An Evaluation of CO\textsubscript{2} Emission Reduction based on the Supply of Condominiums in Central Kyoto

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Abstract

New residential needs have recently caused a construction boom in central areas of Japanese metropolises leading to population recovery and compact conversion in many cities, such as Kyoto. This study shows how central Kyoto has become compact by an investigation of condominiums. An evaluation of CO\textsubscript{2} emissions based on the supply of condominiums was carried out. The investigation shows that the supply of condominiums within the central district of Kyoto has been increasing faster than that in the fringe district recently. Travel distance and modes of transportation are changed by such compaction process. The estimation shows that compact housing arrangement, which shortens traveling distance and changes the transportation modes of residents, helps to reduce CO\textsubscript{2} emission in Kyoto. The results also indicate that, in the central district of Kyoto, the supply of dwelling units for households with more than two family members is more effective in reducing CO\textsubscript{2} emission.

Keywords: compact city; reduction; CO\textsubscript{2} emission; condominium; personal trips

1. Introduction

1.1 Compact Conversion in Central Areas of Japanese Metropolises

Generally, the housing arrangement determines the extent of urban sprawl, which is a primary factor in environmental impact. During the economic bubble period in Japan, the influx of people to cities led to housing in the fringe areas of cities. This sprawling housing arrangement has enlarged the urban area and increased the energy consumption of transportation. Following the collapse of the economic bubble, land prices in the urban centers have continuously declined. At the same time, suburban residents are tired of the excessive time spent in commuting and increasing numbers prefer to live near the urban center. These residential needs have recently caused a construction boom for apartments in central areas of Japanese metropolises which has led to population recovery and a conversion of cities to a more compact form.

The population in Kyoto city has been declining due to the low birthrate and an aging population. However, in Nakagyo-ku and Shimogyo-ku, which are generally regarded as the central district of Kyoto, the population has continually increased since 1999\cite{1}. It is indicated in the statistics that this population recovery is due to the supply of newly built apartments and the opening of a new subway line (General Planning Bureau of Kyoto City, 2005). Goto et al. (2006) explored the changes in apartment construction in central Kyoto from 1990 to 2004 and concluded that enforcement of Kyoto's municipal construction laws has resulted in newly built apartments being larger and Kyoto becoming more compact.

Studies of compact cities have found that compaction allows cities to function better as a result of modified land utilization and downtown densification. Compaction not only shortens travel distance and decreases traffic density in the urban center, but also allows alternative modes of transportation (Suzuki, 2001). Consequently, a compact city produces less CO\textsubscript{2} emissions from trips to the urban center than a sprawling city.

1.2 Households' Annual CO\textsubscript{2} emission (HACO\textsubscript{2})

Measuring changes in CO\textsubscript{2} emission that results from housing supply during a city's compaction process can help to establish this induction, may result in the construction of housing supplies and lead to an urban renaissance and a satisfactory urban environment.

In this paper, the possible reduction of CO\textsubscript{2} emissions in Kyoto is used to illustrate the compaction degree of this city. It is estimated based on both the changes in travel distance and the transportation modes of residents based on the supply of condominiums.

The environmental load from a households (regarded as the residents who live in the condominiums in this...
paper): annual CO₂ emission (HACO₂) is defined as the sum of family behaviors, including commuting trips, mode of transportation, home location, and power consumption in daily life, all of which influence a city’s environmental load. This idea can be clarified using a homogeneous city model called the Alonzo Model[2], which relates home locations and the above behaviors to a city's environmental load. It assumes that all employment, goods, and services are available only at the urban center, and that commuters travel daily to the urban center for work and personal purposes. Therefore, the HACO₂ of a household in this city is the sum of the dwelling's CO₂ emissions during its life cycle (LCCO₂), the CO₂ emissions from one year of personal trips to the urban center (CTCO₂), and the CO₂ emissions from one year of power consumption (ELCO₂). This HACO₂ can be expressed as (Tang et al., 2005 and Tang, Munemoto 2007):

$$\text{HACO}_2 = \text{LCCO}_2 + \text{CTCO}_2 + \text{ELCO}_2$$

If a household moves closer to the urban center, its CTCO₂, and consequently its HACO₂, will decrease. It will also save energy and reduce ELCO₂. By reducing CO₂ emissions, if the HACO₂ level is lower than the constraint, this household could enjoy a better quality of life, e.g., by living in a larger apartment (requiring a greater LCCO₂).

