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The introduction of a new form of passenger transportation into a region is a risky and expensive venture, requiring careful evaluation of all potential effects of the investment. One of the most important considerations is to determine who the potential users of the system might be, and the pattern of their trips that might be changed by the new mode of transport. There are two aspects to this problem. First, in the short run, some travelers will be diverted from their present mode of travel and will utilize the new mode for the trips formerly made by the old mode. Second, over a longer period of time, the new mode of transport may exert an influence of its own to alter the structure of the community.

The second effect, the long-run or secondary effect of an improved transportation system, is the subject of this study. It is much less susceptible to quantitative analysis than the first effect, and few attempts have been made toward its isolation and prediction. This paper develops a theoretical framework for evaluating one aspect of the possible change in travel patterns--changes in the residential location of urban commuters that alter the mode and length of their work trips.

Our approach to this problem is based on a theory of residential location. This theory is developed in Section I and assumes that each household, in choosing its location site, faces a three-way trade-off between the site, the quality and quantity of housing located on the site, and a composite commodity representing all other goods and services. The household bases its decision on its income, the prices of the three "goods," and its preferences for the three types of goods.

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The theory also assumes that the general level of rents varies in a more or less regular manner over the region; that is, that a particular housing unit on a certain size lot will be more expensive in a central urban location than in a suburban location. If this is true, the household may trade off a centralized location against more or better housing and/or more of the "other goods and services." Thus, the relative level of rents throughout the region is one aspect of the price of location.

The other aspect of the price of location is the commuting costs incurred by the head of the household. He is assumed to commute daily from his home to his place of work. The farther he lives from his place of work the more of his income is spent on commuting and the less is available for other expenses.

This model can be manipulated to observe the effects of a change in transport costs arising from the introduction of a new mode of commuter transportation. The prices of all three goods in the model influence each household's preferred location. A change in any of these prices may cause a family to desire to move. Our interest is in deriving an estimating equation relating changes in travel costs brought about by improvements in the transport system to changes in the household's preferred location.

In Section II we estimate this equation for a particular but hypothetical transport situation--the introduction of intraurban air transport into the San Francisco Bay Area. This application allows us to gain some insights into the implications of the theory.

I. A THEORY OF RESIDENTIAL LOCATION

The economic model presented in this section is adapted from the studies of Alonso and Muth.[1,2] Our treatment is much simpler than theirs and concentrates on a slightly different aspect of the model. Alonso was concerned with establishing and explaining the equilibrium relationships between the supply of and the demand for land for housing, industry, and agriculture. Muth was concerned with understanding the myriad details of the interactions between the demand for and supply of housing. Our interest is primarily on the relationship between the costs of transportation and the commuting patterns that are found in one city.

HOUSEHOLD BEHAVIOR

The basic model of household decisionmaking is straightforward. The household is assumed to value three variables: housing, location, and other goods and services. The housing variable, H, represents all the housing attributes that are commonly discussed, including size of the lot, type of structure, number of rooms, the age and condition of the unit, furnishings, etc. The location variable represents neighborhood attributes, environmental surroundings, access to private and public services, and proximity to business and industrial areas. It is represented by the proxy D, distance from the center of the city. The variable X represents a composite of all other goods and services valued by the household. The household is thus viewed as a single decisionmaking entity employed in the central city and possessing a utility function that may be represented as

$$U = U(X, H, D). \tag{1}$$

The household is also assumed to face a budget constraint of the form

$$Y = PX + RH + T(D, Y), \tag{2}$$

where Y represents the income of the household, P represents the price (index) of the composite commodity X, R represents the price of housing, and T stands for the travel costs that the head of the household will incur in commuting to his place of work. The time component of these costs is assumed to increase with the traveler's income.

In this formulation of the budget constraint, the price of location (or residential site rent) is not represented explicitly. It is assumed that site rents are included in the price of housing; that is,

$$R = R(D).^{*} \tag{3}$$

The household will be as well off as possible when the first-order conditions are satisfied:

$$\begin{aligned} U_x - \lambda P &= 0, \\ U_h - \lambda R &= 0, \\ U_d - \lambda(R'H + T_d) &= 0, \\ Y - PX - RH - T &= 0, \end{aligned} \tag{4}$$

where the subscripted variables represent partial derivatives and R' represents dR/dL. As is usually the case in models of this type, λ represents the marginal utility of income. The conditions in Eq. (4) can also be written as

$$\lambda = \frac{U_x}{P} = \frac{U_h}{R} = \frac{U_d}{R'H + T_d}. \tag{5}$$

Thus, the utility of the household will be maximized when its income is allocated in such a manner that the ratios of the marginal utilities of the goods to their prices are equalized; that is, the last dollar spent on each good results in the same increment of satisfaction.

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*This relation may become clearer conceptually if we think of H as a vector of housing attributes. Then R becomes a vector of prices, and the price element associated with the land element of housing represents the site rent and varies from location to location.

From Eq. (5) it is clear that the "price of location" in this model is composed of two factors: the site rent portion of R and travel costs T. If the household contemplates moving to a more desirable neighborhood it will encounter a rise in its housing costs of R'H and a change in its travel costs of T_d.

At this point, it should also be obvious that the relationship between the rent function, R(D), and the travel cost function, T(D), is critical for the attainment of equilibrium. As $U_d < 0$, Eq. (5) can hold only when $(R'H + T_d) < 0$. If we limit our analysis to households employed in the central city T_d will necessarily be positive. R'H, on the other hand, will generally be negative.* Hence, an interior solution is possible only if $R'H > - T_d$. That is, living away from the center of the city is undesirable, and the household will be induced to do so only if the savings in housing expenditures are greater than the increased commuting costs.

DISPLACEMENT OF EQUILIBRIUM

In this section we shall derive an equation relating changes in commuting costs to changes in commuting patterns. First, we will demonstrate the peculiarities of a theory of residential location (in contrast to the simple model of consumer behavior) by observing how

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*In most densely developed and centralized urban areas, workers encounter rents that are high in the central, downtown area and, in general, decrease with distance from the city center, reaching their lowest values in the outlying suburbs. See, for example, Refs. 3 and 4.

