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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ABSTRACT

Because the global warming involves the accumulation of carbon emission in long run, the concept of Life Cycle Assessment (LCA) is required to introduce into every transportation project. The transportation project needs various kinds of resources in construction phase, operation phase and demolish phase. The input-output scheme is very useful to analyze those direct and indirect effects. Many kinds of extended input-output models have been widely applied for environmental and energy-related analysis. Leontief, Herendeen, and Bullard are to name a few. A lot of recent works have been carried out to estimate the carbon emission from various production activities. In most studies, however, the amount of CO2 from many products produced in a sector has to be aggregated by assuming that a sector produces only one unique product. Nishimura 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 needs a lot of energy for extracting, processing, and transporting from the original source to the construction site. This study accounts 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. The study compiled available data from many sources and presented a basic model to estimate the amount of CO2 from a proposed highway project construction. The model was applied to the construction of Tohoku expressway in Japan.

Regarding the effect of technological change to the level and structure of the emission from road construction in broad sense, the amount of CO2 per one unit of general road construction work in many categories between the Japanese technology in 1975 and 1990 are then compared. A basic model to estimate the amount of carbon dioxide is introduced for a proposed highway project construction. The input-output model was applied to estimate the amount of emission from Tohoku expressway construction in Japan. The result clarified 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, the amount of carbon dioxide per one unit of construction in many construction categories between 1975 and 1990 technology is compared.

1. Introduction

The main theme of this research relates to Life Cycle Inventory (LCI) of carbon emission from transport system using economic Input-Output framework. Input-Output framework is adopted because of the availability of detailed data in economy (more than 400 sectors) and its capability to deal with both direct and indirect effects. The conventional way to deal with the problem, so-called the process analysis approach, is to draw the boundary for the system a priori. The drawback of this approach is not able to account for all indirect effects. Moreover, the results are inconsistent among various system boundaries.

In LCA framework, it is also necessary to know the effect of the change in each component in the system to the overall change in emission. An alternative road construction technology, change in economic structure, and/or change in energy technology would affect the amount of emission from the same scale of a transportation facility project. Under the input-output framework, the sensitivity analysis of the model to the change in each factor is possibly developed using the Input-Output Structural Decomposition Analysis (I-O SDA) approach.

Based on the stated problems, the objectives of this study are

1. To develop the model based on Input-Output framework to estimate the amount of life cycle carbon emission from transportation system.
2. To develop a model for a Life Cycle Inventory Sensitivity Analysis based on input-output structural decomposition analysis framework
3. To make a comparative study of life cycle carbon emission of transportation systems in the context of intercity expressway project and high-speed railway project in Tohoku region of Japan.

The essence of life cycle assessment is the evaluation of the relevant environmental, economic, and technological implications of a material, process, or product across its life span over their entire life.

Lave (1977) compared the construction of railway BART (San Francisco Bay Area Rapid Transit) and the extending of the existing highway system. He considered construction of transportation structure, production and operation of vehicle. He concluded that it used enormous of energy to invest in building a rail system and thus difficult to repay because the saving of energy in operating phase is smaller or even negative when considering on energy viewpoint only. Lave et al. (1995) applied input-output analysis to estimate economy-wide discharges. The national 519 sectors input-output table of the United States was applied to the LCA study of automobiles, refrigerators, and computer purchases, and to a comparison of paper and plastic cups. The model has the advantage of tracing out the full direct and indirect implications of a material, process, or product at low cost of analysis. However, there are still some limitations in their model such as the conventional input-output matrices do not include activities associated with final consumers such as energy for product use or wastes of product disposal are not included in the model.

Input-output model is used to analyze interdependence among industries in the economy. Conventional economic input-output model when modified for environmental study has advantage in capturing the complex chain of the economic interdependence. The extended input-output models have been widely applied for environmental and energy-related analysis. For example, Leontief (1970) extended input-output model to include environmental externalities and pollution abatement activities. Leontief (1972) computed the direct air pollution output coefficients (amount of pollution emitted per dollar of output). Using the same framework like Leontief (1970), he calculated the total (direct and indirect) air pollution output coefficients for the US. 90 sectors I-O table.

Gutmanis (1975) discussed on many extensions of I-O model for environmental policy analysis such as analysis of pollution generation, pollution generation trends under economic assumptions, comparison of alternative pollution abatement costs, effects of alternatives of raw materials, end product uses, and others .Rose (1977) extended the conventional I-O model to cope with dynamic problem including technological changes and investment. Rose (1983) made critical review of previous I-O models for macro economic impact of air pollution abatement and suggested some biases in previous models. He proposed a framework of 3-stage model including input-output balance, price adjustments, and input substitution. Herendeen (1974) and Bullard et al. (1975) 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. (1993) estimated the amount of CO_2 emission per one unit of commodity's production using Japan's 1985 input-output tables. Hetherington (1996) did similar work for UK. Kondo et al. (1996) 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 (1996) 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. (1997) 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, by our awareness, 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, it is usually accounted only for the direct energy used to construct transport facilities, for example, required energy 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. (1977).

2. Life Cycle Inventory Model of Transport Using Input-Output Framework

When the concept of LCA is applied, there are two important dimensions need to be considered. The first dimension is to account the emission throughout the project’s life cycle. This makes the LCA study different from the conventional environmental impact studies that mostly consider only the impact in the operation stage. The emission occurred during the project construction before the operations as well as the emission from the maintenance of the project were considered. The second important dimension need to be considered is the indirect emission caused during the production of the ancillary products. To overcome the limitation mentioned above, the economic Input-Output model is utilized for the analysis of the life cycle emission.

2.1 Hybrid Input-Output Model

Although the ordinal input-output tables are usually recorded in monetary term, the model employed here is derived in physical term. The total amount of emission (ton-C) by relating the emission with the output put of fuel in monetary term as shown in Eq. 2.1.

$$\begin{aligned} \textit{Emission (ton - C)} &= \textit{(Estimated Output of Fuel)} * \textit{(Price of Fuel)} \\ &\quad * \textit{(Carbon Content of Fuel)} \end{aligned} \tag{2.1}$$

$$= \$ * \left(\frac{liter}{\$}\right) * \left(\frac{ton-C}{liter}\right)$$

However, this method may not give the correct amount of emission when non-uniform energy price across sectors exists. Due to different fuel price, one $ purchased by different sector may give different in quantity of fuel and also the emission. Another reason is caused by the aggregation of various fuel commodities in the fuel supply industry. For example, heavy oil and gasoline are in the same fuel supply industry. Different sectors demand mainly for different type of fuel. One sector may intensively use heavy oil while another sector may use more gasoline. In this case, one $ of purchase from fuel supply industry may imply different amount of emission if it is purchased from different sectors. The broad discussion can be found in Miller and Blair (1985).

To avoid the error mentioned above, a Hybrid I-O model is introduced in this study. In hybrid model, the monetary units in primary energy sectors as well as limestone sector were replaced by the associated emission in physical term (ton-C). The primary energy sector considered here are Limestone, Coal mining, Crude petroleum, Natural gas, Petroleum refinery products, Coal products, and Gas supply.

The input-output table is modified into hybrid unit. The uses of the primary energy as well as limestone are expressed in term of carbon. Performing the same procedure of calculation as in the basic input-output model, the balance equation is obtained in the form

$$\begin{bmatrix} X_{ne} \\ X_e \end{bmatrix} = \begin{bmatrix} A_{ne/ne} & A_{ne/e} \\ A_{e/ne} & A_{e/e} \end{bmatrix} \begin{bmatrix} X_{ne} \\ X_e \end{bmatrix} + \begin{bmatrix} Y_{ne} \\ Y_e \end{bmatrix} \tag{2.2}$$

Where the hybrid units are; $\begin{bmatrix} X_{ne} \\ X_e \end{bmatrix} = \begin{bmatrix} \$ \\ ton\text{ - }C \end{bmatrix}$, $\begin{bmatrix} A_{ne/ne} & A_{ne/e} \\ A_{e/ne} & A_{e/e} \end{bmatrix} = \begin{bmatrix} \frac{\$}{\$} & \frac{\$}{ton\text{ - }C} \\ \frac{ton\text{ - }C}{\$} & \frac{ton\text{ - }C}{ton\text{ - }C} \end{bmatrix}$,

$$\begin{bmatrix} A_{ne/ne} & A_{ne/e} \\ A_{e/ne} & A_{e/e} \end{bmatrix} = \begin{bmatrix} \frac{\$}{\$} & \frac{\$}{ton\text{ - }C} \\ \frac{ton\text{ - }C}{\$} & \frac{ton\text{ - }C}{ton\text{ - }C} \end{bmatrix}, \quad \begin{bmatrix} Y_{ne} \\ Y_e \end{bmatrix} = \begin{bmatrix} \$ \\ ton\text{ - }C \end{bmatrix}$$

X_{ne} = Output of non-primary energy sectors
X_e = Output of primary energy sectors
Y_{ne} = Final demand of non-primary energy sectors
Y_e = Final demand of primary energy sectors
$A_{ne/ne}$ = Input of non-primary energy sector required by non-primary energy sector's output
$A_{ne/e}$ = Input of non-energy sector required by primary energy sector's output
$A_{e/ne}$ = Input of primary energy sector required by non-primary energy sector's output

$A_{e/e}$ = Input of primary energy sector required by primary energy sector's output

The emission by primary sectors of emission can be extracted from a hybrid output vector X by applying matrix S. Eq. 2.9 is expressed in block matrix form of non-primary energy sectors (ne) and primary energy sectors (e).

$$\begin{aligned} \boldsymbol{E} &= \boldsymbol{S}\,(\boldsymbol{I}-\boldsymbol{A})^{-1}\boldsymbol{Y} \\ &= \boldsymbol{S}\begin{bmatrix} \boldsymbol{B}_{ne/ne} & \boldsymbol{B}_{ne/e} \\ \boldsymbol{B}_{e/ne} & \boldsymbol{B}_{e/e} \end{bmatrix}\begin{bmatrix} \boldsymbol{Y}_{ne} \\ \boldsymbol{Y}_{e} \end{bmatrix} \\ &= \boldsymbol{B}_{e/ne}\boldsymbol{Y}_{ne} + \boldsymbol{B}_{e/e}\boldsymbol{Y}_{e} \end{aligned} \tag{2.3}$$

E = Carbon emission by primary source sectors

S = (mxn) matrix of zeros and ones where every row; like $\begin{bmatrix} \mathbf{0} & \mathbf{0} & \mathbf{1} & & \\ \vdots & \vdots & & \ddots & \\ \mathbf{0} & \mathbf{0} & & & \mathbf{1} \end{bmatrix}$

S_{ij} = 1 , when j is the primary sector of that row. =0 , otherwise.

The life cycle of expressway can be illustrated in Fig 2.5. The emission from the construction of transport facilities, the emission from the operation and maintenance, and the emission from the car production were considered.

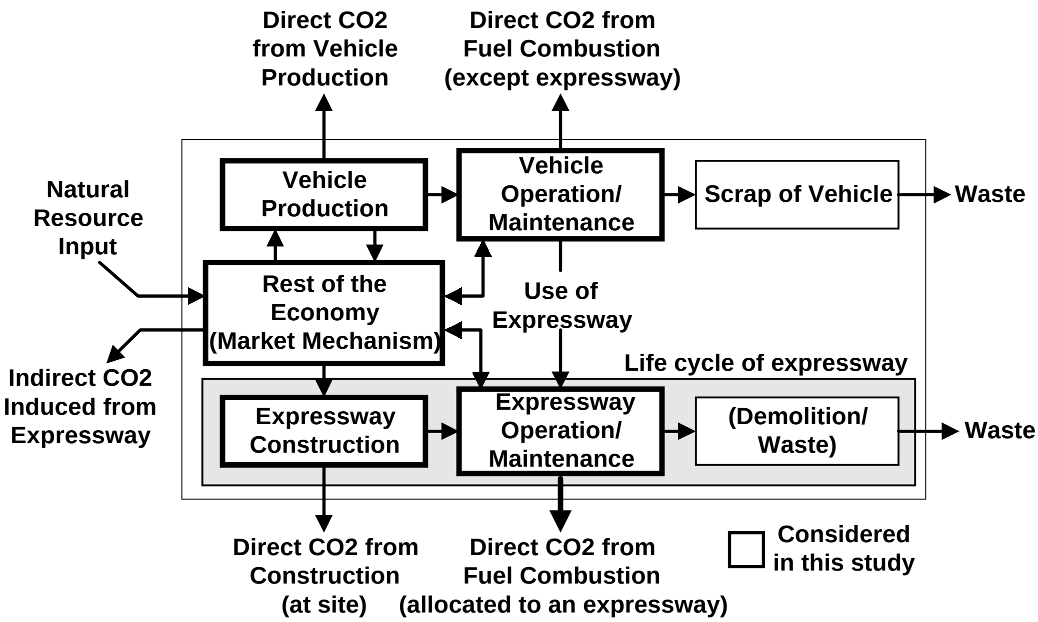

Fig. 2.1 Framework of the Analysis of Life Cycle Emission of Expressway

In the model, the construction technology is expressed by the quantity 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, the input coefficient for construction is defined as

$$c_{ij} = \frac{C_{ij}}{\sum C_{ij}} \quad \text{where} \quad \sum c_{ij} = 1 \tag{2.4}$$

C_{ij} =Cost of input from sector i for construction category j (million yen)

c_{ij} =Cost share of input from sector i for construction category j (million yen / million yen)

2.2 Construction Cost, Maintenance, and Car Production

The construction cost can be separated into the cost of raw materials and services from intermediate sectors and the cost of value added (wages, rent, and profit). Since the construction cost of the expressway was reported by construction category (bridge, pavement, tunnel, earthwork, etc.), the project construction cost at base year price by category is multiplied with the associated column vector of input coefficients for construction to obtain the final demand vector by subcategory.

Emission from the project maintenance can be estimated in the same way as in the construction works using the estimated annual maintenance cost.

Because the car industries are already included in the basic 405 sectors I-O table, the amount of emission per one unit of final demand in car industry directly (ton-C/million yen of vehicle production) can be estimated. The result gives the emission per one million yen of car production. However, to estimate the amount emission per one car, the composite cost of vehicle production in the market was applied. Three vehicle types, such as passenger vehicles, buses, and trucks were considered.

The amount of direct emission from the operation of vehicles is directly related to the fuel consumption of the vehicle. The emission from the operation of vehicle are assumed to be effected by the following factors. They are Engine size, Average running speed, Weight of vehicle, and Weight of loading.

2.3 Case Study

The Tohoku expressway in Japan was picked up as a case study. Fig. 2.6 shows the framework of the analysis. Tohoku expressway is an inter-city toll way passing through the major cities in the north-eastern region of Japan. The analysis sections included the total length 679.5 km. of the expressway. Since the LCA result can be varied according to the geological location of expressway, the analysis was done in sub-sections as shown in Fig. 2.7 and the results were compared. Although the expressway can be used for hundred years, some structures such as bridge has the limit durable time. For the basis of evaluation, in this study, the project life was set to be 60 years after opening to the operation.

Input-output tables used here are

1) Input-Output table of Japan, 1990
2) Input Coefficient for road construction works from Construction I-O table of Japan, 1990

