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Inland transportation system planning by life cycle impact assessment: a case study

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Abstract The comparison of land and inland water transportation from economical and ecological points of view is discussed. Required freight rates for trucks and ships are calculated and compared to find which has economic superiority. From the environmental impacts of these two transportation types, the comparative environmental destruction indices for two different time-durations are estimated. All these investigations were conducted for the Yokohama–Fukuoka route in Japan. Life cycle impact assessment, a very useful tool for quantitatively evaluating the environmental influence of a product, was used to compare the environmental burden imposed by these types of transportation. Finally, the way that these results can be used for inland transportation system planning is discussed.

Key words Transportation · Environment · Modal shift · Life cycle impact assessment · Kyoto Protocol

List of symbols

RFR	required freight rate
LCA	life cycle assessment
LCIA	life cycle impact assessment
P	price of transport or first cost (¥)
C	annual cost (¥)
L	amount of cargo carried (ton/year)
spw	series present worth factor
i	rate of return (%) on investment
N	number of years in operation
¥	Yen (Japanese currency)

Introduction

In the past two decades environmental issues have caused greater public and legal concern. People all over the world have become more aware of their consumption of goods and services and their impact on natural resources and the quality of environment. The gradually increasing devastating effects of climate change are imposing more and more pressure on people to think about the environment of this planet. Recent natural calamities such as long-lasting floods in various parts of the world, including Bangladesh, frequent cyclones and hurricanes, and coral bleaching[1] in the Pacific Ocean as well as the Indian Ocean and Caribbean Seas are some of the devastating effects of climate change. Scientists believe that global warming is the main reason behind the increasing frequency and strength of all these disasters. Since the industrial revolution, the global mean surface temperature has risen by 0.3°C to 0.6°C.[2] This is the effect of increased atmospheric concentrations of various greenhouse gases. It has been found that during this period carbon dioxide (CO_2) concentration in the atmosphere has increased nearly 30%, methane (CH_4) concentration has more than doubled, and nitrous oxide (N_2O) concentration has risen by about 15%.[2]

The governments of industrialized countries and countries with economies in transition have been trying to convince those sectors, companies, and sources which are involved in emitting greenhouse gases of the danger, so that they adopt new methodologies to reduce these emissions. The Kyoto Protocol[3] has been a turning point in this regard for future economic and environmental policies for both industrialized and developing countries.

The emissions from various methods of transport are one cause of the increasing atmospheric concentrations of greenhouse gases. For example, in the USA motor vehicles are responsible for about two-third of the carbon monoxide, one-third of the nitrogen oxide and one-quarter of the hydrocarbon emissions to the atmosphere.[4]

A modal change from road to inland water transport could be one of the most effective measures to reduce such emissions[5] as trucks and cars are the methods of transportation which emit most greenhouse gas. It has been found that inland shipping is about 600% cleaner

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than road transport, and 150% cleaner than the train.[6] However very often this modal change is considered to be a hindrance to economic development. Recent work has attempted to find a way to satisfy environmental as well as economic requirements.

In this paper the authors have tried to establish a model to compare inland water transport with road vehicles to find the most suitable mode of transport to satisfy both economic and ecological considerations. The Yokohama–Fukuoka route was chosen for this comparison. The required freight rate (RFR) for the two modes of transport was calculated to find which was economically superior for an assumed amount of cargo shipment. By considering seven environmental impacts (energy consumption, heat radiation, CO_2 emission, NO_X emission, SO_X emission, phosphorous emission, and particle matter emission) which have an influence on six different problem areas (fossil fuel exhaustion, local warming, global warming, acid rain, eutrophication, and air pollution), the environmental destruction indices for both trucks and water transport were estimated for the same amount of cargo shipment using life cycle impact assessment. The "not so familiar" term eutrophication[7] is the process by which bodies of water are made more eutrophic (well nourished) by an increase in their nutrient supply and made more productive biologically, generating large populations of algae and other organisms.

A different weighting factor was used for each different environmental effect, and the sensitivity of the estimated environmental index to the environmental impacts was analyzed. Finally, the scope of these findings for use in future planning is discussed.

