

1 **Environmental Efficiency Model Based on Data Envelopment Analysis and**
2 **Its Application to Environmentally Sustainable Transport Policies¹**
3
4

5 Daisuke Yoshino (corresponding author)

6 Strategic Economic Planning Group, Fukken Co. Ltd., Japan

7 2-10-11, Hikari-machi, Higashi-ku, Hiroshima 732-0052, Japan

8 Tel: +81-82-506-1853; Fax: +81-82-506-1893

9 E-mail: d-yoshino@fukken.co.jp

10
11 Akimasa Fujiwara

12 Professor

13 Graduate School for International Development and Cooperation, Hiroshima University

14 1-5-1, Kagamiyama, Higashi-Hiroshima 739-8529, Japan

15 Tel/Fax: +81-82-424-6921; E-mail: afujiw@hiroshima-u.ac.jp

16
17 Junyi Zhang

18 Associate Professor

19 Graduate School for International Development and Cooperation, Hiroshima University

20 1-5-1, Kagamiyama, Higashi-Hiroshima 739-8529, Japan

21 Tel/Fax: +81-82-424-6919; E-mail: zjy@hiroshima-u.ac.jp

22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38 **Submission date:** 2009/11/15

39
40 **Word count:** Words (4,992) + Figures (7)*250 + Tables (3)*250 = 7,492

41 **Keywords:** Environmental Efficiency, DEA, Energy consumption, Urban transport system,
42 Developed and developing cities
43

¹ Paper submitted to the 89th Annual Meeting of the Transportation Research Board, January 10-14, 2010, Washington D. C.

Please send any correspondence to Mr. Yoshino, Tel: +81-82-506-1853, Fax:+81-82-506-1893,
E-mail: d-yoshino@fukken.co.jp

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, irreversibility 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

1 infrastructure development, transport investment, land use pattern, and so on. However,
 2 existing studies put even weights for all factors. The ignorance of diversity of transport
 3 systems in deciding its own countermeasures of the energy saving may mislead to set a
 4 uniform target of efficiency across cities. To solve this issue, we need a new EE models to
 5 deal with adjustable weights.

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

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

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

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

$$\text{[Empty box representing equation (1)]}$$

(1)

35 where, x_{ij} is the observed input index i ($i=1,2,\dots,m$), p_{ij} is the observed cost per unit
 36 input i , c_k is the observed energy consumption. Then, c_k^* is the optimum energy consumption
 37 that minimizes the total energy consumption for public/private transports under the condition
 38 of securing the current level of output index, and x_i^* is the optimized amount of input i
 39 obtained by the following cost efficiency model (2)-(7).
 40
 41

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

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

$$3 \quad \sum_{j=1}^n y_{rj} \lambda_j \geq y_{rk}, \quad (r = 1, 2, \dots, s), \quad (4)$$

$$4 \quad \sum_{j=1}^n \lambda_j = 1, \quad (5)$$

$$5 \quad \lambda_j \geq 0, \quad (j = 1, 2, \dots, n), \quad (6)$$

$$6 \quad x_i \geq 0, \quad (i = 1, 2, \dots, m), \quad (7)$$

7

8 where, y_{rj} is the observed output index r ($r = 1, 2, \dots, s$), λ is the weight of j th city
 9 (non-negative n dimension vector). The equation (2) includes the input vector
 10 $\mathbf{X} = (x_1, x_2, \dots, x_m)^T$ as a set of causal factors that vary across cities. It minimizes the total
 11 amount of energy consumption based on the vector of energy consumption intensity \mathbf{P}_k .

12

13

14 3. DEVELOPMENT OF ENVIRONMENTAL EFFICIENCY MODEL

15

16 3.1 Efficiency Analysis Considering Heterogeneous Energy Consumption Structures 17 Across Cities

18

19 *Introduction of the Input Index with a Political Threshold*

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

27

28

29 *An Integrated Frontier Curve by Considering Heterogeneous Energy Consumption Structure 30 Efficiency across Cities*

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

36 Against this problem, this study supposes not to allow the convexity of productivity
 37 set in PT-oriented, PC-oriented, and PT/PC balanced cities. Concretely speaking, at first,
 38 three frontier curves (cf., dashed curves in FIGURE 1) are independently drawn based on
 39 reference sets of three groups respectively. Then they are combined as an integrated frontier
 40 of each group (cf., bold solid curve). Finally, to measure the EE, each city universally

1 searches the reference sets on the integrated frontier curve cross the boundary of its own
 2 production area. This approach allows us not to deprive the possibility of potential city
 3 development and enable us to effectively evaluate the EE (15).

