

**Residential Self Selection and Rail Commuting:  
A Nested Logit Analysis**

Robert Cervero and Michael Duncan  
Department of City and Regional Planning  
Institute of Urban and Regional Development  
University of California, Berkeley

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Berkeley, California

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## Note

An error was discovered in the original Table 1 of this study. Notably, the Inclusive terms for the upper-nest model were incorrectly calculated thus the theta terms were in error. This revised working paper corrects this error. Also, the corrected upper nest model has a slightly different specification than originally shown in Table 1 in order to satisfy the condition that the theta values lie between 0 and 1. Some additional text is added to the original working paper regarding the new upper level model, however none of the substantive findings or conclusions of the research change as a result. The additional variables added to the upper nest model reveal that low automobile ownership levels tended to be associated with transit-oriented living. We acknowledge that automobile ownership likely both influences and is influenced by transit-oriented living, thus the coefficient on the automobile ownership variables could be subject to endogeneity bias. The revised equation also shows that controlling for other variables in the equation, having individuals 55 years of age and above in a household reduced the likelihood of living near transit. It is also noted that the estimated coefficients in the lower nest binomial logit models for predicting rail commuting (shown in the right-hand panel of Table 3) are unchanged from the original Table 3.

## **Abstract**

Past studies show that those living near train stations tend to rail-commute far more often than the typical resident of rail-served cities. Some contend this is largely due to self-selection, marked by those with an affinity to transit riding consciously moving into neighborhoods that are well-served by transit. This article explores the self-selection question by constructing a nested logit model that jointly estimates the probability someone will reside near a rail stop and in turn commute by rail transit, using year-2000 travel data from the San Francisco Bay Area. A multinomial logit model is also used to predict car ownership levels. The research reveals that residential location and commute choice are jointly related decisions among station-area residents. A comparison of odds ratios among those living near and away from transit, controlling for the influences of other factors, suggests that residential self-selection accounts for approximately 40 percent of the rail-commute decision. These findings suggest that supportive zoning should be introduced and barriers to residential mobility should be eliminated to allow the self-selection process to occur naturally through the marketplace.

## **1. TRANSIT-BASED HOUSING AND RESIDENTIAL SORTING**

The inventory of housing near train stations is rapidly expanding in many of America's rail-served cities. In California, over 12,000 apartment and condominium units were built between 1998 and 2001 within ½ mile of stations along the Tasman light-rail corridor in Santa Clara County, the Mission Valley Trolley line in San Diego, the Walnut Creek-Concord axis served by the Bay Area Rapid Transit (BART) system, and Los Angeles Metrorail's Westlake-Hollywood subway corridor. At the Ohlone-Chynoweth light rail station in San Jose, 194 apartment and condominium units were constructed atop what only a few years ago was a surface park-and-ride lot.

Transit-based housing, some contend, promote a number of public-policy goals (Calthorpe, 1993; Cervero, 1993; Bernick and Cervero, 1997). One, increased transit ridership enhances urban mobility and relieves peak-hour traffic congestion. Surveys of residents of multi-family complexes near suburban BART stations from the early 1990s showed upwards of 45 percent took rail-transit to work, much higher than the regional average of 9 percent (Cervero, 1994). Studies from metropolitan Washington, D.C. and Toronto found even higher transit market shares (up to 65 percent of commutes) among apartment-dwellers living near rail stops (Stringham, 1984; JHK and Associates, 1987, 1989).

Other benefits assigned to transit-based housing included increases in the supply of affordable units and improved air quality. Housing is more affordable, proponents maintain, because those living near rail transit stops own fewer cars and spend less money on private mobility, therefore freeing up money for housing consumption. Indeed, a central premise of Location Efficient Mortgage (LEM) programs, currently under way in Los Angeles, Chicago, Seattle, San Francisco, and Salt Lake City, is that prospective home-buyers can more easily qualify for home mortgages when living in transit-served settings since they usually spend smaller shares of their disposable incomes on transportation (Holtzclaw, et al., 2002). A string of studies have correlated living in compact, mixed-use, transit-served neighborhoods with lower automobile ownership rates and reduced automobile travel, providing empirical support for the LEM concept (Holtzclaw, 1994; Cervero and Gorham, 1995; Cervero, 1996; Schimek, 1996; Holtzclaw, et al., 2002). Air-quality benefits accrue from transit-based housing to the

degree rail access trips switch from park-and-ride to walk-and-ride. From an air-quality standpoint, transit riding does little good if a car is driven to reach a station. This is because disproportionately large shares of tailpipe emissions occur over the first mile of travel (due to inefficient cold engines) (Barry and Associates, 1991). Thus the emissions of a typical 3-mile park-and-ride trip are not too much different than those of a typical 10-mile solo commute (Cervero, 2001).

How much of the ridership bonus assigned to transit-oriented living is due to spatial proximity or the nature of people who opt to live in these settings? Might many residents of transit-based housing still be riding transit even if they lived away from a rail station? Boarnet and Crane (2001) argue that travel patterns are partly a result of the decision on where to live and this needs to be accounted for when studying how urban design, including transit oriented development (TOD), influences travel behavior. Self-selection – i.e., the tendency of those with a predisposition toward transit to reside in areas well-served by transit – could be occurring for any number of reasons: to reduce the stress of driving to work, to save time and money, or to express one’s support of “green” transportation. Voith (1991) suggested that residential sorting largely explained ridership gains during the 1980s along commuter rail lines in Philadelphia’s middle-class suburbs, though no statistical evidence was presented. Several California surveys provide some empirical support for the self-selection argument. A 1992 survey of 27 housing projects near rail stations in northern and southern California asked residents how they got to work at their prior residence (for those who previously lived in the same metropolitan area but beyond one mile of a station and whose work sites remained unchanged). The study found 42.5 percent and 13.7 percent previously commuted by rail and bus, respectively – some four to five times higher than regional averages (Cervero, 1993; 1994). Another study found those living near Santa Clara County’s light-rail line patronized transit as their predominant commute mode five times as often as residents countywide; self-selection was evident in that 40 percent of the respondents who moved close to rail stops said they were influenced in their move by the presence of light rail (Gerston & Associates, 1995).

This article examines the influence of transit-based housing on rail commuting in the San Francisco Bay Area, focusing on the self-selection question. Past research has

modeled mode choices among residents of transit-based housing using single logit model structures (Cervero, 1994) or regression models based on highly aggregate data (Pushkarev and Zupan, 1977; Bernick and Carroll, 1991; Parsons Brinckerhoff Quade and Douglas, Inc., et al., 1995). Under a logit formulation, factors like travel times of competing modes and demographic characteristics of trip-makers are used to predict probabilities residents opt for rail transit to reach their workplaces. This research aims to improve upon model specifications by rooting the analysis more firmly in urban location theory – namely, by expressing mode choice as a derivative of peoples’ decision to reside near a rail station. The decision to commute by rail, it is hypothesized, is significantly explained by residential choice.

Using year-2000 travel data from the Bay Area, a nested logit model is estimated that expresses the decision to live near a rail station as an antecedent to the decision to commute via transit. Those whose workplaces are well-served by transit, and especially those who live in less traditional, smaller households, are thought to be drawn to residences that are well-served by transit. Transit-oriented living in turn is thought to lower automobile ownership levels, further inducing transit ridership.

