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Detangling the impacts of age, residential locations and household lifecycle in car usage and ownership in the Osaka metropolitan area, Japan[*]

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Abstract: Using large cross-sectional datasets that were collected in the Osaka metropolitan area (OMA), Japan, this study systematically analyzes the structural changes in car ownership and usage in the OMA from 1970 to 2000. A simultaneous equations model system is developed for individuals that considers age, household lifecycle stage, built environment of the household location, car ownership levels, proportion of car trips on a given day, and total car travel duration. The estimation results show that private car ownership and car usage for the residents in OMA have expanded over time. Each residential area, each lifecycle stage, and each age group has their own unique characteristics of car ownership and car usage. The results further indicate that this expansion is largely due to changes in their structural relationships, while the changes in demographic factors play a relatively small and contradictory role.

Key words: Urban car travel, Family lifecycle, Structural change, Simultaneous equations model system
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1 Introduction

Some parts of the world are in the midst of a major demographic transition. Not only is population growth slowing, but the age structure of the population is changing, with the share of the young falling and that of the elderly rising (Kitamura and Susilo, 2005). At the same time, urban and social structures are also changing, such as decreasing household size, increasing labor force participation by women, general increases in income, and increasing car ownership and car usage. Further, structural relationships in the built environment continue to change. Motoriza-

tion and suburbanization produce urban settings with opportunities spread-out and the need for less essential city centers. For example, the Osaka metropolitan area (OMA), Japan has been changing in terms of its geographical expansion, internal land use structure, transportation networks, and car-oriented development which has affected the way people travel (Kitamura and Susilo, 2005). The overall effects on travel from these changes are complex and future trends are not immediately obvious, partly because some of the changes have opposite, cancelling effects on travel, and partly because these changes themselves are not independent but closely linked to each other.

While the tendencies in travel, so far, have been expanding over time in terms of total travel time, distance, car usage, energy consumption, and the spatial extension of their action space (Krizek, 2003;

Susilo and Kitamura, 2005; Scheiner, 2006; Sun *et al.*, 2009; Susilo and Waygood, 2012), it is not clear whether these trends will continue in the future, especially due to the aging of the urban population and also that some evidence of plateauing car usage has been found (Millard-Ball and Schipper, 2011).

Travel time and trip frequency change with people of different ages. Benekohal *et al.* (1994) found that older drivers tend to drive less than they did when they were younger and they drove fewer miles as they age. Nevertheless, although older drivers travel for different reasons than those in the labor force, their reliance upon their private car for transportation is still significant in some countries (Newbold *et al.*, 2005). When older people curtail their driving, younger family members or friends may have to increase (or lengthen) their trip-making to provide needed services or additional transportation for older people. Seo *et al.* (2011) found that the elderly who lived with adult children made the fewest trips, while the ones who lived alone made many more trips. Thus, household structure is important when examining travel behavior.

Using large cross-sectional datasets that were collected in the OMA, the objective of this study is to offer a possible explanation of the change in car ownership and usage found in that area from 1970 to 2000. The analysis examines how car travel by individuals has changed over time with changing demographics, residential location, and metropolitan structure. A simultaneous equations model system is developed for individuals that takes into account age, household lifecycle stage, built environment of the residence to explain its dependent (or endogenous) variables of car ownership, proportion of car trips on a given day, and total car travel time. Using repeated household travel survey results from the OMA, the stability over time of the simultaneous equations system is statistically examined, and thereby the effects of demographic changes are separated from those of structural change in the built environment overall.

2 Literature review

Verhoeven *et al.* (2007) found that travel behavior is not fixed but continuously evolves throughout one's lifecycle. When and where these changes take place depend on two main elements: individual travel habits (which will remain relatively stable overtime as long as the behavioral context stays unchanged) and key events (e.g., a crash and job loss) that have, at least, a potential to change the driving behavior of individuals (van der Waerden *et al.*, 2003; Prillwitz *et al.*, 2007; Jones, 2013; Scheiner and Holz-Rau, 2013a). For example, when one moves his/her home location, the level of access to various daily needs will likely change. In addition, this change may also go hand-in-hand with other life events, such as marriage, childbirth, or a new job. Zimmerman (1982) described lifecycle as a process of change over time that allows for various stages to be identified in the birth-to-death cycle of an individual or household.

Jones *et al.* (1980) argued that lifecycle stage is an important classification variable, partly because it is a composite concept; it subsumes a host of causal factors which act in combination to produce the consistently different between-group patterns of behavior that are observed. The existence and strength of influence depends on personal characteristics (e.g., age, gender, educational level, ability, and profession) and other characteristics (e.g., infrastructure, traffic system, safety, and weather conditions) (van der Waerden *et al.*, 2003).

Travel behavior is a continuous learning process of an individual throughout his/her lifecycle. Lanzendorf (2003) argued that how we grow up will influence the way we travel, including our perspectives on travel modes and our habits. In-line with this, Simma and Axhausen (2001) found that the use of a particular travel mode positively influences the usage of the same mode for the rest of an individual's life course, and the usage of other modes negatively. Thus, it may not be travel behavior of the current older persons, but the companions of the old, which is important for predicting future travel behavior. A study that examines behavior over a significant amount of time is better able to answer such questions.

Heggie (1978) and Zimmerman (1982) found that the lifecycle effect in travel was caused by two separate components: household structure and the age of the household members. Zimmerman (1982) argued that over the lifecycle, a household's trip-making will be determined by the relative contribution of these two separate components. The household types without compositional changes over the lifecycle (e.g., childless couples, single persons,

and unrelated individuals) are subject to the age effect alone. The travel behavior of household members that do experience compositional shifts, such as a typical family lifecycle, will reflect both structural complexities imposed by the presence of household members with different abilities and roles, and the independent age effects of each household member. Thus, without taking the household lifecycle into account, some intra-household constraints are lost and individual travel behavior results are less clear.

