PERGAMON

Transportation Research Part D 7 (2002) 225–242

TRANSPORTATION RESEARCH PART D

www.elsevier.com/locate/trd

Travel behavior at the household level: understanding linkages with residential choice

Sumeeta Srinivasan [a,*], Joseph Ferreira [b]

[a] *Division of Engineering and Applied Sciences, Harvard University, Pierce Hall 117, 29 Oxford Street, Cambridge, MA 02138, USA*

[b] *Department of Urban Studies and Planning, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*

Abstract

Previous work with data from the Boston Metropolitan Area has suggested that land use characteristics can have measurable impacts on travel behavior such as trip linking and mode choice at the individual level. However, trip planning, especially in households with children or more than one worker, is quite possibly done at the household level. In this paper, we begin to understand the travel behavior choices of households and understand the relationship of these choices with socio-economic characteristics as well as spatial characteristics of the places where the household resides, works and travels through. The results of preliminary models estimated indicate that the travel behavior of a household is indeed related to the household's residential location. The models estimated are not for the purposes of travel demand forecasting as in the case of the household based Stockholm models. The results do indicate if land use, network and accessibility characteristics also affect household trip linking and mode choice and their relationship to residential choice. Thus, one can begin to determine whether planners can make a difference through the implementation of the ideas of neo-traditional theories in local level planning. These models should provide a starting point for further exploration of the land use and transportation linkages explored from the point of view of the more realistic unit of the household.

Keywords: Land use and transportation; Travel behavior; Household travel demand; GIS

1. Introduction

In recent years, the economic and environmental implications of traffic congestion have been linked to the lack of coordination between land use and transportation planning. As fine-grained

* Corresponding author. Tel.: +1-617-496-4413; fax: +1-617-496-1457.
E-mail addresses: sumeeta@deas.harvard.edu (S. Srinivasan), jf@mit.edu (J. Ferreira).

1361-9209/02/$ - see front matter
PII: S1361-9209(01)00021-9

data about land use and travel activity becomes available, it provides an opportunity to improve our understanding of the linkage between land use and transportation. Thus, one can now add a land use element to the models that have been used in the past in order to investigate travel behavior. Mackett (1994) believes that there are three sets of effects of land use changes due to transportation changes. First round effects include change of route and mode, second round effects include change of residential location, employment location, shopping location, and trip distribution, third round effects are the location of new dwellings, jobs and shops. In this paper, we use a discrete choice model to estimate changes in household travel behavior due to changes in spatial characteristics controlling for residential and employment location. Thus, we try to understand first round effects, which may in turn lead to other effects at the second and third round.

The proponents of land use and travel behavior linkage have argued that people who live in transit/pedestrian oriented developments make shorter trips and walk or use transit more frequently than residents of areas with lower density (Friedman et al., 1994; Ewing et al., 1994). Handy (1996) notes that a greater range of destination choices (accessibility) is valued by residents. Shen (1998) finds that average commuting time varies systematically between center-city and suburbs as well as within neighborhoods located within the center-city. His models indicate that employment accessibility is an important causal factor in explaining travel time. Crane and Crepeau (1998) on the other hand suggest that people who live in one kind of neighborhood cannot be compared to those in another since they are self selected and thus samples are biased. His analysis reveals that neo-traditional design features with the exception of traffic calming can have unknown outcomes for car travel and their actual outcomes depend on specific details of their implementation in each location (Crane, 1995). Crane and Crepeau (1998) in an analysis of data for San Diego, find no evidence that neighborhood street pattern affects either mode choice or car-trip generation. They note that results from other regions may be different but suggest that this would indicate that it is not the design features but other factors unique to other regions that play a role in generating different results.

In this paper, we include measurable spatial and socio-economic characteristics that may affect a household's choice of mode and residence. We also characterize neighborhood characteristics as ratio variables rather than dummies or ordinal variables, which as Cervero and Kockelman (1997) note, tend to have a predictive disadvantage over income and transportation time and cost, which are measured on a ratio scale. Neighborhood characteristics are derived as latent indicators that combine several observed measures. Also, unlike previous research in this area we look at the household as the basis for analysis since it is likely that trip planning especially in two worker households tends to be done at the household level.

2. Data and study area

2.1. Data

Daily activity data from a central transportation planning staff (CTPS) survey are used for the analysis. The data are from a 1991 survey by CTPS of 3854 households in the Boston metro area, with a total of 9281 persons who made 39,373 trips. The survey data were from a random sample stratified based on the transportation analysis zones (TAZs), number of people in the household

and auto ownership level. Of the 787 zones, 664 were included in the sample. The actual number of persons sampled in a TAZ ranged from 1 to 107 and sampling proportions varied from 0.02% to 21.4% of the population in a TAZ. Of this sample, the total number of persons who had work trips was 3405, the number of persons per TAZ varied from 1 to 36 and the proportion varied from 0.01% to 1.6% of the population in 595 TAZs. These data are combined with other related 1990 data from CTPS for employment and origin destination surveys of time and cost of travel by automobile and transit. A rich assortment of spatially disaggregated data about land use, road and transit networks, and socio-economic characteristics for the Boston metro area are also used. These data include 1990 US Census data, 1991 land use and road network data from MassGIS, parcel-level data from several towns within metro Boston, office and shopping center locations from various third-party sources.

2.2. Study area

The area selected for this study is shown in Fig. 1. This covers a northwestern part of the Boston metropolitan area and includes the cities of Boston, Lowell and Lawrence. This study area includes 484 TAZ and 43 towns. The CTPS activity survey sampled for this area includes 4680 residents in 2096 households making 15,098 trips and living in 388 TAZ. The number of persons sampled per TAZ varied from 1 to 107 and sampling proportions varied from 0.02% to 21.4% of the population in a TAZ.

