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Developing a new green ship approach for flue gas emission estimation of bulk carriers

Levent Bilgili[a,*], Ugur Bugra Celebi[b]

[a] Bandirma Onyedi Eylul University, Maritime Faculty, Bandirma, Balikesir, Turkey
[b] Yildiz Technical University, Naval Architecture and Maritime Faculty, Besiktas, Istanbul, Turkey

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A B S T R A C T

Shipbuilding industry and shipping sector comprise of various complex production and operating processes, which consist of manufacturing, operation, repair/maintenance, scrapping/dismantling/recycling. Operation phase is the main source for production of various atmospheric contaminants. In the latest report of IMO, it is estimated that shipping activities are responsible for 2.2% and 2.1% of global CO_2 and GHG emissions CO_2 equivalent (including CH_4 and N_2O), which correspond to 35,640 and 39,113 million tons, respectively. IPCC estimates that the total fuel consumption will increase by 43.5% in 2050, at best. In this study, it is aimed to develop some equations in order to estimate the potential airborne emissions of a bulk carrier based on two main characteristics (DWT and C_B) during pre-design. For this purpose, the three-year operation data of nine bulk carriers are examined and a regression analysis was applied to obtain the equations.

1. Introduction

The concern for shipping emissions started to rise during 1980s and early comprehensive studies are realized during 1990s. After International Maritime Organization (IMO) set into shipping-related emissions and innovative abatement techniques, the issue became more popular and important. Considering the future projections for ensuing years of 21st century, the hazardous effects and reducing techniques of exhaust emissions generated by ships will be focused more in detail.

In a recent study, it is estimated that there are approximately 450 different types of gaseous emissions formed during internal combustion process of a ship engine system [5]. On the other hand, only the emissions (nitrogen oxides, sulfur oxides, particulate matter, carbon dioxide, carbon monoxide, methane and nitrous oxide) which have the greatest share and most significant impacts on human health and environment amongst all are considered and investigated in this study.

Nitrogen oxide (NO_x) is a term used for gases which consist of various percentages of nitrogen and oxygen. Because NO_x is formed during internal combustion process, the amount of NO_x strongly depends on combustion temperature, oxide concentration and fuel type [5]. Nitrogen oxides have a positive effect on ground level ozone, which is known as harmful for human health and agricultural areas. Besides, nitrogen oxides are one of the main sources of acid rains, which decrease the land productivity [5,56,49]. The formation of sulfur oxides (SO_x) is totally related with the sulfur amount in the fuel [54,34]. Reacting with nitrogen oxides, sulfur oxides may cause acid rains and it is known that they have a positive effect on global cooling [5,2]. Particulate matter (PM) is a term which identified the various types of particulates generated from ship engines. Although the fuel type has the greatest effect on formation of PM, the characteristics of combustion process has also a significant role. PM consists of soot, ash, metals, oxides, water mixed with sulfate and fuel particulates in exhaust gas [39]. PM has both effects on global warming and global cooling [27,33,52]. Carbon dioxide (CO_2) is the main end product of combustion process in which carbon-based fossil fuels are used. It is well known that CO_2 provides a great contribution to global warming [2]. Besides, CO_2 causes ocean acidification, which has an effect on global warming, indirectly [69]. Carbon monoxide (CO) is another carbon-based end product of fossil fuels and it is known as extremely toxic and it has positive effects on global warming and formation of ground-level ozone [2,59,40]. Methane (CH_4) and nitrous oxide (N_2O) is accepted as greenhouse gases in Kyoto Protocol [51]. Besides, black carbon (BC) is accepted as a rising threat particularly for Arctic region due to its remarkable ability to absorb radiation from incident sunlight and sunlight reflected from the surface. BC may also reduce surface reflectivity, when deposited to the snow or ice surface [21]. Shipping emissions are responsible for 15% of NO_x, 5–8% of SO_x [32,18], 2.6% of CO_2, 0.3% of CH_4 and 6.1% of N_2O [43], 15% of PM and 2% of BC [21]. However, for nearly 70% of these emissions occurred within 400 km from land [17] comprehensive studies on identifying and minimizing of emissions are

* Corresponding author.
E-mail addresses: leventbilgili1661@gmail.com (L. Bilgili), ugur.celebi@gmail.com (U.B. Celebi).

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realized.

There are several various papers on which shipping emissions are studied in recent years. While some of these studies are about developing emission factors and estimating current and future emissions, some of them focused on single emission type and its impacts. The impacts of shipping emissions on human health and environment are well investigated.

