B-14.5 A study on the development of comprehensive technology assessment of countermeasures (Final Report)

Contact Person Hisashi Ishitani
Professor, Department of Geosystem Engineering,
Graduate school of Engineering, University of Tokyo.
1-1-3 Hongo, Bunkyo-ku, Tokyo 113, Japan
Phone +81-3-3812-2111 ext. 7050, Fax +81-3-3818-7492

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Abstract

This study deals with the cost-effectiveness of CO_2 mitigation options. Evaluating mitigation options inevitably requires assessments of all possible impacts of the options. Life cycle assessment (LCA) is therefore expected to be one of useful tools for evaluating mitigation options. In this study, we first investigated technical issues in LCA approaches. Next we developed a novel mathematical model called Process-relational model. Utilizing this model, we can dissolve the difficulties of LCA in retracing complicated repercussions among production systems and in allocating environmental emissions among multiple products. Then conventional and alternative fuel vehicles are assessed utilizing Process-relational model as numerical examples of LCA Computed results indicated that our method of allocation is useful for evaluating the cost-effectiveness of CO_2 mitigation options.

Key Words: Cost-effeciveness, CO_2 mitigation option, Evaluation, Methodology, Life cycle assessment

1. Introduction

Degradation of environment and depletion of resources are becoming the most serious issues for humankind. Under these circumstances, it is important to promote life cycle assessments of various products, in which we evaluate "from cradle to grave" impacts of the products to the environment. However, there are always some difficulties accompanying life cycle assessments on how to retrace repercussions in production systems and how to allocate inputs and outputs among multiple products.

This article deals with a novel mathematical model of life cycle assessment called Process-relational Model. Utilizing this model, we can dissolve the difficulties of LCA in retracing complicated repercussions and in allocating resource requirements and environmental emissions. This model consists of input and output matrix, including every process or activity in investigated systems. Thus it is similar to the Input-output analyses in economics, but different in including emissions and in taking recycle of wastes into consideration. Calculation of inverse matrix enables us to estimate direct and indirect resource requirements and emissions attributed to each activity in the systems.

2. Research Method

2.1 Method of Life Cycle Assessment

Bottom-up method is most commonly used in developing life cycle inventories of investigated systems. In this method, inputs and outputs are listed up in a table of each estimated process, taking the relationships between the processes into consideration. Hence it has difficulties in allocating inputs and outputs among multiple products as well as retracing repercussions between the systems. In particular, we have to establish the method of proper allocation in the systems including multiple production or recycling of products. For instance, fig.2-1 shows the system including recycling of waste materials. The waste 2 from Process 1 is recycled in Process 2 to be transformed into Product B. Suppose that Process 1 represents production of automobile, Waste 2, Process 2 and Product B correspond to iron scraps in producing automobiles, electric furnaces and recycled steel products, respectively. Then the question is how to allocate consumption of resources and environmental emissions among automobiles and iron scraps. Resource consumption and environmental emissions allocated to iron scraps are consequently added to steel products through the process of electric furnaces. Thus life cycle inventories of automobiles and steel products have a different results, depending on the allocation. In the bottom-up method, inputs and outputs are usually allocated to each product in proportion to the weight or the mole number of them. These are called weight-based or mole-based allocation.

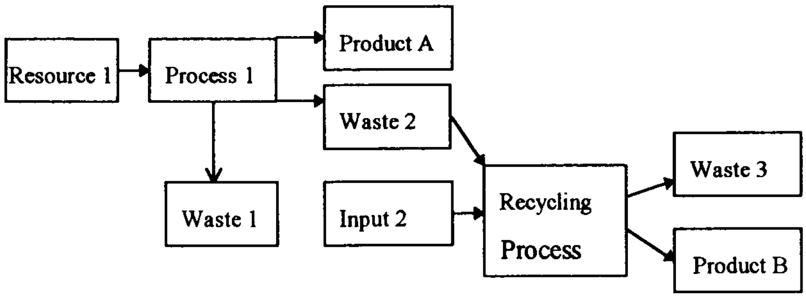

Figure 2-1. Life cycle assessments including a process of recycling

Life cycle inventories allocated to each product should be consistent with those of overall systems. For instance, if there are automobiles A and B, of which CO_2 emission allocated to automobile A is higher than that of B, and if all consumers select automobiles B, CO_2 emissions from overall systems should decrease. However, weight-based allocation do not generally insure the above mentioned consistency. We developed a novel mathematical formation called Process-relational Model, which can insure the consistency between each product and the overall system [1].

