Environmental Efficiency Model Based on Data Envelopment Analysis and Its Application to Environmentally Sustainable Transport Policies[1]

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ABSTRACT

In order to realize the environmental 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 mobility policies often come into conflict with the environmental ones, policy decision makers need to find a way to solve the exclusiveness between these two policies. This study attempts to apply the concept of “Eco-efficiency” originally proposed by WBCSD to relax the dilemma between urban mobility and environmental load in developed/ing cities.

This study newly proposes an environmental efficiency (EE) model expanding the concept of DEA (Data Envelopment Analysis) cost efficiency model. The EE model aims to measure the efficiency of energy consumption at a given level of mobility in each transport system, by incorporating some feasible conditions such as inter-city heterogeneity, irreversibleness of transport infrastructure investment, and so on. In addition, the model finds multiple sets of frontier cities which are most efficient among three homogeneous developed cities; i.e., public transport oriented city, private car oriented city and balanced city. Consequently, the proposed method will contribute to put a feasible goal of transport energy consumption in each city.

Moreover, the panel analysis is carried out to examine temporal changes in EE in each city. The Malmquist index is used to resolve the efficiency into two components; the change in technical efficiency and the change in technological innovation.

Finally, the effects of some EST policies to raise the efficiency are simulated based on the EE model, those are the modal shift in city, the technological innovation to improve the intensity of energy consumption in city and the emissions trading scheme between developing and developed cities. It is turned out that the method will be a useful tool to set more plausible targets of transport energy saving policies.

1. INTRODUCTION

Currently, the public concern about environmental issues is growing. It is no exception in transport sector, and the heat debate and serious negotiations about countermeasures have been done at nation and city levels. Meanwhile, it is no doubt that motorization brought by transport infrastructure investments has contributed to improve the economical growth and the QOL in developed cities (i.e., cities in wealthy developed countries with higher GDP per capita). Similar as developed cities, developing cities (i.e., cities in developing countries with poor GDP per capita) also have a right to guarantee the economic growth and the QOL, policies promoting motorization are still required in there.

From the viewpoint of global warming issues, developed/ing cities should make efforts collaboratively to reduce energy consumption from transport sector toward a low-carbon society. Each city therefore has to execute appropriate policies of the environmental sustainable transport (EST). On the line of the Kyoto Protocol, it would become quite important for developing cities not only to minimize environmental load, but also to maintain the level of mobility. Policy decision makers need to find solutions of the exclusiveness between these two countermeasures. The concept of “Eco-efficiency” proposed by WBCSD in 1992 (*1*), in short which is concerned with creating more value with less impact, must be useful to have compatible between their economical growth and environmental conservation.

This study attempts to expand the concept to develop an Environmental efficiency (EE) model based on Data Envelopment Analysis (DEA) cost efficiency model focusing on transport systems. The basic ideas behind DEA date back to Farrel (*2*), but the resent series of discussions started with articles by Charnes et al. (*3*). In addition, Coelli et al. (*4*), and Cooper et al. (*5*) offer us well-organized overviews systematically. In this paper, the EE model is newly estimated by using a four-wave panel data collected from 46 cities all over the world (*6*,*7*). Finally, models are applied to evaluate some policies for efficient energy consumptions.

This paper is organized as follows. Section 2 reviews existing literatures focusing on the EE. In section 3, the theory and characteristics of the EE model are described. The following section 4 describes the estimation results of the EE models and section 5 evaluates some EST policies. In the final section, the key conclusion and future tasks are summarized.

2. ENVIRONMENTAL EFFICIENCY: METHODOLOGICAL REVIEW AND DEFINITION

There are some literatures dealing with EE in transport studies. Senbil et al. (*8*) employed Stochastic Frontier Analysis (SFA) to evaluate the structure of transport energy consumption. In addition, they argued some factors significantly affects on the EE by using Tobit model. Pitt and Smith (*9*), Feng et al. (*10*), Ahmad et al. (*11*) also evaluated the EE in transport sector by using SFA or DEA. Nevertheless these studies used different approaches, they commonly defined the EE as a ratio of transport index (input) and environmental index (output)..

The above definition however remains some unsolved problems. One of them is the diversity of transport systems inherent in each city. Obviously the EE must be influenced by several factors. The weight of each factor could also vary depends on the levels of infrastructure development, transport investment, land use pattern, and so on. However, existing studies put even weights for all factors. The ignorance of diversity of transport systems in deciding its own countermeasures of the energy saving may mislead to set a uniform target of efficiency across cities. To solve this issue, we need a new EE models to deal with adjustable weights.

Another problem is inter-city heterogeneity of the energy consumption structure. In general, cities have different historical paths of the development and the investment for urban facilities and transport infrastructures, and consequently they have the different attributes (i.e., levels of infrastructure developments, population density and distribution, land use patterns) currently. Also they would like to put different targets depend on their philosophy of city perspectives and city master plan. The sets of influential factors on current energy consumption are not stable across cities. The existing SFA and DEA models based on the simple ratio between input and output cannot argue the heterogeneous structure of energy consumption in detail. We are also required to employ a new of EE model to cope with this methodological issue.

According to the problems, this study attempts to apply a new cause-effect structure of energy consumption based on the concept of DEA cost efficiency model (*12*,*13*). To consider the inter-city diversity of transport systems, we will discriminate all cities into some homogeneous groups beforehand with the model estimation. Moreover regarding the inter-city heterogeneity of the energy consumption structure, we will propose a new EE model which consists of measurement equations to capture causal factors and their inconstant weights.

In the cost efficiency model, we suppose input indices can be expressed by the function of factors related to the travel demand, and the energy intensity can set as cost indices that mean input unit value. Concretely speaking, average annual trip distances [km] for public and private transports are employed as input indices, and the energy intensities that indicate energy consumption per passengers-kilometer [MJ/passenger-km] for each mode are employed as cost indices. By multiplying input indices by cost indices, total amount of energy consumption is obtained. Moreover, the average trip speed (the average of two modes) [km/h] is used as output indices which explain the level of city mobility.

The proposed DEA cost efficiency model assumes m inputs, s outputs and n cities, respectively. The efficiency (EE_k) of city k can be express as in equation (1):

(1)

where, x_{ij} is the observed input index i $(i = 1, 2, \cdots, m)$, p_{ij} is the observed cost per unit input i, c_k is the observed energy consumption. Then, c_k^* is the optimum energy consumption that minimizes the total energy consumption for public/private transports under the condition of securing the current level of output index, and x_i^* is the optimized amount of input i obtained by the following cost efficiency model (2)-(7).

$$\text{minimize} \quad \sum_{i=1}^{m} p_{ik} x_{ik} \tag{2}$$

$$\text{subject to} \quad -\sum_{j=1}^{n} x_{ij}\lambda_j + x_i \geq 0, \qquad (i = 1,2,\cdots,m), \tag{3}$$

$$\sum_{j=1}^{n} y_{rj}\lambda_j \geq y_{rk}, \qquad (r = 1,2,\cdots,s), \tag{4}$$

$$\sum_{j=1}^{n} \lambda_j = 1, \tag{5}$$

$$\lambda_j \geq 0, \qquad (j = 1,2,\cdots,n), \tag{6}$$

$$x_i \geq 0, \qquad (i = 1,2,\cdots,m), \tag{7}$$

where, y_{rj} is the observed output index r $(r = 1,2,\cdots,s)$, λ is the weight of *j*th city (non-negative n dimension vector). The equation (2) includes the input vector $\mathbf{X} = (x_1, x_2, \cdots, x_m)^T$ as a set of causal factors that vary across cities. It minimizes the total amount of energy consumption based on the vector of energy consumption intensity $\mathbf{P}_k$.

