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IS TRAVEL DEMAND INSATIABLE? A STUDY OF CHANGES IN STRUCTURAL RELATIONSHIPS UNDERLYING TRAVEL

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Stability in travel over time is examined in this study, and the source of observed instability is decomposed into: change in socio-demographic and other contributing factors, and change in structural relationships underlying travel. As a tool for this analysis, simultaneous equations model systems are developed to describe urban residents' activity-travel patterns. The models are estimated using repeated cross-sectional data from the Kyoto-Osaka-Kobe metropolitan area of Japan, collected in 1980, 1990 and 2000. The results of statistical analysis indicate that the structural relationships are instable, that changes in non-workers' travel patterns are largely due to the instability in the structural relations while changes in demographic and socio-economic factors play relatively minor roles, and that urban residents' travel has the tendency to expand over time.

KEYWORDS: Temporal stability, travel time budgets, trip generation, trip chaining, motorization, household travel surveys

1. INTRODUCTION

As in most metropolitan areas of industrialized countries, metropolitan areas of Japan underwent substantial changes in the second half of the 20th century. With the rapid urbanization after the World War II, metropolitan areas expanded outwards with the suburbs absorbing much of the influx of population. The pace of population increase was phenomenal at the time. For example, consider the Kyoto-Osaka-Kobe metropolitan area (hereafter the "Osaka metropolitan area"), the second largest metropolitan area of Japan. The City of Osaka is situated in its geographical center and has the largest population and economy in the area. The City of Toyonaka, a municipality located 6.5 km north of the City of Osaka,[3] had a population of 102,355 in 1950, which almost doubled to 199,133 by 1960. While the population of Toyonaka peaked in 1985, cities further north of Osaka, e.g., Kawanishi and Takarazuka, continued to grow through 2000. The City of Sanda, located at the fringe of the metropolitan area, started to grow rapidly in 1985 and almost tripled its population in 15 years (Figure 1).

Motorization in Japan was not appreciable before 1960. The number of registered automobiles in the country began to rise in the first half of the 1960's. In fact annual growth peaked in 1960 with a growth rate exceeding 30%. Vehicle ownership in Japan increased from a mere 0.0018 vehicle per person in 1955 to 0.33 in 1999. At the same time, rail's share, dominant at 90.0% of total person-kilometers in 1950, declined to 34.0% in 1995; auto's share increased from a mere 0.6% to 51.7% in the same period.

Suburbanization, which progressed hand in hand with motorization, represented the predominant force that defined urban growth in this period. Japanese urban areas have retained until now their dense and mixed land use patterns. At least three major reasons are conceivable for this: the shortage of suitable land for urban development, resulting high land prices, and absence of forceful zoning regulations that would have restricted

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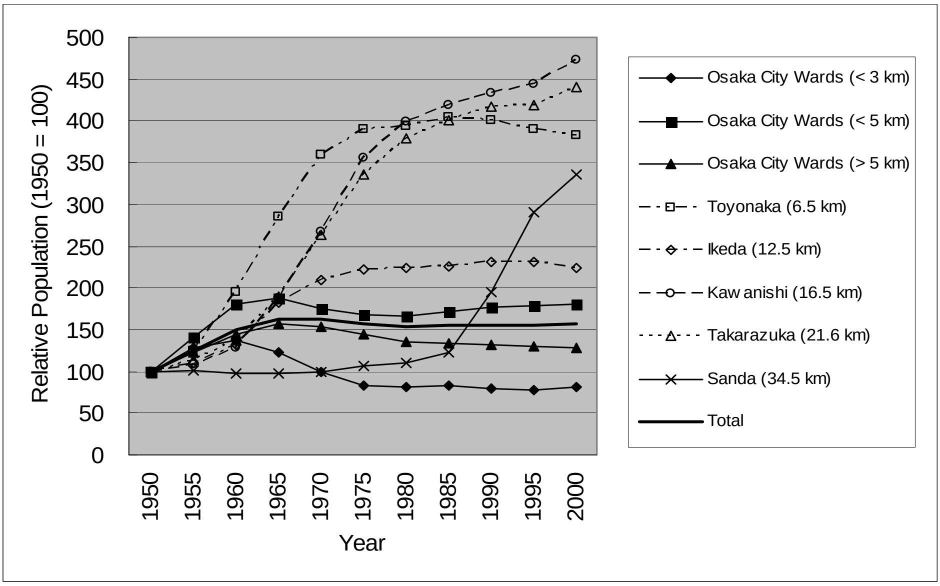
[3] The distance between two municipalities is represented by the straight-line distance between the city halls.

land use. Nonetheless the expansion of urban areas in Japan has led to increases in the relative weight of suburbs, and caused declines of central cities that are noticeable in all but the few largest metropolitan areas.



( ): Distance from the Osaka city hall

FIGURE 1: Population growth in selected municipalities of the Osaka metropolitan area: 1950-2000

The automobile offers levels of mobility that cannot be provided by public transport or by non-motorized means of travel, especially in the fringe of metropolitan areas. Motorization, at the same time, produces urban forms with low densities, spread-out opportunities, and less essential city centers. As increasing numbers of opportunities are situated at auto-oriented locations, urban residents' travel patterns are modified in many profound ways. Yet, exactly how urban travel has changed is not evident, beyond obvious changes in trip distribution and modal split. For example, despite the worsening road congestion and substantial shifts of work and non-work opportunities away from the city center to the suburbs, the mean commute duration in the Osaka metropolitan area remained surprisingly stable at around 36 minutes from 1980 to 2000.

The literature contains an accumulation of studies that report stability in travel. For example, Zahavi and Ryan (1980) eloquently report stability in travel time expenditures.[4] This argument is supported by results of time use studies (Szalai, 1972). Yet, some claim that such stability can be observed only at aggregate levels (e.g., Supernak, 1982).

Conflicting empirical findings on temporal stability stem in part from differences in study design. Quite often, study designs mask whether an observed change in behavior is due to changes in contributing factors, or behavior itself given the contributing factors, has changed. Stability in the structural relationships underlying travel has been examined in studies that attempted to establish the temporal and spatial transferability of

[4] See Mokhtarian and Chen (2004) for a review on the subject of travel time expenditures.

disaggregate models of travel behavior (e.g., Atherton and Ben-Akiva, 1976; Koppelman and Wilmot, 1982; Badoe and Miller, 1995; Fujiwara and Sugie, 1997; Elmi et al., 1999). They too, however, have not produced consistent results (Koppelman and Wilmot, 1982; Badoe and Miller, 1995).

This study is an attempt to examine the stability in activity engagement and travel; to determine empirically whether there exist invariants in urban residents' activity-travel patterns through the period when the urban area underwent substantial changes; and to infer general principles that govern changes in urban residents' activity-travel patterns. To these ends, simultaneous equations model systems of urban travel are developed, and their stability over time is statistically examined using empirical data.

The model systems aim at representing causal mechanisms underlying activity engagement and travel. Changes in specific aspects of activity-travel patterns (e.g., the number of trips or travel time expenditure) have often been examined in the past, most typically using cross-sectional data from multiple regions, or repeated cross-sectional data from a region, and by focusing on one aspect at a time. Little is known, however, as to how urban residents' adaptations to changes in their travel environments have yielded changes in their activity-travel patterns as a whole. This study represents a more holistic approach to the stability in activity-travel patterns. The data used are from conventional large-scale household travel surveys conducted in the Osaka metropolitan area in 1980, 1990 and 2000, with sampling rates of 2.4% to 3.0%. The travel data have been supplemented with land use and network data in this study.

The next section offers a brief overview of changes in the Osaka metropolitan area. Section 3 describes the model system, and discusses the methods adopted to examine stability in activity-travel patterns. The model system for non-workers is discussed in Section 4, and its stability between 1980 and 2000 is discussed in Sections 5. Section 6 presents results with the model system for workers. Section 7 is a brief summary of the study.

2. CHANGES IN THE STUDY AREA

The Osaka metropolitan area is located approximately 410 km west of Tokyo and contains three major cities, Kyoto, Osaka and Kobe. Osaka used to be the center of commerce until the beginning of the Meiji Era, which began in 1868. Kyoto is an ancient capitol of Japan, while Kobe, which is endowed with a good natural harbor, has been a center of maritime transportation in the area.