One way in which one can classify residential location within a city is to consider its urbanization intensity. This would include at the most general level – population and employment density. It also includes, in a metropolitan area like Boston, differing levels of service with respect to transit, various measures of proximity to major roads and highways, differing mix of residential densities, and network design characteristics that indicate differing street density, three-way and four-way intersections density and the like. These residential location types are derived from confirmatory factor analysis of several measures that describe land use, network and accessibility characteristics of locations in a city. The methodology and measures used are described in detail elsewhere (Srinivasan, 2000) and the results are used to classify residential location based on the derived urbanization factor. Indeed, the urbanization factor derived through exploratory factor analysis of the spatial characteristics indicated that differences in urbanization accounted for almost 40% of the variance in the spatial characteristics data. Thus, one could characterize urbanization as a latent descriptor of the city that is measured by several observed measures. We use this idea to characterize three distinct types of residential locations – the downtown, the middle suburb and the outer suburbs (Fig. 2). This categorization is based on the distribution of the TAZ in the study area into three equal parts with roughly equal numbers of TAZ. This categorization of location is then used to study the relationships between mode choice and residential and destination location for both work and non-work tours. Other land use characteristics like transit access, commercial-residential balance, cul-de-sac design, non-work accessibility and pedestrian convenience, also derived through factor analysis, are used as independent variables in predicting household travel behavior.

Downtown locations have higher population and employment density but fewer households. Also, in terms of actual population, the middle and outer suburban locations have higher numbers. The average household size is also higher in the outer suburbs. The downtown locations are concentrated mostly in Boston and cities close to it like Cambridge, Brookline, Somerville, etc.,

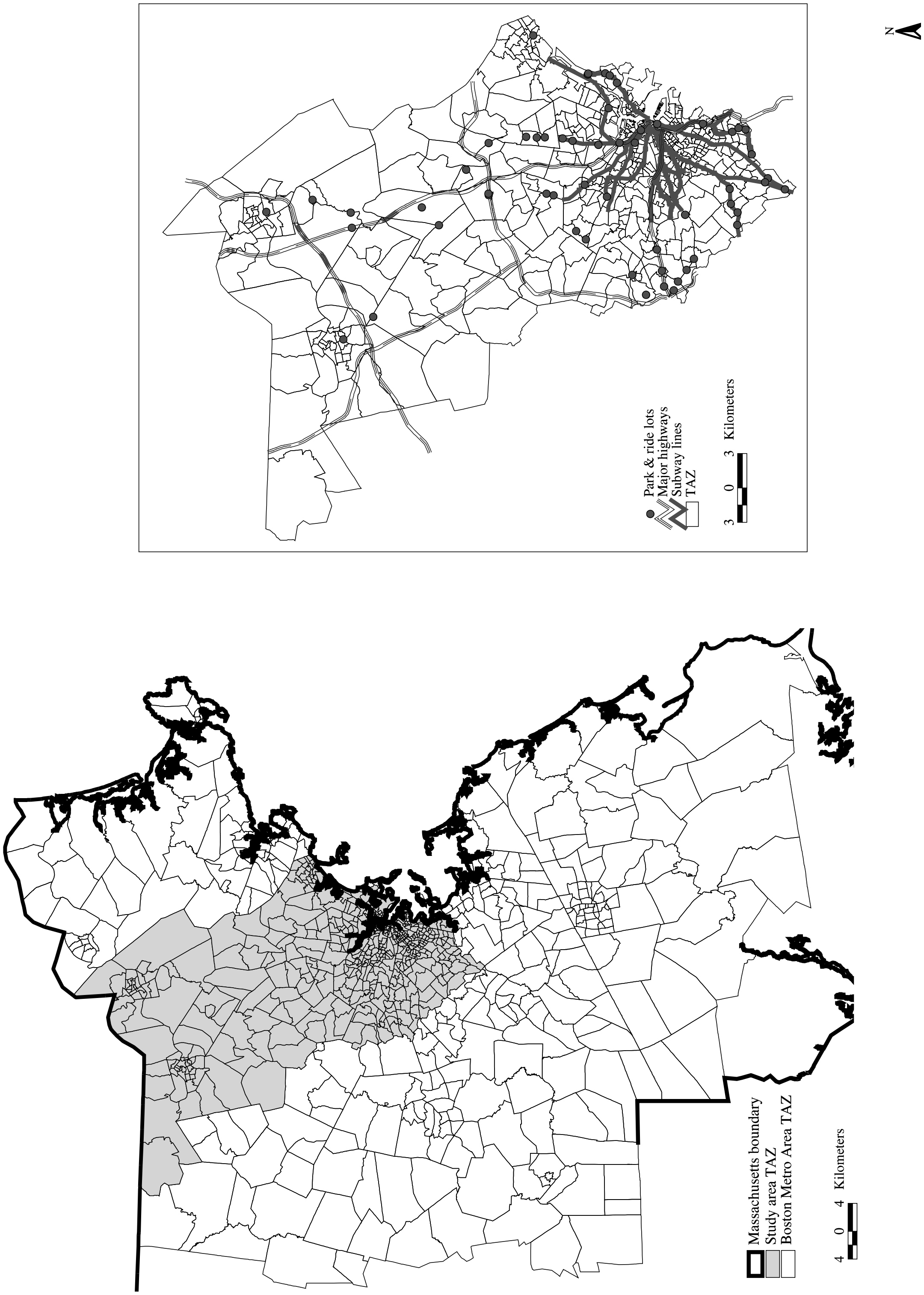

Fig. 1. The study area and its relationship to the Boston metropolitan area.