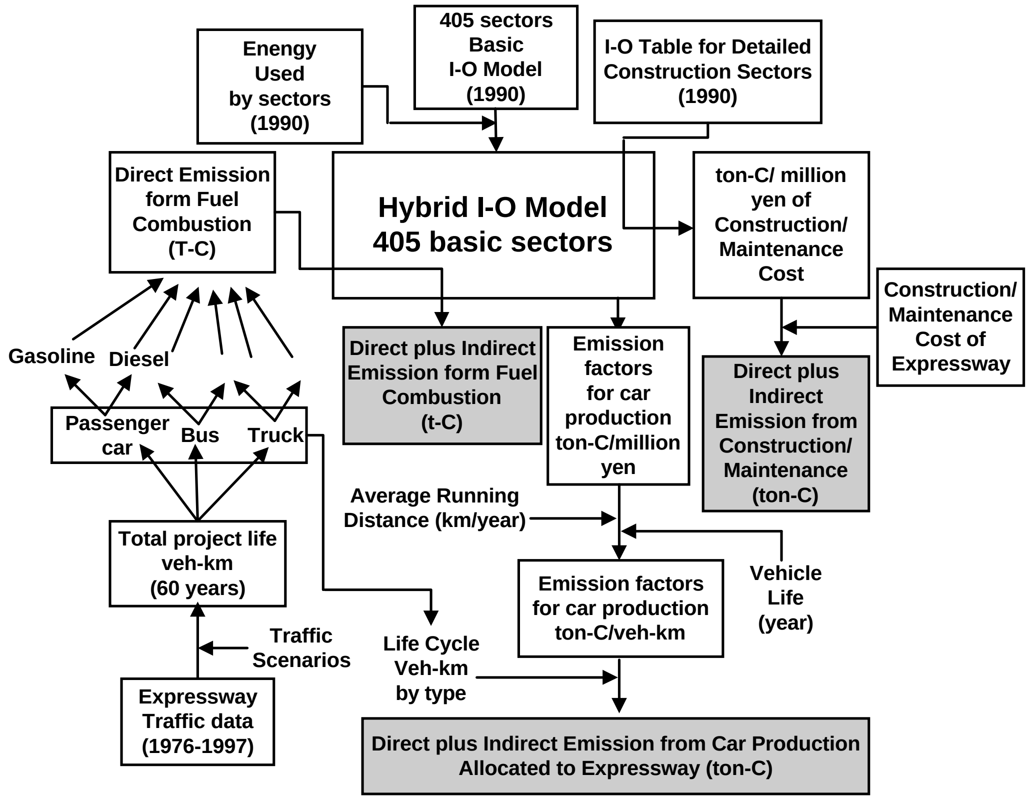

Fig. 2.2 Framework of Life Cycle Emission Inventory Study of Expressway

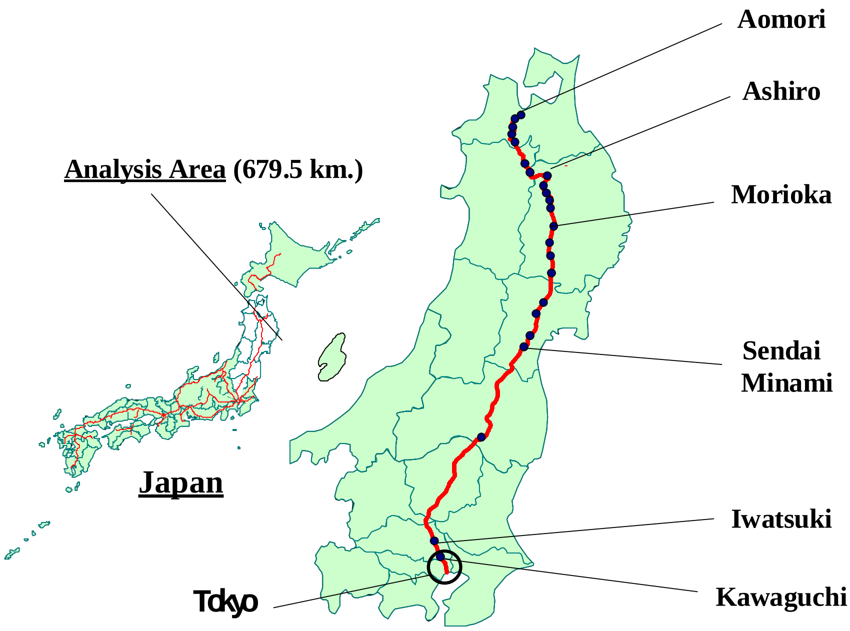

Fig. 2.3 Study Area (Tohoku Region)

The I-O table of Japan used was aggregate into 405x405 sectors while the input coefficient was obtained in 7 digits commodity I-O code and then aggregated into 405-sector code. The set of input coefficients for road construction work was utilized as the final demand in the I-O model. The coefficients represent the input requirement for one million yen of road construction by category. Table 2.1 shows the input coefficients in some major sectors. Fig. 2.4 shows the input structure of pavement as an example.

Table 2.1 Input Coefficients for Road Construction Works

	Pavement	Bridge	Earth Work
Crushed stones	0.052	0.002	0.061
Cement	0.001	0.004	0.003
Ready mixed concrete	0.014	0.053	0.025
Cement products	0.031	0.021	0.038
Steel bar (ordinary steel)	0.001	0.022	0.003
Paving materials	0.134	0.002	0.005
Metal products for construction	0.024	0.155	0.026
Machinists' precision tools	0.003	0.002	0.000
Electric power	0.006	0.004	0.005
Water supply	0.001	0.001	0.000
Wholesale trade (distributive trade margin)	0.047	0.044	0.042
Road freight transport	0.001	0.001	0.001
Transport service in harbor (fee)	0.001	0.001	0.001
Information service	0.001	0.001	0.005
Civil engineering and construction services	0.036	0.022	0.031
Activities not elsewhere classified	0.014	0.009	0.015
Total of gross value added sectors	0.375	0.478	0.389
Total domestic products (gross outputs)	1.000	1.000	1.000

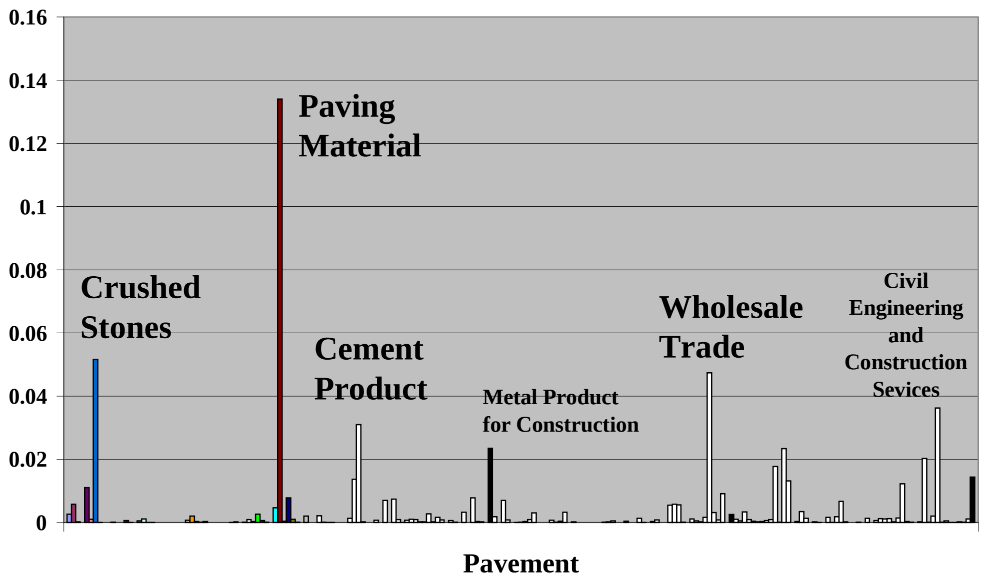

Fig. 2.4 Input Structure of Pavement Construction (1990)

The construction cost of the expressway was obtained by the contract cost estimation that was expressed in the contract year price. To apply the data to the model, we used the cost deflators for road construction works to convert the cost at contract year price into the base year (1990) price. Maintenance Cost of Tohoku Expressway is supplied from Japan Highway Public Corporation (JH). Cost Deflators for Road Construction Works is picked up from Japan Statistical Yearbook. The Japan Highway Public Corporation (JH) prepares traffic Data of Tohoku Expressway 1976-1997 and Average Daily Traffic (ADT) by section. The traffic was categorized into three major vehicle classes; passenger car, bus, and truck.

Each vehicle classes is further subdivided into gasoline and diesel powered to account for different emission rate from different fuel type. See Fig. 2.5.

The result after combining with construction input coefficient can be summarized in Table 2.2. It can be seen that bridge construction creates the most unit emission among the expressway construction works. It is noted that the direct plus indirect unit emission of fuel is expressed in kg-C/kg-C due to the application of the hybrid model. The direct emissions was calculated first by applying the carbon content by the chemical property of each fuel type and then convert to the total emission to include the indirect emission from fuel mining, transporting, and production process. The result showed that the indirect emission accounts about 4 percent of total emission from using the fuel. The amount of life cycle emission for Tohoku expressway can be estimated by applying the calculated emission factors in Table 2.2 to the project data. The results are shown in Table 2.3. It can be seen that the emission from vehicle operation plays most important role in the life cycle emission of expressway. The result was shown by the life stage of expressway. If emission from the construction and maintenance of public facilities was allocated to each vehicle type, the result can be shown in Table 2.4. It revealed that most of emission from the expressway comes from freight transportation (truck). The unit emission per functional unit of transportation (passenger-km. for passenger transportation and ton-km. for freight transportation) can be calculated as shown in Table 2.5. It is noted that the result included the emission from every stages of expressway and averaged by the total usage of expressway during the expressway's lifetime.

Different geological area requires different road construction techniques. For example, the mountainous area may need more tunnel construction. The structure of the life cycle emission by expressway construction category and geological location can be shown in Fig.2.11. The sections on the left hand side are near Tokyo where the sections on the right hand side go to northeastern area that is full of mountains.

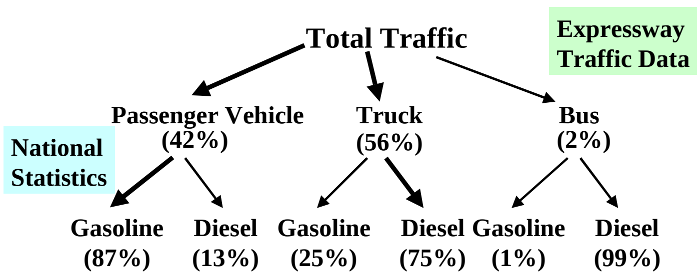

Fig. 2.5 Vehicle Classification by Type and Fuel

Table. 2.2 Emission Factors Calculated from the Model

Item	Direct	Direct + Indirect	Unit
Expressway Construction			
Bridge	0.207	1.200	ton-C/million yen
Pavement	0.267	0.877	ton-C/million yen
Tunnel & Earthwork	0.257	0.901	ton-C/million yen
Other works	0.204	0.915	ton-C/million yen
Expressway Maintenance	0.195	0.922	ton-C/million yen
Vehicle Production			
Passenger Car	0.023	1.042	ton-C/vehicle
Truck	0.029	1.552	ton-C/vehicle
Bus	0.077	4.179	ton-C/vehicle
Fuel		1.047	kg-C / kg-C
Gasoline	0.643		kg-C / liter
Deisel	0.721		kg-C / liter

Table. 2.3 Carbon Emission from Tohoku Expressway by Life Stage (Unit = 1,000 ton-C)

	Direct	Direct +Indirect	Share
Production of vehicle	47	2,200	5.0%
Passenger Car	33	1,500	
Bus	1	55	
Truck	13	7,200	
Expressway construction	12	2,200	4.8%
Earthwork	2	500	
Pavement	2	200	
Tunnel	1	180	
Bridge	1	470	
Other works	6	850	
Expressway maintenance	52	250	0.5%
Vehicle operation	39,000	41,000	89.6%
Passenger Car	9,400	9,800	
Bus	990	1,040	
Truck	28,000	30,000	
Total	39,000	45,000	100.0%

Table. 2.4 Carbon Emission from Tohoku Expressway by Vehicle Type

	Car Production	Expressway Construction	Expressway Maintenance	Car Operation	Total
Passenger Car	1,500	920	100	9,800	12,000
Bus	55	44	5	1,000	1,100
Truck	720	1,200	140	30,000	32,000

Note : The emission from the construction and maintenance public facilities was allocated to each vehicle type by the traffic volume (Unit = 1,000 ton-C)

Table. 2.5 Amount of Life Cycle Emission per Functional Unit

Vehicle type	Life Cycle Emission	Unit
Passenger Car	44.91	ton-C / million passenger-km
Bus	6.91	ton-C / million passenger-km
Truck	44.27	ton-C / million ton-km

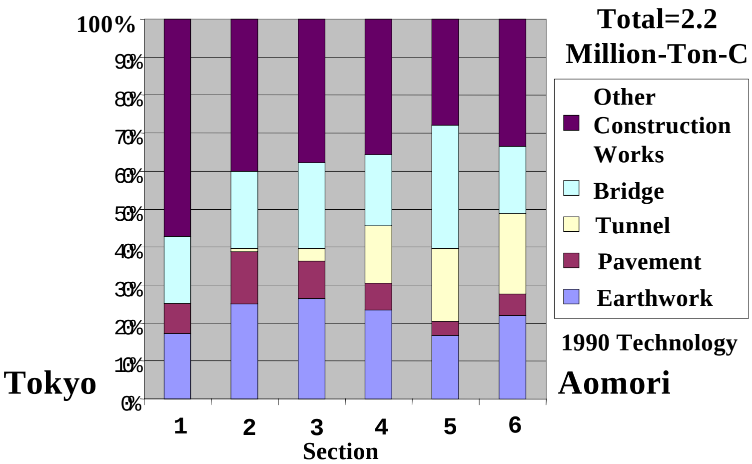

Fig. 2.6 Carbon Emission from Expressway Construction by Geological Location

3. A Sensitivity Analysis Using the Structural Decomposition

In I-O framework, the source of change in emission is reflected by the change of final demand and economy's technology (economic structure). Structural Decomposition Analysis (SDA) is one of appropriate approaches to decompose the source of change under I-O framework. The SDA is a pragmatic alternative of econometric estimation (Rose & Casler, 1995). The input-output tables of the initial year and the terminal year are used to perform the basic decomposition analysis in this paper.

Equations 3.1-3.5 show some possible decomposition schemes that are different by the choice of base year weight.

$$\Delta X = B_0 \Delta Y + \Delta B Y_t \tag{3.1}$$

$$\Delta X = B_t \Delta Y + \Delta B Y_0 \tag{3.2}$$

$$\Delta X = B_0 \Delta Y + \Delta B Y_0 + \Delta B \Delta Y \tag{3.3}$$

$$\Delta X = B_t \Delta Y + \Delta B Y_t - \Delta B \Delta Y \tag{3.4}$$

$$\Delta X = \left(\frac{B_0 + B_t}{2}\right)\Delta Y + \Delta B\left(\frac{Y_0 + Y_t}{2}\right) \tag{3.5}$$

$$dX = (B)(dY) + (dB)(Y) \tag{3.6}$$

In a discrete time analysis, the interaction terms always present and the choice of base year weight is arbitrary. This scheme applied the average approach, proposed by Betts (1989), to eliminate the problem of arbitrary weight and interaction terms. This method takes an average for the polar weights between the periods of study. For example, taking an average of equation 3.1 and 3.2, or taking an average of equation 3.3 and 3.4 would give the same result of the average scheme 5 as shown in equation 3.5.

We shall show an example by applying a set of the country's final demand in 1975 and 1990 to estimate emission change. The result of decomposition by various schemes is shown in Table 3.1.

Table 3.1 Result of a decomposition of national emission change during 1975-1990 (Mt-C)

Scheme	Final Demand	Technology	Interaction	Total change
1	273.7	-257.4	0.0	16.3
2	111.6	-95.3	0.0	16.3
3	273.7	-95.3	-162.2	16.3
4	111.6	-257.4	162.2	16.3
5	192.7	-176.4	0.0	16.3

Note: Total amount of emission in 1975 and 1990 were estimated as 283.7 Mt-C and 300 Mt-C respectively.

During the period, technology change could reduce the amount of carbon emission considerably (minus sign). However, the effect of final demand change overshadowed the change in technology, therefore, resulted in net increase in carbon emission.

Equation 3.6 shows the decomposition in differential form when small change occurs during the short time period. In this case, interaction term does not exist. If we subdivide the study period into many sub-periods, and calculate small changes during each sub-period, the error term (interaction term) will be reduced by n times when n is the number of sub-periods. If we assume that the coefficients change continuously in time, n approaches infinity, the summation of error terms will converge to zero as shown in table 3.2.

If we assume technical coefficients (A) and final demand (Y) change linearly during the period, summing up all changes of sub-periods would yield the total change during that period and the error term would be distributed equally to final demand and technology in exactly the same manner as the result from the average method (scheme 5) as presented in table 3.1.

Table 3.2 Empirical result from the assumption of linearly coefficients change in time.