The area can be characterized by its very dense, mixed-use land developments, and by the well developed rail networks which serve it.[5] As a consequence, the 2000 share of auto trips is only 31.4% in the metropolitan area, which compares with 53.4% in the Nagoya metropolitan area in 1996, and 33.1% in the Tokyo metropolitan area in 1998 (Kei-Han-Shin Transportation Planning Commission, undated). Auto ownership is lower in the area, compared with the nationwide average of 1.12 vehicles per household in 2000.[6] Auto ownership has nonetheless increased from 0.41 vehicle per household in 1970 to 0.66 in 1980, 0.88 in 1990, and to 0.97 in 2000 (Table 1).

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[5] The population density of the most densely populated Nishinari-Ward of the City of Osaka is 18,614 inhabitants per km^2 in 2000. The average population density of the City of Osaka is 11,743 inhabitants per km^2.

[6] Based on published statistics on vehicle registration, population, and household size. A 1999 statistic based on household travel survey results is 1.07 vehicles per household. This presumably over-represents urban areas.

TABLE 1: Changes in household vehicle ownership in the Osaka metropolitan area and selected urban areas: 1970 to 2000

Area	Area type[†]	Vehicles per household by year			
		1970	1980	1990	2000
Metropolitan area		0.41	0.66	0.88	0.97
Chuo-Ward, Osaka	Commercial	0.33	0.59	0.56	0.49
Fukushima-Ward, Osaka	Mixed commercial	0.32	0.49	0.50	0.50
Suita City	Old suburbs	0.30	0.53	0.70	0.77
Ikoma City	Suburbs	0.67	0.75	1.03	1.19
Nishi-Ward, Kobe	New suburbs	0.91	0.99	1.12	1.20
Sanda City	Emerging suburbs	0.67	1.25	1.34	1.37

Sources: Census and other published statistics
[†] See footnote 7 for the definition of area types.

The six municipalities shown in Table 1 represent different phases of urbanization. Such older parts of the metropolitan area as established commercial center (Chuo-Ward, Osaka) and mixed commercial and residential area (Fukushima-Ward, Osaka), show very slow progress of motorization. In particular, the number of vehicles per household declined in Chuo-Ward after 1980, in part reflecting declining household sizes in the area. Suburban areas in general show higher levels and faster growth rates of vehicle ownership. With the increase from 0.67 vehicle per household in 1970 to 1.37 in 2000, the growth rate is largest in Sanda City, whose population growth has been seen in Figure 1.[7]

As is well acknowledged, the process of motorization transforms urban area; the area expands outwards, creating lower density urban developments which favor the automobile. In the Osaka metropolitan area, suburban roadside commercial development became prevalent since the 1980's, and employment, as well as population, has gradually been decentralized. The decentralization of employment, however, appears to be limited largely to retail employees; suburban office campuses that have emerged as a result of motorization and suburbanization in North America, are not found in the Osaka metropolitan area.

Suburbanization has been the ongoing trend in the study area, nonetheless. To quantify the trend, the second moments of residential population, employment, and retail stores are evaluated around their respective mass centers and also around the center of the metropolitan area. The municipality is used as the unit of data organization, and the Kita

[7] Two schemes of classification of urban areas are adopted in this study: one is static and the other is dynamic (Fukui, 2003). The static classification is based on a principal component analysis of attributes of the municipalities in the metropolitan area for 1970, 1980, 1990 and 2000, respectively. In the dynamic classification, each area is classified based on the series of static classes assigned to it for 1970 through 2000. In the static classification, the *commercial city* is a municipality (or other governmental unit) where the daytime population exceeds the nighttime population. The *mixed commercial/residential city* has both commercial and residential developments and high density, but the daytime population does not exceed the nighttime population. The *autonomous city* is one with a small fraction of workers who commute to outside the municipality. The *suburbs* are a municipality which is urbanized, but not an autonomous, commercial or mixed commercial/residential city. The *unurbanized area* is one where the ratio of daytime population to nighttime population is more than a half standard deviation below the metropolitan average, and with no concentration of commercial activities. In the dynamic classification scheme, commercial cities, mixed commercial/residential cities, suburbs and autonomous cities refer to ones that retained the same respective status between 1970 and 2000. The *old suburbs* refer to a municipality that has grown from the suburbs in 1970 to the mixed commercial/residential city by 2000. The *new suburbs* are ones that have changed from an autonomous city to suburbs in 1980. The *emerging suburbs* refer to ones that have changed from an unurbanized area or autonomous city to suburbs in 1990 or 2000. An unurbanized area in 2000 in the static classification is classified as unurbanized in the dynamic classification.

Ward of the City of Osaka, where the city hall is located, is used as the center of the area.[8] Table 2 shows the results in terms of the length of moment arms.

TABLE 2: Changes in second moments of residential population, employment, and retail stores: 1970 to 2000

	Total	Ratio	Moment arm (km) around	
			Mass center	Kita-Ward
Population				
1970	14771324	1.000	30.98	31.01
1980	16852051	1.141	31.74	31.74
1990	17766306	1.203	32.12	32.12
2000	18217017	1.233	32.56	32.56
Employment				
1969	6083519	1.000	28.13	28.13
1978	7197906	1.183	28.90	28.90
1991	8924866	1.467	29.33	29.33
1999	7858106	1.292	29.89	29.89
Retail Stores				
1970	201616	1.000	31.81	31.81
1982	246124	1.221	31.74	31.74
1991	223589	1.109	31.99	31.99
1999	194645	0.965	32.34	32.34

Sources: Census and other published statistics

The second moment around the mass center of population increased steadily, especially between 1970 and 1980, when the moment arm increased by 0.76 km. A similar trend can be found for the second moment around the Kita-Ward of Osaka City. Likewise, the second moment of employment has kept on increasing despite the fact that the total number of employees in the area peaked in 1991, when the "bubble" economy of Japan was at its peak. There is no clear indication that the rate of this growth is declining, suggesting a steady trend of decentralization in employment from 1969 through 1999.

The number of retail stores peaked in around 1982, presumably representing the shift from "mom and pop's stores" toward supermarkets and larger retail outlets. Interestingly, the moment arm of retail stores was larger than that of population in 1970, but increased much more slowly, and the 1999 value is smaller than that of population in 2000. This is probably because suburbs tend to have fewer and larger retail stores; if a different measure (e.g., retail floor area or retail employment) were used, it would have shown more rapid progress of decentralization.

Other characteristics of changes in the Osaka metropolitan area include (Kitamura et al., 2003):

- Motorization has not progressed uniformly within the metropolitan area; established commercial areas are virtually unaffected by motorization as far as modal split is concerned (Fukui, 2003). In newly developed areas, on the other hand, the automobile has become the dominant mode of travel by the residents.
- Despite the well developed rail networks in the area, the automobile has consistently provided better accessibility to both population and employment.[9]

[8] The Cities of Osaka, Kyoto and Kobe are subdivided into 24, 11 and 9 wards, respectively. These wards are used as the unit of data organization for these cities. As in Fig. 1, the distance between a pair of municipalities is represented by the airline distance between the city halls (or ward offices) of the respective municipalities.

[9] Accessibility measures are computed using governmental jurisdictions as the unit of analysis. See Section 3.

- Accessibility indices, when averaged over municipalities, increased between 1980 and 2000. Decentralization has not adversely affected accessibility in the Osaka metropolitan area.
- There is some indication that accessibility by auto is improving more than that by rail in fringe areas, but the indication is weak.
- The action space of an urban resident, expressed as the second moment of out-of-home activity locations around the home base, has expanded over the years. Residents of the Osaka metropolitan area have been consuming the urban space more extensively in recent years.
- The mean commute trip duration is quite stable at 35.8 to 35.9 minutes between 1980 and 2000. But trip durations for non-work purposes are increasing.
- The use of rail and bus has declined, especially for work and school trips. The number of non-work trips by rail is increasing, however.
- These changes have led to changes in the total amount of time spent for traveling from 54.1 minutes in 1970 to 60.9 minutes in 2000, an increase by 12.5%. Changes in travel time expenditure are most noticeable for the residents of new suburbs (an increase of 16.8%), emerging suburbs (12.6%), and unurbanized areas (12.5%). The mean travel time expenditure is stable in autonomous cities, mixed commercial cities and commercial cities.

