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GREENHOUSE GAS EMISSIONS FROM ONSITE EQUIPMENT USAGE IN ROAD CONSTRUCTION

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ABSTRACT: Onsite usage of construction equipment accounts for a 6.8% of air pollution in Korea. The high concentration of carbon dioxide in such emissions impact not only climate change, but also people's health. However, greenhouse gas emissions from onsite equipment usage have not yet been fully investigated. This study presents a comparative analysis on how much greenhouse gas is generated by various equipment types used in different construction activities. Two ongoing cases which involve a typical road construction project in Korea were selected for the comparison purpose. Greenhouse gas emissions from each onsite equipment usage of the different activities were estimated on the ground of design documents. The estimates were compared and analyzed to derive the main sources of greenhouse gas emissions. The result showed that earthwork constituted the largest part–more than 90%–among work types. Dump truck, bulldozer, and loader were major sources for such emissions. The study results are expected to be used as a basis for reduction of greenhouse gas emission from onsite equipment usage.

Keywords: Road Construction; Greenhouse Gas; Equipment; Construction Phase

1. INTRODUCTION

The world has witnessed the dramatic increase of environmental concerns and issues related to global climate change over the past decade. Global warming is "very likely" associated with greenhouse gas (GHG) emissions [1]. In accordance to the United Nations Framework Convention on Climate Change (UNFCCC), industrialized nations are obliged to lower their GHG emissions. As a result, all industries should join the efforts to cut back on the emission of GHGs, and the construction industry is no exception.

In road construction, the emission sources can be classified into eight different components–materials extraction and production, transportation, onsite equipment, traffic delay, concrete carbonation, roadway lighting, albedo, and pavement structure and roughness (rolling resistance) [2]. Among them, onsite equipment is mainly related to the project site, but equipment used for transport of materials from production facilities to the project site belongs to transportation. According to the National Institute of Environmental Research [3], air pollutant emissions from onsite construction equipment usage accounts for a 6.8% (253,058 ton/year) of the overall emissions produced in Korea. The main components in such emissions are carbon dioxide and nitrous oxide. However, GHG emissions from onsite equipment usage have not yet been fully investigated. It is not clear as to which work type or equipment are the main sources of emissions from onsite equipment usage during construction. Answers to such questions can lead to methodologies for effective reduction of GHG emission.

The objective of this study was to estimate how much GHG is generated by various equipment types used in different construction activities, and then to identify major emission sources of onsite equipment. In the remaining part of this paper, we begin with a review of the literature to thoroughly investigate previous efforts related to GHGs with an emphasis on the construction industry. We then present the calculations of GHG emissions from a range of equipment usages for different construction activities. These estimates are based on the design documents of two ongoing cases which involve a typical road construction project in Korea for comparison purpose. The values are compared and analyzed to derive the main sources of GHG emissions. Finally, findings and recommendations for future research conclude this paper.

2. LITERATURE REVIEW AND RESEARCH OBJECTIVES

In construction industry, various efforts have been made to evaluate environmental impacts associated with built structures from raw materials to recycling or disposal. Most of these studies have been concerned with energy inventories–"the phase of life cycle assessment involving the compilation and quantification of input and output [4]" and GHG emissions across various stages of the structure's life-cycle.

Stripple [5] performed a life cycle inventory analysis of road projects with different geo-technical and meteorological conditions in Sweden in order to calculate the total energy consumption of road construction, maintenance and operation. Park et al. [6] estimated the energy consumption associated with road project in Korea using a life cycle assessment approach. Zapata and Gambatese [7] compared energy consumption of asphalt and reinforced concrete pavement for the selection of design type in terms of green design and sustainable development. Athena Institute [8] presented estimates of energy usage and global warming potential (GWP) over the life cycle of construction and maintenance of six pavement design alternatives in Canada. Santero and Horvath [2] suggested the eight expanded components of GWP for pavements and estimated impact ranges of GWP based on scenario analyses.

Although these previous studies advanced the state-of the-art in the knowledge of energy consumption and GHG emissions of road projects, GHG emissions from onsite equipment usage have been relatively overlooked. As a result, a practical way to reduce GHG emissions from onsite equipment has not yet been suggested. This paper presents the result of an effort to quantify GHG emissions from onsite equipment usage in construction. The main hypothesis is naturally that equipment energy consumption accounts for significant portion of the total energy consumption.

The main objective of this research was to identify major emission sources. The specific objectives included:

1) Greenhouse gas emissions from various onsite equipment usages for different work activities are estimated using actual cases.
2) Major emission sources are identified and analyzed for the potential strategy of GHG reduction.

