CO₂ Emission from the Rail and Road Transport using Input-Output Analysis: an Application to South Korea

Phirada Pruittichaiwiboon¹, Cheul-Kyu Lee^{1†}, Kun-Mo Lee²

¹Korea Railroad Research Institute, Suwon 437-757, Korea

²School of Environmental, Civil and Transportation, Ajou University, Suwon 443-749, Korea

Abstract

This paper deals with the evaluation of environmental impact of rail and road transport in South Korea. A framework of energy input-output analysis is employed to estimate the total energy consumption and CO₂ emission in acquiring and using a life cycle of passenger and freight transport activity. The reliability of CO₂ emission based on uncertainty values is assessed by means of a Monte Carlo simulation. The results show that on a passenger-kilometers basis, passenger roads have life cycle emissions about 1.5 times those of rail, while that ratio is ten times greater when the scope of evaluation regards the tailpipe. In the case of freight transport, on a million ton-kilometers basis, the value for road mode is estimated to be about three times compared to those of rail mode. The results also show that the main contribution of CO₂ emission for road transport is the operation stage, accounting for 70%; however, the main contribution for rail transport is the construction and supply chain stage, accounting for over 50% emission.

Keywords: CO₂ emission, Input-output analysis, Transport sector

1. Introduction

In order to provide a clear and complete picture of energy consumption and greenhouse gas (GHG) emission for rail and road transport, activities related to energy-GHG from the supply chains of both systems should be evaluated. Life cycle assessment (LCA) is an acceptable tool for performing this assessment. This method requires specific and detailed data on target product or service from cradle to grave. Since rail and road transport are composed largely of parts, materials and processing, it is not an easy task to gather all data. To cope with this problem, input-output analysis, which is the only method and database now available for calculating life cycle energy and GHG emission of transportation in a consistent and integrated way, is applied. Miller and Blair [1] stated that the fundamental information used in the input-output table deals with national economic activity representing the flow of products from each industrial sector to each sector, itself and others. The contributions of many researchers have extended the input-output framework incrementally in the direction of employing physical units particularly material and energy flows. Yoshida et al. [2] applied an input-output table for the estimated life cycle of CO₂ emission intensity of a specific passenger car. Lenzen and Treloar [3] employs an extended input-output framework to estimate and compare an embodied energy in building material of wood and concrete. Nakamura and Kondo [4] evaluated the alternative waste man-

agement for the recycling of end-of-life electrical home appliances using input-output and life cycle cost analyses. Facanha and Horvath [5] combined the economic input-output approach and the process LCA approach to assess the environmental load of freight transport in the USA. Crawford [6] applied input-output analysis to quantify embodied CO₂ of timber and reinforced concrete railway sleepers. Acquaye and Duffy [7] estimated the energy and GHG emission intensities of Irish construction and its subsectors using the input-output analysis. Currently, with regards to work, the environmental burden of the transport supply chain can be estimated by applying the merits of input-output analysis.

The objective of this paper is to investigate the net energy consumption and GHG emission of passenger and freight on rail and road transport. Input-output analysis is the approach of this work. In order to increase the reliability of the results, uncertainty analysis using a Monte Carlo simulation was performed.

2. Methods

2.1. Goal and Scope of the Study

The goal of this study was to evaluate the energy and GHG emission of Korea's rail and road transportation economic activities. The scope includes energy production, supply chain activ-

© This is an Open Access article distributed under the terms of the Creative Commons Attribution Non-Commercial License (<http://creativecommons.org/licenses/by-nc/3.0/>) which permits unrestricted non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.

Received September 10, 2010 Accepted February 23, 2012

[†]Corresponding Author

E-mail: cheul@krri.re.kr

Tel: +82-31-460-5372 Fax: +82-31-460-5359

ity and transportation activity. End of life management was not included due to lack of sufficient technical data. The function of transport was to deliver passengers and goods from the origin to its destination. The economic activities of rail and road transportation of the year 2005, including passenger and freight traffic volume, were set as the functional unit of energy and CO₂ emission calculation.