3. DEVELOPMENT OF ENVIRONMENTAL EFFICIENCY MODEL

3.1 Efficiency Analysis Considering Heterogeneous Energy Consumption Structures Across Cities

Introduction of the Input Index with a Political Threshold

Because the energy intensity of public transport (PT) is superior to that of private car (PC) in general, it is necessary to reduce the PC use more than the PT use. It also seems hard to assume that the infrastructure for PT (i.e., railway, station, etc.) which has already been constructed will be abandoned to improve the inner-city energy consumption structure. Therefore, another condition is added in equations (2)-(7) that the input index of PT should be maintained the status quo (*14*). Here, the condition is called as the input index with a political threshold.

An Integrated Frontier Curve by Considering Heterogeneous Energy Consumption Structure Efficiency across Cities

Due to its own philosophy of transport planning, each city has different targets of transport mode to improve the mobility level in a whole city. The conventional DEA looks for an optimum solution on the frontier curve referring all PT-oriented, PC-oriented and PT/PC balanced cities with different attributes. However, it is not reasonable to compromise the cities with different perspective and approach to decide a frontier.

Against this problem, this study supposes not to allow the convexity of productivity set in PT-oriented, PC-oriented, and PT/PC balanced cities. Concretely speaking, at first, three frontier curves (cf., dashed curves in FIGURE 1) are independently drawn based on reference sets of three groups respectively. Then they are combined as an integrated frontier of each group (cf., bold solid curve). Finally, to measure the EE, each city universally searches the reference sets on the integrated frontier curve cross the boundary of its own production area. This approach allows us not to deprive the possibility of potential city development and enable us to effectively evaluate the EE (*15*).

In this approach, all cities should be a priori distinguished into several exclusive groups. The cluster analysis was used to decide groups in this study, where Euclid distance was calculated based on levels of infrastructure development such as the road length per capita and the operation distance of public transport per capita. As a result of the analysis, we categorized each city into three clusters; PC-oriented, PT-oriented and PT/PC balanced cities at four different points in time from 1960 to 1990 as seen in TABLE 1. Note that due to the reason descript in the following section, developing cities (i.e., GDP is less than 10,000 [USD/capita] at each time point) are not included in reference sets.

Introduction of Non-Reference Set

There exists irreversibleness in transport infrastructure investment. Developed cities which have already invested in transport infrastructure do not retrocede their mobility level to the lower one as developing cities, even if developing cities is identified as more efficient cities due to their excessively less energy consumption. Thus we additionally assume that developing cities belong to the non-reference set, which is they are not included in any reference sets for developed cities to avoid infeasible evaluation.

3.2 Development of Environmental Efficiency Model

Supplementing the conditions of equations (2)-(7) as discussed in the previous section, we derive a new EE model of city *k* as the mixed integer non linear programming given in equations (8)-(20):

minimize $$c_k = \sum_{i=1}^{m} p_{ik} x_i \tag{8}$$

subject to $$\sum_{j=1}^{n'} x_{ij}\lambda_{Aj} + \sum_{j=n'+1}^{n''} x_{ij}\lambda_{Bj} + \sum_{j=n''+1}^{n'''} x_{ij}\lambda_{Cj} \le x_i, \quad (i = 1,2,\cdots,m'), \tag{9}$$

$$x_{ik} \le x_i, \quad (i = m'+1,\cdots,m), \tag{10}$$

$$\sum_{j=1}^{n'} y_{rj}\lambda_{Aj} + \sum_{j=n'+1}^{n''} y_{rj}\lambda_{Bj} \ge y_{rk}, \quad (r = 1,2,\cdots,s), \tag{11}$$

$$\sum_{j=1}^{n'} \lambda_{Aj} = z_A, \tag{12}$$

$$\sum_{j=n'+1}^{n''} \lambda_{Bj} = z_B, \tag{13}$$

$$\sum_{j=n''+1}^{n'''} \lambda_{Cj} = z_C, \tag{14}$$

$$x_i \ge 0, \quad (i = 1,2,\cdots,m), \tag{15}$$

$$z_A + z_B + z_C = 1, \tag{16}$$

$$\lambda_{Aj} \ge 0, \quad (j = 1,2,\cdots,n'), \tag{17}$$

$$\lambda_{Bj} \ge 0, \quad (j = n'+1,\cdots,n''), \tag{18}$$

$$\lambda_{Cj} \geq 0, \qquad \left(j = n'' + 1, \cdots, n'''\right), \qquad (19)$$

$$z_A, z_B, z_C = 0 \; or \; 1, \qquad (20)$$

where, i is the input index without threshold $(i = 1,2,\cdots,m')$ and with threshold $(i = m'+1,\cdots,m)$, r is the output index $(r = 1,2,\cdots,s)$. A,B and C are the groups of cities, j indicates cities in group A: PC oriented cities $(j = 1,2,\cdots,n')$,in group B:PC oriented cities $(j = n'+1,\cdots,n'')$, and in group C:PT/PC balanced cities $(j = n''+1,\cdots,n''')$ in non-reference set $(j = n'''+1,\cdots,n)$. λ_{Aj} , λ_{Bj} and λ_{Cj} are n' , $n''-(n'+1)$ and $n'''-(n''+1)$ dimensional non-negative vectors, respectively. z_A , z_B and z_C are dichotomous variables (0,1).

FIGURE 1 illustrates the concept of the proposed EE model, where for example the x-axis indicates the ratio between average PC trip distance (i.e., demand as an input index) and average trip speed (i.e., mobility level as an output index) and the y-axis indicates the ratio between average PT trip distance and average trip speed. Thus the lower value in x-/y-axis implies more efficient in terms of PC/PT energy consumption, respectively. Suppose a city *T* in group B (i.e., PC-oriented city) whose contour line of the energy consumption is drawn by dash-dotted line. The point *T'* on the integrated frontier curve meets the optimum. Accordingly the ratio of the optimal efficiency level of energy consumption *OT'* to the current efficiency level of energy consumption *OT* represents the EE score of city *T*.

3.3 Explore to the Panel Analysis

When the EE model is used as cross-section analysis, z_t^t is a solution of z_t in this model as shown in FIGURE 2. In the instance of time series, however, the frontier may shift within a given range of time period from time *t* to *t+1*. Moreover, as we saw results of the cluster analysis in TABLE 1, each city has temporally changed the group belonging to during four time periods in 1960-90. In the circumstance, the performance at time *t* should be re-evaluated by the frontier at *t+1*. The Malmquist approach can be applied to evaluate the frontier shift caused by a technological innovation (*16*).

In FIGURE 2, z_t and z_{t+1} indicate the performances of a city at times *t* and *t*+1. f_t and f_{t+1} express frontiers at times *t* and *t*+1. It is known that the Malmquist index (*17*) can be resolved into the catch up (CU) index with the frontier shift (FS) index as in equation (21), where the former one means the temporal change of the distance to the frontier and the latter states the temporal shift of the frontier.

$$M_k = CU \; Index * FS \; Index$$
$$= \frac{F^{t+1}\left(x^{t+1}, y^{t+1}\right)}{F^{t}\left(x^{t}, y^{t}\right)} \cdot \left[\frac{F^{t}\left(x^{t+1}, y^{t+1}\right)}{F^{t+1}\left(x^{t+1}, y^{t+1}\right)} \cdot \frac{F^{t}\left(x^{t}, y^{t}\right)}{F^{t+1}\left(x^{t}, y^{t}\right)}\right]^{\frac{1}{2}}$$

$$\begin{pmatrix} F^{t}\left(x^{t}, y^{t}\right) = z_t^t / z^t \\ F^{t+1}\left(x^{t+1}, y^{t+1}\right) = z_{t+1}^{t+1} / z^{t+1} \\ F^{t}\left(x^{t+1}, y^{t+1}\right) = z_t^{t+1} / z^{t+1} \\ F^{t+1}\left(x^{t}, y^{t}\right) = z_{t+1}^{t} / z^{t} \end{pmatrix} \qquad (21)$$

where, $F(x, y)$ indicates the EE score of a city with input *x* and output *y*. The superscript of *F* indicates the time period of frontier and the superscripts of *x* and *y* indicate the time periods of input and output indices, respectively. If the FS index is less than 1.0, the technology falls retrogressive over the cities. Otherwise, the technology gets progressive. If the CU index becomes less than 1.0, the EE score in the corresponding city declines between two time points, otherwise the EE score increases. Therefore, the Malmquist indices calculated before and after the introduction of EST policies implies the effects of the policy implement.