3. METHODOLOGY

3.1 Basic Assumptions

As previously mentioned, this study is predicated on the realistic assumption that GHG emission amount from onsite equipment usage during construction are directly related to the energy consumption of the equipment usage. Such energy consumption increases in exact proportion to the working hours of construction activities. The working hours are calculated on the ground of design documents including quantity takeoff and unit pricing data. This study considers carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) for GHG selection, since they account for 98.9% of the entire GHG emissions.

3.2 Calculation Methodology

The energy consumption during construction activities can be quantified by two representative methods–process analysis and input-output (I-O) analysis. The former is a method based on direct computation, whereas the latter is an indirect estimation method borrowing a mathematical framework introduced by Leontief [9]. In this study, process analysis is selected as a calculation methodology for the fuel consumption of equipment for construction activities. It is well suited to specific activities for which physical processes can be clearly identified; I-O analysis is more appropriate for national wide problems [10].

Based on the assumption, the calculation of GHG emissions associated with onsite equipment usage is conducted in three stages: working hour estimation, energy consumption quantification, and finally GHG emissions calculation in carbon dioxide equivalent. The first stage in the calculation procedure is to estimate working hour of each equipment used in construction activities. The working hour is normally estimated as Eq. (1):

$$H_i^j = \frac{X^j}{Q_i^j} = \frac{X^j}{q_i^j \times n_i^j \times f^j \times e_i^j} = \frac{\mathrm{m}^3}{\frac{\mathrm{m}^3}{\mathrm{cycle}} \times \frac{\mathrm{cycle}}{\mathrm{hour}} \times \% \times \%} \tag{1}$$

where H_i^j is working hour of equipment i for activity j; X^j is total quantity for activity j; Q_i^j is unit quantity of equipment i for activity j; q_i^j is quantity per one cycle; n_i^j is cycles of equipment per unit time; f^j is soil conversion factor; e_i^j is production efficiency.

X^j can be accurately determined based on the completed specifications and drawings. Q_i^j is the rate of output of equipment i for activity j; it leads to the link with the equipment productivity; n is the cyclic rate or speed of the equipment; q is the capacity of the equipment, which establishes the number of quantities produced per cycle. Here, the capacity is nominal value that needs to be adjusted considering the soil conversion factor; f is the conversion factor, the volume-to-volume ratio of the material that is to be processed; e is the nationally averaged value by considering the work condition at the site.

The second stage is to quantify energy consumption as shown in Eq. (2):

$$E_i^j = H_i^j \times C_i = \mathrm{hour} \times \frac{\mathrm{L}}{\mathrm{hour}} \tag{2}$$

where E_i^j is total energy consumption of equipment i for activity j; C_i is energy consumption of equipment i per unit time and this information is shown in Table 1.

Table 1 shows energy consumption of equipment during unit operating time. In case of transport equipment such as trucks, loading time has been excluded from the operating time when the loading time is more than ten minutes, because the equipment is idle during the loading time.

Table 1. Energy Consumption of Equipment [11]

Equipment	Capacity		Energy Consumption (L/hr)
Asphalt distributor	3,800	L	10.9
Asphalt paver finisher	3	m	13.0
Bulldozer	19	t	25.0
	32	t	41.6
Concrete finisher	105.9	kW	10.6
Concrete pump car	41	m	23.3
Concrete saw	320~400	mm	5.6
Concrete vibrator	0.75	kW	1.0
Crane	10	t	3.8
	15	t	4.7
	40	t	11.5
	50	t	12.0
Cultivator	1,000	kg	1.3
Dump truck	2.5	t	3.0
	6.0	t	8.0
	10.5	t	14.1
	15.0	t	15.9
Excavator	0.7	m^3	11.6
Pneumatic crawler drill	3.5	m^3/min	6.2
	17.0	m^3/min	23.5
Line marker	10	km/hr	20.7
Hydraulic ripper	32	t	41.6
Loader	1.34	m^3	7.7
	1.72	m^3	9.8
	2.87	m^3	16.4
Macadam roller	8~10	t	7.6
	10~12	t	9.3
Motor grader	3.6	m	16.2
Plate compactor	1.5	t	1.0
Rammer	80	kg	0.7
Road line removal	4.1	kW	3.4
Sprinkler truck	5,500	L	9.3
Tamping roller	32	t	35.2
Tandem roller	10~14	t	8.4
Tire roller	8~15	t	8.0
	15~25	t	10.0
Track crane	50	t	12.0
Trailer	20	t	15.0
Truck crane	5	t	5.1
Vibration roller	10	t	14.4

