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BRIDGE TYPE SELECTION SYSTEM INCORPORATING ENVIRONMENTAL IMPACTS

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Abstract

Environmental problems in global as well as local levels have led commitments for reduction of greenhouse gases by various industrial nations. This has urged finding out effective ways of reducing greenhouse gases in all sectors of the national development. A large amount of natural resources are consumed during construction of infrastructures. This gives more justification of need for proper planning of the infrastructures to ensure that resources will be used optimally. In this research, a bridge type selection system is developed including environmental impact as one selection factor in addition to cost, driving comfort and aesthetics. The environmental impact of each candidate bridge type is evaluated on the basis of the energy consumption and the CO_2 emissions from the construction materials and equipment. Most parts of the environmental impacts are found to be due to the use of construction materials. Recycling of construction materials is considered as a method of reducing the environmental impacts. This study aims to demonstrate inclusion of the environmental impact as one criterion in bridge type selection process.

KEYWORDS: *Environmental Impact, Bridge Type Selection, Energy Consumption, CO_2 Emissions, Recycling*

1. Introduction

Recent focus on problem of global warming is drawing worldwide attention to find out the effective ways of reducing the emissions of greenhouse gases (Dwyer 1992, IPCC 1995). Recently, Kyoto Protocol has gone ahead in reducing the greenhouse gases in coming years with specific numerical targets proposed by the industrial nations (Kyoto Protocol, 1997). For example, Japan has

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committed 6% reduction of greenhouse gases emissions in 2012 by the level of 1990 according to the Kyoto Protocol. This has shown urgent need for researches on development strategies considering environmental impacts. It has provided challenges to national policy makers to find out the more effective ways of reducing emissions of greenhouse gases to meet such numerical targets. Construction of infrastructures needs use of huge amount of natural resources and construction equipment consuming fossil fuels. For example, the manufacturing of cement contributes significant portion of anthropogenic carbon dioxide (CO_2) emissions (Masters 1991, IPCC 1995). The Civil Engineering sector of Japan contributes about 17% of energy consumption and 21% of CO_2 emissions among the total global impacts from Japan (PWRI 1994). However, there are few decision-support systems that can help in the evaluation of environmental impacts of construction projects.

Selection of a bridge type presents optimization of several objectives such as cost minimization, durability, pollution reduction and so on. In this research, a bridge type selection system is extended to include environmental impacts of bridges in addition to cost, driving comfort and aesthetics that were considered in previous studies by Nishido et al. (1989) and Nishido and Itoh (1993). The methodology of evaluation of environmental impacts is described in order to consider it as a selection criterion similar to cost and safety of a bridge. Some part of this paper has already appeared in Japanese language in the paper by Itoh et al. (1996).

Construction of a bridge affects the environment in several ways. Air pollution, noise pollution, and loss of greenery due to construction of approach roads for bridges are some examples of environmental impacts having more concern at local level. On the other hand, depletion of natural resources and fossil fuel consumption have effects such as emissions of greenhouse gases like CO_2, methane (CH_4), nitrous oxide (N_2O), and so on. Energy consumption is an indicator of uses of natural resources that can be used as an indicator for environmental impacts (Wang et al. 1980). Among various greenhouse gases CO_2 is found to be increasing steadily in the atmosphere constituting more than 50% of total greenhouse gases causing global warming (Moavenzadeh 1994). It constitutes more than 80% of total greenhouse gases in the present inventory of USA (EPA 1997). Further, CO_2 has more acceptable procedures of measurement available than other greenhouse gases (IPCC 1995). Therefore, CO_2 emission can be taken as an important indicator to estimate the environmental impacts of global concern. Several studies have considered CO_2 to study the effect of global warming (Hobbs 1994, Tung and Haith 1995). Therefore, in this research, the environmental impact from each candidate bridge type is evaluated by the amount of energy consumption and CO_2 emissions from the materials and construction equipment. The effect of recycling construction materials is considered in reducing the environmental impacts. CO_2 emissions at the service stage of a bridge resulting from the traffic and maintenance activities, including painting of steel bridges, are significant sources of environmental impacts. However, this study concentrates only on the construction stage. Considering the lifecycle of bridges should be done in future research.

The environmental impacts from a bridge include all the impacts from the bridge components such as superstructure, abutments, piers, piles and so on. At this stage, the proportions of environmental impact by each type of bridge component among all components are unknown. Therefore, in this research, the environmental impacts of several types of bridge components are calculated in order to find the contribution of each bridge component. At present the developed system includes database of costs and unit impacts prevailing in Japanese condition. The system may be applied in other countries by adjusting part of the basic data to suit the conditions of each country. This paper first introduces the development of a decision support system for selection of a bridge type with detailed procedures of calculation of environmental impacts. Then the calculation of environmental impacts from different bridge components such as superstructure and substructure is shown including the proportions of environmental impacts from construction materials and equipment. Effect of recycling of construction materials on environmental impacts is described in the subsequent section. An example application of the bridge type selection system is shown in another section.

2. Bridge Type Selection System

2.1 Development of Bridge Type Selection System

Various factors need to be considered when selecting a proper bridge type in the preliminary design stage. Cost, aesthetics and durability of the bridge are a few such criteria that are only possible to be judged and balanced by experienced designers. A bridge type selection system is developed combining the knowledge base of design manuals and design specifications including heuristic knowledge of experienced designers. Fig. 1 shows the structure of the bridge type selection system developed. This system basically follows the practical procedures adopted in Japan during preliminary design stage. The inputs to the system are: river cross section, bridge length, bridge width, soil conditions, river discharge and so on. Various span arrangements are generated by the system based on these input conditions. The basic criterion for the candidate bridge type is the economical span depicted in design manuals (JSSC 1991, Pre-stressed 1997). Based upon this criterion, candidate bridge types are obtained corresponding to span lengths. The system has functions for evaluating each candidate bridge type from the cost, driving comfort, aesthetics and environmental impact points of view. At the beginning, the system was developed using the LISP language on a workstation (Nishido et al. 1989). The present version of the system is developed in C++ on a personal computer. The knowledge base of the system has rules from design specifications used in Japan such as River-Crossing Structure Law (1974) and Specifications for Highway Bridges (1996), in addition to heuristic rules taken directly from experienced designers.

After generating the numbers of spans and span lengths, the possible combinations of the superstructure as simple or continuous supports are generated with respect to span arrangements. The next step in the superstructure type selection is to create all possible combinations of bridge types for each span arrangement by the generate-and-test method. Fig. 2 shows the bridge types included in the system. These bridge types are classified according to the materials into steel bridges and pre-stressed concrete bridges. Within each group, bridges are further classified according to their shapes and continuities over the supports. The rules used to decrease the number of combinations are classified as structural restrictions and heuristic rules given by the experienced designers. An example of the structural restriction is that different bridge types, such as steel and PC bridges can not be used together. This restriction eliminates the combination of bridge types having mixtures of steel and PC bridges. An example of the heuristic rule is that combining four or more bridge types is not feasible.

A rule written in the program eliminates combinations having more than three different bridge types. The system calculates the approximate costs of the superstructure and substructure and then total cost. The cost estimation is carried out according to the chart information of design manuals used by the designers in the preliminary design stage. Several functions are prepared to calculate the cost of superstructure, abutments, piers and piles considering various types of each component.