1.3 Purpose

The possible reduction of HACO₂ is estimated concerning the changes in trip distance and modes of transportation, and is used to illustrate the compaction degree of the city.

This study firstly shows how central Kyoto has become compact by an investigation of condominium supply. Secondly, it evaluates reduction in CO₂ emissions by comparing recent cases of compact distribution and sprawling distribution (pre-1999) of condominiums in Kyoto.

2. Investigation of Condominiums

2.1 Investigation outline

The investigation area is Kyoto city. In this paper, Nakagyo-ku and Shimogyo-ku are termed the 'central district,' and other districts of Kyoto are termed the 'fringe district.' The cross section at Karasuma Street and Shijo Street ('Karasuma-Shijo') is used as the urban center of Kyoto (see Fig.1.).

First, a survey of the distribution of condominiums is made, which clarifies the number of condominiums located in the central and fringe districts. This information is gathered by collating and supplementing the data published on several well-known Kyoto real estate Web sites[3].

Secondly, the investigation focuses on newly-built condominiums completed during 1999-2006 in the central district of Kyoto. The general information of the buildings is acquired by inspecting the construction outline in advertisements that are published in newspapers or on the Internet, or by verifying the application that is submitted to the government office.

Finally, the locations of these condominiums are identified and marked on the Digital Atlas Z map[4]. The "Neighborhood Search" tool can identify the nearest train station, and the "Route Search" tool can identify the shortest route from each condominium to the nearest train station and measure the distance.

2.2 Distribution of condominiums in Kyoto before and after 1999

The number of condominiums located in the central and fringe districts of Kyoto before and after 1999 are shown in Table 1.

| Year | Before 1999 | After 1999 (1999~2006) |
|------|-------------|------------------------|
| 1999 | 200 | 18 | 18 | 18 | 22 | 25 | 19 | 20 | 20 | 20 | 160 |
| 2000 | 674 | 20 | 29 | 18 | 21 | 12 | 14 | 7 | 11 | 132 |
| Total | 854 | 38 | 47 | 40 | 49 | 37 | 35 | 27 | 31 | 302 |

The number of condominiums located in the central and fringe districts by year are shown in Table 1. and the changes in their distribution are illustrated in Fig.2. Before 1999, about 30% of condominiums were built in the central district and the remaining 70% in the fringe district. In contrast, after 1999, 56.3% were built in the central district and 43.7% in the fringe district. The percentage of condominiums located in the central district increased continually from 1999 to
2006. Therefore, condominiums are increasingly built in the central district, increasing the number of people moving into the area. Hence, condominium distribution has recently changed from the sprawling to compact form.

### 2.3 Supply of condominiums built in the central district from 1999 to 2006

During the study period, the central district of Kyoto had a total of 440 condominiums, with 170 being completed from 1999 to 2006. The annual variation in the supply of condominiums is shown in Table 2. Approximately 20 condominiums are built in this area each year. From 1999 to 2003, the supply, which represented the total gross floor area (GFA), increased, and a major construction boom took place from 2001 to 2003. Supply decreased in 2004, and by 2005, the level was even lower than that in 1999. These condominiums supplied 10,113 dwelling units to residents in the central district; that is, at full occupancy, more than 10,000 households moved to the central district of Kyoto during this period. The increase in the Nakagyo-ku and Shimogyo-ku households and the supply of dwelling units each year from 1999 to 2005 are illustrated in Fig.3. The rate of change is similar to both these values, indicating that the supply of new condominiums is a primary factor in the population growth.

Among new condominiums, 20% of units are one-room dwellings, namely a one-person household. This kind of dwelling unit has an average GFA of about 30m$^2$ and is considered as a supply for one-person households, named "one-room type unit". Those units with an average GFA of 85m$^2$ to 100m$^2$ are considered as supply for households with more than two persons, and are named "family type unit".

