Household Behavior Selections under CO₂ Emission Constraint

Peng Tang*1 and Junzo Munemoto2

1 Research Associate, Graduate School of Engineering, Kyoto University, Japan
2 Professor, Graduate School of Engineering, Kyoto University, Japan

Abstract
Reducing human-caused CO₂ emissions to acceptable levels must become a global objective of our modern society. One way to meet this objective is to introduce a constraint on household annual CO₂ emission (HACO₂). However, behaviors that reduce CO₂ emissions, may appear too expensive, or to worsen living conditions. Although the goal of controlling CO₂ emissions is widely accepted, in practice it is not easy to reduce energy consumption. This paper develops a CO₂ emission trading scheme (CETS) framework for households based on the definition HACO₂. In this study, a city's CO₂ emission is assumed to be the sum of all HACO₂. The CO₂ constraint for a single household is determined by the city's total CO₂ emission reduction target. Multi-agent simulator is applied to clarify household behavior-selections under such constraint, and to find the effects of total CO₂ emission within the urban model. Simulations are performed with CETS (Case 1) and without CETS (Case 2). Results indicate 1) Under a CO₂ constraint, agents choose behaviors to meet the HACO₂ constraint. Total CO₂ emissions within the urban model decrease toward the pre-determined reduction target. 2) The CETS framework for household level is proved not only cost-efficient but also promotes the process of reducing CO₂ emissions. 3) An agent that acts for self-benefit will not consider the completeness of the total target. As a result, the reduction target within the urban model is never achieved even with the implementation of CETS.

Keywords: household annual CO₂ emission (HACO₂); CO₂ emission trading scheme (CETS); CO₂ emission allowance (CEA) reduction target

1. Introduction
Human activities have changed the atmosphere's composition by releasing excessive CO₂ into the air (Karl and Trenberth, 2003). Reducing human-caused CO₂ emissions to acceptable levels must become a global objective of our modern society. One way to meet this objective is to introduce a CO₂ emission constraint to each household. Tang et al. defined a household's annual CO₂ emission (HACO₂) as:

\[ \text{HACO}_2 = \text{LCCO}_2 + \text{CTCO}_2 + \text{ELCO}_2 \]

(1)

In which LCCO₂ is the life cycle CO₂ emission of the house in which the household lives; CTCO₂ is the CO₂ emission from commuting trips made throughout a year and ELCO₂ is the quantity of power used in daily living. The definition helps to grasp the quantities of CO₂ emissions related to human behavior if we have information about housing type, distance to and from the workplace, and daily power consumption (Tang et al., 2006). An emission constraint on HACO₂ would affect choices relating to corresponding behavior-selections. For example, a person living close to his or her workplace will produce less CTCO₂. When this reduction in CO₂ emission is applied to the given constraint, he/she could enjoy a better quality of life, for example by living in a larger house (Tang et al., 2005).

However, decisions concerning social behavior are usually based on individual benefit. Behavior that reduces CO₂ emissions, such as moving closer to the workplace or conserving electricity, may appear too expensive, or to worsen living conditions. Although the goal of controlling CO₂ emissions is widely accepted, in practice it is not easy to reduce energy consumption.

Researchers have developed some practical market-based instruments to reduce CO₂ emissions. One notable effort in this respect is a CO₂ emission trading scheme (CETS). This scheme is widely supported because it is a cost-efficient way to reduce greenhouse gas emissions. It proposes that governments set a maximum quantity of pollutants and then allow market trading of CO₂ emission allowance (CEA). This proposal has the benefit of allocating an emission allowance to those who value it more. Many countries already participate in an international emission-trading scheme, especially within the manufacturing field.

Fig.1. and Table 1. (left side) show the CETS cost efficiency to companies. Generally, emission trading...
takes place between companies with different reduction costs (RC), e.g., between Company A with an RC of 10 (monetary unit/kg-C) and Company B with an RC of 20 (monetary unit/kg-C). By introducing CETS, both companies can achieve reduction targets along with reduced costs.

In Japan, the Public Welfare Department is responsible for 28.7% of all anthropogenic CO₂ emissions, and 45% of this fraction comes from households (Ministry of Economy, Trade and Industry, 2004). Significant increases in these CO₂ emissions have highlighted the need for controlling CO₂ emissions at the household level, and introducing CETS to households seems a promising idea. Kondo et al. used an awareness investigation to conduct a feasibility study and found the system to be practical (Kondo et al., 2003).

Obstacles still remain, such as difficulties in estimating CO₂ emission related to human behavior (Nishimura 2004). This paper develops a CETS framework for households based on the definition of HACO₂. And an emission constraint is assumed and assigned to each household. As shown in Fig.1. (right side), trading is designed to take place between households with different CEA. In this context, 'CEA' refers to the difference between HACO₂ and the constraint on CO₂ emission. In Fig.1. Household A produces one unit of CEA and Household B produces three units. If no CETS is available, each household must meet the HACO₂ constraint, so Household A is permitted to produce additional CO₂, while Household B must reduce its CO₂ emission. In contrast, under CETS, Households A and B have several choices. Household A may participate in emission trading, reduce its CO₂ emission, or do nothing. Household B may decrease its HACO₂ by reducing CO₂ emission, by buying CEA, or both. Table 1. shows the effects on household expense for both cases. The application of CETS reduces total household expense: costs for Household B are lower than without CETS, and Household A profits through emission trading.

2. Purpose

As a basic economic unit within a society, a constraint on HACO₂ is intended to keep households from exceeding the constraint with the lowest related costs. This type of phenomenon is reflected in a multi-agent system (MAS) based simulation model. The primary purpose of this study is to use simulations to clarify household behavior-selections under a constraint placed on HACO₂. Simulations are performed with CETS (Case 1) and without CETS (Case 2).

The study addressed the following questions:
1) What are an agent's behavior-selections under the constraint on HACO₂?
2) How do the behaviors change before and after introducing CETS to households?
3) How do these behavior-selections affect total CO₂ emission within a city?

Table 1. Individual expenses related to reducing CO₂ emissions without and with CO₂ emission trading scheme (CETS)

|                | CETS for companies | CETS for households |
|----------------|--------------------|---------------------|
|                | Without CETS | With CETS | Without CETS | With CETS | Without CETS | With CETS |
| Reduction cost unit (monetary unit/kg-C) | 10       | 20       | 10         | 20       | 20         | 20       |
| CEA trading price (monetary unit/kg-C)  | -        | -        | -          | -        | 10         | 15       |
| Amount of reduction (kg-C)                 | 1        | 3        | 2          | 4        | 0          | 3        |
| Amount of purchase (kg-C)                   | 2        | 3        | -          | -        | 1          | 1        |
| Reduction cost (monetary unit)              | 10       | 60       | 20         | 40       | 0          | 60       |
| Cost to purchase (monetary unit)            | -        | -15      | -10        | 20       | -15        | 15       |
| Expense (monetary unit/kg-C)                | 10       | 69       | 55         | 60       | 60         | 60       |

Fig.1. Reducing CO₂ emissions without and with a CO₂ emission-trading scheme (CETS)
(Left: CETS for companies; right: CETS for households)
3. Method and Materials

3.1 MAS-based Model

This study adopted a multi-agent system (MAS) simulator to construct a model in which a household acts as an 'agent', and to develop an urban model in which the agent acts, termed the ‘space’.

3.1.1 Household as an 'Agent'

In this study, a ‘household’ is defined as a nuclear family: two adults with two children. All households in the city live in the same detached house, and each of them has one commuter who works in the urban center.

The life cycle of a residential building includes several stages including material production, construction, occupation and repair, recycling and disposal, etc. LCCO₂ is the sum of CO₂ emissions during all the stages; an approach proposed by Munemoto et al. (2002) can be used to estimate the LCCO₂ of a detached house.

This research used a representative wooden standard building model (SBM, established by Udagawa, 1985) with a gross floor area of 125.9 m² (Fig.2.). Table 2. presents the specific material usage and the thickness of each component; thickness meets the criteria for the Japanese ‘Next Generation House’ (IBEC, 1999). The house framework duration life is assumed to be 24 years. The housing model is constructed in Osaka (applying local outdoor air temperatures and sunlight conditions).

3.1.2 Urban Model as a "Space"

The urban model applies the general characteristics of the Alonso Model: all employment, goods, and services are available only at the city center.

A 2-km wide and 25-km long segment of the urban space from the urban center to the suburban area is selected as the space within the MAS-based model in which the agent acts (Fig.3.). It is divided into 500 cells, and each cell represents a location of an agent within the urban space. In the figure, the left-hand column of cells represents the urban center. The number of agents is assumed to be constant, indicating that no agents move in or out of the space. An agent’s commuting distance is determined by the horizontal distance from its location to the urban center.

Matsuhashi (2000) developed a method to estimate energy consumption during commuting trips considering both distance traveled and time taken in one commuting trip by assessing differences in fuel efficiency by vehicle, and average travel speed. This study applies the similar method to calculate CTCO₂. For simplicity, the model used cars as the only mode of transportation. The following formula calculates CO₂ emission during one commuting trip:

\[ T_{\text{em}} = t_{\text{em}} \times u_{\text{em}} + D_{\text{c}} \times u_{\text{d}} \]

where \( T_{\text{em}} \) represents CO₂ emission during one commuting trip (kg-C); \( t_{\text{em}} \) represents the trip time taken by the main transportation (min); \( u_{\text{em}} \) represents CO₂ emission unit per minute of main transportation (kg-C/min); \( D_{\text{c}} \) represents commuting distance (km); and \( u_{\text{d}} \) represents CO₂ emission unit per kilometer of main transportation (kg-C/km).

In the model, commuting distance \( (D_{\text{c}}) \) represents the distance from an occupied cell to the urban center.

### Table 2. Housing model material usage and component thickness

| Part       | Component          | Material          | Thickness (m) |
|------------|--------------------|------------------|---------------|
| Framework  | Framework          | Conventional     |               |
| Wall       | Frame              | Wooden           | 0.03          |
|            | External finish    | Mortar           | 0.005         |
|            | External substratum| Plywood board    | 0.005         |
|            | Insulator          | Rock wool        | 0.115         |
|            | Inner substratum   | Lumber           | 0.01          |
| Window     | Type               | Double glass     | Area ratio of |
|            | Sash               | Aluminum         | window to floor |
|            |                    |                  | 0.18          |
| Floor      | Frame              | Plywood board    | 0.005         |
|            | Finish             | Lumber           | 0.01          |
|            | Insulator          | Rock wool        | 0.115         |
| Ceiling    | Frame              | Lumber           | 0.21          |
|            | Substratum         | Plaster board    | 0.025         |
|            | Insulator          | Lumber           | 0.21          |
| Roof       | Frame              | Wooden           | 0.005         |
|            | Finish             | Cement board     | 0.005         |
|            | Substratum         | Lumber           | 0.005         |
|            | Insulator          | Rock wool        | 0.21          |
Trip time \( (t_m) \) is determined by the distance and the travel speed within the urban space (refer to Fig.4). Travel speed can be estimated using Formula (3), and then \( t_m \) is calculated using Formula (4). If a commuter lives in the urban center (where \( D_c \leq 1 \text{ km} \)), it is not realistic that he or she would commute via car, so data for this area are not included.

\[
v = 7.1019 \ln(D_c) + 0.8067 \tag{3}
\]

\[
t_m = D_c/v \tag{4}
\]

where \( v \) represents car speed \((\text{km/h})\).

In Japan, the average CO 2 emission resulting from household electric power consumption (four family members) is 2000 kg-CO2/yr \((545.0\text{kg-C/yr})\) in 2000 Note [1]. This study uses this as the initial value of ELCO2 for each agent.

Within this urban space, there is a market for CEA trading amongst agents. Supply and demand determine CEA market pricing. According to the supply-demand model, the price of a commodity is determined by the point at which quantity supplied equals quantity demanded, i.e., the price at which the supply and demand curves cross. Basic analyses often approximate the supply and demand curves as straight lines (NetMBA.com). In this study, the straight-line supply and demand functions have the following structures:

\[
u_{PS} = -a \times Qs + b \tag{5}
\]

\[
u_{PD} = -c \times Qd + b \tag{6}
\]

where \( u_{PS} \) represents the price of CEA supplied \((\text{monetary unit/kg-C})\); \( u_{PD} \) represents the price of CEA demanded \((\text{monetary unit/kg-C})\); \( a, c \) represent constants for each particular supply and demand curve; and \( b \) represents the initial price of a CEA purchase \((\text{monetary unit/kg-C})\).

### 3.2 Agential Behaviors

A city's CO 2 emission is assumed as the sum of all HACO2. The CO 2 constraint for a single household is determined by the city's total CO 2 emission reduction target. In simulations, the reduction target within the urban model is to bring the total HACO2 to a predetermined level [such as shown in Formula (7)] over a pre-determined period.

\[
CL = aHC^0 \times m\%
\tag{7}
\]

where \( CL \) represents the reduction target; \( aHC^0 \) represents average initial HACO2 \((\text{kg-C/yr})\); and \( m \) represents the ratio of CO 2 constraint to average HACO2 \((0 < m < 100)\).

To achieve its target, the system acts as the city management divides the total target into individual targets according to the number of agents in the space. This initial target \((iRT)\) is a CO 2 emission constraint on an agent's HACO2.

During reduction progress, the implementation period is divided into several stages. In the initial stage, agents produce different levels of HACO2 according to their varying locations in the space. An agent's CEA \((my.CEA)\) is the difference between its HACO2 and the CO 2 constraint, as shown in Formula (8).

\[
my.CEA = HC' - CL
\tag{8}
\]

where \( my.CEA \) represents an agent's CO 2 emission allowance \((\text{kg-C/yr})\) and \( HC' \) represents the current HACO2 of agent \( i \) at stage \( t \) \((\text{kg-C/yr})\).

Agential behavior is designed based on three factors: energy saving, moving, and CEA trading. At the beginning of each stage, an agent first judges whether or not its HACO2 is greater than the CO 2 constraint \((if\ my.CEA > 0)\). An agent with \( my.CEA > 0 \) may produce any remaining CO 2 emission. This kind of behavior could include moving to a larger house, increasing energy consumption, or selling CEA (if CETS has been introduced). Agents with \( my.CEA < 0 \) must reduce their CO 2 emission; their reduction target \((iRT)\) equals \( my.CEA\). \( iRT \) at a certain stage is determined by the exceeded CO 2 emission and the remaining accomplishment period [Formula (9)]. Reduction behaviors include moving near the urban center, decreasing energy consumption, and buying CEA (if CETS has been introduced) (Fig.5.).

\[
If\ my.CEA > 0
\]

\[
iRT^i = my.CEA \times (T - t)
\tag{9}
\]

where \( iRT^i \) represents the reduction target of agent \( i \) at stage \( t \) \((\text{kg-C})\); \( t \) represents the number order of the current stage; and \( T \) represents the number of total stages.

Each behavior related to changes in HACO2 results in loss (positive cost) or profit (negative cost). The corresponding costs are estimated Note [2]-[4]. Table 4. and Fig.6 detail behaviors and their corresponding costs. An agent evaluates the estimated cost corresponding to each behavior before making a selection. The value of each behavior is calculated according to cost, so a behavior resulting in a high cost would receive a low.
Finally, the agent selects a behavior that has a higher probability of a greater evaluated value. This selection is based on roulette strategy.