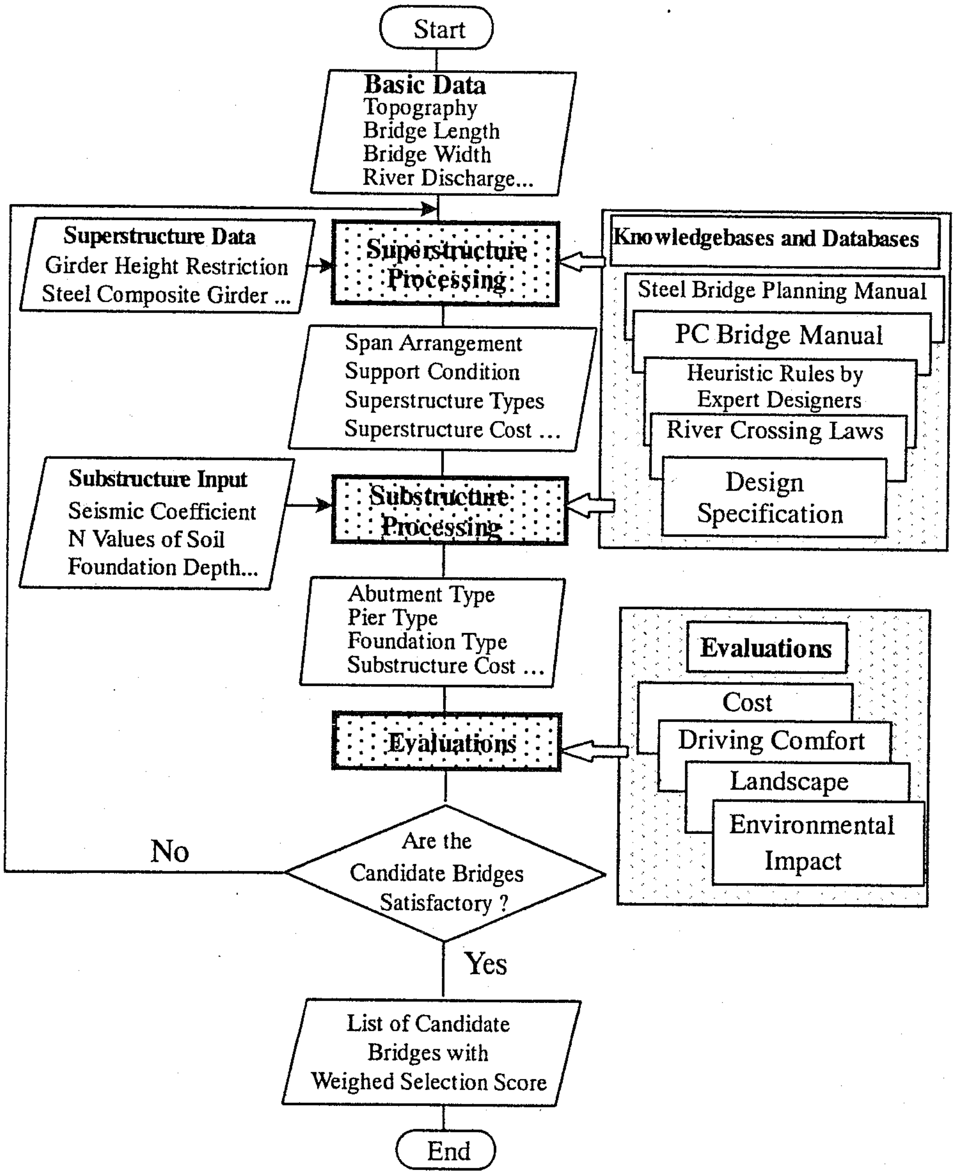


Figure 1. Structure of Bridge Type Selection System

In addition to cost estimation, the system assists in evaluating driving comfort and landscape of the candidate bridges. Driving comfort is evaluated considering number of expansion joints, vibration that drivers feel and the view obstruction, and so on. In Japan, landscape as aesthetics of bridge is evaluated taking considerations of change in scenery after construction of bridge in the surrounding. It is evaluated in the developed system by assigning scores to each bridge type according to its harmony with the surrounding environment. The basic criteria for these scores are assigned based on the results of a questionnaire survey carried out including mostly bridge designers and city planners (Nishido and Itoh 1993). In addition to these factors, the environmental impact is added to the system as a new selection factor. The following subsection explains about the evaluation of the environmental impacts in the system.

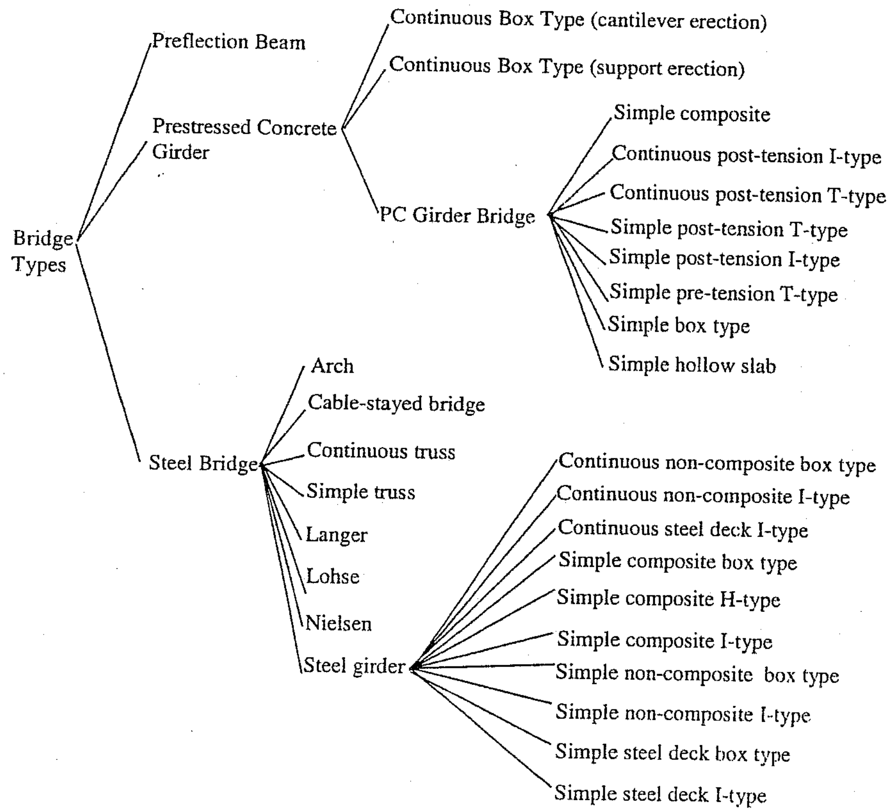


Figure 2. Bridge Types Included in the System

2.2 Evaluation of Environmental Impacts

The environmental impacts are measured in this system by two indicators: the amount of energy consumption in kilocalorie (kcal) (1 kcal = 4.185 kilo Joules) and the CO_2 emissions in ton of equivalent carbon (1 ton = 9,810 Newton) during the bridge construction stage (Gielen and Ybema 1995, PWRI 1994). Figs. 3(a) and 3(b) show the procedures used in calculating environmental impacts from materials and construction equipment in the form of energy consumption and CO_2 emissions. The energy consumption and the CO_2 emissions are calculated by estimating the amount of materials and construction equipment's fuel at the construction stage. These are input to the calculation of environmental impacts obtained from the processing of the superstructure and substructure with the system. Then, these values are multiplied by the unit values of energy consumption (kcal) and CO_2 emissions (ton) from material or equipment. Unit energy consumption and CO_2 emissions values of some common materials used in the bridge construction are obtained by the input-output analysis of the various industrial sectors of Japan (PWRI 1994). The evaluation of environmental impacts includes the impacts during the fabrication of the construction materials.

