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Accessibility and the journey to work

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This study analyzes the effect of accessibility to jobs and houses at both the home and work ends of trips on commuting duration for respondents to a household travel survey in metropolitan Washington, DC. A model is constructed to estimate the effects of demographics and relative location on the journey to work. Analysis finds that residences in job-rich areas and workplaces in housing-rich areas are associated with shorter commutes. An implication of this study is that, by balancing accessibility, the suburbanization of jobs maintains stability in commuting durations despite rising congestion, increasing trip lengths, and increased work and non-work trip making. © 1998 Elsevier Science Ltd. All rights reserved

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Introduction

The influence of land use patterns on commuting time remains an important issue for planners and policy makers. While congestion rises, and commuting distances increase, commuting durations have held steady over the long term in metropolitan Washington DC (Levinson and Kumar, 1994a,b). Nationally, similar trends are found, and while there is some dispute as to whether commuting durations are rising slightly (Rosetti and Eversole, 1993) or dropping (Gordon *et al*, 1991), it is clear that commuting time is not rising at the same rate as congestion and trip-making. Reflecting the classic dichotomy between social costs (congestion, pollution) and individual costs (commuting time), some favor altering land use patterns to reduce the amount of commuting (Newman and Kenworthy, 1989; Cervero, 1989; Levine, 1992), while others recoil at (or at least resist) further government intervention in the land markets, suggesting any effects will be minimal if not counter-productive because households and firms locate with respect to each other (Gordon and Richardson, 1989; Bae, 1993; Giuliano and Small, 1993). Independent of the merits of government intervention, the market process of mutual co-location can be unpacked into its constituent parts, the location of houses and firms.

How much does location influence commuting behavior? This question has immediate policy relevance because attaining, or maintaining, a balance between jobs and housing is becoming an explicit goal of many regional and local plans (Cervero, 1996). Furthermore, there are numerous government policies which implicitly impact this balance, through tax, zoning, and growth management policies most noticeably. Within this debate are two related strands, positive and normative. The positive strand attempts to simply correctly quantify the magnitude of the relationship. The normative strand asks whether there are government policies which can successfully use the empirical relationship to achieve balance, or whether balance is achieved by the marketplace anyway. Clearly the success of the normative approach depends on the positive strand, which is the primary thrust of this paper.

Previous studies have used a fixed sub-regional geography, implicitly considering municipalities as labor market districts, to measure job/housing balance (Cervero, 1989, 1996). If the ratio of jobs to employed residents is one, then the area is balanced; deviation from that number indicates degrees of imbalance. Cervero argues that there are job/housing mismatches, suggesting that a scarcity of housing sites, resulting in high housing costs in areas of high job concentration, push workers toward longer commutes, and advocates a variety of government policies to remedy this situation. Giuliano (1992) counters that the relationship between job and housing location is complex, and where people choose to live "may have little to do with job access considerations," that jobs and housing are balanced as part of the process of urban growth, and the reason for supporting such a balancing policy is the underlying (and wrong) assumption that individuals choose to locate as close to their job as possible.

In contrast to Scott's (1988) analysis of animation studios in Los Angeles which purports to "dispel any notion that metropolitan areas invariably constitute the minimum geographical level of local labor market differentiation," Giuliano (1992) concludes that as commutes average in the order of 25 min, the region as a whole is the appropriate level of analysis for labor markets. Using the entire region for analysis, the 'minimum required commute' approach calculates what would happen if an omniscient central planner could associate the existing stock of individual jobs and housing units to minimize the amount of total commuting (Hamilton, 1982). The difference between the minimum and actual commuting times is dubbed 'excess' or 'wasteful'. Giuliano and Small (1993) found that this 'excess' commute ranges from 50 to 90%, leading them to conclude that travel time, though statistically significant, has only a small influence on residential location decisions.[1]

Even if we accept the concept of job–housing balance as a valid and significant, though by no means the only, influence on commuting times, the question remains as to how balance is best measured. The geographic unit of study for measuring job–housing balance is typically municipal, which has the beneficial property that it represents the political region where land use policy is made. But by taking municipalities as the unit of analysis, these studies artificially limit the actual commuting range and do not differentiate the value of an activity by discounting for spatial separation. The geography of labor markets and government jurisdiction do not necessarily coincide. Even if the geography of the labor market for a given firm is highly localized as suggested by Scott (1988) and Hanson and Pratt (1995), the labor markets between firms overlap, indicating support for considering the metropolitan area as the appropriate scale.

An alternative measure, considering the entire region but also recognizing that local effects matter more than those far away, is *accessibility*, which according to Wachs and Kumagai (1973) "is perhaps the most important concept in defining and explaining regional form and function." Accessibility, as used here, is a continuous variable which is measured by counting the number of activities (e.g. jobs) available at a given distance from an origin (e.g. the home), and discounting that number by the intervening travel time (Hansen, 1959). By looking at accessibility to both opportunities (jobs in the case of workers, labor markets in the case of firms) and competitors (competing employers in the case of firms, competing workers in the case of households), some of the analytical problems of earlier studies can be overcome. First, we can consider a continuum of opportunities rather than being spatially confined to a politically and historically defined municipality. Second, we can look at the system as a market, where the number of competitors for jobs or housing alter the environment (cost of housing and travel times) faced by other individuals in choosing where to live and work. Furthermore, by using individual records from a travel diary in this analysis, the aggregation bias common in other research, which evaluates the average commute duration over an area, is avoided.

Consistent with the standard model of urban economics, it is the hypothesis of this research that living in an area with relatively high accessibility to jobs is associated with shorter trips, as is working in an area of relatively high housing accessibility (Mills, 1972; Mills and Hamilton, 1989). Furthermore, and distinguishing this paper from much of the existing literature, is the explicit consideration of competitors, who absorb opportunities, in addition to the opportunities themselves. This paper argues that the relative location of houses and firms, measured using accessibility, is an important determinant of commuting duration, and strives to measure that importance. That is, while challenging the methodological and geographical limitations of some earlier work advocating jobs–housing balance to reduce commuting durations, this research supports their empirical (if not their policy) conclusions — location matters. This contrasts sharply with the thrust of the wasteful commuting literature. While the underlying question is clearly not a new one, it has not been completely resolved either, arguing for more theoretical and empirical work.

