A MODEL TO EVALUATE ENERGY EFFICIENCY FROM THE VIEWPOINT OF INDIVIDUAL QUALITY OF LIFE *

by Yanhong YIN **, Risa MURAKAMI*** and Shoshi MIZOKAMI****

1. Introduction

Expanding explosion of human activities has already given a heavy burden on the environment with warmer earth and more disasters. Climate change and energy security have received much attention and being hot topics both globally and nationally. Sustainable urban development has being a crucial element affecting the long-term outlook of humanity. Growing concerns about urging oil prices and greenhouse gases produced by burning fossil fuels require the urban development to minimize the use of resources, spatial displacement of environment and improve energy efficiency.

Energy consumption within and across urban regions has distinct spatial and urban dimension [1)]. There are many researches focus on the relationship between energy consumption and land use or urban structure. Newman first compared the energy consumption in different cities at the macro level[2)]. Recently, researchers are seeking to simulate the relationship between energy consumption and housing location choice, travel behavior of household and, to lesser extent, firms at micro level [3)4)]. Hensher [5)] developed an integrated transport-land use simulator to forecast GHG emissions from transport sector in Sydney, Australia. In the midst of such researches, estimation of individual current and minimum energy consumption via travel , residential location and consumption behavior change will no doubt be helpful in crafting local, regional policies to address climate change and energy security.

This study attempts to better understand the relationship between energy consumption, individual quality of life and urban structure. A model was developed to estimate the real and minimum energy consumption on maximum individual utility level. The reminder of this paper is organized as follows. In section 2, a description is given of the model development and framework. Section 3 describes case studies and discussion of the results. Section 4 ended with conclusions.

2. Model development

(1) Basic description of model

According to economics theory, quality of life can be reflected by the utility, which is determined by the consumed goods. There are two kinds of goods included in this research: mobility good and composite good. Since transportation sector is a big attributor of energy consumption, mobility good, which includes car trips and Mass Transit trips (MT trips), is analyzed. Composite good is all other goods except mobility good, such as housing heating, food, clothes and so on.

Generally speaking, more consumed goods mean higher utility level, and thus higher quality of life. In reality, people would like to choose different kinds of goods to achieve the maximum utility level within limited income. Consuming goods means energy consumption, our model tries exactly to find optimal amount of different kinds of goods and corresponding minimum energy consumption based on maximum utility level. The model structure is shown by (1).

$$\begin{aligned} \min_{\{x_{1i},x_{2Ci},x_{2Mi}\}} \quad & E=\sum_i E_i=\sum_i \left(e_1 x_{1i}+e_2 t_{2Ci} x_{2Ci}+e_3 t_{2Mi} x_{2Mi}\right) \\ s.t. \quad & u_i\left(x_{1i},x_{2Ci},x_{2Mi}\right)=u_i^* \end{aligned} \tag{1}$$

Where E_i (kcal/person·day) is the daily individual energy consumption in zone i and E is the total energy consumption of all zones. U^*_i is the daily maximum individual utility in zone i. x_{1i}, x_{2ci} and x_{2mi} are the amount of daily consumed composite good, number of car trips and MT trips produced by each person in one day in zone i, respectively. e_1(kcal/en), e_2(kcal/trip·min), e_3(kcal/trip·min) are the energy consumption units for each composite good, car trip and MT trip. t_{2Ci} and t_{2Mi} are the average time of each car trip and MT trip in zone i.

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(2) The maximum utility

A two-level nested CES (Constant Elasticity of Substitution) function was applied to express utility (2).

$$u_i(x_{1i}, x_{2i}) = \{\alpha_1 x_{1i}^{(\sigma_1-1)/\sigma_1} + \alpha_2 x_{2i}^{(\sigma_1-1)/\sigma_1}\}^{\sigma_1/(\sigma_1-1)}$$
$$x_{2i}(x_{2Ci}, x_{2Mi}) = \{\alpha_{2C} x_{2Ci}^{(\sigma_2-1)/\sigma_2} + \alpha_{2M} x_{2Mi}^{(\sigma_2-1)/\sigma_2}\}^{\sigma_2/(\sigma_2-1)} \quad (2)$$

Where σ_1, σ_2 are the substitute elasticity of composite good and mobility good, substitute elasticity of car trips and MT trips, respectively. α_1 and α_2 represent the expenditure proportion of composite good and mobility good in the total income. α_{2c} and α_{2m} are the expenditure proportion of car trips and MT trips in the total transport fee. σ_1, σ_2, α_1, α_2, α_{2c}, α_{2m} are CES parameters that need to be estimated.