It is expected that changing patterns of travel depend on intra-household interaction, which are closely associated with an individual's lifecycle stage. However, the changing patterns would not necessarily be the same for different age companions. Wachs (1979) argued that early-stage households behave in a similar fashion to later-stage households that exist today. Sun *et al.* (2012) showed that a companion cohort effect existed for car usage over time, while previous studies (Benekohal *et al.*, 1994; Newbold *et al.*, 2005; Sun *et al.*, 2009) found that different age groups of people have different behaviors with respect to car ownership and usage.

How travel and activity patterns are developing during the life course has been previously examined (Hjorthol *et al.*, 2010). The interaction between individual lifecycle, companion cohort, and aggregate changes over time has recently been studied by Scheiner and Holz-Rau (2013b). However, how these different people with different lifecycles behave, evolve and interact over time is still a problem to be further investigated. Given that the urban structure of many major metropolitan areas that have been constantly changing in the last few decades (Susilo and Kitamura, 2008), it is reasonable to expect that people's constraints and their travel behavior will also change.

3 Data and study area

For this study, separate datasets in 1970, 1980, 1990, and 2000 for the OMA's person trip survey were used. These surveys were conventional large-scale household travel surveys with a sampling rate of 3.0%. The datasets contain the socio-demographic characteristics of the observed samples as well as their household characteristics. Information on children under the age of 15 years was entered by a responsible adult. It records the duration, purpose, and number of activities and trip engagements of the observed samples on the observed day and the chosen mode, as well as home and work locations (zones) of the observed individual. Information limits on the classification of lifecycle stage categories in 1980 and 1990, and datasets in 1970 and 2000 were used in the analysis section.

The OMA itself is the second largest metropolitan area in Japan, after the Tokyo metropolitan area, with three core cities of Osaka, Kyoto, and Kobe. Osaka is the largest among the three and is the center of commerce in this metropolitan area; Kyoto was the ancient capital of Japan established in the year 794; and Kobe is the maritime center of the area. It covers a total area of 7800 km^2 within a radius of about 50 to 60 km from the center of Osaka. With a population totaling about 18 million as of the year 2000, it is one of the largest metropolitan areas in the world (SBSJ, 2000). The area has a very dense, mixed-use land development, and has well-developed rail networks. However, within the study area, there are also low-density areas that are primarily for agriculture.

To support our study, this dataset has been supplemented with land use and network data from subsequent analyses (Fukui, 2003; Susilo and Kitamura, 2008). To define the different area types, Fukui (2003) used cluster analysis that included a large number of measures, such as number and variety of services and industries, population size and distribution including daytime and nighttime variation, and working population size and distribution. Areas were determined by ward boundaries; ward sizes are smaller as one approaches highly commercial, denser areas. The different residential areas are defined as follows:

1. Highly commercial areas: the highest densities of commercial development and a higher daytime population compared to the nighttime population.

2. Mixed commercial areas: a high density of commercial development, though not as high as a commercial area and also having residential development as well, often of a high density. This type area also has less distinction between day and night populations.

3. Mixed residential areas: do not have sufficient work for the population, and most residents commute elsewhere. There is a larger nighttime than daytime population.

4. Autonomous areas: roughly an equal amount of residential and commercial development, and allows residents to live and work within the area. There is no difference in day and night population. Population density is lower than that for mixed residential areas. This type area is separate from the main urban development, and typically includes towns in agricultural areas.

5. Undeveloped (rural) areas: low density commercial and residential development. This type area often represents smaller farming communities.

4 Sample profiles and socio-demographic changes in the OMA

The lifecycle stages were developed primarily through analysis of household characteristics, such as children's age(s) and the age of the "head-of-household". Ten distinct stages of lifecycle were formulated (Sun *et al.*, 2009), as shown in Table 1.

Table 1 Descriptions and definitions of lifecycle stages

Lifecycle stage	Description	Definition
Younger single	Younger single household	Single adult younger than 60
Younger childless couple	Younger childless couple household	Oldest person younger than 60
Pre-school nuclear	Nuclear families with pre-school children	Youngest child younger than 6
Young school nuclear	Nuclear families with young school children	Youngest child 6 or older but younger than 12
Older school nuclear	Nuclear families with older school children	Youngest child 12 or older but younger than 18
All adults	Families of all adults	Nuclear families and single-parent families with all members of working age
Older childless couple	Older childless couple household	Oldest person 60 or older
Older single	Older single household	Age 60 or older
Single parent	Single parent household	Youngest child younger than 18
Others	Other households	Families with three generation, other related persons, and unrelated persons

The weighted sample profiles (based on census profiles of the population of the OMA) of the person's trip dataset can be seen in Table 2.

Table 2 Database profiles of the Osaka metropolitan area person trip data

Parameter	1970	2000
Number of samples	317 464	429 627
Male [D]	48.5%	47.3%
5–9 years old [D]	8.8%	5.1%
10–14 years old [D]	7.3%	5.6%
15–19 years old [D]	8.1%	5.9%
20–24 years old [D]	11.2%	6.0%
25–29 years old [D]	11.1%	7.4%
30–34 years old [D]	10.2%	7.4%
35–39 years old [D]	9.4%	7.0%
40–44 years old [D]	7.6%	6.4%
45–49 years old [D]	6.1%	7.1%
50–54 years old [D]	4.8%	9.0%
55–59 years old [D]	4.4%	7.8%
60 years old or over [D]	11.0%	25.3%
Number of household (HH) members	3.40	2.44
HH with dependent child (<15 years old) [D]	67.9%	45.1%
Number of cars per adult household member	0.28	0.40
Driver's license ownership per HH [D]	21.1%	52.7%
Resides in highly commercial area [D]	2.8%	2.4%
Resides in mixed commercial area [D]	24.4%	24.5%
Resides in mixed residential area [D]	37.9%	63.0%
Resides in autonomous city [D]	33.9%	9.1%
Resides in undeveloped (rural) area [D]	1.0%	1.1%
Worker [D]	48.4%	47.8%
Non-worker [D]	28.9%	34.1%
Student [D]	22.7%	18.1%
Average number of trip per day	2.37	2.39

