Invoking Household Cooperation in the Commons Dilemma of CO₂ Emission Reduction

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Abstract

In the modern community, global effort is required to reduce the CO₂ emissions resulting from human actions to acceptable levels. However, global objectives may contradict individual benefits; attempts to reduce CO₂ emissions can result in the commons dilemma. This paper explores how the cooperation of individual households can be invoked to achieve a global target of reducing CO₂ emissions from households (HACO₂) in cities. A commons payoff function linked household benefits to the number of cooperators in a city: a CO₂ emission trading scheme (CETS) for households was introduced into the payoff function as a way to support cooperators. A multi-agent simulator was applied to a search for relationships among parameters in the payoff function and social cooperation from households (R). Results indicate that levying only household maintenance charges is an ineffective way to gain the cooperation of more than half of the households in a city, and extremely high maintenance also discouraged cooperative behavior; the use of CETS could increase cooperation, and R > 0.6 when emission trading prices were five times higher than unit reduction costs, and when unit maintenance charges were almost the same as reduction costs; and it was impossible to gain cooperation from all households until opinions about resource use and reducing emissions were changed.

Keywords: CO₂ emission reduction; CO₂ emission trading scheme (CETS); commons dilemma; cooperation; households; payoff

1. Introduction

1.1 The tragedy of the commons

Hardin (1968) published an article discussing the dilemma of the commons. Commons refers to any resource (e.g., fish, water, forest, or clean air) shared by a group of people. Every member of a society has the right to take from and add to the commons resource pool. To accumulate wealth, each member believes that he/she must acquire one unit of resource or dump one unit of waste while distributing one unit of cost across all members with whom resources are shared. Thereby, individual gain appears large and cost appears very small. Ultimately, as a population grows and greed runs rampant, this system collapses and ends in "the tragedy of the commons."

Human activities have changed atmospheric composition; they are responsible for excessive increases of CO₂ in the air (Karl and Trenberth, 2003). In the modern community, global effort is required to reduce the CO₂ emissions resulting from human actions to acceptable levels (Kyoto Protocol, 1992). However, global objectives may contradict individual benefits, so attempts to reduce CO₂ emission can lead to a type of commons dilemma. Humans share the earth’s atmosphere, into which they freely emit CO₂. In terms of households, the environmental load from one household is then multiplied by all households in the area. Reducing CO₂ emissions could limit household activity and increase costs to the family budget; those who do nothing to reduce CO₂ emissions pay nothing. While there is an obvious payoff from cooperative activity, according to game theory, defectors tend to win in a commons dilemma (Yamamoto, 2003). As a result of these circumstances, global warming is likely to reach damaging levels. The cost of controlling carbon emissions is high and a hydrogen-dependent economy may only be a dream (Kennedy, 2003). According to Hardin (1968), there is no technical solution to the problem. Can the catastrophe be averted?

Researchers have developed practical instruments for controlling environmental impact. One remarkable effort is a CO₂ emission trading scheme (CETS), which allows domestic companies to trade a CO₂ emission allowance (CEA). CETS has been implemented worldwide because of its cost effectiveness (Nishimura, 2004).

The Public Welfare Department is responsible for 28.7% of the total anthropogenic CO₂ emission, and 45% of this fraction comes from households (Ministry of Economy, Trade and Industry, 2004). Significant increases in these CO₂ emissions highlighted the importance of controlling CO₂ emissions at the household level (Ministry of Environment, 2005). With respect to individual households, our previous study proposed an instrument to manage housing arrangement based on the maximum average gross floor area. In
area (GFA) in an urban condition given a constraint on a household’s annual CO₂ emission (HACO₂) (Tang et al., 2005). HACO₂ was defined as the sum of the CO₂ emission during the life cycle of house construction and operation (LCCO₂) (Munemoto et al., 2002) and CO₂ emissions resulting from commuting (CTCO₂). The given constraint led to a trade-off between LCCO₂ and CTCO₂. Simulations revealed that both household location and resident commuters’ modes of transportation affected housing arrangement, suggesting the constraint could influence household activity. A feasibility study showed the practicability of introducing CETS among households (Kondo et al., 2003). Recently, we expanded HACO₂ to include the CO₂ emitted from energy usage in daily life (ELCO₂) and further evaluated the consequences of introducing a household CETS (Tang et al., 2006). Simulations revealed that a CETS could affect household activities, effectively reduce household costs, and subsequently lead to a compact city. However, the study was based on the assumption that all households would cooperate to reduce CO₂ emission, which is often not the case, as shown by the common dilemma.