It is assumed that people would like to maximize not only utility, but also the mobility. With the hypothesis that all the income is spent on consuming goods without saving, the maximum utility can be calculated by the maximization process as (3).

$$\max_{\{x_{1i}, x_{2i}\}} u_i = \{\alpha_1 x_{1i}^{(\sigma_1-1)/\sigma_1} + \alpha_2 x_{2i}^{(\sigma_1-1)/\sigma_1}\}^{\sigma_1/(\sigma_1-1)}$$
$$s.t. \quad p_{1i} x_{1i} + p_{2i} x_{2i} \le I_i \quad (3)$$
$$\max_{\{x_{2Ci}, x_{2Mi}\}} x_{2i} = \{\alpha_{2C} x_{2Ci}^{(\sigma_2-1)/\sigma_2} + \alpha_{2M} x_{2Mi}^{(\sigma_2-1)/\sigma_2}\}^{\sigma_2/(\sigma_2-1)}$$
$$s.t. \quad p_{2Ci} x_{2Ci} + p_{2Mi} x_{2Mi} \le I_{2i}$$

Where I_i is the individual income and I_{2i} is the personal transport fee in zone i (en/person·day). p_{2ci} and p_{2mi} are the cost of each car trip and MT trip; p_{1i} and p_{2i} are the price of composite good and mobility good in zone i.

(3) Energy efficiency index

As a close relationship existing between energy consumption and utility, we introduced three kinds of energy efficiency indexes: real energy efficiency, estimated real energy efficiency and estimated optimal energy efficiency, which are shown as (4), (5), (6), respectively. Meanwhile, a weighted index of all zones was applied to reflect the regional energy efficiency level (7).

$$UE_i = \frac{u_i}{E_i} \quad (4) \qquad UE_i = \frac{u^*_i}{E_i} \quad (5) \qquad UE^*_i = \frac{u^*_i}{E^*_i} \quad (6) \qquad UE = \sum_i (UE_i) * (P_i / P) \quad (7)$$

Where u_i is the real utility, u^*_i is the maximum utility, E_i is the estimated real energy consumption and E^*_i is the minimum energy consumption. P_i is the population in zone i, and P is the total population of all zones in the region.

3. Case study

(1) Studied region

We selected Kumamoto and Nagasaki metropolitan region as studied regions. Both areas are located in Kyusyu island in south of Japan. The Kumamoto metropolitan region consist of 177 traffic analysis zones spread over two cities (Kumamoto and Uto), fourteen towns and one village. In 1997, there were approximately 30,511 households and over 919,779 people in Kumamoto region. There are total 88 traffic analysis zones in Nagasaki metropolitan region, which includes three cities (Nagasaki, Isahara, Omura) and four towns.

(2) Data acquisition

The data used in this paper were from Kumamoto Person Trip Survey 1997, Nagasaki Person Trip Survey 1996, supplied by Kumamoto Metropolitan Circle Synthesis Urban Transport Planning and Consultation Organization and Nagasaki Metropolitan Circle Synthesis Urban Transport Planning and Consultation Organization.

To estimate the parameters, various data was necessary. Following is the introduction of these data acquisition.

a) Car trips x_{2Ci} and MT trips x_{2Mi}

The data of average car trips and MT trips x_{2Ci}, x_{2Mi} (trips/person·day) by each person in zone i in one day was from the PTS, by dividing the total original trips in zone i by all population.

b) Average trip time t_{2Ci}, t_{2Mi} in zone i

We estimated the travel time from zone i to zone j by user' equilibrium assignment model and transit assignment model. The average trip time in zone i was the average trip time from zone i to all other zones weighted by the trips.

c) General cost of each trip G_{2Ci} and G_{2Mi}, and price of each trip p_{2Ci}, p_{2Mi} in zone i

The general cost consisted of two kinds of cost. One was the time cost, which was multiplying result of time value and trip time. The other one was money cost, the price of each trip p_{2Ci}, p_{2Mi}. The running fee, including oil, tyre, tube, maintenance, vehicle depreciation is calculated as the p_{2Ci}, p_{2Mi}[6)].

d) Income I_i

e) Energy consumption unit e_1, e_{2C}, e_{2M}

The composite good energy consumption unit e_1 (Kcal/en) was calculated as the result of dividing the all energy each household consumed (Kcal/household·month) to the monthly household expenditures except the transport fee. Car trip and MT trip energy consumption unit e_{2C}, e_{2M} (Kcal/trip·min) not only have relationship with the running distance, but also speed. Having the data of weighted average speed (Km/min) of all trips, the result of e_{2C}, e_{2M} can be calculated and are as shown in Table 1.

