Evaluating Compactness of Cities by Energy Consumption Efficiency

Abstract: We present a micro-economic based quantitative analysis scheme to evaluate the energy consumption efficiency of cities considering 1) the utility theory based on transportation and composite goods consumption behavior, and 2) a consistency between the level of utility and energy consumption. By representing the level of quality of life by utility, this study develops a CES-based model to estimate the actual and minimum individual energy consumption for present utility. Estimated actual and optimal energy consumption efficiency are introduced to analyze the energy consumption efficiency. We applied this model to Kumamoto and Nagasaki region and found higher energy consumption efficiency in Nagasaki which has more compact city structure and mass-transit usage. Zones with higher energy consumption efficiency are mainly located in city center and along mass-transit lines in both regions. Such findings suggest that compact urban structure and higher mass-transit usage can induce greater urban energy consumption efficiency.

Key Words: quality of life, energy consumption efficiency, compact city

1. INTRODUCTION

Our research attempts to analyze the compact city and urban sustainability from the view of energy consumption based on two reasons. Firstly, from the physical point, compact urban spatial configuration affects the total amount of energy consumption. Secondly, density and intensity of activities, such as traffic, are major factors influencing energy consumption. Furthermore, growing concerns about urging oil prices and greenhouse gases produced by burning fossil fuels require the urban development to minimize the usage of resources, spatial displacement of environment and improve energy consumption efficiency (Burgess, 2000; Williams, 1999). Consequently, energy consumption has become a major concern of urban sustainable development. The amount of energy consumption is very important and effective index to evaluate the sustainable development of cities.

At present, there are two main methods to study the energy consumption in urban area. One is statistical analysis of the relationship between energy consumption and some indicators of urban characteristics, such as population density, trip, land-use type et al. The famous research by Newman et al. (1999) which represents a relation between population density and gasoline consumption in worldwide major mega-cities, is one example of these discussions (Holden et al., 2005; Lu et al., 2008; Musti et al., 2010). The effect of policy scenarios on energy consumption is also analyzed (Pascal, 2008; Verhoef, 2005). In recent years, modeling approaches that address energy use and air pollution are becoming hot research points(Affuma et al., 2003; Sadownik et al., 2001; Mario et al., 2009, Koen et al., 2008, Yoshitsugu et al., 2006, Fong et al., 2009). These researches are focused on forecasting pollution from traffic, constructing regression models and indicators that relate urban form to energy consumption. Several integrated land-use and transportation models also have been
developed (e.g. TRAUNS). This kind of method requires extensive data for inputs and calibration, and is difficult to relate to the processes to the output. Some models are so sophisticated that being conceived as forecasting rather than exploratory tools for policy evaluation.

From a macro-view, energy consumption is closely related to actual land-use and transportation. Importantly, it affects the quality of life from the individual viewpoint. Aoyama et al. (2006) proposed a micro-economic model to seek a representative consumer’s traffic pattern that minimizes energy consumption while keeping the present mobility level. He also investigated the urban structures and transportation policies in order to realize such traffic pattern. It is a good try to solve the energy consumption problem based on the individual mobility through some kind of micro-economic model. However, his research limits to personal mobility. How to estimate and achieve the minimum energy consumption without declining the level of quality of life will no doubt be more helpful in urban sustainable development. This is the main aim of this study.

Four sections are included in this paper. In the section 2, we show the development of a model to estimate the minimum energy consumption. In section 3, we apply this model to Kumamoto and Nagasaki regions in Japan, to analyze energy consumption and energy consumption efficiency. The section 4 presents conclusion and discussion.

2. METHODOLOGY

2.1 Model Framework

Based on economics theory, quality of life can be measured by utility. People are assumed to maximize the utility to achieve the present level of quality of life. Maximum utility is achieved by consuming various kinds of goods, like food, clothes, house, trips et al. Consuming goods is also actually a process of energy consumption. So the problem becomes to how to estimate the corresponding amount of consumed goods that minimizing energy consumption and maximizing the utility at the same time. Then how much the minimum energy consumption should be?

Some assumptions are needed in order to formulate the model.

1. As transportation sector is a bigger contributor to energy consumption, we classified all goods into two types: mobility goods and composite goods. Mobility goods include car trips and mass-transit trips. Composite goods are all other goods except mobility goods. We assume that the representative consumer in zone \( i \) consumes three types of goods: composite goods and trips by car and mass-transit. The demands are shown as \( x_{i1} \), \( x_{i2} \) and \( x_{i3} \), respectively.

