Effects of Land Use and Socio-Demographic Characteristics on Household Travel Pattern Indicators

M. Kermanshah[1] and R. Kitamura[2]

This paper examines the effects of zonal land use and socio-demographic characteristics on travel behavior by exploring how land use development in rapidly changing urban areas, due to expansion and growth, can affect daily travel pattern. It aims to evolve an improved methodology for travel demand forecasting by a revision in the conventional trip generation analysis stage of the four steps sequential demand analysis technique. The effects of zonal land use variables and household socio-demographic characteristics on ten household travel pattern indicators comprising mode choice, trip generation, travel time expenditure and vehicle usage are studied. Two-way analysis of variance and dummy variable linear regression are employed for statistical analyses. The results of this study show that land use variables, represented by the population density and square root of employment density, are important determinants in describing most travel pattern indicators. Population density implying congestion cost shows negative association with car usage and positive association with transit usage, whereas employment density reflecting access to opportunities indicates negative correlation with both car and transit usages.

Non-motorized trip generation is positively associated with density variables. The total number of trips and number of trip chains are both independent of land use variables. The finding further shows that household income, the number of workers in a household, car ownership and household size have significant effects on most travel indicators examined in this study. Modal split is weakly correlated with household size, and total trip time expenditure is almost independent of car ownership. The type of residential area is another determinant that affects travel pattern indicators significantly. It is also shown that the relationship between population density and total number of trips is invariant across different income classes. The results have potential for application in situations where there is a need for consistent land use and transport predictions and evaluations.

INTRODUCTION

Around the world, urban areas are undergoing rapid and major changes. The geographical boundaries of many cities are expanding as suburbanization continues unabated due to the relocation of certain strata of society representing the upper/high income business class and civil servants in almost all metropolitan areas [1]. While old land use activities in central areas are abandoned or changed, new land uses, occupied by specifically targeted

1. Department of Civil Engineering, Sharif University of Technology, Tehran, I.R. Iran.
2. Department of Transportation Engineering, Kyoto University, Japan.

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socio-economic groups in fringe areas, are established resulting in activity locations that are strongly influenced by the new patterns of land use/ socio-demographic arrangements [2]. Considering travel as a linkage between activity locations [3–6], such changes have significant effects on the travel behavior of individuals and households in urban areas. Bearing in mind that the influences of the counter effect of transportation on land use patterns are significant in situations such as a congested transportation system in which congestion is fairly extensive in both demographic and temporal terms, people are led to relocate their residences to be closer to work or other facilities, resulting in shift in their daily travel pattern [7].

It is apparent that the understanding of interaction between land use and transportation is prerequisite and fundamental to the development of travel demand models which include land use variables together with socio-demographic characteristics. The present paper is designed to enhance the basic understanding of the land use socio-demographic panorama on transportation. Most of the current travel demand models have not adequately addressed the effects of land use, together with socio-demographics, on various aspects of travel patterns, but have, typically, focused on limited indicators such as the number of trips, possibly by purpose, produced by households.

The main focus of this study is on the analysis and explanation of the effects of land use and socio-demographic characteristics on the set of households travel patterns indicators including trip generation, travel time expenditure, modal split and vehicle usage. Modal split and vehicle usage are also included in the analysis in order to emphatically investigate the effects of land use variables on mode choice and vehicle usage patterns. While the term land use covers a variety of topics, including activities such as residing, working, shopping and physical infrastructure (e.g. homes and workplaces), these topics are inherently associated with population and employment and can represent the two-way process between land use and transportation.

The analysis is then extended to include variables reflecting types of residential area. The objective is to study the influence of location variables together with land use variables on household travel patterns. The stability of land use-trip making variation across household income groups is also investigated.

Several aspects of travel patterns are examined and modeled in this study, including number of trips and chains, number of trips by public and private modes, travel time expenditure, vehicle usage and modal split variation. These indicators are used to examine the relationships between household travel patterns with household socio-economic attributes and land use variables of the zone where the household's residence is located.

AN APPRAISAL OF CONVENTIONAL TRIP GENERATION MODELS

In conventional trip generation models, the total number of trips generated in a given geographical unit, such as a traffic zone, is related to the characteristics of the unit and/or average characteristics of the households in that unit. Land use variables, representing the features of the geographical unit in these models, are usually characterized by some measures of the intensity of the activity, such as zonal population, employment or residential density, or the number of dwelling units in the zone. Household size and car ownership have been found as being the most influential household characteristics in conventional trip generation models [8]. These zonal trip generation models, however, have been criticized for their aggregative nature and other limitations [e.g. 9,10]. In order to alleviate some of the shortcomings of the zone-based trip generation models, disaggregate models have been developed during the last two decades [11,12,13].

Many results produced suggest that the exercise is more complex than it was originally appreciated and their dynamic behavior is not well understood. The effects of land use on transport can be modeled at disaggregate levels using well established methodologies [7]. Disaggregate trip generation approaches consider the number of trips by an individual or household as a function of person and/or household characteristics, respectively. Variables such as the individual's age, sex, household size, auto ownership and income have widely been incorporated in these studies [e.g. 14,15]. Also a variable such as the number of workers in a household has been used in trip generation models [16,17]. Some researchers have employed a life-cycle concept in explaining trip generation and travel expenditure behavior [12,18–21]. Only in a few instances land use variables have been explicitly considered and incorporated into the analysis of household trip generation and travel time expenditure [22,23].

In summary, the appraisal of the state-of-the-art on the effects of zonal land use characteristics and household socio-demographics on daily travel behavior indicates the importance of further studies. Therefore, it is believed that a comprehensive investigation on the effects of land use and socio-demographic parameters on a wide range of travel pattern indicators, using the disaggregate approach, would provide a sound and rational basis for future demand forecasting procedures.