Besides improving model specification, framing mode choice as part of the residential sorting equation can aid policy-making in several ways. One, transportation planners can use the results to improve forecasts of ridership impacts (and related mobility and air-quality benefits) of transit-based housing -- e.g., in testing a transit-oriented development (TOD) scenario using a integrated land-use and transportation modeling, such as the recently done in Sacramento (Hunt et al., 2001). Two, evidence on rail usage among residents of transit-based housing can be used to establish credits and off-sets against transportation impact fees. In the Bay Area, the Santa Clara County Congestion Management Agency presently recommends a 9 percent reduction in estimated trip generation levels when setting impact fees for new housing projects that lie within 2,000 feet of a light rail or commuter rail station. Research can also help inform policy initiatives like LEM programs by shedding light on the commuting cost savings of transit-based housing. And for the growing legion of developers who are building housing near rail stations, research on self-selection can throw light on the kinds of households who are most inclined to move to station areas.

The demand for transit-based living, proponents argue, will likely increase on the heels of America’s smart growth movement. One contributor to transit-based housing could be changing demographics – e.g., baby-boomers reaching retirement age, forming a market of empty-nesters who are apt to be more receptive to transit-oriented living; increases in the share of non-traditional and childless households; and the steady influx of foreign immigrants, some who bring with them a heritage of transit-oriented living (Cervero, et al., 2002). Such trends underscore the value of studying the mechanisms that shape mode choice among those living near rail stops.

## 2. ANALYTICAL FRAMEWORK

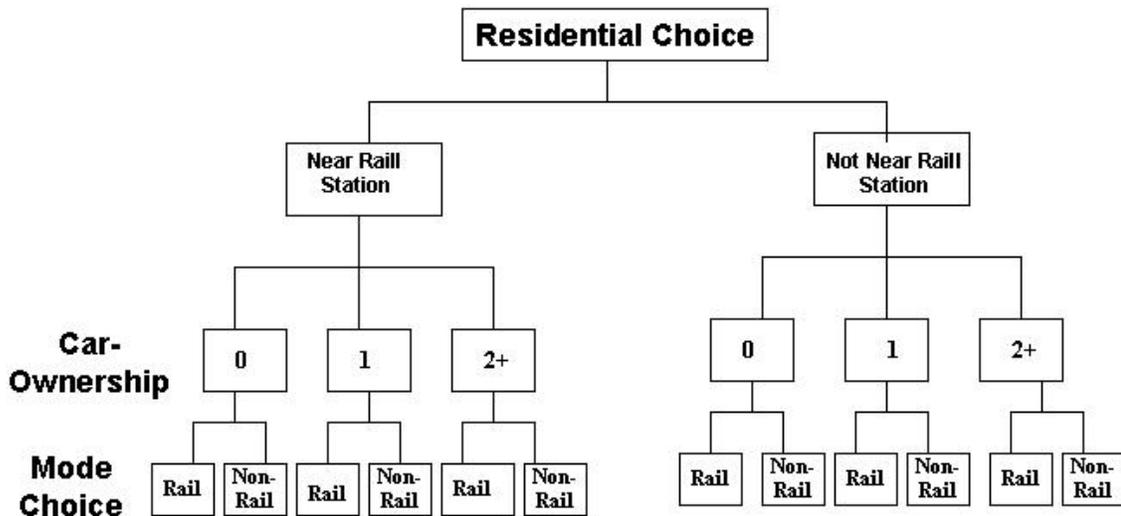
A conceptual three-tiered model of residential sorting, vehicle ownership, and mode choice is shown in Figure 1. In this tree diagram, residential location is expressed in binary terms: either one lives near (i.e., within ½ mile) of a rail station or not. Residential location in turn influences car ownership levels, expressed in the figure as zero, one-, and two-plus car households. The lowest level of the tree, mode choice, is represented as a product, in part, of car-ownership. This nested model structure is hierarchical and sequential, treating the influences of proximity to transit on mode choice as indirect – i.e., channeled through the car ownership variable.

Multinomial logit (MNL) equations of the following form could be used to model choice sets at each branch of the tree – i.e., residential, vehicle ownership, and commute mode choices:

$$P_{n,i} = \exp(V_{n,i}) / [\sum_{j \in C_n} \exp(V_{n,j})] \quad (1)$$

- $P_{n,i}$  = probability person n chooses option i
- $C_n$  = choice set available to person n
- $V_{n,i}$  = measurable component of utility for person n choosing option i.

In the case of mode choice, the equation predicts the probability someone will choose a private car, public transit, or some other travel means as a function of differences in utilities among competing modes as well as attributes of the traveler, drawing its logic from consumer choice theory (McFadden, 1974; Ben-Akiva and Lerman, 1985). The utility of an alternative is a function of the explicit terms in the utility expression ( $V_{n,i}$ ), unknown parameters, and an additive, Gumbel-distributed error term. The assumption



**Figure 1. Three-Tiered Nested Choice Structure: Residential Sorting-Car Ownership-Commute Mode**

that error terms are identically and independently Gumbel-distributed leads to a tractable estimation of the model's parameters. Whenever inter-related hierarchical relationships exist, as in Figure 1, however, the assumption of independence breaks down, producing potentially biased parameter estimates. This is because some of the alternatives are more related to each other than others (e.g., zero-car households are more strongly a function of transit-oriented living than 2+ car household). It is the relatedness among subsets of utilities that violates the MNL model's assumption of independence. Nested logit (NL) models that explicitly account for interdependence among alternatives are preferred to MNL under such circumstances (Sobel, 1980; Hensher and Green, 2002). Nested logit has been used extensively to estimate mode choice wherein a lower level choice (e.g., bus or rail) is a derivative of an upper level choice (e.g., transit), thereby accounting for the correlation of utilities and unobserved effects. Past studies by Lerman (1976) and Anas

(1986) have adopted a similar model structure for estimating travel demand as a consequence of residential location choice. Our study is, as far as we know, the first to apply this approach to jointly model mode and residential location choices among those residing near rail transit.

## **2.1 Case Context**

The San Francisco Bay Area was chosen as a case context for this research for several reasons. One, according to the Texas Transportation Institute, the Bay Area has among the worst traffic congestion in the United States, ranking second in terms of annual person-hours of delay in 2000 (Lomax and Schrank, 2002). Congestion increases commuting costs, which in turn likely draws households to rail-served locations that wish to economize on travel costs. Two, the Bay Area has among the highest housing prices in the United States, prompting many households to give up private single-lot living for smaller, more affordable units, some of which have been built by not-for-profit housing corporations around rail stations (Bernick and Cervero, 1997; Parker et al., 2002). Third, the Bay Area features a variety of inter-city rail services that are intensively used for commuting, and each of the main systems serves a different geographic setting – BART, which serves the East Bay plus the city of San Francisco; the Valley Transit Authority’s (VTA) Light Rail Transit (LRT) system, serving the city of San Jose and other communities in the Silicon Valley; and three commuter rail systems: CalTrains (spanning San Mateo County between the cities of San Jose and San Francisco); Altamont Commuter Express (ACE, connecting San Jose to pockets of affordable housing in California’s central valley); and the Capitol Corridor Express (that runs from the coastal areas of the East Bay to the city of Sacramento). Last, fairly recent travel data were available from the Bay Area that supplied sufficient numbers of cases and suitable variables to support the analyses.

## **2.2 Data Base and Sample Frame**

The chief data base used to carry out this research was the 2000 Bay Area Travel Survey (BATS) which contains up to two days of daily activity information for members of 15,066 randomly selected households in the nine-county San Francisco Bay Area. Trip records were extracted from the household activity survey, providing information on the purpose, mode, longitudinal-latitude coordinates of origins and destinations, and

other features of the journey. Records were then extracted for commute trips (for journeys in the home-to-work direction) that began in cities that have one or more rail stations within their jurisdictions, excluding the city of San Francisco. We focused solely on journeys to work since classic location theory holds workers trade-off commuting and housing costs when choosing a residential location (Alonso, 1964). San Francisco residents were excluded since residential sorting is thought to hold mainly for non-central locations where high levels of transit services are limited to rail corridors. In dense cities like San Francisco, residential sorting becomes less relevant since high-quality transit is fairly ubiquitous. Also, we examined only commutes by motorized means since residential location is mainly influenced by regional transportation systems, like highways and rail transit, as opposed to neighborhood-scale bicycle and pedestrian facilities.

