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An analysis of the influence of urban form on energy consumption by individual consumption behaviors from a microeconomic viewpoint

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HIGHLIGHTS

- Energy consumption is estimated by demand of composite goods, mobility goods.
- 52.84 GJ of energy is estimated to satisfy one person per year in Kumamoto.
- 80% of energy is for composite goods and 20% for mobility goods.
- Land use diversity and distance to city center, affect energy consumption most.
- Employment density and transit fare are influential factors of energy efficiency.

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ABSTRACT

Using 1997 personal trip survey (PTS) data in the Kumamoto metropolitan area, this paper examined the influence of urban form on energy consumption through an energy estimation model from a microeconomic perspective. As all goods and service are assumed to satisfy the need of people, we estimated the individual energy consumption based on the demand of goods, which is explained by a utility maximization problem constrained by income. 52.84 GJ of energy is estimated for one person one year in Kumamoto metropolitan area. 19.57% of energy is used for mobility goods. A spatial regression was performed to analyze the relationship between energy efficiency and urban form characteristics in terms of density, diversity, and accessibility. The results of regression analysis show that employment density, ratio of employee in retail department, transit fare, and distance to city center are the most influential factors of energy efficiency. Findings suggest compact development and integrated policies for increasing employment density, especially, employment proportion of local residents are suggested. Moreover, measures to improve the attractiveness of mass transit should be encouraged to increase energy efficiency in Kumamoto.

1. Introduction

Urbanization is occurring at an accelerating pace, accompanied with the creation of some megacities, which is currently defined by the United Nation as cities with more than 10 million population (Bugliarello, 2006). The magnitude and rate of urban growth make urban sustainable development become a crucial matter of global sustainability. Many studies have discussed that the urban forms attribute to sustainable urban development, such as the compact city (Frey, 1999; Williams et al., 2000; Jabareen, 2006). Urban from is considered to be an important factor in addressing urban sustainable development and climate change. The spatial configuration of urban land use within a metropolitan area resulted in diverse social, ecological, and environmental consequences (Camagni et al., 2002; Holden, 2004). These consequences of urban form have been analyzed by energy consumption because of two reasons. First, from the physical standpoint, the urban spatial configuration and land use affect the total amount of energy consumption. Second, the density and intensity of activities, such as traffic and industry, is a major factor influencing energy consumption. Moreover, growing concerns about surging oil prices and the greenhouse gas produced by burning fossil fuels require that urban development not only minimizes resource use and spatial displacement for ecosystems, but also improves energy efficiency.

The debate regarding the relationship between energy consumption and urban form have attracted lots of studies from

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both theoretical and empirical aspects. Some literatures analyzed the relationship between energy consumption and urban form factors among cities. Aggregate studies examined the bivariate relationship between urban form and energy consumption (Crane, 2000; Ewing and Cervero, 2010). Newman and Kenworthy (1999) analyzed the relationship between population density and gasoline consumption in megacities worldwide, which suggested an obvious negative relationship between population density and transportation energy consumption per capita. Their analysis did not consider socioeconomic variations among cities. Such an analysis fails to emphasize the social and economic effects on energy consumption.

Socioeconomic attributes are very influential to household travel and energy consumption (Susilo and Stead, 2008; Musti et al., 2010; Liu and Shen, 2011). Increasing the income leads to a change in consumer needs, which results in rising energy consumption due to growing numbers of household electrical appliances and shifting toward energy intensive transportation modes (Feng et al., 2010). Previous studies utilized disaggregate household data to investigate the differences of household energy consumption in different urban living environment. Using the data of 2001 National Household Travel Survey, Brownstone and Golob (2009) analyzed the relationship of residential density, vehicle use, and fuel consumption for California households. They found the most influential variables were the number of household drivers, the number of workers, education and income. Based on six case studies in the United Kingdom and the Netherlands, Banister et al. (1997) found factors significantly affecting urban energy consumption were density, employment, and car ownership. This kind of disaggregate studies included a rich set of socioeconomic variables and clearly demonstrated the effects of urban form on energy consumption. However, most studies focused on household, and the data included only household energy consumption in Residential and Transportation sectors, such as energy for space heating and cooling, appliances and lighting, domestic hot water and private cars. Energy consumption for Commercial and public services, which shared largely in household energy consumption, was not considered. According to a statistic report from Agency for Natural Resources and Energy, METI (Ministry of Economy, Trade and Industry), energy use in Commercial sector accounts for 25.07% of total energy consumption in all sectors in Kumamoto prefecture, 1997, compared to that of 23.07% in Residential sector. A study in China demonstrated the decreased absolute amount of energy consumption and CO_2 emissions for making food, but growth for education, cultural and recreational services as income increased (Feng et al., 2010).

It is essential but difficult to obtain household energy data of all sectors. The way to solve this problem is to build models to estimate the household energy consumption. Models that describe behaviors under a number of demographic conditions enable us to estimate energy consumption and assess the impact of urban form on energy use. One commonly applied model was to forecast urban energy consumption in transportation sector over a range of driving conditions (Stone et al., 2007; Swana et al., 2011). We previously developed a quantitative model for estimating energy consumption based on individual consumption behaviors (Yin and Mizokami, 2011). The model was applied to assess compact level of cities based on individual energy consumption and utility. Moreover, models that integrated land use, transportation and residential location choice have been built to estimate energy consumption, such as integrated land use and transport model TRANUS (Bravo et al., 2010). TRANUS enables users to study the effects of land use and transport policies, either singly or in combination. The location and interaction of activities determine the demand of energy consumption. Its effort to model the causal mechanisms, which combines direct and indirect links through intermediate variables of urban form to travel and energy consumption, making TRANUS a very attractive point. However, the model requires extensive data for calibration which limits its application.

Anderson et al. (1996) provided a good literature synthesis by reviewing the basic concepts of urban form, the relationships among urban form, energy use, and the effects of using various land use and transportation policy instruments to achieve energy reduction. Although a growing body of literature support the notion that urban form plays a role in energy consumption, the empirical findings on energy consumption and urban form outcomes are less conclusive, and little is known about how urban form influences resident consumption behaviors. They concluded that the influence of urban form on energy consumption is still unclear. This uncertainty therefore requires more empirical work and more comprehensive quantitative models that involved more behavior analysis. So far, few researchers have empirically investigate the linkage between the urban form factors and individual energy consumption by behavior data.

This paper studies the link between urban form and energy consumption through individual consumption behaviors from a microeconomic perspective. At micro level, the effect of urban form on energy consumption is reflected by the individual consumption behaviors. A focus on behavior allows for consideration of influence of socioeconomic factors, such as income. Moreover, focusing on consumption behaviors promotes ways to estimate individual energy use for daily living. It is expected that this estimation approach based on consumption behaviors would be more feasible and rational for a better understanding of the effects of urban form on energy consumption, which will have positive returns for both the environment and city policy making.

Section 2 presents the methodology, including a model for energy estimation, an index of energy efficiency, and the linear regression. Section 3 describes the context of the empirical work, the studied areas of Kumamoto, data set, and quantitative process for energy estimation. Section 4 presents and discusses the energy estimation results and relationship analysis of urban from and energy consumption by a regression model. The main findings and suggestions for policies in Kumamoto are summarized in Section 5.

