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Macro-level Methodology for Estimating Carbon Emissions, Energy Use, and Cost by Road Type and Road Life Cycle

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ABSTRACT

PURPOSES : The authors set out to estimate the related carbon emissions, energy use, and costs of the national freeways and highways in Korea. To achieve this goal, a macro-level methodology for estimating those amounts by road type, road structure type, and road life cycle was developed.

METHODS : The carbon emissions, energy use, and costs associated with roads vary according to the road type, road structure type, and road life cycle. Therefore, in this study, the road type, road structure type, and road life cycle were classified into two or three categories based on criteria determined by the authors. The unit amounts of carbon emissions and energy use per unit road length by classification were estimated using data gathered from actual road samples. The unit amounts of cost per unit road length by classification were acquired from the standard cost values provided in the 2013 road business manual. The total carbon emissions, energy use, and cost of the national freeways and highways were calculated by multiplying the road length by the corresponding unit amounts.

RESULTS : The total carbon emissions, energy use, and costs associated with the national freeways and highways in Korea were estimated by applying the estimated unit amounts and the developed method.

CONCLUSIONS : The developed method can be employed in the road planning and design stage when decision makers need to consider the impact of road construction from an environmental and economic point of view.

Keywords
carbon emissions, energy use, cost, road life cycle

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1. INTRODUCTION

Many countries have been making various and considerable efforts to protect the environment by minimizing the negative impact of global warming and climate change. Carbon dioxide (CO_2) in the atmosphere is known as a major contributing factor in global warming and climate change. An agreement was signed during the UN Climate Change Conference in Doha, Qatar (Doha COP18/CMP8, 2014) to launch a new commitment period under the Kyoto Protocol from 2013 to 2020 and to set a firm timetable to adopt a universal climate agreement by 2015.

According to the estimation from Carbon Dioxide Information Analysis Center (CDIAC, 2014) in 2010, South Korea is the world's 8th largest CO_2 emitter. Therefore, the Korean government has been taking various actions including setting 'Low Carbon, Green Growth' as a national vision. The Korean government also set a national goal of a 30% reduction in greenhouse gas (GHG) against the business as usual (BAU) projection by 2020.

In Korea, the road sector contributed about 15% of the total national GHG emissions from the energy sector in 2009 (Greenhouse Gas Inventory and Research Center of Korea, 2011). In order to make the road sector to play its own responsible role in the national sustainable green growth efforts, various green road policies were proposed and executed. Various green road technologies were encouraged to be developed as well.

To measure the effectiveness of these new policies and technologies, how much carbons are emitted in the existing conditions are needed to be known first. The method described in "A guideline on the estimation of carbon emissions for each facility type" (Ministry of Land, Infrastructure and Transport, 2011)" can be used, but this method requires various and detailed input data which can be acquired only when detailed road design is completed. In other words, this method produces more reliable estimation values, but it is not applicable in the road policy decision making or planning stage. For instance, the amount of carbon emissions from the existing roads in Korea is needed to be estimated to set the carbon reduction goal by 2020. Therefore, a method of estimating carbon emissions at the macro level needs to be developed.

This paper describes a newly developed macro level method of estimating carbon emissions, energy use, and cost by road type, road structure type, and road life cycle. It also explains how the developed methodology was applied for estimating the total amount of carbon emissions, energy use, and cost of the national freeways and highways in Korea.

2. LITERATURE REVIEW

There are some decision-making support systems developed for evaluating road projects in a view of sustainability. REAP (Resources and Energy Analysis Programme) created by the Stockholm Environment Institute is one of those . It is software used by local, regional, and national governments in the UK to analyze potential environmental impacts of policies and to monitor the actual impact of policies over time (Stockholm Environment Institute, 2008). REAP helps policy makers to measure the environmental pressures caused by human consumption in a wide range of policy areas including transport, housing and planning by generating indicators on: carbon dioxide and greenhouse gas emissions measured in tonnes per capita, the ecological footprint required to sustain an area in global hectares per capita, and the material flows of products and services through an area measured in thousands of tonnes. HDM-4 (Highway Development & Management) developed by the World Bank includes a road investment appraisal method. It provides a system for road management, programming road works, estimating funding requirements, budget allocations, predicting road network performance, project appraisal, and policy impact studies (HDM Global, 2014). US FHWA developed INVEST (Infrastructure Voluntary Evaluation Sustainability Tool) as a practical web-based tool to help transportation agencies voluntarily evaluate the sustainability of their road projects (US FHWA, 2014).

