Analytical Modeling of Cruise Ship Emissions in the Bay of Kotor

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Keywords*: air pollution, cruise ships, emission of pollutants, Port of Kotor, sustainable development*

Abstract: Since 2005, the Port of Kotor has seen a significant increase in cruise ship arrivals, which has had a positive impact on the local economy and the Port's reputation as a prominent tourist destination. To ensure sustainability and quality in the context of cruise tourism in Kotor, environmental impacts must be monitored and managed. This research paper introduces the utilization of an analytical model to predict exhaust emissions originating from cruise ships, using the Port of Kotor as a case study. This model considers various operational and technical characteristics of ships, as well as the properties of marine fuels. This study aims to evaluate how these variables interrelate with each other and their collective impact on the overall volume of air pollutants released within the Bay of Kotor in 2015. The assessed annual emission of environmentally hazardous compounds into the local atmosphere from 399 ship arrivals is estimated to be 18.6 kilotons.

1. INTRODUCTION

The issue of exhaust emissions from marine engines today represents one of the primary challenges faced by the international community. The endeavor to address this issue fundamentally entails the adoption and implementation of appropriate legal regulations at both the international and national levels, encompassing fundamental definitions, legal and technical guidelines and instructions, as well as punitive provisions in the event of non-compliance with the adopted regulations.

The highest international legal standard addressing the issue of pollution from ships in marine and coastal areas is the International Convention for the Prevention of Pollution from Ships (MARPOL), adopted by the International Maritime Organisation (IMO). The Annex VI of the MARPOL Convention prescribes technical standards, control and certification

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principles, as well as measures for reducing emissions of pollutants and achieving improved energy efficiency aboard modern global commercial vessels [1], [2].

The composition of exhaust emissions from marine diesel engines is influenced by the quality of the fuel, engine technology and aftertreatment systems. According to official data, the predominant fuel used on ships in the global merchant fleet is heavy fuel oil (HFO), accounting for around 80% of usage, while only 20% is comprised of marine diesel oil (MDO) or liquid natural gas (LNG) [3], [4]. Marine fuel is characterised by its high residue content, high viscosity, increased density, and high sulphur content. These characteristics directly increase the toxicity of exhaust emissions.

When it comes to the percentage representation of constituent parameters in exhaust emissions, the data for slow-speed two-stroke marine diesel engines are as follows: 13.0% O_2, 75.8% N_2, 5.6% CO_2, 5.35% H_2O, 1500 ppm NO_x, 600 ppm SO_x, 60 ppm CO, 180 ppm HC, and 120 mg/Nm^3 PM [5]. The user has provided a numerical reference. In the case of four-stroke medium-speed marine diesel engines, the composition differs somewhat, consisting of 11.3% O_2, 74.3% N_2, 6% CO_2, 8.1% H_2O, and 0.3% other pollutants (NO_x, SO_x, CO, HC, and PM) [5].

In recent years, the primary focus has been on the analysis of the negative effects that certain components of exhaust emissions can have on the environment. Special attention is paid to monitoring and controlling the emission and concentration of pollutants such as nitrogen oxides (NO_x), sulfur oxides (SO_x), suspended particles PM and gases that contribute to the greenhouse effect. When it comes to the health impact, several conducted studies have demonstrated causal relationships between exposure to excessive concentrations of air pollutants and the occurrence of respiratory and cardiovascular diseases, and in extreme cases, even death [6] - [8].

The ecological impacts manifest themselves in the formation of photochemical smog and acid rain, as well as contributing to the depletion of the ozone layer [9]. The issue of the formation of photochemical smog or ground-level ozone is particularly significant for areas located in basins that surround high mountain ranges, as is the case with the city of Kotor and the Bay of Kotor in general. Such a geomorphological feature enables long-term exposure to the harmful environmental impacts of the aforementioned emissions during the warmer periods of the year, i.e. during the cruise season. In relation to this matter, the consequences of eutrophication and acidification processes on vulnerable ecosystems and limestone formations are becoming apparent.

