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Estimating pollutant emissions from sea cruise in the Adriatic Sea in 2022 and regulatory measures

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Abstract

Climate change and the fight against global warming have become the central issue of our contemporary society occupying an important place in various sectors. New regulations have been implemented like SECA areas in the North Sea or the reduction of fuel-emissions for all ships (International Maritime Organisation (IMO), MARPOL Convention annex VI).

This paper proposes an analysis based on Automatic Identification System (AIS) signals to study polluting emissions from cruise ships in the Adriatic Sea in 2022. The AIS is a tracking system used on ships to provide information on surrounding traffic situation and supplements marine radar for safety and security uses.

Based on an AIS database, combined with a ship database, this approach aims to provide an effective tool for assessing ship emissions and for estimating them. We applied a methodology based on the energy consumption of the ships, as well as their routing and position. As a result, we obtain the estimation by type of pollutant (CO₂, PM, SOX, NOX, N₂O, CH₄, ...) by ships and by ports.

The second part of our paper estimates the impact of setting up an ECA zone on ship emissions in the Adriatic. This model can be used to assess the impact of public policy decisions on port development or the introduction of new regulations to reduce pollutant emissions.

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1. Introduction

Climate change and the fight against global warming are now central issues in contemporary society, playing an increasingly impact in all sectors of activity. Today, it is scientifically proven that climate change is mainly caused by human activity, as stated in the 6th report of the IPCC (Intergovernmental Panel on Climate Change) in August 2021. Combating climate change, or rather mitigating it, involves multi-sectoral adaptations: food, mobility, housing....

Temperatures rose by 0.85 degrees Celsius between 1880 and 2012, and according to the IPCC's forecasting scenarios, they could rise by between 1 and 3.7°C by 2100. At the Copenhagen summit in 2009, governments committed to keeping the temperature increase below 2°C. But this 2°C target can only be achieved if CO₂ emissions fall by 10% per decade.

The economy has been internationalised since 1950, with the development of trade, tourism and industrial exchanges between countries. Without maritime transport, world trade and globalisation would not have been the same (Frémont, 2019), associating global shipping over the past recent years to being a major polluter. The cruise sector is particularly in the spotlight with major Med ports such as Venice, Dubrovnik, Marseille and Barcelona where cruising activities has been singled out for its impact on local *art de vivre* (too many tourists) but above all on the environment, with its impact on fine particles.

However, it should be remembered that on a per tonne loaded basis, maritime transport is the least polluting mode of transport. Every year, maritime transport moves 11 billion tonnes of goods, i.e. more than 80% of the volume traded worldwide, and is responsible for less than 3% of greenhouse gas emissions linked to human activity. On a per tonne loaded basis, maritime transport is the mode of transport that emits the least greenhouse gases. However, its impact on the environment should not be overlooked. Indeed, a global study estimates that by 2020, emissions from maritime transport will be responsible for almost 400,000 premature deaths a year worldwide, largely due to the exposure of populations to concentration of fine particles (Sofiev and al. 2018). Heavy fuel oil is responsible for polluting emissions from ships. This fuel is the most polluting because it is the most viscous part of crude oil and is not treated with additives, for example.

Maritime transport has begun to change in order to reduce its ecological footprint through international conventions, which we will present in the first part. These conventions have made it possible to set precise targets for the maritime transport sector, such as reducing total emissions from ships by at least 50% by 2050, compared with 2008 levels. Numerous initiatives and measures are already in place or under development (dockside connections, alternative fuels and propulsion, etc.). Since 1 January 2020, the world's shipping fleet has been required to use fuel oil with a sulphur content capped at 0.5%, compared with 3.5% previously.

The IMO has developed a methodology for modelling pollutant emissions from maritime traffic based on the energy consumed by ships. The aim of this paper is to use this methodology, which we will present in the first part of the paper, to modelling pollution emissions from cruising in the Adriatic Sea in 2022. This model can be used to draw up an inventory of the situation, which can be useful for public policy by assessing the impact of developments such as dockside connections for ships calling at port, or regulatory measures to set up an emission control area (SECA).