1.2 Purpose

This study explored methods for invoking cooperation from individual households to reach a global target of reducing HACO₂ within cities. A common payoff function linked household benefits to the number of cooperators in a city, and a household CETS was introduced into the payoff function as a way to support cooperators. A city household was treated as an agent in a multi-agent system (MAS); a multi-agent simulator was applied to search for relationships among the parameters in the payoff function and the social cooperation of households.

The study addressed the following questions:

1) How does CETS influence the payoff function and household cooperation in reducing CO₂ emissions?

2) Is it possible to increase social cooperation by applying a household CETS?

2. Method and Materials

2.1 MAS-based model

A MAS is composed of several agents capable of reaching goals that are difficult to achieve (Weiss, 1999). All the agents have an identical internal structure, including goals, domain knowledge, possible actions, and decision procedures. This study adopted a multi-agent simulator to construct a model in which a household acts as an agent. Agents do not affect others directly, but because of physical proximity, the behaviors of one agent will change the sensory inputs of the others and thereby influence their behaviors.

Household as an agent in MAS

In this study, ‘household’ refers to a nuclear family belonging to the same social group. Family members were assumed to live in the same detached house, and one member was assumed to be a commuter working in the city. This research used a representative wooden standard house model (SHM) with a gross floor area of 125.9 m² (Fig. 1.). Annual CO₂ emission from the household (HACO₂ (kg-C/yr)) includes LCCO₂, CTCO₂, and ELCO₂ and can be expressed as

\[ HACO₂ = LCCO₂ + CTCO₂ + ELCO₂. \]

(1)

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 stages; an approach proposed by Munemoto et al. (2002) can be used to estimate the LCCO₂ of a detached house.

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

CTCO₂ relates to a vehicle and commuting distance using the following formula:

\[ T_j = \sum E_j \times D_j, \]

(2)

where \( T_j \) represents CTCO₂ (kg-C/yr), \( D_j \) represents the commuting distance by vehicle \( j \) (km), and \( E_j \) represents the CO₂ emission unit of vehicle \( j \) (kg-C/km/yr).\(^{\text{Note 2}}\)

Our previous study examined the effects of different vehicles on the energy-efficient housing arrangement (Tang et al., 2005). For simplicity, cars were the only mode of transportation considered.

In the MAS-based model, each agent was labeled cooperative (C) or defective (D) in reducing HACO₂ emission: a cooperative agent took action to reduce CO₂ emission (Agent-C) and a defective agent acted in no way to reduce emissions (Agent-D). An Agent-C could become an Agent-D if it changed its behavior, and vice versa.

Fig. 1. Definition of the Standard Housing Model

Environment

Urban space served as the MAS-based model environment; houses were randomly located within this space. Commuting distances for each household did not exceed 50 km, and the number of households in the city was assumed to be constant. The city’s management department gave each household a reasonable constraint on their CO₂ emissions within a designated period.
2.2 Payoff function

Reducing CO\textsubscript{2} emission involves additional expense to an agent. Defection, i.e., taking no action, involves no expense. A strategy of levying maintenance charges for environmental recovery was applied to prohibit defective behavior. If maintenance charges are related to the number of cooperators, the payoff function for each household can be expressed as

\[ f(b, nC) = \begin{cases} 
-RC - (N - nC - 1) \times L & \text{if } b = C \\
-(N - nC) \times L & \text{if } b = D 
\end{cases} \]

where \( f \) represents the expense to an agent (the payoff value), \( b \) represents either C or D behavior, \( RC \) represents the cost of reduction, \( N \) represents the number of households in the city (\( N = \{1, 2, \ldots, n\} \)), \( nC \) represents the number of cooperators (\( nC = 0, 1, \ldots, n \ldots 1 \)), and \( L \) represents the unit maintenance charge (monetary unit) (\( L \geq 0 \)).

