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Original Paper

Fuel-related emission estimation from the navigation profile of the ROKN combat vessel

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Abstract: While the Departments of Defense are not obliged to reduce its emissions, according to global emission reduction efforts, some countries are changing this trend by promoting emission reduction in the Ministry of Defense as well. To accurately estimate emissions using the bottom-up method, it is necessary to calculate the annual exhaust emissions due to the weapon system operated in the military and the infrastructure used for maintenance and service of troops. In the case of calculating the emissions of naval vessels, the vessel's output, navigation distance, speed, fuel consumption rate, and emission factor for each type of fuel used are needed. In this work, emissions from the naval vessel are calculated based on the annual activity data of the OOO-class destroyer, the main combat vessel operated by the Republic of Korea Navy, and results were obtained for component analysis of the MGO used in the target vessel. Emissions subject to calculation are carbon dioxide, nitrous oxide, sulfur dioxide, and PM_{10}. The investigation covers one year of the target vessel. The emission was calculated based on the EF calculation formula and the emission calculation formula presented by the EPA; upon comparing the result with the top-down method, the two values are determined to be close.

Keywords: Emission, Naval vessel, Navigation profile, Fuel, Top-down method

Abbreviations

AIP	Auto Identification System
AMP	Alternative Maritime Power
CODOG	Combined diesel engine or gas turbine
EEA	European Environment Agency
EF	Emission Factor
EPA	United States Environmental Protection Agency
GHG	Greenhouse Gas
GWP	Global Warming Potential
IMO	International Maritime Organization
MGO	Marine Gas Oil

1. Introduction

Now is the time that mitigation and adaptation strategies are urgently needed in the military to respond to future climate change. To concretely establish action plans for the military's greenhouse gas reduction, it is necessary to build a specific greenhouse gas inventory resulting from weapon systems such as vehicles, vessels, and aircraft operated by the military and infrastructure used for the maintenance and service of troops. However, greenhouse gas reduction in the military is not mandatory, unlike in the industrial and energy sectors. However, some countries that operate so-called advanced militaries are currently attempting to classify the emission sources and absorbers of greenhouse gases generated by the maintenance of military forces and the use of their weapon systems to calculate the total emissions associated with their operations **[1]**. Most of these attempts are based on the fuel statistics-based top-down method, and bottom-up based emission calculations by tiers 2 and 3 prescribed by IMO, EEA, and EPA are required to calculate emissions with lower uncertainty **[2]**. However, it is necessary to consider the practical problem that the access and use of the weapon system activity data necessary for this are very limited due to military specificity and security issues. To estimate emissions at Tier 2 and 3 levels for weapon systems such as naval vessels, activity data (power, navigation distance, speed, fuel

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consumption rate, etc.) of the weapon system and emission factors for each type of fuel used are needed. However, this is not an easily accessible resource to civil researchers, except naval researchers.

The purpose of this study is to calculate the amount of greenhouse gases emitted from vessels operated by the Republic of Korea Navy as accurately as possible. Here, we estimate the GHG emissions of the target vessel using a bottom-up method based on the annual activity data of destroyers, the main combat vessels operated by the Republic of Korea Navy, and the component analysis results of MGOs used by the target vessel. The navigation profile is divided into high-speed operation by a gas turbine, low-speed operation by a diesel engine, and arrival and departure by a diesel engine. The operation modes of the generator set are AMP mode, harboring mode, normal operation mode, and battle mode. The average load for each mode was applied.

Component analysis of MGO was performed by requesting the Korea Petroleum Quality Management Institute. Subsequently, formulas for estimating emissions according to the type of fuel and engine used in the target vessel were established, and the emission inventory was estimated by applying the activity data of the target vessel. The level of the emission estimation applied in the paper corresponds to the Tier 3 level defined by the EEA.

2. Why emission control for national defense

Emissions reduction has recently been requested in the military sector, which is not subject to mandatory reduction, because future climate change is expected to have the following effects on military operation **[3]**:

1) Flood damage to maritime infrastructure in the Navy will increase.
2) The energy demand of infrastructures for the maintenance and service of troops will fluctuate and require higher energy intensity.
3) The reliability of the energy and fresh water supply at some military bases will deteriorate.
4) Changes in the ecosystem and restrictions on military activities by unreported viruses or bacteria will come to the fore.
5) Deformation of runways and roads due to extremely hot weather increases, which increases maintenance budgets.
6) In terms of the operation of current and planned weapons and equipment, variables due to environmental changes increase, resulting in increased maintenance and design change requirements and budget use.
7) Reduced availability and accessibility of materials, resources and industrial infrastructure needed to manufacture weapons systems and supplies will deteriorate.
8) On the storage and stockpiling of materials or manufactured equipment and supplies, restrictions increase.
9) The availability and access to food and water supplies for military activities will deteriorate.