Next we describe the mathematical framework of the process-relational model. Fig. 2-2 depicts mathematical formation of a single process or a plant. We can deal with an element in fig.2-2 either as a process or as a plant according to the boundary and purpose of evaluation.

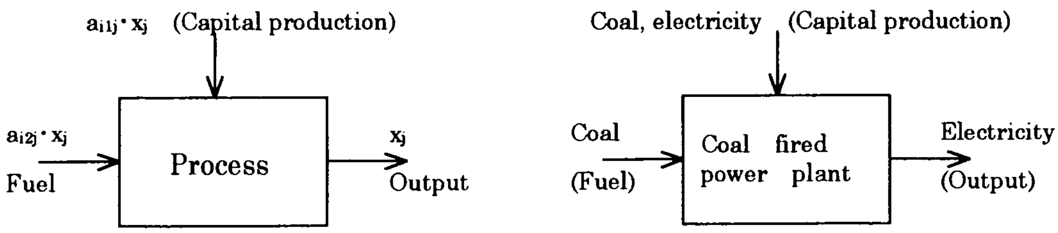

Figure 2-2. Modeling of inputs and outputs.

Fig. 2-2 indicates that all necessary inputs (i=1,..,n) for activity x_j are expressed as follows.

$$input = a_j x_j \tag{2-1}$$

Then all necessary inputs for all process's activities are expressed in equation (2-2).

$$\sum_{j=1}^{n} a_j x_j = Ax \tag{2-2}$$

On the other hand, products, byproducts and emissions are expressed as follows. Here we should note that this mathematical formation is different from input-output analyses in economics. Life cycle inventories must allocate resource requirements and emissions to multiple products from a single process, which is impossible in input-output analyses based on the principle of one activity-one commodity. We have to modify the principle so as to make life cycle assessments including recycling or multiple production. For this purpose, we define the vector x not to be materials, but to be processes. Then it follows that Ax and Ex represent the materials to be inputted into or outputted from the processes x. Thus we can include multiple outputs or emissions such as CO_2, NO_X, SO_X and heavy metals in equation (2-3).

$$y = Ex = \sum_{j=1}^{n} e_j x_j \tag{2-3}$$

The following condition is obtained from equations (2-2) and (2-3), assuming f as a vector of final demand.

$$\begin{aligned} Ex &\geq Ax + f \\ (E - A)x &\geq f \end{aligned} \tag{2-4}$$

In order to determine x, we need criterion function for optimization or simulation such as rojit function, on which actual systems depend. If actual systems are determined to minimize the total cost of overall systems, x is obtained by minimizing the criterion function, cx. Equation (2-5) expresses the solution x, where the matrix B represents optimal basis of the minimization problem.

$$x = B^{-1} f \tag{2-5}$$

$$\frac{\partial x_j}{\partial f_i} = {B^{-1}}_{ji} \tag{2-6}$$

From equation (2-6) and (2-3), we can estimate outputs of Section k per unit of Demand i as shown in equation (2-7).

$$\frac{\partial y_k}{\partial f_i} = \sum_{j=1}^{n} \left(E_{kj} \times B^{-1}{}_{ji} \right) \tag{2-7}$$

Thus we can allocate resource or emissions to each product, even if a system include recycling or multiple production. This allocation principle is called BI allocation[1].