Life cycle impact assessment

The concept of the life cycle simply means that the inputs (energy, materials, etc.) and outputs (energy, waste materials, products, etc.) of the cycle are evaluated for each step of the life of a product or process. As a method for quantitatively evaluating the environmental influence of a product, life cycle assessment (LCA; standardized as ISO 14040)[8] is now widely used. Through a product's life from raw material acquisition through production, use, and disposal, LCA studies the environmental aspects and potential impacts of that product.[9]

Life cycle impact assessment (LCIA; standardized as ISO 14042)[10] is another tool to evaluate a product's influence on the environment. There exist various kinds of methodologies and procedures for considering the LCIA method. The flow process followed here for calculating the environmental burden using LCIA is shown in Fig. 1

Transportation model considered

The particulars of the Yokohama–Fukuoka route and the transport methods considered for the comparison are shown in Table 1. The truck and ship under consideration were assumed to be operated by 600 PS and 12 000 PS engine power, respectively.

The cost and specific gravity of the light oil used by truck were taken to be 70 ¥/l and 0.85, respectively. These values for the heavy oil used by ship were 15 ¥/l and 0.9, respectively. The cost of carrying cargo from the stock point to the ship was taken as 25 ¥/ton-km.

Most of the data mentioned in Table 1 were collected from sources associated with various transport companies, and the others were reasonably assumed.

Methodology

To evaluate the economic and environmental performance of these methods of transport, a model case was

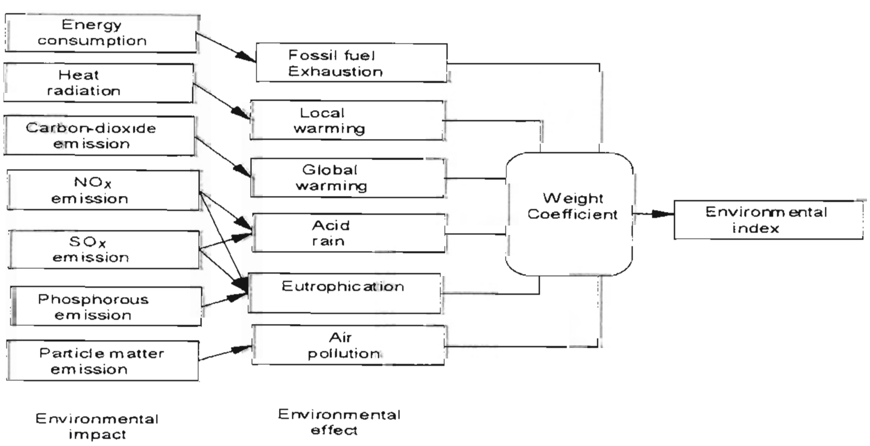

Fig. 1. Environmental index from environmental impact

Table 1. Route and transport particulars

	Truck	Cargo ship
Route length	1160 km	1000 km
Capacity	11 tons	5000 tons
Transport velocity	50 km/h	23 knots
Total trip time	32.5 h	40 h
Travel time	24 h	24 h
Loading and unloading time	2 h	8 h
Delay	25%	25%
Off-hire days per annum	30	45
Max. round trip per annum	124	96
Fuel type used	Light oil	Heavy oil
Fuel consumption	4 km/l	150 g/PS-h
Average loading condition	90%	50%
Harbor charge/trip		20000 ¥
Life time	10 years	20 years
Transport between stock point and ship (by truck)		
Distance		10 km
Travel time		12 min
Price of transport	1×10^7 ¥	1.50×10^9 ¥
Transport tax/year	43600 ¥	250000 ¥
Depreciation	2.0×10^6 ¥	7.5×10^7 ¥
Maintenance cost/year	100000 ¥	2000000 ¥
Other cost/year (weight tax, insurance, etc.)	192000 ¥	2000000 ¥
Labor cost/man-hours	2500 ¥	2500 ¥

