Estimating the Efficiency of Transportation Energy Consumption based on Railway Infrastructure and Travel behavior Characteristics

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Abstract

In recent years, energy consumption in the transportation sector by expanding motorization continues to increase in almost every country in the world. Moreover, the growth rate of the transportation energy consumption is significantly higher than those of the civilian and industrial sectors. Therefore, every country strives to reduce its dependence on private transport, which is the main contributor to the transportation energy consumption. In many countries, concepts such as Transit Oriented Development (TOD) or New Urbanism, which controls road traffic by increasing the proportion of the public transportation significantly, have been implemented to encourage a modal shift to public transport. However, the level of change required for eliminating environmental problems is a challenging task. Minimizing transportation energy consumption by controlling the increase of the traffic demand and maintaining the level of urban mobility simultaneously is a pressing dilemma for each city. Grasping the impact of the diversity of the urban transport and infrastructure is very important to improve transportation energy efficiency. However, the potential for reducing urban transportation energy consumption has often been ineffectively demonstrated by the diversity of cities. Therefore, the accuracy of evaluating the current efficiency rate of the urban energy consumption is necessary. Nevertheless, quantitative analyses related to the efficiency of transportation energy consumption are scarce, and the research on the current condition of consumption efficiency based on international quantitative analysis is almost nonexistent. On the basis of this background problem definitions, this research first built a database of the transportation energy consumption of private modes in 119 cities, with an attempt to reflect individual travel behaviors calculated by Person Trip data. Subsequently, Data Envelopment Analysis (DEA) was used as an assessment method to evaluate the efficiency of transportation energy consumption by considering the diversity of the urban traffic features in the world cities. Finally, we clarified the current condition of consumption efficiency by attempting to propose a target values for improving transportation energy consumption.

Keywords : Efficiency of transportation energy consumption, Global cities database, Railway infrastructure, Travel behavior, Data Envelopment Analysis (DEA), Person trip data (PT data)

1. Introduction

In recent years, in each city in the world, people's travel range has expanded due to motorization in parallel with economic development, and the urban structure is changing with suburbanization processes. Moreover, the transportation energy consumption is increasing, resulting in serious urban problems such as air pollution and excessive energy consumption in the urban environment (Nakamura *et al*., 2004).

New city planning methods and management of technical developments for traffic systems or cutting transportation energy consumption have developed. Since 1970, many planning techniques and research projects have aimed to develop urban structure based on the concept of sustainable development. In Europe, the concept of the compact city is well-received and the urban planning related to constructing efficient urban space is underway and also, in Japan, compact cities have even been speci-

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fied as a basic policy of urban planning (Taniguchi *et al.*, 2008). Since suburbanization with low population density and increasing trip length are connected with increasing transportation energy consumption (Choi *et al.*, 2011), it is indispensable to control an individual's travel behavior for reducing transportation energy consumption, and it is important to understand the urban-transport factors according to the development of transport infrastructure. Especially, the rail infrastructure in cities contributes to reducing transportation energy consumption in general. However, the size of effects on reducing transportation energy consumption could be different from cities at the condition of rail development. Therefore, it is critically important not only to estimate the transportation energy consumption of a city, but also to clarify how the relationship between transportation energy consumption and individual travel behaviors differ according to the rail development. In order to realize the environmentally sustainable transport (EST), it becomes quite important to mitigate environmental load from the transport sector as well as to maintain the level of mobility. Because the mobility policies often come into conflict with the environmental ones, the policy decision makers need to find a way to solve the exclusiveness between these two policies (Yoshino *et al.*, 2010). We endeavor to clarify the efficiency of transportation energy consumption from the various urban-transport factors with DEA(Data Envelopment Analysis) cost efficiency model focusing on the transport system. In this context, Feng *et al.*, (2007) and Ahmad *et al.*, (2009) evaluated the energy efficiency in transport sector by using SFA(Stochastic Frontier Analysis) or DEA. Moreover, Yoshino *et al.*, (2010) applied DEA to measure the efficiency of energy consumption at a given level of mobility in public and private transport system. They defined the efficiency of transportation energy consumption with the ratio between energy consumption and the average travel speed of each mode. Nevertheless, these studies used different approaches, they commonly defined the energy efficiency as a ratio of transport index (input) and environmental index (output) or defining mobility with only trip speed is not sufficient enough to reflect the actual travel behavior. The above definitions remain an important problem which does not consider the diversity of transport systems inherent in each city. Obviously the energy efficiency must be influenced by several factors. The weight of each factor could also vary depending on the level of infrastructure development, transport investment and so on. However, most of the existing studies put equal weight on all factors. Meanwhile, the economic level of city has an effect on the relationship between urban density and characteristics of travel behaviors. Choi

et al., (2012) clarified that despite similarities in urban structure, the economic level of the city influences modal choice and the characteristics of travel behaviors which impacts transportation energy consumption and infrastructure development. However, their research did not consider how the condition of transportation infrastructure (i.e., railway system) could have effects on the propensity to transportation energy consumption or its efficiency related to economic feasibility.

Therefore, we defined the efficiency of transportation energy consumption as creating more economical value with less environmental impact of Private Motorized Modes (PMM) by imposing adjusted weights. Here, we consider that GRDP is the economical outcome of the traffic activities generated by people who participate in social economical activities in a city. And, daily trip number of public modes and PMM also can be thought of as the results of traffic activities purposing production activity in a city. In this context, the outputs reflect the economical concept attributed to traffic activities.