Studies on calculating carbon emissions across a road life cycle have increased. The methodologies developed by these studies are also known as Carbon Footprint (CFP) tool, which calculate carbon emissions during road construction stage and carbon amounts constantly emitted during maintenance and operation stages after construction. During construction and maintenance stages, carbon emissions are calculated based on the amounts of materials and equipments used during the construction and maintenance works. In operation stage, they're calculated based on the amounts of electricity and fuel consumed for the operating road facilities. The World Bank compared 12 existing CFP tools and reported that the most of the tools were never used in Asia and have poor applicability to other regions. The report also reported that six tools including the Australian Victoria State tool (VicRoads), the Highways Agency Carbon tool, the Technical University of Denmark tool (Road-Res), the IRF GHG calculator (CHANGER), the EGIS infrastructure carbon tool, and the LCPC tool (Ecorce) acquired higher score than the average score in their evaluation (The Word Bank Group Asia, 2011).

Among these CFP tools, ROADEO (The Word Bank Group

Asia, 2011) has two level evaluation methods. One level has a function to estimate carbon emissions when precise volumes of materials and equipment types and usages are available. The other level has a function to estimate carbon emissions based on the overall project information like the type of road, number of lanes, and the length of road section by type of road structures. Currently, ROADEO covers road construction stage only.

The estimation method developed in this study has similar concept with the ROADEO's in the fact that the method is based on the overall project information, but it covers not only carbon emissions but also energy use and cost in the road construction stage as well as maintenance and operation stages. Most importantly, the method developed in this study has better applicability in that the method reflects the regional characteristics of the road works in Korea because the unit amounts of carbon emissions and energy use per unit road length used in the developed method were estimated based on the data gathered from actual road construction, maintenance, and operation work samples in Korea.

3. METHODOLOGY

The amounts of carbon emissions, energy use, and cost of roads vary according to the road type, road structure type, and road life cycle.

Therefore, the road type, road structure type, and road life cycle were classified into two (national freeways and national highways), three (basic earth work, bridge, and tunnel), and three (construction, management, and operation) categories, respectively.

Unit amounts of carbon emissions and energy use per unit road length by the road classification were estimated using the data gathered from actual road work samples. Unit amounts of cost per unit road length by the classification were acquired from the standard cost values provided in the 2013 road business manual (Ministry of Land, Infrastructure and Transport, 2013).

3.1. Estimating Unit Amounts of Carbon Emissions and Energy use

(1) Road Construction Stage

In order to estimate the amounts of carbon emissions and energy use in the construction stage, the amounts of the materials, material transportations, and equipment uses applied in road construction were counted. For this, the following types of data were gathered : detail statement of design, breakdown cost table, unit price statement, equipment use statement, and required resource table.

About a half of Korean roads (70% of national freeways and 40% of national highways) are four-lane roads. Furthermore, almost all roads newly constructed for the recent decade are four-lane roads in both road types. Therefore, four-lane road