2. Methodology

2.1. Energy estimation model

The purpose of all urban activities is assumed to satisfy the demand of residents, which need energy to support. Thus, the energy consumption can be estimated based on the demand of individuals. In microeconomics, the demand is represented by the need of goods and service, which are explained by personal consumption behaviors. In economics, utility is a representation of preferences over some set of goods and services. Although it is impossible to measure the utility derived from a good or service, it is usually possible to rank the alternatives in their order of preference to the consumer. Economists have theorized that a utility function could be used to express the scale of preference to describe consumer behaviors. Individual demand is mathematically modeled as the process of maximizing utility under given constraints, such as income (Stigler, 1950).

This study focuses on the individual final energy consumption of some categories that closely relate to the daily living, including energy use in Residential, Commercial, and Transportation sectors. Energy in Industry sector is not considered in this study because it has less direct influence on individual daily life compared to the other three sectors. Moreover, it is complex and not suitable to include energy in Industry sector into the model which focuses on individual consumption behaviors.

Goods are carefully selected to represent all consumption behaviors in daily living. As transport is a major contributor to energy consumption, all goods are classified into two types: mobility goods and composite goods. Transportation services are called mobility goods, including car trips and mass transit trips. Composite goods are all other goods except mobility goods. It represents all goods in Residential and Commercial sectors, such as heating, cooling, food and recreation.

The subject of this study is a "representative individual" in a traffic zone. To estimate the energy consumption of a "representative individual", it is essential to estimate the demand of goods consumed by the "representative individual", which is explained by a utility function. Following assumptions are vital to develop the utility function: (a) The consumption preference of the "representative individual" in a "representative household" is applied as a representation of all individuals' behaviors in one zone. (b) The "representative individual" in each zone is assumed to consume two kinds of goods: composite goods and mobility goods. The demands is expressed by variables x_{1i} and x_{2i}, respectively, in zone i. (c) The demand of mobility goods x_{2i} is a function of the numbers of car trips x_{2Ci} and mass transit trips x_{2Mi}. (d) Composite goods are all other goods except mobility goods. (e) Utility u_i is a function of three kinds of goods consumption. (f) The individual is assumed to maximize utility and mobility under an income constraint. (g) All income is spent on consuming without saving.

Based on these assumptions, a nested constant elasticity of substitution (CES) function is chosen to express the utility function (Fig. 1). CES is a particular type of aggregator function that combines two or more types of consumption into an aggregate quantity (Kanemoto et al., 2006). This aggregator function is used to represent the constant elasticity of substitution between composite goods and mobility goods at the first order (Eq. (1)), and between car trips and mass transit trips at the second order (Eq. (2)). Here, σ_1 and σ_2 are the elasticity of substitution between two kinds of goods at the first and the second order. α_1 and α_2 are the share parameters of composite goods and mobility goods, which means the spending share for composite goods and mobility goods in total income. α_{2C} and α_{2M} are share parameters of car trips and mass transit trips, indicating the spending share of car trips and mass transit trips in total transport budget.

We assume that people attempt to maximize both utility and mobility. The maximum utility is achieved by solving two maximization problems. The first is mobility maximization problem provided in Eq. (3). It determines the number of car trips and mass transit trips subject to the transportation budget. The second maximization problem is to calculate the maximum utility based on consumption of composite goods and maximum mobility under the income constraint (Eq. (4)). p_{1i}, p_{2i}, p_{2Ci}, p_{2Mi} are prices of composite goods, mobility goods, car trip, and mass transit trip in zone i, respectively. I_i is the individual income and I_{2i} is the individual transportation budget. The solution process of the maximum mobility and maximum utility was outlined in Appendix A.

The energy consumption is estimated based on the demand of three kinds of goods on the maximum utility. E_i is the individual energy consumption in zone i, which is determined by the demand of goods and trip time (Eq. (5)). Trip time is introduced into the estimation function considering the relationship between energy consumption and traffic congestion. e_1, e_2, e_3 are energy consumption unit of composite goods, car trip, and mass transit trip, respectively. x^*_{1i}, x^*_{2Ci}, x^*_{2Mi} are the optimal demand of composite goods, car trips, and mass transit trips on the maximum utility u^*_i, respectively.

2.2. Energy efficiency

The concept of energy efficiency refers to reducing the amount of energy required for production and services. In general, improvement in energy efficiency is achieved by adopting a high efficient technology or production process. Similar concept of energy efficiency is also applied in energy economic field. Energy intensity is a measure of the energy efficiency of a nation's economy. It is calculated as units of energy per unit of GDP. High energy intensities indicate a high price or cost of converting energy into GDP. Many factors influence an economy's overall energy intensity, such as the general standards of living and weather conditions in an economy. Different from energy per unit of GDP, this paper introduces the indicator of energy unit of expenditure to evaluate energy efficiency. It represents how much energy is needed for spending one unit of expenditure on goods from viewpoint of consumption. The energy unit of expenditure is calculated as the ratio of energy consumption to expenditure of one kind of goods. Bigger energy unit of expenditure means lower energy efficiency, indicating more energy is needed for spending one yen for goods consumption.

This paper also introduces a synthetic indicator of energy efficiency, which is called synthetic energy unit of expenditure. It evaluates the energy unit of expenditure for all kinds of goods. Energy unit of expenditure of car trips, mass transit trips and composite goods are aggregated into synthetic energy unit of expenditure, which is calculated as follows:

Synthetic energy unit of expenditure = (energy unit of expenditure of composite goods × expenditure share of composite goods)+(energy unit of expenditure of car trips × expenditure share of car trips)+(energy unit of expenditure of mass transit trips × expenditure share of mass transit trips).

2.3. Multilinear regression analysis

A multiple linear regression model is applied to analyze the effect of urban form on energy consumption. The synthetic energy unit of expenditure is chosen as dependent variable. Explanatory variables are indicators of urban form characteristics.

Urban form is not simply the structure of land use, but also involves population distribution, transport accessibility, and commercial development. Characteristics of urban form are represented by nine variables from density, diversity, and accessibility aspects. Density is highly correlated with almost all

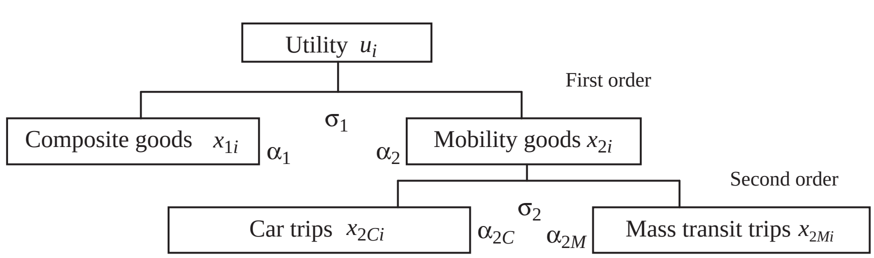

Fig. 1. The structure of CES utility function.

