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Does commuting distance matter? Commuting tolerance and residential change

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Abstract

This research uses a longitudinal data set of commuting behavior to test the nature and strength of the association between residential change and employment location. Do households minimize commuting distances when they change residences and what are the differences for one-worker and two-worker households? The analysis utilizes descriptive measures of distance and time to work for pre- and post-residential relocations and develops estimates from a probability model of work-place attraction. We extend earlier research on commuting distances by using a multinodal rather than a monocentric city, by specifically considering the commuting responses of two-worker households and by formally estimating a model of the response to commuting distances. The findings indicate that both one- and two-worker households with greater separation between workplace and residence make decreases in distance and time. Overall, as other studies have shown, women commute shorter distances and are more likely to minimize commuting after a move than are men. The probability model fits the likelihood of decreasing distance with greater separation and provides a more exact specification of the connection between residence and workplace than previous analyses of this relationship. © 2002 Published by Elsevier Science B.V.

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1. Introduction

Urban areas have experienced profound social, economic, and spatial transformations since the development of the classical monocentric models of the urban structure. The decentralization of jobs and the growth of ‘edge’ cities (Garreau, 1991; Gordon et al., 1989a,b) have altered urban spatial structures and changed commuting patterns and processes. The rise of the policentric city with a complex set of employment nodes in place of the traditional attraction of the downtown core has changed the connection between home and workplace. Changing household structures have added to the complexity. Now the number of two-worker households with two separate commutes are equal, or nearly so, to the number of traditional single-worker households. Thus, the question of whether, and how, commuting behavior has changed is even more relevant.

In a changed spatial context and for changing labor-force participation of two-worker households, what is the nature of the link between residence and workplace? We know that job access is influenced by both the spatial distribution of jobs and individual spatial flexibility and in turn individual flexibility is related to the number of workers in the household. Hence, changing spatial concentrations of jobs and the ability of workers to change residences are both relevant. Do households with one and two workers differ in their adjustment process to commuting? In addition, the rise in female labor-force participation raises questions about their commuting behavior and especially for those in two worker households. How are female workers affected, by the residential relocation process? It is in this context too, that the concept of commuting tolerance has been used to ask at what point do commuters become resistant to further increases in commute time. Empirical observations have suggested a tolerance zone in the range of about 30–45 min (Getis, 1969; van Ommeren et al., 1997), but there remains a lack within the literature of a formal probabilistic model of the relationship between work travel before and after residential change. The guiding questions for this research are whether separation matters and do households reduce their commute distance (and time) when they move?

There are some studies that have provided models of the relationship between residence and workplace (van Ommeren, 1999), but up till now this research has carried out only limited empirical tests of the behavioral response to *changes* in residences or jobs. While we know a great deal about the actual commuting distances and times of workers, we know much less about the behavioral limits on these commuting distances and times. Little is known as to how they vary by household type or the behavioral responses to the length of the commute. In this study we examine the interdependence of job location and residential relocation at the local scale in the Seattle metropolitan region, a case study for large US metropolitan areas. We extend earlier research on commuting distances by using a multinodal rather than a monocentric city, by specifically considering the commuting responses of two-worker households, and by formally estimating a model of the response to commuting distances.

2. Background

The connection between home and workplace has been, and remains, a central part of theories of urban spatial structure. Economic models have emphasized the trade-off between commuting costs and housing costs and placed this trade-off at the core of models of residential location (Wingo, 1961; Kain, 1962; Alonso, 1964; Muth, 1969). While it is clear that the monocentric model of the city is no longer a good description of the changing US metropolitan area (Berry and Kim, 1993) equally clearly, we need not reject the notions of accessibility and economic competition (Gordon et al., 1989a,b). Indeed, it is the continuing if changing separation of jobs and residences which still produces much of the commuting in cities, and despite the changing urban structure, those links are as relevant in the policentric city as in the monocentric city (Clark and Kuijpers-Linde, 1994). However, in practice the dispersal of job opportunities has created a much more complicated behavioral response to the linkage between work and residence.

It is clear that households do not just use commuting distance as the only reason for residential relocation as accessibility to work is only one of several important variables in explanations of moving behavior (Quigley and Weinberg, 1977). In fact it appears that many moves within the city in effect hold the distance to work as a constant. There is previous work which shows that there is an ‘indifference zone’ within which commuters are relatively indifferent to access to work (Getis, 1969). Brown (1975) found that households with employment changes outside their original work zone were much more likely to move than were households within the original work zone. Clark and Burt (1980) established that there is a marked tendency for households to move closer to their workplace as that separation increases. Simply, if a household is a long distance from the workplace, when the household moves it is likely to move nearer the workplace.

Cervero and Wu’s (1997) study of commuting and residential location in the policentric San Francisco Bay Area found evidence that suburban employment tends to generate shorter commute times than central city employment. Research on policentric urban structures, at least in what have become known as edge cities, confirms the link between workplace and residence but now it is a link between households and a set of nodes scattered throughout the metropolitan region (Gordon et al., 1989a,b; Levine, 1998). A number of studies have examined the impact on the commuting times and distances for workers in firms that have relocated to the suburbs (Doorn and van Rietbergen, 1990; Bell, 1991; Cervero and Landis, 1992; Wachs et al., 1993). The findings are variable and suggest that commuting patterns are adjusting to evolving metropolitan dispersal and may be self-adjusting in a way that is decreasing congestion and commuting times and may substantially affect the notion of the commuting threshold.

Until recently, few studies had examined the complex intersection of residential location, job location and commuting in a dynamic context. Simpson (1987) notes that most data sources are cross-sectional and simply do not take into account the dynamic nature of residential decision making. In the absence of longitudinal data, Levinson (1997) attempts to unravel the complexity of the job-commute-residence nexus by focusing on job duration and residence duration. Levinson (1998) argues that individuals who have recently changed their jobs or residence should have shorter than average commutes if indeed these relocations are induced by the desire to reduce commuting distance or time. Similarly, individuals with a long duration of employment and residence should have shorter than average commutes since these households have remained spatially stable. Although he finds support for his hypothesis, it remains weak since commuting tolerance is only one of many motivations for residential mobility. However, he does establish the interdependence of workplace and residential location, unlike much other research which continues to treat workplace and residence choice as exogenous.

A recent series of Dutch papers (van Ommeren et al., 1997; van Ommeren, 1999; Rouwendal and Rietveld, 1994; and Rouwendal, 1999) take up the issue of the residence-commuting link by examining job search behavior and job locations. Using a search model framework they ask how residential changes and job changes are interrelated. These studies develop sophisticated theoretical frameworks to show that an increase in commuting distance increases the probability of accepting a job offer or a residential offer. In other words, it increases the probability of adjustment and subsequent decreases in the commute distance. Additionally, this work suggests that employment location is more sensitive to the residential location than the reverse, due in part to the high costs of changing residence. van Ommeren et al. (1997) suggest that there is no trigger effect of job change on residential change. This lies in contrast to Clark and Withers (1999) who found a job change to trigger residential mobility, especially for renters in the United States. It seems there is an apparent contradiction in the Dutch research that has yet to be reconciled. On the one hand they identify a correlation between residential and labor-market mobility and on the other they downplay the role of the trigger effect of a job change. Nonetheless, this body of work has served to emphasize the importance of the interrelated nature of residence and job change.

There are few models that allow for simultaneous search in the labor market and the housing market. An important exception is the research by van Ommeren et al. (1996) which analyzed residential and labor market mobility in the Netherlands using a bivariate duration model. Others have examined the sequence of residence and workplace choice, and also found them to be related (Waddell, 1993; Gordon and Vickerman, 1982; Linneman and Graves, 1983). Zax and Kain (1991) link commuting distance to the propensity to quit a job or to change residence and Crane (1996) shows that the connection between workplace and home is not static; it is based on expectations of future employment opportunities and residential aspirations.

The largest gap in the research on commuting and residential change is in the area of dual labor market attachments. Do households with one and two workers differ in their adjustment process to commuting? It is as yet unclear whether the locational constraint imposed by the primary worker (the head) restricts the residential mobility of the spouse. There is some evidence that women's earnings opportunities and commuting burdens influence the residential location and workplace choices of both partners (Freedman and Kern, 1997). In addition, as hypothetically the probability of moving is more strongly related to commuting distance for women than men, we might expect women to have a shorter commute distance after a move (Abraham and Hunt, 1997). In an effort to disentangle these interdependencies, Sermons and Koppelman (1999) consider the sequencing of residence change and job changes for women to determine whether their workplace tends to be exogenous to the residential location of the household. They find that they are not exogenous and that there is evidence to support the household responsibility hypothesis.

Over the past 30 years consistent gender differences in the journey to work have been well established in the literature (Blumen, 1994; Turner and Niemeier, 1997; Wyly, 1998). Within this voluminous literature most studies compare men and women in the aggregate and consistently find that women tend to commute shorter distances and travel less time than men. The difference is frequently explained by women's low wages, their need to balance the dual role of mother and worker, and a relatively even spatial distribution of jobs (MacDonald, 1999). Johnston-Anumonwo (1992) is one of the few authors that has considered variations in gender differences in commuting by the number of workers in the household, and she finds women's greater time constraints lead to selecting shorter commute distances and time. She concluded that women are not 'indifferent' to job locations. Singell and Lillydahl (1986) found that in two-earner married households it was the male's job location that propelled residential location decisions. Moreover, they found a residence change increased female commute times. The seemingly contradictory findings may well be due to the various spatial and temporal scales of analysis but it is clear that there is much more that we need to know about the mechanics of these processes of commuting and residential mobility.

This review serves to reiterate that separation is a critical component of residence change and job location. By examining the behavioral links in decision making between these spheres we focus on a major element of the commuting process and on the nature of the linkage itself. This study will provide answers to the question of how sensitive households of different types are to the separation within a local labor market.

3. Data and hypotheses

To assess the connection between residential changes and commuting behavior we use a unique longitudinal panel survey of households in the greater Seattle area—the Puget Sound Transportation Panel (PSTP). The PSTP was collected by the Puget Sound Regional Council during the early and mid 1990s and was the first application of a general-purpose urban travel panel survey in the US (Murakami and Watterson, 1995). The data set is a longitudinal sample of approximately 2000 households within the Seattle labor market. Commuting and limited demographic characteristics for each household member were collected over a series of years, including 1989–1990, 1992–1994 and 1996–1997. The survey was not conducted in 1991 or in 1995 and although it would be possible to construct moves for 1990–1992 and 1994–1996 we elected not to do this as it would be a 2-year move interval which would introduce unknown bias into our analysis. A 2-year, rather than a 1-year interval may or may not affect decisions about work location. The data source provides a number of key measures required for this study: the residential location (measured by census tract), the workplace (also measured by census tract), and the distance and time of the journey to work for each employed household member. In addition, the survey measures changes in both residences and job location (Watterson, 1995). We used distance calculated from tract centroids and reported time by respondents in the survey.

We use both distance and reported time in the descriptive analysis but distance in our model construction. Distance can be measured within about a half mile accuracy which is determined by the tract sizes. Reported times have significant clustering at particular intervals 15, 20, 25, 30 and 35 min which raises serious difficulties in formulating a model of continuous times.[1] The has always been a concern and debate about the use of time versus distance in measuring the interaction of residence and workplace. In response to a referee's concerns we examined the relationship between distance and time. While the correlation is substantial, it is not perfect ($r^2 = 0.6$), but it does show a general tendency for time and distance to be related. However, we have chosen to formally model distance as it is distance and the interaction of places of work and residence which can be examined within the explicit spatial structure of the city. It is only with location and distance and the associated angular relationships that we can model the relationship of distance and direction. It is worth reiterating that the relationship between the new and old residence does affect the distance and directions of the links between the workplace and the residence, thus it is a critical spatial element of the model.

Some measures of household characteristics are also available in the survey including family size and composition. Clearly, trips beyond those by the workers will likely influence the decision to change residence but these trips are reported

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[1]A reviewer suggested the interesting idea of translating times via GIS coding of exact street addresses but we have been unable to secure the detailed housing locations which would make this possible.

only for a smaller selection of respondents who completed a travel diary and have not been analyzed in this study.[2]

The primary focus of this research is the nature of changes in the commuting link. We examine all households that experienced a residence change and we examine the nature of the move in relation to the workplace destinations of individuals in the household. We will examine two types of households: (1) households with one worker (single persons or families); and (2) households with two workers. We examine all relocations between the available pairs of years 1989–90, 1992–93, 1993–94 and 1996–97. There were approximately 460 households who changed residence and/or changed workplace in the four pairs of years.[3] There were 326 households who changed residences and did not change job locations and this subset is used for tests of the model specification.

The review of the literature suggests the following preliminary hypotheses. First, the most straightforward hypothesis examines the basic question: are commuters distance/time resistant?

Ceteris paribus, households who move will choose residences that are closer to their workplace. The larger their initial separation between residence and workplace the greater the likelihood of moving closer (*and decreasing the commute time*) *to the workplace.*

Second, given the complexity of the job search and housing search process for two-earner households, Freedman and Kern (1997), Waddell (1993), and van Ommeren et al. (1998) found residential mobility to be negatively influenced by the distance between the workplaces of the two-wage earners. These findings suggest that mobility will be lower and that there will be a lower probability of reducing the distance to the workplace.

Individuals in dual-earner households that move are likely to have higher average commutes both before and after a move than single earner households due to the additional spatial constraints of the second earner's place of employment and labor force attachment.

Zax and Kain (1991) suggests that the dominant locational constraints are imposed by the workplace of the primary worker. However, numerous studies at the national and metropolitan scale have found that being married increases commuting times for men. There is also persistent empirical evidence that wives tend to have shorter commuting times than their husbands (Gordon et al., 1989a;

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[2]The question of whether school age children and their trips will influence residential change is an important one but will require further elaboration of the model to one or more trips to schools in addition to the one or two work trips. This study is beyond the scope of this present paper.

[3]The numbers are slightly different for one-worker and two-worker households. In some cases, although the household is reported as a two-worker household, the data for the second worker is missing.

Turner and Niemeier, 1997). Consistently, these gender differences in commuting times are explained by the household responsibility hypothesis.

In two-worker households women will have shorter commutes but (*for women who remain in the workforce*) *commutes will, on average, increase with residential changes*.

If this hypothesis holds it suggests support for the dominance of the primary worker in the residence-workplace link.

3.1. Descriptive interpretations

A set of descriptive tables provides the first tests of the hypotheses of work attraction for residential change. To provide a base line standard of commuting distance we include a table which shows those distances for all individuals in the sample separated by those who change residences and those who do not change residences (Table 1). We note that there is no relationship between pre-move distance and the likelihood of moving. The tables are organized by commuting distance (Table 2) and commuting time (Table 3). The tables differentiate one- and two-worker households as well as residence changes in isolation or in concert with job changes. They show the number of movers who had the same or a decreased commute after moving versus those households who increased their commute after moving. The categorization of distance and time was designed to overcome the 'rounding' that occurs when people record their travel distance and travel times (Rietveld et al., 1999). As we noted earlier, reported commuting times have serious clustering at the deciles.

In the aggregate more households, whether with one or two workers, reduced their commutes after moving. Analyzing the results by the pre-move commute

Table 1
Commuting distance for the total sample by change of residence status

Commute (miles)	All (%)	Nonmovers (%)	Movers (%)
0–4.0	19.19	18.92	21.47
4.1–8.0	22.95	22.85	23.20
8.1–12.0	16.67	16.33	16.93
12.1–16.0	13.77	14.32	10.97
16.1–20.0	9.37	9.63	9.25
20.1–24.0	6.07	5.95	6.11
24.1–28.0	4.59	4.56	4.55
28.1–32.0	2.69	2.74	2.82
32.1+	4.70	4.69	4.70
Sum	100	100	100
total *n*	7953	6669	638

For movers, the commute is pre-move distance.

Table 2
Change in distance to work for households that changed residences

Pre-move distance (miles)	No change in work place				Changed work place			
	One worker		Two workers		One worker		Two workers	
	Same or decrease	Increase	Same or decrease	Increase	Same or decrease	Increase	Same or decrease	Increase
0–4.0	7	10	20	27	8	6	8	11
4.1–8.0	14	12	20	22	7	4	5	14
8.1–12.0	17	10	19	17	7	5	1	8
12.1–16.0	12	4	16	14	1	1	5	1
16.1–20.0	6	3	16	8	4	0	7	3
20.1–24.0	7	3	9	3	1	0	6	0
24.1–28.0	6	0	7	3	0	1	3	0
28.1–32.0	2	1	2	2	3	0	3	0
32.1+	2	1	12	0	4	0	1	0
Total *n*	73	44	121	96	35	17	39	37

reveals a distinct pattern in which households with longer commutes before the move almost always reduced their commuting distance and time. The breakpoints, that is the distance or time at which more households reduced rather than increased their commutes are shaded on the tables and reveal different patterns for one and two workers. There are also difference patterns for households that changed residences and those who changed both residences and job locations. One-worker households with relatively short commutes (less than 8 miles) tended to increase

Table 3
Change in time to work for households that changed residences

Pre-move time (min)	No change in work place				Changed work place			
	One worker		Two workers		One worker		Two workers	
	Same or less	Increase	Same or less	Increase	Same or less	Increase	Same or less	Increase
0–7.5	0	1	2	3	1	0	4	0
7.6–12.5	2	2	7	6	1	1	1	3
12.6–17.5	11	3	7	10	6	3	5	4
17.6–22.5	5	4	17	8	2	1	1	7
22.6–27.5	8	1	12	5	1	1	1	4
27.6–32.5	12	2	16	4	5	0	2	1
32.6–37.5	3	1	4	1	4	0	3	1
37.6–42.5	1	0	4	3	1	1	1	2
42.6–47.5	7	1	7	2	1	0	5	0
47.6+	11	4	22	4	9	0	8	0
Total *n*	60	19	98	46	31	7	31	22

their commuting distance. Households which commuted more than 8 miles tended to decrease their commutes (Table 2). The table uses a shaded area at the breakpoint of 8 miles to emphasize the difference between one- and two-worker households where the breakpoint is about 12–16 miles.

Generally, the households that increased their commutes were those that had short commutes, either in distance or time, before they moved. This finding is especially true for one-worker households. For the very longest commutes before a residence change there is clear evidence of a tendency to maintain or reduce the commute with the residential relocation. At the same time a larger number of households increase the commute time when they had relatively short commutes prior to moving. Clearly, changing jobs and houses has a significant effect on the amount of commuting. In terms of our first two hypotheses there is substantial support for reduced commute distances and times with residential relocation.

An alternative way of looking at commuting change is to measure the proportion of one and two-worker households who commute the same or a similar distance and time and the proportion who decrease or increase their commuting (Table 4). Almost 60% of all households, one or two workers, commute the same distance or within plus or minus 4 miles before and after the move. For households that changed both residence and jobs the results are different, especially for two-worker households. Many households have the same commutes and more so in time than in distance. However, for two-worker households that change jobs only a little more than a third maintain a similar commute time or distance. The impact of changing both jobs and residences creates additional commutes but we know from the previous tables that these increased commutes are not over large distances.

The third component of the descriptive tests is the analysis of gender differences for dual earner households (Tables 5 and 6). In general, women have shorter commutes than men, especially when there is no change in workplace where women are more likely to decrease their commute distance. In contrast, the

Table 4
Percent of workers who commute similar distances or time

	No change in work place		Changed work place	
	One worker	Two workers	One worker	Two workers
(a) Distance				
Decrease 4.1 miles +	15.0	14.5	24.4	20.6
Same + 4.0 miles	58.0	57.8	56.2	34.9
Increase 4.1 miles +	27.0	27.8	19.4	44.4
(b) Time				
Decrease 5.1 min +	19.1	19.8	34.6	20.0
Same + 5.0 min	57.0	47.7	42.3	42.2
Increase 5.1 min +	23.8	32.4	23.1	37.7

Table 5
Change in distance to work for two-worker households that changed residences by sex

Pre-move	No change in work place				Changed work place			
distance	Men		Women		Men		Women	
(miles)	Same or decrease	Increase	Same or decrease	Increase	Same or decrease	Increase	Same or decrease	Increase
0–4.0	10	9	10	18	1	6	7	5
4.1–8.0	8	13	12	9	3	6	2	8
8.1–12.0	9	10	10	7	1	3	0	5
12.1–16.0	6	7	10	7	3	0	2	1
16.1–20.0	4	3	12	5	5	2	2	1
20.1–24.0	6	2	3	1	5	0	1	0
24.1–28.0	4	2	3	1	1	0	2	0
28.1–32.0	1	2	1	0	1	0	2	0
32.1+	6	1	5	0	1	0	0	0
Total *n*	54	49	66	48	21	17	18	20

findings for dual earner households who changed both workplace and residence had a large number of women with increased commutes in distance or time. Amongst women who had commutes which were under 27.5 min, or less than 12 miles more than twice as many increased as stayed the same or decreased their commutes after changing jobs *and* residences. There is certainly an indication in the data that women who are in two-worker households and where both residences and jobs change are impacted in their commutes. Even so, most of the increases for women as for men were less than 8 miles and 27.5 min.

Table 6
Change in time to work for two-worker households that changed residences by sex

Pre-move	No change in work place				Changed work place			
distance	Men		Women		Men		Women	
(miles)	Same or less	Increase	Same or less	Increase	Same or less	Increase	Same or less	Increase
0–7.5	2	2	0	1	4	0	0	0
7.6–12.5	6	4	1	2	0	1	1	2
12.6–17.5	4	6	3	4	3	0	2	4
17.6–22.5	7	5	10	3	0	4	1	3
22.6–27.5	2	3	10	2	0	0	1	4
27.6–32.5	12	3	4	1	2	1	0	0
32.6–37.5	1	1	3	0	2	0	1	1
37.6–42.5	0	0	4	3	1	1	0	1
42.6–47.5	2	1	5	1	4	0	1	0
47.6 +	10	1	12	3	5	0	3	0
Total *n*	46	26	52	20	21	7	10	15

4. Modeling workplace attraction

While the frequency distributions contribute partial answers to the question of workplace attraction, a specification of the links between residential mobility and workplace requires a model that has testable statements regarding the probability of moving closer to or further from work, produces distributions of move distances consistent with our existing knowledge of residential moves, and allows us to examine the effect of distance on workplace attraction. To devise this analysis it is useful to use a simple diagram of the relationship between residence and workplaces. In the conceptualization we show a residence and distance from work followed by a new distance to work after a residential relocation (Fig. 1). The figure shows two sets of relationships. In Fig. 1a we envisage the relationship between residence and workplace for a household with one worker. The change of residence generates two separate distances from work for the locations before and after a move, and an angle of change between the old and new distances. In a two-worker household, as illustrated in Fig. 1b, the two workers produce two sets of distances corresponding to before and after a residential move and two angles for the relationship between the residence and workplace. Clearly the commuting relationship is much more complex.

The central question relates to the distances between workplace and residence before and after the move. The conceptualization of links between residence and workplace which incorporates direction and distance can be structured as a two parameter model in which the move is a vector that has length and direction and the distribution of moves is a joint distribution of move lengths and move directions. The effect of this formulation is to discard information about the city structure and to focus on the dynamic relation between the residence and the work location.

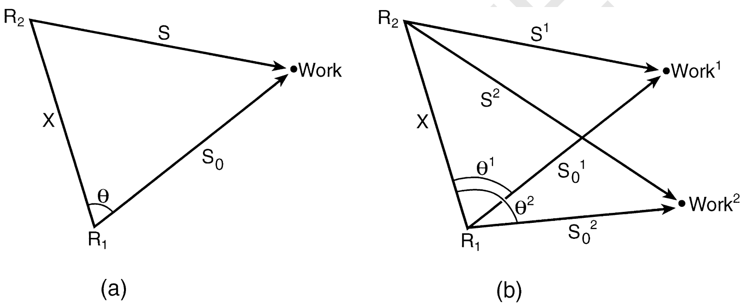

Fig. 1. (a) The vector structure of work–residence relationships. A move of X miles in the direction q is made from the old residence, R_1, to the new residence, R_2. Commuting distances before and after the move are s_0 and s, respectively. (b) The same vector structure for a two worker household, where s_1 is worker one and s_2 is worker two, and Work 2 is the second work place.

The figure shows the vector structure of an initial location (R_1) and initial work–residence separation s_0, followed by a new residential location (R_2) and the corresponding new work-residence separation following the move s.

A model[4] that formalizes the relationship of Fig. 1 assumes, consistent with empirical findings (Quigley and Weinberg, 1977; Clark and Burt, 1980), that move distances are distributed exponentially:

$$f(x) = \alpha\, e^{-\alpha x},\ x > 0 \tag{1}$$

where x is the distance moved in miles and $f(x)$ is the reciprocal of miles. A second assumption is that move directions follow a von Mises distribution with a mean direction of zero (Gaile and Burt, 1976). For a mean direction of zero the density function is given by:

$$g(\theta) = \frac{1}{2\pi I_0(k)}\, e^{k \cos\theta}, \quad -\pi < \theta \le \pi \tag{2}$$

where θ is the move direction in radians and $g(\theta)$ is in inverse radians. I_0 is a modified Bessel function of the first kind and order zero. The distribution has a single mode at zero and its dispersion is controlled by the parameter k (Fig. 2). As the figure shows, k is not bounded. When $k = 0$, $g(\theta) = 1/2\pi$ and there is no preferred direction, k is a measure of the degree to which movers are attracted to the work location. The larger the k is, the stronger the attraction to the workplace. Setting $k = 0$ is thus a test of the null hypothesis of no work attraction.

We also assume that move distances and move directions are independent.

$$h(x,\theta) = f(x)g(\theta) \tag{3}$$

If the assumption is incorrect and there is interaction between direction and distance the fit between the expected and observed distributions will be lower. The basic point is that dependence rather than independence can only reduce the fit between the observed and the expected distribution from the model. Thus, if the fit between observed and expected is good, we are confident of the results of the model. There is a behavioral basis also, to expect that there is independence between distances and direction. Household search for jobs at various locations and distances and those distributions are increasingly scattered throughout metropolitan areas. Thus the distributions of events is such that there is no a priori reason to expect an interaction.

Given these assumptions we derive a model of the likelihood of a person moving to a finite area defined by two distances (x_1, x_2) and two angles (θ_1, θ_2), such that:

$$P(x_1 < x < x_2, \theta_1 < \theta < \theta_2) = \int_{x_1}^{x_2} \int_{\theta_1}^{\theta_2} h(x,\theta)\, d\theta\, dx \tag{4}$$

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[4] The formal model is based on Clark and Burt (1980).

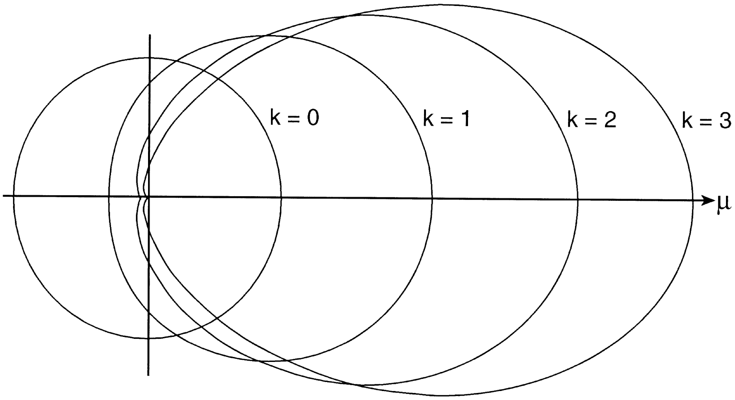

Fig. 2. The von Mises distribution for different values of k. As m increases the distribution becomes more elliptical. Source: Gaile and Burt, 1976.

where

$$h(x,\theta) = \frac{\alpha}{2\pi I_0(k)}\, e^{k\cos\theta - \alpha x}, \; x > 0, \quad -\pi < \theta \le \pi$$

Integrating Eq. (4) over the region where $s < s_0$ we can evaluate the distribution using the law of cosines. In effect the law of cosines is a way of evaluating triangles when theta is not a right angle. A fuller discussion is contained in Thomas (1966).

$$\begin{aligned} P(s < s_0) &= P(s^2 < s_0^2) \\ &= P(s_0^2 + x^2 - 2s_0 x\cos\theta < s_0^2) \\ &= P(x < 2s_0\cos\theta) \\ &= \int_{-\pi/2}^{\pi/2}\int_0^{2s_0\cos\theta} h(x,\theta)\mathrm{d}x\,\mathrm{d}\theta \\ &= 2\int_0^{\pi/2}\int_0^{2s_0\cos\theta} h(x,\theta)\mathrm{d}x\,\mathrm{d}\theta \\ &= 2\int_0^{2s_0}\int_0^{\cos^{-1}\frac{x}{2s_0}} h(x,\theta)\mathrm{d}\theta\,\mathrm{d}x \end{aligned} \tag{5}$$

After transformations and integration by parts, the above equation can be transformed into the following:

$$P(s < s_0) = \frac{1}{\pi I_0(k)}\int_0^1 \frac{1}{\sqrt{1-t^2}}\, e^{kt}(1 - e^{-2\alpha s_0 t})\mathrm{d}t \tag{6}$$

Eq. (6) does not yield a simple analytical expression for $P(s < s_0)$ as a function of s_0. Yet, through numerical integration, the relationship between $P(s < s_0)$ and s_0 can be achieved.

It is important to note that even if the workplace has no effect on the move, movers having a long pre-move trip will experience a higher probability of moving closer to work than those who are already close to work (in effect the zone of indifference). For any value of k, the value $P(s < s_0)$ is an increasing function of s_0. To illustrate, imagine the case of no bias. As s_0 increases the circular region corresponding to $s < s_0$ grows larger, approaching the half plane in the limit. Even if the workplace has no effect on the move, movers having a long pre-move trip will experience a higher probability of moving closer to the workplace than those who are already close to work. Thus, the fact that $P(s < s_0)$ increases with s_0, does not in and of itself indicate workplace attraction. What we must do is to compare an observed curve of $P(s < s_0)$ with one generated from the null hypothesis of $k = 0$.

4.1. Estimating workplace attractiveness

We first examine the hypotheses of observed and expected distributions for move distance.[5] Mean move distance is 6.28 miles. Fig. 3 shows the that the fit of

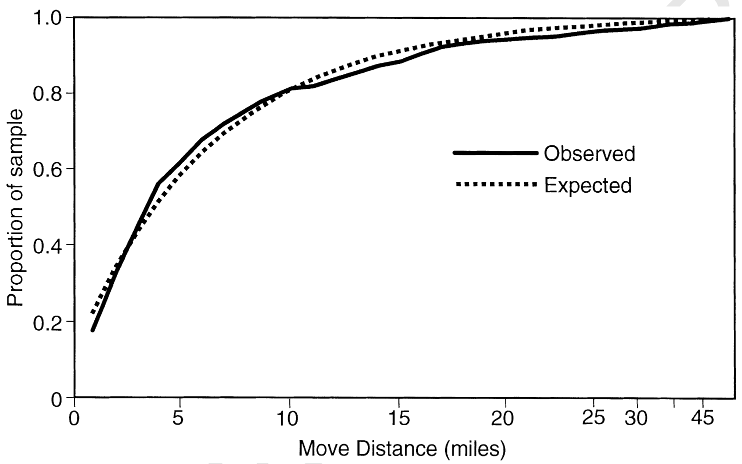

Fig. 3. Observed and expected distribution functions for move distance.

[5] The results are consistent with an earlier analysis of commuting in Milwaukee (Clark and Burt, 1980), although the work bias attraction is greater in Seattle.

the observed and expected distributions is reasonable.[6] According to the Kolmogorov–Smirnov test, these two distributions are the same ($P = 0.594$). The second assumption focuses on the mean direction of all moves. Using directional statistics in which each direction in the sample is represented by a unit vector with direction θ, means that the sample as a whole can be characterized by the vector resulting from the addition of the sample vectors. The direction of the resultant vector θ_R, the mean direction,

$$\theta_R = \tan^{-1} \frac{1/n \sum \sin \theta_i}{1/n \sum \cos \theta_i} \tag{7}$$

is a measure of centrality for a set of move directions just as the arithmetic mean is a measure of centrality. The length of the vector R reflects the degree of clustering in the sample and can be compared to the variance in a non-directional data set. Perfectly opposing vectors will sum to zero. R is standardized by n (Eq. (8)) to yield an index between zero and one as follows:

$$\bar{R} = R/n = \frac{1}{n} \sqrt{(\sum \sin \theta_i)^2 + (\sum \cos \theta_i)^2} \tag{8}$$

The value $\bar{R}$ and the concentration parameter k are related by:

$$\bar{R} = I_1(\hat{k})/I_0(\hat{k}) \tag{9}$$

where I_0 is a modified Bessel function of first kind and zero order.

For the Seattle data, θ_R is 5.56 in degrees and $\bar{R}$ is 0.318. Distribution theory for θ_R and $\bar{R}$ when the parent population is von Mises are given in Mardia (1972) and when n is large and $k = 0$ the statistic 2 $n\bar{R}^2$ is approximately χ^2 distributed with two degrees for freedom. The value for the Seattle data is 65.73 and we reject the hypothesis of no bias. Having shown that bias exists, the question is whether the bias is in the workplace direction.

Solving (9) numerically we find that $k = 0.668$. Interestingly the value is somewhat larger than the k value computed for Milwaukee (Clark and Burt, 1980) which suggests, as we noted, greater work bias in Seattle. A 95% confidence interval around the work direction is $1.96/\sqrt{324 \cdot 0.668 \cdot 0.318}$ in radians or 0.0 ± 13.5 in degrees. The mean move direction 5.56° falls in the confidence interval, so we accept the hypothesis that move directions are centered on the workplace.

We can evaluate the relationship of $P(s < s_0)$ for selected values of s_0, the

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[6] Since there is a large proportion of households that move within a very short distance, the fitted distribution function for move distance is $f(x) = \alpha\ e^{-\alpha(x-d_0)}$, where $x > 0$. The intercept on x-axes d_0 is negative in this case, although this is not meaningful in the sense that one cannot commute a negative distance.

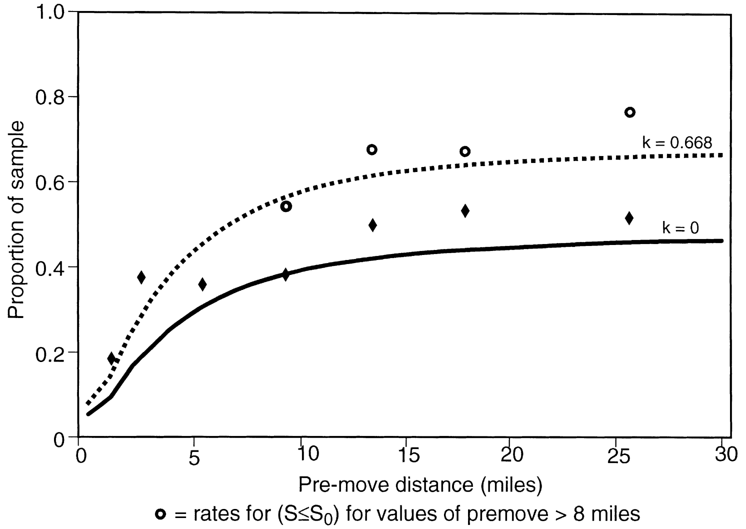

Fig. 4. Observed and expected probabilities of shortening the distance to work. The expected curves are $k = 0$ (no bias) and $k = 0.668$ (bias).

pre-move distance. Observed value of $P(s < s_0)$ were computed for specified distance intervals and plotted against the curves for $k = 0$ and $k = 0.668$ (Fig. 4).

We have plotted two sets of observed values for $P(s < s_0)$ for all pre-move distance s_0. For $P(s < s_0)$ for all pre-move distances (diamonds) and for $P(s \leq s_0)$ for values greater than 8 miles. As we cannot be more exact in our measurement than centroid to centroid of census tracts we find a small number of households (less than 1%) who moved within the same tract, thus have the same distance to the job location before and after the move. Certainly, following the arguments of the paper it is likely that a large proportion of movers at greater distances from the workplace would have decreased distances after the move. We can ask the question is the likelihood of reducing the distance between work and residence greater, for pre-move distances above 8 miles? In this sense we are evaluating the notion of a postulated critical isochrone. That is, do pre-move work residence separations when they are estimated as shorter or similar work-trip distance, fit the estimate of k more exactly? The plots of $s < s_0$ lie between the $k = 0$ and $k = 0.668$ but the plots of $s < s_0$ for values above 8 miles are a close fit to the curve for $k = 0.668$. This suggests that the workplace bias is not a constant for we find that at very large values of s_0 the values of $P(s < s_0)$ are even greater than the probabilities indicated by curve with k value of 0.668. Thus, at very large distances the bias towards workplace is greater than that evaluated by the constant k. By using a threshold value (in our case about 8 miles) we find that there is a difference between the population within that limit and those beyond. A test of significance

Table 7
Parameter estimates for men and women commuters

	Men	Women
X distance moved	6.59	5.96
Pre-move commute	9.31	7.56
Post-move commute	11.08	7.95
$2\ n\bar{R}^2$	22.57[a]	46.13[a]
k	0.536	0.831
G	10.314[b]	

[a] Reject hypothesis of no bias.
[b] Reject hypothesis of no difference in work attraction.

for observed values of $s_0 < 8$ and $s_0 > 8$ is statistically significant at the 0.05 level ($P = 0.029$). This is a test of those who move the same or less between work and residence at this break point. The test is of those who move the same or less distance, below and above $s = 8$. These results provide support for the notion that those within the limit (less than 8 miles) are much less concerned about an increase in work trip as long as it does not pass the critical limit[7]. Those beyond that limit are much more likely at worst to maintain and at best to lower their commute.

It is possible to use the model and estimates of *k* to provide additional interpretations of the hypotheses. We develop separate estimates from the model by gender for all men and women (Table 7), and for one and two-worker households[8] (Table 8). Recall that overall the *k* value is 0.668. How does the value vary by gender and for one and two-worker households? Are there major differences in the *k* value, or work attraction, by these measures? As expected

Table 8
Parameter estimates for one- and two-worker households

	One-worker	Two-worker
X distance moved	6.14	6.62
Pre-move commute	8.28	8.6
Post-move commute	9.29	9.72
$2\ n\bar{R}^2$	23.13[a]	30.2[a]
k	0.716	0.571
G	5.05[b]	

[a] Reject hypothesis of no bias.
[b] Reject hypothesis of no difference in work attraction.

[7] This is not to suggest that 8 miles is an exact measure of the critical isochrone rather it is an empirical value which separates the distributions in the case of Seattle.

[8] As the sample is relatively small we do not attempt to calculate *k* values for men and women in two-worker households.

there are important differences by gender. The mean distance to work is lower for women. Moreover, when households move, men add nearly two miles on average to their commute, and thus are willing to travel a somewhat greater distance, yet women add less than half a mile and are clearly influenced by workplace location. Mean distances moved in residential relocation do not vary markedly nor are there theoretical reasons to expect significant differences in relocation behavior of households. Both men and women exhibit workplace bias. In every case $2n\bar{R}^2$ is significant but for men the *k* value is much lower than the *k* value for women. The *k* value for women if 0.832 compared to men's *k* value of 0.536. In other words, work attraction is stronger for women than men. To test if the work attractions are statistically different, we calculate the statistic *G*,[9] which is normally distributed with mean zero and variance unit (Mardia, 1972). The value of *G* is 10.314, larger than the critical value at 95% level of 1.96, so we reject the null hypothesis of no difference. Work attraction for men is statistically different from that for women. To reiterate, on average women commute less than men, both before and after a move, a finding that is consistent with much of the literature on women's commuting.

The results are equally revealing and interesting for one versus two-worker households. The pre- and post-move commutes are slightly higher for two-worker households, which is consistent with the hypothesis that one-worker households find it easier to relocate with respect to the workplace than two-worker households who have two workplaces to balance. Again, the bias towards the workplace ($2n\bar{R}^2$) is significant. The *k* value is much larger for one-worker households (0.716) than two-worker households (0.571), confirming that one-worker households have stronger work attraction. Similarly, we calculate the *G* statistic to test if the work attraction for the two types of households are statistically same. Here $G = 5.051$,[10] larger than 1.96. So we reject the null hypothesis, and work attraction for one-worker households is statistically different from that for the primary worker in two-worker households. Two-worker households exhibit less workplace attraction.

5. Conclusions and policy significance

This research provides an enriched theoretical understanding of the links between residential moves and job location and specifically the extent to which households are sensitive to the length of commutes. By examining the way in

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[9] According to Mardia (1972), the calculation of *G* is based on the value of $\bar{R}$. When $\bar{R} < 0.45$, $G = \frac{2}{\sqrt{3}}\left|\sin^{-1}(1.22474\bar{R}_1) - \sin^{-1}(1.22474\bar{R})\right| / \left|(n_1 - 4)^{-1} + (n_2 - 4)^{-1}\right|^{1/2}$. In this case, $\bar{R}$ for women is 0.383 and $\bar{R}$ for men is 0.258, and the number of observations *n* for women is 157 and *n* for men is 169. So $G = 10.3135$.

[10] For one-worker households, $\bar{R} = 0.337$, and $n = 102$; for two-worker households, $\bar{R} = 0.274$ and $n = 201$.

which commuters respond to separation we have provided a new look at the variable nature of separation for different households. We have advanced previous knowledge by providing a specific model of the probability of decreasing the commute with greater distance from the workplace. The findings from the descriptive analysis of changes in commuting distance and time, as well as the evaluation of the probability function $P(s < s_0)$ emphasize the rational behavior of reducing the commute distance and time with greater separation. The data for Seattle provide another confirmation of the importance of a critical isochrone, in this case about 8 miles, beyond which the likelihood of decreasing the distance to work grows rapidly.

This research is innovative because it extends previous model specifications to include the spatial complexities of two-worker households. A number of avenues for further research are suggested by this study. It is clear that there is a dearth of research addressing the spatial complexity of dual-earner households, yet economic, social, and spatial restructuring (Crampton, 1999) indicate the continued dominance of this household type for the foreseeable future. Specifically, how do couples negotiate the spatial and temporal complexities of dual labor-market attachments and family life and community? Green et al. (1999) find evidence that longer distance commuting serves as a substitute for migration for dual-career households. Within households we do not as yet know what impact a job change on the part of one partner has on the other partners employment. Given that Zax and Kain (1991) suggest job changes and quit propensities are related to long commutes, to what extent are women moving in and out of the labor force in response to dynamic spatial constraints? A great deal remains unknown as to the connection between the employment dynamics of partners and the residential dynamics of the household. Further longitudinal research is needed to answer these questions. What remains clear is the complexity of the geography of two-worker households.

The policy implications are less direct but no less important. Commute distance does matter and households are acutely aware of the trade-off between distance to work and residential location. As households in large cities struggle with the time of commuting and the changing patterns of jobs, the extent to which they will undertake residential adjustments to fit their job locations is an indication of the sensitivity of residential behavior to job location. Now that there are a very large number of two-worker households the intersection of residential location and job location is likely to increase in importance as household's struggle with the changing separation of work and residence.

6. Uncited references

Shen, 2000; van Ommeren, 1998; Zax, 1991

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