Table 1 Energy consumption unit

	Kumamoto(1997)	Nagasaki(1996)
Composite good e_1 (kcal/en)	3.639	3.512
Car trip e_{2C} (kcal/trip·min)	197.178	256.589
MT trip e_{2M} (kcal/ trip·min)	18.155	20.086

(3) Parameter estimation

Model parameters, like elasticity of substitution σ_1 and σ_2, and expenditure distribution α_1, α_2, α_{2C} and α_{2M}, are needed to be estimated before application of the model. Following Table 2 described the estimated results of theses parameters.

Table 2 Estimated parameters

	σ_1	σ_2	α_1	α_2	α_{2C}	α_{2M}
Kumamoto (1997)	0.6577	1.0787	0.9995	0.0005	0.8040	0.1960
Nagasaki (1996)	0.6508	1.0368	0.9993	0.0007	0.3949	0.6051

From the results, it is interesting to find a greater substitution elasticity of car trip for MT trip in Kumamoto. As expected, the parameter α_{2C}, α_{2M} shows a greater car trips expenditure share in Kumamoto and bigger MT trips expenditure share in Nagasaki, since Kumamoto residents is much more auto-dependence than in Nagasaki. As for the substitution elasticity of composite good for mobility good σ_1, and composite good expenditure share α_1, the similar value is found in both cities.

(4) Minimum energy consumption

An iterative process is needed to estimate the minimum energy consumption. Four main steps are included.

Step 1: Minimum energy consumption based on maximum utility was estimated. We obtained the zonal total original trips by timing x^*_{2Ci}, x^*_{2Mi} (the trip number for each resident in one day) and zonal population.

Step 2: Trip distribution was carried out by destination choice model, which include three variables: center zone dummy D_i (takes the value 1 for DID zone and 0 in other cases), job population Z_i, general cost G_{2Cij}, G_{2mij} (general cost from zone i to zone j visa car or mass transit). The logit form was chosen as (8).

$$Q^m_{ij} = \frac{\exp(V^m_{ij})}{\sum_{j=1}^{n}\exp(V^m_{ij})} \qquad V^m_{ij} = a_1 D_j + a_2 Z_j + a_3 G_{2mij} \qquad (m=C, M) \qquad (8)$$

Step 3: Then the new distributed trip matrix was checked with the original trip matrix. If the bias is within 5%, the two trip matrix will be considered be same. We can use the data p_{2Ci}, p_{2Mi}, t_{2Ci}, t_{2Mi} from original trip matrix to estimate the minimum energy consumption directly. Otherwise, we turn to step 4.

Step 4: Reassigning the new trip matrix on the network to get a new p_{2Ci}, p_{2Mi}, t_{2Ci}, t_{2Mi}, then repeat step 1, 2, 3 until the changes of trip matrix are sufficiently small.

(5) Results

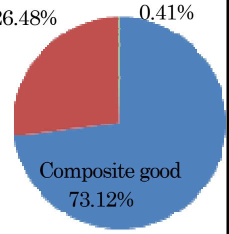
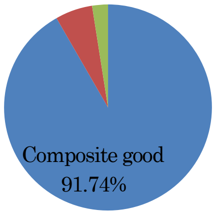
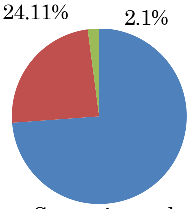
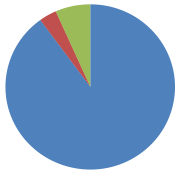
After the above preparing of essential data, we finally obtained the following results.

a) Estimated real and minimum energy consumption

Predicted by the model, it would be possible to decrease 5300kcal energy consumption in Kumamoto, with a corresponding energy of car trip reduction of approximately 81.2% and 419% increase energy consumption of MT trips. Meanwhile, approximately 12.8% energy reduction was observed in the minimum compared to real energy consumption. Increasing energy share of composite good and MT trips, with increasing rate 5.7%, 175%, decreasing share of car trips decreased by 87.8%, are the main attributors.

The results indicated that the effects of constraining car trips and promoting the MT trips is significant to reducing energy consumption. It is evident that difference between estimated minimum and real energy consumption in Nagasaki is smaller than in Kumamoto, with a decreasing rate of 12.8% and 14.2%, respectively (Table 3). This may contribute to larger MT trip share in Nagasaki city.