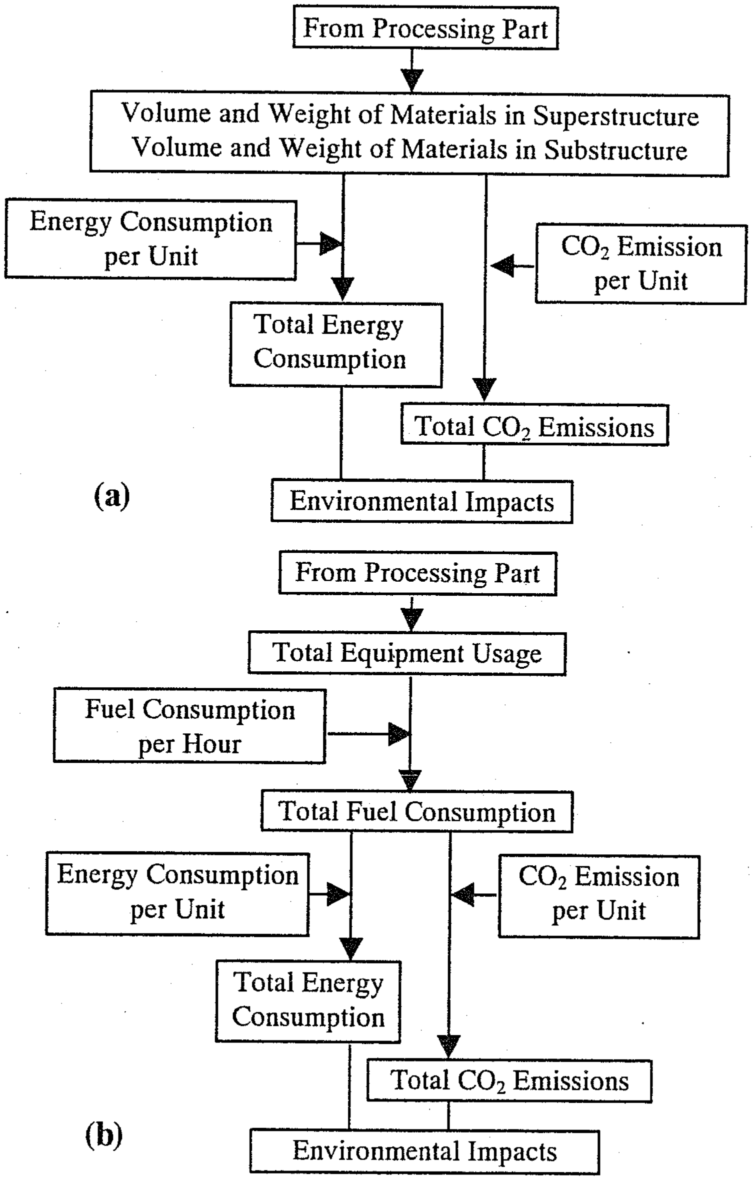


Figure 3. Procedures of Calculating Environmental Impacts
(a) From Materials; (b) From Equipment

In case of concrete bridges, the environmental impacts are calculated for the concrete, reinforcement bars, pre-stressing cables, and molds. In case of steel bridges, the environmental impacts from the different types of steel are calculated. By considering these materials, more than 90% of the environmental impacts of the materials are evaluated (PWRI 1994). The statistical data of previous concrete bridges available in Pre-stressed (1997) are used to find the concrete volumes approximating to a polynomial equation of the third order. The steel weight of steel bridges is also calculated using an approximation equation fitted to polynomial equation from the statistics of existing bridges available in JSSC (1991). Following polynomial equation of third degree is used to estimate the volume and weight of materials:

$$V = ax^3 + bx^2 + c\,x + d \tag{1}$$

In which V is the volume or weight of the materials, x is the bridge span and a, b, c, and d are regression coefficients that are found with the least square method (Nishido 1992). This Eq. (1) is used for various types of bridges, in some cases the fitness was only fair. Since the target of the system is type selection at the preliminary design stage, this type of equations is assumed to give satisfactory results.

As for the evaluation of the environmental impacts from construction equipment, the equipment used in each construction steps are found by interviewing a number of bridge engineers and using previous statistical data (Calculation 1995). The movable equipment is assumed to be powered by electric power generators, and its environmental impact is taken into account by calculating the fuel used for the generators.

Following equations are used to account environmental impacts from all construction materials and equipment used in the bridge construction:

$$\mathbf{E} = \sum_{i=1}^{n} U_i \times E_i \tag{2}$$

$$\mathbf{C} = \sum_{i=1}^{n} U_i \times C_i \tag{3}$$

where, **E** and **C** are the total energy consumption and CO_2 emissions of n numbers of materials or equipment respectively. U_i is the i-th item of bridge construction either material usage or equipment usage. If it is material usage its unit will be in volume (m^3) or weight (ton). If it is equipment usage the unit will be in fuel volume (lit). E_i and C_i are unit energy consumption and unit CO_2 emissions from i-th item of bridge construction respectively. These two amounts **E** and **C** are used to rate a bridge type with respect to environmental impacts by assigning the lowest value a score of 1.5, the highest value a score of 0.5 to be consistent with the score of other factors. The maximum and minimum values will be 3 and 1, respectively, when summed for both indicators. The values lying in between highest and lowest values are given score by linear interpolation. The score for environmental impact is the total of the values of these two indicators on a 3 points scale.

Since the role of the present system is to support engineers in the process of bridge type selection, not only the bridge type with the highest total score is displayed, but also other several bridge types satisfying design conditions. These bridge types are displayed in the descending orders of the total evaluation score.

3. Environmental Impacts from Bridge Components

In order to see the possibility of reductions of the environmental impacts from the bridge construction, it is necessary to find out the contributions of bridge components to the total environmental impacts. In this section, the environmental impact from each bridge component is evaluated using the system discussed above. The environmental impacts from the superstructure, substructure including piers, abutments, and piles are calculated and compared for several cases. Then, the environmental impacts from the whole bridge are calculated and proportions of environmental impacts from superstructure and substructure are shown for several bridge types.

3.1 Environmental Impacts from Superstructure

The superstructure is the main bridge component including the deck. For example, it consists of the deck, main girders and secondary girders in case of girder bridges and the deck, main truss and supporting stringers in case of truss bridges. The environmental impact value from the superstructure are calculated and compared according to the materials consumed in the superstructure and impacts from the construction equipment. In this sub-section, the environmental impacts from the construction materials are considered for investigating the general tendency of the environmental impacts from superstructure types.

Figs. 4(a) and 4(b) show the environmental impacts per unit deck area from materials used in the superstructure of several bridge types grouped according to materials for several bridge lengths. Calculation is carried out according to material requirement of each bridge type. In case of precast PC bridges, the material amount is estimated depending upon the number of girders and corresponding volumes and weights of secondary girders. The volume of concrete, the area of formwork and the weight of reinforcing bars are available in design manuals for different types of precast and cast-in-place bridges corresponding to ranges of economical spans (Pre-stressed 1997). In case of steel bridges, the unit weight of superstructure per unit deck area is available for each bridge type in JSSC (1991). Figs. 4(a) and 4(b) show the average environmental impact values per unit area of the bridge deck for precast PC bridges, cast-in-place PC bridges, and steel bridges. Environmental impacts are shown only for the span ranges applicable for these bridge types from economical point of view. From these figures, it is clear that the environmental impacts of PC bridges are less than those of steel bridges. Precast PC bridges have the lowest environmental impacts. The precast PC bridges are fabricated according to standard specifications in the precast yard so that materials and equipment are used efficiently. It can also be noticed that the increase of environmental impacts of PC bridges corresponding to the increase in the span length is smaller, while this increase is significant for steel bridges. This is due to the difference of the energy per unit weight of concrete (81 kJ/N) and steel (1700-3400 kJ/N). In addition, it can be noticed that in the case of cast-in-place PC bridge, environmental impacts near the bridge length of 60m may decrease with the increase of the bridge length. This is due to the increase of the number of spans and the decrease of the length of each span, which result in smaller cross section of the girders.

The environmental impacts from equipment for construction of the superstructure depend upon the methods of construction. Depending upon the method of construction, total fuel consumed by various equipment is found out. These fuel consumption values are multiplied by the unit impact values to find the impacts from construction equipment. The environmental impacts from materials used in supporting the equipment such as bent and staging are also included in the calculation.