### 2.4 Locations of newly-built condominiums in the central district

The locations of condominiums, marked on the residential map of Kyoto, are shown in Fig.4.

The digital map's Neighborhood Search tool is applied in this study to search for stations near each condominium, and the Route Search tool is used to determine the shortest route from each condominium to the neighborhood stations. The nearest station is the one with the shortest time distance to the condominium. The 20 relevant stations, which are relatively close to the condominiums, are illustrated in Fig.5. The accessibility of each station to the urban center is presented in Table 3. by time–distance. Among the 170 condominiums in the central district, 14 are located in areas less than 400 m from the urban center, that is to say, residents could walk to the urban center within five minutes. Another 52 condominiums are located in areas less than 1000 m from the urban center, so these residents could walk to the urban center within 10 minutes. The remaining 104 condominiums are located more than 1000 m from the urban center, and the residents there are likely to use a mode of transportation other than walking to reach the urban center. Only two condominiums are far from any railway station, and are located 2700 m and 3800 m from the urban center, respectively. The residents of these two condominiums possibly travel to the urban center by private car or moped. It is indicated by this finding that condominium developers use building sites near the urban center to provide commuting convenience to the urban center, which is an important housing requirement.

### 3. Estimated Reductions in CO$_2$ Emissions

#### 3.1 Estimation model

The model used to estimate reductions in CO$_2$ emissions was applied in this study to search for stations near each condominium, and the Route Search tool is used to determine the shortest route from each condominium to the neighborhood stations. The nearest station is the one with the shortest time distance to the condominium. The 20 relevant stations, which are relatively close to the condominiums, are illustrated in Fig.5. The accessibility of each station to the urban center is presented in Table 3. by time–distance. Among the 170 condominiums in the central district, 14 are located in areas less than 400 m from the urban center, that is to say, residents could walk to the urban center within five minutes. Another 52 condominiums are located in areas less than 1000 m from the urban center, so these residents could walk to the urban center within 10 minutes. The remaining 104 condominiums are located more than 1000 m from the urban center, and the residents there are likely to use a mode of transportation other than walking to reach the urban center. Only two condominiums are far from any railway station, and are located 2700 m and 3800 m from the urban center, respectively. The residents of these two condominiums possibly travel to the urban center by private car or moped. It is indicated by this finding that condominium developers use building sites near the urban center to provide commuting convenience to the urban center, which is an important housing requirement.

### Table 2. Annual Variation in the Supply of Condominiums in the Central District from 1999 to 2006

| Year | One-room type unit | Family type unit | Total | Number of Dwelling Units | GFA (m$^2$) | Average GFA per unit (m$^2$/unit) |
|------|-------------------|------------------|-------|--------------------------|------------|-------------------------------|
| 1999 | 170               | 56               | 226   | 170                      | 1406       | 866                           |
| 2000 | 18                | 1                | 20    | 18                       | 987        | 946                           |
| 2001 | 22                | 5                | 27    | 22                       | 1359       | 1291                          |
| 2002 | 27                | 5                | 32    | 27                       | 1536       | 1592                          |
| 2003 | 25                | 2                | 27    | 25                       | 1718       | 154660                        |
| 2004 | 19                | 3                | 22    | 19                       | 1039       | 90670                         |
| 2005 | 20                | 9                | 29    | 20                       | 1117       | 75219                         |
| 2006 | 20                | 2                | 23    | 20                       | 957        | 78302                         |
| Total| 170               | 56               | 226   | 170                      | 1406       | 866                           |
emissions is illustrated in Fig.5. A concentric circle urban model is established, setting Karasuma-Shijo as the urban center. The inner circle represents Kyoto's central district, and the outside circle indicates the fringe district. The urban center contains maximum employment, goods, and services. Residents of the newly built condominiums are assumed to work and shop in the urban center.