STUDY HYPOTHESES

The study hypothesizes that zonal land use attributes for given socio-demographics have significant effects on several household travel pattern indicators, including trip generation, modal split, travel time expenditure and vehicle usage. The conjecture is that most travel pattern indicators are strongly associated with land use variables represented by population and employment densities. The effects of the variables, however, vary across the indicators under consideration. It is expected that as employment density increases, facilities become closer and so motorized trips are likely to be fewer. Non-motorized trips most likely increase as the distance between facilities decreases. On the other hand, as the population density increases, more congestion is expected. Car usage tends to decrease and transit usage increases. Thus, the study assumes that variations in travel patterns can be explained by both the land use variables and socio-economic attributes of the household, as well as household structure.

It is further hypothesized that the geographical characteristics of a residential area are important determinants in explaining travel patterns. Area size and type of transportation network are among those characteristics that most likely influence travel behavior.

The study also concerns itself with another conjecture. Household income and land use density factors affect most of the travel indicators with opposite effects. The dominant pattern between zonal population density and household income is negative. It is implied that land use-travel relationships remain stable across income groups.

In summary, household travel patterns of mode choice, trip generation, trip time expenditure and vehicle usage are highly affected by land use attributes, together with household structure and socio-economic characteristics. Type of residential area plays a significant role in explaining the variations of households travel pattern indicators. Land use-travel relationship is invariant across households with different income groups.

STUDY APPROACH

This study uses data from 7,091 households obtained from the nine-county area wide survey in the San Francisco Bay Area, assuming the household as the unit of analysis. There are several reasons for this choice. First, the household is the survey and analytical unit of the conventional trip generation models. Second, the household is a unit in which many decisions are made collectively, including those related to trip making and time allocation. Third, trip rates are less variable at household level than at the individual level, so parameters estimated during the trip generation model development are expected to be more efficient when a household is the unit of analysis.

A two-way ANOVA is used to examine the hypothesis about the dependency of household travel patterns on land use variables and household descriptors. Various travel pattern indicators are considered including total number of trips, number of chains, number of trips by public transportation (herein called transit trips), number of trips by car, ratio of the number of transit trips to the number of car trips (modal split), number of driver trips, total trip time expenditure, total driver trip time, total transit trip time and number of walking trips (non-motorized trips). Household car usage is represented by the number of driver trips and total driver trip time. Land use and socio-demographic variables (which involve annual household income), the number of workers in a household, population and employment densities of the zone where the household lives, are used together with household size and car ownership as a grouping factor.

Land use variables applied in this study represent the characteristics of the zone where the household resides. In the preliminary stage, three density variables were selected including population density expressed by the zonal population divided by zonal area in acre, employment density expressed by zonal total number of employment divided by area in acre and a land use mixture variable expressed by the total number of employment divided by zonal population. Based on the results of one-way analysis of variance, the mixture variable was excluded from the analysis. The square roots of density variables are found to be the best variables that are correlated with travel pattern indicators.

Household descriptors include household size, income, car ownership and number of workers. Square root transformation is also applied to household income. Household size and car ownership variables are used as grouping factors in the analysis of variance.

In order to understand the nature of relationships between household travel patterns and land use characteristics, together with household socio-demographics, the study is further extended by developing several mathematical models using a dummy-variable linear regression approach. Linear regression is employed in order to have a better understanding of the relationship between household travel patterns and land use variables, together with socio-economic characteristics, and to make a forecast of future travel demand more reliable. Dummy variable multiple linear regression is employed as an equivalent approach to the analysis of variance. Two-way analysis of variance is insufficient to provide such specific models.

The dummy-variable linear regression approach is generally equivalent to the two-way analysis of variance. A good example of the equivalency of the two approaches for balanced data may be seen in [24]. The approaches, however, become approximately equivalent as observations include unequal cell frequencies (unbalanced observation). The error term no longer shows homoscedasticity property required by the ANOVA assumption.

DATA SET, SAMPLE AND STUDY VARIABLES

The Bay Area Transportation Study conducted a telephone interview survey across the nine-county area wide in the San Francisco Bay Area Region in 1981. (The area includes Alameda County, Contra Costa County, Marin County, Napa County, San Francisco County, San Mateo County, Santa Clara County, Solano County and Sonoma County). The survey results have been recorded in three data files: household, person and trip. The household file includes information on travel day, residence location, type of dwelling unit, household's tenure duration at residence location, household size, household income, vehicle ownership and types of vehicle owned by the household including detailed information on vehicle models and energy consumption rates. The total number of households for which data are available is 7,091.

The person file includes information on 17,087 individuals who reported their travel activities during the survey day. Personal characteristics include position of the person in household, relationship to the head of the household, sex, age, driver license holding, ability to use transportation (handicapped or not), occupation, industry and work location. Individuals with more than one job are also indicated in the file.

The trip data include 53,026 weekday trips with information on trip origin, destination, purpose, starting and ending times, vehicle occupancy, type of ride (car pool or not), type of parking, parking cost, bridge toll, transit fare, number of transfers, walking time and total waiting time.

A set of variables was selected from each file and then merged together using BMDP Data Manager Package [25]. Then, trip records for households members were examined for completeness using a set of criteria similar to those used by the authors in previous studies [26,27]. All households in which at least one member has valid trip records have been retained for the analysis. Records of all trips made by household members age 5 or over are included. Households in which all members have either missing trip information or have trip records with a missing origin and/or destination are regarded as invalid and excluded from the analysis. The number of households in the screened sample was 6,139, about 87% of the original data, from which 5,120 households owned at least one car.