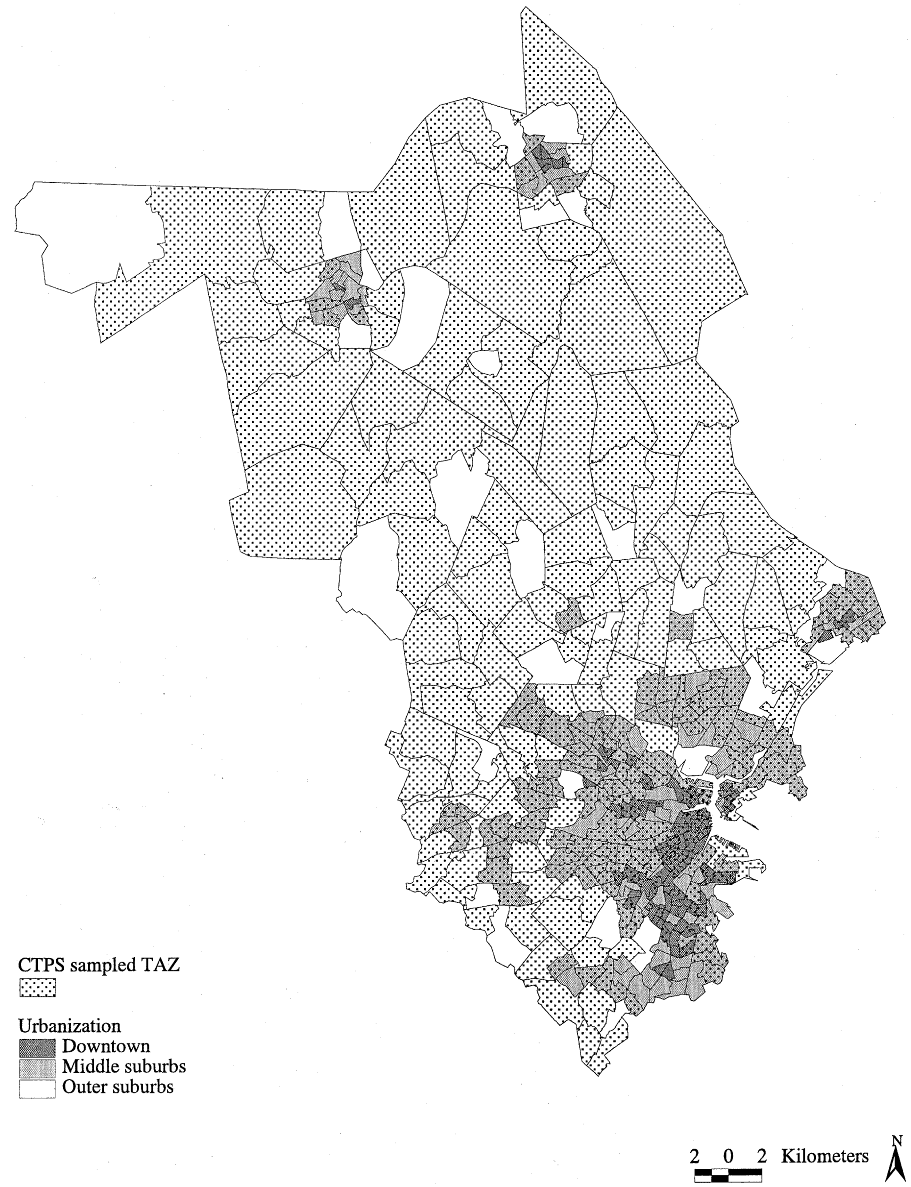

Fig. 2. The residential location categories by TAZ in study area.

and in farther locations within the cities of Lynn, Lawrence and Lowell. Middle suburbs are also found close to the downtown Boston and its environs and fall rapidly away from Lowell, Lynn and Lawrence (Fig. 2). Note that this categorization is not based on a simple distance from CBD and that outer suburban TAZ are found within the city of Boston. Transit access and suburban character are closely correlated – highly urbanized TAZ they have higher transit access. Pedestrian convenience and commercial-residential mix and balance also appear to be higher in more urbanized TAZ. However, non-work accessibility by auto is higher in outer and middle suburban

locations rather than downtown locations since it measures access to recreation area and access by auto to shopping malls. Thus categorization by urbanization also appears to be related to other land use characteristics.

3. Household type and travel behavior relationships

First, we study relationships between specific household types of interest and these travel behavior characteristics. We only look at those households that had a work trip (households without work trips were dependent on home based non-work tours in order to carry out all their non-work activities). Also, we only examine non-work activities that could be shared by different members of the household such as shopping, drop-offs and personal banking and exclude social and recreation activities, school or eating out which may be more dependent on the individual members.

The survey data indicate that while non-work activities on the way to and from work average travel times remain quite similar non-work travel and activity times showed more variation. It appears as though families with children have higher non-work travel and activity times. This, perhaps, indicates that they also have more non-work activities on a week day than a household without children. Single parent and two-worker families also tend to have shorter non-work travel and activity times than one-worker, two-adult households. This might indicate that non-work tours are likely to be shifted to the weekend when such households have more time. Households without children tend to have a large proportion of tours without non-work activity (40% or more). In contrast, households with children especially those with two workers tend to have very few (6% or less) tours without non-work activity chaining. For households without children most non-work activities are chained with the work trip (more than 50% of the tours with non-work activities tend to be all work based). In households with young children (less than age 5), the one-worker family predominantly carries out non-work tours while the two-worker family tends to chain with the work tour. In households with school age children, however, the demarcation between one-worker and two-worker family is not so clear. Both households seem to carry out non-work activities as non-work tours in relatively high numbers (40% or more are all non-work) and have few all work based tours.