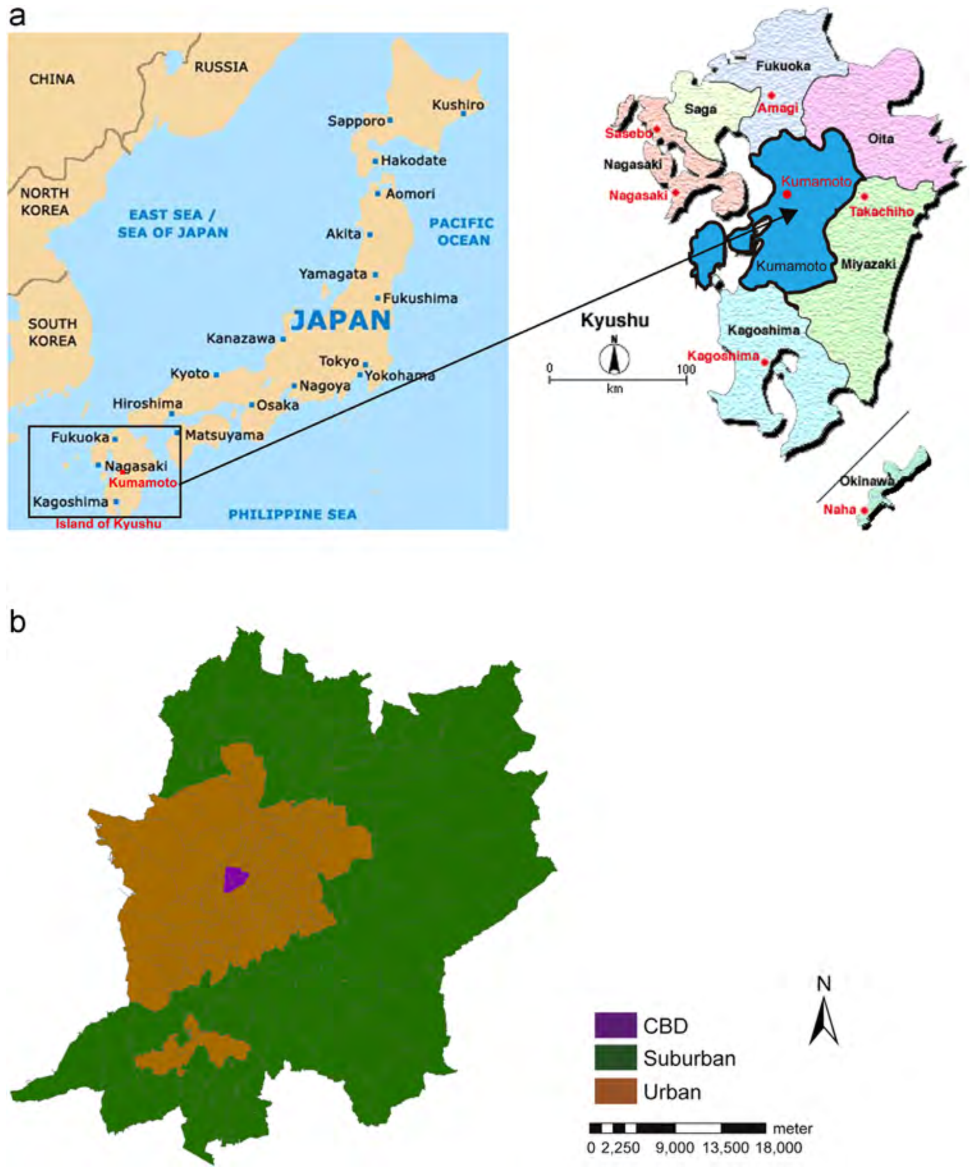

Fig. 2. The Kumamoto metropolitan area. (a) The location of Kumamoto prefecture in Japan, (b) Urban structure of the Kumamoto metropolitan area.

measures of urban form and is a measure most frequently used (Ewing and Cervero, 2010). It is interpreted as a density of population, employment, and students in this paper. Population density and employment density refers to the number of person or employees in per square meters, respectively. Of note is that little is known about how school commuting influences energy consumption. With the data of student numbers, study density is also included as a density indicator in this study. The number of employees in retail department is chosen as the indicator of diversity of urban form by some study (Jenks and Jones, 2009), because it captures the variety of attractions within a designated area. However, the number of employees in retail department is not the perfect indicator of diversity for this study, which focuses on energy consumption. Even with same number of employees in retail department, the proportion of local employees who live and work in the same zone affect the amount of energy consumption. More residents live and work in the same place, less and shorter commute trips are expected, contributing to less energy consumption. Thus, we developed the indicator of “ratio of employees in retail department to population” as a variable of land use diversity. It evaluates the ratio of employees in retail department to population in each zone. Accessibility reflects potential spatial interaction and is categorized as trip-based and activity-based. Trip-based accessibility is expressed by car trip accessibility and mass transit trip accessibility. Road density is chosen to evaluate the accessibility to car trips which is defined as the length of expressways and highways per square kilometer. Mass transit trip accessibility is represented by three variables: transit stop density, frequency of mass transit service, and the mass transit fare. As services are mainly concentrated in city center, distance to city center zone is used to evaluate the activity-based accessibility. It is a simple geometric distance computed from a map.

Multicollinearity may exist among selected explanatory variables because the dataset employed are aggregated at the level of traffic zone. A variance inflation factor (VIF) analysis is performed to examine the independence of the explanatory variables before regression. If VIF is greater than 20, multicollinearity is assumed to exist. The condition number is also investigated as a general measure of multicollinearity. If the condition number is bigger than 15, multicollinearity is assumed to exist.

3. Case study

3.1. Studied area

Kumamoto metropolitan area is chosen as the study area because of data availability. Kumamoto metropolitan area is part of Kumamoto prefecture located in the center of the Kyushu Island (Fig. 2). Kumamoto city is the center of the prefecture, culturally and economically. It takes ninety-five minutes to reach the city from Tokyo by airplane (1072 km), but only eighty-five minutes from Seoul in Korea (631 km). Kumamoto prefecture, the fifteenth largest area in Japan, covers approximately 7402 square kilometers. Kumamoto metropolitan area covers roughly 1077 square kilometers, including two cities (Kumamoto and Uto), fourteen towns, and one village. The west part reaches to the Ariake and the Yatsushiro seas which link to the East China Sea. The population of Kumamoto prefecture is 1812,255 in 2010, which ranks 23rd in Japan. There is a decreasing and ageing trend of population since 1995. The phenomenon of aging has begun ten years ahead of the rest of the country. Kumamoto prefecture is blessed with rich greenery and abundant groundwater. It is an agriculture-based region, famous for the production of rice, vegetable and fruits. Electronics, vehicle manufacturing and food processing are major secondary industries in Kumamoto. In particular, the IC (integrated circuit) industry commands around 12% share of domestic production and it constitutes the major production hub in Kyushu Silicon Island.

3.2. Data

3.2.1. 1997 Personal trip survey (PTS)

Personal trip survey (PTS) is a person-based travel survey conducted every ten years by Ministry of Land, Infrastructure and Transport (MLIT). Daily travel is collected using one-day trip diaries for all household members in selected households. The main part of PTS dataset is the personal trip files which provide the information of trip purpose, trip distance, travel time, and travel mode. Raw PTS data has been aggregated at the traffic zone level, which is available from reports provided by Kumamoto Metropolitan Area Urban transport Planning and Consultation Council. Data of car trips and mass transit trips in 1997 are aggregated at zone level. We only focus on trips for purposes of commuting, business, shopping, and returning home.

3.2.2. Price of goods

The price of composite goods, p_{1i}, is set to be as one. The price of mobility goods, p_{2i}, is determined by the price of car trip and mass transit trip (Eq. (6)). The price of a mass transit trip p_{2Mi} (yen/trip) is calculated by the mass transit fare based on assignment results. It is essential to decide the running fee unit before determining the price of car trips. The running fee unit is defined as unit of yen/km·vehicle by MLIT. It measures the monetary cost for running per vehicle kilometer, including fees related to oil, tire, tube, vehicle maintenance and vehicle depreciation. Without access to running fee unit in 1997, we referred to a report titled "A method to calculate unit value of time and running fee unit in 2003" from MLIT. Considering the economic slump in Japan, it assumed that there is limited influence of inflation on the price. Utilizing the running fee unit in 2003, the price of car trip is calculated as follows:

p_{2Ci} (yen/ trip)=(running fee unit (yen/km·vehicle) × minimum distance from zone i to j (km/trip))/average number of passengers (trip/vehicle).