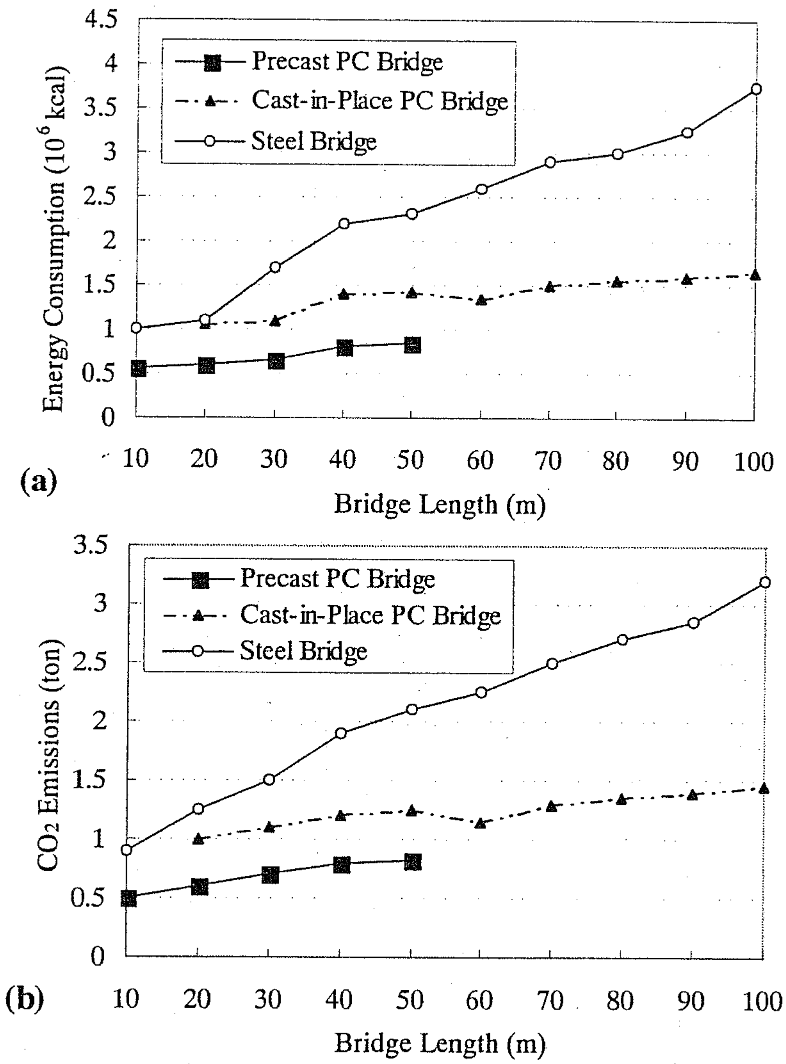
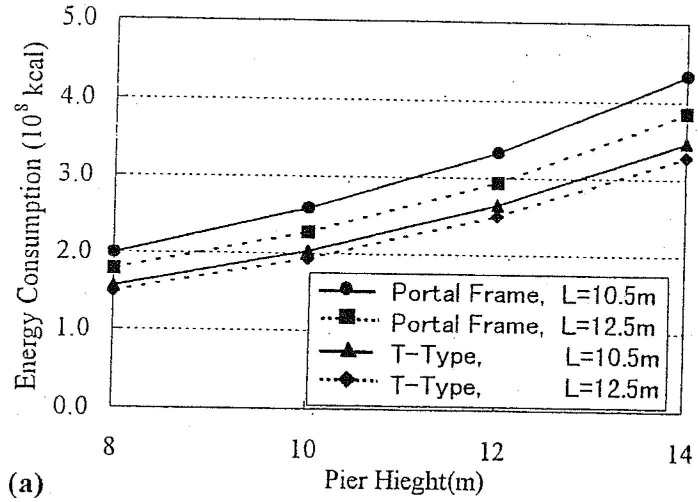


Figure 4. Environmental Impacts from Superstructure
(a) Energy Consumption; (b) CO_2 Emissions

3.2 Environmental Impacts from Piers and Abutments

The evaluation of environmental impacts from piers and abutments is carried out for one pier or abutment and then compared with the impacts of other types. Since this study considers only river-crossing bridges, only concrete piers and abutments are considered. The amount of equipment usage in the construction of piers and abutments can be considered nearly equal irrespective of the specific conditions of the structure. The major materials used in the construction of pier are concrete, formwork and reinforcement steel. Volumes as well as weights for these materials are estimated fitting available statistical data to polynomial equation as in Eq. (1) from the design manuals depending upon the types of piers. Energy consumption and CO_2 emissions from the construction of the bridge piers are shown in Figs. 5(a) and 5(b). Both figures show the same tendency of increasing energy consumption and CO_2 emissions. The piers considered in these calculations are T-types and portal frame types having widths of 10.5m and 12.5m depending upon the width of the bridge. The thickness of all these piers is 2.3m. These figures show that the environmental impacts of the T-type piers are a little higher than those of the portal frame piers and that the difference between these two types increases slightly with the increase in the pier height. This is because the material quantity used in the portal frame type is less than that used in the T-type. As in case of the superstructure, the contribution of the construction equipment in the total environmental impacts of the piers is small, which results in that the material part has a dominating influence on the total environmental impacts of the piers.



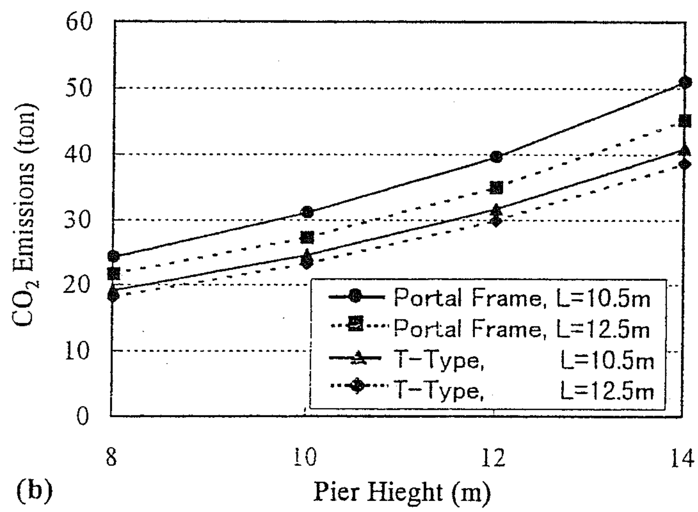


Figure 5. Environmental Impacts from Piers
(a) Energy Consumption; (b) CO_2 Emissions

Figs. 6(a) and 6(b) show the energy consumption and CO_2 emissions from three types of abutments having the same width of 12.5m. The type of abutment is decided according to its height. These figures show the energy consumption and CO_2 emissions in the economical height range of each abutment type. In the range from 10m to 12m heights, the environmental impacts from the inverted T-type piers are a little higher than those of the buttressed type. The amount of materials used in the abutment is estimated in the same way as of piers. The contribution of the construction equipment in the total environmental impact is found to be about 2% in case of the abutment. From this discussion, it can be observed that the types of the piers and abutments with low environmental impacts are also more economical. The contribution of the energy consumed by the construction equipment to the total environmental impacts is found to be very small compared to the contribution of the materials. So the amount of materials used on these bridge components is found to be reflecting the environmental impacts.