To each trip record, we appended information about trip-makers (e.g., occupation) and their households (e.g., vehicle availability) from the BATS personal and household data files. Several additional sets of variables were also linked to each record. One set consisted of 0-1 dummy variables that designated whether a traveler's residence was within  $\frac{1}{4}$ ,  $\frac{1}{2}$ , and one mile radii of an inter-city rail station in the San Francisco Bay Area. (Rail systems that operate within a single city, like San Francisco Municipal Railway's light rail, trolley, and cable car services, were excluded since they do not provide regional connectivity; this was necessary given that residential location choices were studied for non-San Francisco residents.) Variables were also created to denote whether a traveler's workplace was within  $\frac{1}{4}$ ,  $\frac{1}{2}$ , or one mile distance rings of stations. Geographic Information Systems (GIS) tools allowed us to pinpoint locations given longitudinal-latitude coordinates. GIS was also used to estimate job accessibility indices via both highway and transit networks, expressed as cumulative counts of year-2000 employment (across traffic analysis zones) within 15, 30, 45, and 60 minute isochrones of residences. GIS was likewise employed to measure neighborhood attributes, like densities and median household incomes, for one-mile radii of residences and workplaces using year-2000 census data and employment estimates maintained by the Association of Bay Area Governments. Additionally, comparative network travel times for highway and transit were assigned to each trip record using the Metropolitan Transportation Commission's

1099x1099 work-trip travel-time matrices. In all, 14,285 observations were available for estimating commute choice as well as residential location (near or not near rail stations) and car ownership levels.<sup>1</sup>

We note that our research focuses on location and mode choices solely with respect to inter-city rail systems as opposed to bus lines or other forms of mass transit. This is because exclusive-guideway rail is generally more time-competitive with the private automobile than conventional bus services and thus confers significant regional mobility benefits, especially during congested peak periods. While residents plausibly locate near rail stations to reduce commuting costs, it is hard to imagine many being drawn to a bus route for this reason.

### **2.3 Model Structure**

The three-tiered hierarchical model shown in Figure 1 suggests a sequential selection process, however there is no a priori reason why this should be the case. The decision to live near transit and reduce the number of cars in the household might be jointly made, and indeed, the decision to routinely take rail to work might be bundled with these choices as well. Absent any theoretical or empirical basis for modeling the process sequentially, a simultaneous-nested logit procedure was chosen (using full information from the lower nests to affect the scaling parameters of the upper nests).

More problematic in simultaneously modeling residential location, car ownership, and commute-mode choice using year-2000 BATS data was the shortage of cases for some of the choice sets at the lowest level. Notably, there were only 23 cases (less than two-tenths of one percent of the sample) of persons who rail-commuted, lived within  $\frac{1}{2}$  mile of a rail stop, and owned no cars, rendering discrete choice modeling impractical given so few degrees of freedom (Greene, 1997). Only a slightly larger share of the sample consisted of rail commuters living near a station from households with two or more cars.

In view of these degrees of freedom problems, a more parsimonious two-tier model was estimated instead, with the upper tier gauging the binary choice of whether to live near rail transit or not and the lower level indicating whether or not rail was taken to work. Nested logit estimation occurred by weighing lower-level factors influencing rail

mode choice in the estimation of upper-level residential location choice. Nested estimation acknowledges that the subset of utilities of mode alternatives is not independent of the utilities that explain transit-based tenancy.

The two-tiered nested logit model used in our analysis took the form:

$$P_{n,i|k} = \exp(V_{n,i|k}) / [\sum_{j \in C_n} \exp(V_{n,j|k})] \quad (2)$$

$$P_{n,k} = \exp(V_{n,k} + \Theta_k I_k) / [\sum_{j \in C_n} \exp(V_{n,j|k} + \Theta_k I_k)] \quad (3)$$

where, for the  $k^{\text{th}}$  branch of the upper tier, the inclusive term,  $I_k$ , is:

$$I_k = \ln \sum_{j \in C_n} \exp(V_{n,j|k}) \quad (4)$$

- $P_{n,i|k}$  = probability person  $n$  chooses mode option  $i$  (e.g., rail) given location choice  $k$  (e.g., near rail station)
- $P_{n,k}$  = probability person  $n$  chooses location choice  $k$
- $C_n$  = choice set available to person  $n$
- $V_{n,j|k}$  = measurable component of utility for person  $n$  choosing mode option  $i$  given location choice  $k$
- $V_{n,k}$  = measurable component of utility for person  $n$  choosing location  $k$
- $\Theta_k$  = estimated coefficient on inclusive term for location choice  $k$ .

The expression  $\Theta_k I_k$  captures feedback between the lower level (commute mode choice) and upper level (residential location choice) of the nested model, where feedback is presumed to occur simultaneously. The inclusive value parameter, theta ( $\Theta$ ), measures the correlation among the random errors due to unobserved attributes of commute-mode choice. Also referred to as a “coefficient of similarity”, significant theta values close to one are suggestive of strong unobserved similarities between residential location and commute choice whereas lower values connote weak similarities and negatives ones suggest dissimilarities.

Among variables entered into the utility expression of residential location choice model were workplace location (within a mile of a rail stop, expressed as a 0-1 dummy), job accessibility via highway and transit networks, household characteristics (such as whether or not a traditional two-adult household), vehicle ownership, and personal attributes of adult members (such as race and profession). It is noted that a separate multinomial model was estimated and is also presented. Both residential and workplace

location as well as job accessibility indicators and household socio-demographic attributes were used to predict whether a household had zero, one, or 2+ cars.<sup>2</sup> The lower tier of the nested model in Table 1, estimated separately for those living near and away from transit, included information on workplace location and car ownership levels in addition to other conventional predictors of mode choice like travel-time ratios (over the transit versus highway network for each origin-destination pair), neighborhood densities, and personal attributes of trip-makers.

The dummy variable denoting whether a workplace was near rail, we note, appears in both upper and lower tier models. Its presence in the residential choice model is in keeping with theories on commute-cost minimization advanced by Alonso (1964) and empirically tested by Giuliano and Small (1993) and others. The workplace location variable appears in the lower nest, in part, as a refined metric of comparative travel times via transit versus highway for origin-destination pairs. As commonly used in mode choice modeling, we computed travel-time ratios using average peak-period centroid-to-centroid durations over regional networks. This resolution of analysis, however, is too coarse to reflect the potential door-to-door travel-time advantages of using transit when one's workplace is within walking distance of a train station. Thus more as a metric of travel-time benefits and convenience at the egress end of a trip, dummy variables denoting whether workplaces were within a 0 – ¼ mile ring and within a ¼ - ½ mile ring of a station were used to better capture the utility of rail commuting.

Our decision to model location and mode choices binomially was based not only on sample-size considerations but also a desire to frame the analysis so as to best support public policy-making. As discussed earlier, recent policy interest in transit oriented development (TOD) has focused almost exclusively on rail transit systems. In the United States, TODs usually comprise a mix of retail, office, and housing development that spans between ¼ mile and one-mile of rail stations (Calthorpe, 1993; Ewing, 1996; Cervero et al., 2002). Thus, given that TODs are conceived as geographic entities with boundaries and edges, their planning and design tends to be binary in nature – i.e., either land lies within the TOD sphere or not. And given that the chief public benefit of TOD is transit riding, travel demand is also best treated as binary as part of an integrated analysis of residential location and commute choice. Furthermore, in the analysis that follows,

there were too few bus transit trips among those living near rail stops to support a tri-modal model of motorized commute choice. Thus, bus trips were excluded from the final analysis. The lower-tier model presented in the next section therefore represents mode choice between rail transit and automobile (drive alone and shared-ride) alternatives.