### 3.3 Simulations

The simulation is built using a multi-agent simulator software platform Note [5]. Initial and terminate conditions are as follows:

**Initial condition:** The number of agents is 200. The CO₂ constraint is set at 90% of average HACO₂ (m% = 90%). The HACO₂ control period is set at 100 stages (T = 100). Every five stages represent one year, so the period is 20 years. Behavior-selections can differ during a year, but behaviors No. 1-1 and No. 2-1 are available only once a year. These initial values are arbitrarily set and can be changed.

Initial CEA purchase price is set at 100 monetary units (b=100). Data are set according to results of the study conducted by Kondo et al. (2003). Prices change according to the function of supply and demand curves, as described in section 3.1.2; a=0.0001 and c=0.00005.

**Terminate condition:** Iteration stops at the end of the period or when average HACO₂ is lower than the CO₂ constraint (exit the simulation when t = T, or, \( aHC = CL \)).

Simulations are performed with CETS (Case 1) and without CETS (Case 2).

**Evaluation variables:** Some evaluation variables are obtained while the simulation is running and include average commuting distance (km), average gross floor area (GFA) per house (m²), and average electricity usage (kwh/month). These are calculated to show the city's energy efficiency. Average expense (monetary unit/yr) and reduction cost (monetary unit/kg-C) are calculated to show the difference in cost efficiency between introducing CETS and not introducing CETS.

### 4. Results and Discussion

#### 4.1 Changes in Agents' Locations and Behavior-selections

In Fig.7., one rectangle represents the locations of agents in the urban model at one stage. From the beginning to the end of the simulation, 30 such rectangles occurring in the same time interval represent changes. This figure also presents the agential behavior-selections; each behavior is represented by a specific color.

In both cases, agents' locations changed from random to compact, i.e., agents gathered to the urban center. In each case, changes in space are caused by different behavior-selections.

There is obviously a boundary in the space; behavior-selections differ markedly between the left and right sides. Agent density also differs on each side of the boundary; the area closer to the urban center has a higher density. This area produces minimal CO₂.
emissions from commuting trips, so almost all the agents in this area produce HACO$_2$ emissions lower than the CO$_2$ constraint. The boundary is called the 'constraint line' and illustrates the reduction target by its location within the space. Changes in agents' locations are caused by agents shifting closer to the urban center.

Evaluation variables and the percentage of selections for each behavior are obtained while simulations are running (Table 5., Fig.8.). Values are averaged over 100 simulations.

In Case 2, behaviors No. 1-3 and No. 2-3 ("Do nothing") are selected most often, with respective values of 46.6% and 45.7%. When CETS is introduced (Case 1), selections of "Do nothing" greatly decreased, to 33.0% and 27.5%, respectively. Introduction of CETS also resulted in about 1/3 of behavior selections involving "Buy CEA" and "Sell CEA", with respective values of 29.2% and 35.2%. "Sell CEA" is mainly selected by agents with $my.CEA > 0$, because this choice could result in profit. Case 1 also results in greatly reduced selection of "move to larger house" (No. 2-1) and "increase power usage" (No. 2-2), which both result in increased CO$_2$ emissions, that can not affect CO$_2$ emission reduction. Average gross floor area (GFA) changed from 129.5 m$^2$ to 136.3 m$^2$ in Case 1 and to 139.4 m$^2$ in Case 2.

No. 1-1 "Move near the urban center" is the least-selected behavior in both Case 1 and Case 2, because of the high costs associated with moving. In Case 2, 8.3% of agents move near the urban center, while in Case 1, 6.2% of agents make the same decision. As a result, the average commuting distance changes from 11.5 km to 5.0 km in Case 2 and 5.7 km in Case 1.

Both average expenses and reduction costs are lower for agents in Case 1 than in Case 2, proving the cost efficiency of CETS.