Examining the relationship between household type and mode choice indicates that very few households made all their tours by non-auto modes. The highest percentage of all non-auto tours was by households without children. Such households also had the highest percentage of auto and non-auto combined tours (40% of the tours or more). For all other households the percentage of all auto tours was above 60%. This is perhaps also an indication of the kinds of places in which such households choose to live (suburban as opposed to downtown). Indeed all the aspects of travel behavior examined are also probably related to the residential location of the households. This is further explored in the next section.

4. Residential location, household type and travel behavior relationships

We now examine the relationship between household type, residential location and travel behavior. Clearly, there are indications that household types and travel behavior are related.

However, the results of models estimated at the individual level in the previous research indicate that travel behavior such as mode choice is related to the type of residential location in which the individual lives. This relationship may be masked in the analysis carried out in the previous section. We therefore characterize three distinct types of residential locations – the downtown, the middle suburb and the outer suburbs as shown in Fig. 2.

Table 1 shows the allocation of non-work activities between the work and non-work tour by household type and location. Households without children tend to have a high percentage of tours without non-work activities especially for those living in the downtown locations (50% or more) and also have fewer tours overall. For households without children living in the outer suburbs the number of tours without non-work activities falls to about 35%. One-worker households tend to have a high percentage of non-work activities in non-work tours or both non-work and work tours as compared to the two-worker households with children below the age of 5 which favor the work trip. Two-worker households with school age children tend to show the same trends as the one-worker households. The differences due to residential location are not clearly evident at this level of aggregation.

Table 2 shows the allocation of mode choice by residential location and household type. Clearly, there are very few all non-auto tours and most of these are by households without children living in the downtown or middle suburbs. Also, there is a steady increase in the

Table 1
Allocation of non-work activity (work or non-work tour) by household and residential location

Household type	Home location	No activity	All non-work	All work	Both	Total
One-worker one-adult	Downtown	50	8	29	4	91
	Middle suburb	24	7	27	6	64
	Outer suburb	19	7	13	6	45
Two-worker two-adult	Downtown	29	9	19	8	65
	Middle suburb	30	12	28	6	76
	Outer suburb	31	13	25	15	84
One-worker two-adult with kids below age 5	Downtown	1	8	2	3	14
	Middle suburb	11	10	3	16	40
	Outer suburb	13	32	6	12	63
One-worker two-adult with kids 5–18	Downtown	4	5	2	4	15
	Middle suburb	1	10	2	10	23
	Outer suburb	5	18	4	16	43
Two-worker two-adult with kids below age 5	Downtown	2	1	5	2	10
	Middle suburb	4	3	11	3	21
	Outer suburb	2	4	13	7	26
Two-worker two-adult with kids 5–18	Downtown	1	2	0	3	6
	Middle suburb		9	2	10	21
	Outer suburb	3	12	1	13	29
Single parent with kids	Downtown	0	1	1	1	3
	Middle suburb	2	3	4	5	14
	Outer suburb	0	8	5	1	14

Table 2
Allocation of mode choice (auto vs non-auto) by household and residential location

Household type	Home location	All auto	All non-auto	Both	Total
One-worker one-adult	Downtown	22	9	60	91
	Middle suburb	36	6	22	64
	Outer suburb	33	1	11	45
Two-worker two-adult	Downtown	17	10	38	65
	Middle suburb	37	5	34	76
	Outer suburb	64	1	19	84
One-worker two-adult with kids below age 5	Downtown	7	1	6	14
	Middle suburb	26	1	13	40
	Outer suburb	51	0	12	63
One-worker two-adult with kids 5–18	Downtown	7	2	6	15
	Middle suburb	18	0	5	23
	Outer suburb	33	0	10	43
Two-worker two-adult with kids below age 5	Downtown	5	0	5	10
	Middle suburb	13	1	7	21
	Outer suburb	20	0	6	26
Two-worker two-adult with kids 5–18	Downtown	1	1	4	6
	Middle suburb	12	1	8	21
	Outer suburb	23	1	5	29
Single parent with kids	Downtown	0	0	3	3
	Middle suburb	8	1	5	14
	Outer suburb	11	0	3	14

percentage of all auto tours within each household type as residential location gets more suburban in character. The presence of children, residential location and possibly the number of workers do seem to affect the mode choice allocation within a household.

We estimate models linking residential location with trip-linking and mode choice to examine the relationships between land use and accessibility characteristics of their home, work and intermediate corridor character and their travel behavior choices at the household level.

4.1. Modeling residential location, household type and travel behavior relationships

In the last section it appeared that travel and activity time and allocation of non-work activities between non-work and work tours were dependent on the type of household rather than its location. The allocation of time or activities between the non-work and work tour seem to measure similar trends in behavior. That is, as more activities are carried out as non-work tours, the travel and activity time allocated should also show similar trends. And indeed, this is true. Households in downtown tend to spend more travel time on work tours than non-work tours when compared to residents in the suburbs. However, estimating discrete choice models of travel time allocation stratified by residential location did not yield significant results. Moreover, it is likely that allocation of time during a work tour is dictated by a more rigid time schedule as compared to time

allocation during a non-work tour. However, modeling the allocation of non-work activity and mode choice at the household level did result in models that estimated a significant difference between residential location of the household and their patterns of non-work activity allocation. In this section, we present models that estimate an aggregated model that estimates travel behavior stratified by residential location type.