2. Definition of Trip in this Research and the Estimation Method of Transportation Energy Consumption

2.1 Definition of trip

From the viewpoint that reduction of the transportation energy consumption can be obtained by controlling individual modes of transportation appropriately, the current research extracted data for trips made by private motorized modes (PMM; passenger car, motorcycle, and taxi). Hence, the freight traffic, from which the travel characteristics are difficult to grasp Person Trip data (here in after PT), was excluded from this research. In addition, the trip mode used in trips with the longest trip time in a complete trip was treated as the representative mode for the trip. Furthermore, extracted trips below 4 km/h on the representative mode were excluded from target trip as walking and maximum trip speed is set as 100 km/h. Moreover, this research restricted a trip length within 150 km/trip for considering maximum diameter of the urban area targeted in the current research. As for counting the passenger numbers on PMM trips on the Japanese PT, the passenger number cells are sometimes left blank or "N/A", despite the presence of a driver. In this case, the PT information was counted as "1" for the driver. Finally, the trips are extracted from the condition that trips made with at least on extremity (origin and/or destination) inside the urban area and based on the household inside the urban area. However, the US cities are only considered household constraint due to the limitation on data contents of the PT

data from NHTS (National Household Travel Survey).

In this research, trips that follow the above constraint conditions were extracted from the total trip made within the target area and used to estimate the transportation energy consumption.

2.2 Estimation method for transportation energy consumption by private motorized modes

The most standard method to estimate transportation energy consumption is to measure the total consumption of fuel in a city by applying statistical data of the total amount of the sold fuel, and then converting the total consumed sold fuel into energy per unit amount of fuel (Kenworthy and Laube, 1999: Morimoto and Koike, 1995). In addition, it is difficult to determine the supplying and consumption districts for fuel (Matsuhashi *et al.*, 2004). Alternatively, in Japan, as an estimation method of transportation energy consumption, the integrating energy intensity and trip length is generally used. Although the former is suitable for grasping a discharge of the total amount or total evaluation of the measure against fuel, there are limitations regarding the vehicle type and the evaluation of travel behavior in an independent trip (Morimoto and Koike, 1995). Since the latter may differ in the estimation value of energy intensity with various statistical materials, comparison between cities not straightfoward.

This research exploits the data on traffic behavior for every individual trip based on the PT data and the formula for fuel efficiency of a gasoline vehicle considering the travel speed defined from measurement of the "Sdsdynamo" experiment conducted by the ministry of the environment in Japan. From this data and estimation formula, the transportation energy consumption is calculated using equation (1).

$$E_k = \left(\frac{\sum_i^n T_i \cdot I_i \times 365}{O_k} \right) / P_k \qquad (1)$$

E_k = Annual transportation energy consumption by private motorized modes per capita in city k (MJ per capita)

T_i = Transportation energy consumption by private motorized modes in single trip i (MJ)

($i = 1, \cdots, n^k$; n^k: the number of trip sample in city k)

P_k = Urban population in city k

I_i = Expansion coefficient of each trip i

O_k = Average occupancy of passenger car in city k

Moreover, in equation (1), the transportation energy consumption by private motorized modes in single trip i can be calculated using equation (2).

$$T_i = FC_{(V_i)} \cdot HV \cdot L_i \qquad (2)$$

HV = Average calorific value of gasoline (MJ/L)

$FC_{(V_i)}$ = Fuel efficiency of a vehicle on trip i at speed v (cc/km; Motorcycle is assumed to have a half the efficiency of a car and vehicle is assumed to be gasoline vehicle; Refer to notes for the background)

L_i = Trip length of trip i (km)

V_i = Trip speed of trip i by private motorized modes (km/h)

However, in this research, the private motorized modes are limited to passenger cars, taxi, and motorcycles. Fuel efficiency of private motorized modes on trip i at speed v is obtained using equation (3) (Oshiro *et al.*, 2001).

$$FC_{(V_i)} = [829.3/V_i] - 0.8572V_i + 0.007659V_i^2 + 64.09 \qquad (3)$$

The model parameters in equation (3) are inferred from the results of the research conducted in at the Japanese research institute. However, the model parameters can be customized to country or vehicle type. The results in equation (3) are based on the use of a passenger car.

Finally, the renewal estimation method becomes a function of the vehicle speed in an individual trip. For cases where the PT data has insufficient trip information, the improved method is a form of equation (1). For European cities and several Korean cities, travel behaviors such as average vehicle speed, average trip length, and modal share of private motorized modes, are representative values due to limitations in gathering international data. Therefore, we evaluated an alternative estimation method for cases lacking these data using equation (4).

$$E_k = P_k \cdot G_k \cdot \gamma_k \cdot l_k \cdot e \qquad (4)$$

E_k = Transport energy consumption in city k (MJ)

P_k = Population in city k (person)

G_k = Average daily trip number in city k (trip)

γ_k = Modal share of private motorized modes in city k (%)

l_k = Average trip length in city k (km/trip)

e = Intensity of energy consumption (MJ/person·km)

This is useful for estimating transportation energy consumption based on average trip length for private motorized modes per day, average number of daily trips in city k, modal share of private motorized modes of transportation, and population in city k. Additionally, the average speed of the private motorized modes and the intensity of heat combustion are multiplied to estimate fuel efficiency of the vehicle. If a city has its own PT data, the renewed estimation method is promising. However, when this model cannot be applied due to a lack of PT data, the alternative method can be improved by incorporating the vehicle speed. This improvement is realized by changing the intensity factor e in equation (4) into e_k. The estimation