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

13 *Introduction of Non-Reference Set*

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

21 **3.2 Development of Environmental Efficiency Model**

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

$$26 \quad \text{minimize} \quad c_k = \sum_{i=1}^m p_{ik} x_i \quad (8)$$

$$27 \quad \text{subject to} \quad \sum_{j=1}^{n'} x_{ij} \lambda_{Aj} + \sum_{j=n'+1}^{n''} x_{ij} \lambda_{Bj} + \sum_{j=n'+1}^{n'''} x_{ij} \lambda_{Cj} \leq x_i, \quad (i = 1, 2, \dots, m'), \quad (9)$$

$$28 \quad x_{ik} \leq x_i, \quad (i = m'+1, \dots, m), \quad (10)$$

$$29 \quad \sum_{j=1}^{n'} y_{rj} \lambda_{Aj} + \sum_{j=n'+1}^{n''} y_{rj} \lambda_{Bj} \geq y_{rk}, \quad (r = 1, 2, \dots, s), \quad (11)$$

$$30 \quad \sum_{j=1}^{n'} \lambda_{Aj} = z_A, \quad (12)$$

$$31 \quad \sum_{j=n'+1}^{n''} \lambda_{Bj} = z_B, \quad (13)$$

$$32 \quad \sum_{j=n'+1}^{n'''} \lambda_{Cj} = z_C, \quad (14)$$

$$33 \quad x_i \geq 0, \quad (i = 1, 2, \dots, m), \quad (15)$$

$$34 \quad z_A + z_B + z_C = 1, \quad (16)$$

$$35 \quad \lambda_{Aj} \geq 0, \quad (j = 1, 2, \dots, n'), \quad (17)$$

$$36 \quad \lambda_{Bj} \geq 0, \quad (j = n'+1, \dots, n''), \quad (18)$$

$$1 \quad \lambda_{Cj} \geq 0, \quad (j = n'' + 1, \dots, n'''), \quad (19)$$

$$2 \quad z_A, z_B, z_C = 0 \text{ or } 1, \quad (20)$$

3

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

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

19

20 3.3 Explore to the Panel Analysis

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

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

33

$$M_k = CU \text{ Index} * FS \text{ Index}$$

$$34 \quad = \frac{F^{t+1}(x^{t+1}, y^{t+1})}{F^t(x^t, y^t)} \cdot \left[\frac{F^t(x^{t+1}, y^{t+1})}{F^{t+1}(x^{t+1}, y^{t+1})} \cdot \frac{F^t(x^t, y^t)}{F^{t+1}(x^t, y^t)} \right]^{\frac{1}{2}}$$

35

$$36 \quad \left(\begin{array}{l} F^t(x^t, y^t) = z_t^t / z^t \\ F^{t+1}(x^{t+1}, y^{t+1}) = z_{t+1}^{t+1} / z^{t+1} \\ F^t(x^{t+1}, y^{t+1}) = z_t^{t+1} / z^{t+1} \\ F^{t+1}(x^t, y^t) = z_{t+1}^t / z^t \end{array} \right) \quad (21)$$

37

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

10 4. EVALUATION OF ENVIRONMENTAL EFFICIENCY IN TRANSPORT SYSTEMS

11
12 For the purpose of confirming its applicability to the policy analysis, the proposed EE
13 model was applied to measure the EE of transport systems by using world-wide city database
14 of 46 cities at four different points in time (1960, 1970, 1980, 1990) as shown in TABLE 2.
15 Due to the space limitation, the analysis results in 1990 will be discussed in this paper.

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

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

38 FIGURE 4 shows changes of CU/FS indices in all cities (1960-1990). As a general
39 trend from 1960 to 1990, each city makes a transition from case 3 to case 2. This trend shows
40 that frontier cities are developing their environmental technologies in this term. Especially,
41 PT-oriented and compact cities (i.e., Copenhagen and Hong Kong) have an advantage. In
42 contrast, PC-oriented cities and developing cities cannot catch up frontier cities. In such a
43 case, it would be effective to make policies to promote technologies transfer from frontier
44 cities to other cities. For example, the effective utilization of intellectual property rights that
45 haven't been gotten in operation yet, the effective utilization of human capital by personal
46 exchanges, promotion of inter-city coordination by the joint research, and so on. Concretely

1 speaking, introduced policies in frontier cities in 1990 might be some help for making
 2 transport policies in other cities. For instance, in Copenhagen, the Finger Plan which goes
 3 ahead with the transport oriented development has been introduced (18). Besides this, many
 4 transport policies are introduced in there, for instance, the regulation of the loading ratio, the
 5 building of the bicycle path, and so on. In regard to the bicycle path, it also has been built in
 6 Canberra. Concerning other frontier cities, in Hong Kong, the high density PT network has
 7 been built. About Denver and Sacramento, the transit network also has been developed in
 8 these cities, and the transit moll was introduced (19). Such kind of advanced policies might be
 9 useful to other cities, and its will be helpful to fill up gaps.

12 5. EVALUATION OF POLICIES IMPROVING ENVIRONMENTAL EFFICIENCY

14 5.1 Transport Policies in Cities

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

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

24 *Modal Shift*

25 In this case study, we will examine a policy promoting the modal shift from the lower
 26 intensity mode (i.e., PC) to the higher one (i.e., PT). To prevent infeasible policies, it is
 27 required to put an upper limit of the modal change. First we will estimate a new DEA model
 28 called as “Energy use efficiency model” (20). The model is basically based on the
 29 output-oriented DEA model (5) that maximizes the output subject to a fixed input. While the
 30 output-oriented model can be directly applied to maximize the use of PT, it cannot be applied
 31 to minimize the use of PC. But unfortunately, the model that minimizes the output subjects to
 32 a fixed input is not computable in DEA program. Then, we transform the model as a
 33 maximization problem in calculate the efficiency of PC as shown in FIGURE 5: the average
 34 annual travel distance of PC in each city (output index) is substituted to a value of
 35 $[2\mu\text{-observation}]$, where μ is a mean between minimum and maximum of observations by
 36 referring Tone (15). In FIGURE 5, observations expressed by grey circles, and this output is
 37 the smaller the better. However, as stated previously, the minimization problem cannot be
 38 solve in DEA, then observations should be converted to $[2\mu\text{-observation}]$ which expressed
 39 by black circles. In this way, we can estimate the PC efficiency.