Then we can estimate the improvement of an overall system as $EB_0^{-1}b_1$ when a new process b_1 is introduced in the system.

$$\begin{aligned} \Delta x &= -B_0^{-1}b_1 \\ \Delta y &= -EB_0^{-1}b_1 \end{aligned} \tag{2-8}$$

2.2 Sustainability of Resources and Emissions

We derive the necessary conditions for sustainable limitations on renewable resources, non-renewable resources and environmental emissions. The definition of sustainable consumption is obtained by investigating whether or not resource depletion and environmental crises can be avoided if the present rates of life-cycle efficiency and energy demands are continued[2].

As far as non-renewable resources are concerned, the sustainability condition is derived as follows. Suppose that grade of a resource is expressed in the function of $f(R,P)$=R/P, then the following equation is obtained by differentiating the function $f(R,P)$.

$$\begin{aligned} \frac{\partial f}{\partial t} &= \lim_{\Delta t \to 0} \left[\frac{1}{\Delta t} \left[\frac{R_0 \exp(r\Delta t) - \dfrac{D_0\left\{1 - C_0 \exp(c\Delta t)\right\} \exp(b\Delta t)}{\mu_0 \exp(a\Delta t) \exp(s\Delta t)} \cdot \Delta t}{\dfrac{D_0\left\{1 - C_0 \exp(c\Delta t)\right\} \exp(b\Delta t)}{\mu_0 \exp(a\Delta t) \exp(s\Delta t)}} - \frac{R_0}{D_0(1 - C_0)/\mu_0} \right] \right] \\ &= \lim_{\Delta t \to 0} \left[\frac{1}{\Delta t} \left[\frac{\mu_0 R_0}{D_0} \times \frac{\exp\{(a + r + s - b)\Delta t\}}{\{1 - C_0 \exp(c\Delta t)\}} - \Delta t - \frac{\mu_0 R_0}{D_0(1 - C_0)} \right] \right] \\ &= \frac{\mu_0 R_0}{D_0} \left\{ \frac{a + r + s - b}{1 - C_0} + \frac{C_0 c}{(1 - C_0)^2} \right\} - 1 \end{aligned} \tag{2-9}$$

$$\frac{\partial f}{\partial t} \geq 0 \tag{2-10}$$

Accordingly equation (2-11) is obtained.

$$a + r + s - b + \frac{C_0 c}{(1 - C_0)} \geq \frac{D_0}{\mu_0 R_0} (1 - C_0) = \frac{P_0}{R_0} \tag{2-11}$$

R_0 = Reserves of the resources at initial time period.
R = Rate of increase of R_0 by improvement of geophysical prospecting and mining.
S = Rate of substitution by other resources.
μ_0 = Life cycle efficiencies of utilizing the resources at initial time period.
a = Rate of increase of μ_0.
C_0 = Rate of recycle of the resources at initial time period. Although recycle is physically impossible in energy resources, it corresponds to the rate of cascading.
c = Rate of increase of C_0.
P_0 =Production of the resources at initial time period.
D_0 = Demand of the resources at initial time period.
b = Rate of increase of D_0.

Condition (2-11) indicates that depletion of a non-renewable resource can be avoided if the left hand side including the factors of technological improvement is larger than the reciprocal number of R_0/P_0. Therefore we define this as a sustainability condition of a non-renewable resource.

Renewable resources can also be dealt with as follows. Stock type renewable resources are evaluated such as biomass resources, since flow-type renewable energy harvested by photo-voltaic or wind turbine systems do not deplete. As conclusion, sustainability condition is the same as that of non-renewable resources except that r in Eq. (2-11) corresponds to a rate of regeneration of a renewable resource.

Next we investigate environmental emissions such as anthropogenic CO_2 emissions. If we regard environmental emissions as negative resources, we are able to apply the same kind of condition as non-renewable resources. In evaluating CO_2 emissions, sustainability condition is the same as that of non-renewable resources except that C_0 in Eq. (2-11) corresponds to the rate of absorption by the environment and that both r and c are zero. In particular, we should note that C_0 is closely related with accumulation mechanism of CO_2 emissions.