Here, the average number of passengers in a car is 1.21 suggested by the report from MLIT.

3.2.3. Trip time

By assigning car trips and mass transit trips on maximum utility, trip time of all trips is obtained. We set average time of all trips from zone i to other zones as the value of trip time in zone i.

3.2.4. Energy consumption unit

According to the statistical summary of energy use by Agency for Natural Resources and Energy, METI, energy consumption unit of Residential and Commercial sector is 16.14 kJ/yen in Kumamoto prefecture, 1997 (includes residential, water supply, sewage and waste disposal, trade and finance service, public service, commercial service, retail servicers). Composite goods include all goods in Residential and Commercial sector. The energy unit of composite goods is assumed same as the energy consumption unit of Residential and Commercial sector, that is 16.14 kJ/yen in this study (Table 1). Referring to energy consumption unit of trip distance (kcal/trip·km) in the report, the energy consumption unit of trips is calculated as follows:

Energy consumption unit of trip (kJ/trip min)=energy consumption unit of trip distance (kJ/trip min) × average speed (km/min).

3.2.5. Income

It is difficult to obtain individual income data (yen/person·day) in each zone. Only the average individual income of each administrative district in 1997 is available from the homepage of Kumamoto prefecture government (http://www.pref.kumamoto.jp/site/statistics/list1288-2370.html). The total income of a town is distributed among zones according to personal income ratio and population in 1997. Since a positive relationship between land price and income is assumed, the personal income ratio is calculated based on the zonal land price ratio in 1997. Land price data is from the Japanese National Tax Agency.

3.2.6. Urban form data

The 1997 PTS provides data related to number of population, employees and students. Data of road length, number of mass transit stops, frequency of mass transit services in 1997 are from Kumamoto prefecture government. The distance to city center is determined by measuring the distance from zone centroid to city center in a GIS map of the Kumamoto metropolitan area.

3.3. Parameter estimation

The elasticity of substitution between composite goods and mobility goods, σ_1, is estimated as 0.6577 (Table 2). The elasticity of substitution between car trips and mass transit trips, σ_2, is 1.0787. Residents spend most of their income on composite goods,

Table 1
Energy consumption unit of goods in Kumamoto metropolitan area.

Goods	Energy consumption unit
Composite goods e_1	16.14 (kJ/yen)
Car trip e_2	825.40 (kJ/trip min)
Mass transit trip e_3	76.02 (kJ/trip min)

Table 2
Estimation of parameters of utility function.

σ_1	σ_2	σ_1	σ_2	σ_{2C}	σ_{2M}
0.6577	1.0787	0.9995	0.0005	0.8040	0.1960

represented as large value of α_1. The estimated α_{2C} is 0.8040, indicating more than eighty percent of transport fare is spent for car trips. Mass transit trips fare accounts for only 20%, shown as the small value of α_{2M}.

3.4. Procedure of energy consumption estimation

It is necessary to estimate the optimal number of car trips and corresponding trip time before energy estimation. However, it is difficult to determine the right number of trips, because there is a relationship between trip number and trip time. Trip number influences the trip time, and verse versa. Trip time and trip number affect each other, and finally reach to a balance solution. To search the solution, a loop is designed to estimate the energy consumption on maximum utility by seven steps (Fig. 3). Step 1: The primary value of trip time and trip price is set by 1997 PTS data. Step 2: The optimal demands of goods are calculated based on solutions of maximum utility problem. Step 3: Using a destination choice model, all car trips and mass transit trips of each zone x_{2Ci} and x_{2Mi} are distributed to all zones to build OD (Original-Destination) matrices by mode. OD matrix is a “trip table” that matches trip makers' origins and destinations. It displays the number of trips going from each origin to each destination. The destination choice model is mentioned in the following paragraph in detail. Step 4: Comparing the new built OD matrix with OD data obtained from previous loop (or OD matrix from survey for the first time running), if the difference between two OD matrix is within 5%, they are assumed be same. Then the whole process stops. Energy consumption is calculated based on the demand data in step 2. Otherwise turn to step 5. Step 5: Car trips and mass transit trips are assigned to renew the trip price and trip time. Step 6: Optimal demand of goods on the maximum utility is renewed based on revised trip price and trip time, p_{2Ci}, p_{2Mi}, t_{2Ci}, t_{2Mi}. Step 7: Return to step 2 again.

An aggregated logit type model is applied to distribute trips by three variables (Eq. (7)): center zone dummy D_j (takes the value 1 for center zone and 0 in other cases), job population Z_j and generalized cost G_{2mij} (generalized cost from zone i to zone j via car or mass transit). T_{ij}^m is the number of trips from zone i to zone j via mode m, while T_i^m represents the all trips in zone i by mode m. Coefficients of D_j, Z_j and G_{2mij} are expressed by *a, b, c*, respectively. All three variables show significant influence on model share with statistical significance level less than 5%. Generalized cost is found negatively related, while job population is positively related with model share. The estimation result of *a*, coefficient of zone dummy, shows different signs on car and mass transit trip share, suggesting more mass transit trips instead of car trips are expected if the zone is closer to the city center.

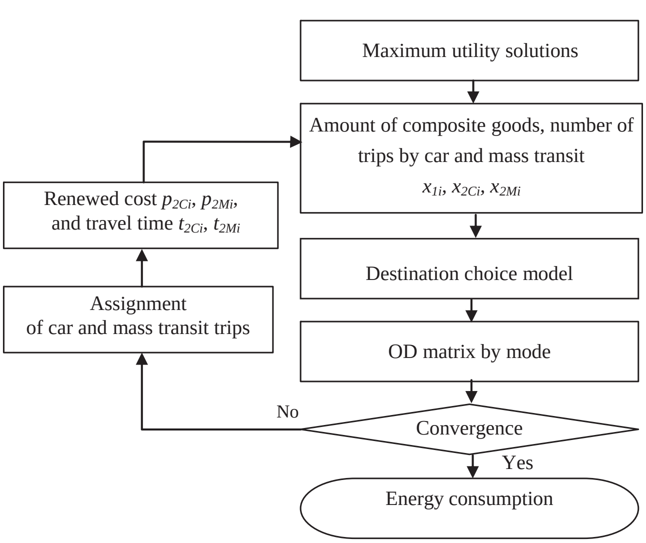

Fig. 3. A loop for energy estimation.

4. Results and discussion

4.1. Energy consumption

Table 3 shows the result of main features of estimated energy consumption, which is summarized to give a brief introduction by Statistical Program for Social Science (SPSS) software 18.0. A total of 52.84 GJ of energy consumption is estimated to be necessary for each resident per year in Kumamoto. Energy for composite goods is 42.50 GJ per person per year, accounting for 80.43% of the total energy consumption. The proportion of energy for private car travelling is 19.13%, that is 10.11 GJ/person year. Only 0.44% of energy is used for mass transit trips. Each resident in Kumamoto is estimated to use 0.23 GJ for mass transit trips. 16.14 kJ is needed for consuming one unit of composite goods. Each car trip costs 4.08 kJ in Kumamoto. While resident spends 0.09 kJ for one mass transit trip.