2.2. Data Source

Calculations of this study were based on primary data for the year 2005 from: 1) energy balance report surveyed by the Korea Energy Economics Institute (KEEI), 2) conventional input-output table prepared by the Bank of Korea (BOK), 3) passenger and freight revenue investigated by the Korea Railroad Research Institute (KRRI), and 4) traffic volume including driving statistics for private and public transport collected by the KEEI.

2.3. Embodied Energy Estimation

Embodied energy is the sum of direct and indirect energy. Direct energy is the amount of energy required to process an industrial activity, while indirect energy is defined as the amount of energy required to operate a given energy production system. To be able to estimate the embodied energy of the transport sector, including its supply chain, through the energy input-output approach, the following procedure is proposed. A basic energy input-output table, in which the transaction number between row and column identifies the energy value of output from the i^{th} row which is used as input to the j^{th} column, is first developed. Ton of oil equivalent (TOE) is the unit in the table. From this table, two forms of normalization energy matrices are established. G^* is the energy normalization matrix of dimensions (12×12) , in which each element expresses a proportion of the energy input per total energy output. E is a $(12 \times n)$ matrix that represents a hybrid unit for which, energy consumption of each industrial sector is normalized by its economic value. Moreover, n is the number of supply chain sectors ($n = 10$ for this paper). The total required economic purchase in all of the supply chain of the transport sector is determined using the Leontief formula i.e., $(I-A)^{-1}F$ where I is the identity matrix, A^* is the direct input coefficient matrix, and F is the vector of desired output. Therefore, the direct energy required by an industry that is processing for the

transport sector is calculated from $E(I-A)^{-1}F$. The term $IG^*E(I-A)^{-1}F$ represents the first level amount of energy to be processed by the energy production system. The infinite series of the energy supply chain can be acquired using the $(I-G^*)^{-1}$ term. So, $(I-G^*)^{-1}E(I-A)^{-1}F$ is a model for estimation of the total energy output required throughout the energy production system. Indirect energy is derived from the difference between total and direct energy.

2.4. Embodied CO₂ Estimation

The calculation of energy consumption through direct and indirect ways enabled us to evaluate a vector of embodied CO₂. By doing so, the energy output was multiplied by a vector of CO₂ equivalent per TOE unit of each fuel. The emission factors of CO₂, CH₄, and N₂O for CO₂ equivalent (eq.) for each fuel type mainly refers to the 2006 Intergovernmental Panel on Climate Change (IPCC) guidelines regarding stationary and mobility combustion. To be able to calculate the equivalent of CO₂, the global warming potentials (GWP₁₀₀) factors for characterizing the climate gases of CH₄ and N₂O were identified. IPCC [8], the GWP₁₀₀ factors applied in this study were 21 and 310 kg CO₂/kg, respectively. The factors used for greenhouse gas emission are presented in Table 1.

Furthermore, the energy conversion factors developed by KEEI [9, 10], were used to convert the mass unit of TOE to the energy unit of Joule equivalent. Then, the fuel or energy consumption in the TOE unit was easily computed to determine greenhouse emissions.

2.5. Productiveness Condition

The most important implication and requirement for conducting the input-output analysis was that all minor principals of determinant $(I-A^*)$ and $(I-G^*)$ have to be positive. The $(I-G^*)^{-1}$ and $(I-A^*)^{-1}$, called the Leontief inverse matrix, used in this study have met this requirement.

3. Application and Results

3.1. Analysis of Energy Consumption

The life cycle stage of the transport sector was divided into six main categories: 1) energy production, 2) raw material extrac-

Table 1. CO₂ equivalent factor (kg CO₂-equivalent per terajoule [TJ])

Fuel and energy type	Application industry					
	Stationary combustion		Mobility combustion			
	Energy	Manufacturing and construction	Rail	Road	Marine	Aviation
Coal	98,786	98,975	-	-	-	-
Crude petroleum	73,549	73,549	-	-	-	-
Natural gas	64,449	64,449	-	-	-	-
Coal product	95,086	95,275	-	-	-	-
Fuel oil	74,349	74,349	83,053.15	75,390.9	70,067	69,930.5
LPG	63,152	63,152	-	64,464	-	-
Naphtha	73,549	73,549	-	-	-	-