Table 3 Estimated present and minimum individual dairy energy consumption in Kumamoto and Nagasaki

	Kumamoto 1997		Nagasaki 1996	
	Estimated real	Estimated minimum	Estimated real	Estimated minimum
Energy share of each kind of good				
Total energy consumption (kcal/person·day)	3.72×10^4	3.19×10^4 (-14.2%)	2.81×10^4	2.45×10^4(-12.8%)
Energy for composite good(kcal/person·day)	2.72×10^4	2.93×10^4(7.7%)	2.08×10^4	2.2×10^4(5.7%)
Energy for car trips (kcal/person·day)	9.87×10^3	1.85×10^3(-81.2%)	6.79×10^3	8.22×10^2(-87.8%)
Energy for MT trips (kcal/person·day)	1.52×10^2	7.89×10^2(419%)	5.92×10^2	1.63×10^3(175%)

b) Estimated real and optimal energy efficiency

We compared three types of energy efficiency indicators: real energy efficiency, estimated real and optimal energy efficiency. The results are shown in Table 4. The difference between estimated present and optimal energy efficiency $\triangle UE^{**}$= estimated real energy efficiency- optimal energy efficiency, was also calculated to compare the achievement level of optimal energy efficiency.

Individual utility in Nagasaki is smaller than Kumamoto. It is the same as expected since lower income level in Nagasaki, where the average income is 6286 (en/person•day) compared to 8290(en/person•day) in Kumamoto. Real utility is a little smaller than the estimated utility, which may be due to the maximization of utility and bias of the estimation of the model. Nagasaki region showed less total energy consumption compared to Kumamoto region as mention before. It is much more meaningful to compare the energy efficiency results of two regions. It is interesting to observe that Nagasaki region showed higher energy efficiency on both real and estimated real energy efficiency, but lower estimated optimal energy efficiency. Nagasaki region seemed to have higher energy efficiency than Kumamoto, which can be reflected by the real and estimated real energy efficiency results. While in Kumamoto, higher optimal energy efficiency could be achieved, but a tougher task with the improving value of energy efficiency 0.0316, compared to 0.028 in Nagasaki.

Table 4 Real, estimated present and optimal individual energy efficiency in Kumamoto and Nagasaki

	Kumamoto 1997			Nagasaki 1996		
	Real	Estimated real	Estimated optimal	Real	Estimated real	Estimated optimal
Utility	6862	6966	6966	5025	5289	5289

Total energy consumption (kcal/person·day)	33283	37276	31888	24131	28154	24496
Energy efficiency	0.2061	0.1868	0.2184	0.2083	0.1879	0.2159
Difference between estimated real and optimal efficiency	-0.0316			-0.028		

c) Zonal energy efficiency

Now we turn to the zonal information, such as zonal real and optimal energy efficiency. We would like to find some relationship between zonal energy efficiency and some urban characteristics, like traffic network, MT lines and population density. Figure 2 and Figure 3 showed the space distribution of real, estimated real, optimal energy efficiency and network in Kumamoto, Nagasaki region. It can be observed that the higher energy efficiency zones are mainly zones with higher road density and population density. This tendency is emphasized again by zonal optimal energy efficiency index. An interesting idea is to consider a compact urban structure, resulting in greater energy efficiency. Concentrating the population in certain areas, making a compacter city, and improving the infrastructure utility seem to be ways to achieve optimal energy efficiency.