### **3. EMPIRICAL RESULTS**

Among the 11,369 cases with complete data for variables used in the nested logit analysis, most individuals (91.4 percent) lived beyond ½ mile of a BART, light rail, or commuter rail station. More than 90 percent of those in the sample, moreover, got to work by private car. Simple statistics suggests that living near rail stops strongly influenced commuting. Among those residing within ½ mile of a station, 19.6 percent got to work by rail transit; among those living beyond the ½ mile radius, the share was 8.6 percent (Chi-Square = 157.1, probability = .000). The flip-side of this is that more than 80 percent of those living within a walking distance of a Bay Area rail station drove to work! Such simple cross-tabulations, of course, fail to control for other factors, like comparative travel times, that explain mode choice, not to mention overlooking the interdependence of residential location and commuting behavior.

Nested logit results are presented in Table 1. Full information maximum likelihood estimation was used in deriving estimates. Variables were included in models' utility expressions on the basis of theory as well as statistical fits. Partly because of smaller sample sizes but also because more variables were available for specifying commute-mode choice than residential location, better statistical fits were obtained at the lower than upper level.

#### **3.1 Residential Location Choice**

The upper-level model, shown on the left-hand side of Table 1, predicts whether someone lives within ½ mile of a rail station. Models were attempted for ¼ and one mile radii as well, however the best-fitting and most interpretable statistical results were obtained for the ½ mile radius. The literature is unclear as to what radius best constitutes a comfortable walking distance to a station. Our nested structure, accounting for the

interdependence between residential location and mode choice, suggests a ½ mile radius is most strongly associated with ridership.

The model results reveal that working within a mile of station induces households to reside near transit, all else being equal. The one-mile workplace radius provided much better statistical fits than the more restrictive ¼ and ½ mile radii, suggesting that being within not only a walking distance but also a convenient feeder bus connection of a work site weighs into residential location choices. Also instrumental in the choice to live near transit is job accessibility via both highway and transit networks. The more jobs that are within a 45-minute isochrone by car over the highway network or within 30 minutes over the rail-bus network, the more likely one is to reside near a rail stop. The positive association with transit accessibility stands to reason, however why might highway accessibility also positively explain transit-based residency? We suspect this is attributable to the fact that many rail stations in the Bay Area have good freeway access, with some lying in freeway medians. This raises the possibility that some households opting to reside near rail stops are also attracted by the close proximity to freeways. Also of note is the fact that the best predicting job-accessibility isochrone was longer for highways (45 minutes) than transit (30 minutes). This could reflect the willingness of commuters to endure more time in the privacy and convenience of their cars than the often crowded conditions of mass transit during commute hours.

In terms of household attributes, the model suggests that lower-income households (making less than \$40,000 annually) tended to be drawn to rail station areas, all things being equal. This could be due to public policies that promote below market-rate housing near rail stations, especially in the redevelopment districts that surround many Bay Area rail stops. Under California law, at least 15 percent of housing produced in redevelopment districts must be leased or sold below market rates. On the other hand, being a traditional household – defined as two adults between the ages of 25 and 54 years with at least one dependent (normally a child) – discouraged transit-based residency. Traditional households presumably value other factors, such as lower density living and school quality, than proximity to transit when making residential choices.

**Table 1. Nested Logit Model Results for Upper Nest (Rail Location Choice) and Lower Nest (Rail Commute Choice).** Note: Revised from original working paper

	Upper Nest		Lower Nest: Rail Commute			
	Location Choice: Live Near Transit		Live Near Transit		Live Away from Transit	
	Coef.	T-Stat.	Coef.	T-Stat.	Coef.	T-Stat.
<i>Location Factors</i>						
Workplace within ¼ mi. of rail station (0-1)	--	--	0.703	2.92***	1.149	10.87***
Workplace ¼ - ½ mi. of rail Station (0-1)	--	--	0.477	1.82*	0.670	5.85***
Workplace within 1 mi. of rail station (0-1)	0.345	4.41***	--	--	--	--
Job accessibility index, highway network, jobs (in 100,000s) within 45 minute isochrone of residence	0.013	2.10**	--	--	--	--
Job accessibility index, transit network, jobs (in 100,000s) within 30 minute isochrone of residence	0.105	1.50	--	--	--	--
<i>Transportation Attribute</i>						
Travel time ratio (transit network/highway network, centroid to centroid)	--	--	-1.422	10.20***	-1.806	26.33***
<i>Household/Neighborhood Attributes</i>						
0 cars in household (0-1)	1.931	7.16***	3.468	6.20***	3.394	9.48***
1 car in household (0-1)	0.859	6.95***	1.537	4.24***	0.709	5.88***
2 cars in household (0-1)	0.302	3.10***	0.673	1.82*	0.400	3.72***
Lower-income household, annual household income < \$40000 (0-1)	0.129	1.162				
Traditional household (2 adults, 1+ dependents; mid-stage of lifecycle, adults 25-54 years of age) (0-1)	-0.206	2.55***	--	--	--	--
Neighborhood density (no. dwelling units, in 10000s, within 1 mi. radius of residence)	--	--	0.287	1.48	0.219	2.81***
<i>Personal Attributes</i>						
Driver's License (0-1)	--	--	-1.235	2.75***	-1.564	5.93***
Age 55+ years (0-1)	-0.620	5.35***	--	--	-0.606	1.91*
Asian-American (0-1)	0.304	2.67***	--	--	0.264	1.85*
Hispanic (0-1)	0.225	1.57	--	--	--	--
Sales-Labor Profession (0-1)	-0.177	2.39**	--	--	--	--
Theta (Live Near)	0.784	2.69***				
Theta (Live Away)	0.620	2.03**				
Constant	-3.10	23.89***	1.347	2.01**	1.985	5.33***
<i>Summary statistics</i>						
No. of cases		10 968		1,031		10,338
X <sup>2</sup> (prob.)		368.2 (.000)		435.1 (.000)		2,864.9 (.000)
Rho-square (Nagelkerke)		0.074		0.521		0.503
*Significant at 0.10 level **Significant at 0.05 level ***Significant at 0.01 level						

Table 1 also shows that lower levels of car ownership (relative to the suppressed category of 3+ cars per household) increased the chance of rail-based residency. We note that car ownership likely influenced the decision to live near rail, however the opposite likely also holds – living near rail reduced car ownership. The endogeneity of this relationship is difficult to untangle with cross-sectional data, however we acknowledge the possibility of endogeneity bias in our analysis.

From Table 1, also positively associated with the decision to reside near rail stations were racial-ethnic, age, and occupational attributes of adult household members. Asian-Americans and Hispanics tended to be more attracted to station areas than whites. This could reflect a cultural dimension, especially in the Bay Area where many residents are recent immigrants from Latin America and Asia, bringing with them a heritage of transit-oriented living (Cervero, 1996). In contrast, older individuals and those working in sales and as laborers tended to shy away from rail locations. This latter negative association could reflect the car dependence of persons engaged in door-to-door sales and among laborers (e.g., construction workers) whose job sites regularly change.

An indicator that nesting is appropriate is compliance with the McFadden condition that holds the theta parameter on the inclusiveness term should lie within a  $|0-1|$  interval (McFadden, 1974). Both theta values meet this criterion and are statistically significant at .05 probability level or better. Based on the signs of coefficients, there appears to be unobserved similarities between rail commuting and transit-based residency, contrasted by unobserved dissimilarities between rail commuting and living beyond a half mile of a station. We infer that the nested logit structure appropriately characterizes residential location and commuting for the Bay Area in year-2000.