2. Methodology and data

Maritime traffic is responsible for releasing various pollutants, mainly from the combustion of the fuel needed to propel the ship and operate its various equipment. The gases emitted by shipping can be divided into two categories. Volatile organic compounds (VOCs), sulphur dioxide (SO₂), carbon monoxide (CO), suspended particulates or fine particulates (PM_{2.5} (diameter less than 2.5 µm) and PM₁₀ (diameter between 2.5 and 10 µm)) and nitrogen oxide (NO_x) have an impact on air quality at local and regional levels. On the other hand, carbon dioxide (CO₂), nitrous oxide (N₂O) and methane (CH₄) are greenhouse gases which, once emitted, are dispersed in the atmosphere and the stratosphere and therefore have a global impact. The methodology presented below is used to estimate pollutant emissions for each pollutant.

We will also detail the results of the modelling according to the status of navigation (in port or in transit) and by source of emissions. The sources of a ship's energy consumption are:

- The main engine, which produces the energy needed to propel the ship and keep it moving;

- The auxiliary generator provides the ship and crew with on-board production capacity to meet energy demand (excluding propulsion), which varies according to the ship's operating mode. In the case of a cruise ship, the auxiliary engine will supply all the energy needs of the various departments (casino, pool heating, electricity, etc.).

2.1. Data

As part of its role and responsibilities in regulating international maritime transport, the IMO has developed a methodology for quantifying emissions based on a ship's energy consumption. This requires access to various databases and information on ships and their movements, which we have acquired and compiled, and which we will present in detail in this section. Data collection proves decisive to being able to carry out the estimation calculations. It is therefore essential to secure this stage and to have clear understanding of how the data is structured in order to obtain the most accurate results and thus minimise the uncertainty.

There are three key data points:

- Data on the sources of ship emissions: engine, equipment model, year, etc.
- Active ship data: distance travelled, average speed, etc.
- Emissions factor: model based on energy consumed.

The first database is a database on ships to obtain information on their technical characteristics. To do so, we have taken out a subscription with IHS Markit Lloyd's to access to the various technical information on ships. ...). The crucial information, for the development of such methodology on the energy consumed, is the year of construction, the properties of the ship's main engine, the properties of the auxiliary generator and the type of fuel.

The second database is a database of ship movements based on AIS (Automatic Identification System) data from cruise ships. Based on the automated exchange of communications by VHF radio and more recently via satellite, the AIS system enables real-time identification of transmitting vessels. Transmission/reception is continuous and autonomous (Chan, 2013). It transmits both static identification and type information about the vessel and dynamic position information (Figure 1), as well as voyage-related information about the nature of the cargo and the ports of departure and destination. Other ships and shore stations are able to receive such information, process it using specific software and display the ships' positions.

For AIS, as for other new technologies, the players who appropriate it gain new advantages, which strengthens their knowledge and power relative to others (Serry and Lévêque, 2015). AIS is therefore data that is free and accessible to all, but which requires prior acquisition, archiving, decoding and exploitation. It is in this context that, since 2015, we have been developing a multidisciplinary project called CIRMAR. This platform enables us to acquire our own data via an antenna located on the roof of the Université Le Havre Normandie and to participate in a collaborative network, AISHUB. This gives us access to all the data from the antennas connected to this collaborative network.



Fig. 1. Nature of AIS data.

2.2. Methodology

The calculation methodology consists of converting the energy consumption of ships (in kwh) into polluting emissions (in grams). Consequently, we first need to calculate the energy consumed by the ship for each source of emissions (main engine and auxiliary generator) and for each navigation status (in transit and in port).

Using a GIS (Geographic Information System), we geolocated all the AIS positions of cruise ships registered in 2022. In this way, we were able to reconstruct the itinerary of each cruise ship transiting the Adriatic Sea, breaking it down by navigation status. For transit, we have determined for each route the date and time of the start of the journey, the date and time of the end of the journey, the distance travelled and the average speed. For calls, we recorded the date and time of arrival at the port, the date and time of departure and the duration of the call. This data is provided by our AIS database.