	Final Demand	Technology	Interaction	Total change
n=1	273.7	-95.3	-162.2	16.3
n=2	235.1	-137.7	-81.1	16.3
n=4	215.3	-158.5	-40.5	16.3
n=8	205.3	-168.7	-20.3	16.3
n->infinity	192.7	-176.4	0.0	16.3

Proposed by Betts (1989), equation 3.7 to 3.9 are the generalizations of the average method when the variable of interest (X) is the product of variables (F_i), ($n \geq 2$).

$$X = \prod_{i=1}^{n} (F_i) \tag{3.7}$$

$$X^t - X^0 \equiv \Delta X = \prod_{i=1}^{n} \left(F_i^t\right) - \prod_{i=1}^{n} \left(F_i^0\right) \tag{3.8}$$

$$\Delta X = 0.5 \sum_{k=1}^{n} \left\{ \prod_{j<k} F_j^0 \Delta F_k \prod_{l>k} F_l^t \right\} + 0.5 \sum_{k=1}^{n} \left\{ \prod_{j<k} F_j^t \Delta F_k \prod_{l>k} F_l^0 \right\} \tag{3.9}$$

It's obvious that equation 3.5 is a just case of equation 3.9 with n=2. This formulation can be used to carry out the detailed analysis when more than two variables effect the final demand and technical matrix change.

Recall that the output or in this case, emission is the function of the level of technology (or matrix B), and the final demand (vector Y). Fig.3.1 shows the simplified version of the combination of the level of final demand and the technology level associating with the amount of emission. Each colored curved shows the same level of emission. For example, if we want to maintain the same level of emission while increasing the level of consumption (or final demand) , we have to use more advance technology in production. For example, moving from initial year with the level of emission is E_o, which is the combination of the technology level Bo, and Final demand level Y_o to the terminal year with the level of emission E_t that is the combination of the technology level B_t and the Final demand level Y_t. Moving from E_o to E_t increases the amount of emission by ΔE , while the technology change from B_o to B_t and the final demand change from Y_o to Y_t.

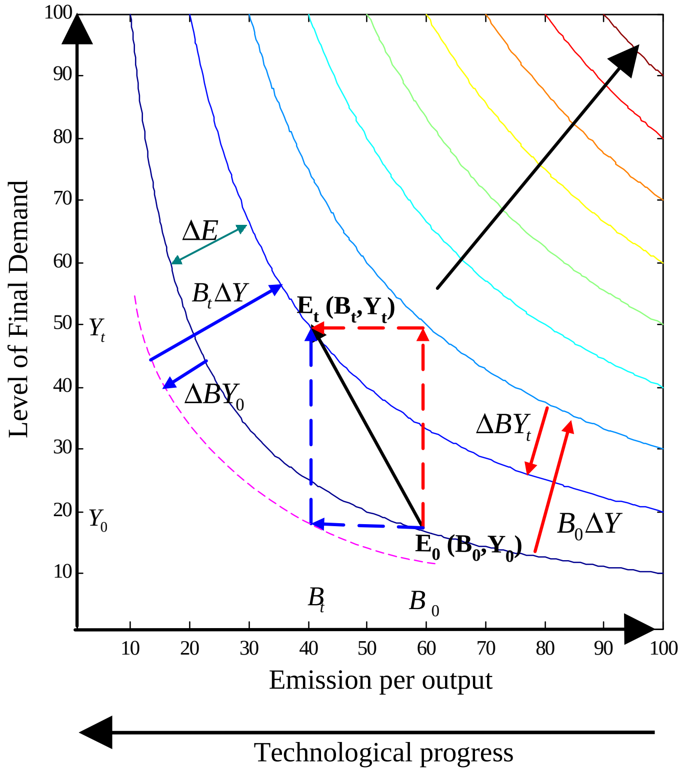

Fig 3.1. Different Assumption of Decomposition Schemes and Growth in Final Demand and Technology

The demand change effect can be defined by holding the technology constant and change the demand. The technology change effect can be defined vice versa. The change can be written as in equation 3.6 if the final demand and technology is defined as the continuous function in time. However, in case of input-output model which is a kind of static model. There are many possible discrete decomposition schemes as shown by the examples of equation 3.1-3.5.

It could be seen that equation 3.1 is just the decomposition scheme assumed the growth path as in the upper right path, while equation 3.2 is just the decomposition scheme assuming the lower left path. It was assumed that the growth path by dividing the study period into many small sub-periods and updating the coefficients and final demand using the assumption of linearly growth in time. The result comes up with the same as the decomposition scheme in equation 3.5.

The decomposition scheme in equation 3.5 is derived from the assumption of linearly growth of coefficients in time. Linearly coefficient change in time implies that;

$$B = B_0 + \left(\frac{B_T - B_0}{T}\right)t \tag{3.10}$$

$$Y = Y_0 + \left(\frac{Y_T - Y_0}{T}\right)t \tag{3.11}$$

The infinitesimal change in output (*dX*) can be expressed as

$$\begin{aligned} dX &= B(dY) + (dB)Y \\ &= \left\{B_0 + \left(\frac{B_T - B_0}{T}\right)t\right\}\left(\frac{\Delta Y}{T}\right)dt + \left(\frac{\Delta B}{T}\right)dt\left\{Y_0 + \left(\frac{Y_T - Y_0}{T}\right)t\right\} \\ &= \left\{\frac{B_0\Delta Y}{T}dt + \frac{(B_T - B_0)\Delta Y}{T^2}t\,dt\right\} + \left\{\frac{\Delta BY_0}{T}dt + \frac{\Delta B(Y_T - Y_0)}{T^2}t\,dt\right\} \end{aligned} \tag{3.12}$$

The total change in output (ΔX) during the period t=0 to t=T can be expressed as the integral of infinitesimal change in equation 3.12 during the period.

$$\begin{aligned} \Delta X &= \int_{t=0}^{t=T} dX = \left\{\int_{t=0}^{t=T}\frac{B_0\Delta Y}{T}dt + \int_{t=0}^{t=T}\frac{(B_T - B_0)\Delta Y}{T^2}t\,dt\right\} + \left\{\int_{t=0}^{t=T}\frac{\Delta BY_0}{T}dt + \int_{t=0}^{t=T}\frac{\Delta B(Y_T - Y_0)}{T^2}t\,dt\right\} \\ &= \left\{B_0\Delta Y + \frac{B_T\Delta Y}{2} - \frac{B_0\Delta Y}{2}\right\} + \left\{\Delta BY_0 + \frac{\Delta BY_T}{2} - \frac{\Delta BY_0}{2}\right\} \\ &= \left\{\frac{B_0\Delta Y}{2} + \frac{B_T\Delta Y}{2}\right\} + \left\{\frac{\Delta BY_0}{2} + \frac{\Delta BY_T}{2}\right\} \\ &= \left\{\frac{B_0 + B_T}{2}\right\}\Delta Y + \Delta B\left\{\frac{Y_0 + Y_T}{2}\right\} \end{aligned} \tag{3.13}$$

Hence, by the assumption of linearly coefficient growth in time, equation 3.13 is equivalent to the decomposition scheme in equation 3.5.

In another view, scheme 5 just assigns the effect of the error terms to each part equally. It can be shown by the following equation.

$$
\begin{aligned}
\Delta X &= B_0 \Delta Y + \Delta B Y_0 + \Delta B \Delta Y \\
&= \left\{ B_0 \Delta Y + \frac{\Delta B \Delta Y}{2} \right\} + \left\{ \Delta B Y_0 + \frac{\Delta B \Delta Y}{2} \right\} \\
&= \left\{ B_0 \Delta Y + \frac{B_T \Delta Y}{2} - \frac{B_0 \Delta Y}{2} \right\} + \left\{ \Delta B Y_0 + \frac{\Delta B Y_T}{2} - \frac{\Delta B Y_0}{2} \right\} \\
&= \left\{ \frac{B_0 + B_T}{2} \right\} \Delta Y + \Delta B \left\{ \frac{Y_0 + Y_T}{2} \right\}
\end{aligned}
$$

From Fig. 3.1., it can be seen that the growth path assumed in this study is just the direct path from initial to terminal year of the study period.

Different weights would produce different results of effect in each factor as illustrate in an example. This problem is called an index number problem. Dietzenbacher and Los (1998) discussed in detail about this problem. In their study, more than two variables were included. They investigated all possible combination of the choices of the weight schemes. They found that the average method that takes an average of the polar weights gives very close result to the average of the results from all possible combinations. We also applied the average method to make further analysis of factors that caused total emission changes in road construction works in Japan during 1975-1990.

4. The Decomposition for the Source of Change of Carbon Emission Intensities for General Road Construction Works in Japan during 1975-1990.

4.1 Fundamental Insights

The total amount of life cycle emission from six selected road construction categories were estimated as shown in table 4.1 and table 4.2. From the primary energy view point, in 1975 most of emission ultimately came from burning of petroleum refinery products (Table 4.1). However, in 1990, the emission from coal products prevailed (Table 4.2). One major finding is that the amount of carbon emission per one unit of road construction works reduced about 40 percent (Table 4.3).

We apply equation 4.1 to recognize what kind of raw material or service embedded high level of emission.

$$E_j = \left(\sum_{i \ni E} B_{ij} \right) Y_j \qquad (4.1)$$

E = primary source of emission sectors (primary energy and limestone sectors)

Using equation 4.1, table 4.4 - 4.5 show the results aggregated into 12 major general industry sectors contributing the emission from road construction.

Tables 4.4-4.5 show the structure of carbon emission embedded in final product required for road construction. For example, using products from iron and steel sector may induce considerably carbon emission share. The result shows the carbon emission from the viewpoint of final use of material and service in construction work. Table 4.6 shows the carbon emission change during the period.

This result reflected more or less the increase in price of petroleum products during that period. From the resource-input viewpoint, most of emission came from using cement, cement products, iron, and steel (Table 4.4-4.5). Each construction categories presented the unique emission structure, for example, emission from pavement construction mostly embedded in paving material and cement while emission from the bridge construction mostly embedded in cement and steel. It was also interesting that transportation sector also contribute much reduction during the period (Table 4.6).

Table 4.1 Carbon emission for 1975 technology assumption
(kg-C per one million yen of construction cost in 1985)

Emission source	Improvement	Pavement	Bridge	Repair	Earthwork	Others
Lime stone	325	91	208	183	308	212
Raw Coal	1	1	1	1	1	1
Coal products	250	176	1095	201	190	422
Crude Oil	85	92	118	99	65	81
Petroleum	767	926	626	880	767	694
Natural gas	11	11	17	12	8	11
Gas supply	11	12	9	13	11	14
Subtotal : emission at site	73	72	23	81	62	51
Subtotal : indirect emission	1378	1237	2052	1308	1290	1383
Total	1450	1309	2075	1389	1351	1434

Note: Dark shaded area shows the major sectors contributing to the emission

Table 4.2 Carbon emission for 1990 technology assumption
(kg-C per one million yen of construction cost in 1985)

Emission source	Improvement	Pavement	Bridge	Repair	Earthwork	Others
Lime stone	229	109	280	218	175	147
Raw Coal	22	17	45	18	13	24
Coal products	325	245	549	302	246	326
Crude Oil	26	32	30	32	30	32
Petroleum	191	287	181	247	204	233
Natural gas	36	44	45	45	44	49
Gas supply	3	4	4	4	3	4
Subtotal : emission at site	67	96	34	60	41	60
Subtotal : indirect emission	765	642	1100	806	674	753
Total	832	738	1134	865	715	814

Note: Dark shaded area shows the major sectors contributing to the emission

Table 4.3 Change in carbon emission between 1975 and 1990 technology assumption
(kg-C per one million yen of construction cost in 1985)

	Improvement	Pavement	Bridge	Repair	Earthwork	Others
Emission Change	-618	-571	-941	-524	-636	-621
%Change	-43%	-44%	-45%	-38%	-47%	-43%

Table 4.4 Carbon emission embedded in raw material and services input
for several categories of road construction works, 1975 technology assumption
(kg-C per one million yen of construction cost in 1985)

	Improvement	Pavement	Bridge	Repair	Earthwork	Other Works
Gravel and crushed stone	89	151	11	62	50	50
Paving material	12	433	4	323	1	1
Cement and cement products	709	198	312	364	708	440
Iron and steel	187	69	865	95	93	328
Metal and metal products	34	30	569	59	70	194
Other products	98	103	41	126	106	115
Machinery	9	1	2	3	12	41
Electric power and self-power generation	110	121	157	143	28	54
Gas Supply	10	11	8	13	11	13
Transportation	136	129	62	139	219	141
Other sevices	56	59	42	61	51	56
Other acitivities	3	3	2	3	2	2
Total	1451	1309	2076	1389	1351	1435

Note: Dark shaded area shows the major sectors contributing to the emission

Table 4.5 Carbon emission embedded in raw material and services input for several categories of road construction works, 1990 technology assumption (kg-C per one million yen of construction cost in 1985)

	Improvement	Pavement	Bridge	Repair	Earthwork	Other Works
Gravel and crushed stone	10	24	1	10	43	13
Paving material	3	88	1	80	3	6
Cement and cement products	381	179	420	338	294	236
Iron and steel	190	112	253	123	59	114
Metal and metal products	46	68	299	81	64	159
Other products	85	122	61	85	104	125
Machinery	5	8	5	8	10	14
Electric power and self-power generation	34	37	26	37	34	31
Gas Supply	1	1	1	1	1	1
Transportation	18	29	19	29	28	21
Other sevices	50	59	41	64	63	81
Other acitivities	10	11	7	11	13	12
Total	832	738	1134	865	715	814

Note: Dark shaded area shows the major sectors contributing to the emission

Table 4.6 Carbon emission change during 1975-1990 by several categories of road construction works (kg-C per one million yen of construction cost in 1985)

	Improvement	Pavement	Bridge	Repair	Earth Work	Other Works
Gravel and crushed stone	-79	-127	-11	-52	-8	-37
Paving material	-9	-345	-3	-243	2	5
Cement and cement products	-328	-19	108	-26	-414	-204
Iron and steel	4	43	-612	28	-34	-214
Metal and metal products	12	38	-270	22	-6	-35
Other products	-13	19	20	-41	-3	10
Machinery	-3	7	2	5	-2	-26
Electric power and self-power generation	-76	-84	-130	-106	6	-23
Gas Supply	-9	-10	-7	-12	-10	-13
Transportation	-118	-101	-43	-111	-191	-120
Other sevices	-6	0	-1	3	12	25
Other acitivities	7	8	6	8	11	10
Total	-619	-571	-942	-524	-636	-621

Note: Dark shaded area shows the major reduction of emission, light shaded area shows the major increase in emission share.

4.2 Sources of Changes in Carbon Emission Intensities of Road Construction Work

Major sources of carbon emission were classified as

1) Construction Technology Effect

This source of change is caused by change in construction technology. The technology change in road construction can be expressed by the change in resource input needed for the construction.

2) Economy's Technology Effect

This source of change is owing to technology change in other sectors. The change can be expressed as a change in the hybrid input-output technical coefficient matrix.

The result of decomposition based on the equation 3.5 is shown in Table 4.7 and Fig. 4.2. The emission change caused by construction technology change was disaggregated further into change of direct emission at construction site and indirect emission change caused by input selection change, using equation 4.2 and 4.3.

$$\boldsymbol{E_d} = \Delta \boldsymbol{Y} \tag{4.2}$$

$$\boldsymbol{E_{ind}} = \left\{ \left(\frac{\boldsymbol{B_1} + \boldsymbol{B_2}}{2} \right) - \boldsymbol{I} \right\} \Delta \boldsymbol{Y} \tag{4.3}$$

The amount of life cycle emission from various road construction works in Japan is estimated by applying hybrid input-output model with technology assumption. All selected construction works revealed considerable reduction in carbon emission per one unit of construction.

Table 4.7 Emission changes due to construction technology change and economic technology change (kg-C per one million yen of construction cost in 1985)

		Improvement	Pavement	Bridge	Repair	Earthwork	Other Works
Construction technology change	Direct emission at site change	-6	24	11	-21	-21	9
	Indirect change in final demand	-462	-128	-406	-72	-520	-367
	Subtotal	-468	-105	-395	-93	-541	-358
Other changes (Economy change)	Subtotal	-150	-467	-547	-431	-96	-263
Total change		-618	-571	-941	-524	-636	-621

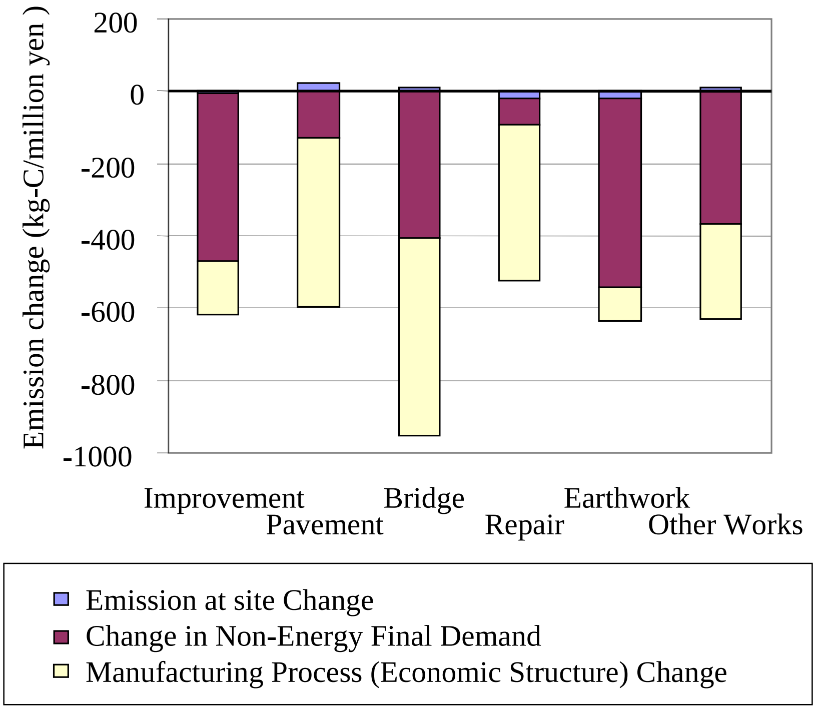

Fig. 4.2 Decomposition of Emission Change due to Road Construction Technology Change and Change Caused by the Economy's Technology Change

The structural decomposition analysis was carried out to reveal the major force driving behind the emission change. It was found that the major driving forces behind the emission change in each road construction category are different (Fig. 4.2). Emission at construction site is very little comparing with indirect emission (Table 4.3-4.4) and contribute very small share in emission change (Fig. 4.2). Road improvement, earthwork, and other construction works showed emission change mainly from final demand change while pavement construction, bridge construction, and road repair shows major change resulted from economy change.

5. Comparative Analysis of Life Cycle Emission of Transport Systems

5.1 A Comparative Analysis of Expressway System and High-Speed Railway System

The Tohoku expressway system and Tohoku high-speed railway system in Japan (hereafter called Shinkansen) are chosen as a case study. There are two problems in comparing between both transport systems.

1. Both systems serve has similar function but not the same. The expressway serves both freight and passenger transport while the high-speed railway serves only passenger transport.
2. The scale of the both systems is similar but not the same in scale of construction and traffic.

Table 5.1 shows the share of traffic on the expressway. It could be seen that freight traffic is dominant. The amount of emission from the initial construction work of the expressway is allocated based on traffic volume. The emission from the maintenance work of the expressway such as pavement should essentially be allocated based on the damage to the pavement. However, because an expressway have to maintain high quality of service, the maintenance cost of expressway in Japan is not necessary to reflect the damage of pavement. In this study, we allocated the emission from the maintenance of expressway by the traffic volume. The life cycle emission from both systems are summarized in Table 5.2-5.3.

Table 5.1 Share of Traffic on Tohoku Expressway

Vehicle Type	Percentage of traffic	
Passenger car		41.73
Bus		2.22
Truck		56.05
Light weight truck	(13.12)	
Heavy weight truck	(42.93)	
Total		100.00

Table 5.2 The Amount of Carbon Emission from Tohoku Shinkansen

Item	Million ton-C
Construction	3.90
Production of coach	0.68
Rail maintenance	1.45
Coach maintenance	0.42
Office maintenance	1.23
Electricity (operation)	3.16
Total	10.84

Table 5.3 The Amount of Carbon Emission from Tohoku expressway

Item	Million ton-C
Construction	0.96
Production of car	1.53
Expressway maintenance	0.11
Gasoline (combustion)	10.85
Total	13.46

Considering the function of both systems to serve the passenger transportation, the unit of the passenger-km is selected for comparison. Fig 5.1 shows the amount of emission from both existing systems in time. It is just the fact that the existing Tohoku expressway project would emit more emission than existing Tohoku Shinkansen project after 30.4 years. We should be careful to make any justification because both systems have different in construction scale and traffic. Fig. 5.2 shows that the expressway system would emit more emission than the Shinkansen system after about 164,000 million of passenger-km.

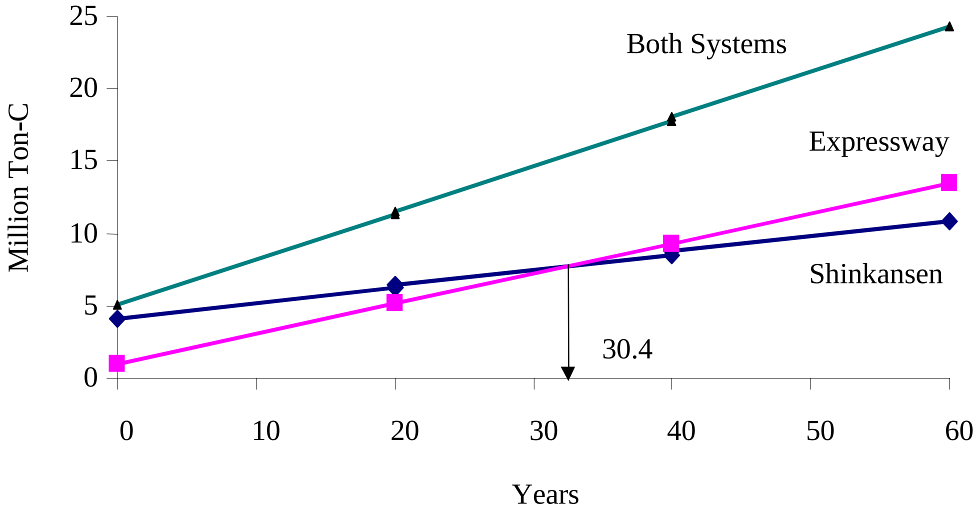

Fig. 5.1. The Emission from Existing Tohoku Expressway and Tohoku Shinkansen by Time

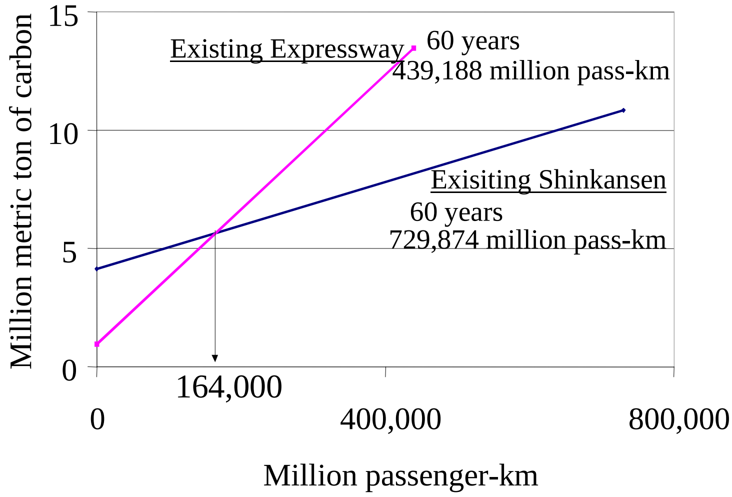

Fig. 5.2. The Emission from Tohoku Expressway and Tohoku Shinkansen by Passenger-Km

5.2 Effects of the System Expansion

Both systems are still at different scale. Tohoku expressway system will serve about 440,000 million passenger-km during its lifetime, while the Tohoku Shinkansen system will serve 730,000 million passenger-km. In Fig. 5.3, we expanded both systems to serve the same level of passenger-km while maintaining the project life to be the same (60 years). Suppose, the Tohoku Shinkansen system would not be constructed, all Shinkansen passengers would shift to the Tohoku Expressway, while we should expand the expressway to be able to serve the increased passenger traffic, and vice versa. The constant return to scale is assumed in the paper. That is, more number of passengers implies more initial investment in construction and maintenance of the project.