According to a report from Agency of Natural Resources and Energy, METI, energy consumption unit of Residential, Commercial and Passenger car transportation is 19.01 kJ/yen in Kumamoto prefecture, 1997. The average individual income is 7,438 yen/person day in 1997 from website of Kumamoto prefecture government (http://www.pref.kumamoto.jp/site/statistics/list1288-2370.html). It means that one resident is estimated to consume 141.40 MJ of energy each day, equaling to 51.61 GJ/person year in this area. The 95% confidence interval for mean of estimated energy consumption by model is from 50.74 GJ to 54.92 GJ. The government data (51.61 GJ/person year) falls into 95% confidence interval, suggesting that the model estimation result is acceptable.

Individual energy consumptions in and out of Kumamoto city are different (Table 4). Compared with people who live outside of Kumamoto city, residents in the city consume more energy for composite goods and mass transit trips, and less energy for car trips. This tendency is also shown in the result of energy share, indicated as high energy share of composite goods and mass transit trips, low share of car trips in Kumamoto city. However, the difference between total energy consumption in and out of city is insignificant.

Table 3
A descriptive report of energy consumption estimation result in Kumamoto metropolitan area.

	Mean	Standard error of mean	95% Confidence interval for mean		
			Lower bound	Upper bound	Median
Energy consumption (GJ)	52.84	1.06	50.74	54.92	50.41
Energy for composite goods (GJ)	42.50 (80.43%)	0.84	40.85	44.15	41.07
Energy for car trips (GJ)	10.11 (19.13%)	0.58	8.96	11.25	8.92
Energy for mass transit trips (GJ)	0.23 (0.44%)	0.07	0.09	0.37	0.11
Energy per composite goods (kJ)	16.14	0.00	16.14	16.14	16.14
Energy per car trip (kJ)	4.08	0.24	3.60	4.56	3.62
Energy per mass transit trip (kJ)	0.09	0.03	0.03	0.14	0.05

4.2. Energy unit of expenditure

Table 5 lists the result of energy unit of expenditure of each kind of goods, and synthetic energy unit of expenditure. All listed values are the medium values, because it is necessary to eliminate the influence of some extreme values. Energy unit of expenditure of composite goods is 16.14 kJ/yen for all residents in and out of Kumamoto city. A total of 168.70 kJ is needed for spending on car trips in Kumamoto metropolitan area per yen. Energy unit of expenditure of mass transit trips is estimated as 13.82 kJ/yen. The aggregated indicator of three kinds of goods is calculated as 5.19 kJ/yen. Comparing values in and out of the city, energy unit of expenditure of car trip is higher in the city than out of city. However, there is no significant difference between values of energy unit of expenditure of mass transit trips in and out of the city. The synthetic energy unit of expenditure in the city is a little higher than the value out of city.

Fig. 4. (a) presents the synthetic energy unit of expenditure of each zone in Kumamoto metropolitan area with values from 0 to 37.44. Five levels are classified with 35 zones in each level. The minimum value of synthetic energy unit of expenditure is zero due to none-residence in four zones named Kumamoto traffic center, Kumamoto station, Kumamoto port, and Kumamoto airport. Lighter color represents lower energy unit of expenditure, which means higher energy efficiency. Comparing to the map of transport network and population density of the area (Fig. 4. (b)), it clearly shows that low energy unit of expenditure mainly located in high population density area, such as the city center. Zones along mass transit lines are also featured by low energy unit of expenditure.

4.3. Relationship between urban form and energy efficiency

4.3.1. Ordinary least squares (OLS) estimation

The effect of urban form on energy efficiency is analyzed by OLS method for 173 zones in Kumamoto metropolitan area. A statistical report of variables is presented in Table 6. The R-square is 0.783, indicating the linear relationship between urban form and energy efficiency could not be rejected at the $p < 0.01$ level. Suggested by VIFs and the value of the condition number, there is no multicollinearity among variables. The mean of standardized residual equals zero and Standard deviation is 0.973, indicating normal distribution of residuals. However, data is spatially auto correlated according to the map of residuals. Spatial regression is necessary to eliminate the influence of spatial correlation of zones.

Table 4
Estimated energy in and out of Kumamoto city in 1997 (GJ /person year).

	Kumamoto city	Out of Kumamoto city
Total energy consumption (GJ)	53.28	52.44
Energy for composite goods (GJ)	43.76 (82.13%)	41.37 (78.89%)
Energy for car trips (GJ)	9.15 (17.17%)	10.96 (20.90%)
Energy for mass transit trips (GJ)	0.37 (0.70%)	0.11 (0.21%)

Note: () indicates energy share of goods.

If the absolute value of residual is bigger than 3, it is assumed to be an outlier. We found two outliers and an influential observation. Zone 78 and zone 169 are the two outliers. In both zones, employees are mainly distributed into farming, and only a few employees are in retail department. The situation causes low ratio of employee in retail department to population (less than 10% of average value), leading to low synthetic energy unit of expenditure in both zones. Zone 2, which is located in the city center, has found be the influential point. The distance to the city center is zero because zone 2 just locates in the city center. High ratio of employee in retail department to population (43 times of the average value), together with zero travel distance to city center contribute the highest synthetic energy unit of expenditure in zone 2. Due to the specialty of the three zones, we do not consider outliers and influential observation into spatial regression analysis.

4.3.2. Primary findings of spatial regression model

A spatial regressive model is applied in order to eliminate the influence of spatial autocorrelation of zones. Spatial regression analysis is performed by GeoDaSpace software. Table 7 lists the estimation results. The model shows strong explanatory power with Pseudo R-square of 0.783.

4.3.2.1. Density. A significant effect of selected density variables on energy efficiency was detected. The density of employee is the strongest influential factor that negatively affects energy unit of expenditure. Our results indicate residents live in the employment dense areas are more likely to use less energy consumption. It is reasonable, because services and goods are easily available and people are less auto-dependent. The estimated coefficient of density indicates that energy unit of expenditure decreases as the population increases. Population density is also a strong influential factor of energy efficiency, which is consistent with previous study (Brownstone and Golob, 2009). Student density has a negative diminishing marginal effect on energy efficiency with positive coefficient with energy unit of expenditure. The influence of student density is relatively small compared to other two density variables.

4.3.2.2. Diversity. Land use diversity has significant impact on energy efficiency. The ratio of employee in retail department to population is the most influential determinant that affects energy unit of expenditure (with the p-value less than 1%). This variable is positively related with energy unit of expenditure. High ratio of employee in retail department to population suggests small proportion of local employee in retail department. Low percentage of local employees in retail sector results in more commuting trips and long travel distance, contributing to more energy consumption.

4.3.2.3. Accessibility. Low mass transit trip fare attracts more residents to use mass transit as a travel mode. Reducing mass transit fare leads to low energy unit of expenditure due to the incentive of mass transit usage, which is in consistent with the previous report that mass transit mode share increases as fare

Table 5
Energy unit of expenditure of goods in Kumamoto (kJ/yen).