Two separate models were estimated for the allocation of non-work activity since there were differences in households choosing to carry out only one non-work activity versus those who did two or more non-work activities. Other studies that have carried out detailed household level travel demand models (Algers et al., 1995) have suggested another level of choice – the decision to make no non-work activity, one non-work activity and two or more non-work activities. We have not tested this choice level in the current specification though it would certainly make for a comprehensive demand modeling tool when done for data collected at the metropolitan level. Table 3 indicates that the percentage of households carrying out all non-work activities within a non-work tours increase as the home location becomes more suburban (35% of the households in the downtown allocate the activity to the non-work tour as compared to 43% of the outer suburban households). In the case of two or more non-work activities a similar trend is observed (29% of the households in the downtown have all non-work tour as compared to 37% of the outer suburban households). However, the percentage of households with both non-work and work activities also shows an increase (35% of the households in the downtown allocate to both work and non-work tours as compared to 43% of the outer suburban households). Thus fewer activities tend to be allocated to the work tour as the residential location becomes more suburban. Clearly

Table 3
Allocation of non-work activity (non-work vs work) by residential location

Home location	No non-work activity	One non-work activity		Two or more non-work activities		
		As non-work	As work	All as non-work	All as work	Both non-work and work
Downtown	126	22	41	30	36	36
Middle suburbs	138	46	53	71	51	91
Outer suburbs	117	37	47	86	47	102
Total	381	105	141	187	134	229

Table 4
Allocation of mode choice (auto vs non-auto) by residential location

Home location	No non-work activity			One or more non-work activities		
	All as auto	All as non-auto	Both auto and non-auto	All as auto	All as non-auto	Both auto and non-auto
Downtown	30	13	83	56	32	77
Middle suburbs	59	18	61	162	43	107
Outer suburbs	81	4	32	249	7	63
Total	170	35	176	467	82	247

this table does not account for differences in the type of household (the presence of children or the number of workers). We test for both these variables in the model specification.

Table 4 indicates the mode choice decisions of the household. Clearly far fewer all non-auto mode choice happens in the outer suburbs especially for households with one or more non-work activity. Households with no non-work activity about 10% of the households living in the downtown or middle suburbs have all non-auto tours but only 3% of the households in the outer suburbs have all non-auto tours. This figure falls when the household has to carry out a non-work activity in the outer suburbs – only 2% of the households had all non-auto tours. Also, the households with both non-auto and auto tours fall from 46% (66% if no non-work activity) of the households in downtown to only about 20% (27% if no non-work activity) of the households in the outer suburbs. By contrast, the household mode choice in the middle suburbs is more like the downtown rather than the outer suburb in that non-auto choice emulates downtown rather than outer suburban trends.

To further understand these trends we estimate discrete choice models of multi-nomial logit (Ben-Akiva and Lerman, 1985) stratified by home location for both the allocation of non-work activities between the non-work and work tour and household mode choice. Note that the models estimated at the household level are relatively aggregated when compared to the individual level models. Thus while incorporating the home location characteristics is straightforward, we make several assumptions while incorporating workplace and home to workplace corridor level characteristics. The maximum of the household's workplace and home-to-work characteristics for transit access, pedestrian convenience, non-work accessibility and commercial residential balance and mix are used as variables where as the minimum suburban character is used (or alternatively the most urbanized workplace or corridor). Therefore, we assume that non-work activity is encouraged by commercial mix or non-work access or relatively urban character and non-auto mode choice is encouraged by high transit access and pedestrian convenience. These models are further described in the next two sections.

4.2. Estimating allocation of non-work activity at the household level

As noted earlier two separate models were estimated for the allocation of the non-work activity. Table 5 shows the models estimated for the 246 households with only one non-work activity stratified by residential location of the households in downtown, middle and outer suburbs. As one would expect, the higher the number of non-work activities in the household the more likely that this is allocated to the non-work tour. Income is significant only for the middle suburban household and the sign indicates that high-income households are more likely to carry out the non-work activity with the work tour (possibly because such households have a larger number of workers). The number of workers and presence of child dummy are significant only for downtown households. The signs indicate that households with more workers are likely to carry out non-work activity as a separate non-work tour while the presence of children means they are less likely to carry out the non-work activity as a part of the work tour.

Very few spatial characteristics are significant. For the downtown model no spatial characteristics are significant. For the middle suburban household the cul-de-sac characteristic is significant and negative indicating that in such neighborhoods it is less likely that the non-work activity is carried out as a non-work tour. Also, in the outer suburban locations relatively high

Table 5
Households with one activity: lower level model of non-work activity allocation by residential location

	Downtown		Middle suburbs		Outer suburbs	
	Estimated coefficient	*t*-Statistic	Estimated coefficient	*t*-Statistic	Estimated coefficient	*t*-Statistic
Independent variable (*option*)						
Constant (non-work)	−4.62	−1.63	−3.16**	−3.10	−4.97**	−2.59
Number of non-work activities in the household (non-work)	0.99**	2.69	0.44**	2.62	0.53**	2.68
Dummy indicating household income >60 K (work)	1.81	1.17	1.88**	1.99	1.15	1.22
Number of vehicles per worker (non-work)	−0.39	−0.56	0.60	1.15	1.12	1.53
Dummy indicating child in household (non-work)	−5.76**	−2.53	0.19	0.24	−0.03	−0.04
Number of workers (work)	−2.09**	−2.53	−0.59	−1.39	−0.44	−0.90
Home characteristics						
Suburban character (work)	−1.58	−1.08	1.00	0.72	−3.43**	−2.44
Commercial-residential mix and balance (non-work)	0.55	1.20				
Cul-de-sac oriented design (non-work)			−0.84**	−2.14	−1.07	−1.38
Non-work accessibility by auto (non-work)			0.16	0.32	−1.03	−1.43
Pedestrian convenience (non-work)	2.11	1.32	0.33	0.40	1.53**	2.24
Workplace characteristics						
Suburban character (minimum of workplaces-work)	−0.11	−0.13			0.30	0.43
Commercial-residential mix and balance (maximum of workplaces-work)	−0.07	−0.17	0.05	0.10		
Non-work accessibility by auto (maximum of workplaces-work)			−0.18	−0.50	−0.26	−0.60
Home-workplace corridor characteristics						
Suburban character (minimum of workplaces-work)	−0.73	−0.42	0.41	0.44	0.01	0.01
Commercial-residential mix and balance (maximum of workplaces-work)	−1.02	−0.99				
Non-work accessibility by auto (maximum of workplaces-work)			−0.54	−0.90	−0.60	−0.80
$\bar{\rho}^2(\rho^2)$	0.08 (0.38)		0.02 (0.20)		0.04 (0.28)	