As this quick review suggests, many aspects of travel show substantial changes. While the number of trips is relatively stable, mode use and trip duration have changed substantially. To what factors, then, can these changes be attributed? In addition to motorization and suburbanization, individual and household attributes have changed substantially as well. For example, the fraction of women aged between 15 and 65 who were employed increased from 34.9 % in 1970 to 49.3% in 2000.[10] Stability in travel is examined in the following sections using model systems while taking into account person and household attributes, residence location, and accessibility.

3. MODEL SYSTEMS

The basic structure of the model systems developed in this study is illustrated in Figure 2. The model systems embody the following set of assumptions: The amount of time spent (time expenditure) for non-work activities is first determined, then this amount of time is allocated to activities at different locations and the number of visits is thereby determined. The visits will then be organized into trip chains, i.e., visits are grouped to be made in a sequence (or sequences) of movements starting from, and ending at, the home or work base. This determines the number of trip chains, which, along with the number of visits, determines the number of trips. This then determines total trip time.

The assumption adopted in the model system that non-work activity time expenditure is first determined and then is allocated to a number of visits, is based on the results in Senbil and Kitamura (2003) where alternative structural equations models are estimated to examine whether activity time determines the number of visits, or the number of visits determines activity time. The results indicated that the former causal relation is predominant.

[10] Based on the Kei-Han-Shin household travel survey data.

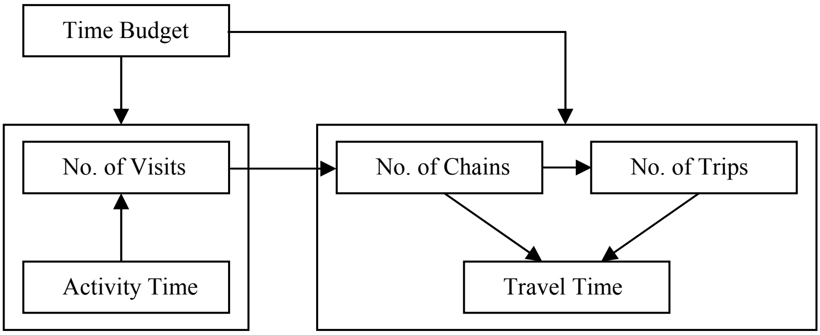

FIGURE 2: Relations among activities and travel

The model system for non-workers, which is less complex than the system for workers, is first illustrated along with the two-stage estimation procedure adopted in this study. Let the endogenous variables of the model system be t_{NW} = total out-of-home, non-work activity time, v_{NW} = the number of non-work visits, n_C = the number of trip chains, n_T = the number of trips (= v_{NW} + n_C), and t_T = total trip time. Note that non-workers are assumed to engage in no work activities and make no work trips.

These endogenous variables are expressed in the simultaneous equations model system as

$$\begin{cases} t_{NW} & = & h_{t_{NW}}\left(R,W\right) \\ v_{NW} & = & h_{v_{NW}}\left(t_{NW},R,W\right) \\ n_C & = & h_{n_C}\left(v_{NW},R,W\right) \\ t_T & = & h_{t_T}\left(n_T,R,W\right) \end{cases} \tag{1}$$

where R = the vector of variables representing the characteristics of the residence and work areas, including accessibility indices, and W = the vector of individual and household attributes.

Note the recursive structure which embodies the causal relationships shown in Figure 2, i.e., t_{NW} is first determined, v_{NW} is next determined given t_{NW}, then n_C given v_{NW}, then finally t_T given n_T $(= n_C + v_{NW})$

The vectors of explanatory variables, R and W, contain: residential area type (indicated by the categories described in footnote 7); accessibility indices to population, employment, and retail establishments, respectively by auto and by rail; and demographic and socio-economic attributes of the individual and household. The accessibility index by activity and mode is defined as

$$I_i^{mp} = \sum_j \frac{A_j^p}{\left(t_{ij}^m\right)^2} \tag{2}$$

where I_i^{mp} = the accessibility index at zone i for activity p by mode m, A_j^p = the attraction measure of zone j for activity p, t_{ij}^m = the mean travel time between zones i and j by mode m, and m = auto, or rail; and p = work, social, or shopping (the number of employees, residential population, and the number of retail establishments are used as the attraction measures, respectively).

Returning to the simultaneous equation system of equation (1), it can be seen that endogenous variables appear on the right-hand side of the equations for v_{NW}, n_C and t_T. This could potentially lead to inconsistent estimation. In order to obtain consistent estimates, a two-stage procedure is adopted in this study. In the first stage, ordinary least-square regression is applied to the respective model equations, which are formulated to have the following specific forms with a normal error term introduced into each:

$$\begin{cases} t_{NW} &= \theta'_{t_{NW}} X_{t_{NW}} + \varepsilon_{t_{NW}} \\ v_{NW} &= t_{NW}\left(\theta'_{v_{NW}} X_{v_{NW}}\right) + \varepsilon_{v_{NW}} \\ n_C &= v_{NW}\left(\theta'_{n_C} X_{n_C}\right) + \varepsilon_{n_C} \\ t_T &= \left(v_{NW} + n_C\right)\left(\theta'_{t_T} X_{t_T}\right) + \varepsilon_{t_T} \end{cases} \tag{3}$$

where $\theta_{t_{NW}}$, $\theta_{v_{NW}}$, θ_{n_C}, and θ_{t_T} are vectors of coefficients, $X_{t_{NW}}$, $X_{v_{NW}}$, X_{n_C}, and X_{t_T} are vectors of explanatory variables, "'" indicates the transposition operation, and $\varepsilon_{t_{NW}}$, $\varepsilon_{v_{NW}}$, ε_{n_C}, and ε_{t_T} are normal random error terms which are assumed to be mutually independent and serially uncorrelated.

Based on the results of the first-stage, the following instrument variables are defined:

$$\begin{cases} \hat{t}_{NW} &= \hat{\theta}'_{t_{NW}} X_{t_{NW}} \\ \hat{v}_{NW} &= \hat{t}_{NW}\left(\hat{\theta}'_{v_{NW}} X_{v_{NW}}\right) \\ \hat{n}_C &= \hat{v}_{NW}\left(\hat{\theta}'_{n_C} X_{n_C}\right) \end{cases} \tag{4}$$

where $\hat{\theta}_{t_{NW}}$, $\hat{\theta}_{v_{NW}}$, and $\hat{\theta}_{n_C}$ are vectors of coefficient estimates from the first stage. In the second stage, the simultaneous equations system of equation (3) is estimated again while applying these instrument variables, i.e.,

$$\begin{cases} t_{NW} &= \theta'_{t_{NW}} X_{t_{NW}} + \varepsilon_{t_{NW}} \\ v_{NW} &= \hat{t}_{NW}\left(\theta'_{v_{NW}} X_{v_{NW}}\right) + \varepsilon_{v_{NW}} \\ n_C &= \hat{v}_{NW}\left(\theta'_{n_C} X_{n_C}\right) + \varepsilon_{n_C} \\ t_T &= \left(\hat{v}_{NW} + \hat{n}_C\right)\left(\theta'_{t_T} X_{t_T}\right) + \varepsilon_{t_T} \end{cases} \tag{3'}$$

Weighted least square estimation is performed in the second stage with the square-root of the predicted value of the dependent variable used as the weight. No iteration is performed between equations (3') and (4) to attain convergence.

Commute trips are introduced into this model system to formulate a system for workers. A typical worker commutes to his workplace and has obligations to work for a certain number of hours each day. The duration of commute trips to and from work and total work duration directly influence the amount of discretionary time that can be allocated to non-work activities. At the same time, commuting brings the worker closer to opportunities along the commute route and around the work location. These opportunities can be visited with little extra travel time over the time spent for commuting to and from work. This enhanced accessibility may imply that a worker with a longer commute tends to pursue activities more frequently and at more locations. Then commute time would positively influence non-work activity time, offsetting, at least partially, its negative effect on time availability. One would also expect that a high level of accessibility at the work location will prompt more frequent activity engagement and will positively contribute to the amount of non-work activity time. This would be the case with the home location as well. These factors therefore enter the model system as explanatory variables.