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

$$\begin{aligned}
 &\text{maximize } \eta && (22) \\
 &\text{subject to}
 \end{aligned}$$

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

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

$$3 \quad \sum_{j=1}^{n'} y_{rj} \lambda_j \geq \eta y_{rk}, \quad (r = 1, 2, \dots, s), \quad (24)$$

$$4 \quad \sum_{j=1}^{n'} \lambda_j = 1, \quad (25)$$

$$5 \quad \lambda_j \geq 0, \quad (j = 1, 2, \dots, n'), \quad (26)$$

6 *if* $j = n'+1, \dots, n$ (Developing Cities)

$$7 \quad - \sum_{j=n'+1}^n x_{ij} \lambda_j + x_{ik} \geq 0, \quad (i = 1, 2, \dots, m), \quad (27)$$

$$8 \quad \sum_{j=n'+1}^n y_{rj} \lambda_j \geq \eta y_{rk}, \quad (r = 1, 2, \dots, s), \quad (28)$$

$$9 \quad \sum_{j=n'+1}^n \lambda_j = 1, \quad (29)$$

$$10 \quad \lambda_j \geq 0, \quad (j = n'+1, 2, \dots, n), \quad (30)$$

11

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

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

18

19 *Improvement of the Energy Efficiency*

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

24

25 **5.2 Emissions Trading Policy among Cities**

26

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

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

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

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

13 In estimating the EE indices of buyers before and after the policy, assumed that the
 14 frontier line is stable, the minimized energy consumption c_k^* can be calculated by inputting
 15 the current data into equation (8). In this sense, the optimum energy consumption after the
 16 policy implementation could be equal to the optimum one calculated in chapter 5. The energy
 17 reduced by the emissions trading scheme can also be calculated by using the following
 18 equation (31).
 19

$$20 \quad EE_k = \frac{c_k^*}{c_k - c'_k} = \frac{\sum_{i=1}^m p_{ik} x_i^*}{\sum_{i=1}^m p_{ik} x_{ik} - c'_k} \quad (31)$$

21 where, c'_k indicates the amount of energy reduced by emissions trading, that assumes a
 22 constant value inherent in each city.
 23
 24
 25

26 6. COMPARISON OF POLICIES BASED ON THE MALMQUIST APPROACH

27 To compare the effects of three policies, those are the modal shift, the improvement of
 28 energy intensity and inter-city emission trading. The Malmquist approach is finally applied to
 29 explain the changes in structure of two frontiers that are obtained before and after the
 30 implementation of policies. In case of the emission trading policy, however, the energy
 31 consumption structure is stable before and after the policy implementation, FS index could be
 32 zero as mentioned in the last chapter.
 33

34 FIGURE 7 shows overall average scores of the CU index, the FS index, and the
 35 Malmquist index accompany each policy. The Malmquist index gives the highest
 36 improvement of the energy intensity. Especially, because the improvement of the energy
 37 intensity is obviously excellent about the FS index, it would appear that this policy is brought
 38 mainly by the technological innovation, and it is expected to lead to the recurrent
 39 development of more advanced technology. On the other hand, the emission trading policy is
 40 excellent in terms of CU index, so that this policy will contribute to catch up the frontier by
 41 utilizing existing technologies. The modal shift shows relatively lower score both in CU/FS
 42 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.

REFERENCES

1. Verfaillie,H.A., Bridwell,R.: Measuring Eco-Efficiency: a Guide to Reporting Company Performance, World Business Council for Sustainable Development, Geneva, 2000.
2. Farrell,M.J.: The Measurement of Productive Efficiency, *Journal of the Royal Statistical Society*, Vol.12, pp253-281, 1954.
3. Charnes,A., Cooper,W.W., and Rhodes,E.: Measuring Efficiency of Decision Making Units, *European Journal of Operational Research*, Vol.2, pp.429-444, 1978.
4. Coelli,T., Rao,D.S.P., and Battese,G.E.: An Introduction to Efficiency and Productivity Analysis, Kluwer Academic Publishers, Boston, 1997.
5. Cooper,W.W., Seiford, L. M., and Tone,K.: Data Envelopment Analysis, A Comprehensive Text with Models, Applications, References and DEA-Solver Software, Kluwer Academic Publishers, 1999.
6. Newman,P. and Kenworthy,J.: Sustainability and Cities -Overcoming Automobile Dependence, Island Press, 1999.
7. Kenworthy,J.R. and Laube,F.B.: An International Sourcebook of Automobile Dependence in Cities 1960-1990, University Press of Colorado, 1999.
8. Senbil,M., Zhang,J., and Fujiwara, A.: Causes of Energy Efficiency in Urban Transportation Sector, *ICCEE*, pp.249-258, 2005.
9. Pitt,M. and Smith,A.: Waste Management Efficiency at UK Airports, *Journal of Air Transport Management*, Vol.9, No.2, 2003, pp.103-111.
10. Feng,T., Zhang,J., and Fujiwara,A.: Environmental Efficiency Analysis of Transportation System: A Stochastic Frontier Approach with Flexible Cause-Effect Structure, *Journal of the EASTS*, Vol.7, pp.1475-1489, 2007.
11. Ahmad,A., Fujiwara,A., and Zhang,J.: 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, 2009.
12. Camanho,A.S. and Dyson,R.G.: Cost Efficiency Measurement with Price Uncertainty: A DEA Application to Bank Branch Assessments, *European Journal of Operational Research*, Vol.161, pp.432-446, 2005.
13. Fukuyama,H. and Weber,W.L.: Modeling Input Allocative Efficiency Via Distance and Quasi-distance Functions, *Journal of the Operations Research Society of Japan*, Vol.46, No.3, pp.264-285, 2003.
14. Banker,R.D. and Morey,R.D.: Data Envelopment Analysis with Categorical Inputs and Outputs, *Management Science*, Vol.32, pp.1613-1627, 1986.
15. Tone,K.: Measuring and Improving Management Efficiency: Data Envelopment Analysis, Union of Japanese Scientists and Engineers, 1993.
16. Fare,R., Grosskopf,S., Norris,M. and Zhang,Z.: Productivity Growth, Technical Progress, and Efficiency Changes in Industrialized Countries, *American Economic Review*, Vol.84, pp.66-83,1994.
17. Malmquist,S.: Index Numbers and Indifference Surfaces, *Trabajos de Estadística*, Vol.4, pp.209-242, 1953.
18. Litman,T: Rail Transit America: A Comprehensive Evaluation of Benefits, Victoria Transport Policy Institute, 2009.
19. Nishi,E.: A Study on the Planning Theory and Strategy of Urban Growth in the Grater