Information on land use characteristics of the study area has been obtained from the 1980 land use data file for 550 zone system. The file included information on number of households, total population, number of employments in different sectors, zonal area, average household income and number of dwelling units classified by types.

The variables are grouped into five categories. The first category of variables describes the socio-economic characteristics of the household, annual income and number of workers in the household. The second group includes variables that describe land use characteristics of the zone where the household residence is located. A set of dummy variables in the third category describes the car ownership level of the household. In the 4th group, household size is represented by dummy variables indicating residence counties.

Travel pattern indicators are considered as dependent variables in the linear regression model formulation. Independent variables include household socio-economic attributes together with the land use characteristics of the zone where the household resides. Table 1 shows the list of variables and their definitions used in the model development process.

DISCUSSION OF RESULTS

The following section presents discussion on some interesting results obtained in this study using data set, as explained in the previous section. The salient results explaining the variations in travel pattern indicators are briefly described in the following subsections:

1. Effects of land use and socio-demographic variables.
2. Effect of residential area.
3. Stability of land use-travel relationship across income groups.

Effects of Land Use and Socio-Demographic Variables

Table 2 indicates the salient representation of variations of several travel pattern indicators in terms of land use and socio-demographic parameters. The effects of land use variables are clearly seen for each indicator. Note that the effect of population density is, in general, more significant than the effect of employment density. While the effects of household size and car ownership are found to be significant in explaining the variation of almost all indicators examined here, zonal density variables, income and number of workers strongly affect most of the indicators. The total number of trips, number of chains and total travel time expenditure are almost weakly correlated with the density variables.

Household income, a variable frequently used as a household descriptor in travel demand modeling, displays a rather important role in

Table 1. Variables used in model formulation.

Variable	Definition
Household Socio-economic Characteristics	
INCOMESQRT	Square root of household annual income
N-WORKERS	Number of full time workers in household
Zonal Density	
POPDENSQRT	Square root of zonal population density
EMPDENSQRT	Square root of zonal employment density
Car Ownership	
CAR0*	1 if household owns no car
CAR1**	1 if household owns one car
CAR2	1 if household owns two cars
CAR3	1 if household owns three or more cars
Household Structure	
SIZE1#	1 if household has one member
SIZE2	1 if household has two members
SIZE3	1 if household has three members
SIZE4	1 if household has four members
SIZE5	1 if household has five members
SIZE6	1 if household has six or more members
Residence County	
ALAMEDA	1 if residence zone is in Alameda County
CONTRA COSTA	1 if residence zone is in Contra Costa County
MARIN	1 if residence zone is in Marin County
NAPA	1 if residence zone is in Napa County
SAN FRANCISCO	1 if residence zone is in San Francisco County
SAN MATEO	1 if residence zone is in San Mateo County
SANTA CLARA	1 if residence zone is in Santa Clara County
SOLANO	1 if residence zone is in Solano County
SONOMA#	1 if residence zone is in Sonoma County

\# Omitted dummy variable
⋆ Omitted dummy variable for $N = 6139$ (all households)
⋆⋆ Omitted dummy variable for $N = 5120$ (no-car households excluded)
N Sample size

explaining all indicators of motorized travel patterns. Non-motorized trips (i.e. number of walking trips) on the other hand are not associated with income, reflecting the fact that non-motorized travel remains stable across different income groups.

All travel time expenditure indicators are strongly influenced by the number of workers in the household. Also the number of transit trips, car trips and their ratio (modal split) show strong relationships with the number of workers. Obviously, the presence of workers in a household and the resulting commute trips greatly affect the household's travel.

Variations associated with the total number of trips, total trip time expenditure and number of chains are quite notable. A rather small set of variables was found influential

Table 2. Salient main and interaction effects of travel pattern indicators. Grouping factors: S, C and co-variates: P, E, I, W.

Effect	$\text{Ln}\left(\frac{\text{no. of transit trips}}{\text{no. of car trips}}\right)$	No. of Trips	No. of Chains	No. Of Transit Trips	No. of Walk Trips
S	⋆	⋆	⋆	⋆	⋆
C	⋆	⋆	⋆	⋆	⋆
SC	⋆	⋆	⋆	⋆	#
P	⋆			⋆	⋆
E	#		⋆		⋆
I	⋆	⋆	⋆	+	
W	+			⋆	

Effect	No. of Car Trips	No. of Driver Trips	Tot. Trip Time Expenditure	Tot. Transit Trip Time	Tot. Driver Trip Time
S	⋆	⋆	⋆	⋆	⋆
C	⋆	⋆		⋆	⋆
SC	⋆	⋆		⋆	⋆
P	⋆	⋆	+	⋆	⋆
E	+	#		#	
I	⋆	⋆	#	+	⋆
W	+		⋆	⋆	⋆

Note: Time indicators are converted to minutes if multiplied by 60/100.
Significant at 5% + Significant at 0.5% ⋆ Significant at 0.05%
S Household size $\{1, 2, \ldots, \geq 6\}$
C Number of cars $\{0, 1, 2, \geq 3\}$
P Square root of zonal population density
E Square root of zonal employment density
I Square root of household annual income
W Number of full time workers in a household

in explaining these indicators. The density variables were not very important in explaining the variations of the indicators when compared with their influences on the other travel pattern indicators. The finding implies that a household maintains a certain level of mobility and activity pursuing household needs, irrespective of land use density factors. Furthermore, the variation in total trip time expenditure is found independent of car ownership, supporting the notion of car ownership's diminishing effect on travel patterns [28].