Total trip time can be viewed as a function of the number of trips, and is expected to be influenced by home and work area characteristics as represented by accessibility indices and other area indicators. Note that the total trip time is approximately twice the one-way commute trip duration if the worker has the simple travel pattern of home-work-home. Let d_X = one-way commute distance, t_W = total out-of-home work duration, v_W = the number of work visits, and v = the total number of visits (= v_{NW} + v_W), and the general form of the model system for workers be

$$\begin{cases} t_{NW} &= f_{t_{NW}}\left(d_X, t_W, v_W, R, W\right) \\ v_{NW} &= f_{v_{NW}}\left(t_{NW}, d_X, R, W\right) \\ n_C &= f_{n_C}\left(v_{NW}, v_W, d_X, R, W\right) \\ n_T &= v + n_C = v_W + v_{NW} + n_C \\ t_T &= f_{t_T}\left(n_T, d_X, R, W\right) \end{cases} \quad (5)$$

Commute distance, d_X, out-of-home work duration, t_W, and the number of work visits, v_W, are assumed to be pre-determined in this study.

As specific functional forms, consider:

$$\begin{cases} t_{NW} &= \beta'_{t_{NW}} X_{t_{NW}} + \zeta_{t_{NW}} \\ v_{NW} &= \begin{cases} t_{NW}\left(\beta'_{v_{NW}} X_{v_{NW}}\right) + \zeta_{v_{NW}} & \text{if } t_{NW} > 0 \\ 0 & \text{otherwise} \end{cases} \\ n_C &= v\left(\beta'_{n_C} X_{n_C}\right) + \zeta_{n_C} = \left(v_{NW} + v_W\right)\left(\beta'_{n_C} X_{n_C}\right) + \zeta_{n_C} \\ t_T &= \begin{cases} 2t_X + \left(v + n_C - 2\right)\left(\beta^{(1)'}_{t_T} X^{(1)}_{t_T}\right) + \zeta^{(1)}_{t_T} & \text{if } v_{NW} \geq 1 \text{ and } v_W \geq 1 \\ 2t_X + \left(v + n_C - 2\right)\left(\beta^{(2)'}_{t_T} X^{(2)}_{t_T}\right) + \zeta^{(2)}_{t_T} & \text{if } v_{NW} = 0 \text{ and } v_W \geq 1 \\ 2t_X & \text{if } v_{NW} = 0 \text{ and } v_W = 1 \\ \left(v + n_C\right)\left(\beta^{(3)'}_{t_T} X^{(3)}_{t_T}\right) + \zeta^{(3)}_{t_T} & \text{if } v_{NW} > 0 \text{ and } v_W = 0 \end{cases} \end{cases} \quad (6)$$

where $\beta_{t_{NW}}$, $\beta_{v_{NW}}$, β_{n_C} and $\beta^{(l)}_{t_T}$, l = 1, 2, 3, are vectors of coefficients, $X_{t_{NW}}$, $X_{v_{NW}}$, X_{n_C} and $X^{(l)}_{t_T}$ are vectors of explanatory variables (which may include t_W, v_W and d_X), $\zeta_{t_{NW}}$, $\zeta_{v_{NW}}$, ζ_{n_C} and $\zeta^{(l)}_{t_T}$ are normal random error terms that are mutually independent and serially uncorrelated, and t_X is one-way commute trip duration. The term, $\beta'_{v_{NW}} X_{v_{NW}}$, represents the mean number of non-work visits per unit out-of-home, non-work activity time, $\beta'_{n_C} X_{n_C}$ the mean number of trip chains per visit (both work and non-work), and $\beta^{(l)'}_{t_T} X^{(l)}_{t_T}$ a pseudo mean trip duration for non-commute trips. Note that different expressions are provided for t_T depending on the travel pattern as defined by v_{NW} and v_W to better represent the share of commute trip durations in total trip time.

An inspection of the data set used in this study has indicated, however, that one-way commute duration, t_X, is not always observed for each worker. For example, if a worker makes an intermediate stop on the way both from home to work and from work to home, then his trip record will not provide a direct measurement of t_X. It is also the case that the sample size is not adequate for some of the four cases defined by v_{NW} and v_W as in equation (6). Accordingly the following simplified version is used in the empirical study presented in the next section:

$$\begin{cases} t_{NW} &= \beta'_{t_{NW}} X_{t_{NW}} + \zeta_{t_{NW}} \\ v_{NW} &= \begin{cases} t_{NW}\left(\beta'_{v_{NW}} X_{v_{NW}}\right) + \zeta_{v_{NW}} & \text{if } t_{NW} > 0 \\ 0 & \text{otherwise} \end{cases} \\ n_C &= \left(v_{NW} + v_W\right)\left(\beta'_{n_C} X_{n_C}\right) + \zeta_{n_C} \\ t_T &= \begin{cases} \beta^{(a)'}_{t_T} X^{(a)}_{t_T} + \zeta^{(a)}_{t_T} & \text{if } v_{NW} = 0 \text{ and } v_W = 1 \\ \left(v_{NW} + v_W + n_C\right)\left(\beta^{(b)'}_{t_T} X^{(b)}_{t_T}\right) + \zeta^{(b)}_{t_T} & \text{otherwise} \end{cases} \end{cases} \quad (6')$$

The term $\beta^{(a)'}_{t_T} X^{(a)}_{t_T}$ represents the mean total commute trip duration for a worker who makes a simple travel pattern of home-work-home, and $\beta^{(b)'}_{t_T} X^{(b)}_{t_T}$ is the mean trip duration for a worker with a more complex pattern. The same two-stage estimation procedure as the one for the non-worker model system is applied to the model system of equation (6'), with instrument variables used for t_{NW}, v_{NW}, and n_C on the right-hand side, defined as

$$\begin{cases} \hat{t}_{NW} &= \hat{\beta}'_{t_{NW}} X_{t_{NW}} \\ \hat{v}_{NW} &= \hat{\hat{t}}_{NW}\left(\hat{\beta}'_{v_{NW}} X_{v_{NW}}\right) \\ \hat{n}_C &= \left(\hat{v}_{NW} + v_W\right)\left(\hat{\beta}'_{n_C} X_{n_C}\right) \end{cases} \quad (7)$$

where $\hat{\beta}_{t_{NW}}$, $\hat{\beta}_{v_{NW}}$, and $\hat{\beta}_{n_C}$ are vectors of coefficient estimates from the first stage. Recall that v_W is treated as exogenous. The model system for non-workers (equation (3)) is obtained as a special case of equation (6) or (6') with $t_{NW} > 0$ and $v_W = 0$.

As the above discussions indicate, mean trip durations are endogenously determined in the model system for workers. Because trip durations are expected to be closely associated with travel mode, the respective models are estimated for auto commuters and non-auto commuters separately. As a predictive model system, then, another component must be developed to determine whether a worker will be an auto commuter or non-auto commuter.[11] This is achieved by developing a nested logit model, which is discussed in the next section.

These model systems are estimated and then applied to examine the stability of activity-travel patterns in the Osaka metropolitan area between 1980 and 2000. The following three methods are used in this study for the analysis of stability:

1. statistically testing the hypothesis that the model coefficients have not changed their values over the years,

[11] Another possibility is that a worker will not make a commuter trip. Non-commuters are not addressed in the empirical analysis of this study, however, because there are relatively few non-commuting workers (see Table 6) and they can be handled by the model system for non-workers.

2. predicting the values of the endogenous variables using the coefficient estimates from 1980, 1990 and 2000, on data from one of the three years and comparing the predicted values across the years, and
3. predicting the values of the endogenous variables on the data from 1980, 1990 and 2000, using the coefficient estimates from one of the three years and comparing the predicted values across the years.