** Indicates significance at the 0.05 level.

urbanization and pedestrian convenience contribute to an increased likelihood of non-work activity allocation to the non-work tour indicating that where it is convenient households are less likely to chain the activity to the work tour. The $\bar{\rho}^2$ for the models estimated are quite low. Thus, this model provides some indication of a link between location choice and activity allocation but still remains only a preliminary model and more data would be needed to test this relationship further.

Table 6
Households with two or more activities: lower level model of non-work activity allocation choice by residential location

	Downtown		Middle suburbs		Outer suburbs	
	Estimated coefficient	*t*-Statistic	Estimated coefficient	*t*-Statistic	Estimated coefficient	*t*-Statistic
Variable (option)						
Constant (all non-work)	−1.09	1.27	−0.55**	2.35	−0.03	−0.09
Constant (all work)	1.08	0.84	−0.04	0.05	1.65	1.53
Number of non-work activities in the household (all non-work or both)	0.93**	4.38	0.32**	3.68	0.47**	4.57
Dummy indicating household income > 60 K (all work)	0.45	0.65	−0.17	0.31	1.02**	2.28
Number of vehicles per worker (all non-work or both)	−0.41	0.90	0.06	0.19	0.59	1.26
Dummy indicating child in household (all non-work or both)	1.72**	2.33	0.36	0.92	0.33	0.85
Number of workers (all work)	1.01*	1.66	0.14	0.43	−0.17	−0.49
Home characteristics						
Suburban character (all work)	1.88**	2.05	0.18	0.23	0.47	0.86
Commercial-residential mix and balance (all non-work)	0.36	1.24	–	–	–	–
Cul-de-sac oriented design (all non-work)	–	–	−0.35*	−1.73	−0.09	−0.33
Non-work accessibility by auto (all non-work)	–	–	0.14	0.62	−0.12	−0.61
Pedestrian convenience (all non-work)	0.12	0.15	0.86*	1.94	−0.02	−0.10
Workplace characteristics						
Suburban character (minimum of workplaces – all work)	0.58	0.95	0.64	1.57	0.03	0.08
Commercial-residential mix and balance (maximum of workplaces – all work)	0.29	0.89	–	–	–	–
Non-work accessibility by auto (maximum of workplaces – all work)	–	–	0.04	0.17	0.49*	1.88
Home to workplace corridor						
Suburban character (minimum of workplaces – all work)	−1.66	1.38	−2.04**	−2.52	−0.43	−0.59
Commercial-residential mix and balance (maximum of workplaces – all work)	−0.51	1.01	–	–	–	–
Non-work accessibility by auto (maximum of workplaces – all work)	–	–	0.41	1.25	−0.22	−0.64
$\bar{\rho}^2(\rho^2)$	0.09(0.20)		0.05 (0.11)		0.09 (0.15)	

* Indicates significance at the 0.10 level.
** Indicates significance at the 0.05 level.

Table 6 shows the models stratified by location estimated for 550 households with two or more non-work activities. As in the previous model estimation, as the number of household activities increase, it is more likely to be performed as a non-work tour or with both the non-work and

work tour. Households with high income, living in the outer suburbs are more likely to perform the non-work activity with the work tour. This is possibly due to the fact that there are more workers in the household and consequently more work tours. Like the previous model the downtown households were the only ones with significant number of workers and presence of children coefficient. Both were positive indicating that households living in the downtown which had children were more likely to carry out the non-work activity as a non-work tour but households with more workers tended to favor the work tour to carry out the non-work activity.

At the home location level, suburban character had a significant coefficient for the downtown locations. Thus, home locations that are suburban in character tend to result in all work tours. For the middle suburbs cul-de-sac character and pedestrian convenience had significant coefficients. The signs of the coefficient indicate that households living in middle suburban locations with cul-de-sac type street design are likely to not allocate non-work activity to non-work tours. This is similar to the sign on the coefficient for the one activity model estimated earlier. On the other hand, households in the middle suburbs with home locations that have a high pedestrian convenience are likely to favor all non-work tours for non-work activity perhaps due to the greater convenience afforded by living in a "walkable" location.

No home location coefficients were significant for the outer suburbs but the non-work accessibility by auto of the workplace was significant and positive indicating that if the household had a worker who worked in a high non-work accessible location then the household was likely to carry out its non-work activities as part of the work tour. Only one corridor characteristic was significant. For middle suburban households, highly suburbanized corridors resulted in a lower likelihood of the non-work activity being carried out with the work tour. This is to be expected since the suburban corridor is likely to provide fewer opportunities for non-work activities.

Both the models estimated for the allocation of non-work activity (for one activity and two or more activity households) have relatively low $\bar{\rho}^2$. The results do, however, suggest that there is a link between the location of the household and the pattern by which it allocates the non-work activities that can be shared between members. Also, even at the relatively aggregated scale at which spatial characteristics are estimated, some characteristics are found to be significant.