Fig. 1. Direct and indirect energy consumed by rail and road transport. a: raw material extraction, b: petrochemical product (processing base), c: petrochemical product (material base), d: non-metallic product, e: basic metal (processing base), f: basic metal (material base), g: textile, wood and pulp product, h: fabricated metal, i: manufacturing, j: construction, k: operation.

tion, 3) material preparation of petrochemical product, non-metallic metal, basic metal, textile and pulp product and fabricated metal, 4) vehicle manufacturing, 5) construction of transport facility such as bridge, and 6) operation. For this study, however, the amount of energy consumed during the energy production stage was expressed as the indirect energy for each life cycle stage. Fig. 1 identifies the quantitative relations between direct and indirect energy in line with the life cycle stage of transportation.

Indirect energy is of little significance in total energy consumption per year for the stage of petrochemical products (material base), basic metal (material base), manufacturing and construction. Conversely, a relatively large part of indirect energy is consumed by passenger rail operation, material preparation of fabricated metal, basic metal and textile products including raw material extraction. For example, indirect energy accounts for a large portion of consumption, i.e., 72%, of the fabricated metal preparation stage. In passenger rail operation, indirect energy accounted for 68% with respect to total requirements. Raw material extraction, textile and wood, including basic metals (processing base) accounted for 66.8%, 61%, and 55.5%, respectively. Even though direct energy in petrochemical product (processing base), non-metallic products, manufacturing, road passenger operation and road freight operation accounted for a great portion, indirect energy consumed during these stages provided a non-negligible total result. In summary, the results of this section point to the significant amount of indirect energy consumption versus direct energy consumption.

Fig. 2 presents a profile for the consumption of direct and indirect energy for rail and road modes for passenger and freight transport. These results clearly show that there was a significant

amount of energy consumption from the rail transport's supply chain and energy production activity. Energy consumption by direct or indirect activity was 0.839 and 0.974 million TOE/yr, respectively. In the case of road passengers, direct and indirect energy were 20.576 and 3.794 million TOE/yr, respectively. The direct was estimated at 0.356 million TOE/yr and indirect energy was about 0.167 million TOE/yr for rail freight transport. Road freight directly consuming energy at the point of use was 12.295 million TOE/yr and indirect energy required for delivery of goods per year was 2.915 million TOE.

In the present section, not only were the amounts of direct and indirect energy provided but also a detailed analysis regarding structural energy for both consumptions. Indeed, this was one of the advantages of the energy input-output approach developed from the current study. The type of direct energy used resulted in a significant amount and type of indirect energy at the energy production stage. For instance, as can be seen in Fig. 2, 0.11 million TOE of fuel oil and 0.21 million TOE of electricity were used to operate passenger rail transport per year. To deliver this amount of energy, approximately 0.67 million TOE was processed and converted by the energy production system. Of these, 0.24 million TOE of coal, 0.01 of crude petroleum, 0.08 of natural gas, 0.27 nuclear, 0.01 of renewable energy, 0.03 of fuel oil, and 0.02 of other energy sources are required. Likewise, freight rail transport was estimated to be using 0.17 million TOE of fuel oil and 0.01 million TOE of electricity in its operation. Calculation results showed that 0.07 million TOE was required for energy production. Passenger road transport consumed 13.291, 4.859, and 0.339 million TOE of fuel oil, other petroleum products (liquefied petroleum gas, LPG) and gas, respectively, for its operation per year. According to these requirements, this model

Fig. 2. Life cycle energy consumption for rail and road passenger and freight transport. TOE: ton of oil equivalent. a: raw material extraction, b: petrochemical product (processing base), c: petrochemical product (material base), d: non-metallic product, e: basic metal (processing base), f: basic metal (material base), g: textile, wood and pulp product, h: fabricated metal, i: manufacturing, j: construction, k: operation.

reports that 0.172, 1.179, 0.414, 0.192, 0.317, and 0.289 million TOE of coal, crude petroleum, natural gas, nuclear, non-fuel oil and other energy sources, respectively, were consumed for operation for energy production. Considering the dimension of direct energy choice from other life cycle stages, for example, for the fabricated metals preparation stage and manufacturing stage, the requirement of electricity consumption for the fabricated metal sector give resulted in a great amount of indirect energy consumption at power generation, whereas the key direct energy consumption of the manufacturing stage were coal products, which require less indirect energy to produce. The results of this section attempted to demonstrate the influence of direct energy selection on indirect energy including total energy consumption. Moreover, the selection of energy strongly correlated with CO₂ emission particularly energy based fossil fuels.