### **Car Ownership Model**

While not estimated as part of the nested model structure, the multinomial logit results shown in Table 2 indicate that both residential and workplace locations had strong bearings on car ownership levels. Coefficient estimates reveal differences relative to the suppressed category, zero-car households. Living within  $\frac{1}{2}$  mile of stations significantly

**Table 2. Multinomial Logit Results of Household Car Ownership (1 Car, 2+ Cars; 0 Car Category Suppressed)**

	1 car in household		2+ cars in household	
	Coeff.	T-Statistic	Coeff.	T-Statistic
<i>Location Attributes</i>				
Reside within 1/2 mi. of rail station (0-1)	-0.943	35.14***	-1.717	102.08***
Work within 1/2 mi. of rail station (0-1)	-0.429	8.193***	-0.890	33.22***
Job accessibility index, auto network, jobs (in 100,000s) within 30 minute isochrone of residence	0.031	1.98	0.032	2.02
Job accessibility index, transit network, jobs (in 100,000s) within 45 minute isochrone of residence	-0.191	1.70	-0.250	2.73*
<i>Household Attributes</i>				
Household size, no. persons	0.114	1.94	1.071	170.02***
Lower-income household: <\$40,000 annual income (0-1)	-2.031	56.16***	-3.961	208.08***
Middle-income household: \$40,000 to \$75,000 annual income (0-1)	-0.871	9.92***	-1.952	50.02***
Own residence (0-1)	0.881	22.47***	2.005	114.58***
African-American householder (0-1)	-0.376	2.59*	-1.183	22.40***
<i>Constant</i>	4.004	137.31***	2.796	66.22***
<p><i>Summary Statistics</i>            No. of cases = 2,760 1-car households &amp; 9,696 2+ car households            Chi-Square (prob.) = 5,243.0 (.000)            Rho-Square: <math>1 - L(I)/L(0) = .341</math>            *** significant at .01 level            ** significant at .05 level            * significant at .10 level</p>				

lowered the likelihood of having one car, and lowered them even more for the two-or-more car option. These findings lend empirical support to the Location Efficient Mortgage (LEM) concept as well as zoning codes that lower parking standards for housing projects near rail stops, such as introduced over the past decade in Portland, Oregon and Montgomery County, Maryland. Working near rail also lowered the odds of owning two or more cars, though more weakly than in the case of rail-based living. Predictably, job accessibility by highway positively influenced car ownership whereas job accessibility by transit was negatively associated, all else being equal. Among household attributes, car ownership tended to increase with household size and home

ownership and was generally lower among African Americans and for low and middle income households.

### **Commute Mode Choice Model**

The right-hand side of the nested logit model from Table 1 presents the commute-mode choice results, stratified by those who live within ½ mile of a station and those who do not. Even controlling for residential location, working in close proximity to transit significantly affected the odds of rail commuting. As noted previously, these dummy variables help to augment the coarser measure of comparative zone-to-zone travel times by providing a finer-grained measure of a destination's proximity to transit. Coefficients suggest a gradient effect, with the likelihood of rail-commuting greatest for workplaces within ¼ mile of a rail stop and higher for the ¼ to ½ mile ring than the suppressed category of ½ mile and beyond. Consistent with mode-choice theory, the travel-time ratio was by far the strongest single predictor of whether one commuted by rail transit.<sup>3</sup>

While car ownership was not imbedded into the nested logit structure, it clearly exerted a strong influence on rail commuting as a direct predictor variable. Living in a zero-car household significantly increased the odds of rail commuting, both for those living near and away from stations. Having one and two cars also increased the odds (relative to the suppressed category of 3 or more cars), although not as strongly as being in a carless household. Together, the findings that transit-oriented living reduces car ownership and that fewer cars are associated with transit commuting lends empirical support for reduced, or at least flexible, TOD parking standards.

Lastly, Table 1 shows that personal attributes also influenced mode choice. Most important was the presence of a driver's license, which tended to deter rail commuting, even after controlling for car ownership levels. Among those living away from transit, the likelihood of rail commuting tended to be lower for workers above 55 years of age and higher for Asian-Americans.

## **4. PROBABILITY ESTIMATION AND SENSITIVITY TESTING**

The nested logit results allowed conditional probabilities to be estimated, which were used to further probe the self-selection process and to conduct sensitivity tests. This section presents these supplemental analyses.

#### 4.1 Probabilities and Self Selection

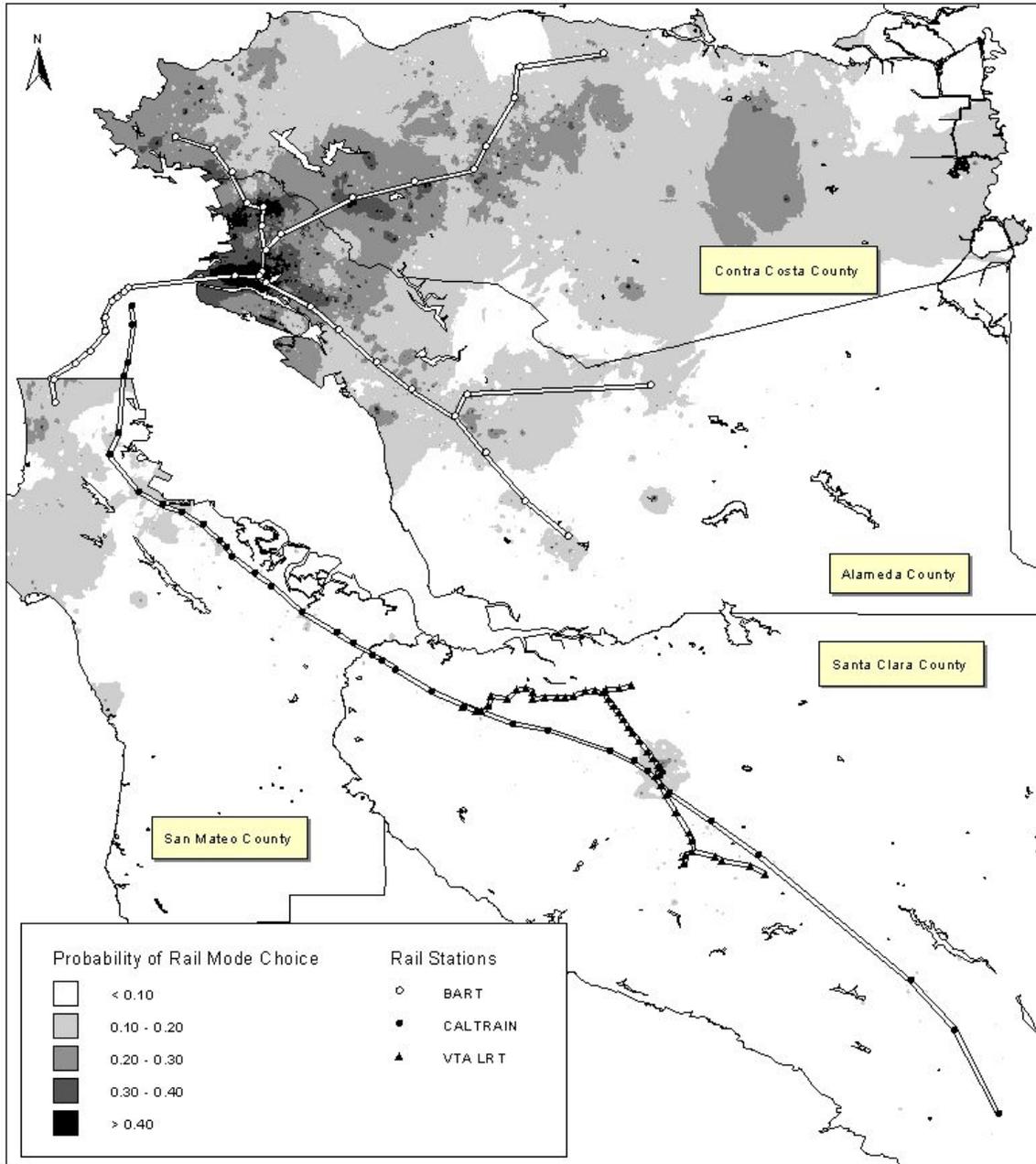
The probability of commuting by rail (R) can be expressed as the sum of the joint probabilities of taking rail and living near transit,  $p(R \& NT)$ , and of taking rail and living away from transit,  $p(R \& AT)$ . These joint probabilities, in turn, can be derived from the conditional probabilities generated from the nested logit output:

$$p(R) = [p(R \& NT) + p(R \& AT)] = \{[p(NT) * p(R | NT)] + [p(AT) * p(R | AT)]\}. \quad (5)$$