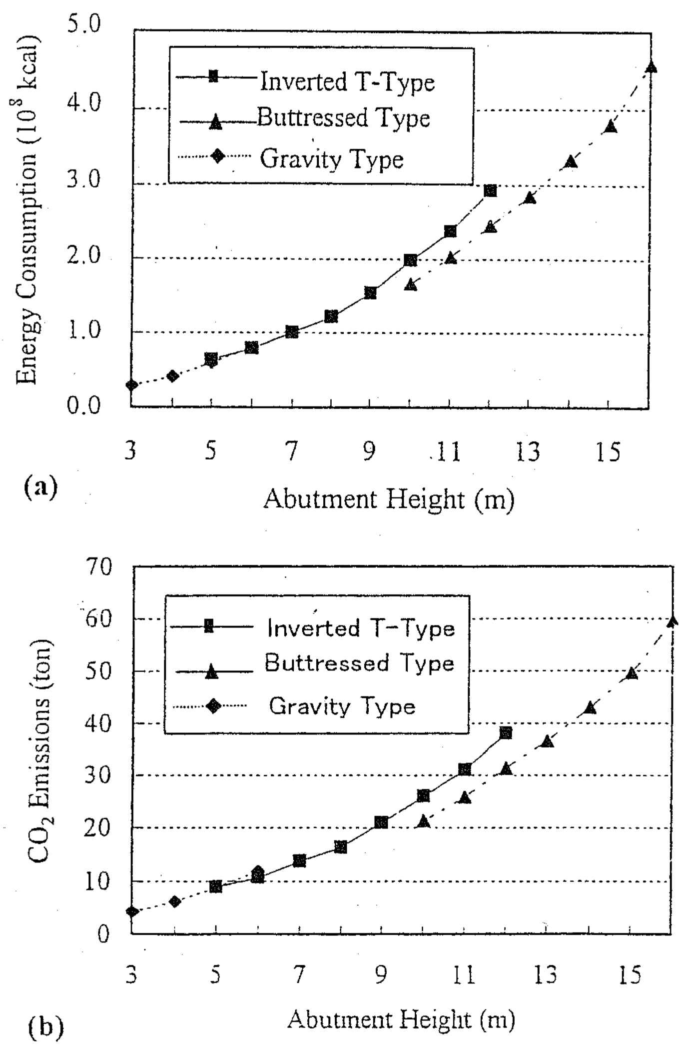


Figure 6. Environmental Impacts from Abutments
(a) Energy Consumption; (b) CO_2 Emissions

3.3 Environmental Impacts from Piles

Because the allowable load of a pile depends on the type of the pile, it is not easy to calculate and compare the environmental impacts from several types of piles. Instead, the number of piles, with the same allowable load, needed to support a load of 70 tonf/m (686 kN/m) of the bridge reaction per unit width is calculated assuming the pier height of 10m. Then, the environmental impacts from the pile construction are calculated and compared based on this number. The pile length is assumed to be 20m. Figs. 7(a) and 7(b) show the environmental impacts from the piles needed to support the reaction force of 70 tonf/m (686 kN/m). From these figures, it is clear that the environmental impacts from the steel piles are much higher than other types of piles. The other types of piles have nearly the same environmental impacts. The reason for the high environmental impacts from steel piles is the same as that in case of the steel superstructure, i.e. the large energy needed for steel production. For piles of the same type, the difference in the diameter of the pile shows that for larger diameter, the environmental impacts are little smaller. The reason for this is that for piles with larger diameter, the number of the necessary piles is less, and therefore, the equipment necessary for driving in the piles or for soil excavation from cast-in-place piles is less. The impact of pile driving equipment is the major part of environmental impact from the piles. The contribution of construction equipment is found to be from 3% to 34% depending upon the type of the pile. This is higher than in cases of superstructure, piers and abutments.

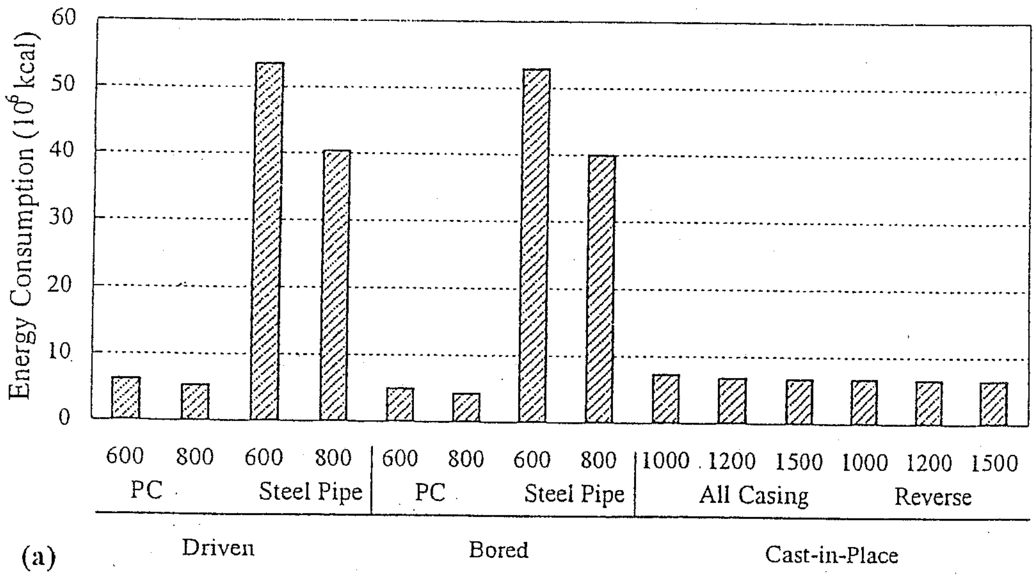
3.4 Comparison of the Environmental Impacts from Superstructure and Substructure

In this sub-section, the proportion of environmental impacts from superstructure and substructure in the total environmental impacts from the bridge is calculated for comparison. A bridge having a length of 150m and 12m width is considered. Table 1 shows the construction methods and span arrangements of the bridge types that are used in this investigation. These bridge types are taken among the 30 cases of various bridge types and span arrangement obtained with the system. The abutments are inverted T-type with 6m height. T-type piers having each 12m height are considered.

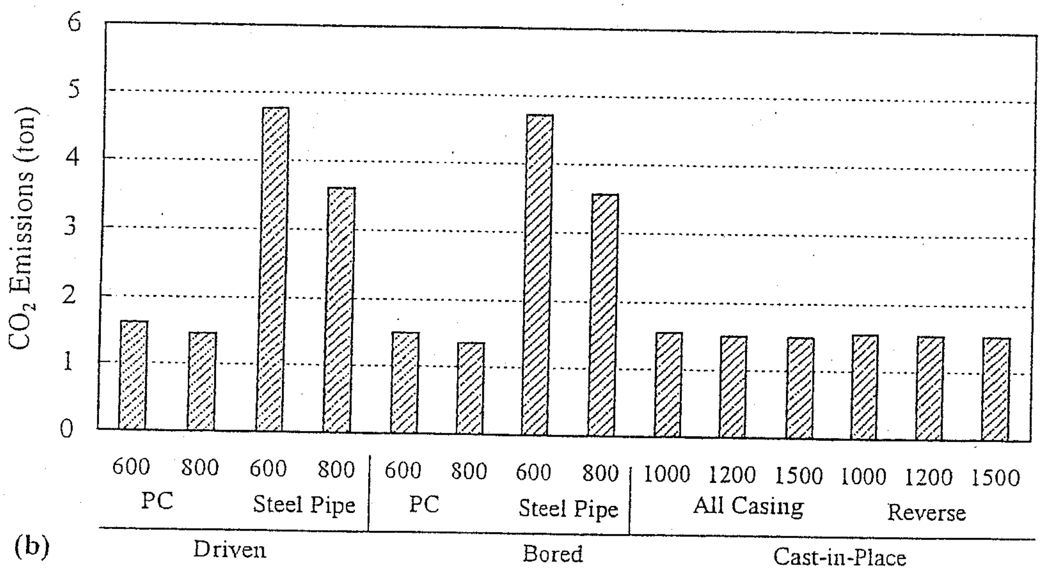
Table 1. Dimensions of Bridges Used in the Comparison

Bridge types (1)	Construction methods (2)	Span arrangement (m) (3)
PC simple pre-tensioned T-girder bridge	Truck crane method	8@18.8
PC simple box girder bridge	Support erection method	3@50.0
Steel simple non-composite box girder bridge	Bent method	3@50.0

Figs. 8(a) and 8(b) show the proportions of environmental impacts from the superstructure and substructure in cases of PC Simple Pre-tensioned T-girder Bridge, PC Simple Box Girder Bridge, and Steel Simple Non-composite Box Girder Bridge. In case of the PC Simple Pre-tensioned T-girder Bridge, the environmental impacts from the substructure are larger than those from the superstructure. It is because this bridge has a short span length of 18.8m, and the number of piers is large. In case of the PC Simple Box Girder Bridge, the span length is 50m, and the environmental impacts from the superstructure are larger than those of the substructure. The reason behind it is that the number of piers is less and the span length of superstructure is high.