Table 2. Unit load of environmental impact

Impact	Truck	Cargo ship
During the production phase		
Energy (MJ)	7.25×10^5	1.39×10^8
Heat (MJ)	—	—
CO_2 (tons)	58.79	1.07×10^4
NO_x (kg)	87.11	4.85×10^4
SO_x (kg)	3.03×10^2	1.32×10^4
Phosphorous (kg)	68	9.65×10^3
Particle matter (kg)	—	—
During the operation phase		
Energy (MJ/ton-km)	3.93	0.62
Heat (MJ/kg of fuel)	42.7	40.7
CO_2 (g/ton-km)	188	58.4
NO_x (g/ton-km)	1.49	0.81
SO_x (kg/ton of fuel)	4.2	48.3
Phosphorous (kg)	—	—
Particle matter (g/kw-h)	0.205	0.2

studied where it was assumed that an average 1500 tons of break bulk-type cargo was to be carried from Yokohama to Fukuoka, and same amount from Fukuoka to Yokohama, in 1 day by truck or ship. According to Table 1, a truck requires 32.5 h for one trip on this route. Allowing for 30 off-hire days, the maximum number of round trips per annum per truck was 124. At a 90% average loading condition, one 11-ton truck (with 10.7 tons cargo capacity) might carry a total of 1194.12 tons of cargo one way in 1 year. To carry 547500 tons of cargo each way in 1 year, 458 trucks were required. Similarly, with 40 h trip time and 45 off-hire days, the maximum number of round trips per annum per ship was 96. Taking the average loading condition as 50% of the 5000-ton ship (4500 tons cargo capacity), the total number of round trips required was 243, i.e., three ships were required to perform the same task as 458 trucks.

To find which method is economically superior, the required freight rates (RFR) at a 5% rate of return on the investment in the truck or the cargo ship were calculated and compared. RFR is the minimum freight rate required to meet the expected rate of return (i) on the principal investment or initial price (P), and the annual cost (C) within a specified period (N). Here, annual cost includes the fuel cost, maintenance cost, crew cost, insurance, etc. The RFR was calculated using the following equations[11]:

$$\mathrm{RFR} = \frac{\left[\dfrac{P}{\mathrm{spw}} + C\right]}{L}$$

where RFR = required freight rate (¥/ton), P = price of the transport or first cost (¥), C = annual cost (¥), and L = amount of cargo carried (ton/year).

$$\mathrm{spw} = \frac{(1+i)^N - 1}{i(1+i)^N}$$

where spw = series present worth factor, i = rate of return, and N = number of years in operation.

The series present worth factor, also called the annuity factor, is the multiplier used to convert a number of regular (annual) payments into the present sum.

Life cycle impact assessments of the trucks and ships were conducted by considering the amount of impact on various environmental factors, as shown in Table 2. It was very difficult to estimate the amount of environmental impact involved during the production and operation of these forms of transport. Hence, these data were collected from the web-sites of a number of transport-oriented organization.[12–15] However, the data for heat and particle matter emitted during production and phosphorus emitted during operation were not available.

Seven different types of impact which have an immense influence on climate change were taken into account while calculating the environmental index. Then the environmental effects of these seven factors in six different categories were calculated for trucks and cargo ships. As these effects were in different unit values, the ratio of the impacts of the road transportation system to those of the marine transportation system were considered for further calculations. Finally, the

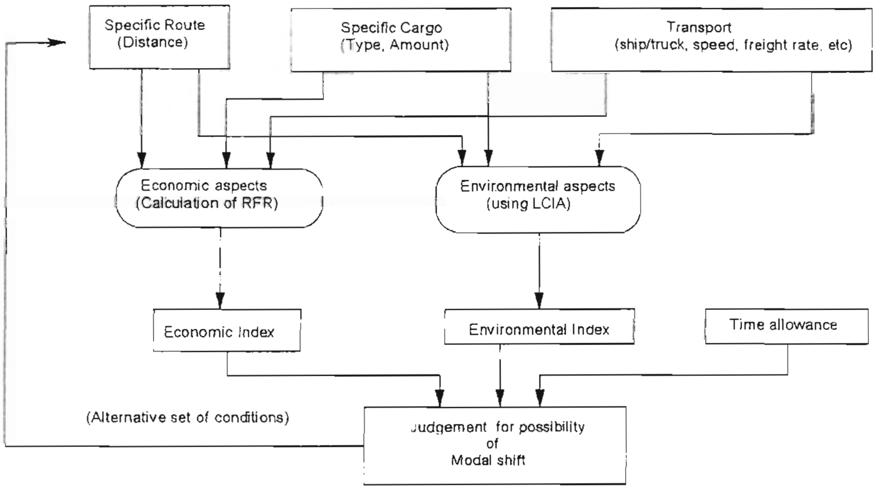

Fig. 2. Flow diagram of the methodology

Table 3. Economic index (RFR)

Transport	Annual expenditure (¥)	Amount of cargo carried (ton/year)	RFR (¥/ton) 10-year operation	RFR (¥/ton) 20-year operation
Truck	68858000	2388	28886	28886
Cargo ship	441438889	365000	1539	1539

environmental destruction indices were calculated by multiplying these effects with a specific weighting factor for each effect category. Estimates were made for two scenarios: 10-year and 20-year operations. The flow diagram of the whole analysis is shown in Fig. 2.