4. EVALUATION OF ENVIRONMENTAL EFFICIENCY IN TRANSPORT SYSTEMS

For the purpose of confirming it applicability to the policy analysis, the proposed EE model was applied to measure the EE of transport systems by using world-wide city database of 46 cities at four different points in time (1960, 1970, 1980, 1990) as shown in TABLE 2. Due to the space limitation, the analysis results in 1990 will be discussed in this paper.

The cities shaded in TABLE 2 have the EE score of 1.0, which means the cities form the frontier. Meanwhile, the bold cities belong to reference sets in corresponding groups. Consequently, it is found that Copenhagen and Hong Kong in PT-oriented cities are referred by many cities in not only PT-oriented cities but also other type cities. These two cities therefore hold a dominant position in terms of the EE. But two third of PC-oriented cities set up reference sets in PC-oriented cities (i.e., Denver, Sacramento, and Winnipeg). This implies that obtained EE scores reflect characteristics of individual cities. Interestingly, Los Angeles, that is originally a member of PC-oriented cities, can potentially improve the EE by referring PT-oriented cities. Namely the city needs to shift from the PC-oriented to the PT-oriented city to improve the EE. Since the EE model proposed in this study allows to cross the border of city groups, we can estimate such a latent potential improvement of EE. Furthermore, relaxing constraints to form reference sets within their own group make us to find more feasible and practical solutions.

FIGURE 3 classifies cities into four cases based on the combination of CU/FS indices (*11*) during the last four decades. For example, case 1 shows a desirable growth of the entire of global society, which implies environmental technologies are developing in frontier cities and intended cities also catch up frontier cities. On contrary, in case 2, the improvement of consumption structure stays stagnant in intended cities. In contrast, it is relatively improved in frontier cities. Therefore, the gap between frontier cities and the rest is widening. In case 3, the improvement of environmental technologies stays stagnant in frontier cities, and other cities catch up frontier cities. Case 4 is the worst case, environmental technologies stays stagnant all cities.

FIGURE 4 shows changes of CU/FS indices in all cities (1960-1990). As a general trend from 1960 to1990, each city makes a transition from case 3 to case 2. This trend shows that frontier cities are developing their environmental technologies in this term. Especially, PT-oriented and compact cities (i.e., Copenhagen and Hong Kong) have an advantage. In contrast, PC-oriented cities and developing cities cannot catch up frontier cities. In such a case, it would be effective to make policies to promote technologies transfer from frontier cities to other cities. For example, the effective utilization of intellectual property rights that haven't been gotten in operation yet, the effective utilization of human capital by personal exchanges, promotion of inter-city coordination by the joint research, and so on. Concretely speaking, introduced policies in frontier cities in 1990 might be some help for making transport policies in other cities. For instance, in Copenhagen, the Finger Plan which goes ahead with the transport oriented development has been introduced (*18*). Besides this, many transport policies are introduced in there, for instance, the regulation of the loading ratio, the building of the bicycle path, and so on. In regard to the bicycle path, it also has been built in Canberra. Concerning other frontier cities, in Hong Kong, the high density PT network has been built. About Denver and Sacramento, the transit network also has been developed in these cities, and the transit moll was introduced (*19*). Such kind of advanced policies might be useful to other cities, and its will be helpful to fill up gaps.

5. EVALUATION OF POLICIES IMPROVING ENVIRONMENTAL EFFICIENCY

5.1 Transport Policies in Cities

The ideal structure of transport energy consumption in each city can be theoretically derived by the EE model. However, this optimal value from EE model is estimated only from I/O indices and the cost index, some solutions may not be necessarily realistic and practical. It is hence required to propose some selected policies to realize environmentally efficient cities.

There are two approaches to efficient in the EE model. One is that promoting shift the value from lower intensity to the higher one. The other is the hold-down of the cost index. The farmer indicates the modal shift, and the latter indicates improvement of energy intensity.

Modal Shift

In this case study, we will examine a policy promoting the modal shift from the lower intensity mode (i.e., PC) to the higher one (i.e., PT). To prevent infeasible policies, it is required to put an upper limit of the modal change. First we will estimate a new DEA model called as “Energy use efficiency model” (*20*). The model is basically based on the output-oriented DEA model (*5*) that maximizes the output subject to a fixed input. While the output-oriented model can be directly applied to maximize the use of PT, it cannot be applied to minimize the use of PC. But unfortunately, the model that minimizes the output subjects to a fixed input is not computable in DEA program. Then, we transform the model as a maximization problem in calculate the efficiency of PC as shown in FIGURE 5: the average annual travel distance of PC in each city (output index) is substituted to a value of [2 μ -observation], where μ is a mean between minimum and maximum of observations by referring Tone (*15*). In FIGURE 5, observations expressed by grey circles, and this output is the smaller the better. However, as stated previously, the minimization problem cannot be solve in DEA, then observations should be converted to [2 μ -observation] which expressed by black circles. In this way, we can estimate the PC efficiency.

Note that in the output-oriented DEA model, the efficiency score $\eta = 1.0$ represents the highest efficiency similar as in the EE model. The efficiency score, however, indicates higher than 1.0 in case of inefficient cities. The detail definition can be seen in TABLE 3. The energy use efficiency model can be given in equation (22).

maximize η (22)

subject to

$if\ \ j = 1, \cdots, n'$ (Developed Cities)

$$-\sum_{j=1}^{n'} x_{ij}\lambda_j + x_{ik} \geq 0, \qquad (i = 1,2,\cdots,m), \qquad (23)$$

$$\sum_{j=1}^{n'} y_{rj}\lambda_j \geq \eta y_{rk}, \qquad (r = 1,2,\cdots,s), \qquad (24)$$

$$\sum_{j=1}^{n'} \lambda_j = 1, \qquad (25)$$

$$\lambda_j \geq 0, \qquad (j = 1,2,\cdots,n'), \qquad (26)$$

$if\ \ j = n'+1, \cdots, n$ (Developing Cities)

$$-\sum_{j=n'+1}^{n} x_{ij}\lambda_j + x_{ik} \geq 0, \qquad (i = 1,2,\cdots,m), \qquad (27)$$

$$\sum_{j=n'+1}^{n} y_{rj}\lambda_j \geq \eta y_{rk}, \qquad (r = 1,2,\cdots,s), \qquad (28)$$

$$\sum_{j=n'+1}^{n} \lambda_j = 1, \qquad (29)$$

$$\lambda_j \geq 0, \qquad (j = n'+1,2,\cdots,n), \qquad (30)$$

where, x_{ij} and y_{ij} are *i*th input and *r*th output variables of city *j*; developed cities $(j = 1,2,\cdots,n')$ and developing cities $(j = n'+1,\cdots,n)$, respectively, and λ is a non-negative weight.

According to equations (22)-(30), developing cities refer all cities including developed/ing ones, while developed cities are restricted not to refer developing cities by considering the irreversibleness of infrastructure developments.