Based on previously elaborated, the purpose of the study is assessment of approximate pollutant emissions from cruise ships in the Bay of Kotor for the year 2015. The findings could be used as a scientific contribution towards defining the strategy for the advancement of the city and port of Kotor, enhancing the general standard of living, strategic planning, promoting sustainability, and protecting cultural and natural resources.

2. DEVELOPMENT OF CRUISING TOURISM IN THE PORT OF KOTOR

International maritime passenger transport over the past few decades is almost exclusively attributable to the success of the cruise industry and statistical indicators of the growing number of tourists taking cruises around the globe. This global circumstance has influenced the positioning of the Bay of Kotor and Port of Kotor as the third largest cruise destination in the Adriatic region [10].

Statistics reveal that percentage increase in cruise ship arrivals in 2015 is 16.43% higher than in 2014, 33.01% higher than in 2010, and 165% higher than in 2006. Statistics show that in 2015 there were 42.9% more cruise ship passengers entering the Port of Kotor than in 2014, 204.46% more than in 2010, and an astounding 1,115.70% more than in 2006 [11].

Accordingly, the Port of Kotor and the Bay of Kotor have gained a global reputation as one of the world's premier cruising destinations, as confirmed by this region's ranking in the top 20 on the Forbes list for 2020 [12]. All of this had a number of positive effects on the economic development of the city and region, the promotion and development of existing and new tourism categories, the strengthening of regional and global cooperation, and global competitiveness.

The attractive positioning of the Port of Kotor, the geomorphology of the bay, and the natural and cultural-historical originality are crucial strategic factors that must be safeguarded against the detrimental environmental effects of the growing number of maritime transport on the long term.

3. DEFINING A MODEL FOR EVALUATING EXHAUST EMISSIONS FROM MARINE ENGINES

The fundamental aspect of estimating the quantity of pollutants emitted by marine diesel engines is the analysis of available data and information, from which a decision is made regarding the selection of an appropriate model. If the quantity of available data permits, it is always advisable to employ detailed assessment techniques during the analysis [13].

The EMEP/EEA Tier 3 model was selected for application in this study based on an evaluation of previous research and developed models for the assessment of the emission of polluting substances from ship engines, as well as the situation in the Bay of Kotor and the volume of collected technical and operational information about cruise ships entering the waters of the Port of Kotor. The preceding model provides support for the reporting process in accordance with the recommendations and instructions of the European Monitoring and Evaluation Programme - EMEP within the context of the Convention on Long-Range Transboundary Air Pollution - LRTAP [13].

The methodology for estimating the total amount of exhaust emission parameters from marine diesel engines in operation included the preparatory phase of data collection, which consisted primarily of working with available databases (IHS tool with technical data from the World Register of Ships, official data available on the Port of Kotor webpage [14], operational data from the automatic identification system Marine Traffic AIS live, etc.). The second part involves laboratory analysis of the sulfur content of marine fuel samples from cruise ships that visit the Port of Kotor and the calculation of total pollutant emissions from marine diesel engines at the level of each individual case, monthly and annually.

Determining model parameters involves defining:

- operational mode of work (maneuvering and hoteling) with determination of spatial and temporal parameters; and

- structural and technical characteristics of the ship (gross tonnage, type of main and auxiliary engines, power output of the main and auxiliary engines, load factor for the particular operational mode, fuel oil type and quality information, selection of appropriate emission factors, etc.).

The results of implementing the preparatory phase include research findings that also represent the evaluation method's parameters. In 2015, 72 different cruise ships entered the Port of Kotor and made 411 arrivals; 66 vessels over 1000 GT were included in the analysis. 57% of the vessels analysed have a diesel propulsion system, 40% have a diesel electric propulsion, and 3% are equipped with gas turbines. In the absence of comprehensive data on the fuel type combusted onboard cruise ships entering the Port of Kotor, the assumption was made that the majority of ships use HFO, as stated by Trozzi (2010) [15]. For the comparative analysis, the total emissions resulting from the use of MDO were determined as well.