- 1 Copenhagen Metropolitan Region in Denmark, *Journal of Architecture, Planning and*
- 2 *Environmental Engineering*, No.575, pp.109-115, 2004.
- 3 20. Fare,R. and Grosskopf,S: Network DEA, *Socio-Economic Planning Sciences*, Vol.34,
- 4 pp.35-49, 2000.
- 5

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

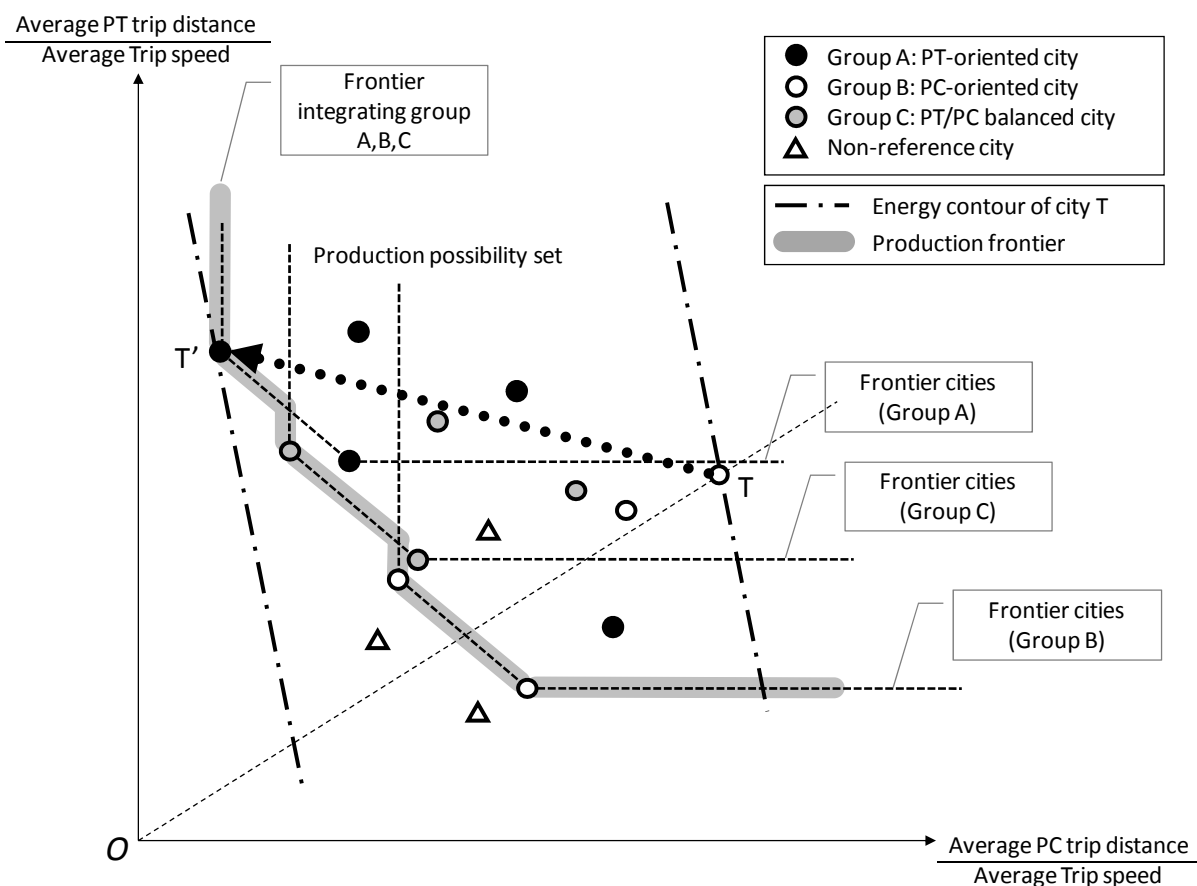


FIGURE 1 Concept of the Proposed EE Model.