Table 1 Definition of data in this research

No	Indicator	Unit	Definition of data
1	Urban density	inhabitants/ha	-Ratio between the population and urban surface area
2	GRDP	$/inhabitants	-Ratio between the GRDP of the urbanized area and its population.
3	Daily trips by PMM or Public modes	Trip/ day/ inhabitants	Characterized as: -Tripsmadebypersonsover5yearsofagewhoresidein the urbanized area -Trips with at least one extreme (origin and/or destination) inside the urbanized area -Allreasonsfortravelandalltransportmodes,motorized,orotherwise -Trips on foot or bicycle are not included -Tripsmadeusingseveralmodesarecountedasonetripandassignedtoa "primary mode"
4	Average trip speed of PMM or Public modes	km/h/trip	-With reference to trips defined by indicator 3, including automobiles, motorcycles, and taxis, as PMM, including bus, metro, tram, railway transit on public as Public transport. -The actual trip speed is sought
5	Average trip distance of PMM or Public modes	km/trip	-With reference to trips defined by indicator 3, including automobiles, motorcycles, and taxis, as PMM, including bus, metro, tram, railway transit on public as Public transport. -The actual distance is sought, not a straight line distance -Inthiscase,tripsextendingbeyondtheurbanizedarea are considered.
6	Average trip duration of Public modes	min/trip	-With reference to trips defined by indicator 3, including bus, metro, tram, railway transit on public as Public transport. -The actual trip duration is sought
7	Total metro length	m/1000 inhabitants	-The computation of the length of metro in the urban area
8	Total tram length	m/1000 inhabitants	-The computation of the length of tram in the urban area
9	Total monorail length	m/1000 inhabitants	-The computation of the length of monorail in the urban area
10	Total road length	m/1000 inhabitants	-The computation of the length of road in the metropolitan area considers all roads open to public traffic located in the metropolitan area.

method for the factor e can be revised by

$$e_k = FC_{(V_k)} \cdot HV \tag{5}$$

e_k = Intensity of energy consumption of city k (MJ/person·km)

$FC_{(V_k)}$ = Fuel efficiency of a vehicle at average speed V_k(cc/km)

V_k = Average vehicle speed in city k (km/h)

3. Database on Transportation Energy Consumption of Cities in the World

3.1 Target metropolitan areas

In this research, the statistical data for each area was collected from 119 metropolitan areas in 38 countries. The data was originally collected by research institutes around the world. (See for the official names of the institutes listed in the notes) to ensure the objectivity that cities and traffic characters of metropolitan areas with similar population capacities were compared, the target cities in this study were defined as metropolitan areas with a minimum population of 800,000.

3.2 Definitions and calculation methods of travel behavior

Table 1 defines the data definition used in the current research and the origin of the data. The definition of the annual transportation energy consumption for the PMM is explained in Chapter 3. Since this research employs PT data, various data regarding different properties of travel behavior can be extracted. The definition of calculation methods agrees with the definition of data possessing bounded means.

To estimate transportation energy consumption, four main travel characteristics are considered: trip length, trip speed, daily trip number, and modal share of private motorized modes, as mentioned in the previous chapter. However, the data fields of the person trip data differ by country. It should be noted that the calculation method of travel behavior in Table 2 differs slightly by country and depends on how the person trip data was configured. Moreover, due to the limitations in the data from European cities and some Korean cities, travel behaviors were estimated throughout the whole urban area using the cities average of trip values on travel behavior.

Table 2 Calculation methods to explain travel behavior data

Data on travel behavior	Applied cities (Num. of sample cities)	Equations	Data resources (Num. of data source)	Note
Trip length (km)	Korea (9) Developing countries (14)	$L_k = V_k \cdot (\sum_1^n (I_i^{r,k} \cdot D_i^{r,k}) / \sum_1^n I_i^{r,k})$	: (4) : (2), (3)	Suwon, Sungnam in Korea are followed the equation of Europe.
	Europe (31), Wealthy Asian (4)	L_k	(2)	
	Japan (14) USA (46)	$L_k = (\sum_1^n (I_i^{r,k} \cdot l_i^{r,k}) / \sum_1^n I_i^{r,k})$	(3)	
Vehicle speed (km/h)	Korea (9)	V_k	(4)	N/A
	Developing countries (14)		(2)	
	Europe (31), Wealthy Asian (4)	$V_k = L_k / D_k$	(2)	
	Japan (14) USA (46)	$V_k = (\sum_1^n (I_i^{r,k} \cdot l_i^{r,k}) / \sum_1^n I_i^{r,k}) / (\sum_1^n (I_i^{r,k} \cdot D_i^{r,k}) / (\sum_1^n I_i^{r,k}))$	(3)	
Number of daily trips (trips/day/person)	Europe (31), Wealthy Asian (4)	T_k	(2)	Suwon, Sungnam in Korea are followed the equation of Europe.
	Korea (9), Japan (14), USA (46), Developing countries (14)	$T_k = \dfrac{\sum_1^n I_i^k}{Total\ population\ in\ city\ k}$	(3) (3) (3)	
Modal Share of PMM (Private passenger vehicle+ Motorcycle)	Europe (31), Wealthy Asian (4)	M_k^r	(3)	Private passenger vehicles, includes taxies.
	Korea (9) Japan (14), USA (46), Developing countries(14)	$M_k^r = (\sum_1^n (I_i^{r,k}) / \sum_1^n I_i^k) \times 100$	(2) (3) (3)	
Average car occupancy of passenger car	Korea (9), Europe (31), Wealthy Asian (4) Developing countries (14)	O_k^r	(3) (2) (2)	N/A
	Japan (14), USA (46)	$O_k^r = \sum_1^n (O_i^{r,k} \cdot I_i^{r,k}) / \sum_1^n I_i^{r,k}$	(3)	

Note: k =Cities (k=1, ···,119), i=Trip sample (i=1,..,n), l_i=Trip length of i, d_i=travel time of i, r=representative trip mode (r=A,B,C; A=PMM, B=PUB, C=NMM), L_k=Average trip length in city k, V_k=Average vehicle speed in city k, $D_i^{r,k}$=Average travel time of trip i by mode r in city k, T_k=Average daily trip number in city k, M_k^r=Average modal share by mode r in city k, $I_i^{r,k}$=Expansion factor of trip i by mode r in city k, O_k^r=Average occupancy of mode r in city k