3.2. Analysis of CO₂ Emission

CO₂ emission rate relates closely with energy consumption. To be able to address the environmental performance of rail and road, the total results for emission were divided by capita and traffic volume of passengers and freight transport.

Table 2 shows the result of CO₂ calculation compared to population and traffic volume for the year 2005. According to International Transport Forum (ITF) [11], the South Korean population was around 48.92 million. As recorded by KEEI [9, 10] the traffic volume for the year 2005 was 45,087.2 million passenger-kilometers (pkm) for rail and 560,363 pkm for road mode (estimated from value for private road transport of 477,146 pkm and for public road transport of 83,217 pkm). These numbers demonstrated the fact that passengers took a service of road transport greater than those of rail transport. In addition, these numbers implied that passenger prefer to use private transport rather than public transport. The traffic volume, which was expressed in million ton-kilometers (tkm) for road and rail mode, was 68,971 and 61,246 tkm, respectively.

As can be seen in Table 2, the first two rows compared the contribution of CO₂ from tailpipe and from life cycle. Note that tailpipe was a consideration of fuel consumption and its contribution on CO₂ emission at the operation stage. The difference between tailpipe and life cycle for rail transport was from 80% to 450% and from 24% to 32% for road transport. Although the majority contribution from both modes was from tailpipe, this study demonstrated the importance of CO₂ in all life cycle stages.

Passenger movement from source to destination by road mode emitted a total amount of CO₂ seventeen times that of the rail mode. Goods delivered between sources by road mode caused an emission of CO₂ 33 times greater than that of rail mode. In regards to traffic volume, total rail and road passenger emission was 67.24 and 95.685 g CO₂-eq./pkm, respectively. In other words, total road passenger emission was approximately 1.5 times larger than rail emissions on the pkm basis. Chester and Horvath [12] showed that emission was between 50-410 g CO₂/pkm for road and between 90-140 g CO₂/pkm for rail transport. Considering the freight traffic volume, road mode produced emissions 2.1 times larger than rail mode due to road mode's emitting on a 607.07 g CO₂-eq./tkm basis, while the value for rail mode was 284.67 g CO₂-eq./tkm. On a capita basis, rail mode generated 62.71 kg CO₂-eq. while road mode emitted 1,110.78 kg CO₂-eq. Prior research reported that road and rail modes emitted 78,330 and 820 million kg CO₂-eq. for the year 2005, while results for normalization per capita were 1,622.07 and 16.98 kg CO₂-eq./yr for road and rail modes [11].

4. Uncertainty Analysis

A crucial problem of energy input-output contributed to the existence of uncertainties in the utilized data. In other words,

uncertainty of data may cause a certain degree of error for energy and CO₂ evaluation. To increase the reliability of the data used, a Monte Carlo simulation procedure, performed with software called Cristal ball (Oracle, Redwood Shores, CA, USA), was used to carry out this work. The uncertainty value, described by the standard deviation divided by the mean, was a term for the communication reliability of the result. To perform the Monte Carlo simulation, input parameters had to be specified for the uncertainty distribution. The Batch Fit tool, contained in the crystal ball, was employed for best fit probability distribution regarding each piece of technical data [13]. Lognormal was the most appropriate type of distribution for the current study. The total number of trial runs performed using the Cristal Ball software was 10,000 times. Table 3 shows the distribution type, including the coefficient of variation or the uncertainty value acquired from simulation. The coefficient of variation (CV) was given by the ratio of the standard deviation to the mean IPCC [8]. The small CV indicated the less variable and more stable.