The payoff function applies the following characteristics to represent the commons dilemma:
1. \( f(C, nC) < f(D, nC) \). In the short term, payoff from cooperation is always lower than payoff from defection, if \( nC \) is neglected. As a result, the great number of Agent-Ds would never allow the global reduction target to be met.
2. \( f(C, N - 1) > f(D, 0) \). If all agents select C, the resulting payoff would be greater than if all agents select D.
3. \( f(C, nC) \) is a monotone increase function of \( nC \). In the long term, a greater \( nC \) would result in a greater payoff from C.

A cooperative household could reduce its HACO\textsubscript{2} to levels lower than the HACO\textsubscript{2} constraint for an individual household. CETS would allow remaining CEA to be sold via the trading market, and profits earned from selling CEA would encourage this cooperative behavior. After the introduction of CETS, the payoff function changes as follows:

\[ f(b, nC) = \begin{cases} 
-RC - (N - nC - 1) \times L & \text{if } b = C \\
-(N - nC) \times L & \text{if } b = D 
\end{cases} \]

where \( RC \) represents the total cost of reduction (monetary unit), \( nC \) represents the number of cooperators (\( nC = 0, 1, \ldots, n \ldots 1 \)), and \( L \) represents the unit maintenance charge (monetary unit) (\( L \geq 0 \)).

The reduction process of HACO\textsubscript{2} can be divided into several stages. The global reduction target is to cut \( m\% \) of total HACO\textsubscript{2} emitted from all households within a designed period. Fig.2. illustrates the flow of the reduction process.

During the initial stage, the total HACO\textsubscript{2} from all households is calculated, and the global reduction target (\( gRT^0 \)) is obtained based on the following formula:

\[ gRT^0 = HC'' \times m, \]

where \( HC'' \) represents the HACO\textsubscript{2} emitted by all households during the initial stage (\( \text{kg-C/yr} \)), and \( m \) represents the reduction rate (\%).

During this first stage, global reduction target \( gRT^0 \) is divided according to the total stage number (\( T \)) and number of households (\( N \)). Part of this target involves the individual reduction target for each household during this stage (\( iRT^0 \)). Any reduction that is not achieved during this stage will be applied to the next stage; a greater remainder will produce a higher reduction target for the next stage. Therefore, the reduction target for an individual household at stage \( t \) (\( iRT^t \)) is determined by the household meeting the target during the previous stage. This is illustrated with the following formula:

\[ iRT^t = (gRT^0 - \sum F^{t-1}) \times (T - t) / N, \]

where \( \sum F \) represents reduced CO\textsubscript{2} emissions during previous stages (\( \text{kg-C} \)) at \( t^\text{th} \) stage, \( \sum F = 0 \), \( t \) represents the number of the current stage, \( T \) represents the number of total stages, and \( N \) represents the number of households in the city.

Reduced CO\textsubscript{2} emission during stage \( t \) (\( F^t \)) is related to the number of cooperators (\( nC^t \)) and individual reduction targets (\( iRT^t \)) as shown in the following formula:

\[ F^t = iRT^t \times nC^t, \]

where \( F \) represents reduced CO\textsubscript{2} emission during stage \( t \) (\( \text{kg-C} \)), and \( nC \) represents the number of cooperators.
2.4 Simulation

Our simulation was built using a multi-agent simulator software platform[^3]. The initial condition, global target, and termination condition were given as follows.

Environmental initial condition: In the initial phase, numbers of Agent-Cs and Agent-Ds were assumed to be equal, so the initial ratio of cooperation was 0.5 \((R^0 = 0.5)\).

Global reduction target: The target was set at a 10% reduction in initial CO\(_2\) emission within a designated period of 100 stages \((m = 10\%, T = 100)\). These initial values were arbitrarily set and can be changed.

Terminate condition: Iteration stops at the end of the period or when the global reduction target is achieved.