3.3 Classification of cities according to development of rail systems

To understand the impact of the diversity of urban transport and infrastructure, as shown Table 3, this research classifies the target areas by the development of rail systems around the world. Rail transit has come into the spotlight for realizing transit oriented development, providing a good service on transportation, and reducing transportation energy consumption. Many researchers suggested that there is abundant evidence that high quality, grade-separated transit does reduce urban traffic congestion, and that

transit improvements can be cost effective investments. Especially, Metro and Tram system are represented as major delegates of rail transit that being in charge of urban mobility. The metro, known as the subway or tube, is the optimal public transport mode for a high capacity (above 50,000 passenger per hour per direction is possible) line or network service. The tram system is the ideal modes carrying between 3,000 and 11,000 passengers per hour per direction in much narrower rights-of-way, and also producing no emissions at street level. In this way, Metro and Tram systems have shown that it can reduce the automo-

Table 3 City classification according to rail systems

City classification	Type I	Type II	Type III	Type IV	Type V
Development of rail systems	No railway (only Road)	(Metro + Tram) only	Metro only	Tram only	Excluding Metro, Tram
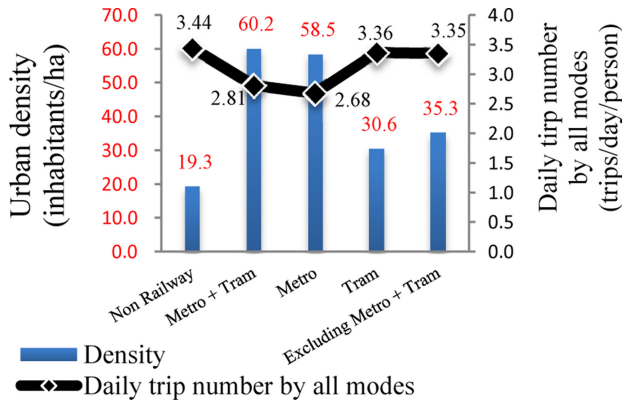
Fig. 1 Relationship between density and daily trip number

Fig. 2 Relationship between density and trip length by private motorized modes
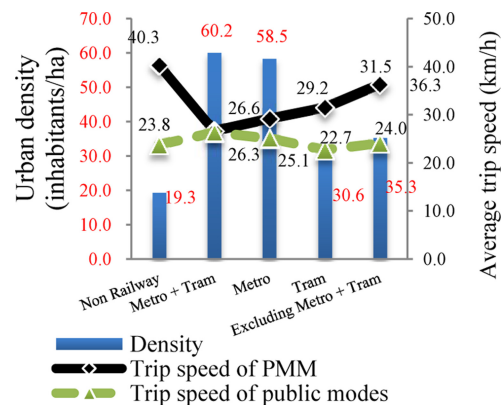
Fig. 3 Relationship between density and average speed of PMM, public modes

bile dependence in urban environments and has many positive attributes that benefit a town or city (UITP, 2001).

In this context, this research categorizes cities into five types by the development level of railway systems: Non-railway, Metro + Tram, Metro only, Tram only, excluding Metro and Tram.

Then, this research considers the relationship between urban density and travel behaviors from the viewpoint of development of rail systems.

Finally, we examine how the efficiencies of transportation energy consumption, interacting with GRDP, trips by private motorized modes and public modes, are differ by the level of railway systems.

4. Difference of Travel behaviors and Efficiencies on Transportation Energy Consumption According to Rail Systems

4.1 Relationship between urban density and travel behaviors according to rail system

This research first presented relationship between urban density and travel behaviors on the PMM and the Public modes according to the level of the rail systems. Specifically, we focused on the features of variables indicating travel behaviors which included in estimation of the transportation energy consumption (trip number, trip speed and trip length) as above Fig. 1 to 5.

Fig. 1 shows that higher urban density yields fewer daily trip numbers on average. Especially, in the case of the rail systems in Type II and Type III, the trip number is quite

low (2.81 trips/day/person in Type II, 2.68 trips/day/person in Type III) compared to other cities. This shows that the trip number in Type II rail system is the lowest under the highest urban density (60.2 inhabitants/ha).

Next, Fig. 2 reveals that higher urban density is favorable for shorter trips by the PMM. Particularly, the Type II rail system under the highest urban density generally makes trip length shorter (10.7 km/trip). In this context, Giuliano and Dhiraj (2003) built the regression model interpreting daily trip number and average trip distance in cities by applying the characteristics of the socio-economic and urban structure. Their result shows that the urban structure has significant effect on travel behaviors and there is a divergence of results. In general, the daily
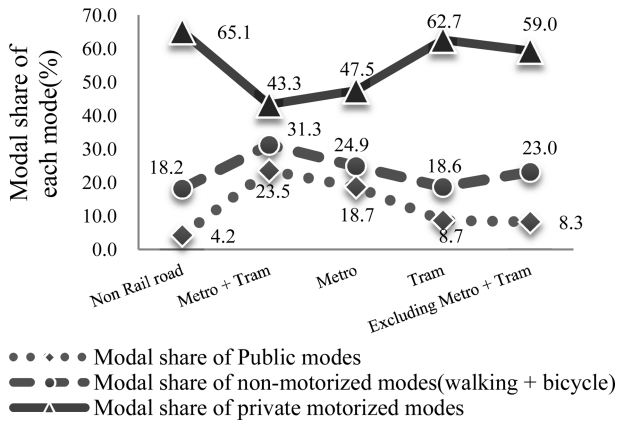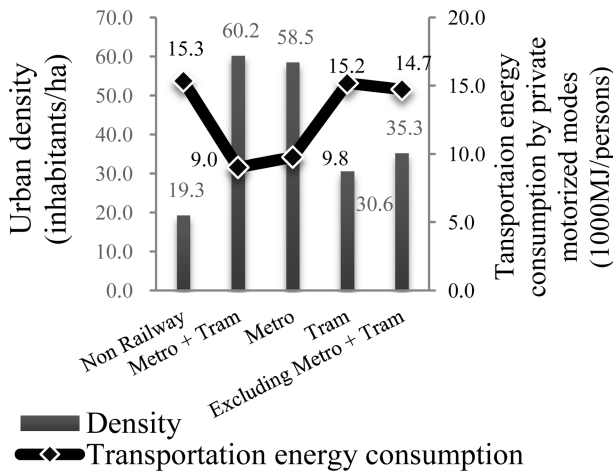
Fig. 4 Modal share of all modes