Results and findings

The calculated RFRs are shown in Table 3. In these calculations, each ship was considered to operate 81 round trips per annum on average. Table 4 shows the environmental effects imposed by the road transportation system of 458 trucks compared with that of the marine transportation system of three cargo ships. The weighting factors for each category of environmental effect are shown in Table 5. A questionnaire was used for a survey among some naval architects, shipbuilding-related personnel, and students in Japan asking them to give weighting factors to various environmental effects. These people were chosen because it was easy for the authors to contact them and get their responses. The people questioned were asked to consider two environmental effects each time, and then compare their dominance with climate changes to fix a weighting factor. For example, they were asked to compare "local warming" with "global warming," and to judge which one is absolutely/very strongly/strongly/weakly more important than the other or whether both are equal in importance for the environment. Eighty-seven people responded to the questionnaire. Then an analytic hierarchy process (AHP)[16] was used to calculate the weighting factors. The weighting factors shown in Table 5 add up to 1.000 because they have been normalized according to Saaty.[16] The comparative environmental destruction indices for the two different scenarios are shown in Table 6. With the available data, it was shown that on the Yokohama–Fukuoka route, moving freight by truck is about twice as harmful as moving it by cargo ships in terms of CO_2 and other harmful emissions to the environment from the view point of LCIA. When considering RFR, the cargo ship is more than 18 times

Table 4. Environmental effect imposed by the road transportation system from 458 trucks compared with that of the marine transportation system from three cargo ships

Effects	In 10 years operation	In 20 years operation
Fossil fuel exhaustion	7.16	7.3
Local warming	3.07	3.07
Global warming	1.16	1.18
Acid rain	1.2	1.2
Eutrophication	2.81	4.43
Air pollution	0.02	0.02

Table 5. Weighting factors for environmental effects

Effect	Fossil fuel exhaustion	Local warming	Global warming	Acid rain	Eutrophication	Air pollution
Weight coefficient	0.145	0.078	0.26	0.185	0.099	0.233

Table 6. Environmental destruction index of the road transportation system from 458 trucks compared with that of the marine transportation system from three cargo ships

	In 10 years operation	In 20 years operation
Environmental index	1.92	2.07

Table 7. Summary of the results

Trucks (458) / Cargo ships (3) (ratio)	In 10 years operation	In 20 years operation
RFR	18.77	18.77
Service time	0.81	0.81
Environmental index	1.92	2.07

better than the truck. The only merit associated with the truck is the service time. "Service time" is used to express the time taken by the transport company to serve their customer. Here it is considered to be the total trip time, as shown in Table 1. A summary of these findings is given in Table 7. These results lead us to realize how much the negative influence on climate change and the cost of transport would be reduced by modal shifting of cargo from trucks to ships.

A sensitivity analysis of the environmental index to the negative impact of ships and trucks was conducted. The results are shown in Figs. 3 and 4. The analysis was done by varying one parameter each time and keeping all other parameters as shown in Table 2. The figures show that the index is more sensitive to negative impacts during operation than to those during production.

Conclusions

It is known that the freight rate of water transport is the most financially attractive of all forms of transport, but it is not generally preferred by domestic users. This is probably because of the length of time taken with this system. Moreover, the quality of service and ease of door-to-door delivery by the trucks are of benefit to the shipper. These factors usually outweigh the cost differential between these two modes of transport. By developing the cargo handling and navigation systems, and also by emphasizing the environmental superiority of water transport, it should be easier to convince users that they have a moral obligation to use this mode in place of other surface vehicles. The growing awareness among people of various disciplines in society about the need to protect the environment will be very helpful in persuading them to change to using water transport when moving their freight.