Therefore, naval vessels and other weapon systems used in the military are required not only to adapt to climate change but also to mitigate climate change as a source of emissions. The amount of GHG generated by the ROK national defense is approximately 3.5 kt CO_2-eq. It is estimated that 30.7% of the total GHG is caused by the air force's use of air weapon systems, and the GHG from naval vessels is estimated to be approximately 15.4% of the total GHGs **[4]**. However, these estimation values are top-down results by applying the same **Equation (1)** to the ratio of fuel oil imported into the military by field as of 2020 specified in the contract information of the Public Procurement Service, and the values' uncertainty is high.

GHG **Equation (1)**;

$$\text{GHG (ton/year)} = \text{fuel usage (k}\ell\text{/year)} \times \text{net caloric value (kcal/k}\ell) \times \text{EF (t GHG/TJ)} \times \text{oxidation rate (0.99)} \times \text{GWP} \quad (1)$$

3. Target vessel and analysis of the operation profile

3.1 Specification of the target vessel

In this study, the emission of ROK Navy's OOO-class DDH, a target vessel type for which activity data have been studied, is estimated in a bottom-up method. The target vessel is used not only for domestic missions but also for overseas missions such as joint force missions and overseas dispatch and cruise training for naval academy midshipmen. **Table 1** shows the specifications of the target vessel.

The CODOG system, a propulsion system operated in the target vessel, is a system that produces propulsion with diesel engines in the low-speed part and gas turbines in the high-speed part. When the target vessel is operated, the prime mover is converted in the area of approximately 15~20 kts. In naval vessels that operate together with gas turbines, the operation ratio of diesel engines to the operation ratio of gas turbines is high.

The generator set operates 2 out of 4 generators at approximately 40% load, and each uses up to 70% load in high-temperature water areas. In addition, during combat or training, one spare generator is additionally operated in an idle state.

The fuel used in the ROK naval vessel is marine gas oil, which is commonly used for diesel engines, gas turbines and generator sets. **Table 2** shows the results of the component analysis of MGO procured and used by the ROK navy.

Table 1: Specification of OOO class DDH

Vessel type	Destroyer Helicopter
Full displacement	5,500 tons
Cruise speed	20kts
Maximum speed	30kts
Propulsion system	CODOG
Diesel engine	2 ×MTU 20 V 956 TB82
Gas turbine	2× GE LM 2500
Gen. set	4 × MTU 12 V 396 TE54
Fuel use	MGO(Marine gas oil)

Table 2: Specification of MGO used in the ROK navy

Carbon contents (wt%)	86.97
Hydrogen contents (wt%)	12.64
Density (15℃) (kg/m3)	849.4
Cetane number	52.8
Sulfur contents (wt%)	0.025
Kinematic viscosity(40℃) (mm2/sec)	3.621
Lower heating value (J/g)	42,710
Net heating value (J/g)	45,570

3.2 Analysis of the target vessel's operation profile

The prime movers related to emissions from the target vessel are 2 diesel engines and 2 gas turbines for propulsion and 4 diesel engine generator sets. There is no boiler as used in merchant ships, and the heating water for the living is supplied using an electric heater, and the power required for this is produced by generator sets.

Among these elements, the engine for propulsion has the highest contribution period for emission, and the gas turbine engine has a high emission contribution per time unit. Emission by the diesel engine with a much higher usage time is expected to be dominant.

The vessel's operation profile must be used to estimate the vessel's emission because the vessel's operation profile corresponds to the values of speed from AIS and distance from AIS among the input data used when estimating the emission of a merchant ship. Although AIS is operated on vessels as an auxiliary means of navigation, uncertainty is high in activity data obtained through AIS because AIS is generally turned off during major operations and training. Therefore, speed data (operation profile), which was collected as an hourly log in the vessel's engine control room for one year, is regarded as activity data.

Figure 1 shows the navigation profile (speed) of the target vessel.