	Kumamoto area	Kumamoto city	Out of Kumamoto city
Energy unit of expenditure of composite goods	16.14	16.14	16.14
Energy unit of expenditure of car trip	168.70	173.07	161.26
Energy unit of expenditure of mass transit trip	13.82	13.18	14.47
Synthetic energy unit of expenditure	5.19	5.35	5.14

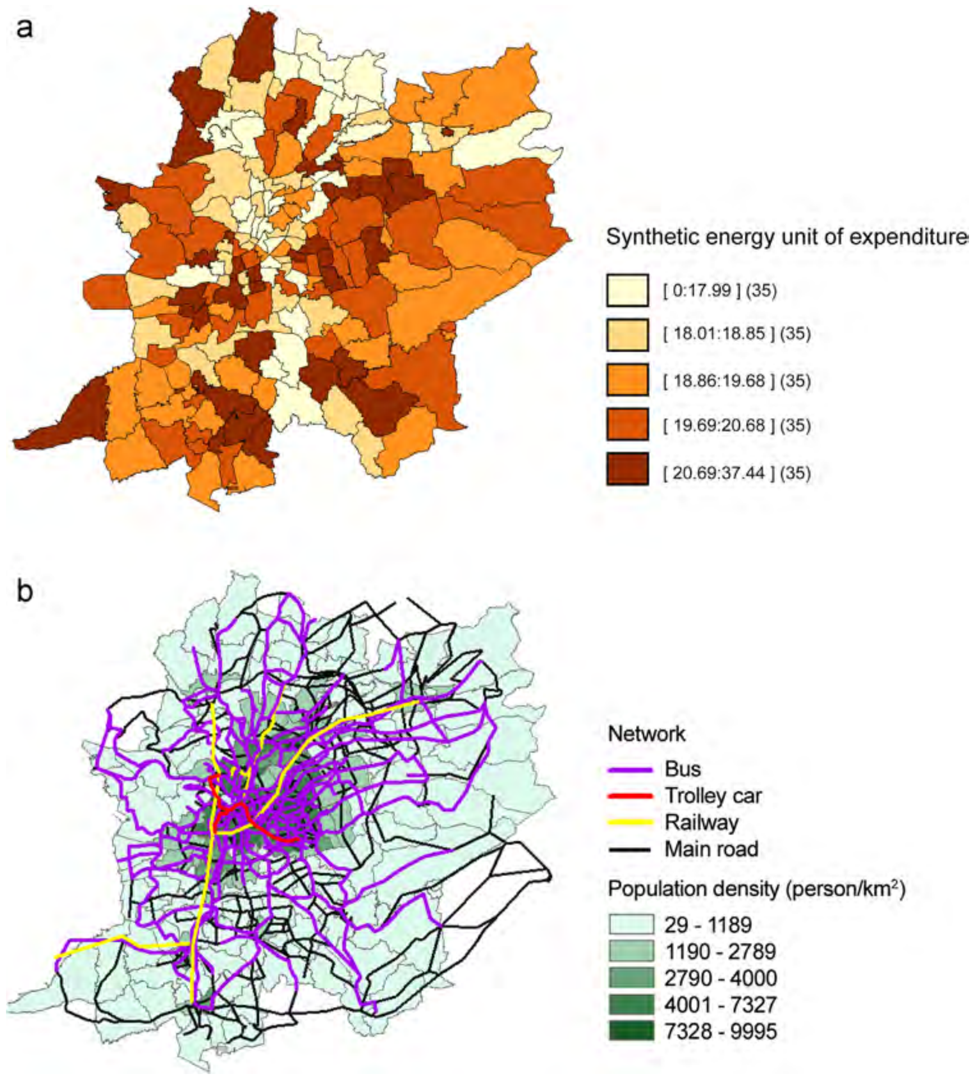

Fig. 4. Energy consumption efficiency, transport network and population density of zone in the Kumamoto metropolitan area. (a) Energy efficiency in the Kumamoto metropolitan area, (b) Transport network, and population density in the Kumamoto metropolitan area.

Table 6
Descriptive statistics of variables in the linear regression model.

Variable	Unit	Mean	Standard deviation	Minimum	Maximum
Dependent variable					
Synthetic energy unit of expenditure	kJ/yen	19.46	2.02	16.13	37.44
Independent variable					
Population density	1000 person per km^2	2.37	2.65	0.03	10.00
Employment density	1000 person per km^2	1.69	5.16	0.00	58.02
Student density	1000 person per km^2	0.65	1.97	0.00	17.90
Ratio of employee in retail department to population	Employees in retail department /population	0.65	1.62	0.00	19.94
Road density	10 km per km^2	2.68	2.40	0.00	16.68
Transit stop density	10 stops per km^2	0.86	1.09	0.00	5.97
Frequency of transit service	100 times per day	3.01	7.29	0.00	49.05
Mass transit fare	100 yen per trip	3.64	1.72	0.00	12.14
Distance to city center zone	km	8.74	5.09	0.00	22.28

Note: the number of samples is 173 for each variable.

reduces (Pucher et al., 1995). High road density increases the accessibility of car trips, which induces individuals to have high preference for private car trips. Energy unit of expenditure increases as road density increases. Our result further supports the previous report that higher road density leads to greater household gasoline consumption (Su, 2010). However, mass transit stop density is found to have negative effects on energy unit of expenditure and the influence is less significant than mass transit fare. The result indicates that reducing mass transit fare is better than increasing the density of mass transit stops for improving the energy efficiency. Although positively related with energy unit of expenditure, the influence of frequency of mass transit service is insignificant. Distance from zone centroid to city center is found be another most influential factor, which shows a

Table 7
Estimation results of a spatial regression model in Kumamoto metropolitan area.

Variables	Coefficients	Std. Error	z-Statistic	Probability	VIF
Constant	17.730	1.539	11.519	0.000	
Population density	−0.092	0.057	−1.603	0.109	4.837
Employment density	−0.113	0.049	−2.283	0.022**	7.019
Student density	0.015	0.042	0.367	0.713	1.388
Ratio of employee in retail department to population	1.366	0.132	10.316	0.000***	10.450
Road density	0.015	0.056	0.268	0.789	3.619
Transit stops density	−0.199	0.176	−1.133	0.257	9.414
Frequency of transit service	0.003	0.019	0.157	0.875	3.518
Mass transit fare (yen/trip)	0.130	0.055	2.385	0.017**	1.801
Distance to city center zone	0.085	0.023	3.708	0.000***	2.876
Spatial Pseudo R-squared	0.782				

*** Indicates that the coefficient is statistically significant at the 1% or less.
** Indicates that the coefficient is statistically significant at the 5% or less.

significantly positive relationship with energy unit of expenditure with the p-value less than 1%.

4.3.3. Discussion of results

4.3.3.1. Population density, employment density, student density. Density is shown to have a direct effect on energy consumption. Some of socio-demographic factors, such as popula tion density and employment density, have significant impact on energy consumption. The distribution of population in high activity centers concentrates economic activities and transports needs. Neighborhoods in dense areas have less and shorter trips because of high facility availability. Moreover, residents are less auto-dependent because of expanding mass transit infrastructure. As a result, residents live in dense areas are more likely to have less energy consumption. The employment density is the strongest determinant that positively affects energy efficiency. The number of employers reflects the amount of services that available in the area. Residents live in dense employment have easy access to services or goods. It induce to less and shorter trips. More employment opportunities attract local residents, resulting less commuter trips. Student density is found influential to energy efficiency, but with limited influence. Findings by Marique et al. (2013) confirm school mobility behaviors are dependent upon the location of residences and education infrastructure in the territory. School commuting and children's mobility behavior are affected not only by the number of student but also the location of schools, that is the school density. From the social-demographic viewpoint, policy implication regarding changes in urban form characteristics should consider the distribution of population and employment simultaneously. Compact city will enable a comprehensive picture of future sustainable development, due to the high population and employment density in the region.