The recent trend is to prevent or minimize waste before it is created instead of treating or disposing of it later. This study has shown that a modal shift from trucks to ships could be a very effective measure to minimize the emission of greenhouse gases and other harmful elements from one section of the transportation system. This would help to support sustainable development of transport systems without causing damage to the environment.

Economic development is sometimes thought to conflict with such a modal shift to inland water transport because it is slower than other methods, even though the freight rate in this mode is the cheapest. However, it has been found that in general consumers are ready to accept this delay, up to a certain limit, when moving their goods.[17] So it is now important to lead a moral shift in consumer thinking to help the modal shift of freight from trucks to ships.

The environmental impact of the materials of which the trucks and ships are made was not considered during this evaluation, as these values were not available. However, it is reasonable to believe that the total environmental effect of the materials needed to build 458 trucks will not be less than that of the materials needed to build three cargo ships.

A new environmental index to compare marine transport with land vehicles in a LCIA has been introduced, but a single comparison index needs to be established to consider the economic and environmental aspects as well as the time value.

The findings of this study will be helpful in future planning of the inland transportation system, and also in imposing an environmental tax on this sector.

Topics for further research in this area are listed below.

— The economic feasibility of this modal shift should be studied in detail.

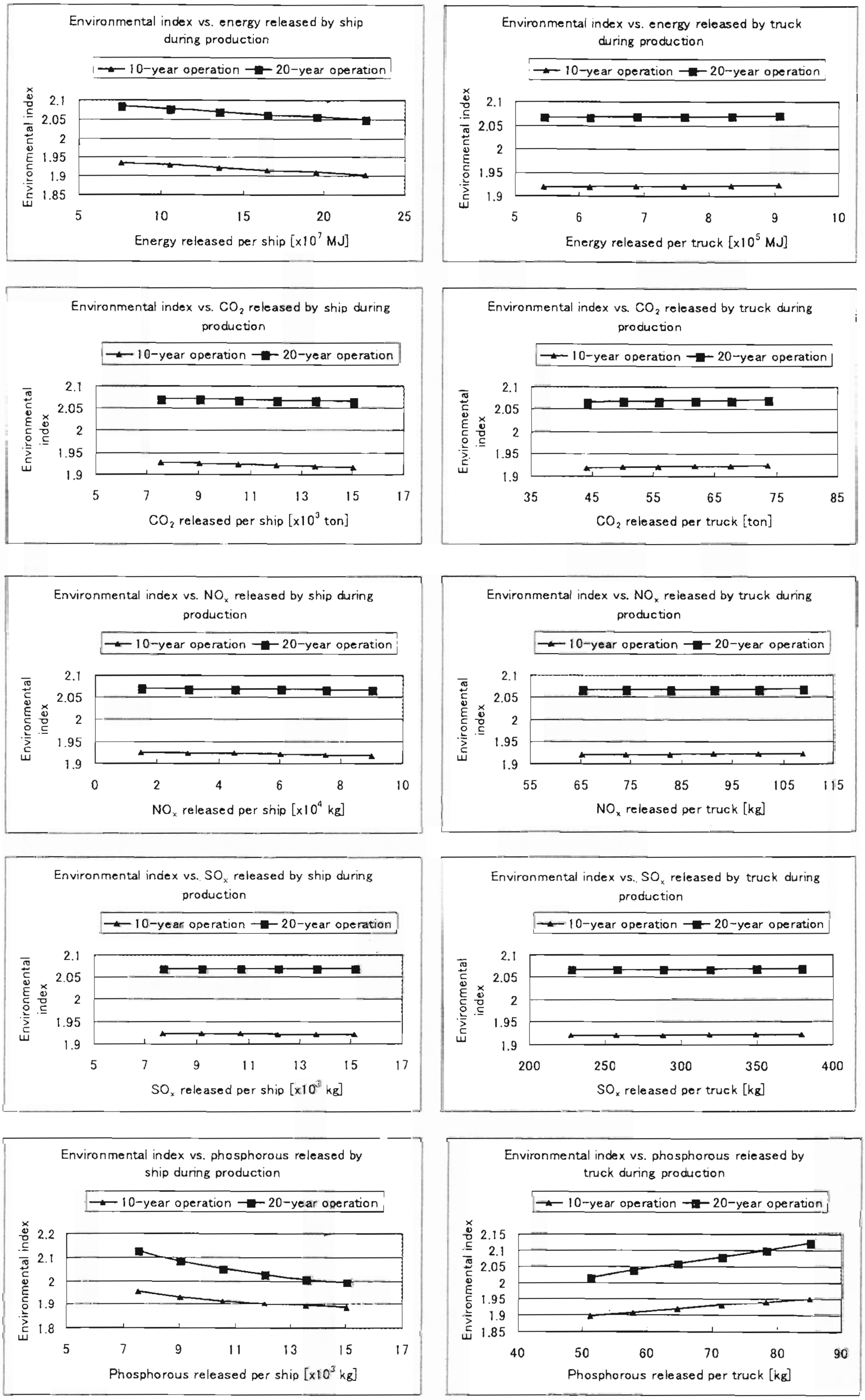

Fig. 3. Sensitivity of the environmental index to the impact on the environment of ships and trucks during their production