This paper uses a household travel survey conducted in metropolitan Washington DC in 1987/88 to examine the influence of jobs and housing accessibility on commuting duration. The next section discusses measures of accessibility. In the following section, the specific hypotheses relating accessibility to commuting times are proposed and tested. Then, the influence of accessibility and physical location of houses and jobs on the journey to work travel times is analyzed. The results are interpreted in the context of job–housing balance by considering the effects of additional oppor-

[1]Some of the criticisms of the wasteful commuting methodology, including the reasonableness of using a central planner without considering that individuals will not voluntarily lower their own utility (Cropper and Gordon, 1991), the aggregate nature of the analysis which doesn't consider stratification by housing and job type, and the feedback of relocation on network travel times, can in principle be overcome. Others criticisms are more difficult to resolve, indicating that the appelation 'wasteful' or 'excess' is misleading at best: first, the approach entirely misses the transaction costs (both monetary and social) of moving and switching jobs, which are likely large since these changes occur only every few years (Levinson, 1997); second it doesn't include nonwork activities as a factor in location (Handy, 1993), it should be noted that, even for workers, work occupies less than a quarter of all time, for the population at large, it is closer to one-eighth; third, it ignores the notion of possible benefits associated with commuting, including a human preference for roaming or expressing territoriality (Marchetti, 1994); and finally it fails to account for the costs of garnering information about new job and housing opportunities, Hanson and Pratt (1995) using data from Worcester, Massachusetts, argue that jobs and houses are found through social networks, based principally on gender.

tunities and competitors on commuting duration and computing point elasticities. The paper concludes with some implications of this study on the theory of mutual co-location of households and firms.

Defining and measuring accessibility

It has long been understood that the interaction between two locations declines with increasing disutility (distance, time, and cost) between them, but is positively associated with the amount of activity at each location (Isard, 1956). In analogy with physics, Reilly (1929) formulated a 'law of retail gravitation', and Stewart (1948) formulated definitions of demographic force, energy, and potential, now called accessibility (Hansen, 1959). The distance decay factor of 1/distance has been updated to a more comprehensive function of generalized cost, which is not necessarily linear — a negative exponential tends to be the preferred form. The gravity model has been corroborated many times as a basic underlying aggregate relationship (Scott, 1988; Cervero, 1989; Levinson and Kumar, 1995). The rate of decline of the interaction (called alternatively, the impedance or friction factor, or the utility or propensity function) has to be empirically measured, and varies by context.

Limiting the usefulness of the gravity model is its aggregate nature. Though policy also operates at an aggregate level, more accurate analyses will retain the most detailed level of information as long as possible. While the gravity model is very successful in explaining the choice of a large number of individuals, (eqns (3) and (4) below show that the R^2 of the impedance function (for each of 19 5 min cohorts) is 0.94 for auto trips and 0.98 for transit trips) the choice of any given individual varies greatly from the predicted value. As applied in an urban travel demand context, the disutilities are primarily time, distance, and cost, although discrete choice models with the application of more expansive utility expressions are sometimes used (Ben-Akiva and Lerman, 1985), as is stratification by income or auto ownership.

An accessibility measure derived from the gravity model can be used to measure jobs–housing balance more powerfully than using the number of jobs and houses in a smaller sub-regional geography. Accessibility is the product of two measures, a temporal element (e.g. the impedance function of a gravity model applied to the travel time between two points) and a spatial element reflecting the distribution of the activity under question (for instance number of jobs or houses) (Burns, 1979; Handy, 1993; Hanson, 1986; Koenig, 1980; Voges and Naude, 1983). The higher the accessibility to jobs, the more jobs which are available in a given commuting time. The accessibility measure weights the available destinations by a measure of time, the higher the travel time the lower the weight.

Beginning with Hansen (1959), accessibility in various forms has been used in a number of studies. Wachs and Kumagai (1973) analyze automobile accessibility in Los Angeles as an indicator of quality of life, while Black and Conroy (1977) conduct a similar study in Sydney to compare autos and public transit. Morris *et al* (1979) and Pirie (1981) examine the use of accessibility as a measure for transportation planning.

Unfortunately, the accessibility measure used in the present study is independent of the measures of housing affordability, income, and wealth due to a lack of disaggregate data. Housing prices and current income are available at the residential census block level, but this masks the large variation found within the area of residence of the survey respondent. Data at the workplace end of trips has even greater variation, as can be seen by the variety of wages in a single firm. Wealth and lifetime income data, which are certainly large factors considered by individuals in making a large and long-term purchase such as a home, are unavailable. The availability of such data would enable a consideration of whether jobs (particularly low paying jobs) can be filled by nearby or far away residents of the region, adding an additional aspect to the question of accessibility, that of spatial match/mismatch (Kain, 1968; Gordon *et al*, 1989). Income effects on commuting due to available housing stock are most significant at short distances, but at longer distances well within the radius of a typical commute, a wide variety of housing affordable by households at all incomes exists. Furthermore, strictly speaking, affordable housing of some sort is generally available at any given commuting duration beyond the very shortest, but the housing may be smaller or of lower quality than desired.

This analysis considers jobs accessibility and housing accessibility for each traffic zone at both the origin (home) and destination (work) ends of trips. Briefly, accessibility is defined using the equations below:

$$A_{iEm} = \sum_{j=1}^{J} (Ej*f(c_{ijm})) \quad (1)$$

$$A_{iRm} = \sum_{j=1}^{J} (Rj*f(c_{ijm})) \quad (2)$$

where:

A_{iEm} = accessibility to jobs (employment) from zone i by mode m

A_{iRm} = accessibility to houses(residences) from zone i by mode m

Ej = number of jobs (employment) in zone j

Rj = number of houses (residences) in zone j

$f(c_{ijm})$ = function of cost/time between zones i and j (equations (3) and (4) below)

Equations (3) and (4) show the impedance function for a work-trip gravity model estimated for metropolitan Washington DC (Levinson and Kumar, 1995). The dependent variable in the estimation of these equations was the number of trips divided by the number of opportunities (possible trip ends), to which a natural log transformation was applied. Travel time and its transformations served as independent variables. Each five minute travel time cohort was a separate observation. It should be noted that this aggregate method for estimating friction factors helps ensure higher R^2 values than would be obtained from a more disaggregate approach because of the central limit theorem.