Improvement of the Energy Efficiency

In this study, the scenario to improve the energy efficiency is based on the leading runner approach that each city sets a target to the most efficient city. Since the energy efficiency score in Copenhagen is smallest in all cities (2.1[MJ-pkm]) in 1990, other 45 cities are trying for this score.

5.2 Emissions Trading Policy among Cities

The EE index calculated in this study can imply more efficient energy consumption structures by reflecting heterogeneous city attributes. It is also able to establish the feasible target of energy reduction for each city. The target could provide a standard of emissions trading policy between a pair of cities as shown in FIGURE 6.

Suppose that there are four cities A-D that have different current energy consumptions per capita [MJ/person] and their EE score. We calculate the total amount of energy surplus (=actual observed consumption - optimum consumption) from all cities by using the EE scores, and then reallocate the total amount to all cities evenly (light shades in FIGURE 6). The total amount of the optimum consumption plus the allocated consumption indicates the energy cap (limit) [MJ/person] for each city.

For example, city A whose current consumption exceeds the cap must buy the allowance (=actual consumption - the cap) from cities B-D. In contrast, the cities B-D rewarded for having reduced emissions by more than was needed can sell their surplus to city A as a transfer of their allowances. Based on this approach, we finally obtained the target of energy reduction and the energy allowance of trading for each city as in FIGURE 6.

The allowance of energy trading between cities is transferred to a monetary value in practice and the equivalent amount of energy is regarded as the energy reduction of the buyer. But in fact, since the seemingly reduced energy does not bring the actual reduction of the annual average travel distance in each buyer as an input index of the EE model, there is no change of the energy consumption structure before and after the trading policy. Furthermore, although the seller will get the value by trading, there is still not the actual change of energy. Consequently, the frontier does not shift with/without the trading policy.

In estimating the EE indices of buyers before and after the policy, assumed that the frontier line is stable, the minimized energy consumption c_k^* can be calculated by inputting the current data into equation (8). In this sense, the optimum energy consumption after the policy implementation could be equal to the optimum one calculated in chapter 5. The energy reduced by the emissions trading scheme can also be calculated by using the following equation (31).

$$EE_k = \frac{c_k^*}{c_k - c'_k} = \frac{\sum_{i=1}^{m} p_{ik} x_i^*}{\sum_{i=1}^{m} p_{ik} x_{ik} - c'_k} \qquad (31)$$

where, c'_k indicates the amount of energy reduced by emissions trading, that assumes a constant value inherent in each city.

6. COMPARISON OF POLICIES BASED ON THE MALMQUIST APPROACH

To compare the effects of three policies, those are the modal shift, the improvement of energy intensity and inter-city emission trading. The Malmquist approach is finally applied to explain the changes in structure of two frontiers that are obtained before and after the implementation of policies. In case of the emission trading policy, however, the energy consumption structure is stable before and after the policy implementation, FS index could be zero as mentioned in the last chapter.

FIGURE 7 shows overall average scores of the CU index, the FS index, and the Malmquist index accompany each policy. The Malmquist index gives the highest improvement of the energy intensity. Especially, because the improvement of the energy intensity is obviously excellent about the FS index, it would appear that this policy is brought mainly by the technological innovation, and it is expected to lead to the recurrent development of more advanced technology. On the other hand, the emission trading policy is excellent in terms of CU index, so that this policy will contribute to catch up the frontier by utilizing existing technologies. The modal shift shows relatively lower score both in CU/FS indices.

7. CONCLUSIONS

This study proposed the EE model based on the DEA cost efficiency model that estimates the EE score by evaluating the performance of city energy consumption structure. We applied the EE model to assess the energy efficiency of 46 world cities including both developed/ing cities. The model is applied to represent the city heterogeneity of the transport energy consumption structure by relaxing the convex assumption across the different cluster groups. Consequently the heterogeneous cities with different characteristics are not distinguished in the same reference set. Moreover cities are allowed to refer the cities in neighboring clusters, and then we can estimate the potential improvement of EE at a city. These could not be achieved unless the proposed EE model.

In addition, the panel analysis shows that the gap of quality in the environmental technology between frontier cities and other cities have been a growing problem in 1960-90. To solve this problem, it is important for frontier cities to extend their advanced technology to other cities.

In terms of evaluating transport policies, we dealt with the modal shift and the intensity improvement. Furthermore, we attempted to evaluate the emissions trading scheme between cities. The proposed method can search the optimum levels of allowance by considering the current energy consumption structure in corresponding cities. It is turned out that the proposed approach will be a useful tool to set more feasible and efficient targets in emissions trading scheme.

On the other hands, there still remains future works to improve the EE model. The EE scores obtained in this study may not always be accurate due to the available data limitation and some string assumptions. For instance, the EE score is based on only two factors: the PT and PC use, but the EE should be composed not only the transport use but also various factors. Therefore, we should note that the applicability of the approach is macroscopic. Furthermore the cost variable was regarded as a fixed one by following the EE model. However, the energy intensity of PT should be changeable due to the change of transport distance. Obviously we must relax such an assumption to realize the evaluation results. Also in policy analyses, limited by the data availability, we did not implicitly include the monetary cost of trading. It is required to improve the database concerning energy consumption both in developed/ing countries. Because of beyond the main study purpose, this paper picked only the limited policies to confirm the performance of the EE model. Needless to say, various kinds of ETS policies should be urgently discussed to mitigate the global warming issues.

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TABLE 1 Estimation Results of the Cluster Analysis

Time	**1960**			**1970**		
Cluster	**PC-oriented**	**PC/PT balanced**	**PT-oriented**	**PC-oriented**	**PC/PT balanced**	**PT-oriented**
Road length [m/capita]	6.94	2.67	2.03	7.29	4.63	3.12
PT length [m/capita]	24.22	60.37	103.80	21.14	57.58	95.34
# of city [1)]	17	11	3	17	16	5
City	Amsterdam Boston Calgary Denver Detroit Edmonton Houston Munich Ottawa Phoenix Portland Sacramento San Diego San Francisco Vancouver Washington	Brussels Chicago Copenhagen Frankfurt Hamburg Los Angeles Montreal New York Paris Toronto Vienna Winnipeg	London Stockholm Zurich	Amsterdam Boston Calgary Canberra Denver Detroit Edmonton Houston Los Angeles Ottawa Phoenix Portland Sacramento San Diego San Francisco Vancouver Washington	Adelaide Brisbane Brussels Chicago Frankfurt Hamburg Melbourne Montreal Munich New York Paris Perth Sydney Toronto Vienna Winnipeg	Copenhagen London Stockholm Tokyo Zurich

[1)] Developing cities are not included in cluster analysis, so that total number of cities changes during four decades.