Fig. 5 Relationship between density and transportation energy consumption

trip number depends on the urban scale. The larger the urban area is, the less daily trip number is generated.

In addition, the trip distance is substantially significant with urban density, and the denser the urban structure is, the shorter the trip distance is. Fig. 3 shows the trip speed of the PMM and the public modes. In general, the speed of the PMM is slower and the speed of the public modes is faster under denser urban structure. Especially, the feature of the Type II in which the trip speed of the PMM is the slowest (26.6 km/h) and the speed of the public modes is the fastest (26.3 km/h) is outstanding. These results from Fig. 3 intensely show that denser urban structure influences travel behavior on PMM and public modes. Also, it could be conjectured that there is a relationship between denser urban structure and the travel pattern for public transport such as metro or tram.

In this context, Fig. 4 shows the ratio of the modal share according to the PMM, public modes and Non-Motorized

Modes (NMM). From here, it is possible to figure out that the modal choice for public modes and NMM are often made under the urban condition of having a railway system. Especially, the condition of the Type II restrains the use of PMM but revitalizes the use of public modes and NMM.

Therefore, it could be conjectured that development of established rail network such as link of Metro and Tram would absorb travel demands. Moreover, depending on the development of railway system, space management could be properly maintained for pedestrians or bicycle riders. Fig. 4 demonstrates that denser urban structure limits the usage of the passenger cars and promotes higher demand for public modes and walking, bicycling. In addition, the specific effect of denser urban structure appears under Type II rail system. Considering all relations between urban density and travel behaviors above, transportation energy consumption is lower under denser urban structure with an established rail system such as Type II or Type III as shown in Fig. 5.

4.2 Definition on efficiency of transportation energy consumption

We define the efficiency of transportation energy consumption in this research as creating more value with less environmental impact on the PMM. Efficiency was evaluated on the basis of two aspects: the economic level and the travel behavior. In this context, this research attempted to observe how much GRDP and trips by private motorized modes and public modes are created by transportation energy consumption of the PMM, which implies the result from the production activity in a city. The maximum efficiency is *1*, which indicates a city creating the most multi-value with less transportation energy consumption of the PMM.

4.3 Estimation method for efficiency of transportation energy consumption

Data Envelopment Analysis (DEA) is a nonparametric method in operations research for an estimation of efficiency. It is used to measure empirically the efficiency of decision making units (DMUs). This allows a best-practice relationship between multiple outputs and multiple inputs to be estimated. DMU is the subject of evaluation and the efficiency of DMU is calculated by the ratio scale of (*output / input*). If there are many entities with similar results, it is possible to make a comparison between them with the relative magnitude of the ratio scale. In addition, evaluation by a changeable weight that ignores the unit of individual variable is possible. However, DEA does not provide a general relationship between output and input. Furthermore, this evaluation method is not for absolute evaluation of efficiency but is for the relative comparison analysis between entities.

Therefore, in carrying out DEA on the efficiency of the transportation energy consumption, one needs to understand the theoretical relationship between the urban-transportation factors on reading analyzed results. Thus, this research utilizes DEA as only an estimation method for comparative analysis on the energy efficiency.

The Charnes Cooper Rhodes (CCR) model can be quoted as the most basic models of DEA. DMUs has a number of N, and when there are m of individual inputs and s of outputs, a virtual input and output are defined by equation (7), (8). Here, put a weight that can be advantageous to DMUs on the input and output. However, the efficiency is represented by a *virtual output / virtual input*, and maximum weight is 1 so that it does not take a negative value. The following formula is a fractional programming equation. The optimal solution obtained from here is (v^*, u^*), and the case of θ^* is the objective function. If $\theta^*=1$: MDU_0 is effective, if $\theta^*<1$: MMU_0 is ineffective.

The weights are obtained from each input value in the entire input on the denominator, and it is called a weighted input value. In the same way, the value on the numerator of DMU is called a weighted output value.

A virtual input $\Theta_i = v_1 \times$ input 1 + $v_2 \times$ input 2
$$+ \ldots + v_m \times \text{input } m \qquad (7)$$

A virtual output $\Theta_o = u_1$ output 1 + $u_2 \times$
$$\text{output } 2 + \ldots + u_s \text{ output } s \qquad (8)$$

Objective function $\theta^* = \dfrac{u_1 y_1 + u_2 y_2 + \ldots + u_s y_s}{v_1 x_1 + v_2 x_2 + \ldots + v_m x_m}$ (9)