We investigated the rent function for San Francisco and found that while distance from downtown San Francisco can by no means explain all of the variation in the level of local rents, it is certainly the dominant factor. We developed the hypothesis that there were three area-wide influences on the level of rents: the distance from downtown San Francisco, the proximity of the areas of basic employment, and the level of service industries in the area. We were able to verify empirically all three of these influences on the level of single-family housing costs in the Bay Area, and to establish the primacy of the distance influence. The geographical differences in apartment rentals, however, proved to be far less susceptible to our analytical efforts. This research is reported in Ref. 5.

the household's consumption of the composite good X reacts to changes in its income and the price of X. Then we shall derive the responses in the consumption of H and D to changes in their prices and household income. Finally, we will convert the expression relating the change in the household's commuting distance, D, in response to a change in travel costs into two terms amenable to empirical quantification.

In the model contained in Eq. (1)

$$U = U(X, H, D)$$

and Eq. (2)

$$Y = PX + R(D)H + T(D, Y),$$

with $U_x > 0$, $U_h > 0$, $U_d < 0$, $T_d > 0$, and $T_y > 0$, the household maximizes its utility by allocating its expenditures on goods, housing, location, and travel in such a manner that the first-order conditions

$$\begin{aligned} U_x - \lambda P &= 0, \\ U_h - \lambda R &= 0, \\ U_d - \lambda(R'H + T_d) &= 0, \\ Y - PX - RH - T &= 0 \end{aligned} \qquad (4)$$

are fulfilled, as long as the second-order conditions

$$|A| \equiv \begin{vmatrix} U_{xx} & U_{xh} & -P \\ U_{hx} & U_{hh} & -R \\ -P & -R & 0 \end{vmatrix} > 0 \qquad (6)$$

and

$$|B| \equiv \begin{vmatrix} U_{xx} & U_{xh} & U_{xd} & -P \\ U_{hx} & U_{hh} & U_{hd} - \lambda R' & -R \\ U_{dx} & U_{dh} - \lambda R' & U_{dd} - \lambda(R''H + T_{dd}) & -(R'H + T_d) \\ -P & -R & -(R'H + T_d) & 0 \end{vmatrix} < 0 \qquad (7)$$

hold.

To determine how the household's preferred level of X would be altered by a change in its price, we differentiate the first-order conditions (4) partially with respect to P and solve the resulting set of equations for $\partial X/\partial P$. This process yields

$$\frac{\partial X}{\partial P} = \lambda \frac{|B_{11}|}{|B|} - X \frac{|B_{41}|}{|B|}, \qquad (8)$$

where B_{ij} represents the submatrix formed by deleting the *ith* row and the *jth* column of B. Equation (8) indicates that the change in the household's consumption of X brought about by a change in its price is composed of two terms. These terms appear identical with their counterparts in the simple model of consumer behavior when location and travel costs are not considered, and we are tempted to write Eq. (8) in the Slutsky formulation:

$$\frac{\partial X}{\partial P} = \left(\frac{\partial X}{\partial P}\right)_{U \text{ constant}} - X\left(\frac{\partial X}{\partial Y}\right)_{\text{prices constant}}, \qquad (9)$$

where $(\partial X/\partial P)_{U \text{ constant}}$ is the "substitution effect" and $- X(\partial X/\partial Y)_{\text{prices constant}}$ is the "income effect." This would not be quite correct, however; the inclusion of the travel cost variable does make a difference.

This difference is most easily seen by deriving the expression for $\partial X/\partial Y$. Proceeding as before, we differentiate the first-order conditions with respect to Y and solve to obtain

$$\frac{\partial X}{\partial Y} = T_{dy}\, \lambda \frac{|B_{31}|}{|B|} + (1 - T_y) \frac{|B_{41}|}{|B|}. \qquad (10)$$

Thus, $\partial X/\partial Y$ is not simply $|B_{41}|/|B|$ but is composed of two complex terms. This is due entirely to the inclusion of the travel cost variable. As the traveler's income enters into his calculation of his travel costs, an increase in his money income of one dollar results in an increase of only $(1 - T_y)$ in his perceived or "real income." Thus $|B_{41}|/|B|$ is the real income term but it represents only a portion of $\partial X/\partial Y$.

Since T is a function of both D and Y, it is quite possible that a change in income will alter the marginal cost of commuting, T_d. But T_d is (one element of) the price of D, so that $T_{dy}\lambda|B_{31}|/|B|$ is simply a cross-price effect, representing the effect of the change in the price of D on the consumption of X, when the change in the price of D is brought about solely by the change in the family's income. This effect will be present whenever the money income of the household is altered, Eq. (10), but is not present when the price of a commodity changes, Eq. (8).

Using Eq. (10) and defining

$$\lambda \frac{|B_{11}|}{|B|} \equiv \left(\frac{\partial X}{\partial P}\right)_{U\ \text{constant}} \qquad \text{and} \qquad \lambda \frac{|B_{31}|}{|B|} \equiv \left(\frac{\partial X}{\partial T_d}\right)_{U\ \text{constant}} \tag{11}$$

we can specify Eq. (12) in an amended Slutsky fashion as

$$\frac{\partial X}{\partial P} = \left(\frac{\partial X}{\partial P}\right)_{U\ \text{constant}} - \frac{X}{1 - T_y}\left(\frac{\partial X}{\partial Y}\right)_{\text{prices constant}} + T_{dy}\frac{X}{1 - T_y}\left(\frac{\partial X}{\partial T_d}\right)_{U\ \text{constant}}. \tag{12}$$