Two kinds of condominium distribution are established according to the surveys: a "compact distribution," referring to the modern situation of condominiums located in the central district; and a "sprawling distribution," based on a survey of condominium distribution before 1999 (see subsection 2.2). Under a compact distribution, all condominiums are located in the central district; the numbers are gathered from the survey. Under a sprawling distribution, some condominiums are located in the fringe district; the numbers are calculated using the ratio of condominiums located in the central and fringe districts, as is shown in Table 2. For example, a total of 38 condominiums were built in Kyoto in 1999: 18 in the central district and 20 in the fringe district. Before 1999, only 29.6% of condominiums were located in the central district, which meant 11 in the central district and 27 in the

![Fig.4. Locations of Condominiums Built in the Central District of Kyoto from 1999 to 2006](image)

![Fig.5. Estimation Model](image)
fringe district. Only the former 18 condominiums are investigated in this study, so calculations could only be made on them. Therefore, under a sprawling distribution, among the 18 newly built condominiums, 11 would be located in the central district and the remaining seven in the fringe district. Under the conditions in 2000, the number of condominiums would have a distribution of 14 in the central district and four in the fringe district. The numbers of condominiums that are located in the central and fringe districts are calculated according to a sprawling distribution, and are presented in Fig. 5 and Table 4.

3.2 Settings for estimates

3.2.1 Settings for average LCCO$_2$ and ELCO$_2$

The life cycle CO$_2$ emission from a condominium constructed of steel-framed reinforced concrete (SRC apartment) is 17.1 kg-C/yr/m$^2$ (see Institute for Building Environment and Energy Conservation, 2002, p. 58). The average LCCO$_2$ of the dwelling unit supplied each year is calculated according to the average area. For example, the average floor area of family units supplied in 1999 was 91.7 m$^2$ (refer to Table 2), the average LCCO$_2$ of the dwelling unit was 1568 kg-C/yr [17.1 kg-C/yr/m$^2$ × 91.7 m$^2$ = 1568 kg-C/yr]. The average CO$_2$ emission resulting from household electric power consumption is used as the average ELCO$_2$. For a household of four family members, ELCO$_2$ is 545 kg-C/yr, and for the one-person household the value is 297 kg-C/yr$^3$.

3.2.2 Calculation of CTCO$_2$

CTCO$_2$, in this study is considered as the CO$_2$ emission from the residents’ personal trips to the urban center for work or for personal reasons. Under both distributions, the number of condominiums is identical; only the numbers in the central versus fringe districts differ. Estimates of CTCO$_2$ focused on CO$_2$ emissions from residents’ personal trips to the urban center for work and other personal reasons.

The CTCO$_2$ (Tt) is calculated through the following formula (1):

$Tt = \sum u_i (\sum (Nc \cdot rc \cdot Dc:\sum (Np \cdot rp \cdot Dp)) \div Pt$ (1)

where $i$ is a mode of transportation (train, bus, car, moped), $u_i$ is the energy consumption of the mode of transportation $i$ (kg-C/km), $Nc$ is the number of trips taken for work, $rc$ is the percentage of trips for work using transportation $i$, $Dc$ is the distance of trips for work using transportation $i$ (km), $Np$ is the number of trips taken for personal reasons, $rp$ is the percentage of trips taken for personal reasons using transportation $i$, $Dp$ is the distance of trips taken for personal reasons using transportation $i$ (km), and $Pt$ is the number of households.

Reductions in CO$_2$ emissions have been estimated in most similar studies based on the compaction of a city using the shortened trip distance. However, as a matter of fact, residents in the central district use different modes of transportation from residents in the fringe district. The calculation of reduced CO$_2$ emissions should include changes in both trip distance and mode of transportation.

Condominiums are assumed to be fully occupied, so the total number of residents was identical in both cases: 10,113 households. For households composed of more than two family members, one member is assumed to travel to the urban center for work (five days a week), and another one is assumed to travel to the urban center for shopping or amusement (three days a week). For a one-person household, that person is assumed to travel to work five days each week. Therefore, trips to work total 10,113 per day, and the number of trips for personal reasons is determined by the supplied number of one-room units.

Under a compact distribution, trips to the urban center are from within the central district, while under a sprawling distribution, some are from the fringe district. The numbers are determined by condominium distribution, as shown in Table 4.

