salomon, I., 2004. Urban density and energy consumption: a new look at old statistics. Transportation Research A 38, 143–162.

Newman, P., Kenworthy, J., 1999. Sustainability and Cities: Overcoming Automobile Dependence. Island Press, Washington, DC.

Pushkarev, B., Zupan, J., 1977. Public Transportation and Land Use Policy. Bloomington University Press, Bloomington, IN.

Schwanen, T., Mokhtarian, P.L., 2005. What affects commute mode choice: neighborhood physical structure or preferences toward neighborhoods? Journal of Transport Geography 13, 83–99.

Singleton, R.A., Straits, B.C., 1999. Approaches to Social Research, Third Ed. Oxford University Press, New York and Oxford.

Sommer, B., Sommer, R., 1997. A Practical Guide to Behavioral Research: Tools and Techniques, Fourth Ed. Oxford University Press, Oxford and New York.

Transportation Research Board and Institute of Medicine, 2005. Does the Built Environment Influence Physical Activity? Examining the Evidence, TRB Special Report 282. Washington, DC.