2. The mobility level \( x_{i2} \) is a function of the number of trips by car \( x_{i2c} \), and trips by mass-transit \( x_{i2m} \).

3. Utility \( u_i \), which reflects the level of quality of life, is defined as a function of these three kinds of goods.

4. Representative consumer in zone \( i \) is assumed to maximize his/her utility and mobility by consuming different amount of goods under the income budget constraint.

5. All the income is spent on consuming goods without saving.
Based on the assumptions, we developed our model framework shown as Equation (1). We would like to explore activities that minimize the energy consumption $E_i$ on the maximum utility level $u'_i$.

$$
\min_{\{x_i,t_{2Ci},t_{2Mi}\}}\ E = \sum_i E_i = \sum_i \left( e_i x_{i1} + e_{2i} t_{2Ci} (x_{2Ci}, x_{2Mi}) x_{2Ci} + e_{3i} t_{2Mi} (x_{2Ci}, x_{2Mi}) x_{2Mi} \right)
$$

$$
s.t. \ u_i(x_{i1}, x_{2Ci}, x_{2Mi}) = u'_i, \forall i \tag{1}
$$

Where, the total energy consumption $E$ is a multi-objective function of $E_i$, which means average individual dairy energy consumption in zone $i$. $e_i, e_{2i}, e_{3i}$ are energy consumption unit of each good. $t_{2Ci}, t_{2Mi}$ are average time of each car trip and mass-transit trip, which are functions of car and mass-transit trips.

### 2.2 Definition of Utility Function

How to express the utility function is very important. First, we assume that there is a substitutive relation between the number of car trips and mass-transit trips. The mobility level can be defined as a function of them. Meanwhile, a substitution relationship also exists between the amount of composite goods and mobility consumption. For representing these two kinds of relationships, two stage nested type CES (Constant Elasticity of Substitution) function is used (Yoshitsugu et al., 2006). The structure is shown in Figure 1. CES function is chosen as the utility function because it has many merits, such as easy to represent actual consumers’ choice behavior, different values of elasticity of substitution can be assumed, functional form is convenient to handle, not difficult to calibrate unknown parameters and so on. The actual functional form of utility and mobility is expressed as Equation (2) and (3).

![Figure 1 Structure of nested type utility function](image)

$$
\begin{align*}
    & u_i(x_{i1}, x_{2i}) = \left( \alpha_1 x_{i1}^{(\sigma_1-1)/\sigma_1} + \alpha_2 x_{2i}^{(\sigma_2-1)/\sigma_2} \right)^{\sigma_1/(\sigma_1-1)} \\
    & x_{2i} (x_{2Ci}, x_{2Mi}) = \left( \alpha_{2C} x_{2Ci}^{(\sigma_2-1)/\sigma_2} + \alpha_{2M} x_{2Mi}^{(\sigma_2-1)/\sigma_2} \right)^{\sigma_2/(\sigma_2-1)}
\end{align*}
$$

$\sigma_1$ and $\sigma_2$ are the elasticity of substitution between two goods at the first and second stage respectively. $\alpha_1$ and $\alpha_2$, $\alpha_{2C}$ and $\alpha_{2M}$ are allocation parameters for composite and mobility goods, car trips and mass-transit trips respectively.

### 2.3 Present Utility Level

It is assumed that people would like to maximize not only utility, but also the mobility. The present utility level is achieved by maximizing utility with the constraint of income. The following procedure is introduced to calculate the present utility level. At first, the model
choice behavior at the second stage is formulated by maximizing mobility level subject to transportation budget constraint, Equation (4). Revealed mobility level is defined as maximum mobility level, which is determined by the number of trips by car and mass-transit.

\[
\max_{x_{2i}, x_{2i}} \Phi_{2i} = \left\{ \alpha_{2c} \Phi_{2i}^{c,x_{2i}} + \alpha_{2m} \Phi_{2i}^{m,x_{2i}} \right\}^{e_{2i}^{(x_{2i})}}
\]

\[\text{s.t. } p_{2c} x_{2i} + p_{2m} x_{2i} \leq I_{2i}\]

where \( p_{2c} \) and \( p_{2m} \) are the average cost (Yen/trip・day, Yen is the unit of Japanese currency) of car and mass-transit trips generated from zone \( i \), respectively. \( I_{2i} \) is the budget which individual consumer can pay for transportation service.