TABLE 1 (cont'd) Estimation Results of the Cluster Analysis

Time	**1980**			**1990**		
Cluster	**PC-oriented**	**PC/PT balanced**	**PT-oriented**	**PC-oriented**	**PC/PT balanced**	**PT-oriented**
Road length [m/capita]	8.39	5.35	3.36	7.11	4.97	2.23
PT length [m/capita]	18.40	56.95	108.82	24.82	62.19	127.69
# of city	9	24	5	12	21	7
City	Boston Denver Detroit Houston Los Angeles Phoenix Portland Sacramento San Diego	Adelaide Amsterdam Brisbane Brussels Calgary Canberra Chicago Edmonton Frankfurt Hamburg Melbourne Montreal Munich New York Ottawa Paris Perth San Francisco Sydney Toronto Vancouver Vienna Washington Winnipeg	Copenhagen London Stockholm Tokyo Zurich	Chicago Boston Denver Detroit Houston Los Angeles Phoenix Portland Sacramento San Diego Washington Winnipeg	Adelaide Amsterdam Brisbane Brussels Calgary Canberra Edmonton Frankfurt Hamburg Melbourne Montreal Munich New York Ottawa Paris Perth San Francisco Sydney Tokyo Vancouver Vienna	Copenhagen Hong Kong London Singapore Stockholm Toronto Zurich

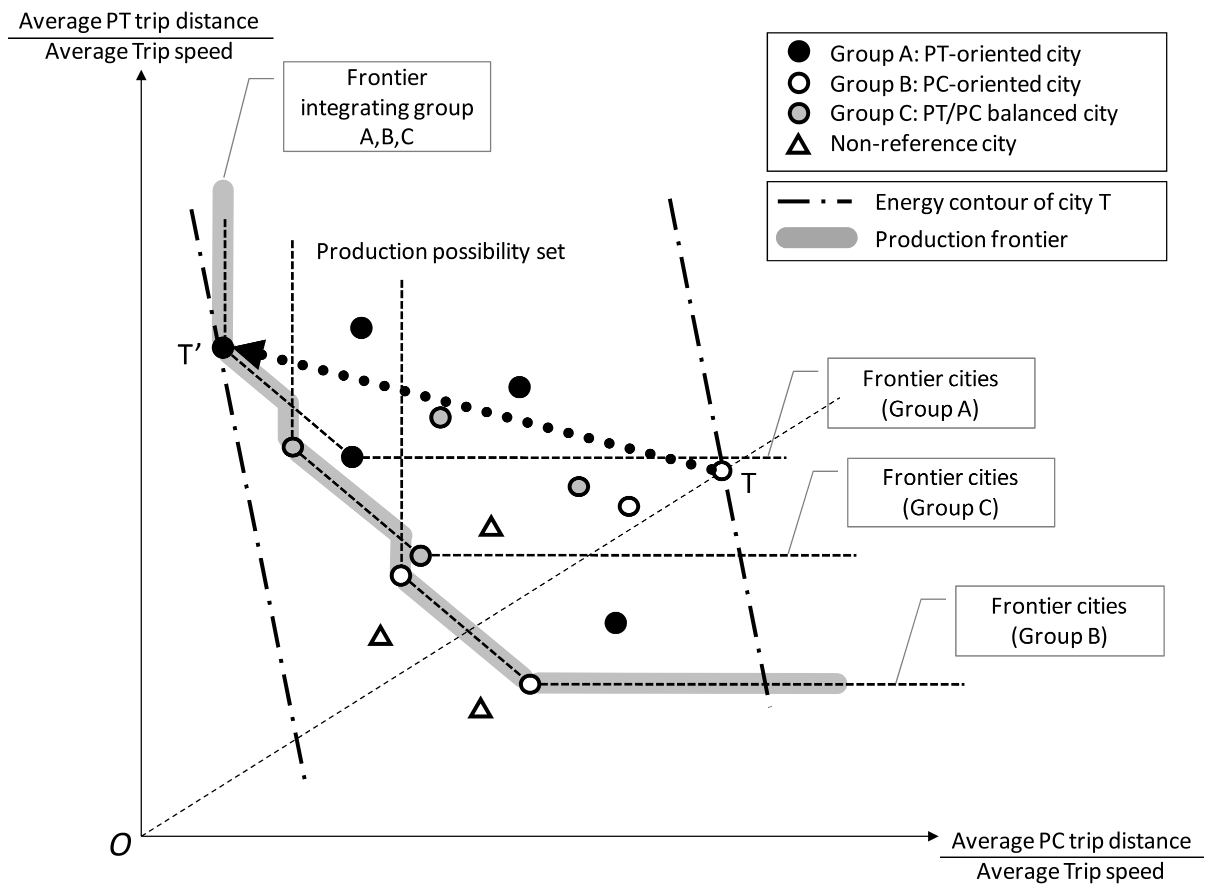

FIGURE 1 Concept of the Proposed EE Model.

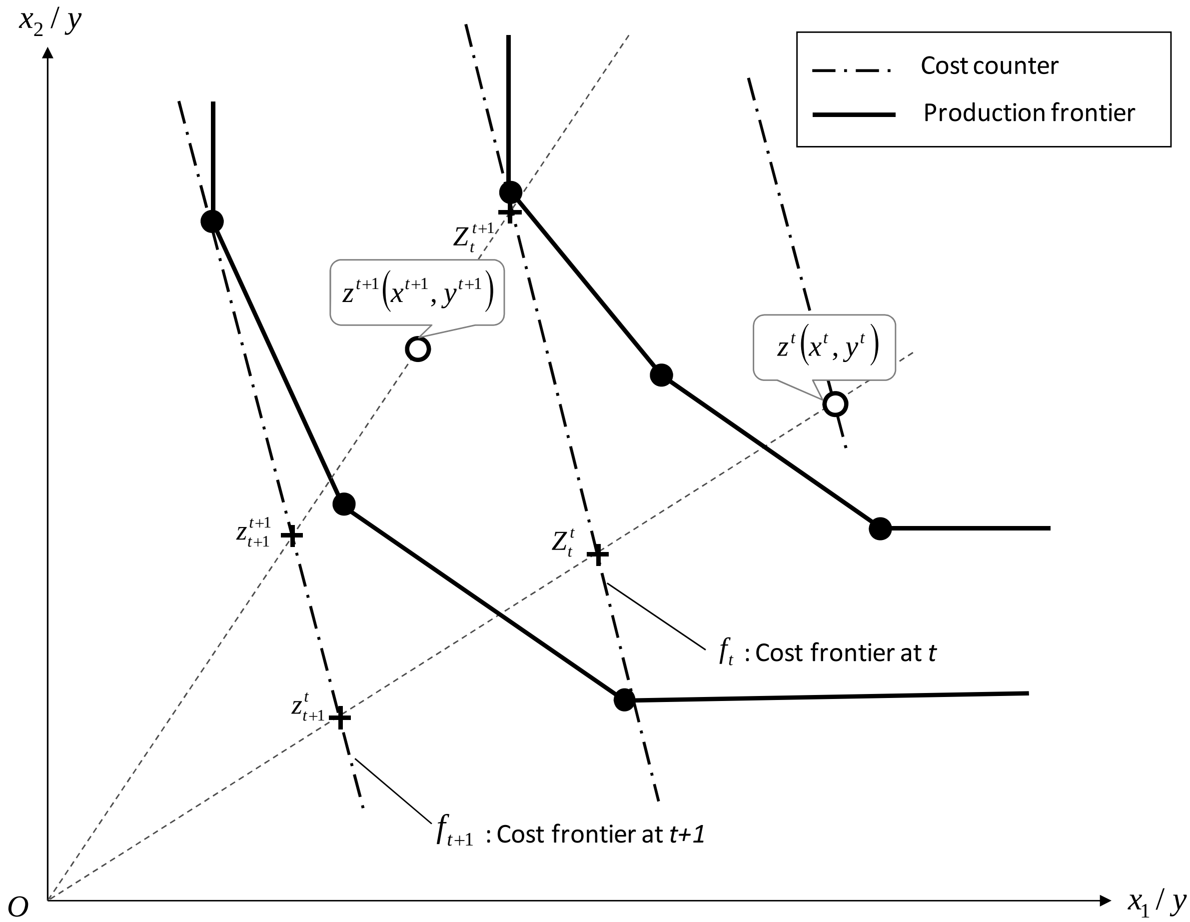

FIGURE 2 Efficiency Evaluation Based on the Malmquist Approach.