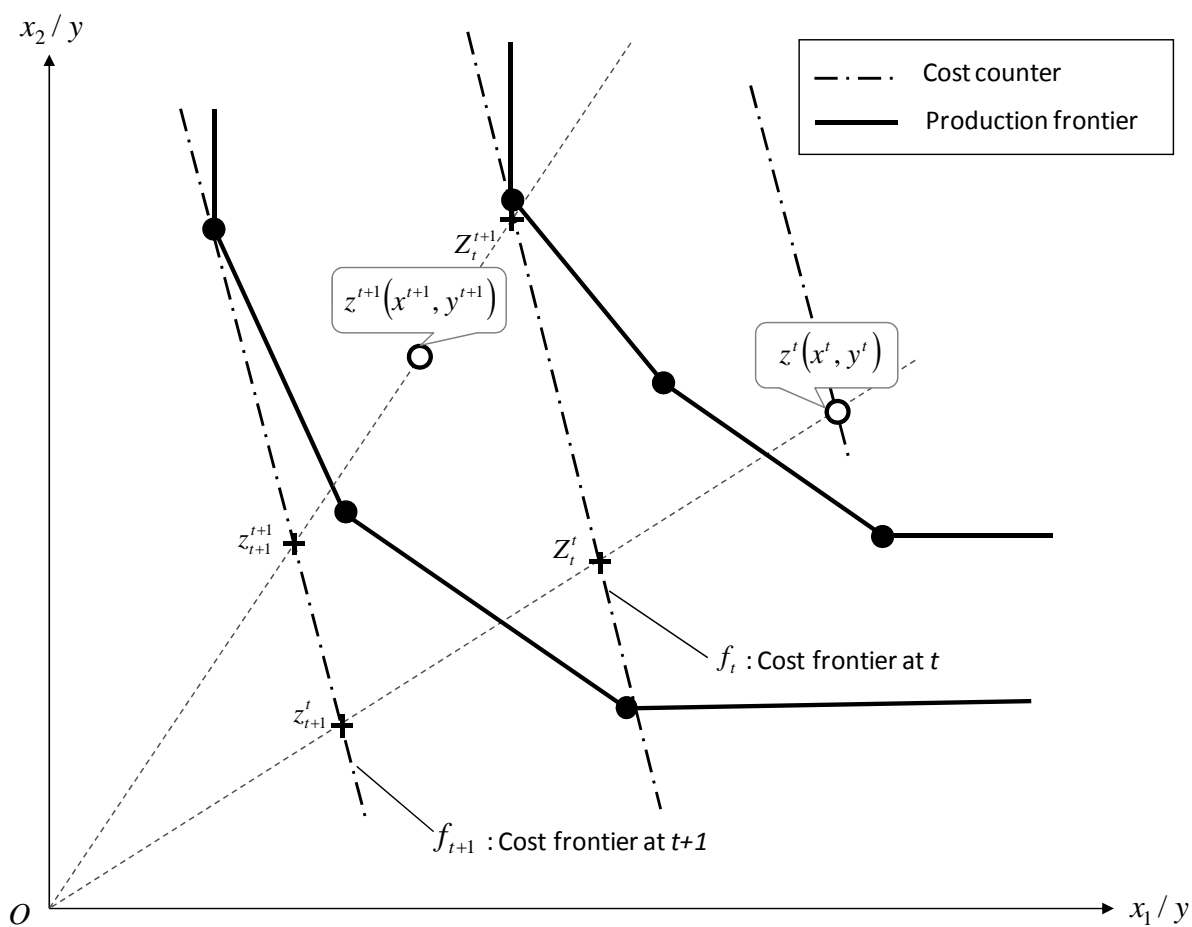


FIGURE 2 Efficiency Evaluation Based on the Malmquist Approach.

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)