Table 4. Settings for the Number of Trips and Trip Distances Used in Estimates

| Compact distribution | Sprawling distribution |
|----------------------|------------------------|
| Number of condominiums (see Table 3) | Number of trips (trips/day) | Number of trips (trips/day) | Number of trips for work (trips/day) | Number of trips for work (trips/day) | Number of trips for personal reasons (trips/day) | Number of trips for personal reasons (trips/day) | Number of trips for personal reasons (trips/day) |
| 1999 | 18 | 1406 | 520 | 11 | 859 | 318 | 202 |
| 2000 | 18 | 987 | 563 | 14 | 768 | 438 | 4 | 219 | 125 |
| 2001 | 28 | 1359 | 592 | 12 | 741 | 323 | 10 | 618 | 269 |
| 2002 | 28 | 1536 | 775 | 14 | 768 | 387 | 14 | 768 | 387 |
| 2003 | 25 | 1718 | 955 | 11 | 756 | 420 | 14 | 962 | 535 |
| 2004 | 19 | 1039 | 523 | 10 | 547 | 275 | 9 | 492 | 248 |
| 2005 | 20 | 1117 | 410 | 8 | 447 | 164 | 12 | 670 | 246 |
| 2006 | 20 | 957 | 457 | 9 | 431 | 243 | 11 | 526 | 287 |
| Total | 170 | 1011 | 4876 | 89 | 5316 | 2568 | 81 | 4803 | 2309 |

Trip distance: From condominium to urban center

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Conference of the Osaka Metropolitan District). It is clearly indicated by the results of this survey that in Kyoto, fewer trips are taken using public transit (trains and buses) from within the central district than from the fringe district. Automobile dependence is also lower, and trips on foot have increased. Commuters in the central district are far more likely to travel by moped, a common mode of transportation in Kyoto (Fig.6.).

Fig. 6. Percentage of Trips Taken Via Various Modes of Transportation from each District to the Urban Center (Calculated by the Author Based on Data from the 2000 Osaka Metropolitan 4th Personal Trip Survey)

All the above data are incorporated into the calculations. In addition, any resident of the 14 condominiums that are located less than 400 m from the urban center (see Table 3.) is assumed to always travel to work or shop on foot. Any resident of the two condominiums that are located more than 1000 m from the nearest train station is assumed to always travel to work or shop by car.

3.2.3 Degree of compaction

Sum of the above CO₂ emission is the average HACO₂ of the entire households (aHC). To clarify the effects of reduction in average HACO₂ during 1999-2006, the reduction rate of HACO₂ (Rr) each year is calculated using the following formula (2). Positive value of Rr means that the city is turning to a compact form, and Rr value itself is considered to show the degree of compaction.

\[
Rr = 1 - \frac{aHC_{compact}}{aHC_{sprawl}}
\]

Where \( Rr \) represents the reduction rate of average HACO₂ under the compact distribution to that under the sprawling distribution; \( aHC_{compact} \) represents average HACO₂ under the compact distribution (kg-C/yr); \( aHC_{sprawl} \) represents average HACO₂ under the sprawling distribution (kg-C/yr).

3.3 Results of estimates

As is stated in subsection 2.2, increasing numbers of condominiums were built in the central district during the study period. The difference in CTCO₂ between the sprawl and compact distributions showed an upward trend from 1999 to 2006 (see Table 5. and Fig.7.). This indicates a reduction in CO₂ emissions from personal trips to the urban center over the study period compared with the conventional sprawl distribution. The value of \( R \) decreased from 1999 to 2000 because in 2000, the central district contained fewer condominiums than the fringe district. However, it increased steadily from 2000 to 2003 because the ratio of condominiums being built in the central district increased during this period. A decline appeared in data for 2004, but the value rose again by 2005.