Having derived these expressions for the composite commodity, it is easy to show that the analogous expressions for the housing commodity, H, are

$$\frac{\partial H}{\partial R} = \lambda \frac{|B_{22}|}{|B|} + H \frac{|B_{42}|}{|B|} \qquad (13)^*$$

and

$$\frac{\partial H}{\partial Y} = - T_{dy}\lambda \frac{|B_{32}|}{|B|} - (1 - T_y) \frac{|B_{42}|}{|B|} \qquad (14)$$

so that Eq. (13) can be expressed as

$$\frac{\partial H}{\partial R} = \left(\frac{\partial H}{\partial R}\right)_{U \text{ constant}} - \frac{H}{1 - T_y}\left(\frac{\partial H}{\partial Y}\right)_{\text{prices constant}}$$

$$- T_{dy} \frac{H}{1 - T_y}\left(\frac{\partial H}{\partial T_d}\right)_{U \text{ constant}} \qquad (15)$$

In the same fashion we can show that

$$\frac{\partial D}{\partial T_d} = \lambda \frac{|B_{33}|}{|B|} - \frac{\partial T}{\partial T_d} \frac{|B_{43}|}{|B|} \qquad (16)$$

Also

$$\frac{\partial D}{\partial Y} = T_{dy}\lambda \frac{|B_{33}|}{|B|} + (1 - T_y) \frac{|B_{43}|}{|B|} \qquad (17)$$

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*We are concerned here with a unit change in the R function that is *not* brought about by a change in D or Y, the arguments of the function. This is equivalent to introducing a shift parameter, say r, into the R function and solving the system for $\partial H/\partial r$ under the assumption that

$$\frac{\partial R}{\partial r} \equiv 1$$

(i.e., r is an element of "fixed costs"), so that

$$\frac{\partial H}{\partial r} \equiv \frac{\partial H}{\partial R}.$$

This approach is also used in the $\partial/\partial T_d$ and $\partial/\partial T$ deviations that follow.

so that we can write

$$\frac{\partial D}{\partial T_d} = \left(\frac{\partial D}{\partial T_d}\right)_{U\ \text{constant}} - \frac{1}{1 - T_y}\frac{\partial T}{\partial T_d}\left(\frac{\partial D}{\partial Y}\right)_{\text{prices constant}}$$

$$+ \frac{T_{dy}}{1 - T_y}\frac{\partial T}{\partial T_d}\left(\frac{\partial D}{\partial T_d}\right)_{U\ \text{constant}} \qquad (18)$$

These are the expressions that are of direct interest to our study.*

DERIVATION OF THE ESTIMATING EQUATION

We have been discussing effects that are difficult, if not impossible, to observe and measure from readily available market information. The object of our study, however, is to estimate the effect of a change in transport costs on the locational behavior of households.

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*At this point, it may be instructive to digress for a moment and investigate the sign of $\partial D/\partial Y$. From Eqs. (17) and (18), $\partial D/\partial Y$ may be expressed as

$$\frac{\partial D}{\partial Y} = T_{dy}\left(\frac{\partial D}{\partial T_d}\right)_{U\ \text{constant}} + (1 - T_y)\frac{|B_{43}|}{|B|},$$

where $(\partial D/\partial T_d)_{U\ \text{constant}} < 0$, and T_{dy} and $(1 - T_y)$ are probably both positive. $|B_{43}|/|B|$ is the real income effect and may be either positive or negative. Its sign is especially difficult to determine a priori as D enters the utility function in a negative manner. We can, however, express it in an alternative, more meaningful form.

Expanding the determinant $|B|$ by its fourth row, we have

$$|B| = P\,|B_{41}| - R\,|B_{42}| + (R'H + T_d)\,|B_{43}|$$

so that

$$\frac{|B_{43}|}{|B|} = \frac{1}{R'H + T_d} - \frac{P}{R'H + T_d}\frac{|B_{41}|}{|B|} + \frac{R}{R'H + T_d}\frac{|B_{42}|}{|B|}.$$

Also, from the first-order conditions

$$\frac{P}{R'H + T_d} = \frac{U_x}{U_d}$$

and

Thus, we need an expression for $\partial D/\partial T$ that is amenable to empirical estimation.

Equation (18) deals with rates-of-change. We can, however, use it to approximate finite changes. With a switch in notation from $\partial D/\partial T_d$ to $\Delta D/\Delta T_d$, we can approximate the finite change in distance as

$$\Delta D = \left(1 + \frac{\partial T}{\partial T_d}\,\frac{T_{dy}}{1 - T_y}\right)\left(\frac{\partial D}{\partial T_d}\right)_{U \text{ constant}} \Delta T_d - \frac{1}{1 - T_y}\,\frac{\partial T}{\partial T_d}\,\frac{\partial D}{\partial Y}\,\Delta T_d. \tag{19}$$

This equation has been constructed on the assumption that the only change in the transport cost function is associated with the marginal cost term. Under this condition, the full change in total transport costs, ΔT, is $(\partial T/\partial T_d)\ \Delta T_d$, which occurs twice in Eq. (19). However, many transport improvements involve a change in the fixed factor of total transport costs as well as a change in marginal transport costs. Consequently, ΔT will be equal to $(\partial T/\partial T_d)\ \Delta T_d$ plus the change in fixed cost. We shall use ΔT to represent this full change in transport costs. Making this substitution in Eq. (19) yields

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$$\frac{R}{R'H + T_d} = \frac{U_h}{U_d}.$$

Now, defining the real income effects $|B_{41}|/|B|$ and $-|B_{42}|/|B|$ as $(\partial X/\partial Y_r)_{\text{prices constant}}$ and $(\partial H/\partial Y_r)_{\text{prices constant}}$, respectively, and making all of these substitutions, we have

$$\frac{\partial D}{\partial Y} = T_{dy}\left(\frac{\partial D}{\partial T_d}\right)_{U \text{ constant}} + \frac{1 - T_y}{R'H + T_d}$$

$$- (1 - T_y)\left[\frac{U_x}{U_d}\left(\frac{\partial X}{\partial Y_r}\right)_{\text{prices constant}} + \frac{U_h}{U_d}\left(\frac{\partial H}{\partial Y_r}\right)_{\text{prices constant}}\right].$$