Table 1. Carbon Emissions and Energy Use of the Selected Construction Cases

Road Class/Construction Site			Length (km)			Carbon Emissions (tCO_2-eq.)			Energy Consumption (TOE)		
			Basic Earthwork	Bridge	Tunnel	Basic Earthwork	Bridge	Tunnel	Basic Earthwork	Bridge	Tunnel
National Freeway	F1	Busan 2 (4.06 km)	1.33	1.41	1.32	3,341.43	17,341.56	19,275.74	948.6	581.5	2,573.1
	F2	Busan 7 (4.76 km)	1.86	2.90	–	3,546.31	18,548.08	–	1,083.4	851.6	–
	F3	Busan 9 (7.42 km)	0.28	–	7.14	5,923.04	–	65,455.02	162.4	–	9,391.0
	F4	Sangju-Yeongdeok (1.60 km)	1.14	0.46	–	7,874.31	16,041.55	–	1,222.7	258.4	–
	F5	88 highway (13.0 km)	7.75	3.88	1.37	13,647.10	49,479.70	51,769.44	1,441.1	894.9	1,821.4
	Subtotal		12.36	8.65	9.83	34,332.19	101,410.89	136,500.20	4,858.2	2,586.4	13,785.5
	Average (Unit Amount)		–	–	–	2,778.81	11,717.03	13,883.26	393.22	298.84	1,402.11
National Highway	H1	Yongwol-Banglim (11.16 km)	8.57	0.84	1.75	25,276.22	14,582.32	32,065.75	2,273.9	358.8	795.1
	H2	Daesan-Seokmun (13.86 km)	11.86	1.47	0.53	43,957.16	27,745.05	11,993.84	3,641.7	272.7	422.3
	H3	Boyeong-Taean (6.14 km)	4.39	1.75	–	23,145.50	9,038.37	–	511.4	141.6	–
	H4	Seorak-Cheongpyeong (3.90 km)	2.16	0.82	0.92	1,399.85	5,319.72	7,611.69	323.7	221.6	402.7
	H5	Singi-Miro (6.50 km)	1.34	1.61	3.55	5,176.71	36,573.65	65,276.57	518.6	1,754.0	3,435.9
	Subtotal		28.32	6.49	6.75	98,955.44	93,259.10	116,947.85	7,269.3	2,748.7	5,056.0
	Average (Unit Amount)		–	–	–	3,493.70	14,385.02	17,325.61	256.65	423.97	749.05

construction samples as shown in Table 1 were selected for the estimation of the unit amount of carbon emissions and energy use.

• Unit amount of carbon emissions

For the estimation of the average carbon emissions per kilometer (unit amount of carbon emissions), the total amount of carbon emissions for each selected road construction site were calculated first according to the carbon emission calculation guideline (Korea Society for the Construction Advancement, 2013). The carbon emission subtotals by road type and road structure type were divided by the corresponding road length subtotal to calculate the unit amount of carbon emissions per kilometer. Table 1 shows the calculation summary for the selected five national freeways and five national highways.

• Unit amount of energy use

Unit amount of energy use per kilometer were estimated using the similar way as the case of calculating unit amount of carbon emissions. Various types of energy sources such as gasoline, diesel, electricity, etc. are used for road construction. To unified the energy unit, all the energy consumptions are expressed in TOE (Tonnage of Oil Equivalent). Table 1 summarizes the calculation results of energy uses.

(2) Road Maintenance Stage

For estimation of carbon emissions and energy use in the maintenance stage, the same types of data as in the construction stage like detailed work statement containing the quantity of construction materials and equipments used in repair or replacement works were collected and analyzed.

For this study, the recent two years (2012-2013) of field data regarding all the maintenance works conducted for national highways in Gyeonggi-Do province were gathered. Using this data, the total amounts of carbon emissions and energy use by road structure type were calculated. Then, these values were divided by the corresponding road structure length and the time periods considered in the analyses (two years) to calculate the unit amount of carbon emissions and energy use per kilometer. It should be noticed that the road lengths applied in the analyses were not the lengths of maintenance work conducted but the total length subject to be maintained in Gyeonggi-Do province. The estimation results of the average carbon emissions and energy consumption per kilometer are shown in Table 2.

Table 2. Average Carbon Emissions and Energy Consumption Per Kilometer (Maintenance Stage)

Road Class/Maintenance Site		Length (Lane*km)			Carbon Emissions (tCO_2-eq.)/year			Energy Consumption(TOE)/year		
		Basic Earthwork	Bridge	Tunnel	Basic Earthwork	Bridge	Tunnel	Basic Earthwork	Bridge	Tunnel
National Highway	Gyeonggi-Do	3184.60	232.97	48.57	970.002	206.306	15.837	340.301	66.499	5.105
	Average (Unit Amount) per km	-	-	-	1.22	3.54	1.30	0.39	1.14	0.42

Table 3. Carbon Emissions and Energy Use of the Selected Operation Cases

Road Class/Fuel Type		Average Fuel Use between 2008 and 2009 (Unit/yr)			Average Carbon Emissions between 2008 and 2009 (tCO_2-eq./yr)			Energy Consumption (TOE)			Length (km)		
		Basic Earthwork	Bridge	Tunnel	Basic Earthwork	Bridge	Tunnel	Basic Earthwork	Bridge	Tunnel	Basic Earthwork	Bridge	Tunnel
National Freeway	Kerosene (L)	77,722	–	–	196	–	–	63.18	–	–	58.7	15.1	6.9
	LPG (kg)	1,546	–	–	5	–	–	1.61	–	–			
	Diesel (L)	107,707	27,715	12,582	287	74	34	92.51	23.85	10.96			
	Gasoline (L)	3,181	819	372	7	2	1	2.26	0.64	0.32			
	Electricity (kWh)	2,398,299	18,053	8,046,885	1,126	8	3,775	362.94	2.58	1216.79			
	Subtotal	–	–	–	1,621	84	3,809	522.50	27.08	1227.75			
	Average (Unit Amount)	–	–	–	27.61	5.56	552.03	8.90	1.79	177.94	–	–	–

(3) Road Operation Stage

In road operation stage, the total amount of carbon emissions and energy use related to road operation including tollgates, business offices, warehouses, petrol cars, cameras, fans, lights, electronic signage boards, etc. were considered. In this study, two years (2008-2009) of field data from 80.6 km long national freeways in Choongcheung-Do province were acquired and analyzed.

• Unit amount of carbon emissions

Table 3 shows the fuel use by road structure type. The amount of carbon emissions were calculated by multiplying the amount of energy consumption and corresponding carbon emission factors by fuel type in IPCC Guideline (IPCC, 2006). Carbon emissions subtotals by road structure type were divided by the corresponding road length subtotal to calculate the unit amount of carbon emissions per kilometer. Table 3 summarizes the calculation results.

• Unit amount of energy use

Energy use was calculated by multiplying the amount of fuel consumption and corresponding caloric value by fuel type. The resulting unit amount of energy use are presented in Table 3.

3.2. Unit Amounts of Cost

The Korean government calculates average construction, operation, and maintenance cost per kilometer for each work type every year based on the recent four or five years of field data. This study adopted most recent values from "Road Business Manual 2013" (Ministry of Land, Infrastructure and Transport, 2013) as shown in Table 4.

Table 4. Average Construction, Operation, and Maintenance Cost Per Kilometer

Road Class/ Life Cycle		Average Cost (100 million won/km)		
		Basic Earthwork	Bridge	Tunnel
National Freeway	Construction	245	555	260
	Maintenance	0.97	0.97	0.97
	Operation	0.08	1.04	0.03
National Highway	Construction	113	500	311
	Maintenance	0.19	0.19	0.19
	Operation	0.08	1.04	0.03

3.3. Method of Estimating Carbon Emissions, Energy Consumption, and Cost Using the Unit Values

Table 5 summarizes the estimated unit amount of carbon emissions, energy use, and cost by road type, road structure, and road life cycle which are also shown in Table 1 through 4. For the operation stage, due to the lack of applicable data, unit amounts of carbon emissions and energy use are estimated for only National freeways. It was assumed that the unit amounts of carbon emissions and energy use for National highways are similar to National freeways.