TABLE 2 Evaluation of EE Indices of Transport Systems

	City	EE score	Energy consumption [MJ/pkm]		Reference set (lambda)				
			Observed	Optimum					
PC-oriented	Boston	0.667	58,429	38,947	Canberra	(0.976)	,	Montreal	(0.024)
	Chicago	0.519	56,128	29,126	Copenhagen	(0.835)	,	Hong Kong	(0.165)
	Denver	**1.000**	**68,275**	**68,275**	**Denver**	**(1.000)**			
	Detroit	0.798	62,733	50,068	Denver	(0.954)	,	Winnipeg	(0.046)
	Houston	0.877	71,603	62,767	Denver	(0.517)	,	Sacramento	(0.483)
	Los Angeles	0.424	62,113	26,336	Copenhagen	(0.847)	,	Hong Kong	(0.153)
	Phoenix	0.751	64,661	48,543	Denver	(0.775)	,	Winnipeg	(0.225)
	Portland	0.803	70,709	56,777	Denver	(0.676)	,	Winnipeg	(0.324)
	Sacramento	**1.000**	**76,636**	**76,636**	**Sacramento**	**(1.000)**			
	San Diego	0.668	67,213	44,900	Denver	(0.930)	,	Winnipeg	(0.070)
	Washington	0.422	60,466	25,514	Copenhagen	(0.728)	,	Hong Kong	(0.272)
	Winnipeg	**0.458**	**39,365**	**18,018**	**Copenhagen**	**(0.363)**	**,**	**Hong Kong**	**(0.637)**
PC/PT-balanced	Adelaide	0.608	37,099	22,557	Copenhagen	(0.860)	,	Hong Kong	(0.140)
	Amsterdam	0.617	19,820	12,237	Copenhagen	(0.303)	,	Hong Kong	(0.697)
	Brisbane	0.906	39,296	35,614	Denver	(0.659)	,	Winnipeg	(0.341)
	Brussels	0.659	28,902	19,039	Copenhagen	(0.378)	,	Hong Kong	(0.622)
	Calgary	0.629	47,157	29,665	Copenhagen	(0.871)	,	Hong Kong	(0.129)
	Canberra	**1.000**	**45,010**	**45,010**	**Canberra**	**(1.000)**			
	Edmonton	0.561	44,026	24,684	Copenhagen	(0.644)	,	Hong Kong	(0.356)
	Frankfurt	0.697	38,268	26,666	Copenhagen	(0.630)	,	Hong Kong	(0.370)
	Hamburg	0.407	36,744	14,949	Copenhagen	(0.155)	,	Hong Kong	(0.845)
	Melbourne	0.623	38,934	24,250	Copenhagen	(0.778)	,	Hong Kong	(0.222)
	Montreal	**0.859**	**77,788**	**66,851**	**Copenhagen**	**(0.588)**	**,**	**Hong Kong**	**(0.412)**
	Munich	0.797	18,195	14,508	Copenhagen	(0.382)	,	Hong Kong	(0.618)
	New York	0.467	51,655	24,142	Copenhagen	(0.483)	,	Hong Kong	(0.517)
	Ottawa	0.646	33,635	21,733	Copenhagen	(0.520)	,	Hong Kong	(0.480)
	Paris	0.666	24,255	16,151	Copenhagen	(0.208)	,	Hong Kong	(0.792)
	Perth	0.534	41,396	22,086	Copenhagen	(0.831)	,	Hong Kong	(0.169)
	San Francisco	0.418	65,806	27,488	Copenhagen	(0.770)	,	Hong Kong	(0.230)
	Sydney	0.508	35,053	17,822	Copenhagen	(0.489)	,	Hong Kong	(0.511)
	Tokyo	0.532	18,243	9,709	Copenhagen	(0.077)	,	Hong Kong	(0.923)
	Vancouver	0.471	37,146	17,508	Copenhagen	(0.560)	,	Hong Kong	(0.440)
	Vienna	0.557	20,616	11,486	Copenhagen	(0.128)	,	Hong Kong	(0.872)

TABLE 2 (cont'd) Evaluation of EE Indices of Transport Systems

City		EE score	Energy consumption [MJ/pkm]		Reference set (lambda)				
			Observed	Optimum					
PT-oriented	**Copenhagen**	**1.000**	**20,430**	**20,430**	**Copenhagen**	**(1.000)**			
	Hong Kong	**1.000**	**9,605**	**9,605**	**Hong Kong**	**(1.000)**			
	London	0.648	23,351	15,126	Copenhagen	(0.281)	,	Hong Kong	(0.719)
	Singapore	0.753	18,078	13,610	Copenhagen	(0.316)	,	Hong Kong	(0.684)
	Stockholm	0.873	26,835	23,420	Copenhagen	(0.541)	,	Hong Kong	(0.459)
	Toronto	0.576	33,573	19,330	Copenhagen	(0.352)	,	Hong Kong	(0.648)
	Zurich	0.666	25,230	16,816	Copenhagen	(0.380)	,	Hong Kong	(0.620)
Developing	Bangkok	0.490	29,959	14,684	Hong Kong	(1.000)			
	Jakarta	1.256	9,072	11,397	Copenhagen	(0.064)	,	Hong Kong	(0.936)
	K.L.	0.525	20,003	10,497	Copenhagen	(0.233)	,	Hong Kong	(0.767)
	Manila	1.540	7,316	11,267	Copenhagen	(0.141)	,	Hong Kong	(0.859)
	Seoul	1.164	9,598	11,169	Copenhagen	(0.214)	,	Hong Kong	(0.786)
	Surabaya	1.286	5,606	7,212	Copenhagen	(0.068)	,	Hong Kong	(0.932)