Now, assuming that X and H are superior goods, and using the signs we have previously attributed to the other terms, we see that

$$- (1 - T_y)\left[\frac{U_x}{U_d}\left(\frac{\partial X}{\partial Y_r}\right)_{\text{prices constant}} + \frac{U_h}{U_d}\left(\frac{\partial H}{\partial Y_r}\right)_{\text{prices constant}}\right] > 0$$

and

$$\Delta D = \left(\Delta T_D + \frac{T_{dy}}{1 - T_y}\Delta T\right)\left(\frac{\partial D}{\partial T_d}\right)_{U \text{ constant}} - \frac{1}{1 - T_y}\frac{\partial D}{\partial Y}\Delta T. \tag{20}$$

For several reasons it will be more convenient to conduct the empirical work in terms of elasticities, or percentage changes and effects. Defining

$$E_{D,Y} \equiv \frac{Y}{D}\frac{\partial D}{\partial Y},$$

the elasticity of D with respect to Y, and

$$E_{D,T_d;R} \equiv \frac{T_d}{D}\left(\frac{\partial D}{\partial T_d}\right)_{U \text{ constant}},$$

the real elasticity of D with respect to T_d, the equation becomes

$$\Delta D = D\left\{\left(\frac{\Delta T_d}{T_d} + \frac{T_{dy}}{1 - T_y}\frac{\Delta T}{T_d}\right)E_{D,T_d;R} - \left(\frac{1}{1 - T_y}\frac{\Delta T}{Y}\right)E_{D,Y}\right\}. \tag{21}$$

$$\left[T_{dy}\left(\frac{\partial D}{\partial T_d}\right)_{U \text{ constant}} + \frac{1 - T_y}{R'H + T_d}\right] < 0,$$

so that a priori the sign of $\partial D/\partial Y$ is indeterminate.

Both Alonso and Muth seem to believe that $\partial D/\partial Y$ is positive (i.e., that location is an inferior good). They argue that an increase in income will cause the household to demand more housing and other goods, and that it will move farther from the center of the city to obtain lower rents to finance these additional purchases. This equation clearly illustrates the conditions under which their argument may be true. See Ref. 1, pp. 106-107, and Ref. 2, pp. 29-34.

II. ESTIMATING THE RELATIONSHIP BETWEEN TRAVEL COSTS AND COMMUTING DISTANCE

Equation (21) indicates that the effect on the preferred residential site brought about by a change in transport costs is composed of two terms--an income effect and a substitution effect. The income effect of a decrease in transport costs may be viewed as an increase in families' disposable income. However far they were commuting previously, they now have some amount of surplus income that had been spent on commuting. According to their preferences, a portion of this surplus income may be allocated to a change in residential location; that is, they may choose a more desirable location with higher rents, or they may choose a location farther from their place of employment with higher commuting costs.

The substitution effect operates in a slightly different manner, but with similar results. A change in transport costs typically includes a change in the cost per mile of commuting--the marginal cost or price--as well as a change in the fixed element of transport costs. This change in the marginal price of location affects the households' marginal trade-offs between location and other goods and may encourage them to make a further locational change.

Each of these effects can be expressed in terms of an elasticity and a multiplier. The income effect can be expressed as the income elasticity of commuting distance--the percentage change in commuting distance brought about by a 1-percent change in money income--deflated by the income multiplier--the apparent change in income due to the change in transport cost, a term dependent on the household's income, the distance the head of household has been commuting, and both the old and the new travel costs. Similarly, the substitution effect can be expressed as the real price elasticity of commuting distance times the change in the price of commuting. The former term is the percentage change in commuting distance brought about by a 1-percent (income-compensated) change in the price of commuting (marginal travel costs), and the second term, called the price multiplier, is a complex term dependent on the household's income, the distance the head of the household has been commuting, and both the old and the new travel cost functions.

This model will now be applied to the problem of the introduction of intraurban commuter air transport in the nine-county San Francisco Bay Area. We will attempt to estimate the locational response of commuters who are employed in the City of San Francisco but resided throughout the region to the introduction of an air transport service.

The response is estimated in three steps. First, the income elasticity of commuting distance is estimated from data collected in a survey of 30,000 households by the Bay Area Transportation Study Commission in 1965. Second, the income and price multipliers are estimated for several levels of household income and commuting distances from automotive and air travel time and cost functions developed in a study prepared for NASA by the Boeing Company in 1971 and a value of travel time concept developed by a group of economists over the last fifteen years. Finally, as it is not possible to estimate the price elasticity with the data at our disposal, we postulate several plausible values for this term.

THE INCOME ELASTICITY OF COMMUTING

The data we use were collected and processed by the Bay Area Transportation Study Commission (BATSC) in conjunction with its master transportation study.[(6)] In 1965, approximately 30,000 households selected randomly throughout the Bay Area were surveyed to obtain detailed information on the household and all trips made by household members (over 4 years old) on a given day.* For locational purposes, the Bay Area was divided into several levels of regions. Each residential location and work site was identified as belonging to one of nine counties, one of 30 super districts, one of 98 districts, and one of 291 analysis zones. We have used the analysis-zone level for all

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*We obtained a complete description of the data files from BATSC; the data conversions we performed for this study may be procured by contacting the author.

of our analytical work.*

Our interest is in the relationships between work sites, residential locations, and changes in travel costs. Although the data at our disposal cover families and locations quite adequately, they contain no usable information on variations in travel costs. The data are cross-sectional, collected at essentially one point in time, and there is no possibility of observing variations in costs over time. The only mode of transportation represented adequately enough for analysis is the private automobile; thus there is no chance of observing variations in costs across modes.** Therefore, we are forced to estimate the effects of changes in travel costs indirectly. As the data do contain almost complete information on household income, our approach is to calculate cross-sectional income elasticities of commuting patterns and use these to estimate, with Eq. (21), the travel cost elasticities.

All of the subsequent work reported in this study is based on the expansion of the "Head of Household" information from the BATSC sample. Hence, we should be reasonably accurate in describing the number of households in the region. The employment totals, however, should be substantially understated, as many households have more than one employed member.***

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*The only other data source we used was the California State Department of Highways. This agency supplied us with a matrix of travel distances and travel times, by automobile, between the centroids of these analysis zones. This information was then merged with the BATSC interview data to complete the commuting profiles of the commuters who travel by car.