Shipping emission estimations are realized by using two basic methods: Top-down and bottom-up approaches. These approaches can be sub-divided into two sub-categories for each, as well. In full top-down approach, total emissions are calculated by using the global shipping data without considering the characteristics of a single ship. Then, the results are applied to different ships. Corbett and Fischbeck [16], Corbett et al. [17], Skjølsvik et al. [65], Endresen et al. [29] have used this method. In some studies [36,72,75,76,80] top-down approach is used for calculating the emissions and bottom-up approach is used for geographic characterization. In these studies, the shipping activities in a single geographic cell is evaluated and the emissions occurred within this cell is used to calculate the total global emissions. Full bottom-up approach is used by ENTEC [30], Wang et al. [73,74], Corbett et al. [20], Jalkanen et al. [45], Olesen et al. [61], Schrooten et al. [64], Miola et al. [58], Paxian et al. [62], and Tzannatos [70]. In this approach, the emissions of a single ship in a specific position are calculated and the estimation is then applied for a fleet to reach the global emissions. Finally, some studies [27–29,18,19,32,81,22,42] have used bottom-up approach for emission estimation and top-down approach for geographic characterization. First, emissions from a single ship are estimated over a period and the aggregation of the emissions is evaluated for realizing the geographic characterization [60]. In addition to these global studies, there are several regional investigations on shipping-related emissions. Corbett et al. [21], Browse et al. [10], Eckhardt et al. [26], and Winther et al. [82] studied on the impacts of shipping emissions on Arctic region. Gutiérrez et al. [38] investigated the shipping emissions caused by maritime transport in the Strait of Gibraltar, Spain. Injuk et al. [41] and Matthias et al. [55] investigated the impacts of shipping emissions to atmospheric pollution in North Sea region. In a different study, the environmental impacts of the expected increase in sea transportation near Norway and northwest Russia is investigated [23]. Fu et al. [35] and Zhang et al. [85] studied on the shipping emissions on Grand Canal and Bohai Rim in China, respectively. The estimation of shipping emissions in Turkish Straits and Sea of Marmara were realized by Kesgin and Vardar [50] and Deniz and Durmusoglu [24]. While Alföldy et al. [4] investigated the emissions occurred by the maritime transport activity on Sulfur Emission Control Areas (SECA), Williams et al. [79] studied on particular emissions from commercial shipping in Texas coastal waters.

These studies generally focused on shipping emissions occurred during operation phase of a ship. Besides operation, port activities have also remarkable impacts on air quality, particularly in harbor cities. Several studies have been realized for Ambarli, Istanbul [25], Tianjin, China [12], Göteborg, Sweden [44], Italy [57], Venice, Italy [13,14], Shangai, China [67], Hong Kong [83], Australia [37], Taranto, Italy [1], Mediterranean Sea [53], Brindisi, Italy [11] and Cork, Ireland [66].

Besides these global and regional emission estimation studies, there are several papers on developing comprehensive models, in which different parameters such as sea and weather conditions, specific fuel consumptions, cargo quantity and some main characteristics are used, for shipping related emissions. Johansson et al. [48] and Jalkanen et al. [46,47] developed a model named as Ship Traffic Emission Assessment Model (STEAM), which uses Automatic Identification System (AIS) to model the emissions from ship traffic around Europe. Besikci et al. [6] used a neural network based decision support system for energy efficient ship operations. Perera and Mo [63] presented a general overview of emission control based energy efficiency measures in ship operations, emission control concepts is Emission Control Areas (ECAs) and energy efficiency concepts of Energy Efficiency Design Index (EEDI), Energy Efficiency Operational Indicator (EEOI) and Ship Energy Efficiency Management Plan (SEEMP). Similarly, Bouman et al. [9] presented the results of a great number of studies in order to provide a comprehensive overview of CO_2 reduction potentials and measures.

In the latest Review of Maritime Transport, United Nations Conference on Trade and Development (UNCTAD) indicated that the total seaborne trade grew from 9843 to 10,047 million tons between 2014 and 2015, which corresponds to an increase by 2.07%. The same report also indicated that world fleet grew 3.5% in the 12 months to 1 January 2016 in terms of deadweight tons (DWT) [71]. In a recent study, a long-term projection for 2050 of world fleet development and thus, increasing on shipping-related emissions are realized. In this study, the authors used the data from Special Report on Emissions Scenario (SRES) published by Intergovernmental Panel on Climate Change (IPCC). There are four scenarios offered by the authors (TS1-Clean Scenario; TS2-Medium Scenario; TS3-IMO Compliant Scenario; TS4-Business-As-Usual but Meeting IMO Emission Limits). It was estimated that the total fuel consumption was 280 million tons in 2001 and according to the results, the estimated fuel consumption will increase 402 and 725 million tons, respectively for the best and worst scenarios, in 2050. Thus, it is also estimated that the emissions will increase in parallel with fuel consumption [32]. Thus, due to shipping-related emissions are already a big problem; preventive approaches must be focused on reducing emissions.

This study is a further version of a previous paper, in which the annual emissions are estimated for three bulk carriers with two main emission estimation methods and some formulas are developed in order to estimate the potential emission amounts of bulk carriers during pre-design stage [8]. Bilgili et al. [7] compared the different emission amounts, which are calculated with two different methods. The authors also compared the routes in terms of emission/distance ratio.

In this study, the authors evaluated nine bulk carriers' real-time noon reports and calculated the emissions occurred during three-year operations both at sea and hoteling. Then, the total amounts of NO_x, CO, SO_x, $PM_{2.5}$, CO_2, CH_4 and N_2O are calculated by using three main emission estimation methods (Fuel Consumption (FC), Engine Power (EP) and Energy (E)). Finally, a regression analysis was implemented on results and some formulas, which are based on deadweight (DWT) and block coefficient (C_B) are developed.

2. Materials and methods

There are three main methods used to estimate shipping emissions: FC, EP and E methods.

FC method is mainly based on the fuel consumption data, which is obtained from noon reports recorded daily by crew. If the reports are recorded studiously, FC method could be used for high accuracy results. The formula for this method is offered by Trozzi [68] and presented below:

$$E_{Trip,i,j,m} = \sum_{p} (FC_{j,m,p} \times EF_{i,j,m,p}) \quad (1)$$

where

E_{Trip}: emission over a complete trip
FC: fuel consumption
EF: emission factor
i: pollutant type
j: engine type
m: fuel type
p: different phases of trip

EP method is a more complicated method than FC. The necessary data for this method is also obtained from noon reports. In case of the lack of FC data, EP is an alternative method for estimating shipping emissions. The formula for this method is also offered by Trozzi [68]: