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An Assessment of the Impacts of the Emission Control Area Declaration and Alternative Marine Fuel Utilization on Shipping Emissions in the Turkish Straits

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Abstract

The Turkish Straits are critical waterways connecting the Mediterranean and the Black Sea. About 38,552 and 43,343 ships pass through the Strait of Istanbul and Strait of Canakkale annually, respectively, and their emissions into the air pose a threat to the regional and global environment, as well as to the people of the region. Herein, the effects of the declaration of the Sea of Marmara as an emission control area and the use of alternative fuels by ships on emission formation were examined. For this purpose, the data of the ships passing through the Turkish Straits were obtained, the engine powers were calculated based on the gross registered tonnage values of these ships, and the emission values were reached. Declaring the Sea of Marmara as an emission control area provides an 80% and 76% reduction in sulfur and nitrogen oxides, respectively. Carbon emissions remained the same. The use of liquefied natural gas dramatically reduces carbon emissions. Alternative fuels, especially liquefied natural gas, effectively reduce sulfur oxide emissions. Despite these positive effects, there seem to be many years ahead of the widespread use of alternative fuels due to the lack of technical and economic infrastructure. Thus, the declaration of the Sea of Marmara as an emission control area will positively affect both the population in the region and the region's environment.

Keywords: Alternative marine fuels, Ship emissions, Turkish Straits, ECA

1. Introduction

Ships consume 6.8% of the total fossil fuels in the world [1], and because of this consumption, 1,076 million tons of carbon dioxide equivalent (CO_2eq) greenhouse gas (GHGs) was produced in 2018, indicating a 9.3% increment compared to 2012. Ships are also responsible for 2.89% of the total anthropogenic emissions [2]. While the world's CO_2 production increased by 31.4% between 1970 and 2019, the value of CO_2 produced by ships increased by 76.8% over the same period [3]. If no measures are taken, ship-related emissions are expected to increase by 50% in 2050 compared with 2018 [2].

Only a small part of the 450 atmospheric pollutants produced from the internal combustion process in ships are harmful enough to be evaluated, and only this group is produced above a negligible level [4]. These are listed as ozone-depleting substances, nitrogen oxides (NO_x), sulfur oxides (SO_x), particulate matter (PM), and volatile organic compounds (VOCs) and are regulated by the International Convention for the Prevention of Pollution from Ships (MARPOL 73/78) Annex-VI. Additionally, although ship-related carbon emissions are excluded in the Kyoto Protocol [5] and the Paris Convention [6], the Initial Strategy on Reduction of GHG Emissions from Ships report

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published by the International Maritime Organization in 2018 offers short-, medium-, and long-term solutions for the decarbonization of ships and plays a guiding role. This strategy aims to reduce ship-related carbon emissions by 40% by 2030 and by 70% by 2050 compared to 2008 [7].

The harmful effects of ship-borne atmospheric emissions are well known, especially CO_2 [8-12], NO_x [13-15], sulfur dioxide (SO_2) [4,14-16], and PM [17-22] are pollutants that have often been emphasized.

Various national and international restrictions have been applied to reduce the effects of these pollutants, among which the regulations contained in MARPOL 73/78 Annex-VI are the most important. The most effective regulations proposed by Annex-VI are Regulations 13 and 14, which contain various restrictions for NO_x and SO_x, respectively. According to Regulation 13, ships are classified as having engines <130 RPM, 130-1999 RPM, and >2000 RPM and as Tier I effective after January 1, 2000, Tier II effective after January 1, 2011, and Tier III [Emission Control Areas (ECAs) only] restrictions effective after January 1, 2016. According to Regulation 14, the allowed fuel sulfur content of 4.5% before January 1, 2012, in regions outside the ECA has been reduced to 0.5% as of January 1, 2020, and this rate has been applied as 0.1% since January 1, 2015, in the ECA regions. In addition to these rules, ships sailing in the European Union waters cannot use fuel containing >0.5% sulfur since January 1, 2020. Similarly, as of January 1, 2020, China has set a maximum sulfur content of 0.1% of the fuel used by ships sailing in its territorial waters and the Yangtze and Xi-Jiang Rivers. The ECA regions include the coasts of North America, US waters in the Caribbean, the Baltic Sea, and the North Sea. Additionally, some studies have declared the Mediterranean as an ECA region as of January 1, 2025 [23].