(a)



(b)

Figure 7. Environmental Impacts from Piles
(a) Energy Consumption; (b) CO_2 Emissions

Finally, in case of Steel Simple Non-composite Box Girder Bridge, the proportion of the environmental impacts from superstructure is larger than that of the PC Simple Box Girder Bridge of the same span arrangement. This is because the superstructure is made of steel which has larger energy consumption and CO_2 emissions than the concrete. Among three bridge types, the steel bridge has the highest environmental impact value in comparison to other two PC bridges. This is due to use of more amount of steel in case of steel bridge that has higher unit impact values. The energy consumption from construction equipment is in the order of 5% in these bridge types. The total CO_2 emissions from construction equipment are in the order of less than 5%. This shows that the major portion of environmental impact of these bridges is due to the use of construction materials.

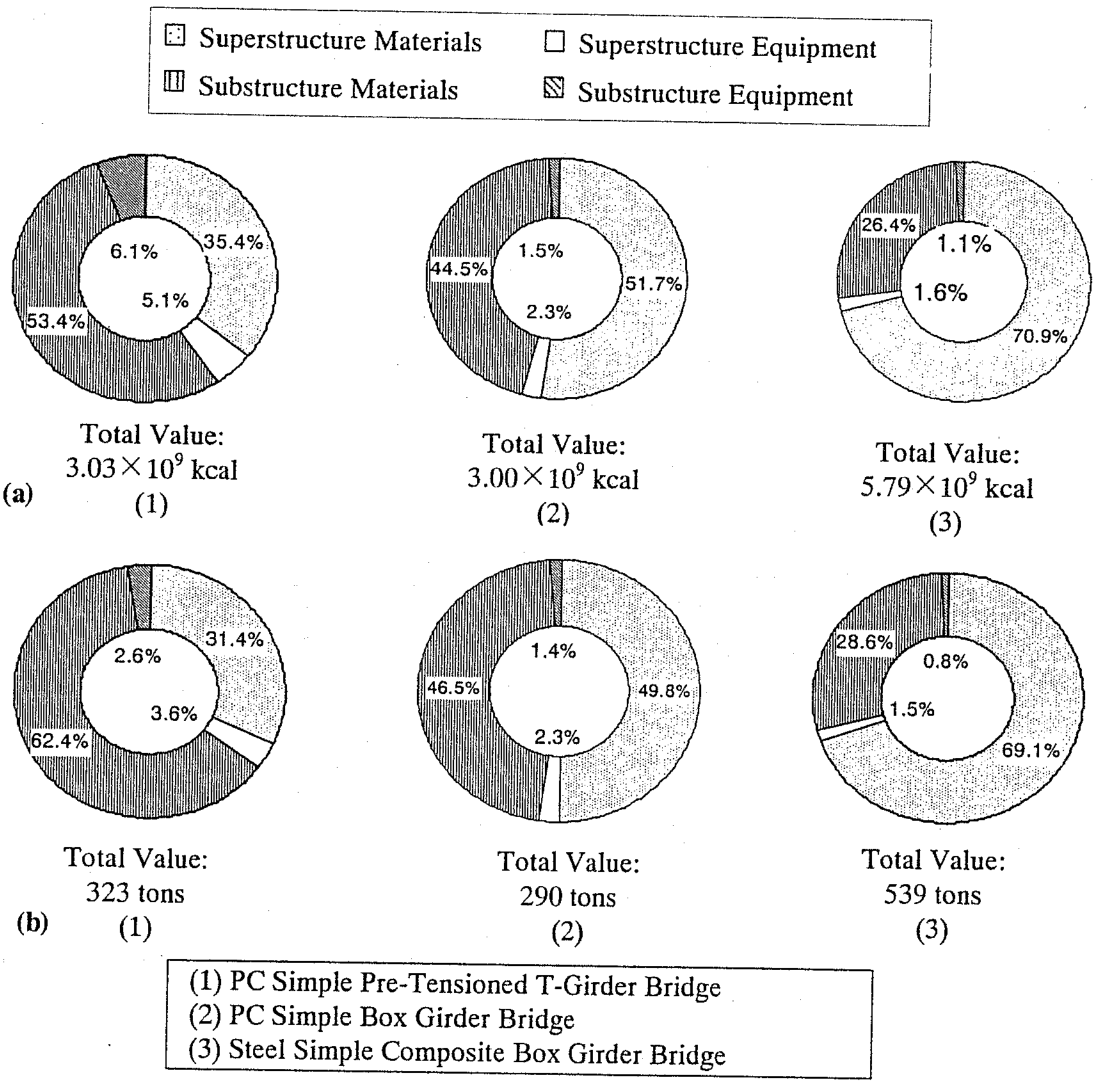


Figure 8. Proportions of Environmental Impacts from Superstructure and Substructure (a) Energy Consumption; (b) CO_2 Emissions

4. Effects of Recycling on the Environmental Impacts

As the aim of this research on environmental impacts from a bridge is to find the possibility of reduction of environmental impacts, effects of change on cost and environmental impacts with various bridge types were considered. In most cases, the score for environmental impacts is found to be increasing with increase in cost. So at this stage, it is observed among conventional bridge types, costly bridge type does not necessarily mean less environmental impacts. Since most part of the environmental impact is from the use of construction materials, minimization of material use is one method of reducing environmental impacts. This section describes the effect of recycling in the environmental impacts.

Recycling of construction materials is one of the methods suggested for reducing the environmental impacts. As a majority of landfills of urban areas is being of limited capacity, recycling will reduce the load to these landfills (Moavenzadeh 1994). This is another advantage of recycling. The steel used in the superstructure is one of the materials that can be recycled most efficiently with a ratio of more than 95% (PWRI 1994, Szekly 1996). Steel can usually be recycled by melting it in the electric arc furnace. This recycled steel can be used instead of virgin iron extracted from mines, which results in about 60% energy saving, and consequently, reduction in environmental impacts (PWRI 1994). On the other hand, concrete can be recycled as aggregate for new concrete, as material for road base course, and so on (Bassan and Vittorio 1995, Tresouthick et al. 1993). Recycling concrete as aggregate for the production of new concrete requires using machines for crushing the concrete. The environmental impacts of this new concrete produced with recycled aggregate will be about 86% compared with conventional concrete. The inferior quality of aggregates obtained by crushing concrete is possible to use in less important works such as road sub-base course. In such works, the recycling can be carried out with manual labor with very small cost in case laborers are cheaply available.

In the present practice, the recycled materials are not used in the bridge construction in Japan because high material quality is normally required to gain the confidence in safety. However, with the progress of recycling technology, it is expected that more recycled materials will be used in the near future. The recycled steels in most cases can already meet the requirement of the structural steel. In this research, the effect of using such recycled materials is considered. The bridge types considered in this comparison are the same as of Table 1. The calculations are carried out considering that by using recycled materials, the environmental impacts can be reduced to 40% and 86% in case of steel and concrete, respectively (PWRI, 1994). Figs. 9(a) and 9(b) show the environmental impacts considering recycling. The impacts from superstructure and substructure are separated during calculation because only concrete substructures are considered in this study. As shown in these figures, use of recycled materials can decrease the environmental impacts to some extent. In particular, recycling the steel of bridge can result in decrease of the environmental impacts up to 50%. As shown in figures, the environmental impact from a steel bridge is about double that of a PC bridge of the same size when new construction materials are used. However, use of recycled steel and concrete may result in decrease of the environmental impacts of steel bridges to almost the same level of concrete bridges. In addition, steel can be considered superior to concrete from the environmental point of view because steel can be recycled as steel, while concrete can be recycled only as aggregates. This means more limestone and other natural resources are still depleted even concrete is fully recycled. Concrete is formed by the chemical irreversible reaction of cement and water. Some research is carried out about extracting the cement that has not been reacted yet, and recycling this portion. More research is needed in order to increase the recycling efficiency of concrete.