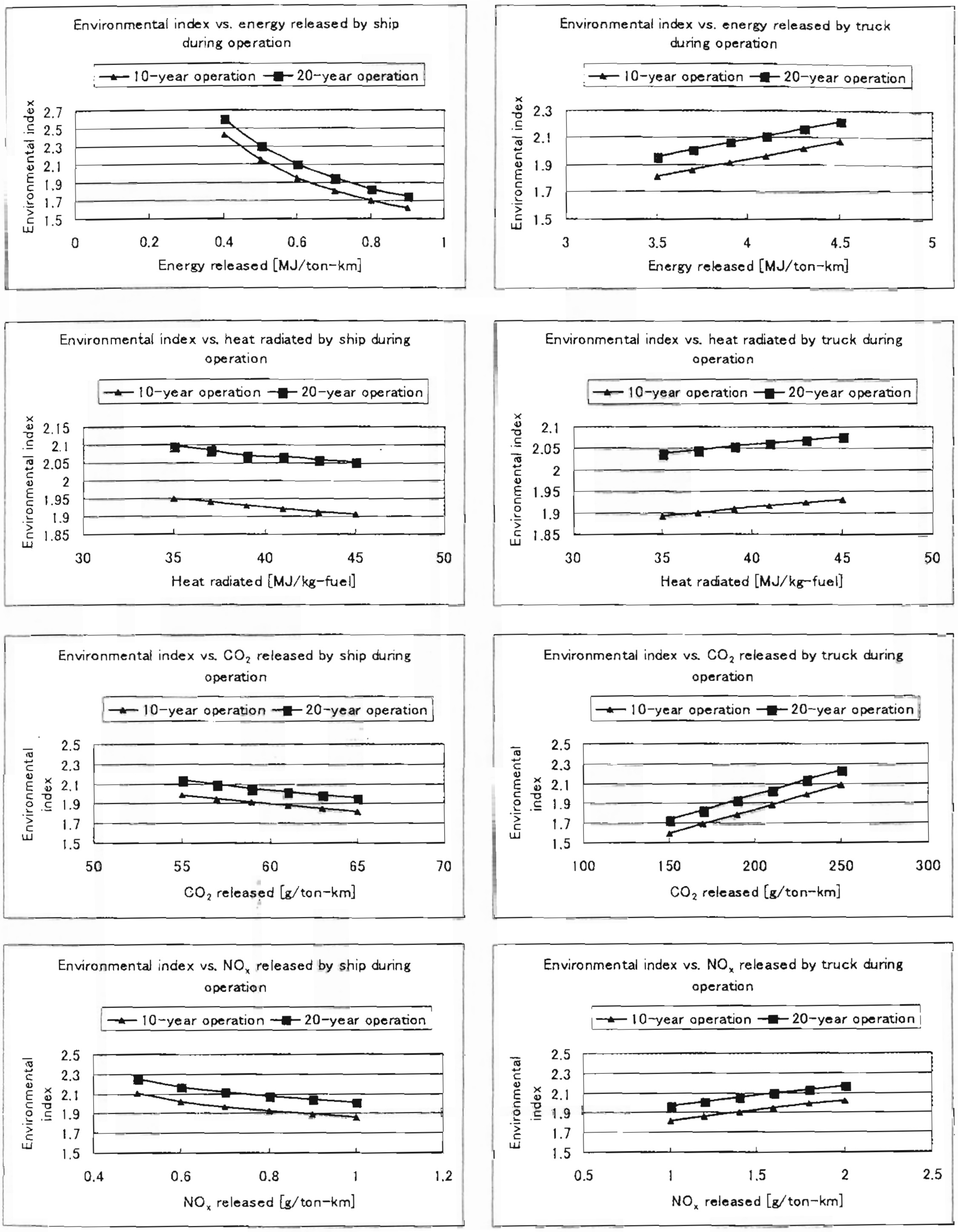

Fig. 4. Sensitivity of environmental index to the impact on the environment of ships and trucks during operation

- The infrastructures necessary for inland shipping and land transport, i.e., harbor facilities, road networks, etc., should be considered in these comparisons.
- Other environmental factors such as the effects of deforestation due to the extension of roads, and the effects on aquatic life of ship movements should be studied.
- Time values should be analyzed in detail.
- The environmental impacts of the materials of which the trucks and ships are made should also be considered during LCIA evaluations.