The pattern of the number of walking trips is slightly different from the other travel pattern indicators, as the number of walking trips is strongly influenced by land use variables and remains invariant with respect to the household income and number of workers. The significant effect of density variables on the number of walking trips reflects the fact that land use arrangements may have significant impact on some aspects of travel patterns which are not captured by conventional descriptors such as income.

The results of estimation, concerning the development of extensive linear models of travel pattern indicators, are shown in Table 3. Interaction terms are not included because of the difficulties involved in their interpretations and a higher level of complexities that they introduced into the models. A description of each model follows. Note that Models 1, 6, 7 and 10 are developed exclusively for households with at least one private automobile.

Modal Split (Model 1)

The logarithm of the ratio of the number of transit trips to the number of car trips is the dependent variable of Model 1. The numerator and denominator of the ratio are both added by

Table 3. Linear models of travel pattern indicators. Grouping factors: household size, car ownership.

Model No.	1 $Ln\left(\frac{\text{no. of transit trips}}{\text{no. of car trips}}\right)$		2 No. of Trips		3 No. of Chains		4 No. of Transit Trips		5 No. of Walk Trips	
	β	t	β	t	β	t	β	t	β	t
INCOMESQRT	-0.002	-5.52	0.013	8.09	0.002	4.16				
NWORKERS	0.120	4.79					0.268	9.23		
POPDENSQRT	0.180	15.99					0.181	14.50	0.131	8.79
EMPDENSQRT	0.022	1.97					-0.023	-2.15	0.087	6.57
CAR1			1.389	6.63	0.466	6.50	-1.019	-15.03	-0.201	-2.47
CAR2	-0.627	-13.58	2.332	9.58	0.760	9.11	-1.756	-22.01	-0.565	-6.03
CAR3	-0.935	-15.51	3.584	12.49	1.171	11.92	-2.180	-23.05	-0.809	-7.37
SIZE2			1.690	8.60	0.789	11.73	0.715	11.53	0.500	6.71
SIZE3			3.603	15.23	1.614	19.92	1.183	15.67	0.942	10.49
SIZE4			6.725	26.39	2.946	33.74	1.547	18.97	1.496	15.49
SIZE5	0.221	2.94	9.020	27.52	4.085	36.37	2.435	23.29	1.970	15.84
SIZE6			12.375	32.54	5.595	42.93	3.601	29.33	3.270	22.64
Constant	-1.753		1.235		0.620		0.411		0.030	
R^2	0.190		0.362		0.447		0.286		0.145	
$F(df)$	171.44(7,5120)		386.24(9,6129)		551.38(9,6129)		222.69(11,6127)		104.30(10,6128)	
N	5120		6139		6139		6139		6139	

Model No.	6 No. of Car Trips		7 No. of Driver Trips		8 Tot. Trip Time Expenditure		9 Tot. Transit Trip Time		10 Tot. Driver Trip Time	
	β	t	β	t	β	t	β	t	β	t
INCOMESQRT	0.014	8.32	0.010	8.12	0.185	2.17			0.261	5.12
NWORKERS			0.131	1.76	29.675	5.73	24.650	7.17	16.521	5.65
POPDENSQRT	-0.302	-6.88	-0.239	-7.18	5.653	3.34	12.946	8.79	-6.788	-5.16
EMPDENSQRT	-0.177	-3.98	-0.102	-3.04			-4.688	-3.64	-2.275	-1.72
CAR1							-104.363	-13.02		
CAR2	2.254	12.46	1.872	13.48			-168.018	-17.82	60.770	11.09
CAR3	4.267	18.55	3.830	21.30			-201.970	-18.06	109.359	15.41
SIZE2	-0.625	-3.66	-0.304	-2.36	87.119	8.41	65.948	8.99	-11.406	-2.24
SIZE3					166.771	13.21	103.407	11.58		
SIZE4	2.303	10.26	1.204	7.11	265.486	19.53	125.402	13.01	27.567	4.13
SIZE5	3.139	10.20	1.374	5.91	387.279	21.98	198.882	16.08	37.176	4.05
SIZE6					535.462	25.39	275.127	18.95		
Constant	3.954		2.800		72.806		59.280		82.028	
R^2	0.238		0.243		0.206		0.156		0.160	
$F(df)$	199.43(8,5111)		182.22(9,5110)		199.29(8,6130)		102.78(11,6127)		107.89(9,5110)	
N	5120		5120		6139		6139		5120	

df Degrees of freedom

N Sample size

Note: Time indicators are converted to minutes if multiplied by 60/100.

0.5 to avoid undefined value for the logarithm. The modal split index is strongly associated with the square root of zonal population density. The effect of employment density is also found significant. The effect of population density, however, is more pronounced than the effect of employment density. Both land use variables positively contribute to the variation of the log-ratio, implying that as the area becomes highly populated and greatly covered by employment opportunities the tendency to choose public transit increases.

Household income has negative effects on modal split, reflecting the fact that high income families tend to use the private car rather than public transportation. The result is compatible with the typical development pattern in urban areas where low income households tend to live in high density areas, as indicated by opposite signs of income and population density.

There is a strong relationship between the number of workers in the household and the tendency toward transit use. As the number of workers in a household increases, the household's tendency toward using transit also increases. The observed tendency is partly attributed to the dependency of workers on transit in their commuting travel patterns. A great number of workers in a household also implies more out-of-home obligatory activities generated by the workers, who may be given a higher priority in using household cars for their commutes. Non-workers may be left with fewer cars available, who may therefore ride transit.