Let Ψ_y be the coefficient vector for year *y*. The hypothesis tested in the first method is

$$H_0 : \Psi_y = \Psi_{y'},\ y, y' = 1980, 1990, 2000,\ y \neq y'$$

Estimates of the coefficient vectors, $\hat{\Psi}_y$, *y* = 1980, 1990, 2000, are used in the test. This method offers statistical indications of behavioral stability as represented by the model coefficients.

Let a model equation in the model system be denoted by $\overline{q} = g\left(\overline{X}_y : \Psi_{y'}\right)$, where $\overline{q}$ is the endogenous variable, $\overline{X}_y$ is the vector of mean explanatory variable values for year *y*. The second method indicates structural change in behavior over time as reflected in the value of the endogenous variable. Let

$$\overline{q}_{y:80} = g\left(\overline{X}_y : \hat{\Psi}_{1980}\right), \overline{q}_{y:90} = g\left(\overline{X}_y : \hat{\Psi}_{1990}\right), \overline{q}_{y:00} = g\left(\overline{X}_y : \hat{\Psi}_{2000}\right)$$

for *y* = 1980, 1990 and 2000. In this methods, the equality among $\overline{q}_{y:80}$, $\overline{q}_{y:90}$, and $\overline{q}_{y:00}$ is inspected. It shows how the behavior of an urban resident of a given set of attributes, living in a certain area and having a certain level of accessibility, has changed over time due to structural change as represented by the change in Ψ_y.

The third method, on the other hand, indicates how changes in the characteristics of urban area and residents have prompted changes in behavior. Let

$$\overline{q}_{y:80} = g\left(\overline{X}_{1980} : \hat{\Psi}_y\right), \overline{q}_{y:90} = g\left(\overline{X}_{1990} : \hat{\Psi}_y\right), \overline{q}_{y:00} = g\left(\overline{X}_{2000} : \hat{\Psi}_y\right)$$

for *y* = 1980, 1990 and 2000. The equality among $\overline{q}_{80:y}$, $\overline{q}_{90:y}$, and $\overline{q}_{00:y}$ is inspected here.

As noted earlier, the simultaneous equations model systems are deployed in this study because they aid in locating the source of instability; using these model systems makes it possible to discern whether a change in behavior is due to changes in the contributing factors, including the attributes of the individual and household, or it is due to changes in structural relationships. It is thus possible to determine the factors that have caused the recent trends of increasing travel demand seen in many urbanized areas of industrialized countries. It is also possible to determine which aspect of travel—out-of-home activity engagement, trip chaining, number of trips, or mean trip length—is contributing to changes in overall travel demand, which may be represented by total travel time expenditure.

4. ESTIMATION RESULTS: NON-WORKERS

The simultaneous equations model systems shown as equations (3) and (6') are estimated using the two-stage procedure described in the previous section. Assuming that the error terms are not correlated across the equations within the model system, each model is estimated individually. As noted in Section 1, the data used are from household travel surveys conducted in the Osaka metropolitan area as repeated cross-sectional surveys in 1980, 1990, and 2000. Since the original survey samples are more than sufficiently large, their sub-samples are drawn randomly at a rate of 5% using an SPSS function, and used in model estimation (the sizes of the original samples and the sub-samples from the respective years are shown for workers in Table 6). The estimation software used is LIMDEP Version 8.0 by the Econometric Software, Inc.

As an example of estimation results, the model system for non-workers estimated using the 2000 data is shown in Table 3. This particular estimation is based on a sub-sample of 14,880 individuals, which is approximately 15% of the original sample. Due to the limited space available, estimation results for 1980 and 1990 are suppressed in this paper.

It can be seen in the table that the coefficients of determination (R^2) are rather small. This, however, is not at all surprising for regression analysis with this large a sample. Moreover, the dependent variables, i.e., non-work activity time, number of non-work visits, number of trip chains, and total trip time, are highly random and are not easy variables to predict.

Travel mode choice does influence, and is influenced by, the number of visits, number of trip chains, trip duration, and therefore total trip time. Travel model choice, however, is placed outside the scope of the model system for non-workers largely because the model system is not trip-based; effects of travel modes are represented indirectly by the explanatory variables representing auto ownership and driver's license holding.

Many interesting observations can be made from the coefficient estimates presented in the table. For example, female non-workers with children tend to have more visits and more trip chains than those without children (on average by 0.1035 visit and 0.0277 trip chain per visit, respectively), but their mean total out-of-home activity time and total trip time tend to be smaller (by 15.53 minutes and by 1.88 minutes per trip, respectively). Household vehicle ownership significantly affects total out-of-home activity time and total trip time, but not the number of visits or trip chains. Holding a driver's license, on the other hand, positively influences all indices of activity and travel examined here.

Models are estimated with the same set of variables using data from 1990 and 1980. The models for out-of-home non-work activity time (t_{NW}) exhibit a number of important changes. For example, the coefficients of *male* are consistently positive and significant, but their values are steadily decreasing from 1980 to 2000. This may reflect changing gender roles in Japan in these two decades. On the other hand, the coefficients of *number of household members* and *female with child*(*ren*) steadily decreased, the former from 2.55 in 1980 to -3.81 in 2000 and the latter from -9.46 to -15.53 (the latter difference, however, are not statistically significant at $\alpha = 0.05$). Members of larger households, or female adult members in households with a child, are spending less time for out-of-home activities. The reason for this tendency is difficult to pinpoint, but it may reflect the general trend that more and more activities are engaged in the privacy of home, like watching television. Interestingly, the coefficient estimates for *number of cars per adult household member* are positive, significant, and increasing (both in terms of value and significance). One would anticipate that the effects of vehicle availability on travel tend to diminish as motorization matures. To the contrary, effects of vehicle availability are clearly increasing among non-workers.

TABLE 3: Model system of non-workers' activity-travel patterns for year 2000

	t_{NW}		v_{NW}		n_C		t_T	
	Coef.	t	Coef.	t	Coef.	t	Coef.	t
Constant	155.79	31.00	2.8097	67.12	2.0973	40.51	70.090	33.53
Male [D]	6.38	2.20					2.189	8.84
25 - 34 Years Old [D]	-29.51	-9.25			0.0437	2.50	-1.545	-6.29
35 - 44 Years Old [D]	-12.65	-3.87	0.1214	6.42	0.0664	3.99	-1.039	-4.29
45 - 54 Years Old [D]					0.0277	1.59		
55 - 64 Years Old [D]					0.0454	2.60		
65 Years Old or Over [D]			-0.1138	-8.42	0.0372	2.00	-0.609	-2.67
Number of Household Members	-3.81	-4.43	-0.0118	-2.06	0.0088	5.18	-0.225	-3.41
Female with Child(ren) [D]	-15.53	-4.49	0.1035	5.64	0.0277	4.28	-1.880	-7.08
Number of Cars per Adult Household Member	20.14	5.61					1.028	3.71
Driver's License Holding [D]	9.91	4.32	0.1760	14.59	0.0276	6.86	1.175	6.58
Resides in Commercial Area [D]			-0.0666	-1.50			1.969	2.86
Resides in Mixed Commercial/Residential Area [D]			-0.0390	-1.80			0.690	1.80
Resides in Suburbs [D]			-0.0586	-3.01			0.557	1.89
Resides in Unurbanized Area [D]							1.247	1.63
Residence Zone Accessibility to Employment (x 1/10)	5.08	1.57					-0.618	-3.51
Residence Zone Accessibility to Population (x 1/100)	57.46	4.29			-0.0251	-3.83	2.812	2.72
Residence Zone Accessibility to Retail Establishments (x 10)	-6.56	-3.22						
Mean of *Y*	147.2		2.867		2.338		66.89	
Standard Deviation of *Y*	111.9		1.085		0.610		45.12	
Regression Sum of Squares	6987640		875.2		259.5		1610475	
Residual Sum of Squares	179197530		16653.5		5271.2		28685463	
Total Sum of Squares	186185170		17528.6		5530.7		30295939	
F	57.98		97.69		81.35		59.61	
Degrees of Freedom	(10, 14869)		(8, 14871)		(9, 14870)		(14, 14865)	
R^2	0.0375		0.0499		0.0469		0.0532	
Adjusted R^2	0.0369		0.0494		0.0463		0.0523	

N = 14880

[D]: 0-1 dummy variable

Mean out-of-home activity time expenditure has steadily increased from 123.2 minutes in the 1980 sample to 147.2 minutes in the 2000 sample. Likewise the mean number of visits has increased by about 12.7% from 2.55 in 1980 to 2.87 in 2000. The mean number of trip chains has also increased, but only by 2.86% from 2.273 in 1980 to 2.338 in 2000. As a result, the mean number of visits per trip chain has increased from 1.120 to 1.226. These changes are presumably due to the increase in vehicle availability. No trends are apparent in the series of coefficient estimates, however. The mean total trip time shows a 20.1% increase from 55.7 minutes in 1980 to 66.9 minutes in 2000.