The amount of carbon emissions, energy consumption, and cost in the construction and maintenance stage is proportional to road width while that is not the case in the operation stage. Because the unit amounts shown in Table 5 are based on the four-lane roads data, the amount of carbon emissions due to the construction and maintenance work for a road can be estimated by using the ratio of the width of the subject road to the width of the four-lane road as shown in Equations (1) and (2). The amount

Table 5. Unit Amount of Carbon Emissions, Energy Use, and Cost

Road Class/ Life Cycle		Carbon Emissions (tCO_2-eq./km)			Energy Consumption (TOE/km)			Average Cost (100 million won/km)		
		Basic Earthwork	Bridge	Tunnel	Basic Earthwork	Bridge	Tunnel	Basic Earthwork	Bridge	Tunnel
National Freeway	Construction	2,778.81	11,717.03	13,883.26	393.22	298.84	1,402.11	245	555	260
	Maintenance	1.22	3.54	1.30	0.39	1.14	0.42	0.97	0.97	0.97
	Operation	27.61	5.56	552.03	8.90	1.79	177.94	0.08	1.04	0.03
National Highway	Construction	3,493.70	14,385.02	17,325.61	256.65	423.97	749.05	113	500	311
	Maintenance	1.22	3.54	1.30	0.39	1.14	0.42	0.19	0.19	0.19
	Operation	27.61	5.56	552.03	8.90	1.79	177.94	0.08	1.04	0.03

of carbon emissions in operation stage can be estimated using Equation (3). The energy consumption and cost for a road also can be estimated using these equations.

$$C_{xyc} = L \times (W / W_4) \times U_{xyc} \quad (1)$$

$$C_{xym} = L \times (W / W_4) \times U_{xym} \quad (2)$$

$$C_{xyo} = L \times U_{xyo} \quad (3)$$

where,

C_{xyc} = amount of carbon Emissions from road type , road structure type y in construction stage (tCO_2-eq.),

C_{xym} = amount of carbon Emissions from road type , road structure type y in maintenance stage (tCO_2-eq./yr),

C_{xyo} = amount of carbon Emissions from road type , road structure type y in operation stage (tCO_2-eq./yr),

U_{xyc} = unit amount of carbon emissions per kilometer for road type , road structure type y in construction stage (tCO_2-eq./km),

U_{xym} = unit amount of carbon emissions per kilometer per year for road type , road structure type y in maintenance stage (tCO_2-eq./km/yr),

U_{xyo} = unit amount of carbon emissions per kilometer per year for road type , road structure type y in operation stage (tCO_2-eq./km/yr).

L = road length (km),

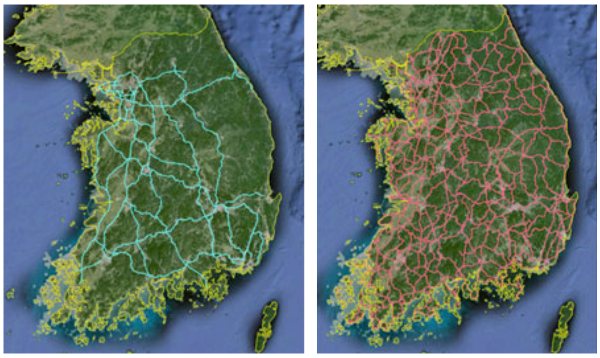
W = road width with n lanes (m),

W_4 = road width with four lanes (20.4m if national freeway or 17.5m if national highway),

4. CASE STUDY

The purpose of the case study was estimating carbon emissions, energy use, and cost of the existing national freeways and highways in Korea. Figure 1 depicts the national freeways and highways in Korea. The total length of the national freeways and highways are about 4,111km and 13,842km, respectively in 2014.

The road information was extracted from the road network data in the Korean Highway Management System (Ministry of Land, Infrastructure, and Transport, 2014). Every road in the road network are divided into many links (segments) according to its characteristics such as directions, road structure type, number of lanes, etc. The link characteristics such as road type, road structure, length, number of lanes by direction, etc. are stored in the road information database. The amount of carbon emissions, energy use, and cost of each link in the network were estimated using the proposed method and the information in the database.