Despite the measurable positive effects of these restrictions, it is also an essential requirement to take stricter measures. Therefore, in addition to conventional fossil fuels, the tendency to alternative fuels that can replace them has been one of the important issues recently. Suppose the ECA declaration is insufficient due to the risk that it lacks the desired effect in reducing CO_2 and other GHGs and other emissions simply because it proposes a transition from one fossil fuel to another, alternative fuels are increasingly relied upon to improve air quality.

The Sea of Marmara and the Turkish Straits, in addition to being an important waterway with heavy ship traffic, are extremely vulnerable to adverse environmental impacts from ship emissions due to the dense settlement around them. Despite this importance, the literature on ship emissions in this region is limited. The first study on the subject was conducted in 2001, and the total amount of emissions in the Strait of Istanbul and Strait of Canakkale was measured as 353,625 and 347,221 t, respectively [24]. Another study in 2008 focused on ship emissions in the Sea of Marmara, and the amounts of CO_2, NO_x, SO_2, CO, VOCs, and PM produced according to 2003 data were 5,451,224, 111,039, 87,168, 20,281, 5801, and 4762 t, respectively, measured in [25]. In a recent study, the number of total petroleum hydrocarbons measured in water at the outlets of the Turkish Straits and polycyclic aromatic hydrocarbons measured in sediments varied between 1.7-11.6 µg/l and 120-2912 ng/g, respectively [26].

Herein, data about the ships passing through the Strait of Istanbul and Strait of Canakkale, which can be declared ECA after the Mediterranean, were compiled for 2021, and first, the emissions in the current situation were calculated. Then, the emission reduction that may occur in the declaration of the ECA announcement was evaluated. Finally, the scenarios for the widespread use of biodiesel, ethanol, liquefied natural gas (LNG), and methanol were created and the gains to be achieved in using these fuels were calculated. These fuels were chosen because, first, their emission factor data can be accessed since the emission factor inventory of all alternative fuels has not yet been completed. Second, the possibility that these selected fuels have already found use and will be preferred more widely in the near future. The research question of the study seeks to find an answer for which option, alternative fuels, or ECA declaration, provides a more environmentally friendly solution. Herein, only the strait passages were considered, and no calculation was made about the cruise of the ships in the Sea of Marmara. The results of the study will contribute to the declaration of the Sea of Marmara and the Black Sea as the ECA and will provide support for promoting alternative fuel use.

2. Materials and Methods

The Turkish Straits are two important waterways separating Europe and Asia, connecting the Black Sea to the Mediterranean. The Strait of Istanbul is located at 41°07’10” N and 29°04’31” E, whereas the Strait of Canakkale is located at 40.2° N and 26.4° E. The transit routes of the two straits are shown in Figures 1 and 2:

