A LIFE CYCLE INVENTORY ANALYSIS OF CARBON DIOXIDE FOR A HIGHWAY CONSTRUCTION PROJECT USING INPUT-OUTPUT SCHEME A CASE STUDY OF THE TOHOKU EXPRESSWAY CONSTRUCTION WORKS *

by Mongkut Piantanakulchai **, Hajime Inamura ***, Yasushi Takeyama ****

1. Introduction

To evaluate the environmental impact of carbon dioxide emission from the construction of a gigantic transport infrastructure, for instance, an inter-city expressway construction, the concept of Life Cycle Assessment (LCA) should be applied because the global warming involves the accumulation of carbon emission in long run. In addition, the project construction involves the acquisition of various resources form the market economy. In this angle, input-output model particularly suits to the analysis due to its salient point of capability to capture both direct and indirect effects within widespread economy.

The extended input-output models have been widely applied for environmental and energy-related analysis. For example, Leontief [1] extended input-output model to include environmental externalities and pollution abatement activities. Herendeen [2] and Bullard et al. [3] applied input-output model to estimate the energy impact of consumption decision. Due to the growing concern of global warming problem during last decades, a lot of recent works have been carried out to estimate the carbon emission from various production activities. For example, Hayami et al.[4] estimated the amount of CO_2 emission per one unit of commodity's production using Japan's 1985 input-output tables. Hetherington [5] did similar work for UK. Kondo et al.[6] used input-output analysis to calculate the embodied emission intensity for economic sectors and applied the model for the life cycle analysis of an automobile. Moriguchi [7] compared the carbon emission between gasoline vehicle and electric vehicle. In most studies, the amount of CO_2 from many products produced in a sector has to be aggregated by assuming that a sector produces only one unique product. Nishimura et al.[8] developed a new model to include the analysis of multiple products in one sector by introducing two sub-models called sector model and process model. Apart from many input-output studies related to the emission from production activities, there are no studies concerning the analysis of life cycle emission from road construction works in Japan.

Most life cycle studies of a transport, in the construction phase, is usually accounted only for the direct energy used to construct transport facilities, for example, energy required to drill tunnels, to make and haul concrete, etc. However, to get every raw material for the construction, it also demands a lot of energy for extracting, processing, and transporting from the original source to the construction site. This energy is considerably enormous but has been usually misleadingly neglected, for example, Kulash et al.[9].

This study differs from previous studies in the view that we accounted not only for the direct energy used in constructing the transport facilities but also the energy embedded in extracting, processing, and transporting of the resources and materials demanded for the project. In this study, we compiled available data from many sources and presented a basic model to estimate the amount of CO_2 from a proposed highway project construction. The model was applied to a case study to estimate the amount of CO_2 emission from the construction of Tohoku expressway in Japan. To account for the effect of technological change to the level and structure of the emission from road construction in broad sense, we also compared the amount of CO_2 per one unit of general road construction work in many categories between the Japanese technology in 1975 and 1990.

2. The model description : An inventory model to estimate the amount of CO_2 emission from a project construction

Sources of data needed to construct the model are general inter-industry input-output table, input-output table for construction works, fuels and limestone used by sector in physical unit. By doing a comparative statistical analysis, the model can be used to estimate the amount of CO_2 emission from the project construction at designated point of time, economic structure, and technology. General input-output table is used to depict the economic structure while input-output table for construction work is used to describe the construction technology. The energy technology is represented by the use of energy by sector. In order to account for the CO_2, the use of limestone by sector was also included in the model. The data above are used to derive the embedded CO_2 coefficients in goods and services by sector in the specific base year technology. The detailed construction cost obtained from the project cost estimation is then applied as a final demand vector to the input-output model. The research methodology can be illustrated in Figure 1. Each parts of the model are described in the following sections.