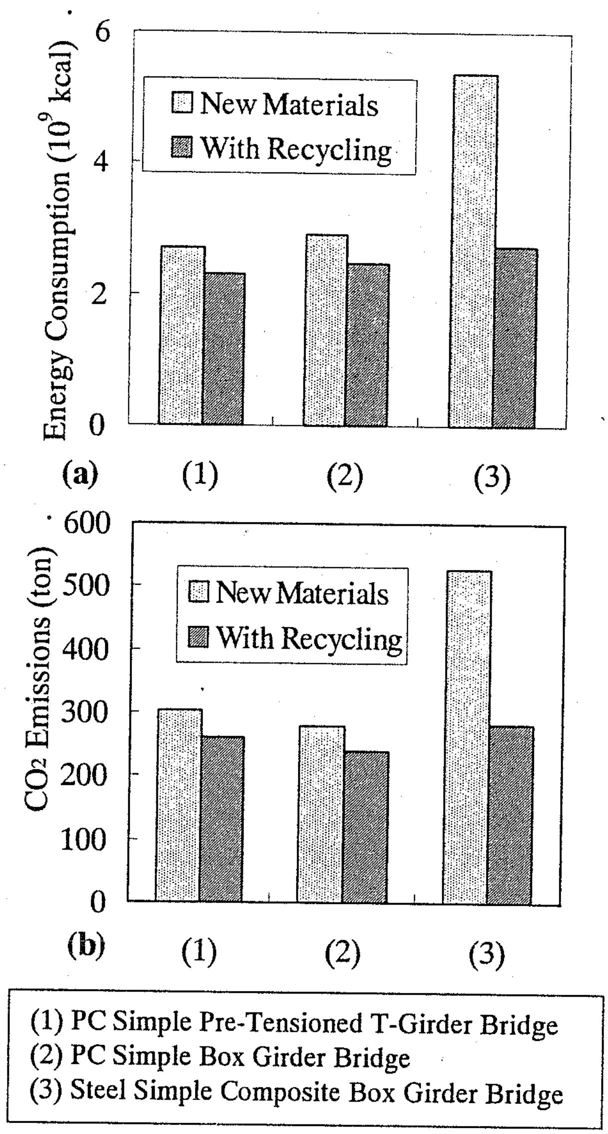


Figure 9. Effect of Recycling on Environmental Impacts
(a) Energy Consumption; (b) CO_2 Emissions

5. Application of Bridge Type Selection System

5.1 Example of Bridge Type Selection

It is obvious that selection of a bridge type does not only depend upon the environmental impacts. This study aimed to introduce it as one criterion of bridge type selection. Cost has been always one of the most important factors considered in selecting bridge types. In this study also generation of candidate bridge types is based upon the cost. The bridge type selection system is further made to consider four selection factors as cost, driving comfort, aesthetics and environmental impacts. According to locality and prevailing conditions, the weights of these factors can be varied to give more importance to a particular factor.

Table 2 shows an example of preliminary design results obtained with the system. Among total 23 cases of various bridge types with different span arrangements obtained by the system, only four cases are considered here for illustration. Table 3 shows the evaluation results considering the economy, driving comfort, landscape and environmental impacts based on the bridge type selection system explained in section 2. It can be seen from this table that, when environmental impact is considered, the Two Spans Continuous Steel Plate Box Girder Bridge moved from the third rating to the first rating in place of the Steel Lohse Bridge that was in first rating when only three selection factors were considered. This shows that if environmental impact is added as one selection factor, there will be change in bridge type preferred with respect to higher selection score. The weight for economy has a value of 1.0 in this example. The weights for the driving comfort, landscape and environmental impact have the value of 0.6. These weights are assigned according to preliminary result of questionnaire survey carried out to give the relative weights using analytic hierarchy process (Sunuwar et al. 1997). However, these weights to each selection factor can be different in various situations according to locality. Analytic hierarchy process can be considered one method to evaluate such weights of selection factors.

Table 2. Example of Candidate Bridges obtained with the System

Parameters	Bridge Types			
(1)	Steel Nielsen bridge (2)	Steel Lohse bridge (3)	Two spans continuous steel plate box girder bridge (4)	Three spans continuous steel plate box girder bridge (5)
Span arrangement (m)	116.0	116.0	58.0+58.0	28.0+60.0+28.0
Space between main girders or arch ribs (m)	17.2	17.2	10.16	10.16
Piers type	NA	NA	Concrete Inverted T-Type	Concrete Inverted T-Type
Piers height (from average water level) (m)	NA	NA	2.8	3.0
Pier width (m)	NA	NA	2.8	2.0
Specific conditions of each bridge type (m)	Height of stiffeners=1.2 Height of arch ribs=1.4 Arch rise=18.0	Height of stiffeners=1.2 Height of arch ribs=1.4 Arch rise=14.0	Height of girder above piers=2.8 Height of girder at side ends=1.7	Height of girder above piers=2.6 Height of girder at side ends and center=1.3

Note: NA = not applicable being single span bridge

Table 3. Evaluation Results for Cost, Driving Comfort, Landscape, and Environmental Impact

Evaluation Items (1)	Weight (2)	Bridge Types			
		Steel Nielsen bridge (3)	Steel Lohse bridge (4)	Two spans continuous steel plate box girder bridge (5)	Three spans continuous steel plate box girder bridge (6)
(a) Economy score	1.0	2.08	2.00	3.00	2.00
(b) Driving comfort score	0.6	2.50	2.66	2.83	3.00
(c) Landscape score	0.6	3.00	3.00	1.00	1.89
(d) Environmental impact score	0.6	2.16	1.72	3.00	1.00
Total evaluation without environmental impact (a)+0.6×(b)+0.6×(c)	Score	5.38	5.4	5.3	4.93
	Rating	2	1	3	4
Total evaluation (a)+0.6×(b)+0.6×(c)+0.6×(d)	Score	6.68	6.43	7.10	5.53
	Rating	2	3	1	4

5.2 Sensitivity of Selection Score with Relative Weight

The selection factors considered for the bridge type selection in this study have quite different basis for evaluation. For example, the money spent on the bridge represents the cost. The number of joints in the bridge and absence of obstruction of views represent the better driving comfort. All such basic requirements do not necessarily become better when more money is spent. This is why relative scores are given to each candidate bridge types to aggregate all these effects. It is assumed in this study that the weights of selection factors are to be decided for each decision process of bridge type selection. The weight of each selection factor depends upon the situation of the bridge site and locality. In this subsection sensitivity analysis is introduced to observe the effect of changing weights of different selection factors.

If there are *n* numbers of selection factors and let $\{W\} = \{W_1, W_2, ..., W_n\}$ be the weight vector containing $W_1, W_2, ..., W_n$ as weight of each selection factor. Similarly, let $\{S\} = \{S_1, S_2, ..., S_n\}^T$ be the column vector containing $S_1, S_2, ..., S_n$ as score of each selection factor. Then the total score **S** can be obtained by the following equation:

$$S = \{W\} \times \{S\} = \sum_{i=1}^{n} W_i S_i \qquad (4)$$

The sensitivity of total selection score with respect to change in the weight of cost has been investigated for the example presented in previous sub-section. The bridge types included in this analysis are the same as of Tables 2 and 3. Fig. 10 shows the effect on total selection score by changing the weight of the cost from 0.3 to 1.5 keeping weights of other factors the same. The final result on the rating of choice is found to change when the weight of cost is 0.61. In case when the weight of cost is less than 0.61, Steel Nielsen Bridge has the highest score. In other cases, Two Span Continuous Steel Plate Box Girder Bridge has the highest total selection score. When the environmental impact was not considered Steel Lohse Bridge has the highest total selection score.