Under a compact distribution, the average CO₂ emission from trips to the urban center is 11.1 kg-C per year; the average under a sprawl distribution is 45.7 kg-C per year, about four times greater. The difference between the two conditions is about 34.6 kg-C. If the reduction in CTCO₂ can be used to enlarge the dwelling's floor area, 34.6 kg-C/yr equals the gross floor area of 2.0 m² in a SRC apartment \([34.6(\text{kg-C/yr})/17.1 (\text{kg-C/yr}m²) = 2.0 m²]\). For the total supply of condominiums in the central district from 1999 to 2006, the total reduction in CO₂ emissions was approximately \(3.5*10^5 \) kg-C/yr, equal to a supply of \(2.0*10^4 m²\) for a SRC apartment. If a satisfactory GFA for a family unit is 100 m², the reduction in CO₂ emissions can be applied to supply an additional 200 dwelling units for families who want to move to the central district of Kyoto city \([3.5*10^5(\text{kg-C/yr})/100(\text{m}²)/17.1 (\text{kg-C/yr} m²) = 204]\).

Average HACO₂ under compact (aHC\(_{\text{compact}}\)) and sprawling distribution (aHC\(_{\text{sprawl}}\)) and the reduction rate (Rr) are also shown in this table. Rr demonstrates an upward trend from 1999 to 2006, which shows that the degree of compaction in Kyoto city is increasing. In 2005, although there were 74.1% condominiums that were located in the central district with half consisting of the one-room units, the reduction in CTCO₂ was not so high, so that Rr in 2005 was not the highest. Correspondingly, because in 2006, only 10% of units were considered to supply for one-person households, the Rr value was higher than that in 2005. The value changes with the ratio of condominiums that are located in the central district compared to the total. In the years that the ratio is high, and the supply of condominiums for households with more

![Fig.7. Average CTCO₂ in Compact Distribution (Modern) and in Sprawling Distribution (Pre-1999) and the Reduction Rate in Average HACO₂ from 1999 to 2006](image-url)
than two family members is large (such as in 2003 and 2006) the reduction rate is also high. The average reduction rate is about 1.8%. That is to say, the average HACO$_2$ of housing supply after 1999 was 1.8% lower than the conventional housing supply before 1999. Compact housing arrangement, which shortens the travel distance and changes the transportation modes of residents, is useful in achieving the reduction target within the city.

4. Conclusions

It is discovered in this study that the supply of new condominiums within the central district of Kyoto has been increasing faster than that in the fringe districts in recent years. It is indicated by this housing distribution that the process of compaction is taking place in Kyoto. From 1999 to 2006, 170 condominiums were built in Kyoto’s central district, supplying more than 10,000 units, which was an important factor in the population recovery within this area. Most of these condominiums are located less than 1000 m from a train station, and within walking distance. The condominiums also tend to be built around the urban center. Commuting convenience is an important influence on location.

Cases in which these condominiums are located in a compact (modern) or sprawling (pre-1999) distribution are compared to estimate the difference between the CO$_2$ emission during residents’ trips to the urban center. The calculation is based on the estimate models within which all the residents of the condominiums are considered to go to work or shop in the urban center.

Compaction not only influences CO$_2$ emissions through shortened travel distance, but also changes the modes of transportation; in particular, more people switched from traveling by car to traveling on foot or by moped. It is demonstrated by the results that CO$_2$ emissions from trips to the urban center are reduced by converting the central district of Kyoto to a compact form. The quantity of reduction in average HACO$_2$ increases, indicating that the degree of compaction of Kyoto increased from 1999 to 2006. The average HACO$_2$ of modern compact housing supply was possibly 1.8% lower than that of the conventional housing supply before 1999. Compact housing arrangement, which shortens the travel distance and changes the transportation modes of residents, is useful in reducing CO$_2$ emission. It is also indicated through the calculation that the supply of dwelling units in the central district for households with more than two family members and with more emission from trips than a one-person household is more effective in reducing CO$_2$ emission in a city.

It is also indicated by the results that when the distribution changes from sprawling to compact form, each household can reduce emissions by 34.6 kg-C/yr. If reductions in CO$_2$ emissions are applied to size of dwelling, each unit could increase the GFA by 2.0 m$^2$. The total reduction in CO$_2$ emissions resulting from the supply of 170 condominiums in the central district could be applied to supply 200 units, each with a GFA of 100 m$^2$. CO$_2$ emissions will be reduced even more after these 200 households move from the fringe district to the central district and there will be potential reduction when the additional 200 households move to the central district.