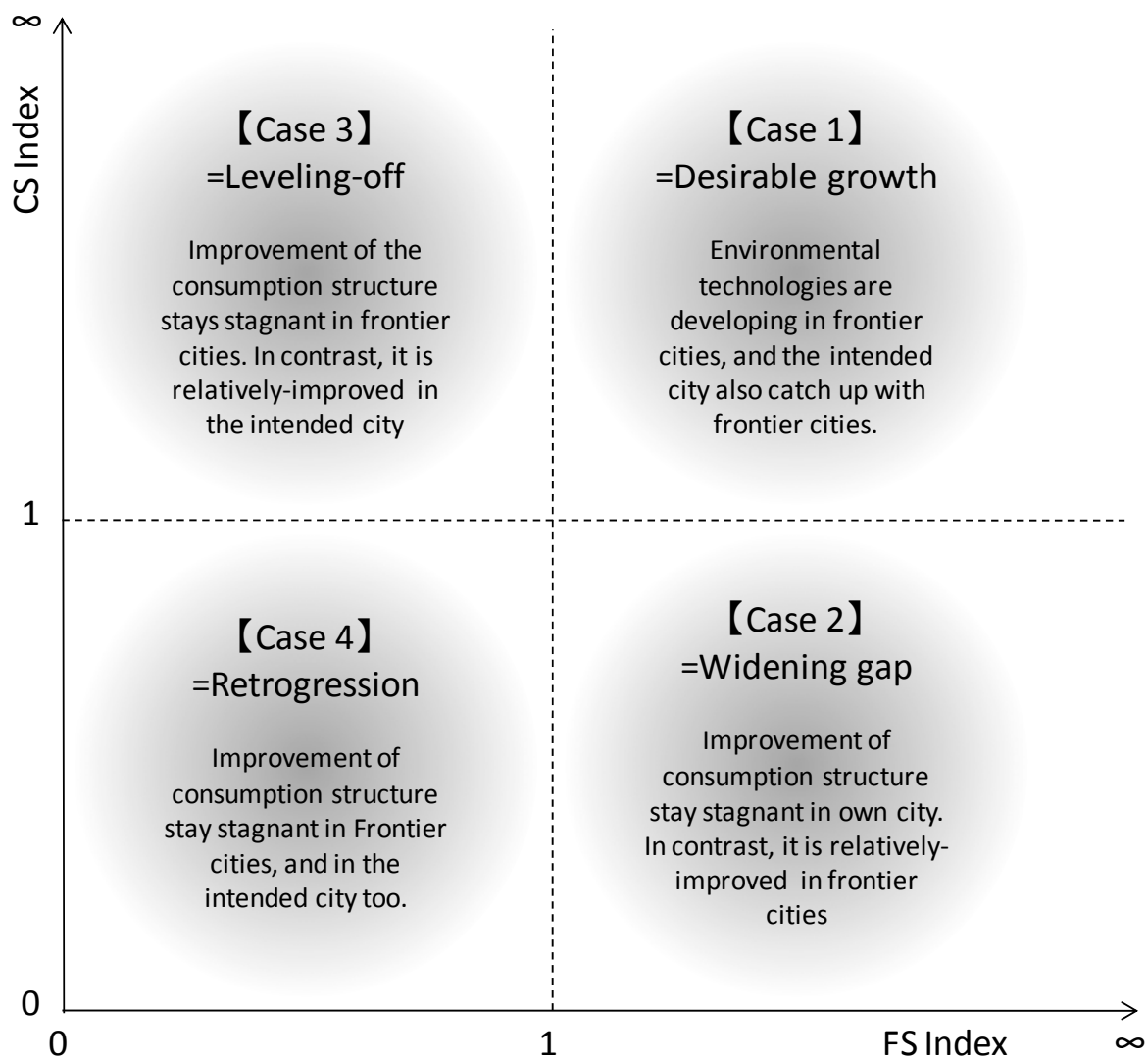


FIGURE 3 Classification of City by the CU Index and the FS Index.

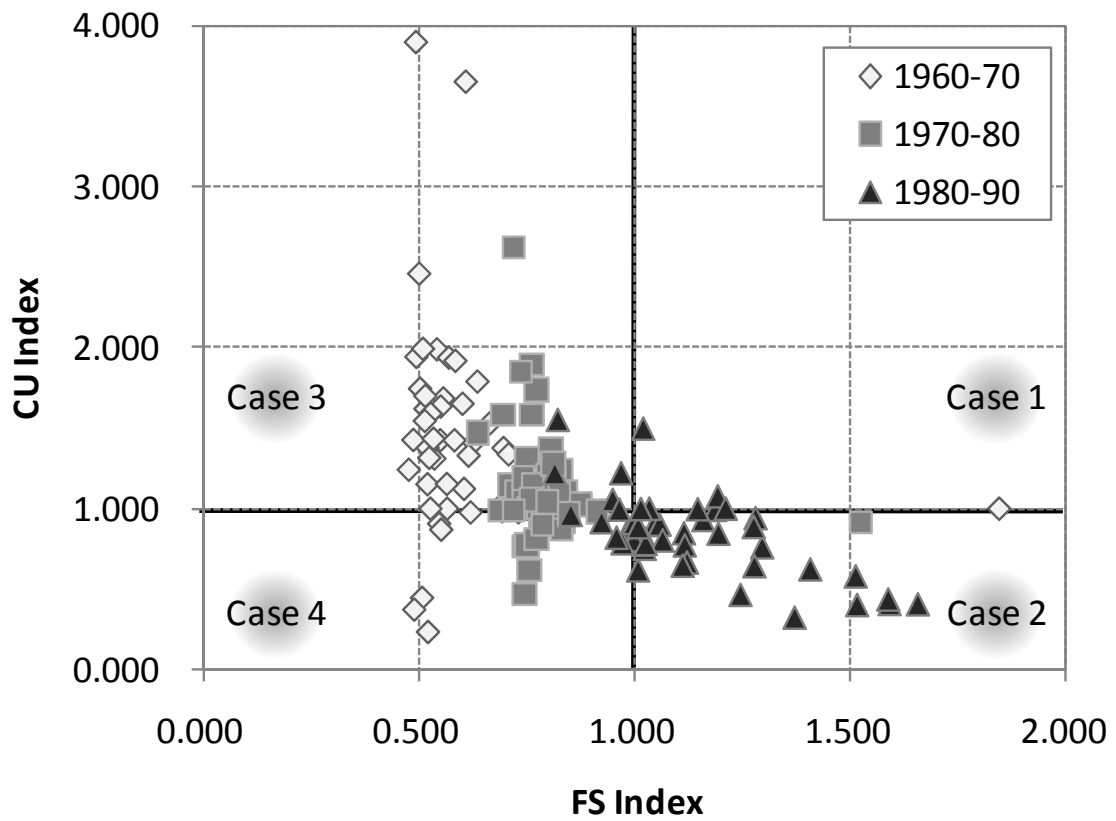


FIGURE 4 Plots of the CU Index and the FS Index.