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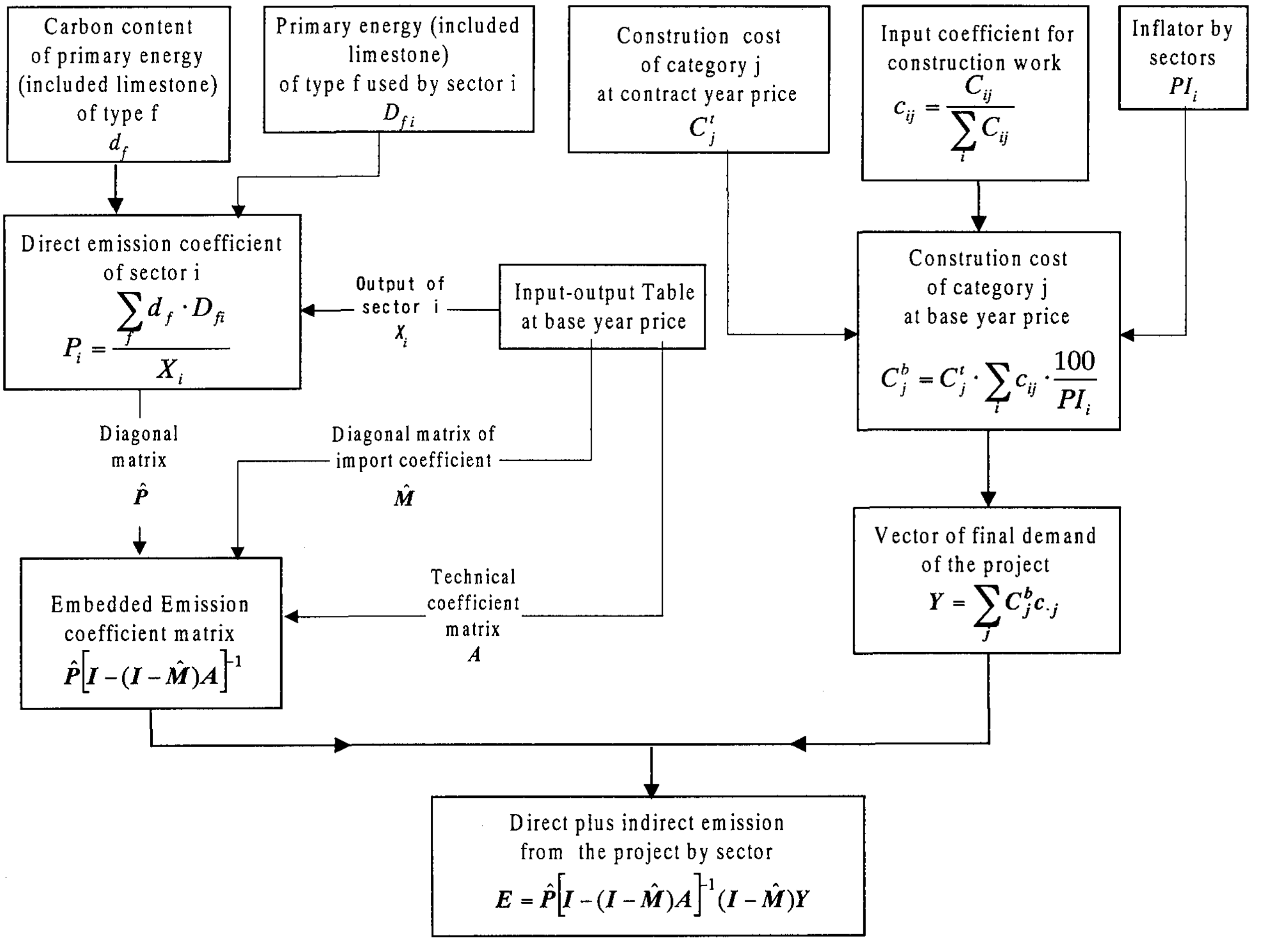

Figure 1: Research Methodology

(1) Input-output analysis

There are two types of input-output model that are usually applied to the environmental analysis. The first type model is of $(I-A)^{-1}$ type. The domestic output *(X)* needed to produce to satisfied a set of total final demand *(Y)* under the base year production technology *(A)* can be expressed by

$$X = (I - A)^{-1}(Y - M) \tag{1}$$

The analysis of $(I-A)^{-1}$ type simply takes the demand for imported product *(M)* exogenously. By assuming that the imported products have the same input structure as the economy being analyzed, it is possible to calculate the amount of CO_2 including both from domestic production and import products.

The second type model, $(I-(I-\hat{M})A)^{-1}$ type, is different from the model of $(I-A)^{-1}$ type by the treatment of import. Contrary to the $(I-A)^{-1}$ model that take the import exogenously, the $(I-(I-\hat{M})A)^{-1}$ model takes import to be proportional to the domestic demand through the use of import ratio matrix ($\hat{M}$). In this study, we applied the second type model to estimate the amount of CO_2 from the production induced from domestic final demand only.

$$X = \left[I - (I - \hat{M})A\right]^{-1}(I - \hat{M})Y \tag{2}$$

Input-output table for 1975 and 1990 were employed in this study. The size of the table selected for this study was 351 sectors and 407 sectors respectively.

(2) Energy technology

The concept of energy input-output analysis can be applied to the analysis of CO_2. Different choices of energy used for the production of commodity can vary the amount of CO_2 emission. In the energy input-output framework, the energy technology is presented by the amount of fuel used by sector. To account for CO_2, not only the uses of energy but also the uses of limestone were included in the analysis. The amount of resource consumed by sector (D_f) is expressed in a unit according to the resource type, for example, gasoline *(liter)*, coal *(ton)*, natural gas *(m^3)*, etc. The carbon content for any resource type f is fixed and can be expressed d_f.

The direct carbon emission factor for sector i is defined by P_i. This coefficient is fixed by base year technology.

$$P_i = \frac{\sum_f d_f \cdot D_{fi}}{X_i} \tag{3}$$

P_i = *Direct emission per one unit of production of sector i, (ton-C/million yen)*
d_f = *Carbon content of source type f (ton-C / liter, ton, m^3, etc)*
D_{fi} = *Resource of type f consumed by sector i (liter, ton, m^3, etc)*
X_i = *Production of sector i. (million yen)*

There are two methods of allocating the amount of CO_2. The first method is to allocate CO_2 to its sources of emission (for example, energy plant). However, in this study, we applied the second method that the amount of CO_2 is allocated to its final users in order to understand the structure of total emission by its raw material or product inputs.

(3) Amount of CO_2 emission induced from construction demand

According to input-output theory, to satisfy the final demand of sector i, other goods and services are also required as direct and indirect inputs for the sector's production. To calculate the amount of emission, we relate the level of production and associated emission by the emission coefficient matrix $(\hat{P})$. Under this assumption, the emission rates are fixed by the economic structure together with the energy technology in the base year. In case of $(I-(I-\hat{M})A)^{-1}$ type model, the amount of direct plus indirect emission by sector *(E)* can be expressed by the following equation.

$$E = \hat{P}\left[I-(I-\hat{M})A\right]^{-1}(I-\hat{M})Y \tag{4}$$

When $\hat{P}$ is a diagonal matrix with the diagonal elements are defined as P_i in equation 3.

(4) Construction technology

Apart from the economic structure and energy technology, different choices of input and technology in construction sector is one of the factors that varies the amount of CO_2 emission. In the model, the construction technology is expressed by the qauntity and mix of products and services needed for the construction via a set of input coefficients. Any changes in the construction technology or relative cost of input for the construction sector will reflect by the change in input coefficients. Using input table for construction work, we define

$$c_{ij} = \frac{C_{ij}}{\sum_i C_{ij}} \tag{5}$$

$$\sum_i c_{ij} = 1 \tag{6}$$

C_{ij} = *Cost of product or service from sector i for one unit of construction category j (million yen)*
c_{ij} = *Cost share of product and service from sector i for one unit of construction category j (million yen / million yen)*

To obtain the amount of CO_2 induced by one unit of construction, we apply the vector of input coefficient for construction work (c_{ij}) as a final demand vector *(Y)* in the general input-output framework. The result of carbon emission per one unit of various general road construction is shown in Table 3-4.

(5) Price level

Since the transaction in monetary term is usually applied in input-output analysis, the price level change due to inflation must be considered when applying the construction cost at current price to different base year data. In this study, we assumed different price change in the each detailed construction item (pavement, bridge, earthwork, etc.). Suppose we have m types of construction in the project (j=1,2, ..., m) and n industrial sectors (i=1,2, ..., n). The cost of construction by category is converted into the base year price by applying the price index (PI_i) weighted by the value of inputs by sector. The construction cost of construction category j at current price converted into base year price can be expressed by

$$C_j^b = C_j^t \cdot \sum_i c_{ij} \cdot \frac{100}{PI_i} \tag{7}$$

C_j^b = Construction cost of construction category j at base year price

C_j^t = Construction cost of construction category j at current price (year t)

(6) Construction cost

The construction cost can be separated into two parts, the cost of raw materials and services from intermediate sectors and the cost of value added (wages, rent, and profit). The former part is used to estimate the CO_2 from the project while the later part contributes no emission associating with the project (However, c_{ij} in the previous section also included value added so that the total cost share is summed to unity).

Since the construction cost of the expressway was reported by construcion category (bridge, pavement, tunnel, earthwork, etc.), we multiply the project construction cost at base year price by category (C_j^b) with the associated column vector of input coefficients for construction ($c_{\cdot j}$) to obtain the final demand vector by subcategory.

The vector of total final demand (Y) of a project includes all of final demand from every construction category (j) of a project.

$$Y = \sum_j C_j^b c_{\cdot j} \qquad (8)$$

$c_{\cdot j}$ = Column vector of input coefficients for construction work of category j

3. Case study

(1) An estimation of CO_2 emission induced from Tohoku expressway construction

In order to show the different structure of the emission by geological location of the expressway, Tohoku expressway was subdivided into sections according to the contracts and construction periods as shown in Table 1. In this study, we carried out a simulation to compare the amount of CO_2 if the project would be constructed in 1975 and 1990. The result is shown in Table 2.

For full length of the expressway considered in the study, the average contribution of emission was about 10% for pavement construction, 21% for bridge construction, 23% for earthwork, 8% for tunnels, and 38% for other construction. Unsurprisingly, the major contribution of CO_2 emission came from the other construction category since its cost ratio contributes the most for the expressway construction. There are a great number of construction items that cannot be classified as general road construction work and then were aggregated into other construction category, for example, interchanges, booth gate, buildings, barriers, service area, parking area, facilities, lighting, planting, etc. At present, the project cost data obtained is not enough to break down this category. However, using the available data we could calculate the amount of CO_2 from major general road constructions such as pavement, bridge, earthwork, tunnels, etc. From Table 2, during 1975-1990, the construction of bridge shows the most reduction of CO_2 emission among categories. It is noted that substituting the 1990 technology with 1975 technology would reduce the amount of emission about 32%-41% in every construction type while the amount of emission from the project would be reduced about 37% totally. The structure of emission can be varied by different geological condition. Figure 2 shows different structure of CO_2 by different geological section of the expressway. For example, the contribution of emission from tunnel and bridge construction is higher in mountainous area.

Table 1: Tohoku expressway sections subdivided in the analysis

Section	From – To			Length(km)	Construction Period
1	Kawaguchi	-	Iwatsuki	10.5	1970-1987
2	Iwatsuki	-	Sendai minami	316.3	1966-1975
3	Sendai minami	-	Morioka	185.3	1968-1979
4	Morioka	-	Ashiro	52.5	1970-1982
5	Ashiro	-	Towada	38.0	1971-1984
6	Towada	-	Aomori	76.9	1968-1986

Table 2: Total emission (million ton of carbon) from Tohoku expressway construction.