The final stage is that the estimated combustion of fossil fuels for onsite equipment usage are converted to carbon dioxide equivalent by the well-accepted method developed by the International Panel on Climate Change (ICPP) as shown in Eq. (3):

$$\mathrm{tCO_2e}_i^j = E_i^j \times \mathrm{OCF}_k \times \mathrm{CEF}_k \times \mathrm{RMW} \quad (3)$$
$$= \mathrm{L} \times \frac{\mathrm{TOE}}{\mathrm{L}} \times \frac{\mathrm{tC}}{\mathrm{TOE}} \times \frac{44}{12} \times \frac{1}{1{,}000}$$

where $\mathrm{tCO_2e}_i^j$ is global warming effect of equipment i for activity j; OCF_k is oil conversion factor of fossil fuel k; CEF_k is carbon emission factor of energy k; RMW is the ratio of the molecular weight of carbon dioxide (44) to the molecular weight of carbon (12). The values of OCF_k and CEF_k are from IPCC [1].

To better understand the procedure, consider the following situation. A hauling activity requires a volume of 13,032 cubic meter of common earth. A wheel loader with a bucket capacity of 1.72 cubic meter loads the earth into a dump truck. In case of earth piles, the bucket capacity is increased by 20 percent in volume. That is, the loader has an output of 1.72×1.2=2.064 cubic meter of the earth per cycle (q). Meanwhile, it has a total cycle time for the activity as follows: $m \times L + t_1 + t_2 = 1.8 \times 8.0 + 10 + 14 = 38.4$ second where m is the reciprocal of the velocity of the wheel loader; L is the average distance; t_1 and t_2 are load time and idle time, respectively. The cycles of equipment per an hour (n) is calculated as: $3600 \div 38.40 = 93.75$ cycles per hour. Soil conversion factor (f) and production efficiency (e) are 77% and 60%, respectively. The aforementioned variables are based on the design documents of a real-life project and the national standard estimating reference published by the Korea Institute of Construction Technology (KICT) [11]. Such values are applied to Eq. (1), producing the working hours of the loader for the hauling activity as: $\frac{13{,}032}{2.064 \times 93.75 \times 0.77 \times 0.60} = 145.8$ hours.

By consulting Table 1, it can be determined that the energy consumption of a loader with bucket capacity of 1.72 cubic meter is 9.8 liter per hour. Using Eq. (2), the diesel fuel consumption of the loader is calculated as: $145.8 \times 9.8 = 1{,}428.84$ liter. In reference to the data in IPCC [1], the value of the consumption is applied to Eq. (3), then the emissions of carbon dioxide can be assessed as: $1{,}428.84 \times 0.845 \times 0.837 \times \frac{44}{12} \times \frac{1}{1{,}000} = 3.705$ $\mathrm{tCO_2e}$.

4. CASE STUDY

4.1 Case Description

Before describing each case, it is needed to address that two thirds of Korea are composed of hill area. To this end, highways are in numerous cases composed of bridge and tunnel sections. To keep a reasonable scope in this study, those sections, composed of bridges and tunnels, were excluded from the scope of this study.

This study selected "two" ongoing cases which involve a typical highway construction project in Korea for comparison purpose. The comparative analysis was to quantify how much GHG emissions from fuel combustion of each functional unit (lane-kilometer) were generated. Two sections were selected from the same province, Jeonlla-do, to have a reference case to each other. Naturally, two cases have similar geographical features. Table 2 summarizes the basic information for the two highway constructions.

Table 2. Basic Information about the Highway Constructions

Category	Case 1	Case 2
Location	Jeolla-do, Korea	
Design speed (km/hr)	100	
Width (m)	20	
Number of lanes	4	
Length (km)	10.137	8.744
Commencement of work	Oct. 23, 2003	Aug. 28, 2003
Unit cost ($/lane-km)	2,127,657	858,759

As shown in Table 2, the road sections share the same location, design speed, width, because they are selected from the same project. The unit cost of case 1 was estimated to be about three times higher than case 2; the earthwork cost was expected to be more than four times.

All supporting data for the design documents used for this study were based on the national standard estimating reference [11] published by the KICT.

4.2 GHG Emissions from Onsite Equipment Usage

Greenhouse gas emissions were calculated by various equipment types used in different construction activities by using the calculation method described in the previous section. The results were analyzed in two stages as illustrated in Figure 1, to identify the major emission sources.