Note: [D] indicates a 0–1 dummy variable

Table 2 shows that the OMA faces a large increase in its elderly population. In 1970, roughly 11% of people were aged 60 or older. By 2000, that had risen to more than 25%. The aging population poses a serious challenge to the support for the elderly, social security, social welfare, and services, including the development of public transportation facilities. At the same time, the average number of people living in a household dropped over the last three decades. The average number of household members dropped from 3.40 in 1970 to 2.44 in 2000. 67.9% of all households in 1970 are households with dependent children, while this number dropped to 45.1% of all households in 2000. The number of cars per adult household member has increased from 0.28 in 1970 to 0.40 in

2000. Driver's license ownership per household has also increased from 21.1% in 1970 to 52.7% in 2000. The percentage of residents who lived in areas classified as mixed residential increased by roughly 25% from 1970 to 2000, while those who lived in autonomous areas decreased by nearly 25%. From employment perspectives, the proportion of the population who were workers was nearly unchanged from 1970 to 2000 while the ratio of students declined from 22.7% in 1970 to 18.1% in 2000, but the ratio of non-employed adults in the area increased by 6% from 1970 to 2000.

If a person belongs to the 35–39 years old category in 2000 (Table 2), and he (or she) has two children, with the youngest child being younger than 6 in 2000, then he (or she) belongs to the pre-school nuclear lifecyle stage (Table 1).

In all areas except for the highly commercial and mixed commercial areas, there was significant growth in the proportion of trips taken by car (2 to 4 times) (Fig. 1). From these results (Fig. 1) it appears that the more densely developed built environments (highly commercial and mixed commercial areas) had a limiting effect on the proportion of car trips. However, without knowing how households of different lifecycle stages behave within each of those areas, it could be argued that the same people are continuing to live in the highly commercial and mixed commercial areas, and that their behavior is simply entrenched (Kitamura *et al.*, 2003; Kitamura and Susilo, 2005).

Previous work that examined this question (Sun *et al.*, 2009; 2012) found that the built environment explained more car usage than lifecycle stage. It is interesting to note that even in the most extreme cases the proportion of trips by car of household travel is only roughly 50%. Speculatively, this may be a result of the mixed land-usage in all areas and children's travel behavior has remained largely non-motorized (Waygood and Kitamura, 2009; Susilo and Waygood, 2012).

Owning a private car in the OMA has become very common except in the two more commercial areas (Figs. 2a–2e). Car ownership in rural and autonomous areas is higher with more than half of households owning two or more cars in 2000. With increased car ownership, it is anticipated that a corresponding increase in usage would be observed, which is demonstrated in Fig. 1.
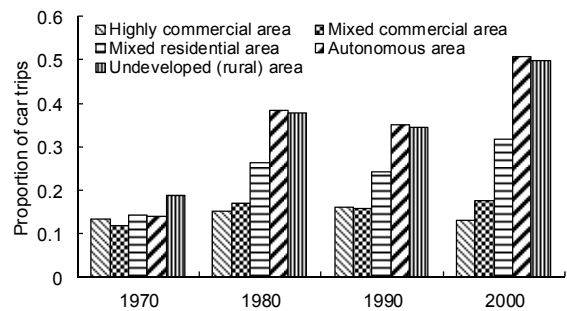
Fig. 1 Changes in proportion of trips by car across different residential areas
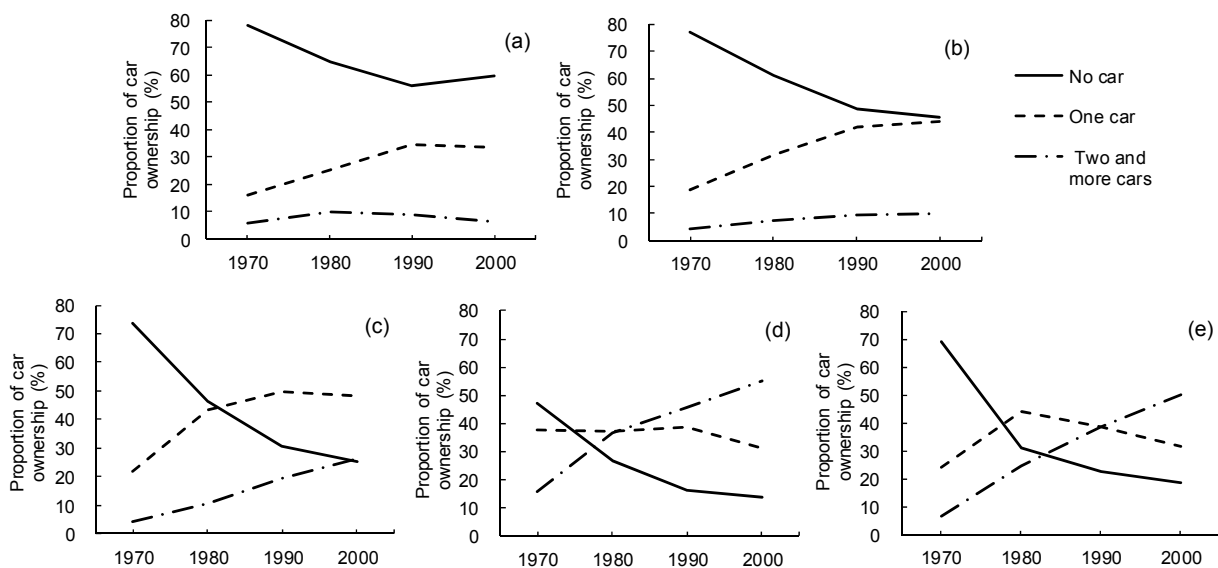
Fig. 2 Changes in car ownership across different residential areas
(a) Highly commercial area; (b) Mixed commercial area; (c) Mixed residential area; (d) Undeveloped (rural) area; (e) Autonomous area