5. TEST OF STABILITY

The estimation results so far have suggested that coefficient values are not stable between 1980 and 2000. Differences in the coefficient vectors as a whole are examined here by applying *F*-tests. Table 4 indicates that the models of out-of-home activity time (t_{NW}), number of visits (v_{NW}) and number of trip chains (n_C) are not stable between any combination of years (i.e.,1990 and 2000, 1980 and 2000, and 1980 and 1990, and among 1980, 1990 and 2000; all significant at α = 0.01). These structural changes, combined with changes in the explanatory variable values that reflect the aging of population, motorization, and other trends, produce the increases in t_{NW}, v_{NW}, and n_C as seen above. The model for total trip time (t_T), on the other hand, is relatively stable. The only significant difference (at α = 0.05) is found between 1990 and 2000.

TABLE 4: Results of *F*-tests of coefficient vectors: non-workers

Endogenous variable of the model	1980, 1990 vs. 2000	1990 vs. 2000	1980 vs. 2000	1980 vs. 1990
t_{NW}	7.45**	8.99**	10.77**	3.39**
	(22, 15350)	(11, 10705)	(11, 10185)	(11, 9810)
v_{NW}	13.53**	14.00**	21.41**	4.45**
	(18, 15356)	(9, 10709)	(9, 10189)	(9, 9814)
n_C	10.14**	14.52**	12.14**	2.93**
	(20, 15353)	(10, 10707)	(10, 10187)	(10, 9812)
t_T	1.30	2.13**	-	1.01
	(30, 15338)	(15, 10697)	(15, 10177)	(15, 9802)

(*n*, *d*): degrees of freedom (numerator, denominator)
*: Significant at α = 0.05
**: Significant at α = 0.01
-: Because weighted least squares estimation is used, no proper F-statistic was obtained.

It would be reasonable to conclude that the structural relation for total trip time has been more stable than those for out-of-home activity time, number of visits, and number of trip chains. Recall that, because of the multiplicative model structure, the stability in model coefficients here implies the stability in the dependent variable, given the values of the explanatory variables. Stability found in the model for t_T therefore does not imply stability in total trip time itself; in the model system of this study, the total trip time is proportional to the number of trips, which is increasing.

To separate the effects of variations in coefficient vectors and those in explanatory variable values on the four indices of activity and travel, the 1980, 1990 and 2000 mean explanatory variable values are input to the respective model to compute index values with the estimated 1980, 1990 and 2000 coefficient vectors. To make the analysis straightforward, only those explanatory variables that represent attributes of the individual or household are included in the tabulation; the effects of the accessibility measures and indicators of residence area type are placed outside the scope of the analysis. Results are summarized in Table 5.

Inspecting the values in the respective columns in section *a* of the table, it can be seen that v_{NW} and t_T increase consistently from 1980 to 2000. Section *b* indicates that t_{NW} increases over 10% due to changes in mean explanatory variable values under any of the three coefficient vectors. It may be inferred that demographic and socio-economic changes between 1980 and 2000 have by themselves induced an increase over 10% in out-of-home activity time. They have also resulted in a slight increase in the number of visits for out-of-home activities (v_{NW}), and about a 2% increase in total travel time expenditure (t_T). No clear effects on the number of trip chains (n_C) are apparent.

The coefficient vectors also have changed over time to increase the values of the travel indices (see section *c*). Regardless of the year of data, the values of the respective travel indices in general increase with the year of the coefficient vector. The rate of increase is about 13% for t_{NW} and v_{NW}, up to 2% for n_C, and over 22% for t_T. Comparing sections *b* and *c* of Table 5, one may conclude that changes in structural relationships have had much larger effects on the four indicators of activity and travel than do changes in demographic and socio-economic attributes of urban residents.

It may also be concluded as an important finding of this study that the levels of out-of-home activity engagement and travel would have expanded during the two decades due to changes in the structural relationships, even when no changes had taken place in demographic and socio-economic characteristics in the study area; even if auto ownership and driver's license holding had not increased, activity engagement and travel would still have expanded.

The statistical analyses of this section have made evident that the structural relationships underlying out-of-home activity and travel have not been stable over time. It is also clear that the structural relationships have been changing in the direction of expanding out-of-home activities and travel. This tendency, combined with changes in individual and household attributes, which are also pointing in the direction of expanding activities and travel, has produced the unmistakable increases in total out-of-home activity time expenditure, number of visits for out-of-home activities, number of trip chains, and total travel time expenditure. Expansion, not constancy, in activity engagement and travel appears to be the universal rule for non-workers.

6. THE STABILITY OF WORKER MODELS

As noted earlier, the model system is estimated for auto commuters and non-auto commuters separately. This is in part because commute trip durations are a significant component of total travel time expenditure, and commute travel mode is expected to be associated with commute trip durations. It is also believed that commute travel mode influences daily activity and travel, including non-work activities and trips made for them.

Although it is outside the scope of this study, application of the model system to forecasting calls for the capability of predicting who will be auto commuters. Nested logit models of trip generation and commute mode choice are therefore developed as a precursor to the simultaneous equations model system, to determine the probabilities that a worker will:

TABLE 5: Travel indices produced with 1980, 1990, 2000 coefficient vectors at 1980, 1990, 2000 mean explanatory variable values: non-workers

(a) Travel index values

Data $\left(\bar{X}_y\right)$	Coefficient vector $\left(\hat{\Psi}_{y'}\right)$											
	t_{NW}			v_{NW}			n_C			t_T		
	1980	1990	2000	1980	1990	2000	1980	1990	2000	1980	1990	2000
1980	112.2	134.7	127.4	2.557	2.704	2.895	2.167	2.219	2.198	55.31	62.72	67.94
1990	120.7	143.2	136.9	2.569	2.736	2.919	2.161	2.216	2.200	55.98	63.57	68.75
2000	127.1	149.3	142.7	2.572	2.750	2.921	2.158	2.214	2.201	56.66	64.29	69.30

For each of the indicator variables (t_{NW}, v_{NW}, n_C and t_T), its mean value, $\bar{q}_{y:y'}$, with the data from year *y* and the coefficient vector from year *y'*, is shown in the cell corresponding *y*, *y'*, and the indicator variable name.

(b) Change in travel indices due to change in explanatory variable values (value with 1980 data = 100)

Data $\left(\bar{X}_y\right)$	Coefficient vector $\left(\hat{\Psi}_{y'}\right)$											
	t_{NW}			v_{NW}			n_C			t_T		
	1980	1990	2000	1980	1990	2000	1980	1990	2000	1980	1990	2000
1980	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1990	107.5	106.3	107.5	100.5	101.2	100.8	99.7	99.8	100.1	101.2	101.3	101.2
2000	113.2	110.9	112.0	100.6	101.7	100.9	99.6	99.7	100.1	102.4	102.5	102.0

(c) Change in travel indices due to change in coefficient vector (value with 1980 coefficient vector = 100)

Data $\left(\bar{X}_y\right)$	Coefficient vector $\left(\hat{\Psi}_{y'}\right)$											
	t_{NW}			v_{NW}			n_C			t_T		
	1980	1990	2000	1980	1990	2000	1980	1990	2000	1980	1990	2000
1980	100.0	120.0	113.5	100.0	105.7	113.2	100.0	102.4	101.4	100.0	113.4	122.8
1990	100.0	118.6	113.4	100.0	106.5	113.6	100.0	102.5	101.8	100.0	113.6	122.8
2000	100.0	117.5	112.3	100.0	106.9	113.6	100.0	102.6	102.0	100.0	113.5	122.3

make no trip ($v_W = 0$, $v_{NW} = 0$),
make at least one trip, but will not make a commute trip ($v_W = 0$, $v_{NW} \geq 0$),
make a commute trip using an automobile ($v_W > 0$), or
make a commute trip without using an automobile ($v_W > 0$)
on a given day. The nest structure is shown in Figure 3, and the distribution of observed choices is given in Table 6 for the respective years. The models are estimated by the full-information maximum likelihood (FIML) method using NLOGIT Version 3.0 in LIMDEP Version 8.0, with the coefficient estimates obtained from sequential estimation used as initial values. The results are presented in Table 7.

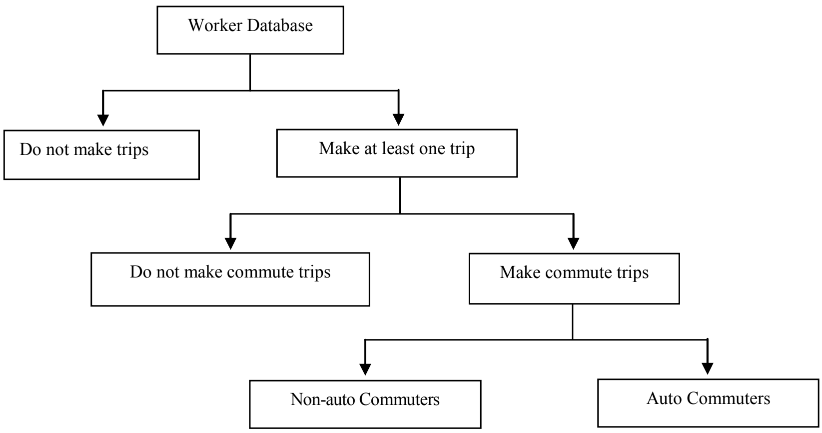

FIGURE 3: Nest structure of the nested logit model of commute trip making

TABLE 6: Distribution of workers by trip making and commute mode choice†

Year		No trips: $v_W = 0$, $v_{NW} = 0$	No work trips: $v_W = 0$, $v_{NW} \geq 0$	Auto commuters: $v_W > 0$	Non-auto commuters: $v_W > 0$	Total	*N*
1980	Full Data	15.4	5.3	45.4	33.9	100.0	86,083
	Estimation Sample	16.9	4.8	45.5	32.8	100.0	4,274
1990	Full Data	13.5	5.5	47.1	33.9	100.0	109,777
	Estimation Sample	13.7	5.3	47.5	33.5	100.0	5,448
2000	Full Data	11.8	8.8	46.2	33.2	100.0	113,444
	Estimation Sample	11.6	9.1	47.0	32.3	100.0	5,691

†In percent
"Estimation Sample" is the sub-sample of the full data set that was used to estimate the nested logit models reported in Table 7.

The coefficient estimates for the choice in the highest level (whether a trip is made at all) indicate that a male worker is less likely to make a trip than his female counterpart, presumably because the latter tends to perform various domestic chores even on days when she is not working. Holding a driver's license has positive effects in the 1990 and 2000 models, but not in the 1980 model. The number of automobiles per adult household member shows negative coefficient in all of the models; automobility thus does not have clear-cut effects on whether a worker makes a trip at all on a given day.

TABLE 7: Nested logit models of trip making and commute mode choice

	1980		1990		2000	
Make Trips vs. No Trip	Coef.	t	Coef.	t	Coef.	t
Male [D]	-0.334	-3.06	-0.290	-2.99	-0.361	-3.74
Household with Children [D]	-0.067	-0.74	0.119	1.35	-0.051	-0.55
Number of Autos per Adult Household Member	-0.865	-5.31	-0.810	-5.21	-0.209	-1.27
Driver's License Holding [D]	0.034	0.23	0.207	1.61	0.300	2.29
Residence Zone Accessibility to Population (×100)	-8.066	-2.74	-0.871	-0.28	0.373	0.27
μ_T†	0.929	1.08	0.831	2.59	0.937	0.85
Make Commute Trips vs. No Commute Trip						
Constant	3.375	16.98	3.133	19.24	2.395	16.40
25 - 34 Years Old [D]	-0.210	-1.22	-0.191	-1.17	-0.003	-0.02
35 - 44 Years Old [D]	-0.722	-4.19	-0.349	-2.25	-0.069	-0.46
45 - 54 Years Old [D]	-0.716	-4.13	-0.541	-3.52	-0.109	-0.75
55 - 64 Years Old [D]	-1.208	-6.39	-0.965	-5.83	-0.532	-3.56
65 Years Old or Over [D]	-1.998	-8.84	-1.884	-8.80	-1.254	-7.31
μ_W	0.105	0.60	0.171	1.46	0.042	0.38
Commute by Auto vs. Commute by Other Mode						
Constant	-1.384	-8.43	-2.460	-11.83	-2.337	-12.42
Residence Zone Accessibility to Employment	0.374	3.76	0.497	7.37	-0.011	-0.43
Work Zone Accessibility to Retail Area (×10)	-0.256	-7.81	-0.441	-14.77	-0.147	-15.31
Household with Children [D]	0.207	2.64	0.106	1.46	0.139	1.96
Number of Autos per Adult Household Member	0.719	4.88	0.886	6.35	1.156	8.46
Driver's License Holding [D]	1.762	18.68	2.993	18.66	2.358	14.34
One-way commute Distance (×10)	0.130	2.00	0.331	6.65	0.017	0.38
N	4273		5448		5652	
$L(0)$	-7742		-10094		-10560	
$L(C)$	-5001		-6254		-6760	
$L(\beta)$	-4599		-5557		6135	
$-2[L(0) - L(\beta)]$ (χ^2, df = 20)	6287		9075		8850	
$-2[L(C) - L(\beta)]$ (χ^2, df = 18)	804		1394		1250	
$1 - L(\beta)/L(0)$	0.406		0.449		0.419	
$1 - L(\beta)/L(C)$	0.080		0.111		0.092	

†*T*-statistics for H_0: $\beta = 1$ are shown.
$L(0)$: Log-likelihood with no model coefficients
$L(C)$: Log-likelihood with constant terms only
$L(\beta)$: Log-likelihood with all model parameters at convergence

The explanatory variables for the choice in the next level, whether a worker will make a work trip, are all dummy variables representing the worker's age. This specification is motivated by the prospect that, among the variables available in the data sets, age is the primary variable that is associated with illness or absenteeism. Marital status was examined but turned out insignificant. Whether a worker works at home is a critical determinant of work trip generation, but unfortunately this information is not available from the data set. The results offer consistent indication across the three years that an older worker is less likely to make a work trip.

The coefficient estimates for commute mode choice indicate that auto availability is its primary determinant. Both the number of automobiles per adult household member and driver's license holding have consistent and significant positive effects on the use of an automobile for commuting. Also there is a clear indication that work zone accessibility to retail activities negatively affects auto use for commuting; evidently a worker commuting to a more commercialized area tends not to use the automobile.

In the table μ_T and μ_W represent the coefficients of the inclusive price variables. Falling between 0 and 1, they take on legitimate values. Notably μ_T are not significantly different from 1.0 in the 1980 and 2000 model, indicating that there is no correlation between the error terms of the two alternatives under *make at least one trip*, i.e., *do not make commute trips* and *make commute trips*. On the other hand, μ_W is not significantly different from 0 for any of the years; the error term associated with commuting by auto and that associated with commuting by non-auto modes are highly correlated, and the choice in the higher level, *do not make commute trips* vs. *make commute trips*, is not significantly influenced by the attributes of the alternatives in the lower level.

The goodness-of-fit statistics presented in the table indicate that the models are all highly significant. This is the case when the contributions of the constant terms, which replicate the sample distribution of chosen alternatives, are excluded (see $-2[L(\beta) - L(C)]$ and $1 - L(\beta)/L(C)$).