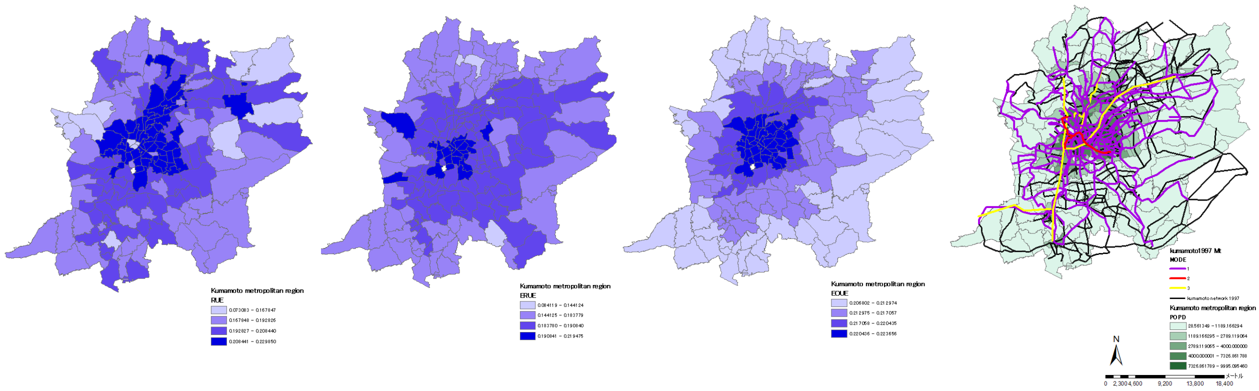


Figure 2: Zonal energy efficiency and network in Kumamoto

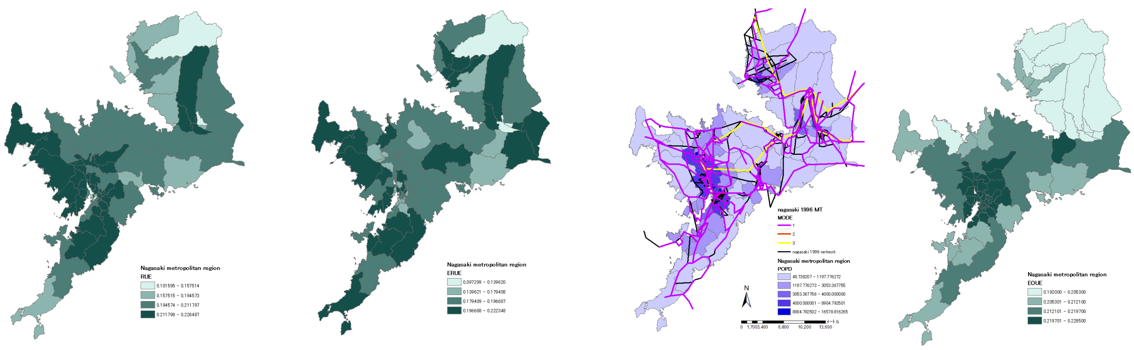


Figure 3: Zonal energy efficiency and network in Nagasaki

*1: Bus Line; 2: Electric Train Line; 3: Railway; POPD: population density (person/km^2)

4. Conclusion

This paper described the development of an evaluation model to estimate the real and optimal individual energy consumption efficiency. We applied the maximum utility, which is determined by the amount and prices of composite good, car trips and Mass Transit trips, to represent the individual quality of life. The real and minimum energy consumption was estimated by a CES-based mode based on maximum utility. In order to compare the energy efficiency on different utility level, real, estimated real and optimal energy efficiency, were introduced.

Kumamoto and Nagasaki metropolitan region were selected as studied regions. By using the data from Kumamoto Person Trip Survey 1997, Nagasaki Person Trip Survey 1996, related parameters were estimated. A greater substitution elasticity of car trip for MT trip and car trips expenditure share was found in Kumamoto. It showed similar values of substitution elasticity of composite good for mobility good, and composite good expenditure share in both regions. This result reflect that residents in Kumamoto are more car-dependent than in Nagasaki.

Compared to Nagasaki, higher utility level was found in Kumamoto due to a relatively higher income. The same tendency was shown on the average individual energy consumption with 33823 and 24131 (kcal/peraon•day) in Kumamoto and Nagasaki, respectively. The real energy efficiency index was found be greater in Nagasaki. It was also found in the model estimated results of the maximum utility, real individual energy consumption, real energy efficiency and minimum individual energy consumption, but except for the estimated optimal individual energy efficiency, which showed a smaller value in Nagasaki.

From the spatial distribution of energy efficiency results, higher energy efficiency was shown in zones, which are higher population density area and along the road lines, especially MT lines in both regions. Zonal estimated optimal energy efficiency also showed a similar result. It is interesting to consider a more compact urban structure and higher mass transit accessibility can induce greater energy efficiency.

There are significant opportunities for the future research on this subject. Further analysis of the relationship between zonal characteristics, such as distance to CBD (Central Business District), population density, job density, number of transit stops, and energy efficiency could provide insight into practical methods to reduce the energy required for achieving maximum utility. Analysis of policy scenarios based on individual energy efficiency and surveys of policy across metropolitan area can provide policy-makers and planners with a vital source of information for preferred policy direction. The results of this paper and future research are important in light of current global warming, energy security and individual quality of life.

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A Model to Evaluate Energy Efficiency from the Viewpoint of Individual Quality of Life *

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In this Paper, a model was built to estimate the real and minimum individual energy consumption and rel ated energy efficiency indexes were analyzed. By applying the method into Kumamoto and Nagasaki, lower indiv idual energy consumption and higher energy efficiency was found in Nagasaki. The zones with higher population density and transit accessibility showed higher energy efficiency. It suggested that a more compact urban structur e and higher mass transit accessibility can induce greater energy efficiency.