Constraints $\dfrac{u_1 y_1 + u_2 y_{2j} + \ldots + u_s y_{sj}}{v_1 x_{1y} + v_2 x_{2j} + \ldots + v_m x_{mj}} \leq 1$

$$(j = 1, \ldots, n) \ldots \qquad (10)$$

$$v_1, v_2, \ldots, v_m \geq 0 \qquad (11)$$

$$u_1, u_2, \ldots, u_m \geq 0 \ldots \qquad (12)$$

4.4 Estimation of the efficiency of transportation energy consumption

This research estimates the efficiency of transportation energy consumption. The efficiency of transportation energy consumption means the ratio between the combination of GRDP, trips by PMM, public modes and the transportation energy consumption. For this, a changeable weight was imposed on the input and output variables for DEA estimation. The efficiency = 1.0 means a Frontier that DMU is relatively the most desirable city on the basis of the efficiency of the transportation energy consumption. As mentioned earlier, the efficiency from DEA does not show the relationship between urban-transportation factors. Therefore, we clarified a relationship between the urban density and the travel behaviors before utilizing DEA. Based on the findings above Fig. 1 to 5, we next examine the efficiency of the transportation energy consumption by considering target cities. And then the result was classified by the level of the rail systems as shown in Table 4, Table 5 and Fig. 6. Fig. 6, and Table 4 show the results of DEA analysis on the efficiencies of 119 cities in Asia, Europe, USA and developing countries. And the result of DEA is classified by the development of the rail systems. As shown in Fig. 6, an inverse relation between the energy efficiency and the energy consumption is observed. The efficiency ranges from 0.061 (Columbus) to 1 (Osaka, Hong Kong, Phnom Penh). Generally, the efficiency in cities of the USA of Type I which have low density is low.

Meanwhile, the cities with denser urban structure, longer railways, combination rail systems and high modal share by the public modes (i.e., Tokyo, Fukuoka, Vienna, Hong Kong, Lima) show higher efficiencies of the transportation energy consumption. Table 5 reveals that the average efficiency of transportation energy consumption is 0.3287 (Type II), 0.3086 (Type III), 0.2110 (Type V), 0.2106 (Type I) and 0.1806 (Type IV) in the order of the level of the rail system, showing high efficiency. In Fig. 6, the urban types having rail systems broadly indicate higher

Table 4 Efficiencies on transportation energy consumption

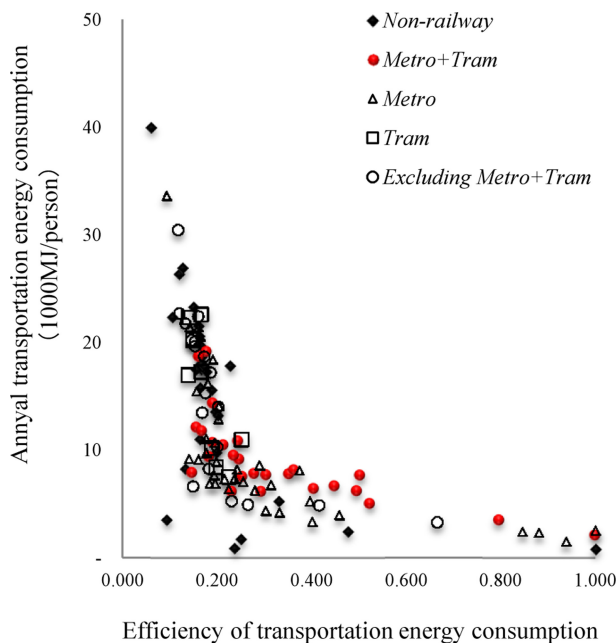| Urban Area	Type	Efficiency of transportation energy consumption	Transportation energy consumption	Urban Area	Type	Efficiency of transportation energy consumption	Transportation energy consumption	Urban Area	Type	Efficiency of transportation energy consumption	Transportation energy consumption
Charlotte	I	0.229	17,816	Vienna	II	0.405	6,483	Inchon	III	0.237	7,372
Houston	I	0.168	18,692	Amsterdam	II	0.251	7,591	Daejeon	III	0.225	6,425
Indianapolis	I	0.164	19,725	Rotterdam	II	0.182	9,428	Pusan	III	0.242	8,231
Milwaukee	I	0.189	15,596	Lyons	II	0.212	10,518	Kwangju	III	0.216	7,359
Columbus	I	0.061	39,980	Rome	II	0.156	12,156	Suwon	III	0.177	9,781
Kansas City	I	0.160	21,534	Brussels	II	0.167	11,828	Athens	III	0.161	9,169