Table 3 presents the CV of CO₂ emission from each stage of the life cycle. In the case of passenger transport, the CV value of the total process by rail mode, estimated at 0.0553, was considerably small compared to the value for road mode, which was estimated at 0.0754. For freight transport, the CV value of rail and road modes yielded values of 0.0548 and 0.0801, respectively. Consideration of the uncertainty of most of the life cycle stages

Table 2. CO₂ emission analysis

Scope of evaluation	Unit	Passenger transport		Freight transport	
		Rail mode	Road mode	Rail mode	Road mode
Tailpipe	million kg CO ₂ -eq./yr	310.00	47,279.32	474.00	29,421.05
Life cycle	million kg CO ₂ -eq./yr	3,015.39	53,087.38	1,099.62	36,813.13
	kg CO ₂ -eq./capita	62.71	1,110.78	68.165	769.085
Life cycle	g CO ₂ -eq./pkm	67.24	95.685	-	-
	g CO ₂ -eq./tkm	-	-	284.67	607.07

Table 3. Coefficient of variation (CV, uncertainty) of CO₂ of passenger and freight transport

Life cycle stage	Passenger transport		Freight transport	
	Rail mode	Road mode	Rail mode	Road mode
	CV (Uncertainty)	CV (Uncertainty)	CV (Uncertainty)	CV (Uncertainty)
Raw material extraction	0.1877	0.1579	0.1864	0.1553
Petrochemical product base: processing base	0.0542	0.0532	0.0531	0.0536
Petrochemical product base: material base	0.1648	0.1043	0.1631	0.1033
Basic metal: processing base	0.0618	0.0626	0.0629	0.0629
Basic metal: materials base	0.0515	0.0527	0.0526	0.0525
Non-metallic metal	0.1971	0.1891	0.1962	0.1886
Textile, wood and pulp product	0.0557	0.0557	0.0557	0.0554
Fabricated metal	0.0657	0.0623	0.0645	0.0638
Manufacturing	0.0643	0.0632	0.0638	0.0638
Construction	0.0839	0.0881	0.0840	0.0885
Operation	0.0644	0.0802	0.0636	0.0903
Total process	0.0553	0.0754	0.0548	0.0801

Fig. 3. Distribution of embodied CO₂ induced by the passenger and freight transport.

gave small values from 0.0515 to 0.0903. The large uncertainty happened at the stage of raw material extraction, and at the preparation of the petrochemical product (material base) and the non-metallic metal stage. The uncertainty values for these stages were from 0.1886 to 0.1971 for the preparation of the non-metallic metal stage, from 0.1033 to 0.1648 for the preparation of the petrochemical product (material base) and 0.1553 to 0.1877 for the raw material extraction stage. In order to reduce the uncertainty level, the number of industrial sectors aggregated in those life cycle stages should be lessened.

Fig. 3 depicts the distribution of CO₂ emission induced by the passenger and freight transport for rail and road modes estimated from the Monte Carlo simulation. The X-dimension provides the CO₂ emission per basis. The Y-dimension shows the probability of each value of the total CO₂ emission. From Fig. 3(a-d), the certainty value ranges for a 95% certainty interval of passenger rail, passenger road, freight rail, and freight road for the year 2005 were 58.62–77.45 kg CO₂-eq./capita, 945.01–1,289.98 g CO₂-eq./capita, 55.91–69.71 kg CO₂-eq./capita, and 646.89–906.26 g CO₂-eq./pkm, respectively. Fig. 3(e-h) presents the certainty value range for a 95% certainty level of freight rail and road transport on a traffic volume basis. The CO₂ emission was 62.86–83.11 g CO₂/pkm for rail mode and 81.32–111.01 g CO₂-eq./pkm for road mode. On the basis of tkm, emission for rail and road mode were 254.06–315.29 and 509.50–716.10 g CO₂-eq.