In order to meet with the summed up traffic demand for its life cycle, the Shinkansen is required to expand its scale to 1.6 times while the expressway has to expand its scale to 2.67 times. The extended system can be plotted as the shifted line of the existing system due to the additional initial investment. The slopes of the amount of emission from the systems are constant because of the constant unit emission per passenger-km in operation phase. Table 5.4 summarizes the analysis scenarios. As illustrated in Fig. 5.4, the Shinkansen system would give less carbon emission than the expressway system after more than about 2.1×10^{11} passenger-km, or 10.8 years after the opening to service.

The benefits in term of carbon emission caused by the substitution of the expressway system by the Shinkansen system are also presented. Two questions are discussed here.

The first, the benefit substituting Shinkansen project with the expressway project is estimated as 18.4 million ton of carbon comparing with the reverse substitution.

The second comparison is the case of having both expressway and Shinkansen at current scale and having only Shinkansen with larger scale. In another words, the benefit of substituting existing expressway with the extension of Shinkansen is estimated as 6.93 million tons of carbon saved.

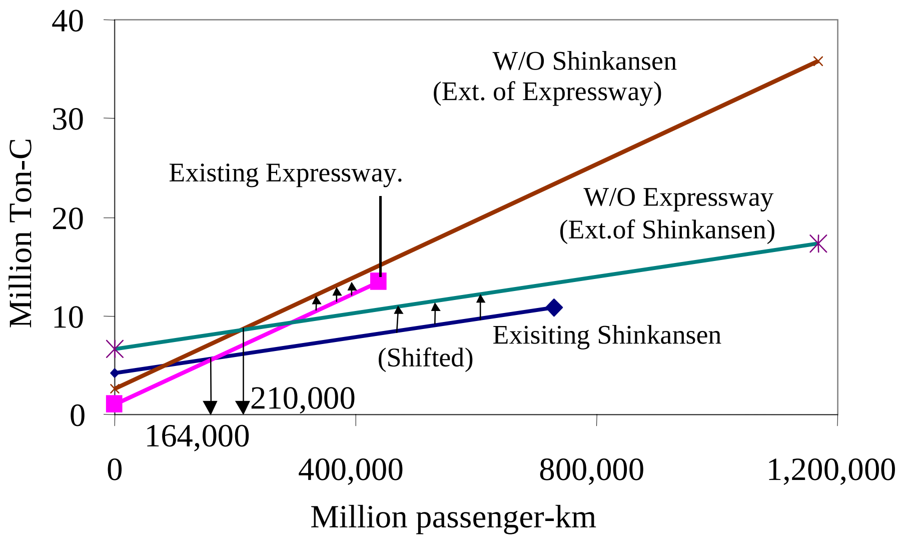

Fig. 5.3. The Extension of the Scale of Expressway System and High-Speed Railway System

Table 5.4 Summary of the analysis scenarios

		Passenger-km ($x10^{11}$)	Life cycle emission Ton-C ($x10^{6}$)	Ton-C / million pass-km (In operation phase)
Existing Shinkansen	Year = 0	0	4.12	9.21
	Year = 60	7.30	10.84	
Existing expressway	Year = 0	0	0.96	28.44
	Year = 60	4.39	13.46	
With Shinkansen&Expressway	Year = 0	0	5.09	16.43
	Year = 60	11.69	24.30	
Without Shinkansen (Extension of expressway)	Year = 0	0	2.57	28.44
	Year = 60	11.69	35.82	
Without Expressway (Extension of Shinkansen)	Year = 0	0	6.61	9.21
	Year = 60	11.69	17.37	

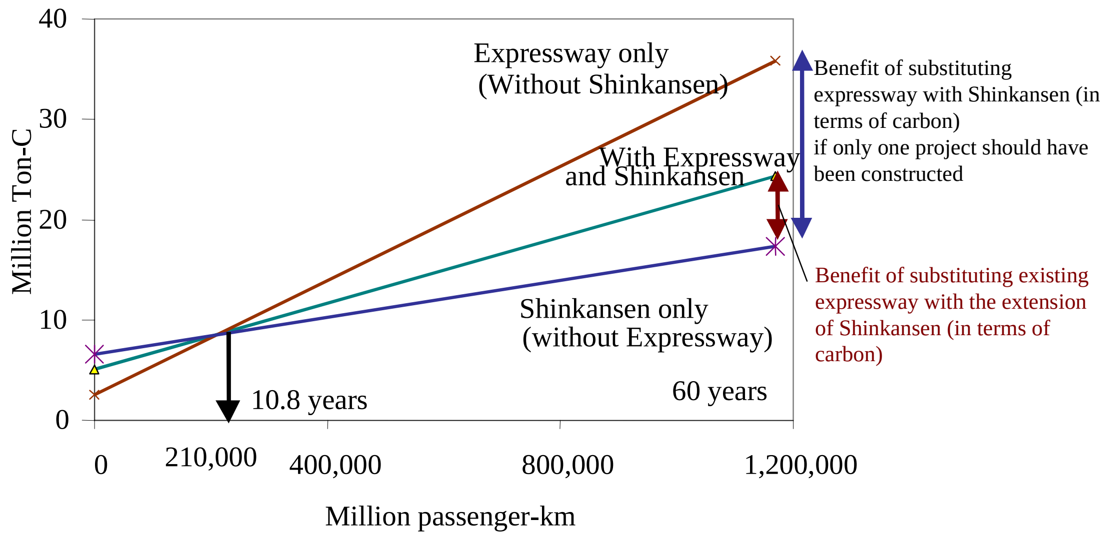

Fig. 5.4. The Benefit in Term of Carbon of Substituting Tohoku Expressway with Tohoku Shinkansen

If we consider the project at the same scale, the initial construction of Tohoku Shinkansen induced about 2.6 times of carbon emission more than the construction of Tohoku expressway. However, the carbon emission rate from the use expressway (including the emission from fuel combustion of vehicle and the emission from expressway maintenance) is about 3 times more than the use of Shinkansen at the same passenger-km unit. This provided us the analysis of the trade off between its cost of huge emission from initial construction and the benefit of saving of emission in operation phase of both system. Considering only both systems, under the assumption of current traffic level on both system and 60 years project life, the result of the analysis shown that, in the context of carbon emission, Shinkansen would regain its benefit over its initial emission about 10.8 years after the opening to the operation.

6. Conclusions

This research focused on the estimation of the amount of carbon dioxide from transport systems introducing the concept of Life Cycle emission. Because the conventional method of estimation cannot cover the indirect emissions through inter-industry network, input-output framework was introduced in this study to overcome this limitation.

The first, a hybrid I-O model was proposed for 405 sectors of Japan's economy. The model was utilized to estimate the amount of life cycle carbon emission from Tohoku expressway system in Japan. The result showed that indirect emissions from car production, expressway construction, and expressway maintenance are relatively large and significant. However, it was found that almost 90% of total emission comes from the fuel combustion in the operation stage while the emission from the production of vehicle and the emission from the facility construction accounted about 5% each. Since environmental technologies of car will be improved much in near future, the emission from the construction would relatively become important. It is worthwhile to estimate the emission from road construction in terms of life cycle carbon emission from major construction works such as bridge, pavement, earthwork, etc.

Since the amount of life cycle emission can be varied by many factors, the development of sensitivity analysis is necessary. The Structural Decomposition Analysis (SDA) under I-O framework was introduced in chapter 2. The model was applied to a case study to decompose the source of change in carbon emission intensity of various road construction works in Japan during 1975-1990. It was found that during the period of study the emission intensities decreased about 40% in all road construction categories. We could be able to clarify the major source of emission intensity change in each construction category.

The model developed can be used to estimate the amount of emission from any transport systems. In case of similar system, it may not be difficult to justify. However, in case of different transport systems that have different functions and scale, they cannot be compared directly. Chapter 5 provided the framework to for the comparison of environmental load in term of carbon emission between different transport systems. The comparison between Tohoku expressway and Tohoku Shinkansen was picked up as a case study. Considering both systems, Tohoku Shinkansen would regained its benefit over its initial emission in 11 years after the opening to service. The benefit in term of carbon emission saved if Tohoku expressway would had been substituted by the extension of Tohoku Shinkansen was also estimated.

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