4.3. Modeling mode choice at the household level

The results of the mode choice model by location estimated for 1177 households is presented in Table 7. Households with higher non-work activities tend to favor auto significantly in middle and outer suburbs though this likelihood is highest for outer suburban residents. Also, low income households tend to have a significantly higher likelihood of choosing non-auto in middle and outer suburbs. Households with a higher number of vehicles are more significantly likely to choose auto in all three locations and the coefficient is highest for the downtown suburbs. High income households living in downtown are also significantly likely to choose auto. The presence of children is not significant in affecting mode choice but the number of workers is significant in affecting the likelihood of all auto tours in the middle suburbs.

Three home location characteristics were significant – transit access for downtown residents and non-work accessibility and pedestrian convenience for outer suburban residents. The sign indicates that higher transit access of a home tended to significantly increase the likelihood of non-auto mode choices in the household. Also, high non-work accessibility tended to increase the

Table 7
Lower level model of household mode choice by residential location

	Downtown		Middle suburbs		Outer suburbs	
	Estimated coefficient	*t*-Statistic	Estimated coefficient	*t*-Statistic	Estimated coefficient	*t*-Statistic
Variable (*option*)						
Constant (all auto)	0.45	0.41	1.58**	2.57	2.12**	2.51
Constant (both non-auto and auto)	1.16**	5.84	0.78**	4.04	1.33**	3.16
Number of non-work activities in the household (all auto or both)	0.13	1.15	0.11*	1.68	0.39*	1.93
Dummy indicating household income < 30 K (all non-auto or both)	0.36	1.00	0.81**	2.69	0.87**	2.26
Dummy indicating household income > 60 K (all auto)	0.81*	1.82	−0.18	0.49	0.43	1.17
Number of vehicles per worker (all auto)	1.50**	4.63	0.85**	3.53	0.79**	2.38
Dummy indicating child in household (all auto)	0.05	0.12	−0.002	0.01	−0.44	1.49
Number of workers (all auto)	0.03	0.10	0.32*	1.66	0.17	0.77
Home characteristics						
Transit access (all non-auto or both)	0.52*	1.92	0.35	1.41	0.18	0.60
Commercial-residential mix and balance (all auto)	−0.07	0.52	−0.01	0.05	–	–
Non-work accessibility by auto (all auto)	–	–	–	–	−0.57**	−1.92
Pedestrian convenience (all non-auto or both)	−0.63	1.10	0.02	0.05	0.47*	1.64
Workplace characteristics						
Transit access (maximum of workplaces – all non-auto or both)	0.46	1.62	0.49*	1.82	0.21	0.67
Pedestrian convenience (maximum of workplaces – all non-auto or both)	0.15	0.47	−0.10	−0.47	0.17	0.47
Home to workplace corridor characteristics						
Suburban character (minimum of workplaces – all auto)	0.17	0.35	0.89*	1.79	1.01	1.23
Transit access (maximum of workplaces – all non-auto or both)	0.19	0.45	0.68**	2.22	0.89**	2.46
Non-work accessibility by auto (maximum of workplaces – all auto)	–	–	–	–	0.17	0.45
$\bar{\rho}^2(\rho^2)$	0.20(0.25)		0.27 (0.30)		0.44 (0.59)	

* Indicates significance at the 0.10 level.
** Indicates significance at the 0.05 level.

likelihood that non-auto mode choice would occur even for an outer suburban location. This suggests the possibility that high non-work accessibility combined with pedestrian convenience within a TAZ could encourage non-auto travel. For middle suburban locations high workplace transit access was significant in affecting the likelihood of the household conducting non-auto tours.

In both the middle and outer suburbs, home to work corridor transit accessibility increased the likelihood of non-auto mode choice by the household, as one would expect. Transit accessibility was not significant for the downtown locations. Also, in middle suburbs the urbanization levels of the home-work corridor was significant in affecting the likelihood of auto travel by the household, in that the more suburban the home-work corridors in the family, the more likely they were to use auto only.

Very few spatial characteristics were significant. However, the model estimated does indicate that the relationship between location and mode choice suggested by the models for the individual (Srinivasan, 2000) hold true even at the more aggregated household level.

5. Policy analysis using the models

The results of the models discussed in the previous section can be translated into specific land use and transportation policies. For example, land use policies that regulate commercial land use, population density, parking and zoning regulations and transportation policy that introduce changes to public transit routes and frequency along corridors. Land use policy suggestions directly related to the examples we present are:

1. In outer suburban locations the pedestrian convenience of the home location was a determinant of non-auto mode choice at the household level. Therefore, providing non-work opportunities within the home TAZ through regulations allowing commercial land uses within walking distance of residential locations would help increase non-auto use even within low-density locations.
2. Another factor that influenced the allocation of non-work activity in the outer suburban households was the non-work accessibility of the workplace. Increasing this by improving the mix of commercial in office locations would allocate some chaining of non-work activities with the work tour especially for two-worker households. If combined with better pedestrian convenience or transit access in workplaces many of these tours could also be work-based non-auto tours.
3. The importance of pedestrian convenience was indicated by the fact that high pedestrian convenience of the home TAZ increased the household's probability of allocating non-work activity to non-work tours.

To summarize, land use policy within towns need to emphasize the need to improve pedestrian convenience and the availability of non-work opportunities.

In the case of transportation planning local level impacts are difficult to implement and corridor level planning would be more effective in bringing about changes in travel behavior. Hence a few suggestions that are relevant include:

1. Improving average transit access and pedestrian access along corridors connecting middle suburban locations to each other as well as to downtown locations could also help to improve the chances that households would make non-auto work tours.

2. Creating multi-modal linkages along corridors is important to the transit mode choice especially for the work tour. Most outer suburban residents are not within walking distance of transit and the poor pedestrian convenience discourages walk tours. Hence connecting car or walk/bike use with transit is vital to increase park and ride usage.