4.3.3.2. Ratio of employee in retail department to population. Land use diversity significantly affects travel behavior, and has direct and positive effect on energy efficiency. Compact city is widely adopted because it is believed to increase the land use diversity. The indicator of land use diversity in this paper is expressed by the ratio of employee in retail department to population. It has a direct effect on energy consumption. High ratio of employee in retail department to population indicates only a few employees work and live in the same area. For most employees who live far away, long commuting trips are necessary. High ratio of employee in retail department to population introduces more trips and more energy consumption. In Kumamoto, employment of service sector accounts for the big share with more than 60% of all employees work in the sector (Census in 2005, Kumamoto). Employment in retail department, such as shopping centers and supermarkets, is a main contributor of employment in service sector. Therefore, it is effective to reduce the energy consumption for commuting trips in retail department as a way to decrease the total energy consumption of the city. Two suggestions have been put forward based on the result. One way is to decrease the travel distance of work trips through changing residential locations. Concentrating population in hot employment areas may increase the proportion of local employees in retail department. Compact development is required for adopting more residents in hot employment places. Moreover, efforts should be made to increase the attractiveness of hot employment places as residential locations.

For employees who live far from their working place, public transportation tools should be encouraged. Big capacity and high speed mass transit mode, such as Shinkansen, could be a good choice for the commuters. Moreover ， improving the mass transit service is another important attractive point.

4.3.3.3. Road density. Road density has a direct effect on energy consumption through traffic choice behavior. Traffic behavior is a complex process which is influenced by a few factors, such as car ownership, gender, income, and so on (Liu and Shen, 2011). Accessibility of road is one of essential driving conditions, but not the determining factor. The effect of road density on travel behavior is limited.

4.3.3.4. Transit stop density, frequency of transit service, mass transit fare. The attraction of mass transit service has the significant effect on individual traffic behavior and energy consumption. Residents are attracted to mass transit due to high accessibility of service and lower traffic fare. Transit stop density is more influential to public transport usage than frequency of transit service. Residents pay more attention to the location of transit stops, rather than frequency. High density of transit stops ensures easy access to service, such as short walking distance to stops, which increases the possibility of choosing mass transit as a travel mode. Importantly, low mass transit fare also makes mass transit a charming attractiveness, which increases the real welfare of mass transit users. It is helpful to emphasize and fix the mass travel behavior and the effect will be enlarged when residents use once more.

4.3.3.5. Distance to city center zone. Distance to city center zone has significant and direct effects on travel distance, and impacts energy consumption positively. In Kumamoto, facilities, such as restaurants, shops, hotels, and bureau of administration, are mainly located in city center. Activities are concentrated in the city center. Residents are attracted to the city center for commuting, recreation and shopping. If the resident lives far away, long trips are needed. From this viewpoint, policy implication regarding changes in urban form characteristics should consider the distance between residential area and main activity centers. A compact city will enable a short travel distance due to limited urban space. Moreover, mixed land use policy ensures the accessibility of facilities and activities in residential area.

5. Conclusion

As a region located in a mountainous basin, the development of Kumamoto is expected to be much denser and transport networks to be more efficient. Kumamoto city has been pointed as one of twenty cities designated by government ordinance since April, 2012. Now, it is undergoing a transition to new urbanization development with vigor. This transition is bringing changes to the urban spatial distribution of population, employment, land use and travel patterns, resulting in different energy consumption. Facing the conflict of land preserving and energy tense situation, Kumamoto needs guide for the future development urgently.

Present study provides a quantitative analysis on the relationship between specific indicators of urban form and individual energy consumption in Kumamoto metropolitan area. First, a model is developed to estimate individual energy consumption based on consumption behaviors. 52.84 GJ of energy is estimated to be needed for one person per year in Kumamoto metropolitan area. 19.13% is for car trips and 0.44% for the mass transit trips. 19.57% of energy is used for mobility goods. The synthetic energy unit of expenditure of three kinds of goods in Kumamoto metropolitan area is 5.19 kJ/yen. The method of energy estimation in this paper enables us to estimate all individual energy consumption in daily life, including energy use in Residential, Commercial and Transportation sectors.

Our research findings provide additional evidences on the relationship between urban form and energy consumption. Considering the spatial autocorrelation of data, a spatial regression is performed by GeoDaSpace software. The results indicate that the urban form has significant effects on individual energy consumption. Employment density, ratio of employee in retail department to population, mass transit fare, and distance to city center, are four most influential factors. Ratio of employee in retail department to population and distance to city center were statistically significant with energy efficiency both with the p-value less than 1%. Shorter distance to city center attributed to higher energy efficiency. Low mass transit fare improves energy efficiency due to more mass transit usage. Results showed that high employment density leads to high energy efficiency. However, high ratio of employee in retail department to population tends to decrease energy efficiency. Two opposite influence directions suggest that: although increasing employment density is effective to improve energy efficiency, it is much better to increase proportion of local residents as employees in retail department.

By examining the relationship between the urban form and energy efficiency, present study suggests two policy implications for urban development of Kumamoto. First, in the micro-level, measures that increase mass transit usage should be encouraged, such as reducing mass transit fare and increasing mass transit stop density. Second, in the macro-level, policies for improving employment density, especially, employment proportion of local residents are suggested. These two levels are correlated with each other as a whole and suggest compact city development for high energy efficiency in Kumamoto. Our study gives a timely policy suggestion for urban sustainable development in Kumamoto. Of note is that, some suggestions have been applied into the planning practice. Kumamoto prefecture government is carrying out a planning for compact development for the future ten years. Moreover, the bullet train, called Shinkansen in Japan, has been operated between Kumamoto and Tokyo in 2012. It improves the mobility of residents along the line and attracts more mass transit usage. The operation of Shinkansen increases the attractiveness of areas along the line of Shinkansen, especially the station in city center area.

6. Equations that referred to explicitly in the text

$$u_i(x_{1i}, x_{2i}) = (\alpha_1 x_{1i}^{(\sigma_1-1)/\sigma_1} + \alpha_2 x_{2i}^{(\sigma_1-1)/\sigma_1})^{\sigma_1/(\sigma_1-1)} \quad (1)$$

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

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

$$\max_{x_{1i},x_{2i}} : u_i = (\alpha_1 x_{1i}^{(\sigma_1-1)/\sigma_1} + \alpha_2 x_{2i}^{(\sigma_1-1)/\sigma_1})^{\sigma_1/(\sigma_1-1)}$$
$$\text{s.t.} \quad p_{1i} x_{1i} + p_{2i} x_{2i} \le I_i \quad (4)$$

$$E_i = e_1 x_{1i}^* + e_2 t_{2Ci}(x_{2Ci}^*, x_{2Mi}^*) x_{2Ci}^* + e_3 t_{2Mi}(x_{2Ci}^*, x_{2Mi}^*) x_{2Mi}^*$$
$$u_i(x_{1i}^*, x_{2Ci}^*, x_{2Mi}^*) = u_i^* \quad (5)$$

$$p_{2i} = (\alpha_{2Ci}^{\sigma_2} p_{2Ci}^{1-\sigma_2} + \alpha_{2Mi}^{\sigma_2} p_{2Mi}^{1-\sigma_2})^{1/(1-\sigma_2)} \quad (6)$$

$$T_{ij}^m = T_i^m * \frac{\exp(aD_j + bZ_j + cG_{2mij})}{\sum_{j \in zones} \exp(aD_j + bZ_j + cG_{2mij})} \quad (7)$$