Table 4 Continued

Urban Area	Type	Efficiency of transportation energy consumption	Transportation energy consumption	Urban Area	Type	Efficiency of transportation energy consumption	Transportation energy consumption	Urban Area	Type	Efficiency of transportation energy consumption	Transportation energy consumption
Kansas City	I	0.160	21,534	Brussels	II	0.167	11,828	Athens	III	0.161	9,169
Austin	I	0.166	18,045	Lille	II	0.189	10,754	Daegu	III	0.194	7,714
Nashville-Davidson	I	0.152	23,291	Berlin	II	0.279	7,874	Sungnam	III	0.290	8,613
Ulsan	I	0.198	9,785	Lisbon	II	0.232	6,193	Sao Paulo	III	0.303	4,428
Orlando	I	0.170	17,618	Prague	II	0.503	7,706	Kuala Lumpur	III	0.141	9,221
Cincinnati	I	0.162	20,586	Valencia	II	0.146	7,965	Lima	III	0.881	2,348
Phoenix	I	0.166	17,495	Warsaw	II	0.524	5,077	Damascus	III	0.938	1,548
Louisville	I	0.173	17,737	Budapest	II	0.360	8,197	Seattle	IV	0.153	22,623
Rochester	I	0.177	17,288	Moscow	II	0.495	6,251	Hiroshima	IV	0.225	7,524
Honolulu	I	0.196	13,552	Bucharest	II	0.448	6,713	Zurich	IV	0.252	11,013
Norfolk	I	0.122	26,343	Cairo	II	0.302	7,747	Portland	IV	0.149	17,287
Oklahoma City	I	0.202	13,237	Nagoya	III	0.314	6,812	New Orleans	IV	0.145	20,240
Providence	I	0.158	17,510	Washington	III	0.149	21,476	Memphis	IV	0.115	22,357
San Antonio	I	0.164	15,790	Boston	III	0.181	18,437	Turin	IV	0.198	8,447
Jacksonville	I	0.130	26,915	Fukuoka	III	0.280	6,279	Melbourne	IV	0.139	17,002
Dubai	I	0.165	11,005	New York	III	0.196	12,931	Manchester	IV	0.189	10,222
Hartford	I	0.106	22,352	Atlanta	III	0.154	20,591	Denver	V	0.153	22,422
Tripoli	I	0.477	2,445	Chicago	III	0.197	14,113	Dallas	V	0.161	18,703
Chengdu	I	0.251	1,747	Los Angeles	III	0.178	16,217	Minneapolis-St. Paul	V	0.108	30,467
Ho Chi Minh	I	0.135	8,252	Sendai	III	0.255	7,116	Salt Lake City	V	0.199	14,041
Hanoi	I	0.239	899	Kyoto	III	0.401	3,397	Detroit	V	0.172	17,229
Jakarta	I	0.266	4,971	Cleveland	III	0.083	33,645	Chiba	V	0.416	4,892
Managua	I	0.331	5,276	Kobe	III	0.332	4,238	San Diego	V	0.151	19,691
Nairobi	I	0.096	3,857	Baltimore	III	0.130	21,476	St. Louis	V	0.138	20,056
Phnom Penh	I	1.000	817	Miami	III	0.156	15,488	Pittsburgh	V	0.103	22,706
Osaka	II	1.000	2,148	Yokohama	III	0.396	5,304	Kitakyushu	V	0.183	8,298
Tokyo	II	0.796	3,548	Saitama	III	0.458	4,001	Copenhagen	V	0.201	10,306
San Francisco	II	0.176	19,197	Singapore	III	0.374	8,139	Kawasaki	V	0.666	3,305
Munich	II	0.189	14,397	Hong Kong	III	1.000	2,562	Sacramento	V	0.127	21,761
Oslo	II	0.245	10,908	Glasgow	III	0.177	11,084	Stuttgart	V	0.169	13,514
Philadelphia	II	0.162	18,738	Bilbao	III	0.184	6,942	Tampa	V	0.134	20,230
Paris	II	0.246	9,187	Seoul	III	0.846	2,438	Buffalo	V	0.163	15,331
Helsinki	II	0.352	7,851	Madrid	III	0.195	10,719	Seville	V	0.150	6,670
London	II	0.235	9,560	Newcastle	III	0.199	8,956	Manila	V	0.231	5,298
Sapporo	II	0.294	6,191	Barcelona	III	0.196	6,934				

Table 5 Characteristic on travel behaviors, efficiency of energy consumption and transportation energy consumption

Variables		Non Railway	Metro &Tram	Metro	Tram	Excluding Metro & Tram
Urban density (inhabitants/ha)		19.3	**60.2**	58.5	30.6	3.3
Daily trip number(trips/day)		**3.44**	2.81	2.68	3.36	3.35
Average trip distance of PMM (km/trip)		**14.3**	10.7	11.8	12.5	12.7
Average trip speed (km/h)	PMM	**40.3**	26.3	26.6	29.2	31.5
	PUB	23.8	**26.3**	25.1	22.7	24.0
Modal Share (%)	PMM	**65.1**	43.3	47.5	62.7	59.0
	PUB	4.2	**23.5**	18.7	8.7	8.3
	NMM	18.2	**31.3**	24.9	18.6	23.0
Transportation energy consumption (MJ/person/year)		**15,340**	9,008	9,764	15,190	14,731
Energy efficiency		**0.2106**	0.3287	0.3086	0.1806	0.2110

Fig. 6 Relationship between efficiency of energy consumption and transportation energy consumption

efficiency on transportation energy consumption than Type I having non-rail system. The efficiencies of Type II having Metro + Tram and Type III having Metro are particularly outstanding. Here, Type I and Type V including many US cities in which urban density is quite low show almost same efficiency.

In Fig. 6 and Table 5, one of the urban type that shows the lowest efficiency next to Type IV is Type I with no rail system. From Fig. 1 to 5, the highest trip generation, the longest trips, the slowest trip speed of public modes and the highest energy consumption are observed for Type I. Choi *et al*, (2011) demonstrated that the longer trip, the

more trips generation under lower density such as Type I including the US cities. And also, it is possible to deduce that the efficiency of transportation energy consumption does not become effective under low urban density on the contrary to Type II and Type III including DUMs which the efficiency is 1 as shown Fig. 6. Meanwhile, Phnom Penh (1.000), Tripoli (0.477), Managua (0.331) in Type I show relatively high energy efficiency as shown in Table 4 even if they are non-railway type for which the common trend of economic level (GRDP) in these cities is quite low. From this result, it is possible to conjecture that people have to rely on the public modes due to less car ownership under low economic status. In this context, the high modal share of the public transport in the above cities could affect the result that the energy efficiency is high due to the adjustable weight of the DEA model. Meanwhile, the efficiency of Type IV is the lowest relative to other the rail systems and Type I. According to Fig. 3, 4 and 5 as shown above, Type IV, with only tram, shows the slowest trip speed of the public modes, the highest modal share of the PMM and transportation energy consumption among urban types having a rail system even though the rail system is constructed. Especially, the urban density (30.6 inhabitants/ha) of Type IV is the lowest among the urban types having the rail system. This might mean that the rail system under low density does not show the correlation between a rail network and restraining usage, energy consumption of the PMM.