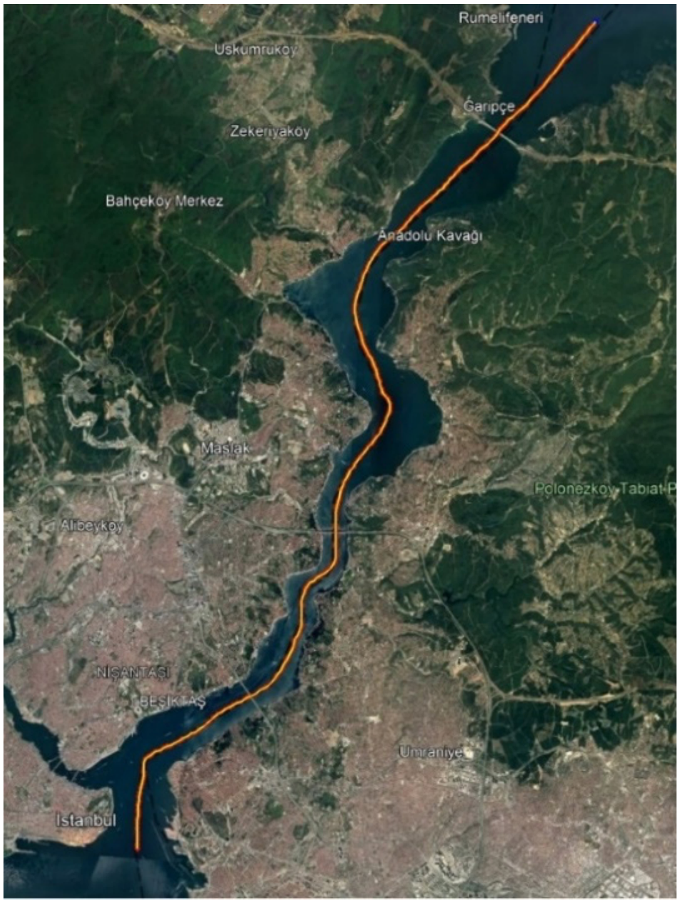

Figure 1. *Route to the Strait of Istanbul*

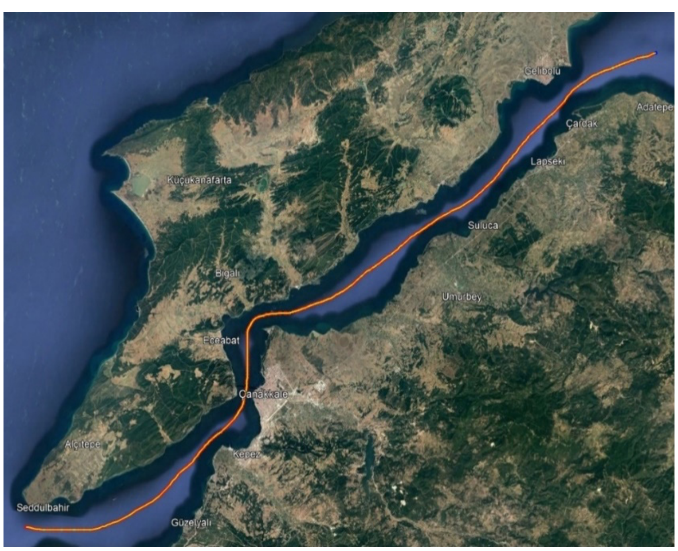

Figure 2. *Route to the Strait of Canakkale*

While 38,552 (7,168,719 gross registered tonnages) transits were made through the Strait of Istanbul in 2021, the number of passages made through the Strait of Canakkale is 43,343 (11,665,114 gross registered tonnages). While the average transit time of the Strait of Istanbul is 1.8 h, the Strait of Canakkale is crossed in 3.3 h on average. In the emission calculations, all the passages made by the ships in the north-south and south-north directions are included in the calculation. The data were obtained from the Ministry of Transport and Infrastructure of the Republic of Turkey and the Directorate General of Coastal Safety.

Since the fuel consumption data were not recorded, the calculations were conducted according to the engine power method. The formula suggested by Trozzi [27] is as follows:

$$E_{Trip,i,j,m} = \sum_p \left[T_p \sum_e \left(P_e \times LF_e \times EF_{e,i,j,m,p} \right) \right] \quad (1)$$

where;

ETrip: Total emissions (t)

T: Voyage duration (h)

P: Engine power (kW)

LF: Load factor (%)

EF: Emission factor (g/kWh or g/MJ)

p: Voyage phases

e: Engine category

i: Pollutant type

j: Engine type

m: Fuel type

Since there is no engine power of the ships in the data obtained regarding the strait passages, the equations presented in Table 1 were used to determine the engine power depending on the gross registered tonnage:

Table 1. *Engine power-gross registered tonnage equations (y as engine power, x as gross registered tonnage)*

Ship Types	Equation	Reference
General Cargo	$y = 5.3799x^{0.7633}$	[28]
Bulk Carrier	$y = 66.728x^{0.4826}$	
Tanker	$y = 18.189x^{0.6093}$	
Container Ship	$y = 2.5008x^{0.8801}$	
Reefer	$y = 1.2462x^{0.9783}$	
Ro-Ro	$y = 692.09x^{0.2863}$	
Passenger	$y = 0.6379x + 1411.5$	
Fishing	$y = 19.266x^{0.6658}$	
Other	$y = 77.806x^{0.5283}$	
Tugs	$y = 27.303x^{0.7014}$	[29]