This information is then linked to the ships database presented above. Using these data and this methodology, we were able to calculate the energy consumption and therefore the estimated pollutant emissions of container ships. The calculation used is that developed by the IMO (IMO, 2018). and enhanced in particular by various research projects and port applications (mainly by the ports of Los Angeles and Long Beach). The emissions are calculated as follows:

$$E_i = Energy_i \times EF \times FCF \times AF \quad (1)$$

Where:

E_i : emissions by shipping status and source of emissions for i ship

$Energy_i$: energy demand by shipping status and by source of emissions for the i ship

EF: emissions factor expressed in grams per kilowatt-hour

FCF: fuel correction factor used to adjust the EF according to the fuel used

AF: adjustment factor for slow speed.

Calculating the energy consumed by ships

The energy consumed by ships by source of emissions and by sailing status is calculated using the maximum power of the main engine or auxiliary generator provided by the IHS fairplay ship database multiplied by the total observation time. The energy consumed by the main engine is adjusted by multiplying this total power in kWh by a coefficient depending on the average speed observed as a function of the theoretical maximum speed of the vessel. It is assumed that the faster the vessel goes, the more energy it will consume. The energy consumed by the main engine is therefore calculated as follows:

$$Energy_i = C_{ij} \times duration \text{ in hour} \times engine \text{ power} \quad (2)$$

Where:

C_{ij} : adjustment coefficient as a function of observed speed and maximum speed.

This coefficient is calculated as follows:

$$C_{ij} = \left(\frac{\text{Average observed speed of the vessel}_i}{\text{Maximum speed of the vessel}_i} \right)^3 \quad (3)$$

The energy consumed by the auxiliary generator is calculated by multiplying the power by the time in hours of observation, but these auxiliary generator power data are incomplete because they are not commercial data. In order to fill in the missing data, we calculated an average of the auxiliary generator power using the data available in our ship database in function of the number of passengers.

Emissions Factors (EF)

Once the energy consumed in kWh has been calculated, it must be converted into pollutant emissions in grams. To do this, the IMO has developed an indicator called the "emissions factor", which is broken down by type of pollutant and considers the fuel used, the year the vessel was built and the power of the main engine. This factor is updated annually by the Port Authorities of Los Angeles and Long Beach in their reports on ship and port emissions.

Table 1. Pollutant Emission Factors for diesel propulsion using 2.7% Sulfur HFO Fuel (San Pedro bay Ports Emissions inventory methodology report).

Category	Model year range	PM10	PM2.5	DPM	Nox	SOx	CO	HC	CO2	N2O	CH4
Slow Speed Propulsion	1999 and older	1.404	1.123	1.404	18.1	10.293	1.4	0.6	607	0.031	0.012
Slow Speed Propulsion	2000 to 2011	1.404	1.123	1.404	17	10.293	1.4	0.6	607	0.031	0.012
Slow Speed Propulsion	2011 to 2016	1.404	1.123	1.404	15.3	10.293	1.4	0.6	607	0.031	0.012
Slow Speed Propulsion	2016 and newer	1.404	1.123	1.404	3.6	10.293	1.4	0.6	607	0.031	0.012
Medium Speed Propulsion	1999 and older	1.489	1.191	1.489	14	11.349	1.1	0.5	670	0.031	0.01
Medium Speed Propulsion	2000 to 2011	1.489	1.191	1.489	13	11.349	1.1	0.5	670	0.031	0.01
Medium Speed Propulsion	2011 to 2016	1.489	1.191	1.489	11.2	11.349	1.1	0.5	670	0.031	0.01
Medium Speed Propulsion	2016 and newer	1.489	1.191	1.489	2.8	11.349	1.1	0.5	670	0.031	0.01

Table 2. Pollutant Emission Factors for Auxiliary Generator using 2.7% Sulfur HFO Fuel (San Pedro bay Ports Emissions inventory methodology report).

Category	Model year range	PM10	PM2.5	DPM	Nox	SOx	CO	HC	CO2	N2O	CH4
Medium Speed Auxiliary	1999 and older	1.54	1.23	1.54	14.7	11.98	1.1	0.4	707	0.031	0.008
Medium Speed Auxiliary	2000 to 2011	1.54	1.23	1.54	13	11.98	1.1	0.4	707	0.031	0.008
Medium Speed Auxiliary	2011 to 2016	1.54	1.23	1.54	11.2	11.98	1.1	0.4	707	0.031	0.008
Medium Speed Auxiliary	2016 and newer	1.54	1.23	1.54	2.8	11.98	1.1	0.4	707	0.031	0.008
High Speed auxiliary	1999 and older	1.54	1.23	1.54	11.6	11.98	0.9	0.4	707	0.031	0.008
High Speed auxiliary	2000 to 2011	1.54	1.23	1.54	10.4	11.98	0.9	0.4	707	0.031	0.008
High Speed auxiliary	2011 to 2016	1.54	1.23	1.54	8.2	11.98	0.9	0.4	707	0.031	0.008
High Speed auxiliary	2016 and newer	1.54	1.23	1.54	2.1	11.98	0.9	0.4	707	0.031	0.008

Fuel Correction Factor (FCF)

The fuel correction factor (FCF) is used to adjust the emissions factors according to the fuel actually used in the area under study. The emission factors defined by default correspond to fuel containing 2.7% sulphur. The emission factor (EF) calculated by the ports of Long Beach and Los Angeles. Since 1 January 2020, the IMO has required ships to use fuels containing a maximum of 0.5% sulphur. It is therefore necessary to apply a correction factor to the emission factor to comply with this 0.5% sulphur limit. The Marine Environment Protection Committee (MEPC) proposes a fuel correction factor, which we have used as the basis for our calculations:

Table 3. Fuel Corrector Factor – FCF (MEPC).

Pollutant	PM10	PM2.5	DPM	Nox	SOx	CO	HC	CO2	N2O	CH4
FCF	0.25	0.29	0.25	0.94	0.19	1	1	1	0.94	1

Source

Adjusted Factor (AF)

According to studies by the Environmental Protection Agency of the United States (EPA), diesel engines are generally less efficient at low engine speeds than at normal engine speeds. The EPA has developed a methodology for adjusting the emission factor. On the basis of this work, the ports of Los Angeles and Long Beach have developed a load adjustment factor (AF), which is a multiplier to be applied when the engine speed is less than 20% of its maximum

speed. This factor, calculated for each pollutant, applies to diesel engines and when calculating emissions for the main engine.

Table 4. Low Load Adjustment Multipliers for Emissions Factors - AF (San Pedro bay Ports Emissions inventory methodology report).

Load	PM10	PM2.5	DPM	Nox	SOx	CO	HC	CO2	N2O	CH4
2%	7.29	7.29	7.29	4.63	3.3	9.68	21.18	3.28	4.63	21.18
3%	4.33	4.33	4.33	2.92	2.45	6.46	11.68	2.44	2.92	11.68
4%	3.09	3.09	3.09	2.21	2.02	4.86	7.71	2.01	0.21	7.71
5%	2.44	2.44	2.44	1.83	1.77	3.89	5.61	1.76	1.83	5.61
6%	2.04	2.04	2.04	1.6	1.6	3.25	4.35	1.59	1.6	4.35
7%	1.79	1.79	1.79	1.45	1.47	2.79	3.52	1.47	1.45	3.52
8%	1.61	1.61	1.61	1.35	1.38	2.45	2.95	1.38	1.35	2.95
9%	1.48	1.48	1.48	1.27	1.31	2.18	2.52	1.31	1.27	2.52
10%	1.38	1.38	1.38	1.22	1.26	1.96	2.18	1.25	1.22	2.18
11%	1.3	1.3	1.3	1.17	1.21	1.79	1.96	1.21	1.17	1.96
12%	1.24	1.24	1.24	1.14	1.17	1.64	1.76	1.17	1.14	1.76
13%	1.19	1.19	1.19	1.11	1.14	1.52	1.6	1.14	1.11	1.6
14%	1.15	1.15	1.15	1.08	1.11	1.41	1.47	1.11	1.08	1.47
15%	1.11	1.11	1.11	1.06	1.09	1.32	1.36	1.08	1.06	1.36
16%	1.08	1.08	1.08	1.05	1.06	1.24	1.26	1.06	1.05	1.26
17%	1.06	1.06	1.06	1.03	1.05	1.17	1.18	1.04	1.03	1.18
18%	1.04	1.04	1.04	1.02	1.03	1.11	1.11	1.03	1.02	1.11
19%	1.02	1.02	1.02	1.01	1.01	1.05	1.05	1.01	1.01	1.05
20%	1	1	1	1	1	1	1	1	1	1