\( x_{2i}^* \) are the optimal solutions of the number of trips by mode \( M \) (car or mass-transit), and \( x_{2i}^* \) is the revealed mobility level, shown in Equation (5), (6), respectively.

\[
x_{2i}^* = \left( \frac{\alpha_{2m}}{p_{2m}} \right) \frac{I_{2i}}{\alpha_{2c} p_{2c}^{\alpha_{2c}} + \alpha_{2m} p_{2m}^{\alpha_{2m}}} \]

\[
x_{2i}^* = \left( \frac{\alpha_{2c}}{p_{2c}} \right) \frac{I_{2i}}{\alpha_{2c} p_{2c}^{\alpha_{2c}} + \alpha_{2m} p_{2m}^{\alpha_{2m}}} \]

Utility maximization problem subject to income constraint is shown in Equation (7).

\[
\max_{x_{1i}, x_{2i}} u_{i} = \left\{ \alpha_{1i} x_{1i}^{e_{1i}^{(x_{1i})}} + \alpha_{2i} x_{2i}^{e_{2i}^{(x_{2i})}} \right\}^{e_{2i}^{(x_{2i})}}
\]

\[\text{s.t. } p_{1i} x_{1i} + p_{2i} x_{2i} \leq I_{i}\]

\( p_{1i} \) and \( p_{2i} \) are the price of composite goods and mobility goods. \( I_{i} \) is income of a representative consumer who lives in zone \( i \). Here the price of composite goods \( p_{1i} \) is set to 1.

\( x_{1i}^* \) is the optimal solution of amount of composite goods. \( x_{2i}^* \) is the revealed mobility level which is satisfied with the optimization problem at the second stage. The demand function of the composite goods and revealed mobility level are written analytically as the solution of the utility maximization problem as Equation (8).

\[
x_{1i}^* = \left( \frac{\alpha_{1i}}{p_{1i}} \right) \frac{I_{2i}}{\alpha_{1c} p_{1c}^{\alpha_{1c}} + \alpha_{1m} p_{1m}^{\alpha_{1m}}} \]

From Equations (5), (6) and (8), the optimal number of trips in zone \( i \) by car and mass-transit can be calculated as Equation (9). Substituting (8), (9) into utility function, the present utility level \( u_{i}^* \), can be obtained.

\[
x_{2i}^* = \left( \frac{\alpha_{2m}}{p_{2m}} \right) \frac{I_{2i}}{\alpha_{2c} p_{2c}^{\alpha_{2c}} + \alpha_{2m} p_{2m}^{\alpha_{2m}}} \]

\[
2.4 \text{ Energy consumption efficiency Index}
\]

As a close relationship existing between energy consumption and utility, we analyze not only the absolute amount of energy consumption \( E_{i} \), but also energy consumption efficiency. In this paper, two kinds of energy consumption efficiency indexes are introduced: estimated actual \( UE_{i} \) and estimated optimal \( UE_{i}^* \), which are shown in Equation (10), (11). Weighted index of energy consumption efficiency, \( UE_{i} \) and \( UE_{i}^* \), are applied to reflect the regional actual and optimal energy consumption efficiency level, shown in (12) and (13). Where \( u_{i}^* \) is
the maximum utility, also the actual utility level, $E_i$ is the estimated actual energy consumption and $E'_i$ is the minimum energy consumption. $P_i$ is the population in zone $i$.

$$UE_i = \frac{u_i}{E_i}$$  \hspace{1cm} (10)

$$UE'_i = \frac{u_i}{E'_i}$$  \hspace{1cm} (11)

$$UE = \frac{\sum UE_i \cdot P_i}{\sum P_i}$$  \hspace{1cm} (12)

$$UE' = \frac{\sum UE'_i \cdot P_i}{\sum P_i}$$  \hspace{1cm} (13)

3. APPLICATION TO KUMAMOTO AND NAGASAKI METROPOLITAN REGIONS

3.1 Study Area

We chose Kumamoto and Nagasaki metropolitan regions for our study. Both regions are located in Kyusyu island in south of Japan. Kumamoto is a little bigger region, with a population of 970,380 in 1997, compared to 726,112 in Nagasaki’s in 1996. Two cities (Kumamoto and Uto), fourteen towns and one village are in Kumamoto metropolitan region, and the core city is Kumamoto city with a population of 0.67 million and area 267 km$^2$. Nagasaki metropolitan region covers three cities (Nagasaki, Isahara, Omura) and four towns. Nagasaki city is the center city with population of 0.44 million and area 241 km$^2$ (Figure 2).