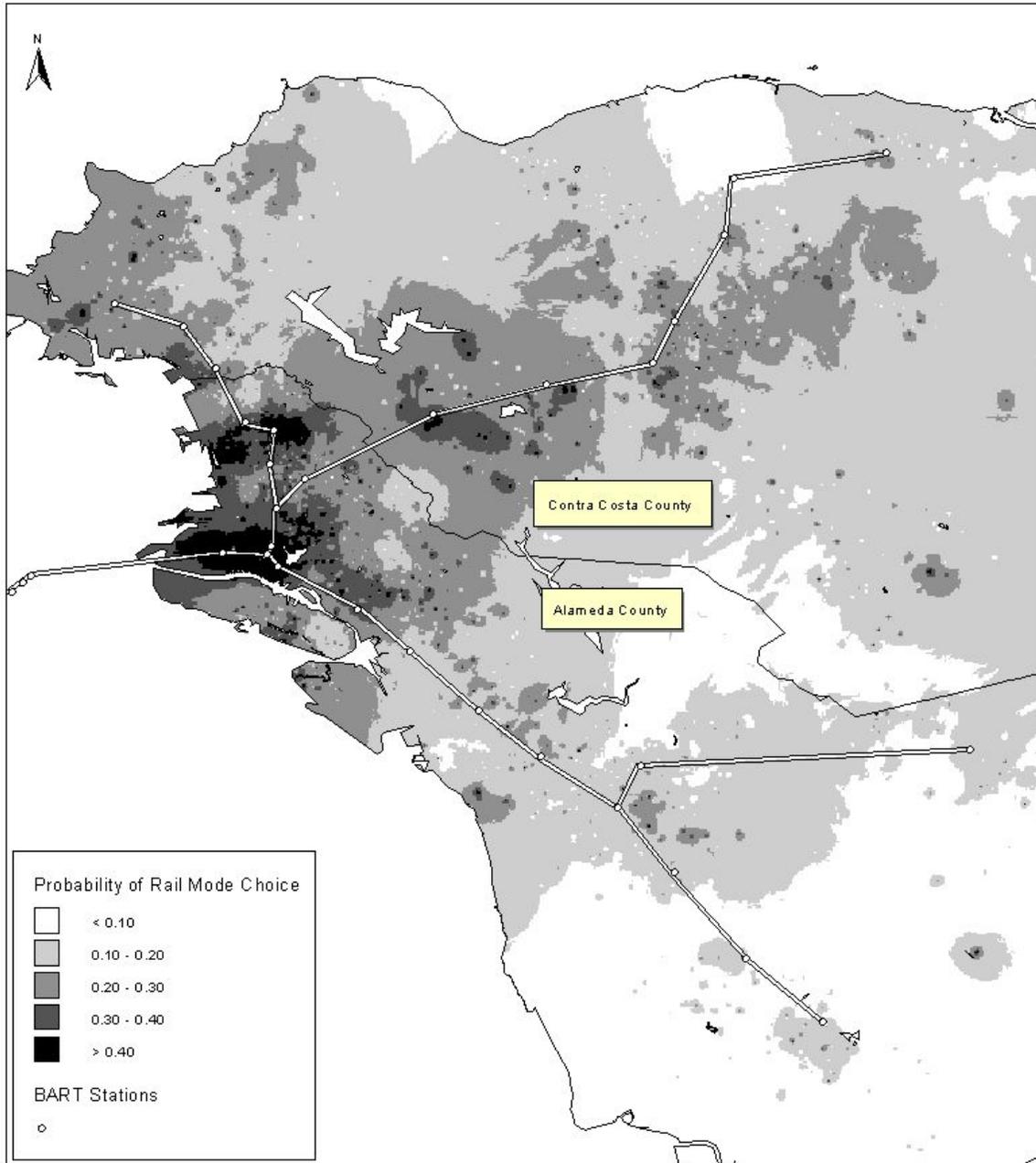
Using equation 5, probabilities of rail commuting were computed for the 11,533 sample cases used in estimating the nested logit models. Figure 2 plots probabilities of rail commuting by places of residence (i.e., according to longitudinal-latitude coordinates) in relation to BART, CalTrain, and VTA light rail transit services. Figure 3 zooms in on plotted probabilities along BART corridors in the East Bay (Alameda and Contra Costa Counties).<sup>5</sup> (Note that the City of San Francisco is omitted from the maps since it was excluded from the analysis.) The figures reveal that the spatial relationship between ridership and proximity to rail stops is fairly strong in the urbanized portions of the East Bay (particularly for the bay-shore cities of Oakland and Berkeley) and weaker as one moves outward from urban centers. Along the CalTrain corridor in San Mateo County and in much of Santa Clara County, no discernable spatial relationship appears to exist. The absence of distinct patterns in these lower density, more outlying settings is likely attributable to the reliance upon park-and-ride as a means of accessing suburban rail stops. Park-and-ride diminishes the value of living within walking distance of stations.

From the 11,533 sample cases, the following probability averages were computed for the upper level and lower levels of the nested logit model:

$$\begin{aligned} p(NT) &= .0880 \\ p(AT) &= .9120 \\ p(R | NT) &= .1547 \\ p(R | AT) &= .1144 \end{aligned}$$



**Figure 2. Probability Plot of Rail Commuting Among Sampled Residents of Four Rail-Served Counties in the San Francisco Bay Areas (Excluding San Francisco): Alameda, Contra Costa, San Mateo, and Santa Clara Counties**



**Figure 3. Probability Plot of Rail Commuting Among Sampled Residents of Alameda and Contra Costa Counties in the East Bay**

where NT = “live near transit”, AT = “live away from transit”,  $R \mid NT$  = “rail commute given live near transit”, and  $R \mid AT$  = “rail commute given live away from transit”. From these results the following joint probabilities were computed:

$$p(R \& NT) = [p(NT) * p(R \mid NT)] = (.0880)(.1547) = .0136$$

$$p(R \& AT) = [p(AT) * p(R \mid AT)] = (.9120)(.1144) = .1043$$

Inputting these values into equation 5 produced the following average probability of rail commuting:

$$p(R) = .0136 + .1043 = .1169$$

In words, the model predicts that well over 90 percent of Bay Area households reside beyond ½ mile of a rail stop, comparable to the sample proportion. All else being equal, if a Bay Area worker lived near transit, the odds of them rail-commuting was higher than if they lived away from transit – on average, a 15.5 percent versus 11.4 percent likelihood. Still, most workers living near stations were not likely to rail-commute: the average probability of not rail-commuting, 84.5 percent, was also in line with the sample proportion. The overall likelihood of rail commuting, regardless of place of residence, was 11.7 percent. The joint probability estimates reveal that a large majority of Bay Area rail commuters live away from transit, underscoring the importance of providing ample park-and-ride facilities and good bus feeder connections in serving this market.