The current process of compaction in the central district of Kyoto is clarified in this investigation and it can be seen from the calculations that when a city moves from a sprawling to a compact distribution, CO$_2$ emissions are reduced. Based on this study, policies of deliberate induction can be established to encourage the conversion of a city to a compact form, and may lead to housing that allows an urban renaissance and a sustainable urban environment.

The method of investigating the current conversion of Kyoto city to a compact form is developed in this study. However, the above results are performed based on some basic assumptions according to the settings of the calculation, such as that the households consist of four persons or one person, and all the personal trips are to the urban center. The issue becomes far more complicated when households have complex social activities. It is unlikely that in the real world all households will have such capacity. Further researches should involve households with various attributions and capabilities.

Notes

1. Compared with the data of censuses in Oct. 2005 and Oct. 2000, the administrative wards with a positive growth rate of population were Nakagyo-ku (7.5%), Shimogyo-ku (5.9%) and Minami-ku (0.4%).
2. The general characteristics of the Alonso Model: all employment, goods, and services are available only at the city center. Land can be bought and sold by free contract, without any institutional restraints and without having its character fixed by any existing ground structure (William Alonso, 1964).
The apartment lists were mainly from: "Old apartment specialty store-Akira", website available at http://www.e-akira.jp/index.shtm; "Condominium apartment information of Kyoto city" website available at http://kyoto-net.co.jp/mansion/index.htm and the website of Hokosetsu Company Ltd. available at http://www.hokusetsu-home.com/annai.htm

The PC map software "Digital Atlas Z Series" developed by ZENRIN CO., LTD.

The increase in number of households from April 1999 to March 2005 refers to the data of a census in Oct. 2005. The number from April 2005 to March 2006 referred to the local resident registration at the city hall.

CO₂ emission from households' Electric power consumption with different number of families (METOCLEAN Environment Inc., 2004)* used in this study.

Energy consumption units of vehicles are as follows: Train: 104 kcal/km/person; regular route bus: 334 kcal/km/person; Car: 658 kcal/km/km/person; Moped: 105 kcal/km/person (pp. 99, Matsuhashi, 2000); Emission unit of gasoline is 0.0183kg-C/MJ (Agency of resource and energy, 2002)

References
1) Agency of resource and energy, Environmental ministry (2002) Reform in standard calorific value chart of specific energy source.
2) General Planning Bureau of Kyoto city (2005). 京都市の住民基本台帳による人口。
3) Goto T., Takada M., Yasueda H. and Nishikawa K., (2006) The change of housing construction in the center of Kyoto city by using GIS, Summaries of Technical Papers of Annual Meeting, AIJ, F-1:811-812.
4) Institute for Building Environment and Energy Conservation (2002) Handbook of houses and buildings' energy saving 2002.
5) Matsuhashi K. (2000) A study on the compact city in view of regional trip energy in the Osaka Metropolitan area, The city planning Institute of Japan, Papers on City Planning, No. 35, pp.469-474.
6) METOCLEAN Environment Inc (2004). 世帯人数別のCO₂排出量の推定。 Website available at http://www.metoclean.co.jp/new/eco_report/ecolife/value.htm
7) Suzuki T. (2001)「持続可能な都市形態としてのコンパクトシティ論」, 特集：地球温暖化とまちづくり, 『都市計画』, No.232: 11-14.
8) Tang P., Munemoto J. and Matsushita D. (2005) Housing Arrangements in Pursuit of Maximum GFA Under CO₂ Emission Constraint. Journal of Asian Architecture and Building Engineering, Vol. 4, No. 2 pp.355-360.
9) Tang P., and Munemoto J. (2007) Household Behavior Selections under CO₂ Emission Constraint. Journal of Asian Architecture and Building Engineering, Vol. 6, No. 1 pp.87-94.
10) Traffic planning conference of the Osaka metropolitan district (2000) Summary table of the 4th Personal Trip Survey in Osaka metropolitan district, website available at: http://www.kkr.mlit.go.jp/plan/persontrip/data/data.html
11) William Alonso, (1964) Location and Land Use – Toward a General Theory of Land Rent, Harvard University Press, Cambridge, Massachusetts.