![Kumamoto and Nagasaki metropolitan region](image)

Figure 2 Kumamoto and Nagasaki metropolitan region

![Population, area and population density of DID](image)

Figure 3 Population, area and population density of DID
According to the Japan Statistics Bureau and Statistics Center, a densely populated district (DID), is defined as a district that has a population density over 4,000 inhabitants per square kilometer and a combined population of more than 5,000. With the tendency of urbanization and the flow of population into major urban spheres, it is projected that the population and area of DIDs will continue to grow up, although at a progressively slow pace in developed countries. The phenomenon is also taken place in Kumamoto and Nagasaki regions, where consistently increasing population of DID, the area of DIDs, and yearly decreasing population density of DIDs, are shown in Figure 3. Both regions are proceeding a process of urban growth and urban sprawl. However, compared two regions, Nagasaki regions shows a slow speed of urban sprawl and seems remaining a relatively more compact urban structure than Kumamoto from the viewpoint of smaller DID area and high population density in city center.

3.2 Data
We apply this model to Kumamoto and Nagasaki at almost same time period, in 1997 and 1996, when person trip surveys were conducted. The Kumamoto metropolitan region consist of 177 traffic analysis zones and 88 traffic analysis zones are included in Nagasaki metropolitan region. The trip data used in this paper are from Kumamoto Personal Trip Survey (PTS) 1997, Nagasaki PTS 1996, supplied by Kumamoto Metropolitan Regional Urban Transport Planning and Consultation Organization, Nagasaki Metropolitan Regional Urban Transport Planning and Consultation Organization. Some basic information about the PTS is shown in Table 1. Residents in Kumamoto are more car-dependence and travel far than the ones in Nagasaki. It can be shown as higher car ownership rate, more average car trips and longer trip length. In Nagasaki, fewer trips are generated each day, and the percentage of trips by mass-transit, including railway, light subway, bus, is the relatively higher.

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>Population</td>
<td>970,380</td>
<td>726,112</td>
</tr>
<tr>
<td>Car ownership rate(vehicle/1000 person)</td>
<td>569</td>
<td>442</td>
</tr>
<tr>
<td>Average trips (one day/person)</td>
<td>2.47</td>
<td>2.38</td>
</tr>
<tr>
<td>Average trip length (km/trip)</td>
<td>6.81</td>
<td>2.66</td>
</tr>
<tr>
<td>Average car trips (one day/person)</td>
<td>1.44</td>
<td>0.94</td>
</tr>
<tr>
<td>Average mass-transit trips (one day/person)</td>
<td>0.18</td>
<td>0.33</td>
</tr>
<tr>
<td>Other mode trips(one day/person)</td>
<td>0.85</td>
<td>1.11</td>
</tr>
<tr>
<td>Mass-transit trip share</td>
<td>7.29%</td>
<td>13.87%</td>
</tr>
</tbody>
</table>

In order to estimate the model and investigate the individual energy consumption in each zone, many kinds of data are needed. Following will explain the way how to collect and make needed dataset.

● Number of trips by car and mass-transit (trips/person·day)
These data are aggregated from original dataset of Personal Trip Survey. We focus on only the trip purpose of commute, business, shopping and returning home trips.

● Average travel time by car and mass-transit from zone $i$ to every other zones
The data is obtained by the average of travel time between OD’s weighted by the number of trips, respectively. Travel time by car and mass-transit is estimated by trip assignment results of road and mass-transit networks.
Generalized cost by car and mass-transit and price of each trip

The generalized cost consists of two kinds of cost here. One is the time cost, which is the result of multiplying time value and trip time. According to statistical report from Japanese Road Bureau, Ministry of Land, Infrastructure and Transport, the time value used in this paper is as follows: for car trip, $\omega_{C,1996,1997}=38.11$ (Yen/min·person), for mass-transit trip, $\omega_{M,1996,1997}=40$ (Yen/min·person). The time cost of each car trip and mass-transit trip in zone $i$ is defined as the average time cost of all trips in zone $i$. The other kind of cost is money cost, the price of each trip. We can get the running fee unit (Yen/km·vehicle) data from statistical report by Japanese Road Bureau, Ministry of Land, Infrastructure and Transport, considering only the fees related to running distance, including oil, tyre, tube, maintenance, vehicle depreciation. We transfer this data to our car trip price $p_{2Cij}$ as this way: $p_{2Cij}$ (Yen/trip) = (running fee unit (Yen/km·vehicle) * minimum distance from zone $i$ to $j$ (km) / average passengers (trips/vehicle). The number of passengers in each car is set to 1.21 according to the report. $p_{2Cij}$ is calculated as the average of $p_{2Cij}$ weighted by zone trips, same as the price of mass-transit trips price.