Table 4 presents data detailing how each life cycle stage of rail and road contributed to the embodied CO₂ emission for a 95% confidence interval on capita, pkm, and tkm base. Operation stage for passenger and freight on rail and road mode accounted for a large portion of the life cycle of CO₂ emission, 47.28–48.73% for passenger rail, 88.54–88.92% of passenger road, 47.37–48.75% of freight rail and 78.88–80.14% of freight road. The construction stage accounted for 17.82–18.79% of passenger rail, 3.66–3.80% of passenger road, 17.85–18.81% of freight rail, and 6.81–6.85% of freight road. Material preparation of textile and wood products accounted for 8.80–9.37% of passenger rail, 2.24–2.46% of passenger road, 8.77–9.36% of freight rail, and 4.05–4.56% of freight road mode. Fabricated metal preparation accounted for 6.93–7.15% of passenger rail, 1.43–1.53% of passenger road, 6.93–7.14% of freight rail, and 2.56–2.80% of freight road mode. The construction phase of rail mode had large CO₂ emissions compared to the other phases of the life cycle. It should also be emphasized that the impact from construction, including other passenger rail supply chain activity, accounted for a great portion of emission, 51.27–52.72% with respect to the life cycle. The International Union of Railways (UIC) [14] reported CO₂ emissions shared by traffic infrastructure in different case studies of rail transport were 94.5% for the Switzerland-study and 65–72% for the US-study. Within this analysis, the main CO₂ emission for road was operation; however, for rail transport, the main emis-

Table 4. The 95% confidence interval of CO₂ emission

Life cycle stage	Passenger transport				Freight transport			
	Rail mode		Road mode		Rail mode		Road mode	
	kg CO ₂ -eq./capita	g CO ₂ -eq./pkm	kg CO ₂ -eq./capita	g CO ₂ -eq./pkm	kg CO ₂ -eq./capita	g CO ₂ -eq./tkm	kg CO ₂ -eq./capita	g CO ₂ -eq./tkm
Raw material extraction	0.61-1.27	0.67-1.36	0.8-1.46	0.07-0.13	0.62-1.28	2.82-5.78	0.80-1.44	0.63-1.15
Petrochemical product: processing base	0.98-1.22	1.06-1.31	4.86-5.98	0.42-0.51	0.99-1.22	4.49-5.53	6.18-7.63	4.87-6.01
Petrochemical product: material base	0.75-1.41	0.80-1.51	1.44-2.16	0.12-0.19	0.75-1.40	3.39-6.37	1.45-2.16	1.14-1.71
Non-metallic metal	2.81-3.57	3.00-3.84	10.79-13.79	0.93-1.19	2.8-3.59	12.71-16.23	13.76-17.61	10.87-13.86
Basic metal: material base	1.17-1.43	1.25-1.54	4.8-5.91	0.41-0.51	1.17-1.44	5.32-6.54	6.11-7.50	4.83-5.91
Basic metal: processing base	0.57-1.25	0.61-1.33	0.61-1.27	0.05-0.11	0.58-1.23	2.61-5.61	0.61-1.27	0.48-1.00
Textile, wood and pulp product	5.48-6.82	5.89-7.31	23.18-28.81	2.00-2.49	5.49-6.84	24.89-30.92	29.53-36.72	23.24-28.99
Fabricated metal	4.19-5.41	4.48-5.76	14.43-18.41	1.24-1.59	4.19-5.38	18.96-24.45	18.11-23.23	14.25-18.36
Manufacturing	3.05-3.92	3.27-4.18	12.65-16.19	1.09-1.40	3.05-3.91	13.86-17.81	16.03-20.55	12.65-16.19
Construction	10.47-14.53	11.2-15.62	34.75-48.92	2.98-4.22	10.47-14.58	47.68-66.30	44.03-62.10	34.56-49.07
Operation	28.54-36.62	30.63-39.35	836.7-1147.08	72.01-98.67	28.55-36.80	130.05-166.99	510.28-726.05	401.98-573.85
Total	58.62-77.45	62.86-83.11	945.01-1289.98	81.32-111.01	58.66-77.67	266.78-352.53	646.89-906.26	509.50-716.10

sion was the construction and supply chain. This result gave an idea related to previous research by UIC [14] and Hendrickson [15] which stated that although the rail mode tends to have a lower environmental impact compared to that of road mode, the environmental effects of the infrastructure and supply chain to accommodate such a shift are substantial if capacity expansion is required.