	1975 technology	1990 technology
Pavement	0.25	0.17
Bridge	0.60	0.38
Earthwork	0.64	0.41
Tunnel	0.22	0.15
Other construction	1.12	0.66
Total	2.83	1.77

** Result from $(I-(I-\hat{M})A)^{-1}$ model*

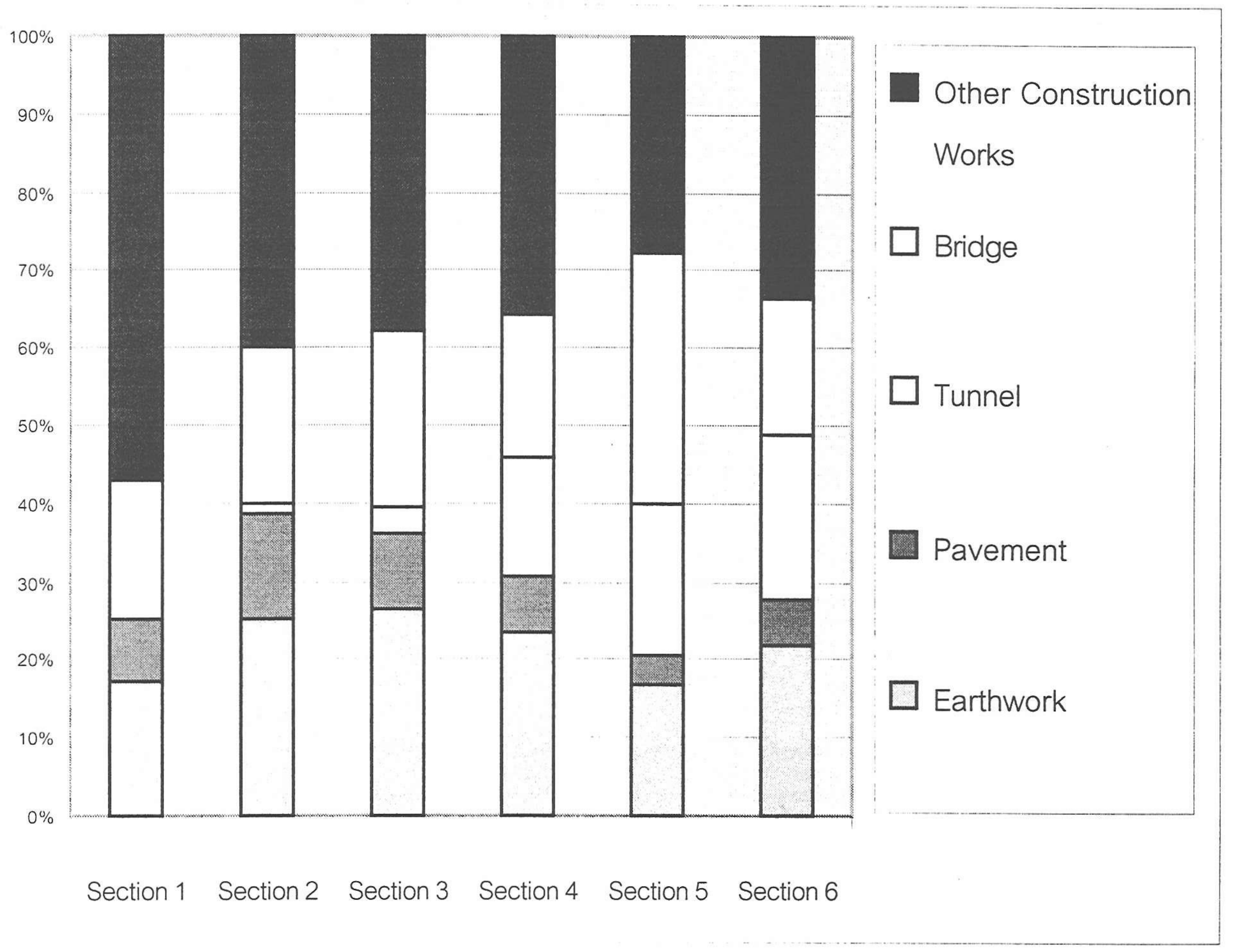

Figure 2: The structure of CO_2 from the construction of expressway by section

(2) Induced CO_2 from one unit of general road construction works : 1975 and 1990 technology

We selected 1985 price level as a price yardstick to compare the amount of emission per one unit of construction between 1975 and 1990. The result was based on 351 sectors and 407 sectors for 1975 and 1990 respectively. To make a comparison between 2 base years, the detailed result was aggregated into 15 major sectors as presented in Table 3-4. Table 3-4 shows the amount of CO_2 induced from one unit of various road-related construction works break down by sector assuming the technology in 1975 and 1990 respectively. For example, from Table 4, the construction of one unit of bridge (one million yen in 1985) using 1990 technology will induced total direct plus indirect CO_2 emission of 1.09 ton-C. The shaded areas show some sectors contributing as major sources of CO_2 in each construction category.