Estimating pollutant emissions is based on a set of technical parameters linked to the characteristics of the vessel and its displacement, enabling the energy consumed to be calculated (Fig. 10). This does not consider parameters such as meteorological conditions of navigation (wind direction, sea swell strength, etc.) or of the ship (acceleration of the ship on leaving port, loading and therefore its draught, etc.), which are factors that will influence its energy consumption and which merit further study.

3. Results of the model and simulations

In 2022, nearly 2,100 cruise calls were made in Adriatic ports (source: IHS Markit Lloyd's) by 90 different ships, representing more than 2 million passengers in total (source: MedCruise, 2022). The map below shows the Adriatic cruise market and its intensity.

We have applied this methodology to estimate pollutant emissions from maritime cruising in the Adriatic Sea in 2022. These results will enable us to draw up an inventory of pollutant emissions in tons by type of pollutant. The results of this model constitute an information base on which we can estimate the potential results of public and regulatory policies in terms of reducing emissions. Using the data from this model can be useful for assessing and estimating the contribution of a project or new regulation before it is introduced (limiting the speed at which ships can sail, docking ships in a port, developing new-generation energy sources, etc.). It should be noted when reading the results that during a stopover, the engine used for propulsion is shut down, but the auxiliary generator is running to maintain the energy required for the various activities offered on board a ship. To illustrate this, we will model the impact on pollutant emissions of the introduction of an ECA zone in the Mediterranean and *de facto* in the Adriatic Sea.

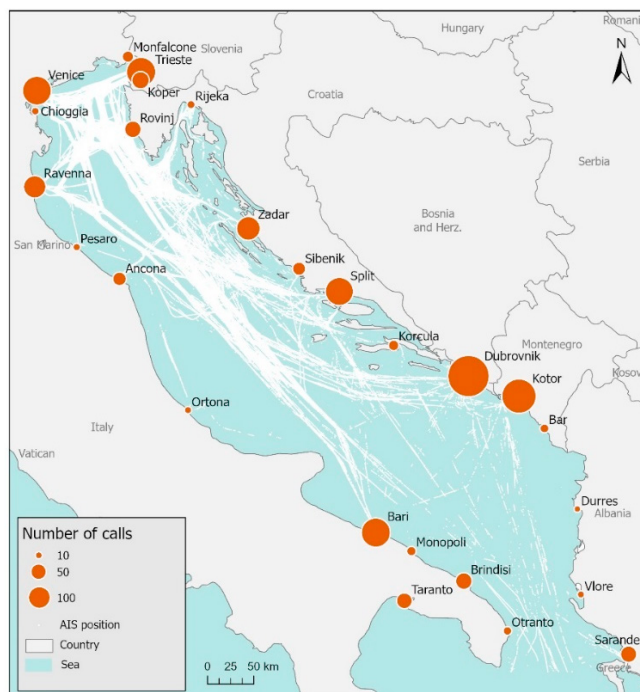


Fig. 2. Number of calls and AIS positions of cruises ship in the Adriatic Sea in 2022.

Table 5. Estimated pollutant emissions from cruise ships in the Adriatic Sea in 2022 by shipping status and source of emissions (in tons)