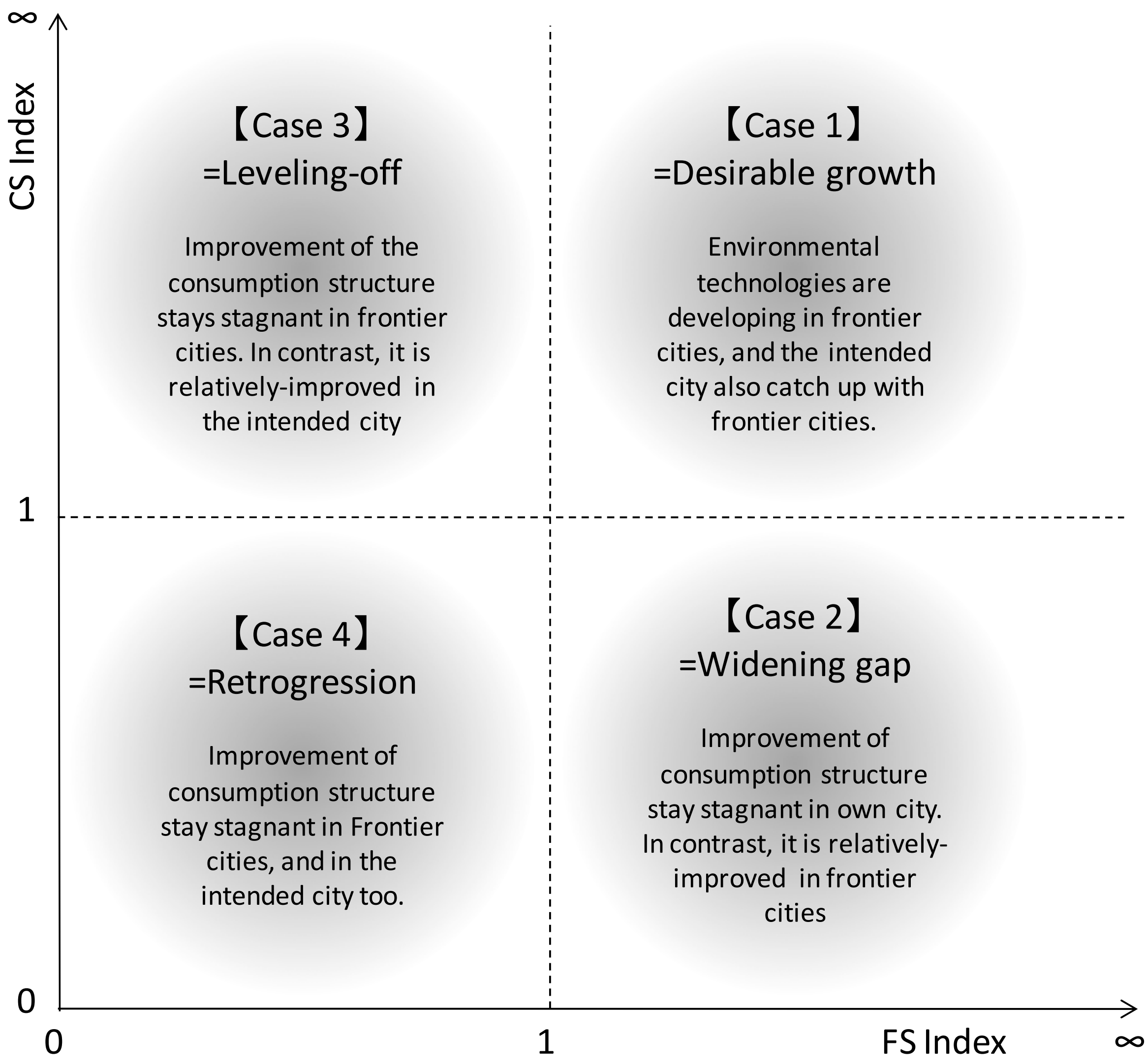

FIGURE 3 Classification of City by the CU Index and the FS Index.

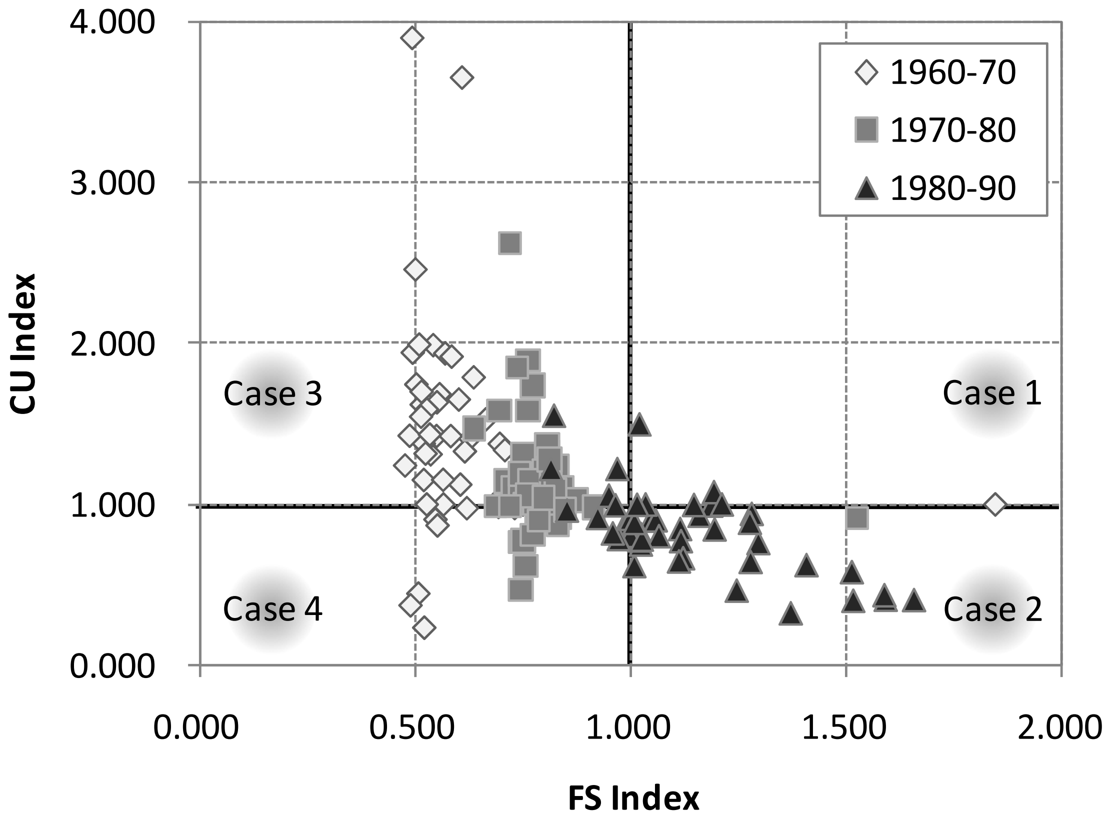

FIGURE 4 Plots of the CU Index and the FS Index.

TABLE 3 Definition of Energy Use Efficiency Models

	Private car energy use efficiency model	**Public transport energy use efficiency model**
Definition	- The model aims at calculating the surplus of average travel distance by private car. The efficiency score=1.0 implies that the PC use has been saturated under the current condition of road infrastructure and land use in the city. When the score>1.0, there remains the potential of PC energy use under the condition.	- The model aims at measuring the margin of average travel distance by public transport. The efficiency score=1.0 implies that the PT use has been saturated under the current condition of railway network and population density in the city. When the score>1.0, there remains the potential of PT energy use under the condition.
Input variables	- Population density [person/ha] - Road length per capita [m/person] - Private car ownership per capita [vehicle/person]	- Population density [person/ha] - Public transport serve length per capita [m/person]
Output variables	- Average travel distance by private car per capita [km/person]	- Average travel distance by public transport per capita [km/person]

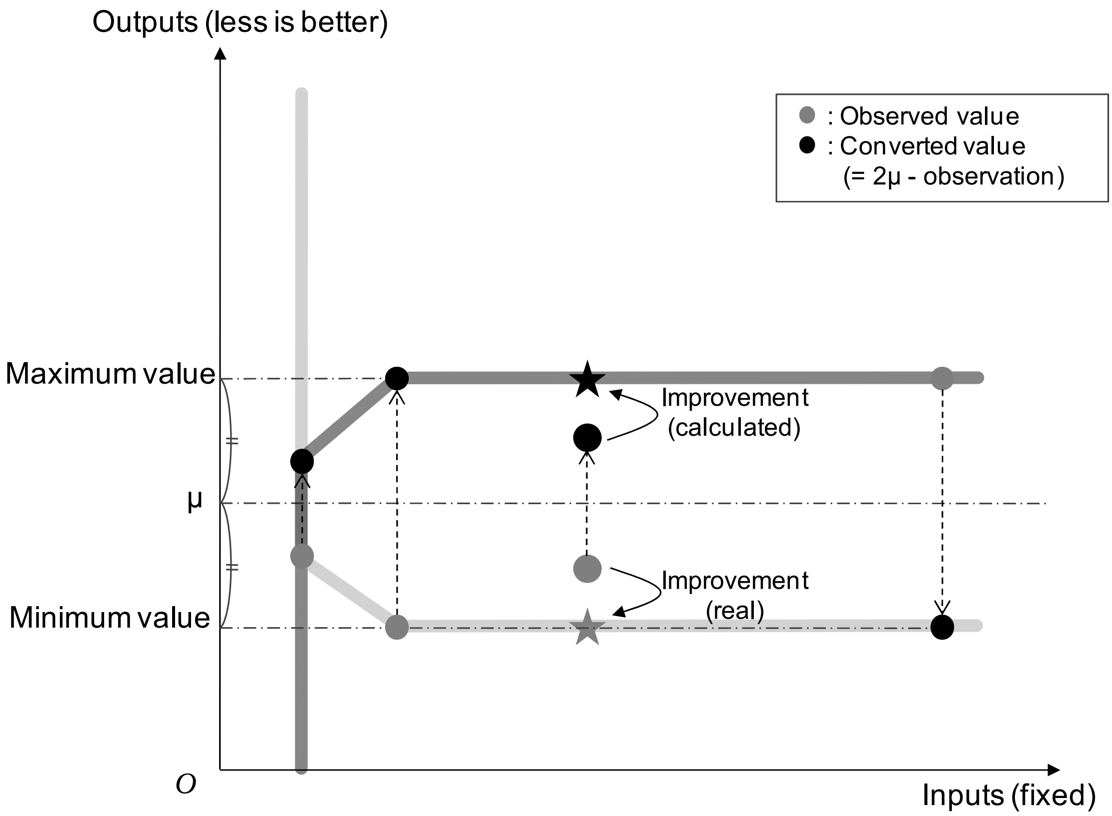

FIGURE 5 Private Car Energy Use Efficiency Model.