It is noted that the classification of construction sector is different from the previous section. In previous section, the classification is for the initial project construction that does not include road improvement and road repair category. Although we have the cost data of the expressway's tunnel but there is no classification for tunnel in general construction input-output table. Therefore, it was not included in the general road construction work in this section. Due to the limitation of data, in the analysis of previous section, we assumed the earthwork construction technology for tunnel construction for the sake of similarity and simplicity.

It can be seen that the structure of carbon emission embedded in raw material and service is different by category of general road construction work. . For example, in case of pavement construction, the emission is mainly embedded in paving material, cement product, and steel while the emission from earthwork is mainly embedded in cement product and transport services. The study revealed the structure of life cycle emission from road construction works that is very useful for an evaluation of the effective improvement assessment (to reduce the total amount of emission effectively).

Table 5 shows changes of emission by sectors in percentage of total emission changed per one unit of construction. For example, bridge construction showed the most reduction of carbon emission during the period of study (-0.71 ton-C/million yen) and the major sources of reduction were caused by the reduction of carbon emission from iron and steel sector, nonferrous metals and product sector, and power supply sector. It was found that most of sectors show reduction in CO_2 emission per one unit of construction during the period. However, some sectors revealed more emission share, for example, it was found that cement was used more in bridge construction during 1975-1990.

Table 3: The amount of CO_2 induced by one unit of construction work break down by major sectors, 1975-technology assumption

(Ton of carbon per 1 million yen of construction cost, in 1985 price)

	Pavement construction	Bridge construction	Earthwork	Road improvement	Road repair	Others
Gravel and crushed stones	11%	0%	4%	6%	4%	4%
Paving material	40%	0%	0%	1%	28%	0%
Cement, clay product, and cement product	17%	20%	62%	58%	29%	41%
Iron and steel	4%	38%	6%	10%	6%	19%
Nonferrous metals and products	2%	26%	5%	2%	5%	13%
Woods for construction	0%	0%	0%	0%	0%	0%
Petroleum refinery product	0%	0%	0%	0%	0%	0%
Other products	3%	1%	1%	3%	5%	1%
Machinery	1%	1%	3%	1%	1%	5%
Electric power, gas, heat supply	10%	9%	3%	8%	12%	5%
Water supply	0%	0%	0%	0%	0%	0%
Transport services	8%	3%	13%	7%	8%	8%
Commerce, finance, and real estate	1%	1%	1%	1%	1%	1%
Other services	1%	1%	1%	1%	1%	1%
Activities not elsewhere classified	0%	0%	0%	0%	0%	0%
Total (ton-C/million yen)	1.2964	1.8016	1.2922	1.3932	1.3527	1.3480

* Shaded area shows major contributions (equal or more than 10 percent) of life cycle emission embedded in raw materials and services by sector.

Table 4: The amount of CO_2 induced by one unit of construction work break down by major sectors, 1990-technology assumption

(Ton of carbon per 1 million yen of construction cost, in 1985 price)

	Pavement construction	Bridge construction	Earthwork	Road improvement	Road repair	Others
Gravel and crushed stones	9%	0%	15%	4%	3%	5%
Paving material	14%	0%	0%	0%	11%	1%
Cement, clay product, and cement product	23%	41%	41%	46%	38%	34%
Iron and steel	11%	20%	6%	19%	11%	12%
Nonferrous metals and products	7%	20%	5%	4%	7%	14%
Woods for construction	0%	0%	0%	0%	0%	0%
Petroleum refinery product	1%	0%	1%	1%	1%	0%
Other products	3%	2%	3%	2%	3%	7%
Machinery	1%	0%	1%	1%	1%	2%
Electric power, gas, heat supply	6%	3%	5%	5%	5%	5%
Water supply	0%	0%	0%	0%	0%	0%
Transport services	17%	8%	16%	12%	15%	14%
Commerce, finance, and real estate	2%	1%	2%	1%	2%	2%
Other services	3%	2%	4%	3%	3%	3%
Activities not elsewhere classified	2%	1%	2%	1%	1%	2%
Total (ton-C/million yen)	0.8255	1.0917	0.8548	0.8662	0.8548	0.8254

* Shaded area shows major contributions (equal or more than 10 percent) of life cycle emission embedded in raw materials and services by sector.