Pollutant	PM10	PM2.5	DPM	NO _x	SO _x	CO	HC	CO ₂	N ₂ O	CH ₄
Transit	36.91	34.23	36.91	1175.32	214.93	108.39	46.71	66776.53	2.86	0.93
<i>Main Engine</i>	27.47	25.49	27.47	883.82	159.12	81.17	36.90	49439.90	2.15	0.74
<i>Auxiliary Generator</i>	9.44	8.75	9.44	291.50	55.82	27.22	9.81	17336.63	0.71	0.20
Calls	18.17	16.84	18.17	503.98	103.95	45.56	20.17	34015.56	1.41	0.40
<i>Main Engine</i>	18.17	16.84	18.17	503.98	103.95	45.56	20.17	34015.56	1.41	0.40
<i>Auxiliary Generator</i>	18.17	16.84	18.17	503.98	103.95	45.56	20.17	34015.56	1.41	0.40
TOTAL	55.08	51.07	55.08	1679.31	318.88	153.95	66.87	100792.09	4.28	1.34

The table below gives an overview of the pollutant emissions from cruise ship traffic in the Adriatic Sea in 2022. Based on this data, we estimated the pollutant emissions resulting from the introduction of an ECA zone and calculated the gain for each type of pollutant. We have summarized the results in the table below (table 6).

Table 6. Estimating the impact of setting up an ECA zone in the Baltic Sea.

Pollutant	PM10	PM2.5	DPM	NO _x	SO _x	CO	HC	CO ₂	N ₂ O	CH ₄
Transit	-50%	-50%	-50%	-5%	-81%	-5%	0%	-2%	0%	0%
<i>Main Engine</i>	-50%	-50%	-50%	0%	-81%	0%	0%	-2%	0%	0%
<i>Auxiliary Generator</i>	-51%	-51%	-51%	-21%	-81%	-19%	0%	-2%	0%	0%
Calls	-61%	-61%	-61%	-31%	-85%	-25%	-25%	-22%	-22%	-25%
<i>Main Engine</i>	-61%	-61%	-61%	-31%	-85%	-25%	-25%	-22%	-22%	-25%
<i>Auxiliary Generator</i>	-61%	-61%	-61%	-31%	-85%	-25%	-25%	-22%	-22%	-25%
TOTAL	-54%	-54%	-54%	-13%	-82%	-11%	-7%	-9%	-8%	-7%

Looking at the results, we can see that the reduction in pollutant emissions generated by the introduction of an ECA zone would be relatively significant for local pollutants. For example, there would be an 82% reduction in Sox emissions and a 54% reduction in fine particles. On the other hand, the impact of an ECA zone would have only a minor impact on greenhouse gas emissions (between -7 and -9%). The introduction of a statutory speed limit would probably have a greater impact on this type of emission.

4. Conclusion

This article validates the methodology for estimating pollutant emissions linked to maritime traffic by applying it to the specific case of the maritime cruise market in the Adriatic Sea. The cruise market is particularly well established for many years in this area. Millions of tourists come to take advantage of this type of holiday to discover a new city every day and enjoy the landscapes offered by the surrounding countries. The cruise market is therefore economically important for certain nations whose economies may be heavily dependent on tourism. But this type of tourism, linked to mass tourism, has significant social and environmental impacts, and can incur the wrath of local residents. Local authorities therefore have to juggle this mass industry tourism coming originally from the sea. Some port cities, such as Venice, have chosen to limit the number of stopovers to relieve the crowded streets of this tourist city. Add to this the need to reduce polluting emissions on a global scale, it should be remembered that maritime transport as a whole is the least polluting mode of transport, responsible for 3% of greenhouse gas emissions worldwide. However, if no measures are taken, it could be responsible for 17% of greenhouse gas emissions by 2050 (source: IPCC 2022).

The development of this type of model is therefore important in order to support public policies in their decision-providing an estimate of polluting emissions from maritime transport and enabling the precise environmental contribution of new regulations or new developments to be assessed.

However, this methodology could be improved and could be the subject of future work by integrating, for example, meteorological models with wind and swell, which have a significant impact on the energy consumption of ships for propulsion. Meteorological wind models are of dual interest, as they would also enable us to study the movement of pollutants that have an impact on local air quality. In this way, we can simulate the movement of pollutants and to analyze the areas and populations that are actually impacted. The advantage of using AIS is that we can work on different geographical areas and also on a multi-scalar basis, enabling us to target specific parts of the shipping industry: containerization, ro-ro, cruise, etc. By transposing the methodology to another area, we can make comparisons between two similar maritime areas.

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