5 Model system

The same simultaneous equation model system (Gujarati and Porter, 1999) was separately developed and applied to the 1970 and 2000 datasets. This model system takes into consideration the automobility characteristics as they are key dimensions of urban travel behavior. The model system includes endogenous variables: car ownership, total car travel time, and proportion of trips by car. A simultaneous equation model was used in the analysis because there are feedback relationships among car ownership, total car travel time, and proportion of trips by car as endogenous variables. Using person trip datasets in 1970 and 2000, the basic structure of the model system developed in this study is illustrated in Fig. 3.
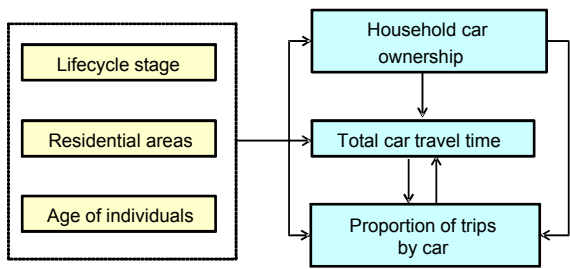

Fig. 3 Relations among car ownership and car usage characteristics

The model system embodies the following set of assumptions: household car ownership, total car travel time and proportion of trips by car are expected to be influenced by the lifecycle stage of the household which the person belongs to, the type of residential area that the person lived in, and the age of the person. Car ownership is expected to affect total car travel time and the proportion of trips by car, and further, total car travel time and the proportion of trips by car are expected to be related to each other.

Using this model system makes it possible to discern whether a change in behavior is due to changes in the demographic factors, including the attributes of urban residents, such as living in a certain area, belonging to a certain stage of lifecycle, at a certain age, or whether it is due to structural changes in the overall built environment of the OMA. It is thus possible to confirm some factors that have caused the recent trends of increasing travel demand seen in many industrialized countries (Millard-Ball and Schipper, 2011).

The model system is first illustrated along with the two-stage estimation procedure adopted in this study. Let the endogenous variables of the model system be Y_{AO}=car ownership (AO) of households which people belong to, Y_{AT}=total car travel time (AT) per person per day, and Y_{FA}=proportion of trips by car per person per day. The simultaneous equation model system is given by

$$
\begin{cases}
Y_{AO} = \begin{cases} Y_{AO}^*, & Y_{AO} > 0, \\ 0, & \text{otherwise,} \end{cases} \\
Y_{AO}^* = \beta_0 + \beta_{AO,LC}X_{LC} + \beta_{AO,RA}X_{RA} + \beta_{AO,A}X_A + \varepsilon_{AO},
\end{cases}
\tag{1}
$$

$$
\begin{cases}
Y_{AT} = \begin{cases} Y_{AT}^*, & Y_{AT} > 0, \\ 0, & \text{otherwise,} \end{cases} \\
Y_{AO}^* = \beta_0 + \beta_{AT,LC}X_{LC} + \beta_{AT,RA}X_{RA} + \beta_{AT,A}X_A \\
\qquad + Y_{AT,AO}\widehat{Y}_{AO} + Y_{AT,FA}\widehat{Y}_{FA} + \varepsilon_{AT},
\end{cases}
\tag{2}
$$

$$
\begin{cases}
Y_{FA} = \begin{cases} Y_{FA}^*, & Y_{FA} > 0, \\ 0, & \text{otherwise,} \end{cases} \\
Y_{AO}^* = \beta_0 + \beta_{FA,LC}X_{LC} + \beta_{FA,RA}X_{RA} + \beta_{FA,A}X_A \\
\qquad + Y_{FA,AO}\widehat{Y}_{AO} + Y_{AT,AT}\widehat{Y}_{AT} + \varepsilon_{FA}.
\end{cases}
\tag{3}
$$

In the model system, LC is the vector of exogenous variables representing the lifecycle stage that the person belongs to (Table 1). RA is the vector of the residential area in which the person lived in (Section 2). A is the vector of variables representing the age of the individuals, containing 11 groups of age levels, which are 5–9, 10–19, 20–29, 30–39, 40–44, 45–49, 50–54, 55–59, 60–64, 65–74, and ≥75. The ages of the individuals were pre-coded into these categories so it is not possible to use a continuous variable. β_0 is a constant; β_{ij} (i=AO, AT, FA, j=LC, RA, A) are vectors of coefficients; X_{LC}, X_{RA}, and X_A are vectors of exogenous variables; ε_{AO}, ε_{AT}, and ε_{FA} are normal random error terms that are mutually independent and serially uncorrelated; and $\widehat{Y}_{AO}$, $\widehat{Y}_{AT}$, and $\widehat{Y}_{FA}$ are predicted values of endogenous variables. Further, the impacts of age on travel behavior are not linear (e.g., the change from youth to twenties, working age to retirement), so categorical values were preferred here.

These model systems are estimated and then applied to examine how car travel has changed for individuals from 1970 to 2000 with changing demographics, household structure, residential location, and metropolitan structure in the OMA in the next section.

6 Estimation results

The simultaneous equation model systems are estimated using the two-stage procedure described in Section 5. Assuming that the error terms are not correlated across the equations within the model system, each model is estimated individually.

Using the 1970 data and 2000 data, the results of the simultaneous equation models for estimated automobility characteristics are shown in Tables 3 and 4, respectively. The two model-fit measures (ANOVA based fit measure and DECOMP based fit measure) shown in Tables 3 and 4 indicate that the fitness of the Tobit models were acceptable (less than 0.5). These measures mimic the R^2 value of the ordinary least-squared method.