Car ownership represented by the dummy variables shows strong negative effects on the ratio of the number of transit trips to the number of car trips. The finding implied that households with a higher level of car ownership use transit less frequently. The household size is introduced into the model through a set of dummy variables. Although variable SIZE5 happens to be significant, household size is essentially uncorrelated with mode choice. As a whole, the model was notable and all variables appearing in the model had expected signs.

Total Number of Trips (Model 2) and Number of Chains (Model 3)

Among the socio-economic and land use variables only household income is significant in the models for the total number of trips (Model 2) and number of chains (Model 3). Model 2 explains 36 percent and Model 3 explains 45 percent of the total variations of the total number of trips and number of chains, respectively. Quite notable is the result that land use variables have no contribution in explaining the variations of total number of trips and number of chains. Almost similar results were observed for two-way analysis of variance in the previous section (employment density is significant in the model for the number of chains. This is presumably due to the fact that the two approaches adopted different assumptions about their error terms, as mentioned earlier).

The number of trips and the number of chains are positively associated with both car ownership and household size. Larger households and households with more cars available show stronger influence on generating trips and chains. It is worthwhile to mention that the ratio between the coefficients in Models 2 and 3 are varied around 2.74, the average number of trips per chain or chain size.

The number of workers is insignificant in both models. The result, apparently, does not agree with previous reports from 1963 and 1974 samples that the total number of trips is positively associated with the number of workers [19]. In comparison, however, the number of workers became less significant in the 1974 sample.

Number of Transit Trips (Model 4) and Total Transit Trip Time (Model 9)

Similarities are observed between the two models of transit trip generation and transit travel time expenditure. Both models are invariant across income groups implying that income was no distinctive factor in generating transit trips. Note that the negative effect of income found earlier in modal split is partly reflected through car ownership variable, CAR1, in these two models.

The number of workers showed positive association with transit usage. The result is compatible with the earlier findings on modal split model. Land use variables appear in both models with opposite signs. Positive contribution is made by the square root of population density. Such a positive effect may partly reflect the negative effect of income, which is absent in the models. Employment density shows a negative influence on transit usage. As employment density increases, it is expected that opportunities cluster together and motorized travel is likely to be less. The effect of population density is more significant than the effect of employment density. As expected, the number of transit trips and transit trip time expenditure decrease with increasing car ownership [29], and increase with increasing household size. A similar result was shown by the modal split model.

Number of Walk Trips (Model 5)

The unique characteristic of non-motorized trip generation can be seen in Model 5. Contrary to all motorized travel indicators, the number of walking trips is independent of the income as well as the number of workers in the household. Land use density, car ownership and household size are important determinants of walking trips.

Land use variables made a significant contribution in explaining the variation of the number of walk trips. As population density increases and the area becomes more congested with high parking prices, people make more walking trips as well as more transit trips (Models 4 and 9). The positive sign of employment density may be attributed to the higher accessibility to facilities within walking distance.

Car ownership showed a negative association with the number of walking trips, with significant effects comparable with land use variables. Household size was the other important variable with a positive influence on the number of walking trips.

Number of Car Trips (Model 6)

The number of car trips was significantly influenced by household income, implying that high income households tend to make more car trips than the low income households. The result contrasts with the finding that neither transit trips nor walking trips vary across income groups. As income increases only the number of car trips increases.

Both density variables contribute negatively to the variation of the number of car trips, while the effect of population density is more significant than that of employment density. The result is consistent with the notion that population density functions as a surrogate for congestion and parking cost, and employment density represents some measure of accessibility to opportunities. Therefore, greater congestion causes less frequent car usage, and higher access to facilities, presumably, reduces motorized trips and substitutes them with non-motorized (Model 5).

As expected, car ownership shows the most significant positive association with the number of car trips. The effect of household size on the number of car trips is rather irregular. Overall, however, the coefficient estimates suggest positive association between household size and car trip generation. About 24 percent of the total variation in the number of car trips is explained by the model.

Number of Driver Trips (Model 7) and Total Driver Trip Time Expenditure (Model 10)

Driver trip generation and travel expenditure models present very similar specifications. The dependent variables in both models, reflecting car usage, are positively associated with the square root of income and number of workers. Land use variables are negatively correlated with car usage, and it is evident that car ownership is strongly associated with driver travel patterns.

In Table 3, the effect of the household structure variables is the least significant for driver travel patterns among the trip generation and travel expenditure indicators. It further confirms the notion of the individually related nature of car use, as cars are often used only by one person, mostly the head of the household [29]. Similar results have been reported across households characterized by life cycle stages [28].

The effects of car ownership and household size variables on driver travel patterns replicate those in Model 6, i.e. number of car trips. Similarities between Models 6, 7 and 10 are mainly attributed to the fact that more than 3/4 of car trips were driver trips.

Total Trip Time Expenditure (Model 8)

Quite notable in a trip time expenditure model are the positive effects of both the income and population density variables. In all previous models, when both variables were present in a model simultaneously, they showed opposite signs. The result is not surprising, given that the variation of the total number of trips remains stable along land use density variables (Model 2). High income households spend more time traveling as they make more trips (Models 2 and 6), and households in densely populated areas spend more time for an average trip due to higher congestion.

The number of workers showed a positive influence on trip time expenditure. The result is not surprising at all, as the number of persons who have to make daily trips increases, travel time expenditure increases too. While the foregoing dependencies of total trip time expenditure contradict the notion of a constant travel time budget across different household types [30], the insignificance of car ownership effect on trip time expenditure again implies the diminishing effect of car ownership reported elsewhere [28]. Car ownership had no contribution in explaining the variation of total trip time expenditure. A similar result was obtained in a two-way analysis of variance, reported earlier.