Thus the sustainability condition on renewables, non-renewables and environmental emissions are shown to be similar. Accordingly we can deal with various resources and emissions in the integrated framework. The sustainability conditions enable us to evaluate how the technologies of efficiency improvement, innovative mining or heat cascading contribute to the sustainability.

Fig. 2-3 shows the sustainability conditions of various resources evaluated based on the following assumptions.

(1) R/P of each resource is estimated based on proven reserves and production.
(2) Sustainability limitation of each resource is evaluated based on the above estimated R/P.
(3) The values in Eq. (2-11) are calculated as the average values between '70 and '90 for mineral resources and between '80 and '90 for energy resources.
(4) We can evaluate the distance between sustainable condition and actual situation of each resource as shown in Fig.1. This distance is defined as actual unsustainability.
(5) Reserves of those resources are supposed to increase as exploring and mining technologies are improved. Therefore we evaluated the value of r in Eq. (2-11) assuming that the proven reserve of each resource will approach the ultimate reserve in fifty years.
(6) We can investigate the potential risk of depletion of each resource, which is defined as potential unsustainability.
(7) As far as CO_2 is concerned, sustainability limitations and present situation is assessed based on airborne fraction, which is the rate of CO_2 accumulating in the atmosphere to anthropogenic CO_2 emission and maximum permissible accumulation in the atmosphere.

Maximum permissible accumulation is assumed to be 560 ppm, twice of that in pre-industrial era.

The real line in Fig.2-3 expressed the sustainability limitation. Then a resource, of which the point is above the line, is judged to be sustainable. For example, copper is judged to be sustainable actually, since improvements in mining technologies increased the proven reserves. However, it is judged to be potentially unsustainable, since the ultimate reserve of copper is not so much. On the contrary, iron is judged to be potentially sustainable because of huge ultimate reserves, although it is actually unsustainable. Whereas oil and natural gas is judged to be actually sustainable, all energy resources except for coal is potentially unsustainable. Unsustainability of CO_2 is lower than that of natural gas, and is comparable with that of oil and higher than that of coal.

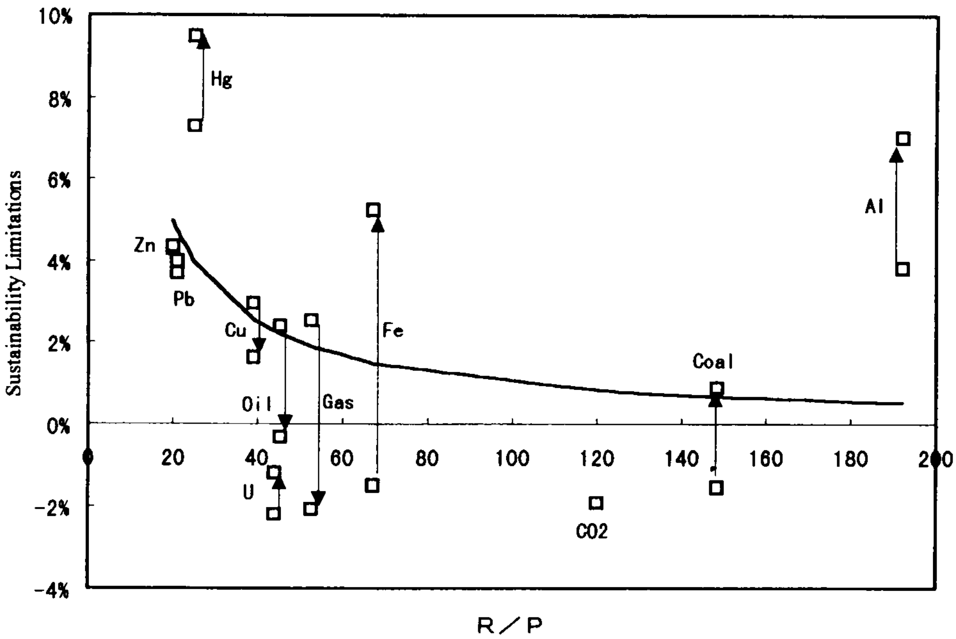

Figure 2-3. Sustainability of the resources and the emissions
* Mark indicates the direction from actual unsustainability to potential unsustainability.