Table 3 Simultaneous equation model for automobility characteristics in 1970

Constant	Car ownership, Y_{AO}		Total car travel time, Y_{AT}		Proportion of trips by car, Y_{FA}	
	Coefficient	t-stats	Coefficient	t-stats	Coefficient	t-stats
	0.615	135.494*	2.531	7.884*	0.017	16.687*
Highly commercial area	−0.001	−0.086	−3.529	−3.541*	−0.016	−5.108*
Mixed commercial area	−0.161	−28.999*	−3.590	−9.380*	−0.021	−17.077*
Mixed residential area	−0.113	−22.911*	−1.583	−4.683*	−0.005	−4.308*
Undeveloped (rural) area	0.249	10.576*	−0.297	−0.184*	0.030	5.835*
Autonomous area	0.000		0.000		0.000	
Younger single family	−0.463	−44.708*	1.782	2.494*	0.005	2.411*
Younger childless couple family	−0.210	−18.345*	1.179	1.495*	0.012	4.610*
Pre-school nuclear family	−0.096	−6.272*	−1.121	−1.065	−0.002	−0.749
Young school nuclear family	−0.096	−12.800*	−1.402	−2.717*	−0.015	−8.998
Older school nuclear family	−0.099	−12.109*	−1.457	−2.584*	−0.014	−7.814
All adults family	−0.078	−10.450*	−0.873	−1.701	−0.002	−1.239
Older childless couple family	−0.404	−22.790*	1.561	1.279*	0.002	0.526*
Older single family	−0.481	−18.776*	−0.474	−0.269	0.001	0.247
Single parent family	−0.361	−19.454*	−4.297	−3.369*	−0.029	−7.071*
Other households	0.000		0.000		0.000	
5–9	0.025	3.028	−1.103	−1.914*	−0.010	−5.231
10–19	0.028	4.183*	0.812	1.795*	0.006	4.271
20–29	0.045	7.880*	16.810	42.708*	0.147	117.690*
30–39	0.000	−0.008	21.276	51.708*	0.183	140.186*
40–44	−0.009	−1.046	15.376	24.856*	0.159	80.996*
45–49	−0.008	−0.760	13.713	20.064*	0.128	58.987*
50–54	0.046	4.085*	9.683	12.601*	0.089	36.751*
55–59	0.055	4.765*	5.963	7.506*	0.069	27.444*
60–64	0.021	1.674	3.948	4.674*	0.043	16.239*
65–74	−0.040	−3.612*	1.688	2.242*	0.019	7.778
≥75	0.000		0.000		0.000	
Car ownership			2.936	24.056*	0.034	86.918*
Total car travel time					8.645	172.361*
Proportion of trips by car			8.645	172.361*		
Log likelihood function	−354 417.0		−398 459.6		−154 807.4	
ANOVA based fit measure	0.304		0.101		0.107	
DECOMP based fit measure	0.437		0.403		0.410	

Note: *N*=317 464; all exogenous variables are dummy variables; * significant at α=0.05

Table 4 Simultaneous equation model for automobility characteristics in 2000

	Car ownership, Y_{AO}		Total car travel time, Y_{AT}		Proportion of trips by car, Y_{FA}	
Constant	Coefficient	*t*-stats	Coefficient	*t*-stats	Coefficient	*t*-stats
	2.078	673.090[*]	−2.421	−11.599[*]	0.042	24.122[*]
Highly commercial area	−1.211	−122.224[*]	−7.526	−15.838[*]	−0.18	−45.482[*]
Mixed commercial area	−1.107	−319.049[*]	−5.057	−27.792[*]	−0.157	−103.496[*]
Mixed residential area	−0.697	−234.735[*]	−0.751	−5.051[*]	−0.083	−67.049[*]
Undeveloped (rural) area	0.070	4.854[*]	1.560	2.288[*]	−0.030	−5.224[*]
Autonomous area	0.000		0.000		0.000	
Younger single family	−1.113	−150.996[*]	1.105	3.097	0.005	1.838
Younger childless couple family	−0.509	−80.263[*]	4.399	14.608[*]	0.029	11.442[*]
Pre-school nuclear family	−0.320	−57.551[*]	2.896	10.986[*]	0.026	11.890[*]
Young school nuclear family	−0.367	−64.415[*]	1.870	6.935[*]	0.027	12.070[*]
Older school nuclear family	−0.255	−42.431[*]	0.368	1.292	−0.003	−1.203
All adults family	−0.046	−10.676[*]	−2.608	−12.955[*]	−0.038	−22.853[*]
Older childless couple family	−0.840	−173.373[*]	5.517	23.347[*]	0.076	38.645[*]
Older single family	−1.257	−172.135[*]	2.879	8.083[*]	0.056	18.748[*]
Single parent family	−0.888	−80.748[*]	3.550	6.794[*]	0.061	14.057[*]
Other households	0.000		0.000		0.000	
5–9	0.203	30.706[*]	−2.382	−7.638[*]	0.017	6.444[*]
10–19	0.286	62.491[*]	−4.310	−19.904[*]	−0.065	−36.073[*]
20–29	0.332	77.537[*]	17.717	87.081[*]	0.201	118.896[*]
30–39	0.162	38.891[*]	24.574	125.07[*]	0.286	175.259[*]
40–44	0.230	38.360[*]	24.064	85.103[*]	0.292	124.179[*]
45–49	0.291	51.054[*]	23.018	85.402[*]	0.270	120.685[*]
50–54	0.339	66.576[*]	21.356	88.408[*]	0.241	119.920[*]
55–59	0.294	54.135[*]	19.953	77.529[*]	0.208	97.420[*]
60–64	0.264	46.334[*]	15.963	59.202[*]	0.152	68.009[*]
65–74	0.109	23.535[*]	7.148	32.816[*]	0.079	43.893[*]
≥75	0.000		0.000		0.000	
Car ownership			7.128	99.069[*]	0.100	167.807[*]
Total car travel time					11.005	357.295[*]
Proportion of trips by car			11.005	357.295[*]		
Log likelihood function	−608 457.0		−886 792.2		−314 184.8	
ANOVA based fit measure	0.303		0.140		0.137	
DECOMP based fit measure	0.407		0.403		0.412	

Note: *N*=429 627; all exogenous variables are dummy variables; [*] significant at α=0.05

The estimation results on Tables 3 and 4 show that undeveloped (rural) areas and autonomous areas were more car-oriented with greater car ownership, duration, and proportion of trips by car in both eras compared with other areas. Although "all adult" households were more likely to own more cars compared with other lifecycle stages, "older childless couple" households travel by car more, suggesting that such households might be more reliant on cars for mobility. For both eras, a clear relationship between

working aged people and car travel time and the proportion of trips by car exists.