Income $I_i$ (Yen/person·day)

It is difficult to obtain the zonal income data since only the total income in each town and city is available from Kumamoto Prefecture Government and Nagasaki Prefectural Government. As a positive relationship observed from land price and income level, we distribute the total income among zones according to the zonal price ratio of land confronting major roads and railway, given the land price data by Japanese National Tax Agency.

Energy consumption unit $e_1, e_2, e_3$

The composite goods energy consumption unit $e_1$ (kcal/Yen) is calculated as the result of dividing the all energy each household consumed (kcal/household·month) by the household monthly expenditures except the transport fee, given by Japanese Statistics Bureau of Ministry of Internal Affairs and Communications and EDMC (Handbook of Energy & Economic Statistics in Japan). Car trip and mass-transit trip energy consumption unit $e_2, e_3$ (kcal/trip·min) have relationship not only with the running distance, but also with speed. Bigger energy consumption unit are associated with higher speed, running longer distance in limited time. Here we transfer the trip distance energy consumption unit (kcal/trip·km), which is available from statistical report by Japanese Road Bureau, Ministry of Land, Infrastructure and Transport, to trip time energy consumption (kcal/trip·min). Having the data of weighted average speed (km/min) of all trips, the result of $e_2, e_3$ can be calculated and are listed in Table 2. Similar energy consumption unit for composite good are found in two regions. Nagasaki shows bigger energy unit for car trips and mass-transit trips.

<table>
<thead>
<tr>
<th>Table 2 Energy consumption unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car trip $e_2$ (kcal/trip·min)</td>
</tr>
<tr>
<td>Mt trip $e_3$ (kcal/trip·min)</td>
</tr>
</tbody>
</table>

3.3 Procedure of estimating minimum energy consumption

We estimate the minimum energy consumption according to the procedure based on the demand forecasting stepwise as shown in Figure 3. The procedure is as follows:

Step 1: As the numbers of car and mass-transit trips by zone can be calculated from mobility maximization process, so the present utility level can be evaluated by Equation (3).
Step 2: By using the evaluation model, which minimizes energy consumption for present utility level, we can calculate the corresponding amount of three kinds of goods: trips by car \( x_{2c} \), trips by mass-transit \( x_{2m} \), and composite goods \( x_i \).

Step 3: The number of trips \( x_{2c} \) and \( x_{2m} \), given by step 2, is distributed to the number of OD trips by mode using a destination choice model which will be mentioned later.

Step 4: An assignment of OD trips by car is done by using user equilibrium assignment model and the OD trips by mass-transit is assigned to transit network using a kind of stochastic assignment model respectively.

Step 5: After network assignments, we solve the model again with a renewed costs, \( p_{2c} \), \( p_{2m} \), and travel time, \( t_{2c} \), \( t_{2m} \).

Step 6: The above steps are continued until \( x_i \), \( x_{2c} \) and \( x_{2m} \) converge.

In order to distribute the number of trips to each zone by mode, we introduced a destination choice model. An aggregated logit-type model is used with three variables: center zone dummy (takes the value 1 for center zone and 0 in other cases), job population, general cost (generalized cost from zone \( i \) to zone \( j \) via car or mass-transit). The related parameter estimates are shown in Table 3. The signs of all parameters of Kumamoto 1997 model and Nagasaki 1996 model are logical and all the values of parameters are statistically significant.