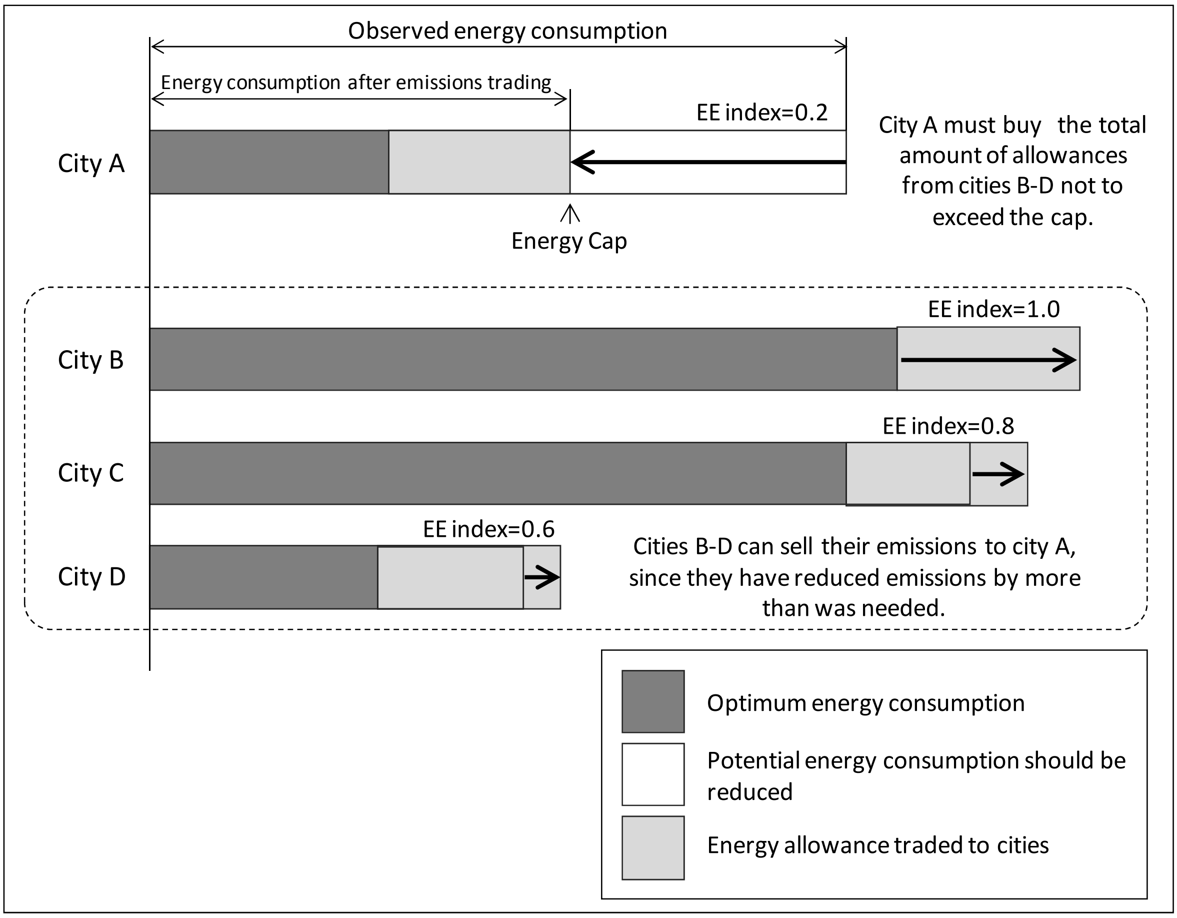

FIGURE 6 Energy Cap in Emissions Trading of Allowance.

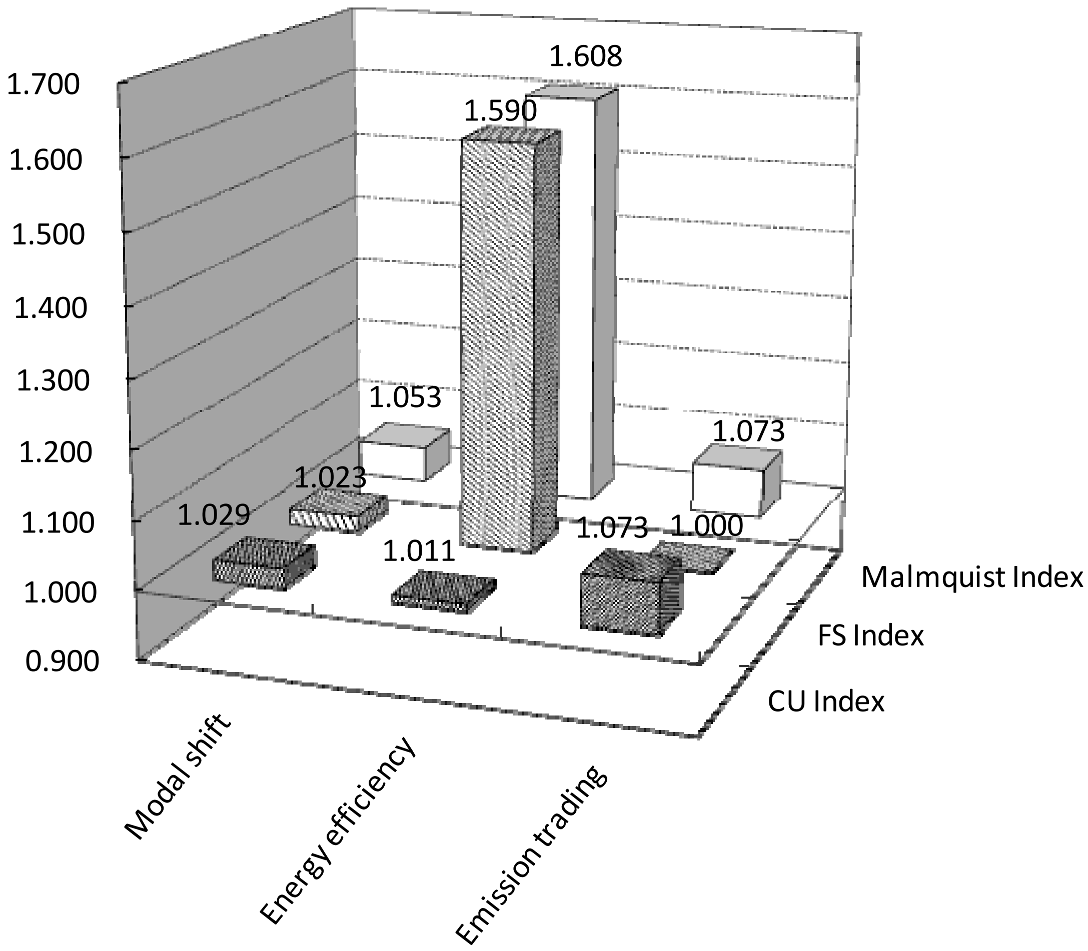

FIGURE 7 CU/FS/Malmquist Indices Score Accompany Each Policy (Overall Average).