It can also be observed that in both eras, there is an inverse relationship between increasing age for working-aged people and car travel time and the proportion of car trips. Based on research about children's travel in the USA, one might assume that this is the result of chauffeuring, but research in Japan (SBSJ, 2000; Sun *et al.*, 2009) showed that children there mostly travel independently on weekdays, which is

suggested in Tables 3 and 4 as well. The second reason might be that as individuals enter into family lifecycle stages that stimulate the desire for a larger residence, each successive generation generally locates further from the urban centers leading to longer trip times and potentially greater reliance on cars for transportation. The increasing level of car ownership is also an important reason for this finding.

Two examples will be used to highlight some of the findings shown in Tables 3 and 4, as well as the changes from 1970 to 2000. In the year 1970 (Table 3), an individual aged 30 to 39 who is part of a "pre-school family" household that resides in a mixed-residential area would have 0.4 cars (according to Eq. (1)) at their disposal, would spend about 21 min (according to Eq. (2)) travelling in it, and would make just under 20% (according to Eq. (3)) of their trips by car. In the year 2000 (Table 4), an individual with the same characteristics would have 1.2 cars at their disposal, spend over 24 min traveling in it, and would make nearly 22% of their trips by car. Thus, although car ownership levels have drastically increased (about 3 fold), the time spent on travelling and the percentage of trips have only marginally increased. Note that Japanese companies typically pay for employees to travel to work by transit, which may act to limit weekday car usage despite the increase of ownership.

However, examining the results for an individual with the same characteristics, where the house is located in an autonomous area shows a much greater increase in the share of car trips. Car ownership levels would increase from 0.5 to 1.9 (nearly 4 fold), travel time from 22.7 to 25 min, and the percentage of trips from 20% to 30%.

7 Behavioral stability test

To examine the stability of automobility characteristics (car ownership, proportion of car trips, and total car travel time) in the OMA from 1970 to 2000, and ask how much of the change in urban travel is due to changes in demographics and how much is due to structural change, the following method is introduced into this study (Kitamura *et al.*, 2008). Firstly, separate explanatory variable values, and estimated coefficient vectors on the three automobility characteristics in 1970 and 2000 are determined. Then, calculate

the mean value of the three automobility characteristics using explanatory variable values from a given year and estimated coefficient vectors from a given year (Table 5). For example, 1.56 (Table 5) was calculated with the data from year 1970, and the coefficient vector from year 2000. Lastly, set the automobility characteristics as 100, and then compare the effects of variations in explanatory variable values and those in estimated coefficient vectors on the three automobility characteristics (Tables 6 and 7).

Table 5 Automobility characteristics produced with 1970, 2000 coefficient vectors at 1970, 2000 mean explanatory variable values

Year,	Y_{AO}		Y_{AT}		Y_{FA}	
y	1970	2000	1970	2000	1970	2000
1970	0.47	1.56	11.56	15.19	0.10	0.13
2000	0.40	1.32	9.60	15.58	0.09	0.12

For each of the automobility characteristics variables (Y_{AO}, Y_{AT}, and Y_{FA}), its mean value, with the data from year y and the coefficient vector from year y', is shown in the cell corresponding y, y'

Table 6 Change in automobility characteristics due to change in explanatory variable values (setting value with 1970 data as 100)

Year,	Y_{AO}		Y_{AT}		Y_{FA}	
y	1970	2000	1970	2000	1970	2000
1970	100	100	100	100	100	100
2000	85.11	84.62	83.04	102.57	90	92.31

Table 7 Change in automobility characteristics due to change in coefficient vectors (setting value with 1970 coefficient vector as 100)

Year,	Y_{AO}		Y_{AT}		Y_{FA}	
y	1970	2000	1970	2000	1970	2000
1970	100	331.91	100	131.40	100	130
2000	100	330	100	162.29	100	133.33

Table 5 shows the overall automobility characteristic changes for the corresponding years. The meaning of 0.40 for Y_{AO} in the table is the average household car ownership, with the explanatory variable values data from the year 2000 and the estimated coefficient vector from the year 1970. For each characteristic, the change can be seen in the diagonal. Thus, household car ownership can be seen to have increased from 0.47 vehicles in 1970 to 1.32 vehicles in 2000 (2.8 times), and travel time by car increased from 11.56 min in 1970 to 15.58 min in 2000 (1.4 times). Further, the fraction of car trips increased by

2 percentage points from 1970 to 2000 (1.2 times).

Table 6 shows the change in automobility characteristics due to changes in the explanatory variable values. Regardless of the year of the coefficient vector, the values of the respective automobility characteristics with the year of data are shown in Table 6. Surprisingly, results show that Y_{AO} decreased roughly 15% due to changes in the mean explanatory variable value under coefficient vectors of 1970 and also decreased roughly 15% under that of 2000. It may be inferred that demographic changes between 1970 and 2000 have by themselves induced a decrease in car ownership. These similar results show that Y_{AT} and Y_{FA} declined due to changes in the mean explanatory variable value under any of the two coefficient vectors, except that Y_{AT} shows a slight increase due to changes in the mean explanatory variable value under coefficient vectors of 2000. This result would suggest that the mixed effects of changes in residential areas, changes in the stage of lifecycle, and urban residents' aging did not prompt an increase of car ownership and car usage; on the contrary, they have cancelling effects on the car travel behavior here.