MEST EN ISO 8217:2012 outlines the requirements for petroleum fuels for use in marine diesel engines. To comply with these standards, and following the guidelines of MEST EN ISO 8754:2010, energy-dispersive X-ray fluorescence spectrometry was used to measure the sulfur content in four samples collected from cruise ships that arrived at the Port of Kotor in 2015. The determined average sulphur content was 2.67 % m/m. Taking into consideration the natural characteristics of the Bay of Kotor, and the cultural and historical heritage under the protection of the United Nations Educational, Scientific, and Cultural Organisation (UNESCO), this region can be viewed as a potential area for the control of sulphur oxide emissions - SECA (Sulphur Emission Control Area). In this regard, as part of the research, sulphur oxide emissions were determined in accordance with the most recent regulations of Annex VI of the MARPOL Convention, which limit the sulphur content of marine fuels to 0.1% [1].

There are two operational modes defined for operational data: manoeuvring and hoteling. There are two phases to manoeuvring operational mode: I - from the moment of entering the Bay until the ship arrives in the Port of Kotor at the position of the berth or anchorage, and II - from the moment of starting the engine after untying and raising the anchor until the moment of achieving cruising speed when departing the Bay. At the time of mooring or anchoring in the Port of Kotor, the ship transitions to hotel mode. When estimating emissions, it is necessary to take into consideration the load of the main engine, which, according to previous research, is 20% for both identified phases [15].

The duration of the hoteling mode is dependent on the circumstances, whereas the duration of the manoeuvring mode is determined by the port pilots' professional judgement. In addition to the aforementioned data, the emission factor, which is dependent on the type and type of engine, fuel type, and operating mode, is a required input parameter for assessing pollutant emissions from the engine. The emission parameters proposed by the Lloyd's Register Engineering Services and shown in Table I were utilised in this study [13], [16].

Table I
Emission factors for different types of marine fuels in maneuvering and hoteling mode [g/kwh]

Engine and fuel type	NOx	Sox	PM	CO_2
Medium speed diesel engines/HFO	10.4	4.2*S	2.4	660
Medium speed diesel engines/MDO	9.9	4.2*S	0.9	660

Taking into consideration all of the previously mentioned parameters, the following algorithm was used to perform an analytical evaluation of the total amount of exhaust emissions from marine diesel engines [13]:

$$E_{ij} = \sum T_j * \left(P_n * LF_j * EF_i\right) \quad (1)$$

where:

Eij is the quantity of exhaust emissions of pollutant during a particular operational mode j (t)

Pn is the nominal engine power (kW)

LFj is the load factor of the engine in a particular operational mode j (%).

Tj is the duration of a particular operational mode j (h).

EFi is the emission factor for pollutant i (g/kWh).

4. RESULTS ANALYSIS

Using the EMEP/EEA Tier 3 analytical model, an evaluation of the cruise ship emissions of nitrogen oxides, sulphur oxides, carbon dioxide, and suspended particulate matter in the Bay of Kotor for 2015 was conducted. The obtained results are shown in table II.

Monthly and annual emissions are considered in the analysis.

Table II
Total emitted amount of exhaust emission pollutants from cruise ships in the Bay of Kotor in 2015 [t/month or year]

Month	NO_x	CO_2	PM	SO_2*
January	6.14	409.18	0.56	6.95
February	9.21	613.77	0.84	10.43
March	6.91	460.81	0.63	7.83
April	11.60	773.33	1.05	13.14

May	34.07	2,271.42	3.10	38.59
June	38.10	2,378.34	3.47	43.26
July	32.47	2,164.79	2.95	36.78
August	34.54	2,304.80	3.14	39.16
September	37.22	2,481.32	3.38	42.16
October	30.60	2,039.91	2.78	34.66
November	19.00	1,266.88	1.73	21.53
December	11.12	741.43	1.01	12.60
Total (t/year)	270.98	17,905.98	24.64	307.09

* estimated mean value of sulfur content of 2.67 % m/m

In the paper, a comparative analysis of the generated results was carried out in the case of combustion HFO and MDO onboard cruise ships (Fig. 1).