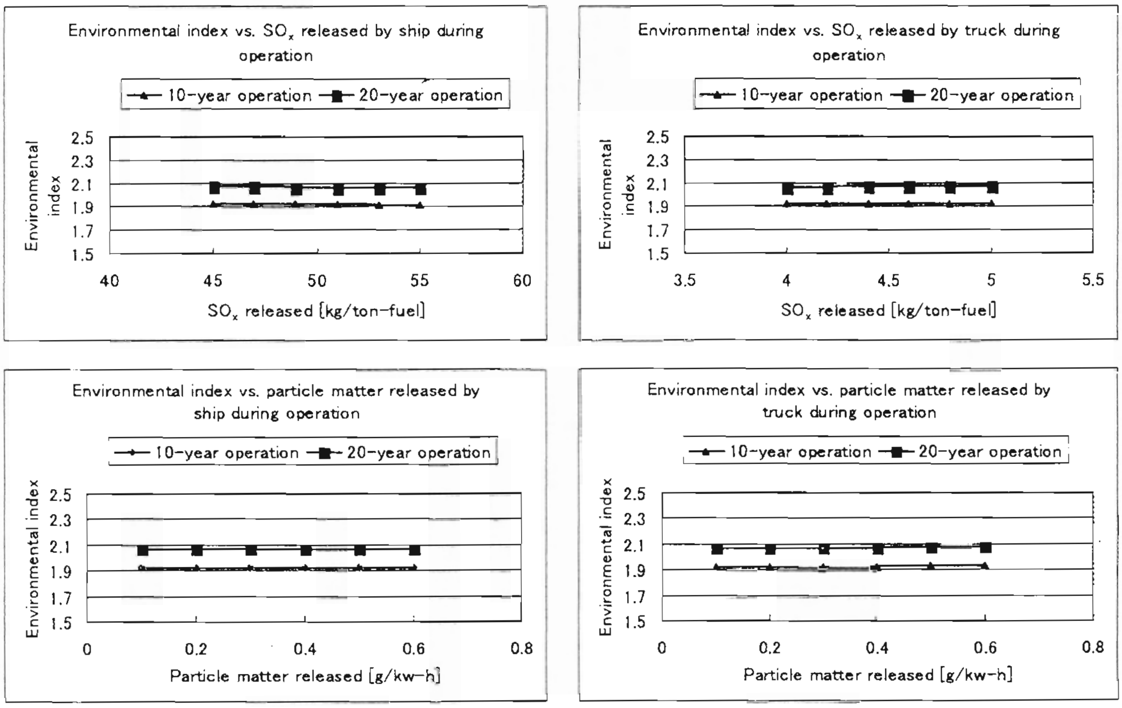

Fig. 4. *Continued*

— To make the weighting factors for environmental effects more acceptable, the opinions of people in other disciplines, including environmentalists and those involved in land transportation, should also be considered.

Japan is a country with good inland and coastal navigation facilities. Inland water transport in Japan has some natural advantages over other modes of surface transport. It is now essential to consider the future development of this sector for the sake of the earth and to ensure the survival of human beings.

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