Thus, at the corridor level improved transit accessibility as well as pedestrian convenience is important in allowing for non-auto mode choice and allocation of non-work activity to non-auto tours. The improvement of transit and pedestrian facilities tends to favor low-income groups more than other income segments. However, improvements to pedestrian facilities and greater availability of non-work opportunities within homes do appear to improve the activity allocation choices of other kinds of households such as the two-worker household with children. Thus, land use improvements address not only ways to make commuters less auto dependent but also friendly in their connections to transit.

None of the above suggestions with respect to transportation and land use planning are original. Proponents of transit oriented development and neo-traditional designers have talked of aspects of all of these suggestions. However, what is different about these suggestions is that they are derived from models that demonstrate that spatial characteristics can affect the likelihood of decision making about mode and trip-linking choices. Thus, the basis on which the suggestions are made has been derived from carefully quantified characteristics of places and corridors which have then been found to be statistically significant in affecting travel behavior. The effects estimated are not, perhaps, as dramatic as proponents of neo-traditionalism and transit oriented design would like them to be. But these suggestions for neighborhood and corridor character when combined with other strategies do indicate that land use and transportation planning when linked can make a difference.

6. Conclusions

The intermodal surface transportation and efficiency act (ISTEA) of 1991 requires regional transportation planning and gives transportation planning agencies the legal power to link efforts with land use plans. To enable planning for corridors local governments should be able to cooperate with each other in making land use and transportation decisions or new corridor-level agencies must be created which can do both land use and transportation planning. Carlson and King (1998) suggest from their research that the factors that influence cooperation include in terms of legislation: the power to cooperate, delegate and create new agencies; and in terms of implementation: support from elected officials, technical help from State, public support, and monetary support from State.

Note that our definition of corridors in this study is on a smaller scale than the corridors Carlson et al. discuss. The travel behavior models in this study have been estimated at an intra metropolitan level unlike the studies made by Carlson et al. which were at the inter-city level. At this smaller scale the need for cooperation is even more relevant as the ability to establish new levels or forms of government is not possible. Implementing transit and pedestrian oriented land use development along corridors also requires a holistic approach. This means that such development (unlike auto-oriented planning) has to be coordinated and planned by several local and

regional government entities. This is not impossible to envision and implement. San Diego has developed transit oriented development guidelines and incorporated them by ordinance (Carlson and Billen, 1996). Thus, mixed land use and pedestrian oriented development are coordinated with the regional transit authority. Perhaps, planners should consider even more proactive measures by which inefficient urban design is taxed at higher rates based on measures similar to those derived in this study. For example, high pedestrian convenience, transit accessibility and commercial-residential balance in new urban developments could be "rewarded" by lower property taxes.

Of course, urban design and integrated land use and transportation planning alone will not necessarily bring about changes in travel behavior that in turn lead to less congestion. Other public policy tools such as growth management and transportation demand management through the use of congestion pricing are also needed for truly effective changes in travel behavior. However, very few transportation planning agencies apart from those in Portland and the Bay Area have even partially implemented tools to predict the ways in which land use and congestion influence each other. Given the estimates made by our study, changes to zoning regulations are a viable means of changing travel behavior and should be seriously considered.

Acknowledgements

This work was partially supported by the Voorhees Fellowship and Lincoln Institute of Land Policy dissertation fellowship. An earlier version of this paper was presented at the ACSP Conference, Atlanta, GA, October 2000. The authors wish to thank Prof. Q. Shen, University of Maryland, College Park and Prof. Ben-Akiva, MIT, Cambridge for their valuable comments on this study.

References

Algers, S., Daly, A., Kjellman, P., Widlert, S., 1995. Stockholm model system (SIMS): application. In: Proceedings of the 7th World Conference on Transport Research. Elsevier, Oxford, UK.

Ben-Akiva, M., Lerman, S., 1985. Discrete Choice Analysis: Theory and Application to Travel Demand. MIT Press, Cambridge, MA.

Carlson, D., Billen, D., 1996. Transportation corridor management: Are we linking transportation and land use yet? Institute for Public Policy and Management. Graduate School of Public Affairs, University of Washington, Seattle, WA.

Carlson, D., King, S., 1998. Linking transportation and land use by fostering inter-jurisdictional cooperation: enabling legislation in eight states. Institute for Public Policy and Management, Graduate School of Public Affairs, University of Washington, Seattle, WA.

Cervero, R., Kockelman, K.M., 1997. Travel demand and the three Ds: density, diversity and design. Transportation Research Part D: Transport and Environment 2, 199–219.

Crane, R., 1995. On form versus function: will the "new urbanism" reduce traffic or increase it? Working paper UCTC No. 266, The University of California Transportation Center, University of California, Berkeley, CA.

Crane, R., Crepeau, R., 1998. Does neighborhood design influence travel?: A behavioral analysis of travel diary and GIS data. Transportation Research Part D: Transport and Environment 3, 225–238.

Ewing, R., Haliyur, P., Page, G.W., 1994. Getting around a traditional city, a suburban planned unit development and everything in between. Transportation Research Record 1466, 53–62.

Friedman, B., Gordon, S.P., Peers, J.B, 1994. Effect of neotraditional neighborhood design on travel characteristics. Transportation Research Record 1466, 63–70.

Handy, S.L., 1996. Understanding the link between urban form and non-work travel behavior. Journal of Planning Education and Research 15, 183–198.

Mackett, R., 1994. Land use transportation models for policy analysis. Transportation Research Record 1466, 71–78.

Shen, Q., 1998. Location characteristics of inner-city neighborhoods and employment accessibility of low wage workers. Environment and Planning B 25, 345–365.

Srinivasan, S., 2000. Linking land use and transportation: measuring the impact of neighborhood-scale spatial patterns on travel behavior. Massachusetts Institute of Technology, Cambridge, MA (unpublished).