All estimated models in Table 3 show relatively simple specifications with highly significant statistics of worth. The R^2 values varied between 0.145 to 0.447, indicating very acceptable values in these types of analyses [e.g. 20,31]. In general, travel time expenditure models of motorized trips showed lower fits than the trip generation models. Almost all independent variables that appeared in the models showed expected signs.

Effect of Residential Area

In the previous sections it was shown that the variations of a selected set of house-hold travel pattern indicators can be explained by household socio-economic characteristics together with land use attributes of the zone where the household resides. While some studies have pointed out the importance of trip generation variation across different types of areas [e.g. 12], further investigations, in which a wide range of different indicators of travel patterns are examined, are necessary. This study extends the analysis to incorporate the effect of residential area together with household socio-economic and zonal land use variables on the set of travel indicators mentioned earlier.

Residential county dummy variables were introduced into the dummy variable regression modeling process, in addition to those variables which appeared in the models of Table 3. Table 4 presents the results of estimated models. A quick overview of the table reveals that among the nine counties in the study area, households in San Francisco County exhibit unique travel characteristics. This is especially the case for transit related indicators (see the positive coefficients for the models for the ratio of the number of transit trips to the number of car trips, number of transit trips and total transit time expenditure). The large F-values in these models are mainly attributed to the effect of San Francisco County variable. The observation is presumably related to the dense transit network in this county.

Models for the number of chains, number of car trips, number of driver trips and driver trip time expenditure (mostly car usage indicators) exhibited negative association with the San Francisco County dummy variable. In fact, the average number of car trips per household is the lowest in San Francisco County. The county variable made positive contributions to the variations of the total trip time and total transit trip time expenditures. Notable in Table 4, is the presence of the square root of population

Table 4. Linear models of travel pattern indicators with county variables grouping factors: household size, car ownership.

Model No.	1 $\text{Ln}\left(\frac{\text{no. of transit trips}}{\text{no. of car trips}}\right)$		2 No. of Trips		3 No. of Chains		4 No. of Transit Trips		5 No. of Walk Trips	
	β	t	β	t	β	t	β	t	β	t
INCOMESQRT	-0.003	-6.38	0.013	8.43	0.002	4.54	-0.001	-1.90		
NWORKERS	0.112	2.89					0.264	8.84		
POPDENSQRT	0.042	2.74	0.072	2.04	0.049	3.05	0.029	1.77	0.138	9.09
EMPDENSQRT	0.032	2.89					-0.012	-1.11#	0.087	6.57
CAR1			1.441	6.65	0.494	6.52	-1.015	-15.09	-0.198	-2.43
CAR2	-0.546	-11.92	2.360	9.07	0.751	8.40	-1.628	-19.95	-0.563	-6.01
CAR3	-0.935	-15.51	3.597	11.79	1.151	10.97	-2.010	-20.84	-0.811	-7.39
SIZE2			1.676	8.55	0.791	11.77	0.709	11.62	0.498	6.68
SIZE3			3.609	15.29	1.623	20.05	1.174	15.81	0.942	10.50
SIZE4	-0.089	-1.89	6.724	26.41	2.957	33.88	1.532	19.12	1.495	15.48
SIZE5			9.039	27.62	4.110	36.59	2.377	23.12	1.976	15.89
SIZE6			12.393	32.63	5.615	43.10	3.546	29.34	3.271	22.65
ALAMEDA			0.500	2.40					0.144	1.85
CONTRA COSTA			0.909	3.35						
MARIN	0.273	2.17								
NAPA	-0.282	-2.73	2.426	3.78	0.555	2.54			0.441	1.82
SAN FRANCISCO	0.715	11.77			-0.256	-3.54	0.886	13.00		
SANTA CLARA	-0.219	-3.97					-0.210	-3.13		
Constant	-1.487		0.649		0.490		0.722		-0.023	
R^2	0.223		0.365		0.449		0.311		0.146	
$F(df)$	121.82(12,5107)		270.39(13,6125)		416.25(12,6126)		197.34(14,6124)		87.50(12,6126)	
N	5120		6139		6139		6139		6139	
F(county variables)	52.57*		7.30*		4.99*		110.50*		3.23**	

Model No.	6 No. of Car Trips		7 No. of Driver Trips		8 Tot. Trip Time Expenditure		9 Tot. Transit Trip Time		10 Tot. Driver Trip Time	
	β	t	β	t	β	t	β	t	β	t
INCOMESQRT	0.014	8.07	0.011	8.36	0.186	2.19			0.269	5.28
NWORKERS	0.175	1.79	0.152	2.06	29.795	5.77	22.856	6.68	16.819	5.75
POPDENSQRT	-0.082	-1.33#	-0.027	-0.58#	-2.242	-0.88#	1.059	0.55#	-3.132	-1.73
EMPDENSQRT	-0.191	-4.29	-0.120	-3.57			-3.818	-2.98	-2.506	-1.89
CAR1							-105.928	-13.31		
CAR2	2.069	11.19	1.760	12.67			-161.959	-17.26	59.027	10.72
CAR3	3.988	16.64	3.674	20.40			-193.251	-17.35	107.050	15.01
SIZE2	-0.623	-3.65	-0.308	-2.40	87.138	8.43	65.070	8.93	-11.371	-2.24
SIZE3					167.470	13.29	102.384	11.55		
SIZE4	2.295	10.25	1.222	7.26	265.754	19.58	124.119	12.96	27.777	4.16
SIZE5	3.156	10.26	1.428	6.17	385.890	21.94	194.656	15.84	38.090	4.15
SIZE6					534.317	25.38	272.189	18.88		
ALAMEDA					26.522	2.12				
CONTRA COSTA	0.486	1.79	0.565	2.69	41.878	2.77				
MARIN	-0.950	-2.07								
NAPA	1.606	2.53	0.942	1.96	64.791	1.85				
SAN FRANCISCO	-1.175	-5.07	-0.878	-4.75	63.561	5.04	73.234	9.44	-20.088	-2.92
SANTA CLARA			0.596	3.52						
Constant	3.478		2.227		67.449		72.317		76.226	
R^2	0.244		0.252		0.210		0.168		0.161	
$F(df)$	127.07(13,5106)		132.15(13,5106)		135.98(12,61260)		103.00(12,6126)		98.10(10,5109)	
N	5120		5120		6139		6139		5120	
F(county variables)	10.31*		15.03*		7.53*		89.10*		8.52*	