Since cost is considered more important than other selection factors, the practical range for weight of cost can be considered higher than that of other factors. This example shows that there will be change in rating if the weight of selection factor is changed considerably.

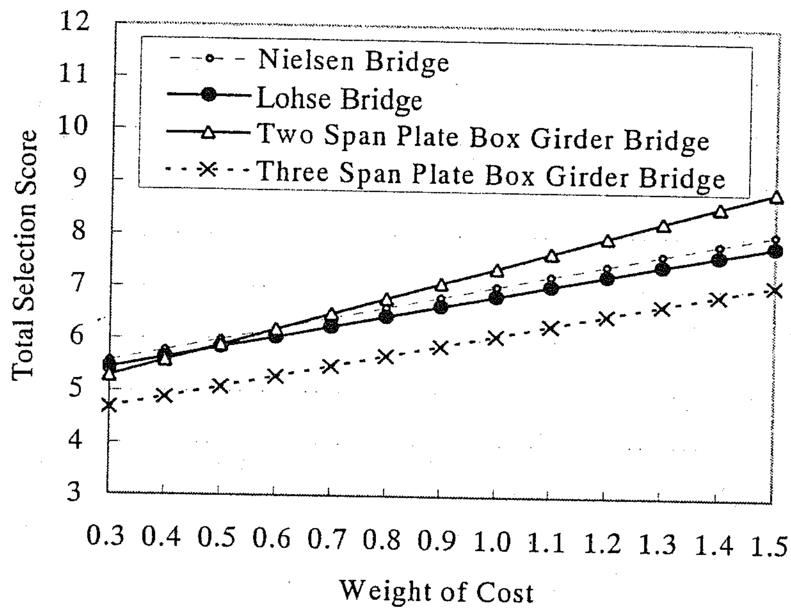


Figure 10. Sensitivity of Total Selection Score with Weight of Cost

6. Conclusions

In this study, a bridge type selection system has been developed considering environmental impact in addition to the cost, driving comfort and aesthetics. Based on this research, the following conclusions can be stated:

1. Taking energy consumption and CO_2 emissions as the indicators, a methodology has been shown to calculate the environmental impacts of bridge construction for a type selection. A system was developed which enabled to compare various bridge types with respect to environmental impact.
2. The characteristics of the environmental impact from bridges were investigated for several bridge types. It was found that the environmental impacts from construction materials used in the bridge are much higher than those of the construction equipment.
3. It is found that the introduction of environmental impact as a new selection criterion in the system changes the decision of selection of bridge type. It is also observed that the changes in weights of selection factors affect the selection result.
4. It was shown that use of recycled materials in the bridge construction could reduce the environmental impact depending upon the type of material. Steel bridges have more potential of reduction of environmental impact than concrete bridges.

This study concentrated on the comparison of conventional types of bridges used in Japan. Reducing environmental impacts from development of new technology such as new materials and composite constructions should be further researched in future enhancing the system. By rating the candidate bridge types with respect to environmental impacts, it has been tried to find out the bridge types and construction methods that are environmentally benign.

References

Bassan, M. and Vittorio, G. (1995). Recycling of Concrete: Forseeable Development Possibilities in Italy, *Collected Papers of the R'95 International Congress*, Geneva, Vol. I, Barrage, A. and Edelmann, X. (eds.), 219-227.

Calculation of Bridge Construction Site (1995). Japan Construction Mechanization Association, Tokyo (in Japanese).

Dwyer, D. P. (1992). California's Tradable Emissions Policy and Greenhouse Gas Control, *Journal of Energy Engineering*, ASCE, 118(2), 59-76.

EPA: United States Environmental Protection Agency (1997). Inventory of US Greenhouse Gas Emissions: Recent Trends in U. S. Greenhouse Gas Emissions, *<URL:* http://www.epa.gov/*globalwarming>*

Gielen, D. J., and Ybema, J. R. (1995). Optimization of Integrated Energy and Material Systems, Techno-Economic Assessment of Materials System Policies for CO_2 Reduction, *Collected Papers of the R'95 International Congress*, Geneva, Vol. I, Barrage, A. and Edelmann, X. (eds.), 39-44.

Hobbs, B. F. (1994). Emission-Cost Trade-Offs and Rate Feedback for Electric Utilities, *Journal of Energy Engineering*, ASCE, 120(3), 103-121.

Intergovernmental Panel on Climate Change (IPCC) (1995). *Greenhouse Gas Inventory: Reference Manual*, IPCC WGI Technical Support Group, Bracknell.

Itoh., Y., Hirano, T., Nagata, H., Hammad, A., Nishido, T. and Kashima, A. (1996). Study on Bridge Type Selection system Incorporating Environmental Impact, Journal of Construction Management and Engineering, JSCE, No. 553/VI-33, 187-199.

James, P. B., Hoesung, L., and Eric, F.H. (1996). *Climate Change 1995 - Economic and Dimension of Climate Change*. Intergovernmental Panel on Climate Change (IPCC).

Japan Society of Steel Construction (JSSC) (1991). *Steel Bridge Planning Manual*, Tokyo (in Japanese).

Kyoto Protocol (1997). Kyoto and the Global Environment Homepage: Kyoto Protocol, <URL: *http://www.pref.kyoto.jp/intro/21cent/kankyo/index2e.html>*

Masters, G. M. (1991). *Introduction to Environmental Engineering and Science*, Prentice–Hall International Editions, Inc.

Moavenzadeh, F. (1994). *Global Construction and the Environment: Strategies and Opportunities*, John Wiley and Sons, Inc.

Nishido, T. (1992). *Study on Use of Computers for Bridge Type Selection and Checking Safety of Erection Procedures*, Doctoral Dissertation, Nagoya University, Nagoya.

Nishido, T. and Itoh, Y. (1993). Advisory System for Evaluating the Landscape of Different Types of River-Crossing Bridges Quantitatively, *Journal of Construction Engineering and Management*, 474/VI-20, JSCE, 95-104 (in Japanese).

Nishido, T., Maeda, K., and Nomura, K. (1989). Practical System for Type Selection of Bridge Crossing River, *Expert Systems in Civil Engineering,* IABSE Colloquium, 311-319, Bergamo.

Pre-Stressed Concrete Road Bridge Planning Manual (1997). Association of Pre-Stressed Concrete Bridge Construction (in Japanese).

Public Work Research Institute (PWRI) (1994). *Report on the Development of Calculation Method and Investigation of Resources, Energy Consumption, and Environmental Impacts (Vols.1 and 2),* Ministry of Construction, Tsukuba (in Japanese).

River-Crossing Structure Law. (1974). Japan River Association, Tokyo (in Japanese).

Specifications of Highway Bridges. (1996). Japan Road Association, Tokyo (in Japanese).

Sunuwar, L., Itoh, Y., Nagata, H., and Nishido, T. (1997). Characteristics of Environmental Impact of Bridges for Type Selection, *Journal of Information Processing in Civil Engineering,* JSCE, Vol. 6, 173-180.

Supply of Steel Scrap in Japan. (1991). *Steel World,* Japan Association of Steel Resources, 5-8 (in Japanese).

Szekly, J. (1996). Steel Making and Industrial Ecology - Is Steel a Green Material?, *ISIJ International,* 36(1), pp. 121-132.

Tresouthick, S. W. and Mishulovich, A. (1993). Energy and Environmental Consideration for the Cement Industry, *Energy and Environment in the 21st Century,* MIT Press.

Tung, C.-P., and Haith D. A. (1995). Global warming Effects on New York Streamflows, *Journal of Water Resources Planning and Management,* ASCE, 121(2), 216-225.

Wang, F. C., Odum, H. T., and Kangas P. C. (1980). Energy Analysis for Environmental Impact Assessment, *Journal of the Water Resources Planning and Management Division,* ASCE, 120(3), 103-121.

White Paper on Environment (1996). Japan Ministry of Finance, Tokyo (in Japanese).