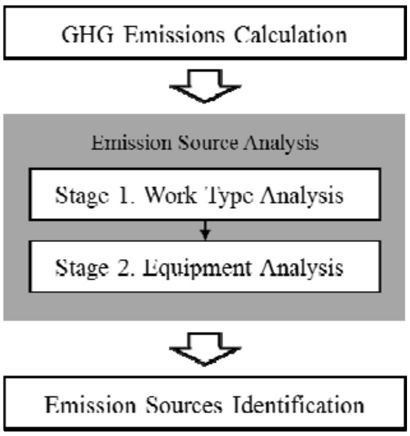

Figure 1. Analysis Procedure

At the first stage, the estimates were totaled by work types, but fuel consumptions less than ten liters were excluded from the sums, for the economy of calculation. Here, work types are classified into four groups: earthwork, pavement, utility, and miscellaneous items. Earthwork consists of all the activities required to produce the profile of the road right before the sub-base layer is installed. This includes not only the typical earthwork activities such as excavating, loading, and hauling, but also soil and rock stabilization. Pavement includes the activities of aggregate base courses, asphaltic concrete paving, and others. Utility mainly is comprised of various types of drainage and culvert. Lastly, miscellaneous items are those that are not included in the other work types; they include traffic stripes, signs, delineators, and noise abatement measures.

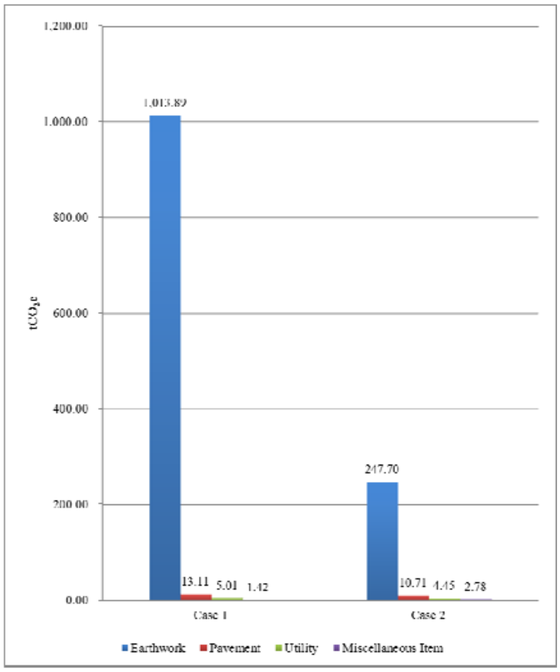

Figure 2. GHG Emissions by Work Type

Figure 2 shows the GHG emissions per lane-kilometer for the two cases by work type. Although the results of same work type are different from each other, the order of the results is same. In particular, earth work requires significantly more fossil fuels than the other work types; they accounted for 98.1% (case 1) and 93.3% (case 2), respectively.

At the second stage, the estimates were summed by equipment in the same work type. Table 3 identifies the GHG emissions by various equipment types. The results are almost same in order. The Dump truck 15.0 ton is the largest contributor to total GHG emissions in earth work, which is also the largest contributor, for all cases.

5. CONCLUSIONS AND FUTURE RESEARCH

This study conducted a comparative analysis on how much greenhouse gas is generated by various equipment types used in different construction activities. Based on the design documents of the two ongoing cases, greenhouse gas emissions from each onsite equipment usage of the different activities were estimated. The values were compared and analyzed to derive the main sources of greenhouse gas emissions. The results showed that earthwork constituted the largest part–more than 90%–among all the work types. Dump truck, bulldozer, and loader were the major sources for such emissions. The study results are expected to be used as a basis for reduction of greenhouse gas emissions from onsite equipment usage.

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Table 3. GHG Emissions from Equipment Usage