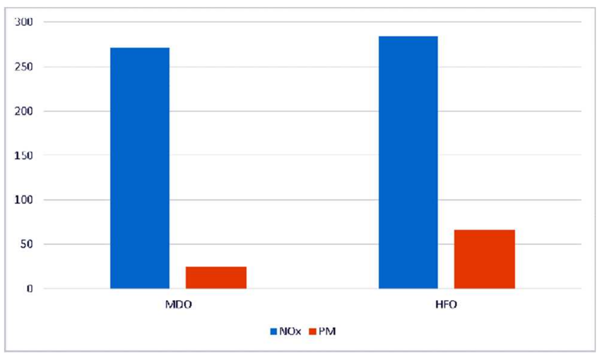

Fig. 1. Comparative analysis of the total amount of NOx and PM emitted in 2015 for the cases of HFO and MDO

In addition, the assessment results for sulphur content determined by laboratory tests and prescribed limit values in SECA areas were compared, as shown in Figure 2.

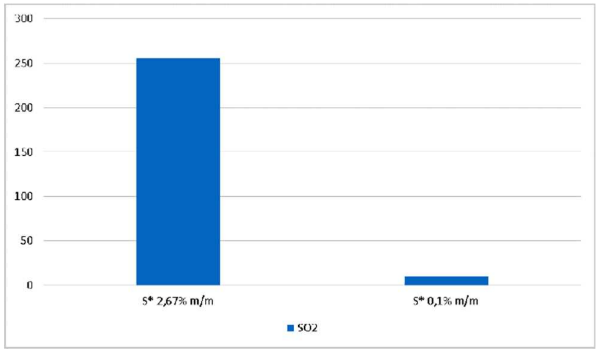

Fig. 2. Comparative analysis of the total amount of SO_x emitted in 2015 for the cases of using fuels with a sulfur content of 2.67% m/m and 0.1% m/m

By analysing the structure of the collected data, it is possible to conclude that the emission level is directly influenced by variables such as the number of ship arrivals, the duration of operational modes, nominal engine power, fuel type and sulphur content.

If the number of ship arrivals and the nominal power output of the ship's propulsion system are taken into account, a direct proportional relation can be established with the total amount of pollutants emitted. It also supports the view that during the high season period, the total emitted quantity of pollutants is higher compared to the low season period.

In addition, the analysis revealed that the total amount of pollutants emitted during the hoteling operational mode is greater than the quantity emitted during the manoeuvring operational mode. This ratio is approximately 4/1 at the annual level.

On the basis of the data presented in Fig. 2, it can be concluded that the deviation of sulphur oxide emission results in the case of the use of fuel with a high sulphur content relative to the use of fuel with a low sulphur content is in accordance with the SECA-applicable restrictions.

According to the foregoing, efficient management of operational factors is of greater importance for the control and reduction of total exhaust emissions from cruise ships, thereby allowing the number of ship arrivals to maintain the current trend.

5. CONCLUSION

The growth in cruise activities and passenger throughput in the Port of Kotor has brought economic benefits, boosted existing tourism, and introduced new attractions for the local community. In this regard, achieving a balance between the sustainable progress of the cruise industry and the preservation of the natural and cultural heritage in the Bay of Kotor is of utmost significance.

Aiming to evaluate the adverse effects of cruise ships on the air quality in the Bay of Kotor the EMEP/EEA Tier 3 methodology was applied to estimate the total volume of exhaust emissions of nitrogen oxides, sulphur oxides, carbon dioxide, and suspended particulate matter for the year 2015.

The results show that amounts of exhaust emission pollutants from ships are significantly affected by technical and operational factors. The findings reveal that as the frequency of large cruise ship arrivals and the duration of hoteling time increase, the overall volume of emitted pollutants also increases. Additionally, the recommendation on the use of Ultra Low Sulfur Marine Gas Oil, in line with SECA regulations, onboard cruise ships entering the Port of Kotor has great potential to decrease the emissions of harmful sulfur oxides.

Future research activities toward assessing the level of environmental and health impacts of cruise ship exhaust emissions in the Port of Kotor will encompass periodical comprehensive chemical analysis of marine diesel oil samples from cruise ships, real-time monitoring of cruise ship activities, and measuring concentrations of specific air pollutants and airborne particles in the Bay.

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