Table 7 shows the change in automobility characteristics due to changes in the coefficient vectors. It shows the values of the respective automobility characteristics with the year of the coefficient vector regardless of the year of data. Y_{AO} increased more than 3 times due to changes in coefficient vectors regardless of the year of data. It may be inferred that changes of structural relationship from 1970 to 2000 have induced a large growth in car ownership. Similar results for Y_{AT} and Y_{FA} found that increases were due to changes in the coefficient vectors under either of the two sample years. This result would suggest that changes in structural relationships (such as geographical expansion, internal land use structure, transportation networks, and auto-oriented development) resulted in a great increase of car ownership and car usage.

Comparing Tables 6 and 7, one may conclude that changes in structural relationships prompt the process of motorization, after offsetting the part of the changes of demographics which had the opposite effect on car travel here.

The statistical analyses of this section have provided evident that the structural relationships have been changing in the direction of expanding automobility activities and travel. This tendency offsets the effects of changes in individual and household attributes on private car travel, which are pointing in the direction of expanding automobility activities and travel, and has produced the unmistakable increases in car ownership, proportion of car trips, and total car travel time.

8 Conclusions

The OMA in Japan, like many other metropolitan areas in the world, experienced substantial change in the second half of the 20th century. The most significant forces of that change have been motorization and suburbanization. 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 recently their dense and mixed land use patterns. As well as residential location changes, changes in demographic factors have been substantial, such as household size shrinking, the residential population aging, "older childless couples" and "older single" households increasing, and non-employed working-age individuals increasing in the OMA.

Significant growth in the fraction of household trips completed by private car can be seen in mixed residential areas, undeveloped (rural) areas, and autonomous areas. Owning a private car has become very common in those areas as well. The exceptions, the highly commercial and mixed commercial areas, are better served by public transportation and services that are likely closer than in the other areas. Their urban form may also be more car-restrictive.

This study has been an attempt to examine how changes in residential and demographic factors have impacted urban residents' car travel patterns. The study has adopted a holistic approach by exploring the stability in structural relationships underlying several pertinent characteristics of automobility through simultaneous equations model systems. The statistical analyses have offered strong evidence that urban residents' car usage has been expanding and each residential area, each lifecycle stage, and each age group has their unique characteristics of car ownership and car usage.

The estimation results suggest that variance of car ownership and car usage within each residential area, each lifecycle stage, and each age group in 2000

were larger than that in 1970. Observed changes in household travel survey data collected in 1970 and 2000 are decomposed to those due to changes in demographic factors, and those due to changes in structural relationships. The results have further indicated that the expansion in automobility has been caused primarily by changes in the structural relationships while changes in demographic factors have had relatively minor effects, and actually were found to have played an opposite role. The inclusion of variables such as income, relative costs of car ownership, distance to urban centers, commuting distance, and commute trip mode choice would provide further insight on the matter.

Note that this study is based on data between 1970 and 2000, and since then the socio-demographic characteristics of the society and the urban structure have been continuously changing and so has the behavior of the population. Recently there has been a sign of "peak car" phenomenon (Metz, 2013) and emerging Y-generation's unique mobility patterns (IFMO, 2013) in various developed countries, where the younger generation consciously starts to prioritize other travel modes than private cars. The impacts of this constitute one of the possible future directions of this study. Further, this study is based on cross-sectional datasets at a regional level. It is difficult to use such datasets to determine the real reasons underlying the interactions between households' lifecycle and their car ownership and usage. A deeper investigation with travel diaries, mixed with longitudinal observations, would further determine the reasons and trade-off mechanisms that underlie the whole decision-making processes. This would form another possible future direction of this research.

Acknowledgement

References

Benekohal, R.F., Michaels, R.M., Shim, E., *et al.*, 1994. Effects of aging on older drivers' travel characteristics. *Transportation Research Record: Journal of the Transportation Research Board*, **1438**:91-98.

Fukui, K., 2003. Longitudinal Analysis of Travel Behavior Change Using Dynamic Urban Area Classification. MS Thesis, Kyoto University, Kyoto (in Japanese).

Gujarati, D.N., Porter, D.C., 1999. Essentials of Econometrics. McGraw-Hill Co. Inc., Part 3, p.347-370.

Heggie, I.G., 1978. Putting behaviour into behaviour models of travel choice. *Journal of the Operational Research Society*, **29**(6):541-550. [doi:10.1057/jors.1978.117]

Hjorthol, R.J., Levin, L., Siren, A., 2010. Mobility in different generations of older persons: the development of daily travel in different cohorts in Denmark, Norway and Sweden. *Journal of Transport Geography*, **18**(5):624-633. [doi:10.1016/j.jtrangeo.2010.03.011]

IFMO, 2013. 'Mobility Y'–The Emerging Travel Patterns of Generation Y, Munich, Germany.

Jones, H., 2013. Understanding Walking and Cycling using a Life Course Perspective. PhD Thesis, University of the West of England.

Jones, P.M., Dix, M.C., Clarke, M.I., *et al.*, 1980. Understanding Travel Behaviour. Oxford, England.

Kitamura, R., Susilo, Y.O., 2005. Is travel demand insatiable? A study of changes in structural relationships underlying travel. *Transportmetrica*, **1**(1):23-45. [doi:10.1080/18128 600508685640]

Kitamura, R., Susilo, Y.O., Fukui, K., *et al.*, 2003. The invariants of travel behavior: the case of Kyoto-Osaka-Kobe metropolitan area of Japan, 1970-2000. 10th International Conference on Travel Behaviour Research, Lucerne, Switzerland.

Kitamura, R., Sakamoto, K., Waygood, E.O.D., 2008. Declining sustainability: the case of shopping trip energy consumption. *International Journal of Sustainable Transportation*, **2**(3):158-176. [doi:10.1080/155683107015173 07]

Krizek, K.J., 2003. Residential relocation and changes in urban travel: does neighborhood-scale urban form matter? *Journal of the American Planning Association*, **69**(3): 265-281. [doi:10.1080/01944360308978019]

Lanzendorf, M., 2003. Mobility biographies: a new perspective for understanding travel behaviour. 10th International Conference on Travel Behaviour Research, Lucerne, Switzerland.