Fig.7. Agents' behavior-selections during the implementation period (Left: Case 1; right: Case 2)
4.2 Changes in Total CO₂ Emission Within the Space

Agent behavior also influences CO₂ emissions within the space. Fig.9. shows changes by illustrating curves of average HACO₂, average CTCO₂, average LCCO₂, and average ELCO₂ within the space. CTCO₂ values decrease and LCCO₂ and ELCO₂ values increase. Decreases in CTCO₂ are greater than increases in LCCO₂ and ELCO₂, so average HACO₂ in both Case 1 and Case 2 decreases toward the level of CO₂ constraint. However, in thousands of simulations, average HACO₂ never achieved the target CO₂ constraint (Fig.10.).

To clarify the reason, agential behaviors are divided into cooperative and defective behaviors by evaluating their effects on the total CO₂ emission in the space. Cooperative behaviors related to reductions in CO₂ emission include No. 1-1, No. 1-2, No. 1-4, and No. 2-4. Behaviors that are not good at reducing CO₂ emission, such as No. 1-3 and No. 2-3, or those even with direct additional CO₂ emissions such as No. 2-1 and No. 2-2, are classified as defective behaviors. In Case 1, 51.1% of behavior-selections are cooperative; while in Case 2, only 26.7% are of that are cooperative (Table 5.). In Case 2, most agents choose to do nothing or to produce additional CO₂ emissions. When CETS is introduced in Case 1, some agents participate in CEA trading. The quantity of sold CEA is then transferred to agents with a negative CEA and does not result in any additional CO₂ being emitted. The final average HACO₂ in Case 1 is always lower than in Case 2. Therefore, the CETS mechanism promotes reduced CO₂ emission.

5. Conclusions

This study used multi-agent system simulations to clarify household behavior-selections under a given HACO₂ constraint. To control CO₂ emission in a cost-efficient way, a CO₂ emission trading scheme (CETS), similar to those used by companies, is being introduced at the household level. CEA trading takes place among agents with different CEAs. Simulations evaluated the effects of introducing or not introducing CETS, using the same constraint target over the same period.

The simulations proved the following findings:

1) Under a CO₂ constraint, agents choose behaviors to meet the HACO₂ constraint. Correspondingly, total CO₂ emissions within the space decrease toward the pre-determined reduction target. Agents tend to move toward the urban center area.

2) CETS is not only cost-efficient but also promotes the process of reducing CO₂ emissions. Without CETS, most agents producing low HACO₂ choose to do nothing or to consume the remaining CEA.
With CETS, some agents participate in CEA trading. Through trading, leftover CEA is transferred to agents with excessive HACO$_2$. If CEA can be considered a kind of resource, CETS assures its optimal usage. Furthermore, CEA trading prevents agents from producing additional CO$_2$.

3) In the simulation, cost is the only basis for behavior-selection, so behaviors resulting in low cost or profit are more acceptable. Many agents with excessive HACO$_2$ choose to do nothing to reduce CO$_2$ emissions. In addition, many agents producing low HACO$_2$ levels choose to consume the leftover CEA, emitting additional CO$_2$. Although total CO$_2$ emissions decrease, the reduction target is never achieved.

The findings reveal that setting a reasonable CO$_2$ emission constraint on each household can induce household behavior-selections which have a considerable effect on reducing a city’s CO$_2$ emission.

The framework of CETS, which is established in this study, is proved to be not only cost-efficient but also promotes the process of reducing CO$_2$ emissions. It is an approval instrument to be introduced at the household-level.

However, as a basic economic unit within society, a household does not act for the greater good of society, such as for the total reduction target within a city, but rather, toward the satisfaction of self benefit. In the simulations, an agent is designed work for itself without considering the completeness of the target within the space, so the results indicate that the reduction target will not be achieved even with the implementation of CETS. The most important impediment to the global reduction target in a city is individual cooperation in CO$_2$ emission reduction. Effective practical strategies, such as a CETS for the individual-level, are required to be modified to satisfy both individual benefit and global targets.

Acknowledgments
This research has been made possible with the help of Grants-in-Aid for Scientific Research [Encouragement of Young Scientists (B)] by the Japan Society for the Promotion of Science, and the authors express their sincere gratitude.