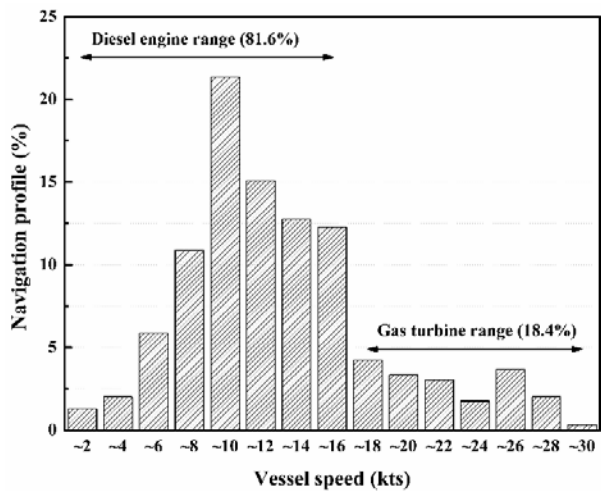

Figure 1: Navigation profile for the destroyers

In the case of ROKN's destroyer, the target vessel, which performs coastal operation with limitations in high-speed navigation, the diesel engine's usage proportion (16 kts or less) with low specific oil consumption is higher than the gas turbine's usage proportion (more than 16 kts). The overall trend is in the form of a negative skew with a high operating ratio of the diesel engine. For reference, the destroyer of the US Navy tends to be positively skewed compared to the target vessel due to the relatively high operating rate of gas turbines **[5]**.

Cases in which gas turbines are operated at the speed range of 16 kts or less include special conditions such as failure of diesel engines or test operation of gas turbines; and cases in which diesel engines are operated at low load for a long time after setting the pitch angle of controllable pitch propellers to 0°, etc. There are some uncommon operation modes, but those cases are extremely rare, so they are excluded from discussion.

The annual operation hour of prime movers of the target vessel is approximately 4,820 h, and Gen. set was driven approximately 750 h additionally by harboring mode.

Table 3 shows the operation rate of the generator set operation mode of the target vessel. This data represents the average load and operating time according to each generator operation mode operated by the target vessel during the survey period, and the generator output at the corresponding load.

Table 3: Operation rate of generator sets into ROKN destroyers

Operation mode	Ratio (%)	Hours (h)	Prime Movers	Aux. (kW)
AMP (indirect emission)	36.4%	3,190	N/A	N/A
Harboring (direct emission)	8.6%	750	1	360
Normal operation (direct emission)	46.8%	4,100	2	480
High temperature operation (direct emission)	8.0%	700	2	840
Battle (direct emission)	0.2%	20	3	600

4. Estimating emissions of the target vessel

4.1 BSFC empirical formulas of prime movers

To estimate the emission inventories of vessels, the specific fuel oil consumption rate according to the load of the main emission sources, prime movers for propulsion and prime movers for generation, is essential. At this time, the required fuel oil consumption rate is the BSFC (brake-specific fuel oil consumption) considering transmission loss in the drive shaft and transmission efficiency of the propeller, not the indicated values measured in the engine. Using the BSFC of the prime mover measured in the vessel, the kW–BSFC empirical formula of each prime mover for propulsion is as follows. These empirical formulas are those derived by drawing a trend line from the survey results of actual fuel consumption per kW measured during the survey period for the target vessel.

P(kW) – BSFC empirical Equation for two diesel engines of the target vessel (empirical **Equation (2)**):

$$\text{BSFC [g/kWh]} = 2 \times (3\text{E-}12\ P^4 - 3\text{E-}08\ P^3 + 0.0001\ P^2 - 0.1658\ P + 315.33) \quad (2)$$

P(kW) – BSFC empirical Equation for two gas turbines of the target vessel (empirical **Equation (3)**):

$$\text{BSFC [g/kWh]} = 2 \times (5\text{E-}15\ P^4 - 3\text{E-}10\ P^3 + 8\text{E-}06\ P^2 - 0.0792\ P + 570.57) \quad (3)$$

In addition, based on the fuel consumption measured in the target vessel, the power (kW) of the diesel engine generator set – BSFC empirical Equation – is obtained as follows.

P(kW) – BSFC empirical Equation for a diesel generator of target vessel (empirical **Equation (4)**):

$$\text{BSFC [g/kWh]} = 54.828 \times (\text{kW}/1200)^2 - 102.83 \times (\text{kW}/1200) + 234.7 \quad (4)$$

4.2 Emission factors for CO_2, N_2O, SO_2 and PM_{10}

The emissions to be estimated in this study are CO_2, N_2O, SO_2, and PM_{10}. To estimate each emission, an emission factor according to the type of engine and fuel is needed, and in this study, the emission factor presented by the EPA was used. Table 4 shows the emission factors for each emission presented by the EPA **[6]**.