Table 5: The comparison of change in the amount of CO_2 induced by one unit of construction work break down by major sectors between 1975-1990

(In percentage of total emission rate change)

	Pavement construction	Bridge construction	Earthwork	Road improvement	Road repair	Others
Gravel and crushed stones	-15%	0%	+16%	-10%	-6%	-3%
Paving material	-85%	0%	+1%	-2%	-73%	+1%
Cement, clay product, and cement product	-6%	+11%	-104%	-79%	-6%	-51%
Iron and steel	+8%	-65%	-6%	+4%	+7%	-31%
Nonferrous metals and products	+5%	-35%	-5%	+1%	0%	-13%
Woods for construction	0%	0%	0%	0%	0%	0%
Petroleum refinery product	+2%	+1%	+1%	+1%	1%	+1%
Other products	-4%	0%	+3%	-3%	-9%	+7%
Machinery	-1%	-1%	-6%	-3%	-1%	-10%
Electric power, gas, heat supply	-19%	-18%	0%	-14%	-29%	-6%
Water supply	0%	0%	0%	0%	0%	0%
Transport services	+9%	6%	-7%	0%	+10%	1%
Commerce, finance, and real estate	0%	0%	0%	0%	0%	-1%
Other services	+2%	1%	+4%	+2%	+3%	+1%
Activities not elsewhere classified	+2%	1%	+3%	+2%	+3%	+2%
Total change (ton-C/million yen)	-0.4709	-0.7100	-0.4374	-0.5270	-0.3818	-0.5226

* Shaded area shows major change (equal or more than 10 percent) of life cycle emission embedded in raw materials and services by sector.

4. Summary

In this study, we introduced a basic methodology to estimate the amount of CO_2 emission induced from a transport project construction. The model developed in this study was applied a case study to estimate the amount of CO_2 from Tohoku expressway construction in Japan under 1975 and 1990 technology assumptions. Because the model was developed based on 7-digit sector code data, it would be useful when the detailed analysis is required, for example, the study of the sensitivity of the amount of CO_2 emission from a transport project with different input substitutions or alternative construction technologies. The result of the breakdown analysis for each construction category showed the reduction of CO_2 emission in most sectors during the study period due to the change of economic structure and technological progress. It is necessary to clarify the effect of change by several factors driving behind (technology change, relative price change, demand change, etc), further analysis to decompose these effect is now under research (see, Piantanakulchai and Inamura [10)])

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A Life Cycle Inventory Analysis of Carbon Dioxide for A Highway Construction Project Using Input-Output Scheme :A Case Study of the Tohoku Expressway Construction Works *

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In this study, we introduced a basic model to estimate the amount of carbon dioxide for a proposed highway project construction. The input-output model was applied to estimate the amount of emission from Tohoku expressway construction in Japan. From the result of study, we could clarify the structure of the emission in major road construction works by sectors and also indicated the sectors that contribute much for the emission. To address the effect of technological change to environment, we also made a comparison of the amount of carbon dioxide per one unit of construction in many construction categories between 1975 and 1990 technology.

産業連関分析の枠組みによる高速道路事業のライフサイクルインベントリー分析
東北自動車道のケーススタディー*

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本研究は多くの機関によって経常的に提供されるデータを使用し、高速道路事業から発生する炭酸ガスを推計するものである。1975 年および 1990 年の産業連関表を用いることにより、高速道路建設の工種別の 15 年間の技術進歩が工事額 1 単位当たりの CO2 排出量の形で評価された。殆どの工種で炭酸ガス排出量（エネルギー消費量）が減少したことが明らかになった。また東北自動車道の各工事区間で CO_2 排出量に大きな差があることも明らかにされた