**Table 3 Estimates of destination choice model**

<table>
<thead>
<tr>
<th></th>
<th>Car parameters</th>
<th>Car T-statistics</th>
<th>( R^2 )</th>
<th>Mass-transit parameters</th>
<th>Mass-transit T-statistics</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Kumamoto</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Center zone dummy</td>
<td>-0.04</td>
<td>-1.99</td>
<td></td>
<td>0.09</td>
<td>4.24</td>
<td></td>
</tr>
<tr>
<td>Job population</td>
<td>1.95×10^{-3}</td>
<td>19.54</td>
<td>0.44</td>
<td>2.99×10^{-3}</td>
<td>-18.06</td>
<td>0.19</td>
</tr>
<tr>
<td>General cost</td>
<td>-1.20×10^{-3}</td>
<td>-99.38</td>
<td></td>
<td>-0.097</td>
<td>-4.24</td>
<td></td>
</tr>
<tr>
<td><strong>Nagasaki</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Center zone dummy</td>
<td>0.28</td>
<td>6.04</td>
<td></td>
<td>0.12</td>
<td>2.81</td>
<td></td>
</tr>
<tr>
<td>Job population</td>
<td>1.03×10^{-4}</td>
<td>29.31</td>
<td>0.35</td>
<td>1.1×10^{-4}</td>
<td>30.48</td>
<td>0.28</td>
</tr>
<tr>
<td>General cost</td>
<td>-1.10×10^{-3}</td>
<td>-46.06</td>
<td></td>
<td>-1.0×10^{-4}</td>
<td>-21.21</td>
<td></td>
</tr>
</tbody>
</table>
3.4 Results

a) Energy consumption

We compared the results of estimated actual and minimum energy consumption (Table 4). More than 70% of the estimated actual energy is consumed by composite goods. The actual energy share of car trips is over 20% in both regions. However, this value is a little bigger in Kumamoto, 2.37% higher than in Nagasaki. The energy share of mass-transit trips in Nagasaki is 1.69%, higher than Kumamoto (2.47% to 0.41%). There is a big reduction in estimated minimum energy consumption, more than 10% cut compared to the actual energy in both regions. It is possible to reduce 5300kcal individual dairy energy consumption in Kumamoto by decreasing 81.2% of energy consumption by car trips and increasing mass-transit trips four times. In Nagasaki, the goal of cutting 12.8% of energy consumption can be achieved by reducing 87.8% of energy for car trips and increasing energy share in composite goods and mass-transit trips by 5.7% and 175% respectively. Big energy share of composite goods (nearly 90%), relative higher energy share of mass-transit trips and reduced car trips energy share contribute to minimum energy consumption in both regions. The main attributors to achieve the minimum energy consumption goal are increasing energy share of composite goods and mass-transit trips, and decreasing energy share of car trips. Compared the estimated actual and minimum energy consumption, Nagasaki shows a smaller difference than Kumamoto, with a decreasing rate of 12.8% to 14.2% (Table 4).

<table>
<thead>
<tr>
<th>Table 4 Estimated actual and minimum individual dairy energy consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Kumamoto</strong></td>
</tr>
<tr>
<td><strong>Estimated actual</strong></td>
</tr>
<tr>
<td>Total energy consumption (kcal/person·day)</td>
</tr>
<tr>
<td>Energy for composite goods (kcal/person·day)</td>
</tr>
<tr>
<td>Energy for car trips (kcal/person·day)</td>
</tr>
<tr>
<td>Energy for mass-transit trips (kcal/person·day)</td>
</tr>
<tr>
<td>Energy share of composite goods</td>
</tr>
<tr>
<td>Energy share of car trips</td>
</tr>
<tr>
<td>Energy share of mass-transit trips</td>
</tr>
</tbody>
</table>

*Note*: the figure in () shows the increasing percentage of estimated minimum compared to estimated actual energy consumption.

b) Energy consumption efficiency

Besides absolute energy consumption, we also investigate the energy consumption efficiency for two types: estimated actual energy consumption efficiency and estimated optimal energy consumption efficiency. The larger the value of index is, the higher the energy consumption efficiency is. We describe the results based on two aspects: regional and zonal energy consumption efficiency.

First, we would like to compare the regional energy consumption efficiency. This index is explained by the value of the average individual energy consumption efficiency weighted by zonal population. The difference between estimated actual and optimal energy consumption efficiency, $\triangle U_{E^*} = U_{E} - U_{E^*}$ (estimated actual energy consumption efficiency-optimal energy consumption efficiency), is also calculated to compare the achievement level of optimal energy consumption efficiency.
From Table 5, we can find that individual utility level in Kumamoto is higher than Nagasaki. It is the same as expected since lower income level in Nagasaki with the average income 6,286 Yen/person·day compared to 8,290 Yen/person·day in Kumamoto. Thus, less energy consumption is in Nagasaki region. The actual energy consumption efficiency is higher in Nagasaki region. It is interesting to observe that Nagasaki region shows higher estimated actual energy consumption efficiency, but with lower estimated optimal energy consumption efficiency. The difference between estimated actual and optimal energy consumption efficiency, is bigger in Kumamoto (0.032 from actual to optimal energy consumption efficiency). While in Nagasaki, this value reduces to 0.028. Nagasaki region seems to be much easily to reach the goal of optimal energy consumption efficiency than Kumamoto.