Not significant at 5% ⋆ Significant at 1% ⋆⋆ Significant at 5% *df* Degrees of freedom *N* Sample size

Note: Time indicators are converted to minutes if multiplied by 60/100.

density variable in two generation models , number of trips (Model 2) and number of chains (Model 3) with positive signs. A similar effect may be observed for income in the same models.

Another interesting result in Table 4 is the diminishing effect of the square root of population density in explaining some indicators as county variables entered into the models. The finding is expected if taken into account that county dummy variables represent environmental and societal attributes of residence counties, including transportation network characteristics. Accepting the hypothesis that population density reflects congestion level in transportation networks, county dummy variables can adequately capture the variations otherwise explained by the population density. The highly significant population density variable in Models 6 through 9 in Table 3, became insignificant in respective models in Table 4 when county variables were included. A similar change for employment density is rather negligible. It should be emphasized, again, that in all models the strong presence of the San Francisco County dummy variable is clearly seen.

Two more additional changes were observed in Table 4 as county variables were introduced into the analysis; the square root of income with a negative sign and the number of workers with a positive sign, are added into the Model 4 (number of transit trips) and Model 6 (number of car trips), respectively. While the change in Model 4 is conceivable, the latter change in Model 6 is presumably attributed to the compensation made in response to the loss of significance of the square root of population density variable in this model. The presence of the number of workers variable in Model 6 may also be related to the rather large impact of this variable on the number of driver trips (Model 7) which needs to be accounted for in this Model. Note that the number of driver trips comprised about 87 percent (0.152/0.175) of the car trips.

Stability of Land Use-Travel Relationship Across Income Groups

Indications from previous analyses and earlier findings reveal that the dominant pattern between population density and household income is negative. Consequently, when an indicator of travel patterns varies with income positively, population density tends to be negatively associated with that indicator. The fact of whether or not such a relationship between population density and trip making is invariant across income groups, is examined in this section. The hypothesis is tested using the number of car trips as a travel pattern indicator. The uniqueness of San Francisco County is introduced into the analysis by a dummy variable. Five income classes are defined in the data set. The hypothesis is stated as follows:

H_0: The relationship between population density and the number of car trips is invariant across households in different income classes.

Assume that I income classes have been defined. A dummy variable regression model can be specified as follows:

$$Y = f(\cdot) + a_1 \times POP + a_2 \times POP \times D_2 + \cdots + a_I \times POP \times D_I \ , \qquad (1)$$

where POP is the square root of population density, D is income dummy variable and a_I is the coefficient of the regression. The linear function of other contributing factors is represented by $f(\cdot)$. For income group 1, the model is:

$$Y = f(\cdot) + a_1 \times POP \ , \qquad (2)$$

since $D_2 = D_3 = \cdots = D_I = 0$. For households in income class 2, $D_2 = 1$ and the model is:

$$Y = f(\cdot) + a_1 \times POP + a_2 \times POP \quad \text{or} \ ,$$

$$Y = f(\cdot) + (a_1 + a_2) \times POP \ . \qquad (3)$$

The coefficient for population density in income class 2 is $(a_1 + a_2)$. Now the hypothesis turns to:

$$H_0 : \ a_2 = a_3 = \cdots = a_I = 0 \ .$$

The estimation results of the models based on Equations 1 and 2 for the number of car trips

Table 5. Linear models for number of car trips which include population density-income interaction variables grouping factors: all households and households in income class 1.

All Households			Households in Income Class 1		
	β	t		β	t
INCOMESQRT	0.017	8.80	INCOMESQRT	0.013	7.17
EMPDENSQRT	-0.181	-4.27	EMPDENSQRT	-0.178	-4.20
PDENSQRT	-0.096	-0.88*	PDENSQRT	-0.246	-8.46
PDENSQRT _ INC2	-0.074	-0.56*			
PDENSQRT _ INC3	-0.098	-0.89*			
PDENSQRT _ INC4	-0.153	-1.37*			
PDENSQRT _ INC5	-0.251	-2.06			
CAR2	2.157	11.89	CAR2	2.163	11.92
CAR3	4.121	17.85	CAR3	4.158	18.04
SIZE2	-0.608	-3.56	SIZE2	-0.624	-3.66
SIZE4	2.298	10.26	SIZE4	2.322	10.37
SIZE5	3.173	10.34	SIZE5	3.179	10.35
Constant	2.878		Constant	3.330	
R^2	0.243		R^2	0.242	
$F(df)$	136.30(12, 5107)		$F(df)$	203.37(8, 5111)	
N	5120		N	5120	