**Of 36,000 individual records, over 87 percent of the commuters who reported their travel mode indicated that they traveled by passenger car or pickup truck. Of the remaining 13 percent, 8 percent used public buses, over 3 percent walked, and the remainder used a number of miscellaneous modes. The bus sample appeared promising until we analyzed it and discovered that the majority of riders were either lower-income heads of household commuting very short distances, or other household members traveling to part-time jobs. Neither of these groups is representative of the people we would expect to be receptive to air transport. The remainder of the sample was too small and heterogeneous to be used.

***From the records of 36,144 persons in the BATSC file, we were able to extract usable data on 23,837 heads of household (21,255 males

To analyze the commuting behavior of the household heads, we have divided the commuting distances into blocks and added up the number of workers traveling the various distances. The percentages of the total workers in each distance block, for both the entire Bay Area and for only those working in San Francisco, are presented in Table 1. About two-thirds of all commuters live within 10 miles of where they work; and another 20 percent live between 10 and 20 miles. The remaining 10 to 15 percent commute appreciable distances each day. This table also indicates that the city worker commutes slightly longer distances than the average for the entire region. This is probably because San Francisco, and the area immediately around it, is one of the most densely developed and populated portions of the region. Also, city workers have higher incomes than their suburban and rural counterparts.

Table 1

COMMUTING DISTANCE PROFILE

Commuting Distance (mi)	Percentage of Total Commuters[a]	
	Nine-County Bay Area	Employed in San Francisco
Less than 5	45.9	39.0
5 to 10	23.7	25.9
10 to 15	11.7	12.1
15 to 20	7.3	7.2
20 to 30	7.5	9.4
30 to 40	2.4	4.0
Over 40	1.4	2.4
Total	100.0	100.0

[a]The total workers are 1,300,465 in the Bay Area and 372,320 employed in the city.

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and 2582 females). Approximately 10,400 additional records were available on fully or partially employed spouses (female), sons, and daughters. The remainder were miscellaneous household numbers. Our hypothesis is that it is the employment site of the head of household that influences the residential location decision, the employment of other household members being on a more or less opportunistic basis.

Our hypothesis is that there is an association between family income and commuting distance. To take a first look at the evidence, we separated the San Francisco workers into five income groups and derived commuting profiles for each group. These profiles are shown in Table 2, and they provide strong support for the hypothesis. There are some substantial differences between the income groups. Households with incomes of over $10,000 are almost twice as likely, compared with lower income families, to live over 5 miles from their place of work. And this holds true for most of the distances. This group is also twice as likely to commute over 40 miles. The most obvious irregularity in the data is for the highest income group, which shows a somewhat increased tendency to live in the city. We would attribute this to the fact that there is a significant amount of very attractive housing within the city for those who can afford it. Other than in the shortest distance block, however, families in this group exhibit behavior consistent with our expectations.

Table 2

COMMUTING DISTANCE PROFILES: HEAD OF HOUSEHOLD EMPLOYED IN SAN FRANCISCO, BY INCOME

Commuting Distance (mi)	Percentage of Total Commuters					
	Less than $5,000	$5,000 to $10,000	$10,000 to $15,000	$15,000 to $20,000	More than $20,000	All Income
Less than 5	53.1	41.8	26.7	26.8	31.3	39.0
Less than 10	75.0	70.5	55.7	47.5	47.4	64.9
Less than 15	85.0	82.1	69.8	63.4	58.7	77.0
Less than 20	91.1	87.5	78.1	73.8	73.0	84.2
Less than 30	96.8	94.7	90.4	91.1	89.2	93.6
Less than 40	98.8	97.8	95.9	96.8	98.0	97.6
Total (all distances)	100.0	100.0	100.0	100.0	100.0	100.0

It is also interesting to compare the commuting behavior of different types of families. We would expect that small families would have different needs and housing preferences than larger families, and that this would be reflected in their locational patterns. We divided the sample into five family-size groups, and the commuting profiles for these groups are presented in Table 3. As can be seen, the evidence again supports the hypothesis. Single-person households show a marked preference for living within the city, and as the size of the family increases the tendency to commute farther does also. There is again one small irregularity in the data, and again it is for the shortest distance block and the largest family size. Apparently, the largest families, like the wealthiest ones, are motivated by special influences that attract or restrict them to the central city.

Table 3

COMMUTING DISTANCE PROFILES: HEAD OF HOUSEHOLD EMPLOYED IN SAN FRANCISCO, BY FAMILY SIZE

Commuting Distance (mi)	Percentage of Total Commuters					
	Persons in Family					
	1	2	3-4	5-6	7-10	All Sizes
Less than 5	69.1	42.6	27.2	29.2	37.6	39.0
Less than 10	87.2	70.9	55.9	54.4	54.5	64.9
Less than 15	94.1	81.8	70.5	68.3	68.4	77.1
Less than 20	96.7	88.2	79.5	77.3	76.2	84.3
Less than 30	99.4	96.0	92.0	89.3	85.5	93.7
Less than 40	100.0	98.5	96.8	97.0	92.2	97.7
Total	100.0	100.0	100.0	100.0	100.0	100.0

Tables 2 and 3 indicate that commuting patterns do differ according to the income and family size of the households. We are now ready to estimate the income elasticity of commuting and to test whether the percentage change in commuting associated with a percentage change in income follows a regular pattern over the range of incomes represented in our data. We shall do this separately for each of the family sizes.

Our procedure in estimating the income elasticity of commuting is to estimate least-squares regressions of distance on family income for each of the five family-size groupings and for the complete sample. Thus far we have presented the data in terms of five income groups. This has been done for illustrative purposes, to keep the tables down to a manageable size, but five income levels are hardly sufficient for a statistical analysis. We have regrouped the data into 13 income groups and used 11 of these in our regressions. These groups are indicated in Table 4, which also contains the data points for the 3- and 4-person household sample.