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]

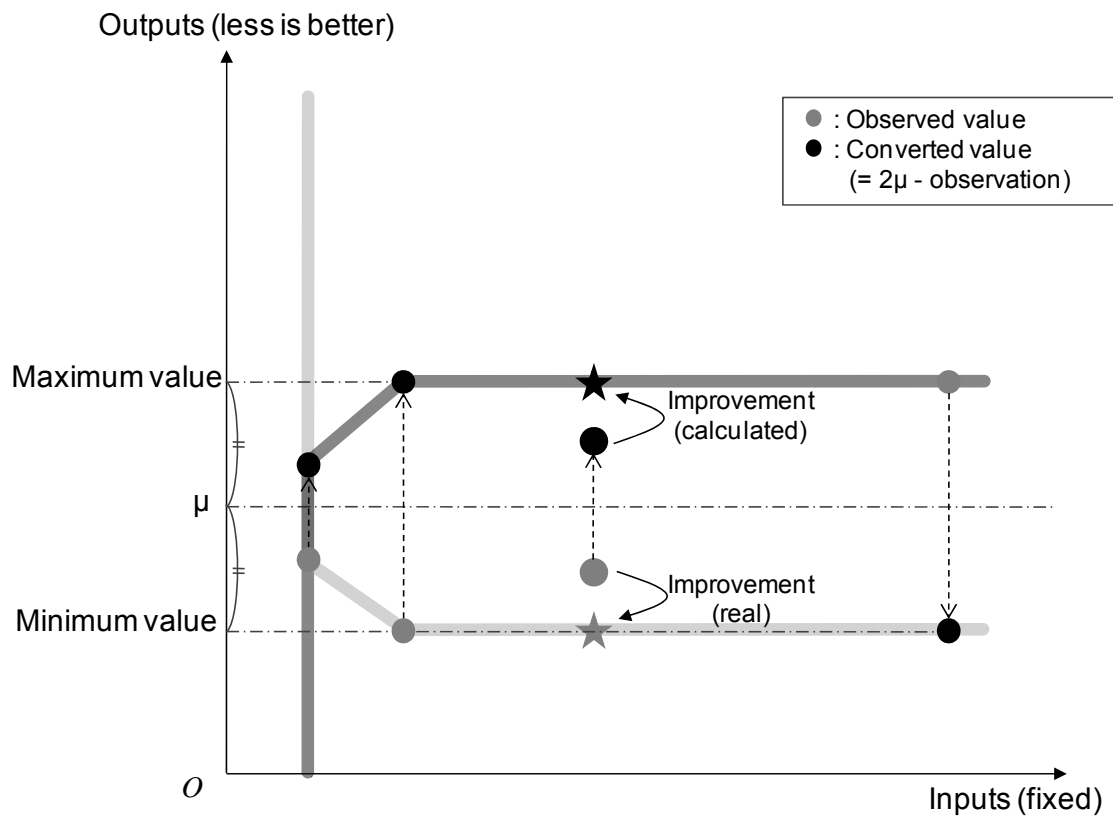


FIGURE 5 Private Car Energy Use Efficiency Model.