* Not significant at 5% *df* Degrees of freedom *N* Sample size

PDENSQRT=POPDENSQRT*C
PDENSQRT _ INC1=POPDENSQRT*INC1*C
PDENSQRT _ INC2=POPDENSQRT*INC2*C
PDENSQRT _ INC3=POPDENSQRT*INC3*C
PDENSQRT _ INC4=POPDENSQRT*INC4*C
PDENSQRT _ INC5=POPDENSQRT*INC5*C

INC1 1 if household income ≤ 6000
INC2 1 if household income > 6000 and ≤ 10000
INC3 1 if household income > 10000 and ≤ 20000
INC4 1 if household income > 20000 and ≤ 35000
INC5 1 if household income > 35000
C 1 if residence zone is in San Francisco County

are shown in Table 5. The calculated F-value is 1.85 with (4,5107) degrees of freedom. The critical value of F is 2.37 at 5% significance level, so the hypothesis is not rejected. Therefore, the stability of the relationship between population density and the number of car trips across income classes of households is supported.

The above discussion has attempted to interpret the results in terms of variations in selected household travel pattern indicators from several land use and socio-demographic models. Although the interpretations can not be regarded as definitive, they do lead to insights into different ways of representing the interactions in theoretical terms. Consequently, they may lead to a better understanding of how household travel pattern indicators respond to changes in zonal land uses and socio-economic characteristics. The fact that different responses can be identified, measured, interpreted and communicated to the interested parties highlights the usefulness of the present study.

CONCLUSION AND DISCUSSION

Based on the present study it can be concluded that land use and socio-demographic characteristics seem to be more meaningful and effective parameters to describe travel pattern/ behavior in an urban situation. Statistical analysis of this study has indicated that household travel patterns are strongly associated with the land use characteristics of the zone where household residence is located as well as with household socio-demographic characteristics. Area type of residential location is another factor which was found significant in describing household travel patterns. Land use variables used in this study included the square roots of population and employment densities. The square root of household income and the number of workers in a household, together with two sets of dummy variables representing car ownership and household size, comprised the socio-economic variables of the analysis.

As conjectured, household travel pattern indicators are largely determined by land use density variables. The square root of population density shows a strong negative effect on car usage indicators and a very strong positive influence on transit usage aspects of travel pattern. Vehicle usage indicators are negatively correlated with employment density, whereas the number of walk trips is positively correlated with employment density. Implication of the empirical results supports the notion that population density and employment density may function as surrogates of congestion cost and accessibility to apportunities, respectively. Models for the total number of trips and number of chains did not include land use variables. The two models show a very simple structure with few variables and still the highest goodness of fit among all indicators.

The results indicate that all trip generation and travel time expenditure models are positively influenced by either income and/or the number of workers. The finding shows that the number of workers is an appropriate descriptor for explaining the number of transit trip indicators, whereas household income is a more appropriate descriptor for the number of car trip indicators. While the effect of the number of workers on modal split remains positive, modal split shows negative correlation with income. Neither income, nor number of workers showed any effect on non-motorized trip generation.

Both car ownership and household size showed significant influences on all travel pattern indicators. Total trip time expenditure is an exception where no contribution by car ownership was apparent. As expected, car ownership dummy variables appeared in transit and non-motorized travel pattern models with negative signs. The effect of household size on driver travel pattern, compared to its effects on other indicators, was relatively stable. In modal split model, car ownership was more influential than household size. Mode choice was negatively associated with car ownership.

The type of residential area reflected by a set of county dummy variables indicated their significant contributions in explaining variations of all travel pattern indicators. San Francisco County was an exception, with its higher influence compared to other counties. In some models, the county dummy variables could account for the variations previously explained by the land use density variables. The land use variables in these models lost their significance as county variables entered into the models. The finding implies that county dummy variables appropriately reflect the environmental characteristics of the residence county, including congestion in transportation network, which was presumably described by land use density variables. However, in the models for the total number of trips and the number of trip chains when county variables are included, population density variable is also introduced.

Stability of land use-travel relationship across household income classes was another conjecture of this study. Whether or not different income groups follow a distinctive land use-trip making relationship was examined. The association between the square root of population density and the number of car trips across five income classes, with the effect of area type for San Francisco County residences included into the analysis, was tested. The result confirmed the stability hypothesis. Similar analyses may be performed for other travel pattern indicators in order to reach conclusive results.

The results of the study demonstrate that application of land use and socio-demographic characteristics in describing travel behavior provide a better understanding and insight into a wide spectrum of different aspects of travel pattern. This may be capable of providing a theoretically advanced, practically viable and policy sensitive tool to resolve complex urban planning problems. However, there are some limitations which are stated. Land use variables employed in the analyses are basically related to the household residence location. The study does not incorporate work-end land use characteristics which usually affect patterns of travel behavior. Also, the number of walking trips used as an indicator in this study may have been underestimated as most travel diaries do not usually record all trips made on foot.

The present study has considered only income as a socio-demographic co-variate in analysis of land use-travel relationship. It could be further extended by examining the effects of other socio-demographic variables to make it truly comprehensive. It could also include the household life cycle stages into the analysis. Life cycle concept has attracted the attention of many researchers in recent years and some promising results have been reported. A future research subject may add life cycle stage as an additional explanatory factor, together with land use variables and socio-demographic characteristics into the analysis of trip generation and travel time expenditure.

Finally, too often today land use decisions are short term and inconsistent. With a guiding framework based upon the study of the effects of land use and socio-demographics on travel pattern indicators in place, future transportation decisions can be coherent, consistent and meet the policy objectives of efficiency, economy, safety and the protection of the environment. The results of this study would assist in the better understanding of some aspects of the complexity of not only today's land use and transportation interaction issues and problems but also those of tomorrow.

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