Fig.2-3 also indicates that energy resources and CO_2 emissions could threaten the sustainable development of humankind. Therefore we focus our analysis on energy resources and CO_2 in the next section.

3. Results

3.1 LCA on conventional and aluminum vehicles

This section deals with life cycle assessment on conventional and aluminum vehicles based on actual data.

Table 3-1 shows the specification of the investigated vehicles. The life cycle inventory is developed based on the weight table of 446 parts constituting the vehicle. On the other hand, energy consumption in driving the vehicle is estimated utilizing simulation model developed in this study.

Table 3-1. Vehicle investigated in this study

Vehicle	1984 Mark II
Weight	1159 kg

In this section, we show the life cycle inventories of a conventional vehicle. Fig.3-1 shows energy, material and wastes resulting from producing, using and disposing of a conventional vehicle. Energy consumption in driving automobiles occupies approximately 74% of total consumption.

This section deals with LCA of an aluminum vehicle. Since energy consumption in driving vehicles is dominant in life cycle inventories, it is efficient to manufacture the light aluminum vehicle so as to improve the fuel economy. Table 3-2 shows the weight ratio of an aluminum vehicle to a conventional vehicle.

Table 3-2 Weight ratio of an aluminum vehicle to a conventional vehicle.

	WEIGHT
ENGINE	50%
BODY	40%

Fig. 3-2 shows computed results of an aluminum vehicle, where Fig. 3-1 depicts the result of a conventional vehicle. In the case of an aluminum vehicle, energy consumption in running is approximately 6 % less than that of a conventional vehicle. On the other hand, energy consumption in producing an aluminum vehicle is more than in producing a conventional vehicle.

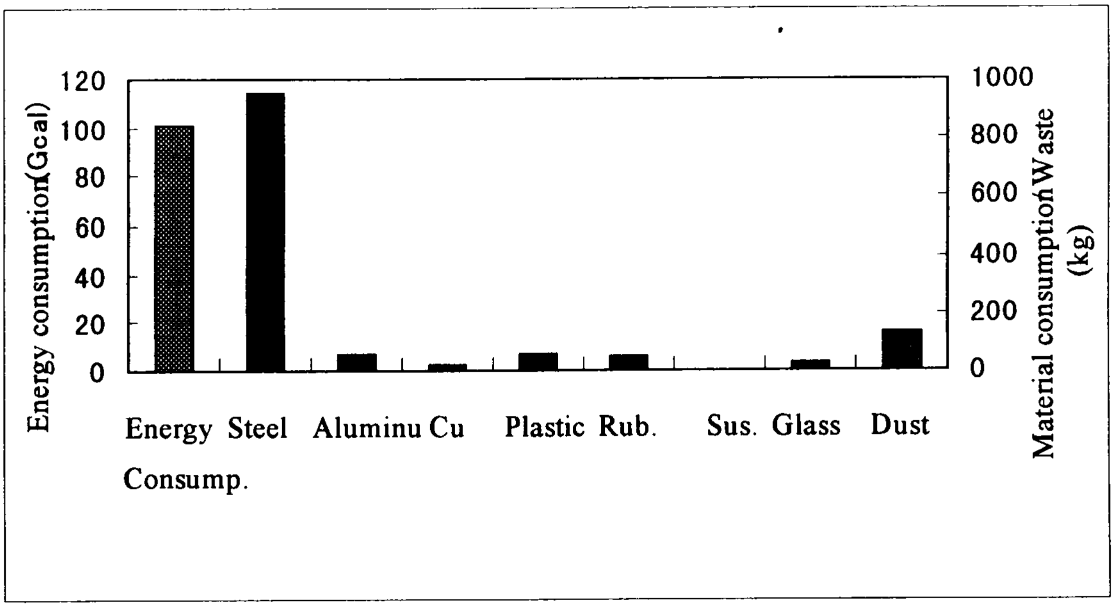

Fig. 3-1. Energy, material and wastes resulting from producing, using and disposing of a conventional vehicle.