***Table 2.** Emission factors*

Fuel Type/Pollutant	CO_2	SO_2	CO	HC	NO_x	PM	Unit	Reference
VLSFO (0.5% sulfur)	588	1.85	1.0	0.6	14.4	0.2	g/kWh	[30]
ULSFO (0.1% sulfur)	588	0.37	1.0	0.6	3.4	0.2	g/kWh	
Biodiesel (SVO)	-	0.37	-	-	17.1	0.19	g/kWh	[31]
Biodiesel (FAME)	-	0.36	-	-	17.9	0.18	g/kWh	
Ethanol	257.04*	-	-	-	-	-	g/kWh	[32]
LNG	201.96*	-	-	-	-	-	g/kWh	
	205.2*	-	1.008*	-	0.612*	0.0324*	g/kWh	[33]
	198.72*	-	-	-	-	-	g/kWh	[34]
	446.0	0.88	0.79	-	8.76	0.34	g/kWh	[35]
	412.0	0.003	-	-	1.17	0.027	g/kWh	[31]
Methanol	248.76*	-	-	-	-	-	g/kWh	[32]
	522	-	-	-	3.05	-	g/kWh	[31]
	548.2	-	0.54	-	2.16	-	g/kWh	[36]
*The units presented in g/kWh are given in g/MJ in the original references								

***Table 3.** Emissions for Strait of Istanbul*

Fuel Type/Pollutant	CO_2	SO_2	CO	HC	NO_x	PM
VLSFO (0.5% sulfur)	199,716.6	628.4	339.7	203.8	4981.0	67.9
ULSFO (0.1% sulfur)	199,716.6	125.7	339.7	203.8	1154.8	67.9
Biodiesel (SVO)	-	125.7	-	-	5808.1	64.5
Biodiesel (FAME)	-	122.3	-	-	6079.8	61.1
Ethanol	87,304.7	-	-	-	-	-
LNG	68,596.5	-	-	-	-	-
	69697.0	-	342.4	-	207.9	11.0
	67,496.1	-	-	-	-	-
	151,485.7	298.8	268.3	-	2975.4	115.5
	139,937.5	1.0	-	-	397.4	9.2
Methanol	84,492.3	-	-	-	-	-
	172,299.4	-	-	-	1035.9	-
	186,198.4	-	183.4	-	733.7	-

Since the gross registered tonnage value of the ships is known, the approximate engine power of the ships can be obtained using the equations presented in Table 1. The cruise time, which is another variable in the formula, is kept separately for each ship and is available as a data set. The engine load of the ships was accepted as 0.8 during cruising. Emission factors are presented in Table 2 for different fuels:

3. Results and Discussions

Tables 3 and 4 present the emission values obtained for the Strait of Istanbul and Strait of Canakkale for 2021, respectively. The emission values are arranged according to the reference order given in Table 2.

The difference between the current situation and the ECA declaration is evident in the first two lines of Tables 3 and 4. Accordingly, the carbon-based emissions (CO_2, CO, and HC) and PM values are unaffected by the ECA declaration. Furthermore, although there is a positive correlation between PM and SO_x emissions, ECA regulations do not seem to provide a direct reduction for PM. However, 80% and 76% reductions were observed in SO_x and NO_x amounts, respectively.

Biodiesels were evaluated as SVO and FAME herein. SVO refers to the biodiesel used directly as fuel, and FAME is a type of fuel called real biodiesel [37,38]. According to the results, biodiesel decreased SO_x formation by ~80% and increased NO_x formation by ~25%. The reason for this may be that biodiesel is used in the form of a mixture with diesel fuel instead of direct use, and this may change the in-cylinder temperature. The lack of a significant effect on PM

Table 4. *Emissions for the Strait of Canakkale*

Fuel Type/Pollutant	CO_2	SO_2	CO	HC	NO_x	PM
VLSFO (0.5% sulfur)	567,598.4	1785.8	965.3	579.2	13,900.4	193.1
ULSFO (0.1% sulfur)	567,598.4	357.2	965.3	579.2	3282.0	193.1
Biodiesel (SVO)	-	357.2	-	-	16,506.7	183.4
Biodiesel (FAME)	-	347.5	-	-	17,278.2	173.8
Ethanol	248,121.6	-	-	-	-	-
LNG	194,952.7	-	-	-	-	-
	198,080.3	-	973.0	-	590.8	31.3
	191,825.1	-	-	-	-	-
	430,525.3	849.5	762.6	-	8456.1	328.2
	397,705.0	2.9	-	-	1129.4	26.1
Methanol	240,128.9	-	-	-	-	-
	503,888.4	-	-	-	2944.2	-
	529,179.3	-	521.3	-	2085.1	-