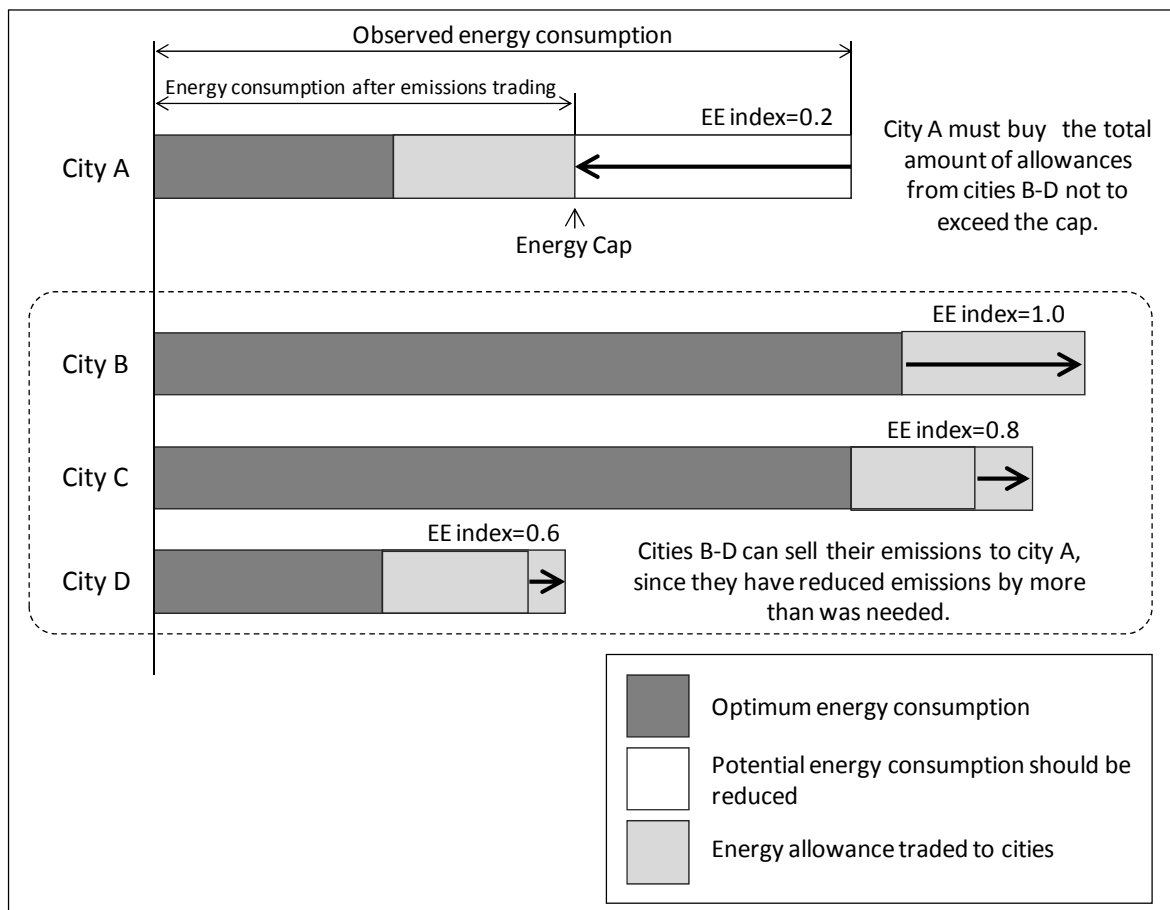


FIGURE 6 Energy Cap in Emissions Trading of Allowance.

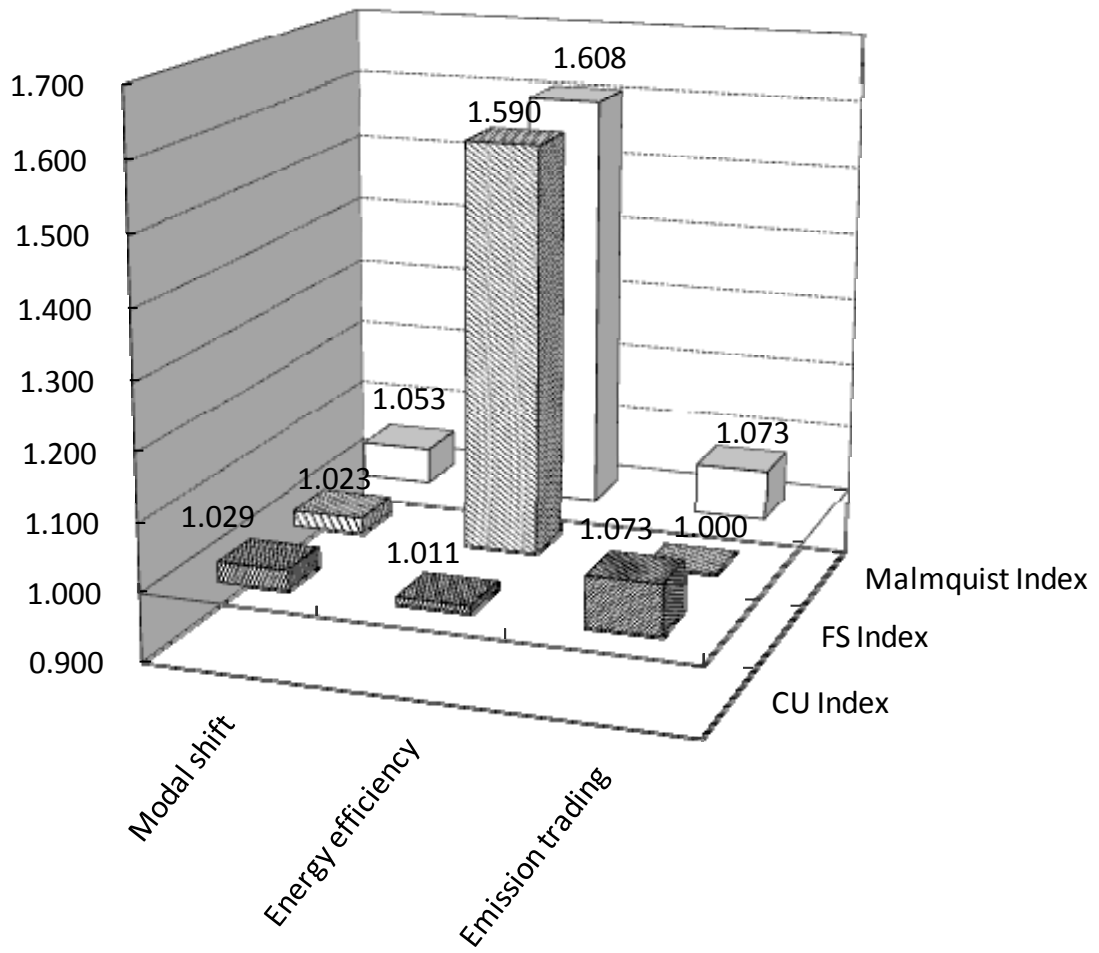


FIGURE 7 CU/FS/Malmquist Indices Score Accompany Each Policy (Overall Average).