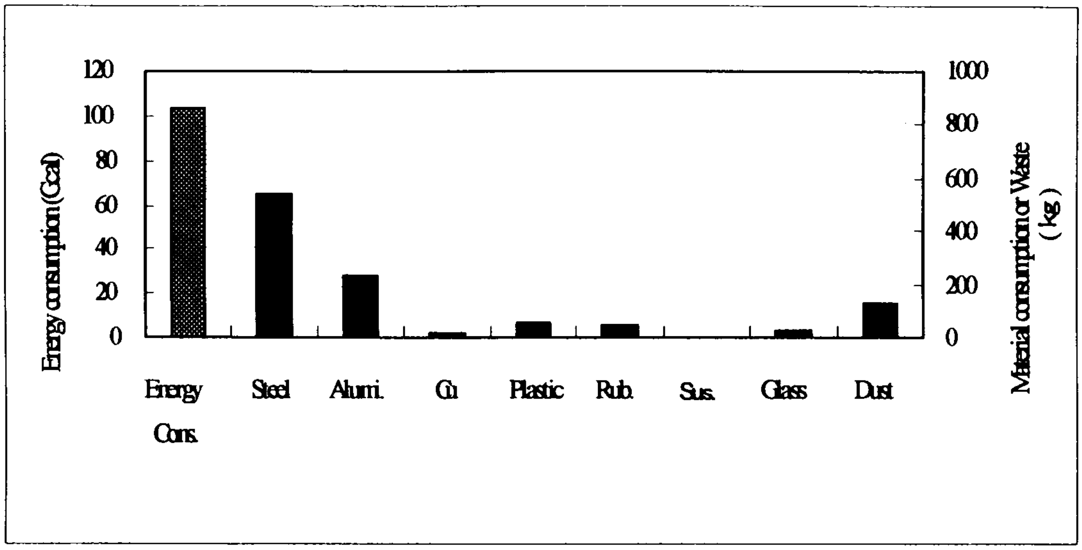

Fig. 3-2. Energy, material and wastes resulting from producing, using and disposing of an aluminum vehicle.

3.2 Analysis on the allocation problem

This section shows the numerical examples of BI allocation, which is described in chapter 3.

We compared the results of weight based allocation with BI allocation in altering demand for recycled aluminum from scraps of the automobiles.

Fig. 3-3 clarifies the point, in which the demand of recycled aluminum balances the supply from the automobiles. At the same time, this figure indicates that CO_2 from the aluminum vehicle is less than that from the conventional one, if the aluminum is fully recycled. This is consistent with CO_2 emissions of the overall system including manufacture of automobiles.

On the other hand, Fig.3-4 does not show such a break even point as in Fig.3-3. CO_2 from the aluminum vehicle is always more than that from the conventional one in Fig.3-4.

These observations indicate that BI allocation is useful in the consistency between LCI of each product and the overall system.