5. Conclusions

This work provided a more complete picture of energy and GHG emission for rail and road transport for the year 2005 which should enable practitioner to compare the results when the improvement regarding energy and emission performance is made. In this study, the input-output analysis and approach is used. Given the modeling approach used for the analysis, with regards to the first result, not only the amounts of direct and indirect energy were provided but a detailed analysis on structural energy for both consumptions was also given. Second, the results show that there were significant differences between tailpipe and life cycle in terms of emission analysis. In line with the comparison of total emission, rail mode generated 130.88 kg CO₂-eq. while road mode emitted 1,879.86 kg CO₂-eq. on per capita basis. In addition, on a traffic volume basis, the results showed that on a pkm basis, passenger road emitted life cycle emissions about 1.5 times greater than that of rail, while that value was ten times greater when the scope of evaluation was tailpipe. In the case of freight transport, on a tkm basis, it was estimated that road value was about three times that of rail. Moreover, the results also demonstrate that the main contribution of CO₂ emission from

road transport was in the operation stage, which accounted for 70%; however, it was the construction and supply chain stage which accounted for over 50% of the emissions concerning rail transport. This indicates that attention should also be focused on those supply chain activities having a potentially sizeable impact on CO₂ emission, particularly passenger and freight rail transport. To quantify the reliability of the CO₂ emission computation, the uncertainties of the CO₂ emission of each life cycle stage for passenger and freight transport were analyzed by means of the Monte Carlo simulation. The uncertainty values for passenger and freight on rail transport were considerably small, being 0.0553 (5.53%) and 0.0548 (5.48%), respectively. In the meantime, the uncertainty values arisen from passengers and freight road transports were 0.0754 and 0.0801.

Acknowledgments

The authors gratefully acknowledge the financial support from Korea Institute of Construction & Transportation Technology Evaluation and Planning (KICTTEP) and also from Ministry of Knowledge Economic (MKE).

References

1. Miller RE, Blair PD. Input-output analysis: foundations and extensions. 2nd ed. New York: Cambridge University press; 2009.
2. Yoshida Y, Ishitani H, Matsushashi R, et al. Reliability of LCI considering the uncertainties of energy consumptions in

- input-output analyses. *Appl. Energy* 2002;73:71-82.
3. Lenzen M, Treloar G. Embodied energy in buildings: wood versus concrete-reply to Börjesson and Gustavsson. *Energy Policy* 2002;30:249-255.
 4. Nakamura S, Kondo Y. A waste input-output life-cycle cost analysis of the recycling of end-of-life electrical home appliances. *Ecol. Econ.* 2006;57:494-506.
 5. Facanha C, Horvath A. Environmental assessment of freight transportation in the US. *Int. J. Life Cycle Ass.* 2006;11:229-239.
 6. Crawford RH. Greenhouse gas emissions embodied in reinforced concrete and timber railway sleepers. *Environ. Sci. Technol.* 2009;43:3885-3890.
 7. Acquaye AA, Duffy AP. Input-output analysis of Irish construction sector greenhouse gas emissions. *Build. Environ.* 2010;45:784-791.
 8. Intergovernmental Panel on Climate Change (IPCC). 2006 IPCC guidelines for National Greenhouse Gas Inventories. Geneva: IPCC; 2006.
 9. Korea Energy Economics Institute. Energy consumption survey. Gwacheon: Ministry of Commerce, Industry and Energy; 2005.
 10. Korea Energy Economics Institute; Ministry of Knowledge Economy. Yearbook of energy statistics. Gwacheon: Ministry of Knowledge Economy; 2008.
 11. International Transport Forum (ITF). Greenhouse gas reduction strategies in the transport sector: preliminary report. Paris: ITF; 2008.
 12. Chester MV, Horvath A. Environmental assessment of passenger transportation should include infrastructure and supply chains. *Environ. Res. Lett.* 2009;4:024008.
 13. Oracle. Crystal Ball, fusion edition: getting started guide. Redwood Shores: Oracle; 2008.
 14. The International Union of Railways (UIC). Carbon footprint of high-speed railway infrastructure (pre-study): methodology and application of high speed railway operation of European railway. Paris: UIC; 2009.
 15. Hendrickson C, Matthews HS, Cicas G. Analysis of regional supply chain economic and environmental effects of expansion of the U.S. freight-rail system [Internet]. Reston: American Society of Civil Engineers; c2006 [cited 2012 Mar 7]. Available from: http://ascelibrary.org/proceedings/resource/2/ascecp/213/40799/123_1?isAuthorized=no.