Table 4: Emission factors for emission inventories

Keel-laid year	Fuel type	Items	Engine type	Emission factor (g/kWh)
2000~2010 (Tier I)	MGO	CO_2	GT	**Equation (5)**
			MSD	
			Aux.	
		N_2O	GT	0.029
			MSD	0.075
			Aux.	0.029
		SO_2	GT	**Equation (6)**
			MSD	
			Aux.	
		PM_{10}	GT	0.01
			MSD	**Equation (7)**
			Aux.	

The empirical formula related to the BSFC of each prime mover is substituted into **Equations (5) to (7)**, and the EF calculated in this process is substituted into **Equation (8)** for each emission and used to estimate the emission emitted from the target vessel. The LLAF (low load adjustment factor) of **Equation (8)** should be applied to the result of analyzing the AIS activity data of naval vessels according to the EPA Guideline, but due to the limitations of information access for special purpose vessels, the value corresponding to ship Category 3 (C3) provided by the EPA was applied. C3 includes high-speed ferries and yachts, and the MTU diesel engine used in the target vessel is also the same medium-high-speed diesel engine and generator mainly used for high-speed ferries and yachts **[7]**.

Equation (5) : $EF_{CO_2} = \text{BSFC} \times \text{CC}$
(CCF for ROK naval MGO = 3.1892)
(CCF = CCR × MWR = 3.1892)
(CCR = Carbon content ratio of ROK naval MGO = 0.8697)
(MWR = molecular weight ratio to CO_2 to carbon = 3.667) (5)

Equation (6): EFSO2 = BSFC × Sact × FSC × MWR
(Sact = ROK naval MGO's sulfur weight ratio = 0.025)
(FSC = fraction of sulfur to SO2 = 0.97753)
(MWR = molecular weight ratio of SO2 to sulfur = 2) (6)

Equation (7): EFPM10 = PMbase+ (Sact × BSFC × FSC × MWR)
(PMbase = base EF assuming zero fuel sulfur = 0.1545)
(Sact = actual fuel sulfur level for non ECA before 2020 = 0.027)
(FSC = fraction of sulfur to sulfate PM20 = 0.02247)
(MWR = molecular weight ratio of sulfate PM to sulfur = 7) (7)

Equation (8): Emission [g] = P(kW) × hour × EF(g/kWh) × LLAF
(LLAF = low load adjustment factor, 1 for generator) (8)

CCR (carbon content ratio of ROK naval MGO) and S_{act} (ROK naval MGO's sulfur weight ratio) when applied to **Equations (5) to (7)** are values measured by commissioning MGO used in the actual navy to the Korea Petroleum Quality Management Institute. **Figure 2** is a diagram showing a series of processes for estimating the emissions of the target vessel.

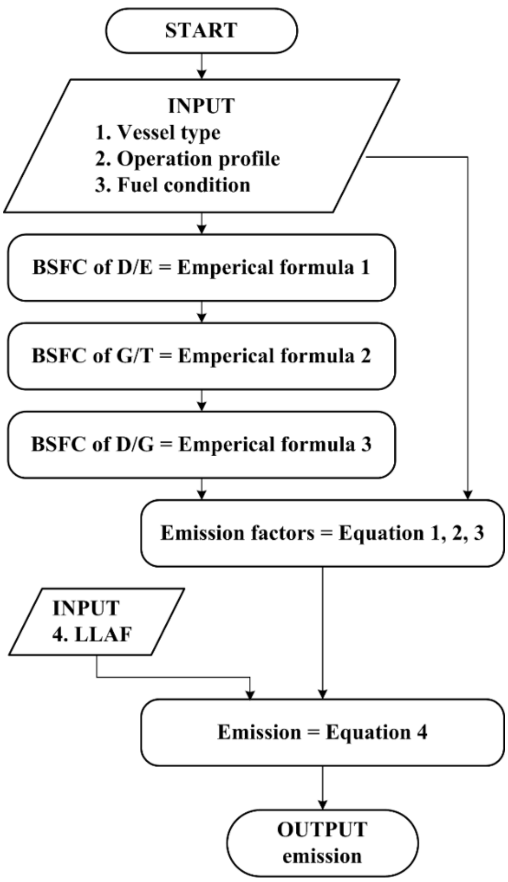

Figure 2: A simple diagram to estimate naval vessel emissions

4.3 Emission estimation

Table 5 shows the estimated emission results. In addition, **Figure 3** is a graph showing the GHG emissions of the Republic of Korea National Defense for 2020 estimated in a top-down method and classified by military forces and fuel use purpose. In the graph, the GHG emissions generated by vessels operated by the Navy are approximately 602 kt CO_2-eq.