For auto trips ($R^2 = 0.94$, $N = 19$):

$$f(c_{ija}) = \exp(-0.97 - 0.08c_{ija}) \quad (3)$$

For transit trips ($R^2 = 0.98$, $N = 19$):

$$f(c_{ijt}) = \exp(-1.91 - 0.08c_{ijt} + 0.265c^{0.5}_{ijt}) \quad (4)$$

where

c_{ija} = peak hour auto travel time between zones i and j; and

c_{ijt} = peak hour transit travel time between zones i and j.

Data

The principal data for this study — a detailed household travel survey — was conducted by the Metropolitan Washington Council of Governments in 1987 and 1988 (Metropolitan Washington Council of Governments, 1988). The sample involved 8000 households making 55000 trips. For each individual demographic and transportation data were collected. Each household was assigned a specific 24-hour 'travel day,' and information was collected on all trips made by members of that household on that day, where a trip was defined as one-way travel from one address to another. The locations of both ends of the trip were reported along with the times of departure and arrival. Trip duration was obtained by subtracting time of departure from time of arrival. Distance from the center of the region was computed as the straight line distance between the trip-end and the ellipse in front of the White House in Washington DC.[2]

This survey was supplemented by accessibility measures calculated using equations (1)–(4) developed from the Montgomery County Planning Department's regional travel demand model (Levinson and Kumar, 1995). Land use data (jobs and housing) from 1990 and afternoon peak hour travel time skims from the model were used in calculating the accessibility measures. The computed zonal accessibility numbers were matched to the origin and destination traffic zones associated with individual trip records of the household travel survey.

Metropolitan Washington DC, because of its government orientation, is highly centralized in terms of employment compared to many other US cities, though even the federal government has decentralized many facilities. It also has a relatively high income and concomitantly a high cost of housing. Associated with its centralization is a Metro system which was built to sustain the urban core. Nevertheless, the basic patterns which relate job and housing accessibility to journey to work times found in Washington are likely replicated elsewhere, to a greater or lesser degree; in other words, while coefficient magnitudes may change somewhat on the statistical models, the signs, general magnitudes, and specific relationships between variables are expected to be transferable between cities.

Overview

Figure 1 shows accessibility to jobs and housing by auto and transit, while *Figure 2* shows home price and commuting time against distance from the center of the region. Consistent with the notion of accessibility as a

[2]While ideally network distance would be used rather than airline distance, accurate data on interjurisdictional network distances were not available to the authors for the 1988 time period.

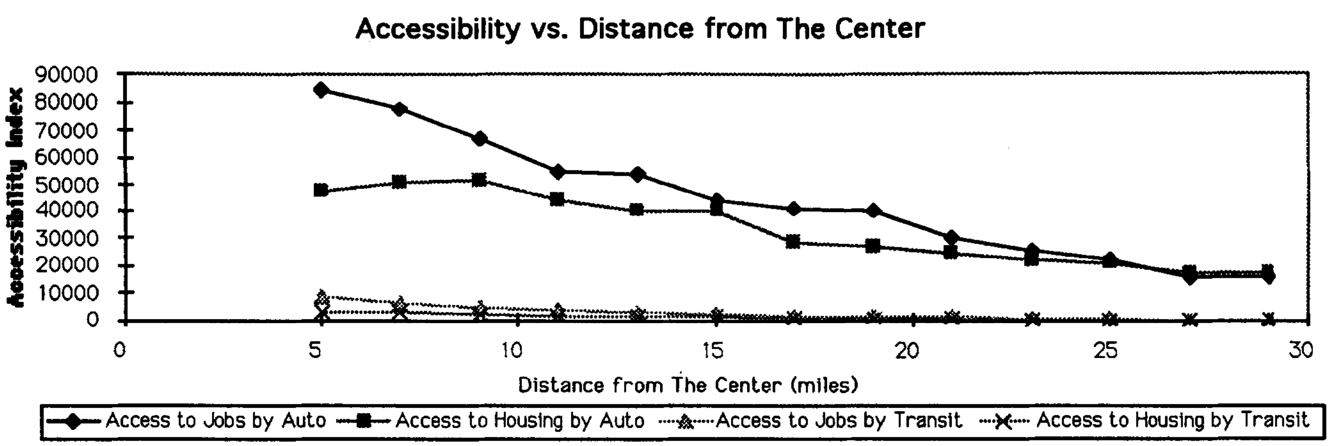

Figure 1 Accessibility vs distance from the center.

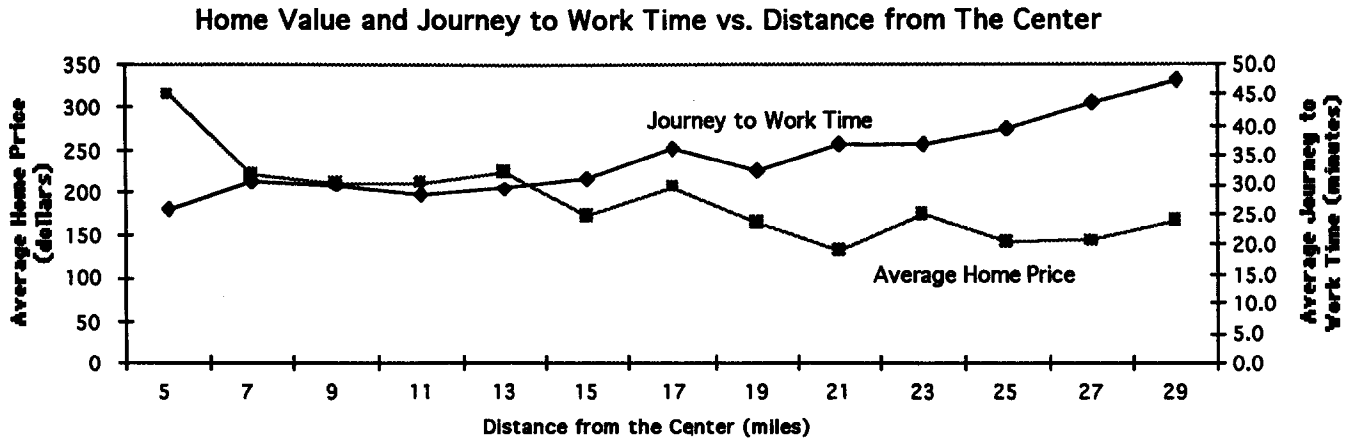

Figure 2 Home value and journey to work time vs distance from the center.

density measure, accessibility to jobs declines with distance from the center. While jobs accessibility declines at a faster rate than housing accessibility, due to low density housing at the edges of the region, the housing accessibility also declines in a relationship similar to the density gradient. Therefore, the ratio of jobs to housing accessibility declines from a surfeit of jobs (ratio of 1.81 for auto and 2.49 for transit at 4–6 miles) to relative scarcity (a ratio of 0.93 by auto at 28–30) as one moves out from the center. For the region as a whole, the ratio of filled jobs to houses is the average number of employed workers per household (about 1.5). By auto, the highest accessibility to housing in Montgomery County is actually found at a radius of 8–10 miles, the radius at which the Capital Beltway is located, showing the interrelationship of transportation infrastructure and accessibility.