Work Type	Equipment	Case 1				Case 2			
		Work Hour	Energy Consumption	tCO_2e	Rank	Work Hour	Energy Consumption	tCO_2e	Rank
Earthwork	Bulldozer 19t	–	–	–	–	13.1	327.1	0.85	12
	Bulldozer 32t	1,637.5	68,119.3	176.65	2	533.2	22,179.5	57.52	2
	Crane 40t	72.3	831.9	2.16	14	–	–	–	–
	Crane 50t	255.2	3,062.8	7.94	11	–	–	–	–
	Dump truck 6.0t	17.2	137.9	0.36	15	–	–	–	–
	Dump truck 15.0t	14,254.1	226,640.7	587.75	1	2,560.5	40,711.3	105.58	1
	Excavator 0.7m3	132.7	1,538.9	3.99	12	200.4	2,324.6	6.03	8
	Hydraulic ripper 32t	213.3	8,873.9	23.01	6	13.6	567.7	1.47	11
	Loader 1.34m3	6.3	48.6	0.13	18	–	–	–	–
	Loader 1.72m3	2,173.2	21,297.0	55.23	3	701.8	6,877.3	17.83	3
	Loader 2.87m3	–	–	–	–	2.4	38.7	0.10	13
	Motor grader 3.6m	468.7	7,592.5	19.69	8	173.1	2,804.6	7.27	7
	Pneumatic crawler drill 3.5m^3/min	327.5	4,650.5	12.06	9	90.5	561.4	1.46	12
	Pneumatic crawler drill 17.0m^3/min	651.1	15,300.4	39.68	5	207.1	4,865.8	12.62	5
	Rammer 80kg	83.0	58.1	0.15	17	–	–	–	–
	Sprinkler truck 5,500L	2,143.8	19,936.9	51.70	4	677.1	6,296.6	16.33	4
	Tamping roller 32t	–	–	–	–	128.7	4,531.3	11.75	6
	Tandem roller 10~14t	–	–	–	–	–	–	–	–
	Tire roller 08~15t	462.2	3,697.3	9.59	10	163.5	1,308.0	3.39	10
	Tire roller 15~25t	131.2	1,311.6	3.40	13	–	–	–	–
	Truck crane 5t	17.2	87.9	0.23	16	–	–	–	–
	Vibration roller 10t	539.9	7,775.2	20.16	7	146.4	2,107.7	5.47	9
	Sum	–	390,966.5	1,013.89	–	–	95,505.2	247.70	–
Pavement	Asphalt distributor 3,800L	1.8	19.6	0.05	9	1.7	18.5	0.05	8
	Asphalt paver finisher 3m	47.5	617.5	1.60	5	33.0	429.0	1.11	5
	Excavator 0.7m^3	4.9	56.8	0.15	8	–	–	–	–
	Macadam roller 10~12t	80.6	749.6	1.94	2	34.2	318.1	0.82	6
	Motor grader 3.6m	45.1	730.6	1.89	3	56.8	920.2	2.39	2
	Sprinkler truck 5,500L	124.7	1,159.7	3.01	1	112.2	1,043.5	2.71	1
	Tandem roller 10~14t	56.3	472.9	1.23	7	30.9	259.6	0.67	7
	Tire roller 8~15t	87.4	699.2	1.81	4	69.2	553.6	1.44	4
	Vibration roller 10t	38.4	553.0	1.43	6	40.6	584.6	1.52	3
	Sum	–	5,058.9	13.11	–	–	4,127.1	10.71	–
Utility	Concrete finisher 105.9kW	23.3	247.0	0.64	4	16.3	172.8	0.45	4
	Concrete pump car 41m	17.6	410.1	1.06	2	13.5	314.6	0.82	2
	Concrete saw 320~400mm	43.5	243.6	0.63	5	–	–	–	–
	Concrete vibrator 0.75kW	28.3	28.3	0.07	7	68.3	68.3	0.18	6
	Crane 10t	83.4	859.0	0.82	3	41.1	156.2	0.41	5
	Crane 15t	–	–	–	–	4.8	22.6	0.06	7
	Excavator 0.7m^3	46.4	538.2	1.40	1	65.1	755.2	1.96	1
	Rammer 80kg	213.3	149.3	0.39	6	294.1	205.9	0.53	3
	Sprinkler truck 5,500L	–	–	–	–	1.5	14.0	0.04	8
	Sum	–	1,933.4	5.01	–	–	1,709.6	4.45	–
Miscellaneous Item	Concrete vibrator 0.75kW	25.5	25.5	0.07	5	11.0	11.0	0.03	8
	Cane 15t	–	–	–	–	5.8	63.8	0.17	4
	Cultivator 1,000kg	25.5	33.2	0.09	4	10.1	13.1	0.03	7
	Dump truck 2.5t	12.1	36.3	0.09	3	–	–	–	–
	Excavator 0.7m^3	35.9	416.4	1.08	1	33.5	388.6	1.01	2
	Line marker 10km/hr	–	–	–	–	21.3	440.9	1.14	1
	Motor grader 3.6m	–	–	–	–	0.8	13.0	0.03	
	Rammer 80kg	52.3	36.6	0.09	2	–	–	–	–
	Road line removal 4.1kW	–	–	–	–	35.7	120.7	0.31	3
	Sprinkler truck 5,500L	–	–	–	–	1.9	17.7	0.05	6
	Truck crane 5t	–	–	–	–	6.4	32.6	0.08	5
	Vibration roller 10t	–	–	–	–	0.7	10.1	0.03	9
	Sum	–	548.0	1.42	–	–	1,075.0	2.78	–
	[Total sum]	–	398,506.8	1,033.43	–	–	102,416.9	265.64	–

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