Notes
[1] Data of statistics by METOCEAN Environment Inc. (2004)

| Number of families | Electric power consumption (kg-CO$_2$) |
|--------------------|---------------------------------------|
| 1                  | 1090                                  |
| 2                  | 1460                                  |
| 3                  | 1840                                  |
| 4                  | 2000*                                 |
| 5                  | 2480                                  |
| 6                  | 2910                                  |

* data used in this study.

[2] Cost of moving is obtained from the website for moving estimation available at:
http://www.hikkoshikikaku.com/index.html

The input information is as the follows: move from detached house to detached house in the same city; a family with two adults and two children; ask for all of the services, etc. The estimations received from several moving companies are almost the same and the cost is about 50,000~80,000yen.

[3] The saved gasoline charge is calculated by the following settings: the amount of gasoline consumption is assumed as 10km/l; price of gasoline is assumed as 120 yen/l. So if one moved 1km closer to the urban center, the saved gasoline charge would be about 4,800 yen/yr.

[4] The saved money from decreasing energy consumption is assumed from the saved electric power. The calculation method is based on the suggestion of "The Reference Data for Energy-saving Behaviors - Energy Saving Made at Home", website at: http://www.pref.yamagata.jp/bk/kanki/1454700/shiryo2.pdf

The suggested price of a typical refrigerator is 68,931 yen and electricity charge is 15,870 yen/yr. The price of an energy conservation refrigerator is 142,000 yen, but the electricity charge is only 4,370 yen/yr. 5,300 yen/yr can be saved if a household changes its refrigerator from a standard model to an energy-conservation model.

[5] Multi-agent Simulator, a software developed by Innovative Information Technology Dept. Kozo Keikaku Engineering Inc.

Reference
1) IBEC (Institute for Building Environment and Energy Conservation) (1999). The energy conservation standard for next generation house, website available at: http://www.ibec.or.jp/
2) Karl T. R. and Trenberth K. E. (2003) Modern global climate change, Science, Vol.302 pp.1719-1723.
3) Kondo A., Yamashita K. and Zhou K (2003), Feasibility study on introduction of CO2 emission trading system between households, Papers on City Planning, No.38-3 pp.1-6.
4) Matsuhashi K. (2000) Spatial formation of the environmental symbiotic city Doctor's degree dissertation of Tokyo University.
5) Ministry of Economy, Trade and Industry (2004). The white paper on national energy, website available at:
http://www.meti.go.jp/report/whitepaper
6) Munemoto J., Hokoi S., Harimoto K., Yoshida T. and Takano S. (2002), Multi objective problem reducing LCC, LCCO2, final waste in selecting materials for detached house – No.2 The system which select a combination of building materials and construction methods to "the standard building model" with GA, Journal of Architecture, Planning, and Environment Engineering, AIJ, No.551, pp.85-92.
7) NetMBA.com, Business Knowledge Center, the Supply Curve. Website available at:
http://www.netmba.com/econ/micro/supply/curve
8) Nishimura K. (2004), 排出量取引導入の動向と課題，ECO INDUSTRY, Vol.9, No.12: pp.35-45.
9) Tang P., Munemoto J. and Matsuhashi D. (2005) Housing Arrangements in Pursuit of Maximum GFA Under CO$_2$ Emission Constraint. Journal of Asian Architecture and Building Engineering, Vol.4, No.2 pp.355-360.
10) Tang P., Munemoto J. and Matsuhashi D. (2006) Invoking Household Cooperation in the Commons Dilemma of CO$_2$ Emission Reduction. Journal of Asian Architecture and Building Engineering, Vol.5, No.1 pp.99-104.
11) Udagawa M. (1985) Proposal of standard problem, the standard building model, J. Archi. Proceeding of the 15th Thermal Environment, Subcommittee on Thermal Environment under Research Committee on Environmental Engineering, AIJ, Tokyo, Japan: pp.23-33.
12) William Alonso, (1964) Location and Land Use – Toward a General Theory of Land Rent, Harvard University Press, Cambridge, Massachusetts.