Table 4

DISTANCE AND INCOME DATA
(Three- and four-person household)

	Income ($)		Distance (mi)		
Number	Range	Midpoint	Average	Standard Deviation	Weight
1	0-2,999	..	..	..	..
2	3,000-3,999	3,500	11.98	11.15	1,089
3	4,000-4,999	4,500	9.09	10.01	1,544
4	5,000-5,999	5,500	9.60	8.61	5,748
5	6,000-6,999	6,500	10.27	10.24	9,601
6	7,000-7,999	7,500	11.05	11.21	12,704
7	8,000-8,999	8,500	12.77	11.20	10,725
8	9,000-9,999	9,500	10.06	9.19	14,483
9	10,000-12,499	11,250	12.45	10.01	21,621
10	12,500-14,999	13,750	15.70	12.91	13,661
11	15,000-19,999	17,500	14.69	11.84	10,359
12	20,000-24,999	22,500	13.86	10.03	4,866
13	25,000 and over	..	..	..	..

For each family-size sample, the parameters α and β in the equation

$$\log (D) = \alpha + \beta \log (Y) \tag{22}$$

were estimated. There were several reasons we chose a double log equation. First, it is the simplest analytical form for estimating an elasticity, since $E_{D,Y} = (d \log D)/(d \log Y) = \beta$. Thus the estimating process directly produces an estimate of the desired elasticity. Furthermore, this elasticity is constant over the full range of the dependent and independent variables. Second, plotting the data and running some trial regressions with the five income groupings indicated that a double log equation probably would provide the best empirical fit. Finally, plots of the individual D values indicated that it was reasonable to assume that D was distributed log-normally. This can be seen in Tables 2 and 3; all of the observations are positive, the mean is low, the upper tail of the distribution is long, and the variance is roughly proportional to the mean.

The data require one final adjustment. As we are dealing with grouped data, the error terms cannot be expected to be homoscedastic unless each mean is weighted by the number of individual observations that it represents.* And as our data themselves are samples of the population of workers employed in San Francisco, we have weighted each mean by the population figure that it represents. These weights are shown in the final column of Table 4.

The results of the estimation process are shown in Table 5.

Table 5

ESTIMATING RESULTS: WEIGHTED REGRESSIONS
OF log (D) ON log (Y)

Equation Number	Sample Family Size	Parameter Estimates		Corrected R^2	Standard Error of Estimate
		$\hat{\alpha}$	Elasticity $\hat{\beta}$		
1	1 person	-2.05	0.42	0.50	0.16
2	2 persons	-2.10	0.47	0.75	0.12
3	3 to 4 persons	-0.54	0.33	0.62	0.10
4	5 to 6 persons	-2.83	0.58	0.60	0.18
5	7 to 10 persons	-4.66	0.79	0.26	0.59
6	All sizes	-3.12	0.59	0.87	0.10

*Ref. 7, pp. 143-146.

All of the equations are significant and, with the exception of Eq. 5, explain large portions of the variance in (log) D.* The largest families do not seem to behave with the regularity of the smaller ones. The elasticity estimates range from 0.33 for the 3- to 4-person households to 0.79 for the 7- to 10-person households, and seem to be centered at about 0.50.** When we use the overall means (Eq. 6 is *not* an aggregation of the data points from the first five equations), the overall elasticity is estimated as 0.60.

These results indicate that the 3- to 4-person families, although commuting farther than the smaller families, are less likely to disperse farther as their income increases, while the 7- to 10-person households would respond the strongest of all of the groups to a change in income. All of the estimates are sufficiently similar, however, that we shall feel confident in using an average elasticity of 0.60 for all of the family sizes.

EVALUATING THE MULTIPLIERS

Our commuting cost function is

$$T = T(D, Y), \tag{23}$$

where D is commuting distance and Y is family income.*** This formulation assumes that there are two components to travel costs: the direct

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*Because of the (high) weighting factors used in these equations, the usual test statistics for the parameters and the equations are meaningless and have been omitted from the tables. For example, Eq. 5 has a corrected R^2 of only 0.26, but as it has almost 12,000 degrees of freedom all of the usual statistical tests are passed at any level of significance.

**We also ran the same equations in semi-log form, that is,

$$D = \alpha + \beta \log (Y),$$

and the results were comparable with the double log equations. In fact, all of the estimated elasticities (computed at the mean of D) and the corrected R^2s were within 0.05 of their values in the double log equations, with the exception of Eq. 5. In semi-log form, this equation yielded an elasticity of 0.36 and an R^2 of 0.21.

***The proper income term is Y_w, the wage income of the head of household, because this is his true opportunity cost of travel. This substitution will be made in the following pages.

money costs incurred by the traveler and the indirect opportunity cost of travel time. We shall further assume that these costs are separable:

$$T = T_1(D) + T_2(D, Y), \tag{24}$$

where T_1 represents the direct costs and T_2 represents the time costs. Furthermore, we shall assume that time costs are a simple combination of the travel time, t, and the traveler's value of time, v:

$$T_2 = tv. \tag{25}$$

The Boeing Company has estimated travel cost and travel time function for both auto and air transport in conjunction with its intraurban air study.* These estimates appear reasonable to us and will be used here. The direct cost and travel time functions, expressed on a per-trip basis, for automotive transport are

$$T_1(\text{trip}) = \$1.20 + (\$0.0625/\text{mile})D \tag{26}$$

and

$$t(\text{trip}) = 10 \text{ min} + (1.67 \text{ min/mile})D. \tag{27}$$

Transforming these functions into annual costs by assuming 240 workdays a year and two trips per day, we have

$$T_1 = \$576 + (\$30/\text{mile})D, \tag{28}$$

$$t = 80 \text{ hr} + (13.36 \text{ hr/mile})D. \tag{29}$$

Substituting these expressions into Eq. (24) yields

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*Boeing estimated direct travel costs and travel times for several intraurban air transport systems. We will only use the values for the 1975 49-passenger STOL system. Ref. 8, pp. 327-328; or see Ref. 9, pp. 8-9.

$$T = \$576 + (\$30/\text{mile})D + [80 \text{ hr} + (13.36 \text{ hr/mile})D]v, \qquad (30)$$

where v is the value of time in dollars per hour.