may also be due to the same reason. The reduction in SO_x and PM emissions is an expected result because biodiesels do not contain sulfur [39-45]. Although studies have shown that biodiesel reduces carbon emissions slightly [46-49], there are also studies showing the opposite. [41,50]. Despite the studies showing that the use of biodiesel reduces NO_x emissions [46,47,51,52], some other studies have shown that this decrement is insignificant [42]. Some studies have indicated that using biodiesel may even increase NO_x emissions [41,53,54].

Ethanol has the chemical formula C_2H_5OH and is the simplest alcohol. It has been observed that ethanol reduces CO_2 emissions by >50%. Studies have proven that ethanol has a reducing effect on PM and NO_x emissions [55]; however, it has been observed that it increases HC emissions [56].

Although it is impossible to reach a definite conclusion due to the different emission factors used for LNG, it is clear that CO_2 emissions have decreased. Also, the use of LNG has a reducing effect on SO_x, NO_x, and PM. LNG is the most studied alternative fuel, and its characteristics are well known. Since LNG does not contain sulfur, it is known to reduce SO_x and PM emissions [57-61]. LNG has also been proven to reduce NO_x emissions in accordance with the Tier-III restrictions [62-64] and to reduce CO_2 [65-68].

Methanol is simple alcohol with the chemical formula CH_3OH. The use of methanol did not dramatically reduce the carbon emissions, but reduced NO_x emissions by 85%. Since it does not contain sulfur, SO_x and PM formation is not expected [55,69-72]. Although it is thought that methanol can reduce NO_x emissions in accordance with the Tier-III restrictions, [69] there are also arguments against it [72].

As seen from the tables and discussions, the expected effects of alternative fuel use on emissions remain unclarified. Some studies support alternative fuels, whereas others offer opposing views. According to the findings obtained herein, there is no fully effective solution for CO_2 emissions from LNG. The reducing effect of fuels, especially LNG, on SO_x emissions is obvious. Significant positive effects were also observed on NO_x and PM, except for biodiesels. The reducing effect of alternative fuels, especially on SO_x and NO_x, is due to the necessity of complying with the restrictions in the scope of MARPOL Annex-VI. This international regulatory pressure is a significant driver for shipowners, companies and fuel manufacturers. However, carbon-zero fuels, such as hydrogen, are highly preferable energy sources for decarbonization, which is another important issue. Biodiesels can be considered a carbon-neutral option as vegetable-based fuels in the carbon cycle. Although the ECA declaration is an ineffective solution for decarbonization at the first stage, it is a very effective method for reducing SO_x and NO_x emissions.

4. Concluding Remarks

Ship emissions are an essential issue that can have very harmful effects, especially for the population living in coastal areas. Ship emissions have been considered a critical issue recently due to their effects on human health, city structures, and global climate change. The Strait of Istanbul and Strait of Canakkale host heavy ship traffic as a significant waterway connecting the Sea of Marmara to the Black Sea and the Mediterranean Sea. Thus, it is inevitable that ship emissions will occur intensively in these regions.

To avoid the negative effects of these emissions, the ships' tendency to use alternative fuels or the declaration of the region as the ECA seem to be two important methods. However, alternative fuels are still in the trial phase, and it will be many years before the establishment of sufficient technical and economic infrastructure for implementing these fuels on all ships, which increases the importance of the ECA declaration. The ECA declaration of the Mediterranean Sea, including the region up to the entrance of the Strait of Canakkale in the Aegean Sea, as of January 1, 2025, will ensure that the Sea of Marmara will also have significant environmental benefits. Herein, the environmental benefits, which positively affect the protection of both the environment and population, to be obtained as a result of the ECA declaration of the Sea of Marmara have been observed. Additionally, it is thought that the development of Annex-VI and ECA rules to cover not only SO_x and NO_x emissions, but also carbon emissions will provide significant benefits.

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