Figure 1 confirms that in many respects Washington has a strong center, as reflected in both the jobs and housing accessibility gradients. However, what is not shown as strongly in *Figure 1* because of aggregation is that it has multiple employment centers. Both downtown and suburban employment centers pull on commuters. Furthermore, because the distribution of housing over the area is lumpy and not smooth, questions about job and housing balance can be addressed by examining the data more deeply, which is done in the following sections.

Another interesting point from *Figure 1* is the relationship of auto accessibility to transit accessibility. Auto accessibility is consistently higher, as more activities can be reached more easily by car than transit. The ratio of accessibility to jobs by auto vs transit declines from 10 to 1 at 5 miles to 156 to 1 at 29 miles, a relationship very similar to that of mode usage at those rings.

The variables in *Figure 2* also show interesting relationships with distance from the center. The average home price tends to decline as one leaves the center, though the relationship is uneven. This reflects the trade-off between increasing home and lot sizes as one travels farther out vs the lower price per unit land, or per square foot of house. Commuting time increases fairly steadily towards the edge of the region.

Table 1 shows the means and standard deviations for various accessibility and demographic variables used in this study, stratified by auto and transit commuters. The variables are defined in *Table 5*. Transit commuters have on average higher accessibility by both transit and car to houses and jobs than do auto commuters, indicating they live closer to the higher

Table 1 Means and standard deviations of accessibility and demographic variables

	All commuters		Auto commuters		Transit commuters	
Variable	**Mean**	**S.D.**	**Mean**	**S.D.**	**Mean**	**S.D.**
A_{iEa}	71698	32730	69148	32242	85314	31984
A_{iRa}	45583	11492	44870	11563	49387	10314
A_{jEa}	101425	45731	93306	43410	144784	31086
A_{jRa}	47165	10340	46365	10811	51438	5671
A_{iEt}	3093	3146	2837	3009	4456	3494
A_{iRt}	1393	1173	1296	1127	1908	1278
A_{jEt}	5645	4339	4959	4154	9307	3365
A_{jRt}	2028	1336	1862	1330	2912	972
Male	0.52	0.50	0.53	0.50	0.49	0.50
HHsize	2.78	1.38	2.84	1.38	2.47	1.36
Children	0.43	0.82	0.44	0.83	0.34	0.76
VPD	0.98	0.36	1.01	0.34	0.80	0.38
SFhome	0.75	0.43	0.78	0.41	0.61	0.49
Fhead	0.17	0.38	0.15	0.36	0.27	0.44
Age (yr)						
10	0.03	0.16	0.03	0.16	0.03	0.16
20	0.18	0.39	0.18	0.38	0.18	0.39
30	0.26	0.44	0.26	0.44	0.29	0.46
40	0.24	0.43	0.24	0.43	0.25	0.43
50	0.15	0.36	0.16	0.36	0.11	0.31
60	0.07	0.25	0.07	0.25	0.05	0.23
70	0.01	0.07	0.01	0.07	0.01	0.07
$c_{ij(min)}$	30.10	16.54	27.65	15.26	43.16	17.02
D_{ij}(miles)	7.25	5.40	7.23	5.46	7.33	5.08
D_{i0}	10.55	6.17	11.08	6.18	7.71	5.26
D_{j0}	7.32	6.17	8.27	6.14	2.25	3.10
$N =$	2327		1960		367	

All values are for metropolitan Washington region.
Source: 1987/88 Metropolitan Washington Household Travel Survey Montgomery County Planning Department. Accessibility indices.

density center of the region, the distance from home to the center of the region (D_{i0}) is 7.7 miles (airline distance) for transit commuters and 11.1 for auto commuters. However all commuters can reach more destinations more quickly by automobile than by transit. Transit commuters also work closer to downtown than auto commuters, the distance from the place of work to the center of the region (D_{j0}) is 2.3 miles for transit commuters and 8.3 miles for auto commuters. The average commute was 28 minutes for auto commuters and 43 minutes for transit commuters. The 1990 US Census reports a mean commute of 29.52 minutes for the area (Rosetti and Eversole, 1993), which is broadly consistent with the household survey.

The sample was 52% male, had an average household size of 2.8, of whom 0.43 were children between the age of 0 and 16. There was an average of 0.98 vehicles per driver, three quarters of the sample lived in single family homes (including townhouses), and 17% of the sample were female heads of household. The age distribution shows that half of the workers were between 30 and 50. Seven percent of individuals did not report their age.

Hypotheses

In the gravity model, which this analysis tests, average commute to work time is determined by three main factors: (1) a function which relates willingness to travel with travel cost or time, (2) the opportunities (jobs) available at any given travel time from the home, and (3) the number of competing workers who absorb opportunities. The underlying theory is that individuals have on average, the same basic preferences concerning commuting. These preferences may be a function of income or job specialization, and possibly other demographic or socio-economic characteristics, and certainly vary by mode of travel, but it is hypothesized that this underlying preference is relatively undifferentiated based solely on location.

Therefore, those individuals residing in areas of high job accessibility are likely to have shorter commutes, while those whose job opportunities are located farther away will have longer commutes, given a fixed number of competing workers in the labor market. Individuals living in an area of relatively high accessibility to houses (a surrogate for competing labor) should have longer commutes as more job opportunities will be absorbed by other residents. Similarly those working in an area of high accessibility to houses should have shorter commutes, while those working near many competing workers will have to travel farther to find housing and will have longer commutes. Even with the trend toward polycentric cities, distance from the center of the region is still an important indicator of relative job and housing accessibility: houses near the center of the region have relatively high accessibility to jobs, and thus should have shorter commutes, while jobs in the center of the region have a relatively low access to workers, and thus have to draw their labor force from a greater distance.

Formally, the geographic factors are defined as follows: the distance between the home and the center of the region (D_{i0}) (the zero mile marker at the ellipse in front of the White House), the distance between the workplace and the center (D_{j0}), the accessibility to jobs from the home (A_{iEm}), accessibility to other houses from the home (A_{iRm}), accessibility to other jobs from the workplace (A_{jEm}), and accessibility to houses from the workplace (A_{jRm}). The hypotheses for the specific variables are manifested in Chart 1, where a positive relationship implies a longer duration trip and a negative relationship implies a shorter trip.

Chart 1: Hypothesized Relationship Between Accessibility and Trip Duration

		Location of measurement	
		Home-end (origin)	Work-end (destination)
Type of access	Accessibility to jobs	A_{iEa}, A_{iEt} negative	A_{jEa}, A_{jEt} positive
	Accessibility to houses	A_{iRa}, A_{iRt} positive	A_{jRa}, A_{jRt} negative
	Distance from center	D_{i0} positive	D_{j0} negative

It should be noted that in a hypothetical city, with densities of both jobs and housing declining uniformly from the center(s), the housing and jobs accessibility variables would be measuring the same way as distance from the center. However, in Washington DC, as in all cities, the hypothetical model is only loosely approached, so it is useful to track both housing and jobs accessibility as well as the more traditional distance measure. The correlation between the job and housing accessibility measures (as shown in *Table 6*), are only 0.62 and 0.51 for auto users at the origin and destination ends respectively. For transit commuters (*Table 7*), the correlations are much higher, 0.90 and 0.84 at the origin and destination ends, values which may pose problems for the significance of one or both of the variables, though they are included for comparison purposes.

Demographic and socio-economic factors are also controlled for; these include gender, age, household size, dwelling unit type, and vehicle ownership. It is generally found that males have longer commutes than women (though not always), that part-time workers (often younger than 20 or older than 50) have shorter commutes, and that individuals in single family homes (often owners) have longer commutes than those living in apartments (often renters). For the age variable, persons aged 30–40 were suppressed from the regression, so the coefficients are relative to that age cohort. Dummy variables were used rather than a continuous age variable because there is no reason to presume that the association between age and commuting is linear, or even in the same direction in youth as in seniority.

A secondary set of hypotheses concern the relationship of the coefficient values between origin jobs accessibility and origin housing accessibility and between destination jobs accessibility and destination housing accessibility. If a job is considered a positive opportunity, a competing worker can be considered a negative opportunity. The sign on the coefficient should be negative because jobs and housing accessibility should have opposite signs.

Results

Table 2 shows the results of an ordinary least squares regression analysis to quantify the factors explaining commuting duration. These regressions are conducted separately for both auto and transit commuters. Note, for transit users, the accessibility was via transit, while for auto users, the accessibility used was via auto.

By and large, the hypotheses about the expected effect of jobs and housing accessibility at the origin (home) and destination (work) locations are corroborated here for auto commuters. Accessibility to other jobs at the work end (A_{jEa}) is positively associated with longer duration trips, while accessibility to jobs at the home end is associated with shorter duration trips (A_{iEa}) and the expected hypothesis is also borne out for accessibility to housing by auto (A_{jRa}, A_{iRa}). It is clear that jobs and housing accessibility are significant influences on commuting duration for auto commuters. However, interestingly, it is accessibility to jobs rather than the number of competing housing units which has the stronger impact, as there is a much greater differentiation in accessibility to jobs (which tend to be clustered) than accessibility to housing (which tends to be dispersed) regionwide. In all four cases accessibility to jobs is statistically more significant than housing accessibility for the same trip end.

Table 2 Regressions to predict commuting duration

Variable	Transit	Auto
Age (yr)		
10	−9.83 (−1.82)[a]	−5.85 (−2.75)[c]
20	0.58 (0.28)	1.901 (1.96)[b]
40	3.39 (1.82)	0.434 (0.50)
50	−1.08 (−0.40)	−0.62 (−0.62)
60	7.26 (2.04)[b]	−0.77 (−0.56)
70	16.96 (1.79)[a]	−6.03 (−1.42)
Male	−0.33 (−0.18)	1.82 (2.52)[b]
Fhead	−0.80 (−0.34)	−0.26 (−0.25)
SFhome	−3.78 (−2.04)[b]	0.16 (0.18)
VPD	−2.30 (−1.13)	1.03 (1.07)
Children	−2.8 (−2.09)[b]	0.936 (1.72)[a]
HHsize	1.83 (2.04)[b]	0.0857 (0.24)
A_{iEt}, A_{iEa}	−1.15E-03 (−2.27)[b]	−8.68E-05 (−4.86)[c]
A_{iRt}, A_{iRa}	1.12E-03 (0.85)	1.18E-04 (2.75)[c]
A_{jEt}, A_{jEa}	−1.14E-03 (−2.56)[b]	7.13E-05 (4.21)[c]
A_{jRt}, A_{jRa}	1.05E-03 (0.75)	−1.47E-04 (−3.26)[c]
D_{i0}	1.71 (9.71)[c]	0.63 (5.82)[c]
D_{j0}	−1.67 (−5.63)[c]	−0.55 (−3.77)[c]
Constant	44.12 (9.21)[c]	23.29 (4.61)[c]
Sample size	346	1950
Adj. R^2	0.38	0.17
F	12.96	22.79
Significance F	0	0

[a]$P<0.1$; [b]$P<0.05$; [c]$P<0.01$. Numbers in parentheses indicate *t*-statistic.
Source: 1987/88 Metropolitan Washington Household Travel Survey Montgomery County Planning Dept. Accessibility indices.

Though, as noted before, the independent variables are correlated to some extent, it would not appear that there is any multi-colinearity 'problem' for the auto model, in that the standard errors are low enough relative to the coefficients that the variables are statistically significant independently as well as jointly. Thus none of the independent variables can be constructed as a linear combination of the others. This is to be expected because the spatial pattern of Washington DC, while still dominated by a strong center, does not have a simple, strictly linear, density gradient from the center, but rather is more complex, with multiple peaks and valleys, which are not exactly coincident for jobs and houses. For the transit model, the higher correlation between the accessibility variables (as well as with distance from the center) may keep them from being independently significant when the other variables are present. However, this does not affect the broader conclusion, as distance from the center, which reflects accessibility by transit to jobs and houses, comes out as anticipated.