Boeing's estimates of the direct travel costs and travel times for the air transport system are*

$$T_1(\text{trip}) = \$2.30 + (\$0.064/\text{mile})D \qquad (31)$$

and

$$t(\text{trip}) = 40.6 \text{ min} + (0.16226 \text{ min/mile})D, \qquad (32)$$

so that annualized transport costs by air would be

$$T = \$1104 + (\$30.72/\text{mile})D + [324.8 \text{ hr} + (1.298 \text{ hr/mile})D]v. \qquad (33)$$

Hence, the cost savings brought about by switching from automotive to air transport are computed by subtracting Eq. (33) from Eq. (30), automotive transport costs, and evaluating the resulting expression at the desired values of D, Y, and v, the value of travel time.

The value that an individual places on the time he spends traveling is subjective and based on his preferences toward travel, work, and his alternative uses of that time. A substantial amount of literature exists relating an individual's value of time to his wage rate, and estimates are available relating wage rates to annual income. Our approach will be to use this literature to compute the costs of travel time.

Four studies have provided empirical estimates of the relationship between the value of time and the wage rate. Becker estimated the value of time from the relation between the value of land and the commuting distance from home to work. His estimate, based on the experience of commuters in Seattle, yielded a value of time that was about

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*Ref. 8, pp. 328 and 341; or see Ref. 9, pp. 8-10.

40 percent of the commuter's average hourly earnings.* Beesley, also working with commuting data, estimated the switching distance between modes of public transportation in London and derived a value of time that was 30 to 50 percent of the hourly wage.**

Studies on air travelers, however, record a higher valuation on travel time. In estimating the future demand for trips by supersonic transport planes, the Institute for Defense Analyses concluded that passengers in the aggregate act as though they value their time at approximately their earning rate, and that there is no evidence that those traveling for personal reasons differ in this respect from other travelers.*** Granau disputes the latter finding. Using data on air passengers provided by the Port of New York Authority, he finds that the value of time for business trips is probably equal to the wage rate, but for personal trips, it may well be zero.†

Granau also attempts to reconcile Becker's and Beesley's estimates of the value of time in commuting as 30 to 50 percent of the wage rate with the evidence that the value of time for business trips is equal to the wage by reference to the peculiar nature of commutation trips:

> Commutation can be regarded as "productive consumption." It is a consumption that serves as an input in the production of the activity "work." ...The value of time in such activity equals the wage rate only if the traveler is free to substitute working time for traveling time and if work does not yield any disutility. If either of these two assumptions is violated, we may expect the price of time to be lower than the wage rate.††

Following this reasoning, we shall use two figures for the value of time in our analysis--a "commuting" case where the value of time is

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*Ref. 10, p. 510

**Ref. 11, p. 182.

***Ref. 12, Vol. I, pp. xv, 16-19; Vol. II, App. C, pp. 31-59. Cited in Ref. 13, p. 58

†Ref. 13, pp. 51-52.

††Ibid., p. 58.

figured at 40 percent of the wage rate, and a "business travel" case where the value of time is equal to the wage.

Granau has also provided estimates of the relation between wage rates and annual incomes.* Using data on annual income, earnings, and hours worked from 1/1000 sample of the 1960 Census of Population, he estimated average wage rates for eight income classes. His estimates are reproduced in Table 6. The average wage values are the average hourly earnings of the head of household. Family income includes income earned by all members of the family and all nonwage income collected by the family.

Table 6

AVERAGE HOURLY EARNINGS CLASSIFIED BY INCOME GROUPS

Annual Family Income ($)	Average Wage ($/hr)
Under 3,000	1.62
3,000 to 4,999	2.07
5,000 to 5,999	2.43
6,000 to 6,999	2.60
7,000 to 9,999	2.85
10,000 to 14,999	3.39
15,000 to 24,999	4.87
25,000 and over	12.96
Average	2.75

SOURCE: Ref. 13, p. 45.

From the information in Table 6, we have derived the following relations between family income and wage rate for use in this study:

Annual Income ($)	Wage Rate ($)
5,000	2.31
10,000	3.05
15,000	3.88
20,000	4.87

*Ibid., p. 44. An alternative method for computing this relationship can be found in Ref. 14, App. A.

Given these income-wage relationships and the two values of time-wage relationships, we can evaluate the price and income multipliers in Eq. (21).

Tables 7 and 8 show the values of these coefficients for four representative levels of family income and two commuting distances. Only positive values are presented; a dash in Table 7 indicates that a household would incur additional travel costs if it switched to air transport, i.e., $\Delta T < 0$. There are two significant differences between the values in these two tables: (1) the values in Table 8 are significantly larger than the values in Table 7; and (2) there are no blank spaces or dashes in Table 8. Both of these differences are due to the structure of the travel time and cost functions we used. The cost functions for auto and air transport are not too dissimilar, but the travel time functions are quite different. Airplanes travel much faster than automobiles once they leave the terminals. Hence, marginal travel times, and therefore marginal total travel costs that are based on both direct travel costs and travel times, are much lower for air transport, so that the change in marginal costs from switching to air transport, ΔT_d, is relatively large.

Table 7

VALUES OF THE INCOME ELASTICITY COEFFICIENT
$[\Delta T/(1 - T_y)](D/Y)$

Family Income ($)	Commuting		Business Travel	
	40 mi	60 mi	40 mi	60 mi
5,000	--	--	--	11.88
10,000	--	0.10	0.99	9.88
15,000	--	0.85	1.46	9.51
20,000	--	1.34	1.70	9.76

Table 8

VALUES OF THE PRICE ELASTICITY COEFFICIENT,
$\{\Delta T_d + [T_{dy}/(1 - T_y)]\Delta T\}D/T_d$

Family Income ($)	Commuting		Business Travel	
	40 mi	60 mi	40 mi	60 mi
5,000	9.08	14.37	17.81	28.72
10,000	11.54	18.10	20.84	33.42
15,000	13.84	21.75	23.37	37.33
20,000	16.10	25.27	25.57	40.80

The income multiplier is based on the savings in total travel costs from switching from auto to air transport as a percentage of the commuter's real income. Our estimates of these percentages range from zero to over 25, but most are less than 5 percent. The price multiplier is based primarily on the percentage change in marginal total travel costs. These estimates are quite evenly distributed from 26 to 61 percent. Thus, the price multiplier is always greater than the income multiplier, and, as there is always a savings in marginal travel costs when a commuter switches from auto to air transport, the price multiplier is always positive.