The model, however, is not stable over time. The results of likelihood ratio tests (Table 8) indicate that the model coefficients are not stable between any pair of years, prompting the conclusion that trip making and commute mode choice are not stable between 1980 and 2000 in the Osaka metropolitan area. The changes seen in Table 6 are thus due to structural changes as well as changes in the contributing factors.

TABLE 8: Stability of the nested logit models of trip making and commute mode choice

Years compared	χ^2	df
1980 vs. 1990	191.6	20
1980 vs. 2000	162.6	20
1990 vs. 2000	172.6	20
1980 vs. 1990 vs. 2000	349.9	40

The critical value of χ^2 at $\alpha = 0.05$ is 31.4 with df = 20, and 55.8 with df = 40.

The model system of equation (6') is estimated for auto commuters and non-auto commuters separately, with Mill's ratio (see Maddala, 1983) introduced into the equation for t_{NW} to account for possible correlation between its error term and the error term associated with mode choice in the nested logit model.[12] For brevity, only salient findings for auto commuters are summarized as follows:

- By far the dominant determinant of time expenditure for non-work activities is work duration, which has a negative effect. Commute trip distance also negatively influences it, but the effect is much smaller.
- A male worker tends to have fewer non-work visits compared with a female worker.
- A worker from a larger household, or one that resides in a commercial area, tends to make more trip chains.
- A worker with a longer commute distance tends to make fewer trip chains.
- The model for the number of trip chains contains many variables that are significant, but they change their signs over time. For example, *male* has a significant positive coefficient in the 1980 model, but a significant negative coefficient in the 2000 model (t = 4.32 and -7.32, respectively).
- The model for total trip time does not have consistently significant explanatory variables across the three time points. The only and obvious exception is commute

[12] Although this creates heteroskedasticity, consistency is retained in this linear model.

distance whose coefficient estimates are decreasing and approaching 1.0 (1.302 in 1980, 1.195 in 1990, and 1.070 in 2000).

Although the model system is relatively stable compared to that for non-workers (Table 4), it is nonetheless not stable over time. The results for auto commuters indicate that model coefficients are significantly different across years and the *F*-statistics are particularly large for the number of trip chains (n_C).

Changes over time in the travel indices are decomposed into those due to changes in the contributing factors and those due to structural changes. Table 9 presents the results for auto commuters in the same format as Table 5. Section *b* of the table offers clear indications that the number of trip chains (n_C) and total trip time (t_T) have both tended to increase with changes in socio-demographic and other contributing factors. Section *c*, on the other hand, indicates that structural changes have tended to reduce n_C by about 10% between 1980 and 1990, while acted to increase t_T by around 14% during the same period. The combined effects of these two can be inferred by tracing the diagonal elements of section *a* where the models' predictions replicate the sample means. Overall, n_C decrease by about 5%, while t_T increase by about 10%. Patterns of change are not clear for time expenditure for non-work activities (t_{NW}) and the number of non-work visits (v_{NW}). The diagonal elements of section *a* indicate that they have both expanded: yet, sections *b* and *c* offer no clear patterns.

Overall, auto commuters exhibit expanding non-work activity engagement, and resulting expansion in total travel time expenditure. The number of trip chains is not increasing, presumably because workers, who must operate under tighter time constraints than non-workers, devise efficient trip chaining patterns by putting more non-work activities into each chain while reducing the number of chains. The model system has revealed that socio-demographic changes are inducing increases in the number of trip chains, while structural changes are more than counteracting potential increases. This, however, does not apply to total trip time; the structural relationship produced the largest travel time expenditure in 1990, presumably representing the vigorous economy of Japan at that time.

Based on simultaneous equations model systems of travel-activity patterns and large-scale household travel survey data from 1980, 1990 and 2000, the analyses of this study have offered sufficient empirical evidence that challenges the conjecture of constancy in travel time expenditure. As has been discussed, some of the changes in the structural relationships may be attributed to motorization or changing gender roles. In general, however, factors that have caused the changes in the structural relationships are difficult to identify. In particular, no clear indications have emerged from the statistical results on the effects of urban structure and accessibility on structural change. Nonetheless, study results offer many indications that economic and socio-cultural changes do influence the structural relationships underlying travel.

Another important finding is that changes tend to lead to expansion of travel. One may conjecture that urban residents tend to increase their travel whenever resources are available to do so. Related to this is the notion that travel—or mobility—is closely associated with the sense of independence and capability (e.g., see Miller, 2001). The ever increasing amount of travel may have to do with the very fundamental desire of individuals in contemporary society.

TABLE 9: Travel indices produced with 1980, 1990, 2000 coefficient vectors at 1980, 1990, 2000 mean explanatory variable values: Auto commuters

(a) Travel index values

Data $\left(\overline{X}_y\right)$	Coefficient vector $\left(\hat{\Psi}_{y'}\right)$											
	t_{NW}			v_{NW}			n_C			t_T		
	1980	1990	2000	1980	1990	2000	1980	1990	2000	1980	1990	2000
1980	32.1	34.2	33.6	0.835	0.983	0.896	1.153	1.055	1.064	50.0	57.9	53.8
1990	33.9	32.8	30.8	0.877	0.869	0.945	1.178	1.064	1.067	53.6	60.5	57.2
2000	24.6	38.2	36.4	0.887	0.908	0.985	1.247	1.085	1.092	55.5	63.5	59.0

For each of the indicator variables (t_{NW}, v_{NW}, n_C and t_T), its mean value, $\overline{q}_{y:y'}$, with the data from year *y* and the coefficient vector from year *y*', is shown in the cell corresponding *y*, *y*', and the indicator variable name.

(b) Change in travel indices due to change in explanatory variable values (value with 1980 data = 100)

Data $\left(\overline{X}_y\right)$	Coefficient vector $\left(\hat{\Psi}_{y'}\right)$											
	t_{NW}			v_{NW}			n_C			t_T		
	1980	1990	2000	1980	1990	2000	1980	1990	2000	1980	1990	2000
1980	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1990	105.7	95.9	91.6	105.0	88.5	105.4	102.2	100.8	100.3	107.3	104.6	106.1
2000	76.5	111.7	108.2	106.2	92.4	110.0	108.2	102.8	102.7	111.0	109.7	109.6

(c) Change in travel indices due to change in coefficient vector (value with 1980 coefficient vector = 100)

Data $\left(\overline{X}_y\right)$	Coefficient vector $\left(\hat{\Psi}_{y'}\right)$											
	t_{NW}			v_{NW}			n_C			t_T		
	1980	1990	2000	1980	1990	2000	1980	1990	2000	1980	1990	2000
1980	100.0	106.6	104.9	100.0	117.6	107.3	100.0	91.6	92.3	100.0	115.8	107.8
1990	100.0	96.7	90.9	100.0	99.1	107.7	100.0	90.3	90.6	100.0	112.9	106.6
2000	100.0	155.6	148.2	100.0	102.4	111.1	100.0	87.0	87.6	100.0	114.5	106.5

7. CONCLUSION

The Osaka metropolitan area of Japan, like many other metropolitan areas in the world, experienced substantial changes in the second half of the 20th century. The most significant driving forces have been motorization and suburbanization. Changes in demographic and socio-economic factors have been substantial as well with more women employed, the household size shrinking, and the resident population aging. This study has been an attempt to examine how these changes have impacted urban residents' activity-travel patterns. The study has adopted a holistic approach by exploring the stability in structural relationships underlying several most pertinent indices of activity engagement and travel, using simultaneous equations model systems. Observed changes in household travel survey data collected in 1980, 1990 and 2000 are decomposed to those due to changes in socio-demographic and other contributing factors, and those due to changes in structural relationships.

The statistical analyses have offered strong evidence that non-workers' activity engagement and travel have been expanding. The results have further indicated that this expansion has been caused primarily by changes in the structural relationships while changes in demographic and socio-economic factors have had relatively minor effects. Although results for workers are not as clear-cut as non-workers', their out-of-home non-work activity time, number of non-work visits, and total trip time are all increasing. The study has also demonstrated that the structural relationships underlying workers' activity-travel patterns have not been stable over time. The results of this study thus challenge the assertion in the literature of constancy in travel time expenditure. The universal rule in activity engagement and travel is not constancy, but expansion.

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