(a) National Freeway (b) National Highway

Fig. 1 National Freeway and National Highway Systems in Korea

5. RESULTS

Table 6 presents the estimated carbon emissions, energy use, and cost of the existing national freeways and highways in Korea by road type, road structure type, and road life cycle. As shown in Table 6, it was estimated that about 17 million tCO_2-eq. of carbon was emitted, two million TOE of energy was used, and 1,144 billion won was used to construct the national freeways until 2014. It was also estimated that about 0.26 million tCO_2-eq. of carbon is being emitted and about 0.08 million TOE of energy is being consumed for the operation and maintenance work every year for national freeways.

The estimated values for national highways are greater than the values for the national freeways because the total length of the national highways are three times longer than the total length of the national freeways. For national highways, about 47 million tCO_2-eq. of carbon was estimated to be emitted to construct the highways until 2014 and 0.53 million tCO_2-eq. of carbon is being emitted and about 0.17 million TOE of energy is being consumed for the operation and maintenance work every year.

Table 6. Total Carbon Emissions, Energy Consumption, and Cost for Korean Road Systems

Value	Life Cycle	Basic Earthwork	Bridge	Tunnel	Total
National Freeways					
Carbon Emissions	Construction (tCO_2-eq)	10,787,708	2,414,212	4,191,412	17,393,332
	Operation (tCO_2-eq./yr)	94,987	1,045	154,863	250,895
	Maintenance (tCO_2-eq./yr)	4,736	729	1,679	7,144
Energy Consumption	Construction (TOE)	1,526,532	61,574	423,303	2,011,409
	Operation (TOE/yr)	30,619	336	49,918	80,873
	Maintenance (TOE/yr)	1,514	235	127	1,876
Cost	Construction (100 million won)	951,122	114,354	78,495	1,143,971
	Operation (100 million won/yr)	275	195	8	479
	Maintenance (100 million won/yr)	3,766	200	293	4,258
National Highways					
Carbon Emissions	Construction (tCO_2-eq)	38,908,592	4,491,734	3,384,523	46,784,849
	Operation (tCO_2-eq./yr)	369,518	1,816	146,344	517,677
	Maintenance (tCO_2-eq./yr)	13,587	1,105	1,086	15,778
Energy Consumption	Construction (TOE)	2,858,256	132,385	146,325	3,136,967
	Operation (TOE/yr)	119,113	585	47,172	166,870
	Maintenance (TOE/yr)	4,343	356	82	4,781
Cost	Construction (100 million won)	1,258,457	156,125	60,753	1,475,336
	Operation (100 million won/yr)	1,071	340	8	1,418
	Maintenance (100 million won/yr)	2,116	59	37	2,212

6. CONCLUSIONS

A macro-level methodology for estimating the amount of carbon emissions, energy use, and cost by road type, road structure type, and road life cycle was developed. It can be used at the road planning stage because the required data for it is only basic road information such as road type, length, and number of lanes. Using the developed method, as a case study, carbon emissions, energy use, and cost for the national freeways and highways in Korea were estimated by road type, road structure type, and road life cycle.

The proposed method can be used for the calculation of BAU (Business as Usual) of carbon emissions. Carbon emitted are whenever new roads are built. Carbon are also emitted during operation and maintenance stage in the existing and future roads.

In the future, the deconstruction and recycling stages of the life cycle need to be included and the effects of traffic during the operation stage should be combined into the methodology. Also, average amount of carbon emissions, energy use, and cost per kilometer by road type and life cycle should be updated using more data samples.

The contribution of this research can be found in the fact that it was the first trial to develop a macro-level estimating method considering the environmental effects of road work by road life cycle. If the methodology's reliability becomes strengthened by using more data samples, it will become a very useful tool for road decision makers, planners, designers, managers, and also operators.

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