THE ESTIMATES

The investigation of the postulated cost functions for automotive and air transport indicate that the introduction of air transport into the Bay Area would significantly alter both the total and marginal transport costs of certain groups of commuters; that is, both the income and substitution effects would be operative. We are able to derive empirical estimates of the income effect. These estimates are obtained by multiplying the values of the income elasticity coefficient by the estimated income elasticity of 0.60, and are shown in Table 9.

Table 9

INCOME-INDUCED CHANGES IN MILES
OF COMMUTING DISTANCE

Family Income ($)	Commuting		Business Travel	
	40 mi	60 mi	40 mi	60 mi
5,000	--	--	--	7.13
10,000	--	0.06	0.59	5.93
15,000	--	0.51	0.88	5.71
20,000	--	0.80	1.02	5.86

We are not able to empirically estimate the substitution effect as we cannot estimate the real price elasticity of commuting. We can, however, pick several hypothetical values for this elasticity and combine these values with the computed price multipliers to gain some idea of the possible magnitude of the price effect and of the combined--substitution and income--effect.

As we have no preconceived notions as to the probable value of $E_{D,T_d;R}$, we shall arbitrarily select working values of 1.0, unitary elasticity, and 0.5, a more conservative value and near the value we have estimated for $E_{D,Y}$.

For the unitary elasticity case, the values for the change in commuting distance are, of course, equivalent to the value for the elasticity coefficient reported in Table 8. Table 10 contains the estimated changes in commuting distance induced by the price effect for the case where we assume the real price elasticity of commuting to be 0.50.

The distances in Tables 8 and 10 are much larger than the distances we reported in Table 9, when the income effect of a change in travel costs was considered. Thus, if our postulated values of $E_{D,T_d;R}$ are anywhere close to being correct, the substitution effect may be much stronger than the income effect, especially for the shorter commuting distances and the less affluent households.

Table 10

PRICE-INDUCED CHANGES IN MILES OF
COMMUTING DISTANCE
ASSUMING $E_{D,T_d;R} = 0.50$

Family Income ($)	Commuting		Business Travel	
	40 mi	60 mi	40 mi	60 mi
5,000	4.54	7.19	8.91	14.36
10,000	5.77	9.05	10.42	16.71
15,000	6.92	10.88	11.69	18.67
20,000	8.05	12.64	12.79	20.40

Table 11 contains values for the total (income plus substitution) induced changes in commuting distance using the more conservative 0.5 value for the price elasticity. These values, along with the "income effect only" values of Table 9, show the results of our estimation process.

Table 11

TOTAL INDUCED CHANGES IN MILES OF
COMMUTING DISTANCE

Family Income ($)	Commuting		Business Travel	
	40 mi	60 mi	40 mi	60 mi
5,000	--	--	3.50	21.49
10,000	--	9.11	11.01	22.64
15,000	--	11.39	12.57	24.38
20,000	--	13.44	13.81	26.26

Table 9 illustrates two of our findings. First, as the dashes indicate cases where air travel would be more expensive than (the present) automotive travel, with the postulated travel cost functions, *air travel would result in travel cost savings only for the longer commuting distances*. Second, *the income effect, where it is operative, results* *in only rather mild tendencies for locational change, except for the longest business travel cases.*

There are dashes in Table 11 as well because we would not expect a traveler to switch to air transport, and hence the substitution effect would not be operative, unless he could reduce his total travel costs. There are fewer dashes here, however, as the added impetus of the substitution effect drives a few of the cases past the break-even point for switching to air.* A comparison of Table 9 with Table 11 reveals our third and fourth findings. *Where the substitution effect is operative, it is probably much stronger than the income effect.* Consequently, *the total, combined influence of the two effects may well be significant.* These results rest crucially on the actual value of the real price elasticity of commuting, but computations reveal that they would hold if the actual value were as low as 0.1 or 0.2.

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*For example, the $5000 income commuter in the 40-mile, business travel base case has an income effect of minus 5.41 miles, as a switch to air travel in his present location would increase his travel costs by $7.76 per year. However, the combined net effect of the income and price changes would be an increase of 3.50 miles. And, at his preferred location, with a commuting distance of 43.50 miles, air is the cheaper mode by almost $87 per year.

III. CONCLUSIONS

The results of our estimation process show that it is possible to quantify at least one of the long-run effects of a transport improvement. We must stress, however, that our estimates indicate probable *ceteris paribus* desires rather than predicted actions. That is, under our postulated transport innovation, workers who are employed in the City of San Francisco and who are commuting 30 or 40 miles would find it to their benefit, in terms of total commuting costs, to switch to air transport *if* the air terminal were located close to their homes. Furthermore, many of these commuters would be willing to move short distances to gain access to an air terminal *if* there is a potential homesite available in that area that offers levels of neighborhood services and amenities at least on a comparable level with what they are presently receiving.

Under these conditions, the major effect of the introduction of transport improvements is undoubtedly that of shaping the future growth of the regions they serve. If air terminals are established in the distant suburbs of the Bay Area and provide an acceptable level of service, they can be expected to attract significant numbers of new families into the regions served.

It should be noted that our analysis, while concentrating on long-run effects, can also be used to estimate the short-run modal-split. In the short run the number of travelers and their origins and destinations are fixed. Our estimates of travel cost changes show the commuters that could be rationally expected to switch to the new or improved mode, provided of course that it offered an acceptable quality of service.

Perhaps the most important implication of our analysis, however, is the significance of the price effect. Although the amount of cost savings and the impact of the income effect are indeed important, especially in the short run, in determining the effects of transport changes on commuting behavior, the price effect should not be ignored. In the long run, and especially for innovations with substantially increased speed or reduced operating costs, its effects may completely dwarf the effects of the income term.

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