The influence of self-selection on transit ridership can be inferred by comparing odds ratios based on mean conditional probabilities of rail commuters living near  $[p(R \mid NT)]$  versus away from  $[p(R \mid AT)]$  stations. For those living near stations, the average odds ratio of rail commuting is .1830 (.1547/.8453). Among those living beyond ½ mile of stations, the average ratio is .1292 (.1144/.8856). And among the entire sample, the mean odds ratio is .1324 (.1169/.8831). Thus, the odds of rail commuting are 41.6 percent  $[(.1830/.1292)*100]$  greater if one lives near versus away from transit, all else being equal. Compared to the typical Bay Area rail commuter, the odds of taking a train to work are 38.2 percent  $[(.1830/.1324)*100]$  higher for those residing near stations. By inference, the approximately 40 percent greater odds of rail commuting among those living near stations is due to proximity since the logit models directly controlled for the influences of other factors like comparative travel times, places of work, and socio-demographic characteristics of travelers and their households. One could interpret this to

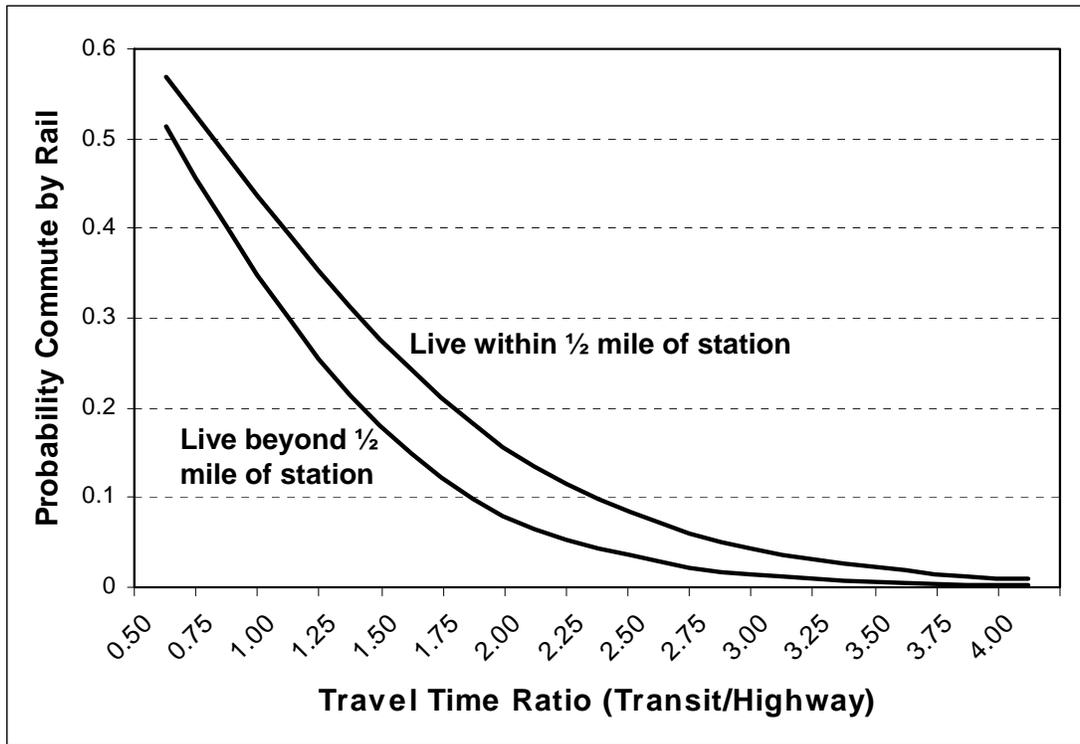
mean that around 40 percent of the higher rail-commuting shares among Bay Area workers living near transit are explained by self-selection. This inference equates proximity to stations with residential self-selection, once other factors are statistically controlled. Given the above-calculated differences in odds ratios and the fact that many other mode-choice factors were imbedded in the utility expressions of the nested logit models, we feel this reasonably reflects the degree to which self selection explains higher ridership among those residing near rail transit.

#### **4.2 Sensitivity Testing**

The affects of several policy variables on the likelihood of rail commuting were probed by conducting sensitivity tests. This was done by inputting average values of control variables in the utility expressions of the lower-level mode-choice models.<sup>4</sup> Values of policy variables, like car ownership levels and travel-time ratios, were then systematically varied to gauge likely changes in the probability of rail commuting for the typical Bay Area worker.

One sensitivity test recorded how probabilities varied by travel time ratios among those living within ½ mile of a Bay Area rail station versus those living beyond ½ mile. Consistent with the mode-choice results, Figure 4 shows probabilities varied sharply with travel-time ratios, both for those living near and away from transit. If transit travel is twice as fast as by car, the models predict that more than half of both sets of commuters will get to work by train. For the median case in the sample wherein it takes 2.25 as much time to get to work via transit as automobile, there is around an 7 percent differential in the probability of rail commuting for those living near versus away from a station – i.e., 0.12 versus 0.05 probability. The largest probability differential, 10 percent, is for a travel-time ratio of 1.50.

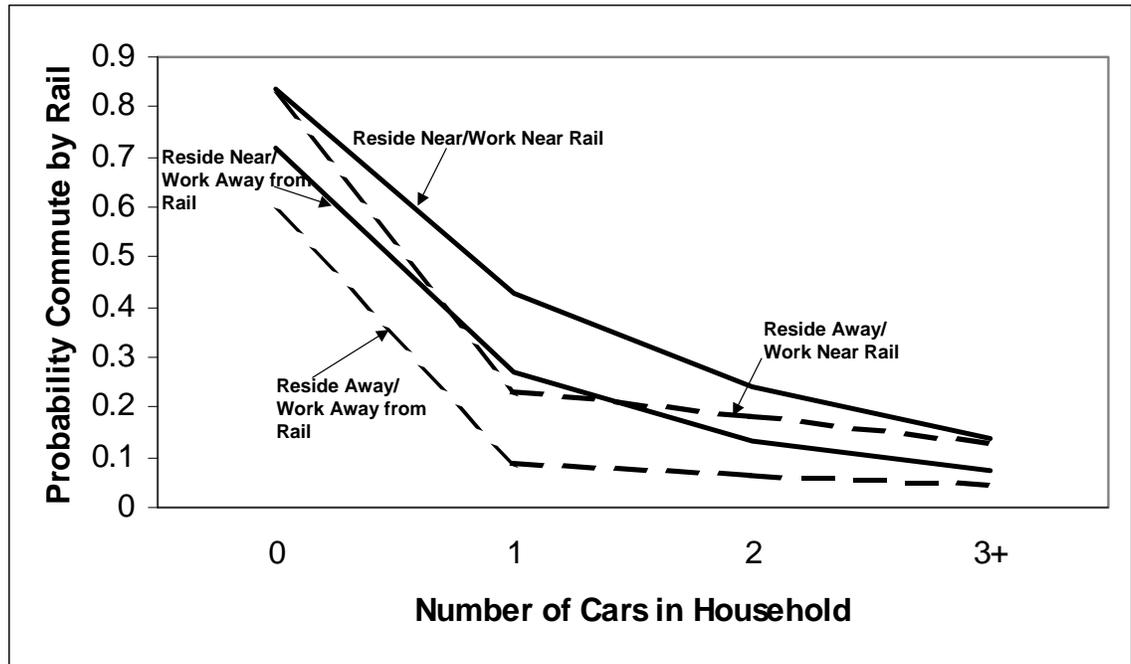
A second set of sensitivity tests examined how probabilities varied as a function of three policy variables: residential location (within ½ mile of a station or beyond); workplace location (within ¼ mile of a station or beyond); and household car-ownership levels (0, 1, 2, 3+). The resulting sensitivity plot, Figure 5, shows probabilities of rail commuting are very high among all groups when the worker lives in a zero-car household. Adding one car results in probabilities plummeting for all groups; they fall most precipitously for those residing and working away from stations. For residents of



**Figure 4. Sensitivity Plots of Rail-Commute Probabilities by Travel Time Ratios for Those Living Near and Away from Stations**

transit-based housing, probabilities fall more gradually with car-ownership levels. For those living away from transit, the likelihood of rail-commuting is not much different between two-car and three-or-more-car households. And for those living and working away from a rail stop, the odds of commuting by rail is about the same for a one and 3+ car household – less than 1 to 10.