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Appendix A

Maximum mobility problem:

$$\max_{x_{2Ci},x_{2Mi}} : x_{2i} = (\alpha_{2C} x_{2Ci}^{(\sigma_2-1)/\sigma_2} + \alpha_{2M} x_{2Mi}^{(\sigma_2-1)/\sigma_2})^{\sigma_2/(\sigma_2-1)}$$
$$\text{s.t.} \quad p_{2Ci} x_{2Ci} + p_{2Mi} x_{2Mi} \le I_{2i}$$

Using Lagrangian method, the likelihood function y is built as follows:

$$y = (\alpha_{2C} x_{2Ci}^{(\sigma_2-1)/\sigma_2} + \alpha_{2M} x_{2Mi}^{(\sigma_2-1)/\sigma_2})^{\sigma_2/(\sigma_2-1)} - \lambda(p_{2Ci} x_{2Ci} + p_{2Mi} x_{2Mi} - I_{2i})$$

The ratio of the first-order partial derivatives equals to 0:

$$\partial y/\partial x_{2Ci} = (\lambda p_{2Ci}/\alpha_{2C})^{-\sigma_2} (\alpha_{2C} x_{2Ci}^{(\sigma_2-1)/\sigma_2} + \alpha_{2M} x_{2Mi}^{(\sigma_2-1)/\sigma_2})^{\sigma_2/(\sigma_2-1)} - \lambda p_{2Ci} = 0$$

$$\partial y/\partial x_{2Mi} = (\lambda p_{2Mi}/\alpha_{2M})^{-\sigma_2} (\alpha_{2C} x_{2Ci}^{(\sigma_2-1)/\sigma_2} + \alpha_{2M} x_{2Mi}^{(\sigma_2-1)/\sigma_2})^{\sigma_2/(\sigma_2-1)} - \lambda p_{2Mi} = 0$$

$$\partial y/\partial \lambda = p_{2Ci} x_{2Ci} + p_{2Mi} x_{2Mi} = 0$$

Solving above three equations, optimal solutions of car trips x_{2Ci}

and mass transit trips x_{2Mi} are obtained as Eqs. (A(1) and A2):

$$x_{2Ci} = \left(\frac{\alpha_{2C}}{p_{2Ci}}\right)^{\sigma_2} \frac{I_{2i}}{\alpha_{2C}^{\sigma_2} p_{2Ci}^{1-\sigma_2} + \alpha_{2M}^{\sigma_2} p_{2Mi}^{1-\sigma_2}} \quad (A1)$$

$$x_{2Mi} = \left(\frac{\alpha_{2M}}{p_{2Mi}}\right)^{\sigma_2} \frac{I_{2i}}{\alpha_{2C}^{\sigma_2} p_{2Ci}^{1-\sigma_2} + \alpha_{2M}^{\sigma_2} p_{2Mi}^{1-\sigma_2}} \quad (A2)$$

The maximum mobility is shown as Eq. (A3):

$$x_{2i} = (\alpha_{2C}^{\sigma_2} p_{2Ci}^{1-\sigma_2} + \alpha_{2M}^{\sigma_2} p_{2Mi}^{1-\sigma_2})^{(1/\sigma_2 - 1)} \cdot I_{2i} \quad (A3)$$

The price of mobility goods is shown as Eq. (A4):

$$p_{2i} = (\alpha_{2C}^{\sigma_2} p_{2Ci}^{1-\sigma_2} + \alpha_{2M}^{\sigma_2} p_{2Mi}^{1-\sigma_2})^{1/(1-\sigma_2)} \quad (A4)$$

Maximum utility problem based on maximum mobility:

$$\max_{x_{1i}, x_{2i}} : u_i = (\alpha_1 x_{1i}^{(\sigma_1-1)/\sigma_1} + \alpha_2 x_{2i}^{(\sigma_1-1)/\sigma_1})^{\sigma_1/(\sigma_1-1)}$$
$$s.t. \quad p_{1i} x_{1i} + p_{2i} x_{2i} \le I_i$$

Using Lagrangian method, the optimal solutions of composite goods x_{1i}^* and mobility goods x_{2i}^* are given by Eqs. (A(5) and A6):

$$x_{1i}^* = \left(\frac{\alpha_1}{p_{1i}}\right)^{\sigma_1} \frac{I_i}{\alpha_1^{\sigma_1} p_{1i}^{1-\sigma_1} + \alpha_2^{\sigma_1} p_{2i}^{1-\sigma_1}} \quad (A5)$$

$$x_{2i}^* = \left(\frac{\alpha_2}{p_{2i}}\right)^{\sigma_1} \frac{I_i}{\alpha_1^{\sigma_1} p_{1i}^{1-\sigma_1} + \alpha_2^{\sigma_1} p_{2i}^{1-\sigma_1}} \quad (A6)$$

As individuals are assumed to maximize their mobility and utility at the same time, the traffic budget is calculated as Eq. (A7):

$$I_{2i} = p_{2i} x_{2i}^* = p_{2i} \left(\frac{\alpha_2}{p_{2i}}\right) \frac{I_i}{\alpha_1^{\sigma_1} p_{1i}^{1-\sigma_1} + \alpha_2^{\sigma_1} p_{2i}^{1-\sigma_1}} \quad (A7)$$

According to Eqs. (A(1),A2),(A4) and (A7)), the optimal solutions of car trips x_{2Ci}^* and mass transit trips x_{2Mi}^* for maximum utility are listed as Eqs. (A(8), and A9)),:

$$x_{2Ci}^* = \left(\frac{\alpha_{2C}}{p_{2Ci}}\right)^{\sigma_2} \alpha_2^{\sigma_1} (\alpha_{2C}^{\sigma_2} p_{2Ci}^{1-\sigma_2} + \alpha_{2M}^{\sigma_2} p_{2Mi}^{1-\sigma_2})^{\sigma_2-\sigma_1/1-\sigma_2} \left\{ \alpha_1^{\sigma_1} p_{1i}^{1-\sigma_1} + \alpha_2^{\sigma_1} (\alpha_{2C}^{\sigma_2} p_{2Ci}^{1-\sigma_2} + \alpha_{2M}^{\sigma_2} p_{2Mi}^{1-\sigma_2})^{\frac{1-\sigma_1}{1-\sigma_2}} \right\}^{-1} I_i \quad (A8)$$

$$x_{2Mi}^* = \left(\frac{\alpha_{2M}}{p_{2Mi}}\right)^{\sigma_2} \alpha_2^{\sigma_1} (\alpha_{2C}^{\sigma_2} p_{2Ci}^{1-\sigma_2} + \alpha_{2M}^{\sigma_2} p_{2Mi}^{1-\sigma_2})^{\sigma_2-\sigma_1/1-\sigma_2} \left\{ \alpha_1^{\sigma_1} p_{1i}^{1-\sigma_1} + \alpha_2^{\sigma_1} (\alpha_{2C}^{\sigma_2} p_{2Ci}^{1-\sigma_2} + \alpha_{2M}^{\sigma_2} p_{2Mi}^{1-\sigma_2})^{1-\sigma_1/1-\sigma_2} \right\}^{-1} I_i \quad (A9)$$

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