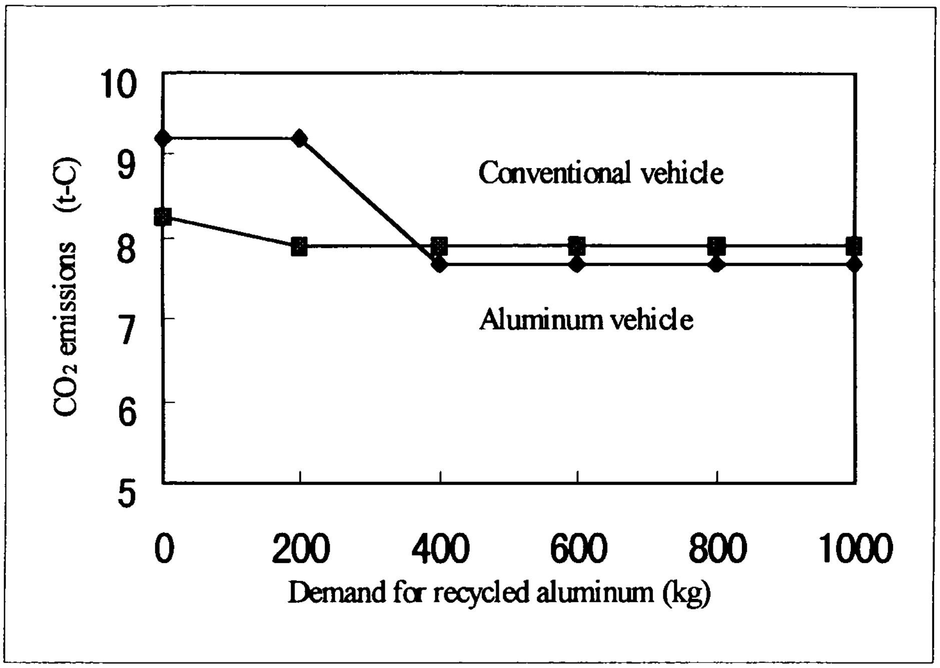

Fig.3-3 CO_2 emissions of conventional and aluminum vehicles.
(BI allocation with one ton of demand for recycled steel)

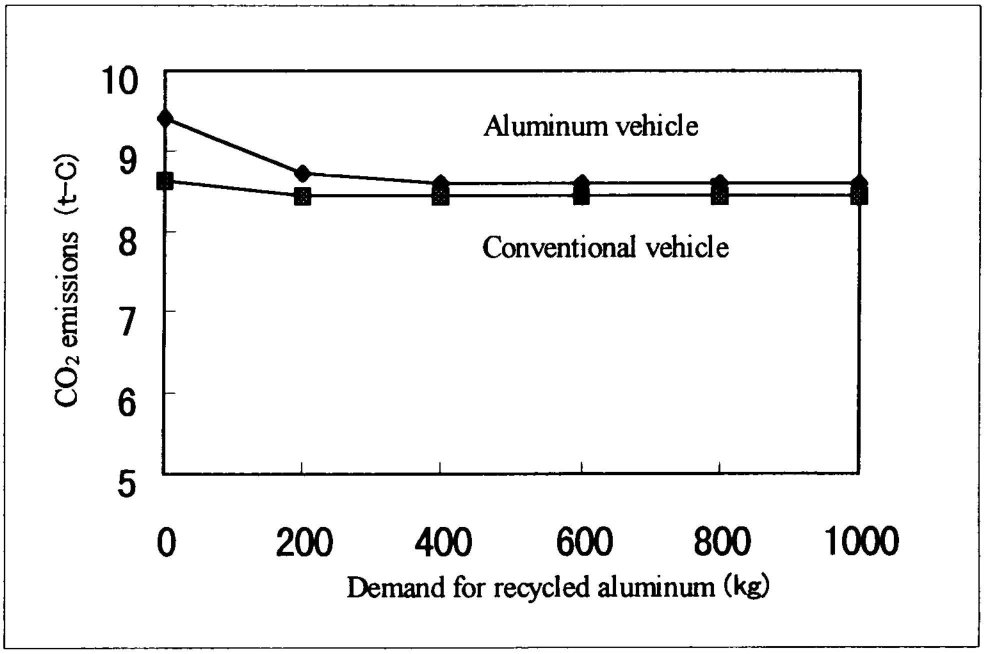

Fig.3-4. CO_2 emissions of conventional and aluminum vehicles.
(Weight based allocation with one ton of demand for recycled steel)

4. Conclusion

This study aims at evaluating the cost-effectiveness of CO_2 mitigation options. Evaluating mitigation options inevitably requires assessments of all possible impacts of the options. Life cycle assessment (LCA) is therefore expected to be one of useful tools for