Further, the importance of the center should not be overlooked. Distance to the center of the region of both the home and workplace (D_{i0}, D_{j0}) were significant variables, in most cases explaining more minutes of commuting time than the job and housing accessibility variables for both auto and transit commuters.

All six elements of this hypothesis are borne out for auto commuters. While the relationships for distance from the center of the region for jobs and houses is supported for transit commuters, excepting origin jobs accessibility (A_{iEt}), the accessibility hypothesis is not supported for transit commuters. For transit commuters, housing accessibility (A_{iRt}, A_{jRt}) is not statistically significant, while location of a workplace in an area with many jobs (A_{jEt}) is negatively associated with commuting duration.

The observation for transit commuters that both origin and destination jobs accessibility are negatively associated with commuting duration requires some explanation. Transit commuting is more efficient in the high density central areas, as the high density (more riders per unit area) enables more routes and higher frequency of service. This is unlike auto commuting where high density is a diseconomy due to congestion. The high density is reflected in our variables as high accessibility for jobs and for housing at either trip-end.

In the transit commuters model that was estimated, only accessibility to jobs from both origin and destination ends came across as statistically significant variables, and both were negatively associated with duration. Apparently the economies of better service (more frequent and more direct) outweigh the competition between firms for workers (destination jobs accessibility) in influencing commuting durations. This affirms the need to analyze auto and transit commutes separately, and the need to consider both economies and diseconomies of density.

The transit models had a higher explanatory power than the auto models as evinced by their R^2 values. This despite the fact that the transit models had fewer significant accessibility variables. The ones that did matter for transit, distance from the center of the region, were far more important than the same variable in the auto model. This reflects the radial nature of transit commuting to downtown Washington, while auto commuting is dispersed. Because transit retains the monocentric model of urban form, it appears to be easier to predict commuting durations from just distance to downtown for those self-selected transit users.

The demographic and socio-economic variables are not as effective as the accessibility variables in explaining commuting duration. Relative to the suppressed age cohort 30–40, teen workers as well as older workers tended to have shorter commutes. Males tended to have longer commutes than females when using the automobile, though for transit users the commutes were indistinguishable. Being a female head of household was not associated with commuting behavior. Home ownership was significant only for transit commuters, being associated with shorter duration commutes than apartment dwellers. Perhaps home owners (in general, higher income) will only commute by transit when it is relatively convenient, while apartment dwellers may be captive commuters more frequently.

Taking the number of children and household size together, it can be seen that each additional child (who also increases the size of the household) is associated with a net one minute reduction in transit commutes, and a net one minute longer auto commute. Again the causality may be indirect, persons with children, who have more household responsibilities and are more likely to need to make chained trips, may only take transit if it is relatively more convenient, thereby resulting in children being associated with shorter transit commutes. The longer auto commutes, though only barely significant at the 90% confidence level, may suggest either life-cycle factors, persons with children are also in a certain stage in their career, or it may suggest unreported chained trips adding time to commutes (though only direct home to work trips were used, one can never be sure that all chained trips were reported).

Job–housing balance: opportunities and competitors

The regressions of the previous section do not directly concern the 'balance' of jobs and housing, but several things are clear from the model and supported by the empirical analysis. In an area with a high proportion of housing relative to jobs (the housing accessibility is greater than jobs accessibility after correcting for the number of workers per household), improving balance, that is increasing the proportion of jobs, will reduce the average commute for individuals living there, though increase the expected commuting duration for the smaller number of individuals working in that area. Similarly, in a place with a high proportion of jobs relative to houses, improving balance by increasing the proportion of houses, will reduce the average commute for individuals working there, but increase the expected commuting duration for the fewer individuals living in the area. These two assertions assume that at least some of the residents living in the housing rich zone (working in the job rich zone) will be able to secure those new jobs (houses), or that individuals will over time relocate their residence (job) to that zone to have a more convenient commute.

This can be confirmed by comparing the ratio of the coefficients of housing to jobs accessibility as shown in *Table 3*. The values vary between −1 to −2. Since all of them were negative, it is clear that overall an additional unit of housing accessibility (a competing worker) will have an opposite effect on commuting duration as an additional unit of job accessibility (an additional opportunity).

We can provide further insight into these issues by conducting an analysis of the point elasticity of travel time with respect to a one percent increase in accessibility, pivoting off of the mean values of accessibility and travel time. *Table 4* shows these results, for

Table 3 Ration of coefficients of housing accessibility to jobs accessibility

Accessibility type	Ratio
Auto origins $\beta(A_{iRa})/\beta(A_{iEa})$	−1.36
Destinations $\beta(A_{jRa})/\beta(A_{jEa})$	−2.06
Transit origins $\beta(A_{iRt})/\beta(A_{iEt})$	−0.97
Destinations $\beta(A_{jRt})/\beta(A_{jEt})$	−0.92

Table 4 Percent change in travel time with a 1% change in accessibility

Auto commuters		Transit commuters	
Variable	Elasticity	Variable	Elasticity
A_{iEa}	−0.22	A_{iEt}	−0.12
A_{iRa}	0.19	A_{iRt}	0.05
A_{jEa}	0.24	A_{jEt}	−0.25
A_{jRa}	−0.25	A_{jRt}	0.07
D_{i0}	0.25	D_{i0}	0.31
D_{j0}	−0.16	D_{j0}	−0.09

Table 5 Variables used in this study

Demographic and socio-economic variables	
Age 10[0,1]	1 if individual aged 10–20, 0 otherwise
Age 20[0,1]	1 if individual aged 20–30, 0 otherwise
Age 30[0,1]	1 if individual aged 30–40, 0 otherwise
Age 40[0,1]	1 if individual aged 40–50, 0 otherwise
Age 50[0,1]	1 if individual aged 50–60, 0 otherwise
Age 60[0,1]	1 if individual aged 60–70, 0 otherwise
Age 70[0,1]	1 if individual aged 70+, 0 otherwise
Children	Number of children 0–16 in the household
Fhead[0,1]	1 if individual is female head of household, 0 otherwise
HHsize	Number of persons in household
Male[0,1]	1 if individual is male, 0 otherwise
SFhome[0,1]	1 if individual lives in single family home, 0 otherwise
VPD	Number of vehicles per licensed driver
Accessibility variables	
A_{iR}, A_{iRa}, A_{iRt}	Origin (home-end) accessibility to housing, by auto, transit
A_{ie}, A_{iEa}, A_{iEt}	Origin (home-end) accessibility to jobs, by auto, transit
A_{jR}, A_{jRa}, A_{jRt}	Destination (work-end) accessibility to housing, by auto, transit
A_{jE}, A_{jEa}, A_{jEt}	Destination (work-end) accessibility to jobs, by auto, by transit
AD_i, AD_{ia}, AD_{it}	Difference in origin accessibility = $A_{iEa} - A_{iRa}$, $A_{iEt} - A_{iRt}$, by auto, transit
AD_j, AD_{ja}, AD_{jt}	Difference in destination accessibility = $A_{jEa} - A_{jRa}$, $A_{jEt} - A_{jRt}$, by auto, transit
AR_i, AR_{ia}, AR_{it}	Ratio of origin accessibility = A_{iEa}/A_{iRa}, A_{iEt}/A_{iRt}, by auto, transit
AR_j, AR_{ja}, AR_{jt}	Ratio of destination accessibility = $A_{jEa} - A_{jRa}$, $A_{jEt} - A_{jRt}$, by auto, transit
c_{ij}, c_{ija}, c_{ijt}	Travel time (minutes) between home and work, by auto, transit
D_{i0}	Distance (miles) between origin (home-end) and White House
D_{j0}	Distance (miles) between destination (workplace) and White House
D_{ij}	Airline travel distance (miles) between home and work

Table 6 Auto commute trips — correlation matrix

A_{iEa}	1.00											
A_{iRa}	0.62	1.00										
A_{jEa}	0.41	0.34	1.00									
A_{jRa}	0.33	0.45	0.51	1.00								
D_{i0}	−0.82	−0.74	−0.42	−0.41	1.00							
D_{j0}	−0.43	−0.43	−0.88	−0.70	0.50	1.00						
A_{Dia}	0.84	0.10	0.29	0.11	−0.53	−0.25	1.00					
A_{Dja}	0.33	0.19	0.93	0.15	−0.30	−0.71	0.29	1.00				
A_{Ria}	0.85	0.14	0.30	0.12	−0.56	−0.27	0.98	0.29	1.00			
A_{Rja}	0.30	0.16	0.88	0.08	−0.27	−0.67	0.27	0.98	0.28	1.00		
c_{ija}	−0.21	−0.11	0.20	0.03	0.20	−0.16	−0.19	0.21	−0.20	0.21	1.00	
D_{ij}	−0.34	−0.24	0.02	−0.02	0.44	0.01	−0.27	0.04	−0.28	0.03	0.67	1.00
	A_{iEa}	A_{iRa}	A_{jEa}	A_{jRa}	D_{i0}	D_{j0}	A_{Dia}	A_{Dja}	A_{Ria}	A_{Rja}	c_{ija}	D_{ij}

Table 7 Transit commute trips — correlation matrix

A_{iEt}	1.00											
A_{iRt}	0.90	1.00										
A_{jEt}	0.04	0.08	1.00									
A_{jRt}	0.08	0.12	0.84	1.00								
D_{i0}	−0.55	−0.50	−0.06	−0.09	1.00							
D_{j0}	−0.01	−0.01	−0.58	−0.41	0.15	1.00						
A_{Dit}	0.91	0.64	0.00	0.02	−0.49	0.00	1.00					
A_{Djt}	0.01	0.03	0.94	0.59	−0.03	−0.59	−0.02	1.00				
A_{Rit}	0.44	0.16	−0.04	−0.05	−0.18	0.01	0.64	−0.03	1.00			
A_{Rjt}	−0.06	−0.06	0.58	0.10	0.07	−0.49	−0.05	0.80	−0.02	1.00		
c_{ijt}	−0.42	−0.37	−0.03	−0.04	0.53	−0.10	−0.39	−0.01	−0.17	0.06	1.00	
D_{ij}	−0.47	−0.44	0.01	−0.03	0.86	−0.03	−0.41	0.04	−0.15	0.14	0.67	1.00
	A_{iEt}	A_{iRt}	A_{jEt}	A_{jRt}	D_{i0}	D_{j0}	A_{Dit}	A_{Djt}	A_{Rit}	A_{Rjt}	c_{ijt}	D_{ij}

instance a 1% increase in origin jobs accessibility (opportunities) for auto commuters will decrease commutes by 0.22%, Likewise a 1% increase in origin housing accessibility (competing workers) increases commutes by 0.19%. The similarity of these two values confirms that an additional competing worker can be seen as the equivalent to a reduction in available jobs. But though the magnitudes are similar on average, the variation in the urban structure and asymmetry between the location of housing (which is dispersed) and jobs (which tend to be concentrated in major employment centers) indicates that both measures are indeed accounting for different things.

From these results, several conclusions are suggested, noting the economist's caveat that the analysis assumes 'all other things being equal.' For a resident of the auto-oriented Washington urban region, any change which brings jobs closer to him (increases the origin jobs accessibility) will, on average, reduce his expected commute, while additional housing (workers competing for the fixed supply of jobs) makes finding a nearby job that much harder. The parallel argument holds for a firm, bringing workers closer (increasing destination housing accessibility) is associated with shorter commutes for its employees. Since, as *Figure 1* shows, the ratio of jobs to housing accessibility is relatively highest in downtown and lowest at the urban fringe, suburbanizing jobs and reurbanizing housing, *ceteris paribus*, will lead to shorter commutes. On the other hand, continued suburbanization of housing concomitant with a re-concentration of jobs in downtown, increases commute lengths. Whether either of these policies is worthwhile remains the subject of debate. Further studies using a longitudinal data base with more qualitative earnings–price data can be used to corroborate or refute the empirical findings. It should be noted that these results treat the location of housing and jobs as separate, and thus may not fully capture all of the effects of the mutual co-location of jobs and houses.

Conclusions

Giuliano and Small (1993) ask "is the journey to work explained by urban structure?" and conclude that other factors have a larger influence on commuting than urban structure. To bound the discussion; the fact that urban regions do not extend infinitely over space indicates that commuting time is a significant factor, the fact that the actual commute exceeds the minimum required commute (however defined) indicates that it is not the only factor.

An aggregate gravity model controlling for mode can explain over 90% of the variation in the share of people in each 5 min travel time cohort (Levinson and Kumar, 1995). Analysis suggests that the required commute is only one-half of the actual commute (Cropper and Gordon, 1991), while the required commute explains 29% of the variation in average travel times of traffic zones (Giuliano and Small, 1993). At a more disaggregate level, that of the individual, this brief analysis largely confirms those estimates, suggesting that, descriptively, 17–38% of the variation in travel time to work of individuals can be explained by attributes of urban structure. Many locational pairs have the same travel time between them, enabling a wide variety in choice of housing and jobs with approximately the same travel (dis)utility. Clearly, urban structure as measured by jobs and housing accessibility is an important, but not the only, element in residential location, corroborating the empirical findings of the excess commuting literature.

It has been noted in previous research that commuting durations are shortening nationally (Gordon *et al*, 1991) and holding steady in metropolitan Washington (Levinson and Kumar, 1994b) The hypothesis for this was that individuals and firms mutually co-locate to maintain commuting economies. The data from this research suggest, given the present amount and location of jobs and housing, that it is the suburbanization of jobs creating a polycentric or dispersed urban form (which serves to balance jobs and housing) rather than the further suburbanization of houses (which creates additional imbalance), which keeps commutes from getting longer. This leads inexorably to the conclusion that all other things being equal, in an auto dominated transportation system, policies favoring a properly defined jobs/housing balance will, at the margins, reduce commuting duration, while policies preventing balance will increase that duration.

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References

Bae, C.-H. C. (1993) Air quality and travel behavior: untying the knot. *Journal of the American Planning Association* **59** (1), 65–74.

Ben-Akiva, M. and Lerman, S. (1985) *Discrete Choice Analysis*. MIT Press Cambridge, MA.

Black, J. and Conroy, M. (1977) Accessibility measures and the social evaluation of urban structure. *Environment and Planning A* **9**, 1013–1031.

Burns, L. (1979) *Transportation, Temporal and Spatial Components of Accessibility*. Lexington Books, Lexington, MA.

Cervero, R. (1989) Jobs–housing balance and regional mobility. *Journal of the American Planning Association* **55** (**2**), 136–150.

Cervero, R. (1996) Jobs–housing balance revisited. *Journal of the American Planning Association* **62** (4), 492–511.

Cropper, M. and Gordon, P. (1991) Wasteful commuting: a re-examination. *Journal of Urban Economics* **29** (1), 2–13.

Giuliano, G. (1992) Is jobs–housing balance a transportation issue?. *Transportation Research Record* **1305**, 305–312.

Giuliano, G. and Small, K. A. (1993) Is the journey to work explained by urban structure? *Urban Studies* **30** (9), 1485–1500.

Gordon, P. and Richardson, H. (1989) Gasoline consumption and cities: a reply. *Journal of the American Planning Association* **55** (3), 342–345.

Gordon, P., Kumar, A. and Richardson, H. (1989) The spatial mismatch hypothesis: some new evidence. *Urban Studies* **26**, 315–326.

Gordon, P., Richardson, H. and Jun, M.-J. (1991) The commuting paradox: evidence from the top twenty. *Journal of the American Planning Association* **57** (4), 416–420.

Hamilton, B. W. (1982) Wasteful commuting. *Journal of Political Economics* **90**, 1035–1053.

Handy, S. (1993) Regional versus local accessibility: implications for non-work travel. Paper presented at the *72nd Annual Meeting of Transportation Research Board*, Washington DC.

Hansen, W. (1959) How accessibility shapes land use. *Journal of the American Institute of Planners* **25**, 73–76.

Hanson, S. (1986) *The Geography of Urban Transportation*. Guildford Press, New York.

Hanson, S. and Pratt, G. (1995) *Gender, Work, and Space*. Routledge, New York.

Isard, W. (1956) *Location and Space Economy*. MIT Press, Cambridge. MA.

Kain, J. F. (1968) Housing segregation, negro employment, and metropolitan decentralisation. *Quarterly Journal of Economics* **82**, 32–59.

Koenig, J. G. (1980) Indicators of urban accessibility: theory and application. *Transportation* **9**, 145–172.

Levine, J. (1992) Decentralization of jobs and the emerging suburban commute. Paper presented at the *71st Annual Meeting of Transportation Research Board*, Washington DC.

Levinson, D. (1997) Job and housing tenure and the journey to work. *Annals of Regional Science* **31**, 451–471.

Levinson, D. and Kumar, A. (1994) Operational evidence for changing travel patterns. *ITE Journal* **April**, 36–40.

Levinson, D. and Kumar, A. (1994) The rational locator: why travel times have remained stable. *Journal of the American Planning Association* **60** (3), 319–331.

Levinson, D. and Kumar, A. (1995) A multimodal trip distribution model: structure and application. *Transportation Research Record* **1466**, 124–131.

Marchetti, C. (1994) Anthropological invariants in travel behavior. *Technological Forecasting and Social Change* **47**, 75–88.

Metropolitan Washington Council of Governments (1988) *Household Travel Survey*. Washington DC.

Mills, E. S. (1972) *Studies in the Structure of Urban Economy*. Johns Hopkins University Press, Baltimore.

Mills, E. S. and Hamilton, B. W. (1989) *Urban Economics*, 4th edn. Scott Foresman Glenview, IL.

Morris, J. M., Dumble, P. L. and Wigan, M. R. (1979) Accessibility indicators for transport planning. *Transportation Research A* **13** (4), 91–109.

Newman, P. W. G. and Kenworthy, J. R. (1989) *Cities and Automobile Dependence: An International Sourcebook*. Glower Aldershot, UK.

Pirie, G. H. (1981) The possibility and potential of public policy on accessibility. *Transportation Research A* **15** (5), 377–381.

Reilly, W. J. (1929) Methods for the study of retail relationships. *University of Texas Bulletin* 2944, November.

Rosetti, M. A. and Eversole, B. S. (1993) *Journey to Work Trends in the United States and its Major Metropolitan Area, 1960–90*. US Department of Transportation, Federal Highway Administration Washington DC.

Scott, A. J. (1988) *Metropolis*. University of California Press, Berkeley.

Stewart, J. Q. (1948) Demographic gravitation: evidence and application. *Sociometry* **21**, 31–58.

Voges, E. M. and Naude, A. H. (1983) *Accessibility in Urban Areas: An Overview of Different Indicators*. National Institute for Transport and Road Research, CSIR, South Africa, Technical Report RT/21/83.

Wachs, M. and Kumagai, T. G. (1973) Physical accessibility as a social indicator. *Socio-Economic Policy Sciences* **7**, 437–456.