<table>
<thead>
<tr>
<th></th>
<th>Kumamoto</th>
<th>Nagasaki</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated</td>
<td>Estimated</td>
<td>Estimated</td>
</tr>
<tr>
<td>Utility</td>
<td>actual</td>
<td>optimal</td>
</tr>
<tr>
<td></td>
<td>6,966</td>
<td>6,966</td>
</tr>
<tr>
<td>Total energy</td>
<td>37,276</td>
<td>31,888</td>
</tr>
<tr>
<td>consumption</td>
<td>efficiency</td>
<td>0.187</td>
</tr>
<tr>
<td>Difference</td>
<td>-0.032</td>
<td>-0.028</td>
</tr>
<tr>
<td>estimated</td>
<td>actual and</td>
<td>optimal</td>
</tr>
<tr>
<td>energy</td>
<td>efficiency</td>
<td>△UE*</td>
</tr>
</tbody>
</table>
| We also analyzed the energy consumption efficiency in different zones. Figure 4 and Figure 5 show the space distribution of estimated zonal actual energy consumption efficiency, estimated zone optimal energy consumption efficiency, network and population density in Kumamoto and Nagasaki. Although a few zones with higher estimated actual energy consumption efficiency are found in suburban or rural area, the energy consumption efficiency decreases with the distance to the city center. Zones along the mass-transit lines are higher energy efficient. For zonal estimated optimal energy consumption efficiency results, zones with higher values are mainly concentrated in the city center.
4. CONCLUSIONS

Facing the energy security issue and environmental stress, governments worldwide are making various kinds of policies to minimize the energy consumption. However individual does not like the idea of decreasing the level of quality of life as a result of energy consumption reduction. Individual desire strongly influences the feasibility and success of policies. How to solve this contraction? What is the acceptable amount of minimum energy consumption the policy should set? It is exactly the aim of our model. By estimating the minimum energy consumption based on present level of quality of life, the model estimates a minimum energy consumption value and corresponding amount of goods that balanced these two sides.

Representing the level of quality of life by utility, the present level of quality of life can be expressed by the maximum utility determined by the amount and prices of goods. Three kinds of goods: composite goods, trips by car and mass-transit, are considered. Besides the total energy consumption, we also introduced energy consumption efficiency index to compare individual energy consumption efficiency in cities which have different utility level.

By applying the model into Kumamoto and Nagasaki metropolitan region, we found that the estimated actual energy consumption efficiency is higher in Nagasaki. With higher income, higher level of quality of life (based on higher utility) is found in Kumamoto, but with even higher energy consumption. Comparing the difference between estimated actual and optimal energy consumption efficiency, greater value is in Kumamoto, which means a tougher task of improving present energy consumption efficiency to the optimal level in this region. The result is as expected as Nagasaki region shows a slow speed of urban sprawl and remains a relatively more compact urban structure from the viewpoint of smaller DID area and high population density in city center. Meanwhile less car trips and relatively higher mass-transit usage share can also attribute to the result. From the spatial distribution of estimated zone actual energy consumption efficiency results, higher energy consumption efficiency zones are mostly found in city center area and along mass-transit lines in both regions. Zones with higher estimated optimal energy consumption efficiency are mainly concentrated in the city center.

The results proved that more compact urban structure and higher mass-transit usage can
induce greater energy consumption efficiency. There are many aspects that related to compact city structure influence the energy consumption, such as population density, land-use et al. Compact city, which is usually mentioned as high density, mix land-use urban structure, does has effect on energy consumption, especially on transportation sector. So how compact city influences the individual energy consumption efficiency and what is the most influential factor? This is exactly the goal of our further research. Investigation of the relationship between energy consumption efficiency and city characteristics, such as land-use, population density, job density, mass-transit services et al., is needed. It will be very helpful to provide insight into practical and feasible approaches to reduce the required energy consumption for present level of quality of life.

The methodology of this paper is important since it gives a research framework to estimate the minimum energy consumption based on individual quality of life. Its result is valuable to give suggestions for policy making in light of current global warming, energy security and individual quality of life.

REFERENCES
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