5. Conclusion

This research built a database of 119 cities concerning transportation energy consumption of the private motorized modes, and it reflects individual travel behaviors cal-

culated by Person Trip data. In addition, we established the relationship between urban density and travel behaviors before utilizing DEA that considers the diversity of urban-transport features. Consequently, we clarified that denser urban structure, with well-maintained railway system (such as Metro + Tram), could divert the private vehicle users to the public transport, hence decrease the transportation energy consumption, and encourage NMM. Therefore, it seems that denser urban structure and well-constructed railway systems have meaningful relationship with realizing higher efficiency of transportation energy consumption.

The results provide practical and reliable information related to reducing transportation energy consumption through the propensities of travel behaviors and efficiencies on energy consumption. Furthermore, understanding the relations between urban structure and travel behaviors according to the level of railway systems will be invaluable for measures to reduce energy consumption in urban development planning.

Notes

1. KTDB: Korean Transport Database. MLITT: Ministry of Land. Infrastructure. Transport and Tourism. JICA: Japan International Cooperation Agency. UITP: International Association of Public Transportation. FHWA: Federal Highway Administration U.S. Department of Transportation

2. Korea: Population and housing census (2005). Wealthy Asian: Periodic surveys(censuses. mobility studies) of International Association of (UITP)2001. countries: The study on master plan for urban transport in the metropolitan area-(Cairo. Tripoli.(2001); Phnom Penh. Belem. Chengdu. Jakarta. Kuala Lumpur(2000); Damascus. Managua(1998); Manila(1997); Bucharest(1999); Lima. Hanoi(2005); Ho Chi Minh(2003); Nairobi(2004))

3. Korea: Household Travel Survey((2005)-Inchon. Suwon. Sungnam (2006)). Japan: The Nationwide Person Trip Survey(2005). U.S.A: NHTS(National Household Travel Survey. 2001). Developing countries: Household Interview Survey of each country-(Cairo. Tripoli.(2001); Phnom Penh. Belem. Chengdu. Jakarta. Kuala Lumpur(2000); Damascus. Managua(1998); Manila(1997); Bucharest(1999); Lima. Hanoi(2005); Ho Chi Minh(2003); Nairobi(2004))

4. Korea: The Statistics Report of each city(2005). Japan: The Statistics Report of each city(2005). U.S.A: U.S. Department of Transportation. Federal Highway Administration. Highway Statistics 2001

5. U.S.A: Regional Economic Accounts Bureau of Economic Analysis U.S. Department of Commerce

6. All of vehicle in this research is assumed as gasoline vehicles

7. Fuel efficiency of motorcycle is assumed a half of passenger car

References

1. Ahmad, A., Fujiwara A. and Zhang, J., (2009). "A DEA analysis of energy consumption in transport sector and carbon dioxide emissions in selected 85 countries of the world", CD-ROM, Proceeding of Infrastructure Planning, Vol. 39.

2. Aratani, T. and Todoroki, T., (2009). "An analysis on inter-city mobility by public transportation service using data environment analysis", Committee of Infrastructure Planning and Management, No. 39 in Japanese.

3. Choi, H., Nakagawa, D., Matsunaka, R. and Oba, T., (2011). "Building a database of transportation energy consumption in cities of the world with information related to travel behavior", Journal of International City Planning 2011, pp. 263-272.

4. Choi, H., Nakagawa, D., Matsunaka, R. and Oba, T., (2012). "International research on the relationship between urban structure and transportation energy consumption according to economic level", The Australian Journal of Regional Science, Vol. 18, No. 1, pp. 128-149.

5. Feng, T., Zhang, J. and Fujiwara, A., (2007). Environmental Efficiency Analysis of Transportation System: A Stochastic Frontier Approach with Flexible Cause-Effect Structure, Journal of the EASTS, Vol. 7, pp. 1475-1489.

6. Giuliano, G. and Dhiraj, N., (2003). "Another look at travel patterns and urban form: The US and great britain", Urban Studies, Vol. 40, No. 11, pp. 2295-2312.

7. Kenworthy, J.R., Laube, F.B., Newman, P.W.G, Bater, P.A., Raad, T., Poboon, C. and Guia, B., (1999). "An international sourcebook of automobile dependence in cities 1960-1990", University Press of Colorado, Boulder, Co.

8. Matsuhashi, K., Kudoh, Y., Kamioka, N. and Moriguchi, Y., (2004). "A study on estimation method for transport CO_2 emissions by municipalities", Environmental System Analysis and Research, Vol. 32, pp. 235-242 in Japanese.

9. Morimoto, A., (2002). "A research review on compact city in terms of transportation environmental load", CD-ROM, Proceeding of Infrastructure Planning, Vol. 25 in Japanese.

10. Morimoto, A. and Koike, H., (1995). "A comparison of the urban structure impact upon transportation energy", Journal of the City Planning Institute of Japan, No. 30, pp. 685-690 in Japanese.

11. Oshiro, Y., Matsushita, M., Namikawa, R. and Onish, H. (2001). "Fuel consumption rate and a carbon dioxide discharge coefficient in a vehicle travel", Civil Engineering Journal, Vol. 43 No. 11, pp. 50-55 in Japanese.

12. Taniguchi, M., Matsunaka, R. and Hirano, M. (2008). "Time-Series Analysis of the Relationship between Urban

Layout and CO_2 Emission by Automobile", Journal of the City Planning Institute of Japan Vol. 43, No. 3, pp. 121-126 in Japanese.

13. Yoshino D., Fujiwara, A. and Zhang J. (2010). "Environmental efficiency model based on data envelopment analysis and its application to environmentally sustainable transport policies", Journal of the Transportation Research Board, Vol. 2163, pp. 112-123.

14. Nakamura, H., Giuliano, G., Sperling, D., May, A., D, Miyamoto, K., Rithengatter, W. (Eds.). (2004). "*Urban Transport and the Environment-An International Perspective*", World Conference on Transport Research Society and Institute for Transport Policy Studies. Amsterdam: Elsevier.