Figure 5 also reveals that working near transit interacts with car-ownership levels to produce different probabilities among station-area dwellers and their counterparts. Working near transit and having no cars means there is a very high likelihood, well over 80 percent, of rail-commuting for both groups. Adding a car to the household results in



**Figure 5. Sensitivity Plots of Rail-Commute Probabilities by Number of Cars in Household for Those Living and Working Near and Away from Stations.** Reside Near = ½ mile or less; Work Near = ¼ mile or less.

the probability dropping far more sharply for non-station-area residents, however – notably, to below the probability (0.28) for station-area residents who work beyond ¼ mile of a station. This suggests that an appreciable share of station-area dwellers who rail-commute do so out of choice rather than necessity, further hinting that self-selection has taken place. Adding a second car to a station-area household, however, reduces the probability of rail-commuting sharply, below that of a non-station-area worker from a two-car household whose job site is near a rail stop. This indicates that the transit-ridership benefits of transit-based housing come from those with relatively few – i.e., under two – cars in the household. This lends further credence to the view that below-code parking standards are appropriate for housing projects near rail stations.

## **5. SELF-SELECTION AND TRANSIT-BASED HOUSING POLICIES**

Our nested logit results suggest interdependence between transit-oriented tenancy and rail commuting, lending empirical support to the argument that self-selection significantly accounts for the ridership bonus of TODs. These results are consistent with other research showing that compact, mixed-use neighborhoods reduce car travel, partly because those who dislike driving consciously choose to live in such settings (Boarnet and Sarniento, 1998; Boarnet and Crane, 2001). A chief difference, however, is that studies on the influences of urban designs on trip generation rates have employed multiple regression and instrumental variable estimation to account for the inter-relatedness of residential location and travel; for purposes of studying discrete choices, however, we adopted a nested logit structure to gain similar insights.

The presence of residential self selection does not in any way diminish the value or importance of targeting housing development to transit station areas. If anything, it underscores the importance of removing barriers to residential mobility so that households are able to sort themselves, via the marketplace, to locations well-served by transit. Public policies should focus less on designing TODs in response to, say, political smart-growth agendas and more on expanding market opportunities that allow those who wish to live near transit to act on their preferences. In particular, more flexible, market-responsive zoning should be introduced in and around rail stations that are poised for residential development. Some U.S. rail cities, notably San Diego and Mountain View, California, Portland, Oregon, Bethesda, Maryland, and Arlington, Virginia, have been pro-active in this regard (Cervero, et al., 2002). Most, however, have focused on zoning for commercial development in hopes of producing higher property tax receipts than normally yielded by housing projects. In a review of land uses near more than 200 existing and proposed rail stations in Southern California, Boarnet and Crane (1998) found little evidence of zoning for residential TODs in local zoning ordinances. They inferred that, in Southern California at least, zoning for housing is viewed as less fiscally remunerative, thus conflicting with large economic development goals.

Besides supportive zoning, a number of other recent public policy initiatives have been introduced in recent years that could spur the production of transit-based housing. One already discussed is Location Efficient Mortgages (LEMs), underwritten by Fannie

Mae and several private banks, that makes it easier to qualify for a loan to purchase a home situated near transit under the premise that lower transportation costs free up earnings for housing consumption. Another noteworthy federal action is the Federal Transit Administration's new joint development rulings that allow transit agencies to sell land, such as parking lots, to private interests without returning the proceeds to the federal treasury as long as the resulting development is "transit-supportive" in its design and tied to a specific plan aimed at station-area redevelopment. To date, transit properties in Washington, D.C., Atlanta, Portland, Southern California, and the San Francisco Bay Area have exploited this new ruling to leverage affordable housing projects on former parking lots. In the San Francisco Bay Area, several public agencies have been particularly pro-active in promoting transit-based housing. The Metropolitan Transportation Commission has set aside \$9 million under a Housing Incentive Program (HIP) as grant funds for local jurisdictions that locate compact housing near transit. To qualify for funds, a housing project must be within a one-third mile walk of a rail station, ferry dock, or bus route and provide at least 25 units per acre. Grants of \$2,000 per unit are being provided for projects built at 60 units to the acre. In fiscal year 2000-2001, HIP funding helped to create 5,323 units of new housing and 2,060 affordable bedrooms within one-third mile of a Bay Area rail or bus line. Even sub-regional governments have introduced incentive programs. The San Mateo City-County Association of Governments (C/CAG) authorizes \$2,000 in State Transportation Improvement Program (STIP) funds for each bedroom built within one-third of a mile of a rail station and at a density of 40 units per net acre or more. In fiscal year 2000-2001, more than \$2.2 million of STIP funds were transferred to local governments as a reward for adding more than 1,200 bedrooms in high-density housing near rail stops.

In close, residential self-selection underscores the importance of zoning for adequate housing production near rail stations as well as breaking down barriers to residential mobility to enable the demand for station-area living to be met. Programs like Location Efficiency Mortgages and Housing Incentive Programs that promote station-area living hold promise not only for redressing affordable housing problems in pricey real estate markets like the San Francisco Bay Area but also in enhancing urban mobility by expanding commute choices. Public policies that recognize transit commuting and

residential location are jointly related can meaningfully contribute to the attainment of such important societal goals.

### **Notes**

1. Since each one-way commute record was for a single person, location choice models were estimated for each person (given their residential longitudinal-latitude coordinates) using the same data base. Similarly, household information for each surveyed person was used to estimate household car ownership levels.
2. The definition of “cars” included vans, minivans, panel trucks, and sports utility vehicles, but excluded motorcycles, recreation vehicles, and commercial trucks kept at one’s residence.
3. Various forms of travel time were attempted as part of the nested logit modeling, including absolute differences as well as absolute values of zone-to-zone travel times via transit networks and highway networks. In all instances, the travel-time ratios provided the best statistical fits.
4. For ratio-scale variables except travel-time ratios, statistical means were inputted. For the travel-time ratio variable, median values were used instead since the sample distribution was skewed toward high values (due to some suburban areas having virtually no transit services, producing very high ratios). For nominal-scale (0-1) variables, the most frequently occurring (i.e., modal) categories were used in the sensitivity tests. The mean values of the ratio-scale variable neighborhood density were 7,100 and 6,300 units per mile radius for those living near and away from transit, respectively. The median values for travel-time ratios were 2.25 and 2.50 for those living near and away transit, respectively. The most frequently occurring categories for nominal-scale (0-1) variables (for both those living near and away from transit) were: workplace with ¼ mile of station (0); workplace ¼ to ½ mile from station (0); zero-car households (0); one-car households (0); two-car households (1); driver’s license (1); age 55+ years (0); and Asian-American (0).
5. The IDW (inverse distance weighting) procedure was applied in creating the plotted probability surfaces using the Spatial Analyst tools of Arcview, produced by Environmental Systems Research Institute, Inc. (ESRI).

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