During each stage, the number of cooperators is calculated and the global reduction target for the next stage is determined based on agent output.

To clarify the effects of introducing CETS, simulations were performed without CETS \((a = 0)\) and with CETS \((a > 0)\).

In addition, to test sensitivity of the defined input values, i.e., initial cooperation \((R^0)\) and global targets \((m)\) resulting from the value of \(R\), simulations involved changing \(m\) and \(R^0\) individually while maintaining a constant \(\alpha\) and \(p\).
3.2. Results from simulations with a CETS

Since $uPT$ is defined as $a$ times $uRC$ ($uPT = a \times uRC$ ($a \geq 0$)), $a$ is therefore a real number. However, an extremely large $a$, which would represent an extremely high selling price of CEA, is not reasonable. In simulations performed with a CETS, both $a$ and $p$ ranged from 0 to 10. Fig. 6. illustrates social cooperation ($R$) varying with $a$ and $p$. One dot denotes a combination of $a$, $p$, and $R$. Most dots are located at around $R = 0.5$. Dots with low $R$ cluster at locations where $p$ is around 0 but $a$ ranges from 0 to 1. $R$ does not gradually change with increased $a$ and $p$; rapid change occurs when $a > 5$ and $p$ is around 1. High levels of social cooperation appear when $R > 0.6$, and the highest $R$ values are achieved when $a = 10$ and $p = 1$. Thousands of simulations using such a combination showed it was possible to obtain $R$ around 0.7, but it was very difficult to obtain $R$ values greater than 0.7.

3.3 Sensitivity of $R$ to initial input values

Fig. 7. shows sensitivity of the initial cooperation ($R^\prime$) and the global reduction rate ($m$) to the resulting $R$ value. No obvious differences appeared between $R$ values resulting from $m = 50\%$, $30\%$, $3\%$, and $R^\prime = 0.1$. Similar results were obtained when changes were made in numbers of agents ($N$) and/or numbers of reduction stages ($T$). $R$ is more dependent on $a$ and $p$, and less dependent on initial input values.

4. Conclusions

This study addressed how cooperation from individual households could be invoked for the purpose of achieving a global target of HACO$_2$ reduction in cities. Introducing a CETS to create a payoff function supports household cooperation towards HACO$_2$ reduction. It was impossible to gain cooperation from all households until opinions about resource use and reducing emissions were changed. The following points summarize our findings.

1) Levying only household maintenance charges is an ineffective way to gain the cooperation of more than half of the households in a city, and extremely high maintenance also discouraged cooperative behavior.
2) Use of CETS could increase cooperation, and $R > 0.6$ when emission trading prices were five times higher than unit reduction costs ($a > 5$), and when unit maintenance charges were almost the same as reduction costs ($p = 1$).
3) While CETS is an efficient strategy to invoke cooperation, it is impossible to obtain cooperation from all households.

Payoff value can be influenced via financial incentives, such as a household CETS. This can help to reduce the total HACO$_2$ emissions in a city. Some parameters, such as the price of emission trading, are difficult to determine, but development of environmental policies could be aided by examining the combinations of parameters that this study found to be relevant to social cooperation.
This paper illustrates the fact that it is impossible to obtain cooperation from all members of a community. Hardin's claim that "there is no technical solution for this problem" (1968) indicates that the problem of cooperation within the commons dilemma can only be ameliorated if opinions are changed; ideal solutions would include both structural and psychological strategies.

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Notes
[1] Unit of energy consumption of vehicles from EDMC (2000)

| Vehicle  | unit (kcal/p.km) |
|---------|------------------|
| Train   | 50               |
| Car     | 575              |
| Bus     | 160              |

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

| Section                     | Age | CO2 emission from households with different number of families (kg-CO2) |
|-----------------------------|-----|---------------------------------------------------------------------|
| Electric power consumption  | 2000| 1090 1460 1840 2000* 2480 2910                                      |
|                             | 1990| 779  1042 1314 1429 1771 2078                                      |

* the data used in this study.

[3] Multi-Agent Simulator: software developed by Innovative Information Technology Dept. Kozo Keikaku Engineering Inc.

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