CO_2 and N_2O are classified into six major GHGs. The total amount of GHG obtained by applying GWP to the amount of CO_2 and N_2O estimated in this study is approximately 8.66 kt CO_2-eq. This amount corresponds to 1.4% of the naval vessels' emissions (602 kt CO_2-eq), as shown in **Figure 3**. When estimated through empirical data (classified) of the operational scale (horsepower) of ROK Navy vessels, the fact that 1.4% of the GHG emissions of all ROK naval vessels per year are emitted from one destroyer has sufficient verification validity.

Table 5: Emission estimation

CO_2	N_2O	SO_2	PM_{10}
8.574 kt/year	0.00027 kt/year	0.069 kt/year	0.003 kt/year
8.66 kt CO_2-eq/year			

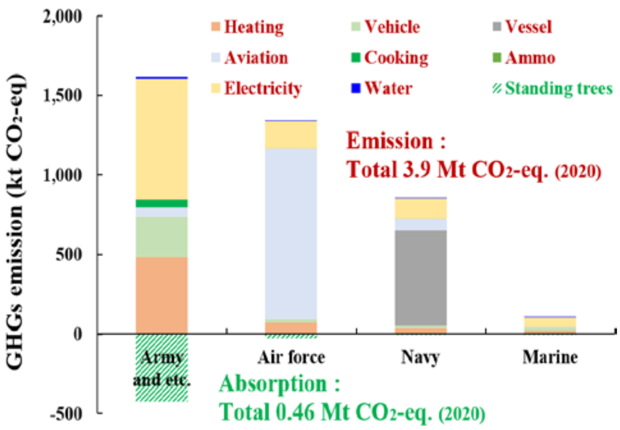

Figure 3: Net GHG emissions in each military force **[4]**

4. Conclusion

For emissions generated by military weapon systems, using a top-down method, with emissions estimation of major classification units of weapon systems (such as vehicle group, vessel group and aircraft group), rather than a different projection platform has been reported in many cases **[8][9]**. However, in these reports, it is difficult to find the case of estimating emissions of a single platform of a year. This is because, as has been consistently pointed out in various studies, that it is difficult to continuously accumulate operation profiles of vessels for a year, and emission estimation applied not to one type of platform but to similar platform groups such as vehicles, vessels and aircraft. A platform's emission inventories do not have great meaning in terms of the military's institutional and logistical operations.

However, considering the universal characteristics of naval vessels using the same oil type, i.e., MGO, it is absolutely necessary to study the methodology of emission estimation based on fuel oil. This is true because if only the operation profile, which is the activity data of other platforms, is accumulated, reliable emissions estimation with low uncertainty is achievable through a bottom-up method. We propose that this study has great significance as a demonstration of such a bottom-up evaluation method.

The contents of this study are summarized as follows:

1. Using a bottom-up method, emission estimation was conducted after assuming the destroyer operated by the ROK navy as the target vessel.
2. The data required for this are the operation profile of the ROKN Destroyer for one year, the result of component analysis of the fuel used, and the emission factor calculation value based on these inputs.
3. The ROKN destroyer's one-year activity data include the speed of the vessel, the number and load of generators operated, the ratio, and the braking fuel consumption rate (BSFC) measured in the target vessel.
4. The emission factor was calculated by applying the parameter values according to the fuel oil component and the prime movers' BSFC. The estimation formula used that defined by the EPA.
5. We confirmed the estimated calculations of the emission estimation values for CO_2, N_2O, SO_2, and PM_{10} for the target vessel. (Table 5.) As a result of converting CO_2 and N_2O into CO_2 equivalents, the amount corresponds to 1.4% of the amount of greenhouse gases attributed to entire ROKN vessels calculated in a top-down method. This amount is proposed as reasonable considering the size (e.g., horsepower) and activity of the vessel.

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Author Contributions

Conceptualization, H. M. Lee and H. M. Baek; Methodology, H. M. Lee and H. M. Baek; Formal Analysis, H. M. Lee and H. M. Baek; Writing-Review & Editing, H. M. Lee.

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