Metz, D., 2013. Peak car and beyond: the fourth era of travel. *Journal of Transportation Planning and Technology*, **33**(3):255-270. [doi:10.1080/01441647.2013.800615]

Millard-Ball, A., Schipper, L., 2011. Are we reaching peak travel trends in passenger transport in eight industrialized countries. *Transport Reviews*, **31**(3):357-378. [doi:10. 1080/01441647.2010.518291]

Newbold, K.B., Scott, D.M., Spinney, J.E.L., *et al.*, 2005. Travel behaviour within Canada's older population: a cohort analysis. *Journal of Transport Geography*, **13**(4): 340-351. [doi:10.1016/j.jtrangeo.2004.07.007]

Prillwitz, J., Harms, S., Lanzendorf, M., 2007. Interactions among residential relocations, life course events, and daily commute distances. *Transportation Research Record: Journal of the Transportation Research Board*, **2021**: 64-69. [doi:10.3141/2021-08]

SBSJ (Statistics Bureau, Statistics Japan), 2000. Ministry of internal affairs and communications. Available from http://www.stat.go.jp/english/index.htm. [Acceseed on

Mar. 18, 2014]

Scheiner, J., 2006. Housing mobility and travel behaviour: a process-oriented approach to spatial mobility. *Journal of Transport Geography*, **14**(4):287-298. [doi:10.1016/j.jtrangeo.2005.06.007]

Scheiner, J., Holz-Rau, C., 2013a. Changes in travel mode use after residential relocation: a contribution to mobility biographies. *Transportation*, **40**(2):431-458. [doi:10.1007/s11116-012-9417-6]

Scheiner, J., Holz-Rau, C., 2013b. A comprehesive study of life course, cohort, and period effects on changes in travel mode use. *Transportation Research Part A: Policy and Practice*, **47**:167-181. [doi:10.1016/j.tra.2012.10.019]

Seo, S.E., Ohmori, N., Harata, N., 2011. Effects of household structure and mobility changes on going-out behavior of the elderly in Korea. 90th TRB Annual Meeting of the Transportation Research Board, Washington, DC.

Simma, A., Axhausen, K.W., 2001. Within household allocation of travel: case of upper Austria. *Transportation Research Record: Journal of the Transportation Research Board*, **1752**(1):69-75. [doi:10.3141/1752-10]

Sun, Y., Waygood, E.O.D., Fukui, K., *et al.*, 2009. The built environment of household lifecycle stages: which explains sustainable travel more? Case of Kyoto-Osaka-Kobe built area. *Transportation Research Record: Journal of the Transportation Research Board*, **2135**:123-129. [doi:10.3141/2135-15]

Sun, Y., Waygood, E.O.D., Huang, Z., 2012. Do automobility cohorts exist in urban travel? Case study of the Osaka metropolitan area of Japan. *Transportation Research Record: Journal of the Transportation Research Board*, **2323**:18-24. [doi:10.3141/2323-03]

Susilo, Y.O., Kitamura, R., 2005. On an analysis of the day-to-day variability in the individual's action space: an exploration of the six-week Mobidrive travel diary data. *Transportation Research Record: Journal of the Transportation Research Board*, **1902**(1):124-133. [doi:10.3141/1902-15]

Susilo, Y.O., Kitamura, R., 2008. Structural changes in commuters' daily travel: the case of auto and transit commuters in the Osaka metropolitan area of Japan, 1980-2000. *Transportation Research Part A: Policy and Practice*, **42**(1):95-115. [doi:10.1016/j.tra.2007.06.009]

Susilo, Y.O., Waygood, E.O.D., 2012. A long term analysis of the mechanisms underlying children's activity-travel engagements in the Osaka metropolitan area. *Journal of Transport Geography*, **20**(1):41-50. [doi:10.1016/j.jtrangeo.2011.07.006]

van der Waerden, P., Timmermans, H., Borgers, A., 2003. The influence of key events and critical incidents on transport mode choice switching behavior: a descriptive analysis. 10th International Conference on Travel Behavior Research IATBR, Lucerne, Switzerland.

Verhoeven, M., Arentze, T., Timmermans, H., *et al.*, 2007. Examining temporal effects of lifecycle events on transport mode choice decisions. *International Journal of Urban Sciences*, **11**(1):1-13. [doi:10.1080/12265934.2007.9693603]

Wachs, M., 1979. Transportation for the Elderly: Changing Lifestyles, Changing Needs. University of California Press, Berkeley.

Waygood, E.O.D., Kitamura, R., 2009. Children in a rail-based developed area of Japan. *Transportation Research Record: Journal of the Transportation Research Board*, **2125**:36-43. [doi:10.3141/2125-05]

Zimmerman, C.A., 1982. The lifecycle concept as a tool for travel research. *Transportation*, **11**(1):51-69. [doi:10.1007/BF00165594]

中文概要：

本文题目：日本大阪都市圈居民的年龄、居住位置与家庭生命周期对小汽车使用与保有的影响

Detangling the impacts of age, residential locations and household lifecycle in car usage and ownership in the Osaka metropolitan area, Japan

研究目的：探究城市居民小汽车交通行为变化的原因有多少来自人口统计特性的变化，有多少来自城市结构的改变。

创新要点：考虑家庭成员的生活任务分工以及家庭资源的分配等对每个家庭成员出行方式的影响，构建基于家庭生命周期的小汽车出行行为模型，为控制小汽车出行对策的研究提供准确依据。

研究方法：采用调查与统计理论，掌握居民的出行行为特征；基于经济计量学建模方法，构建居民小汽车出行行为联立方程模型。

重要结论：城市结构关系的改变在抵消了人口统计特性的变化对小汽车交通产生的负面影响之后，小汽车交通总体呈上升趋势。

关键词组：城市小汽车交通；家庭生命周期；城市结构变化；联立方程模型