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Emission Inventory of Marine Traffic for the Port of Rijeka

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ABSTRACT

The paper estimates the exhaust emissions of marine traffic in the Port of Rijeka based on the ship's data obtained from the pilot company. The Port of Rijeka is the largest port in Croatia that includes several berthing locations with different terminals. The estimation is made for each of them respecting carbon dioxide (CO₂), nitrogen oxides (NO_x), sulphur oxides (SO_x) and particulate matter (PM) as well as for the amount of total emissions for the area. The aim is to prepare basic records for estimation and further monitoring with respect to changes in the ongoing environmental regulation and restrictions. This paper will contribute to the overall national strategy of preparing shipping emission inventories for the Republic of Croatia. The estimation method is based on the bottom-up approach widely used in such research that starts with ship characteristics and activities when approaching the port.

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1 Introduction

The Port of Rijeka consists of several basins: port basins Rijeka and Sušak, Bay of Bakar basin, Omišalj basin (a bay on the island of Krk) and Raša basin (in Istria). This article considers basins of Rijeka port in Bay of Rijeka excluding Raša basin.

The emissions are estimated for carbon dioxide (CO₂), nitrogen oxides (NO_x), sulphur oxides (SO_x) and particulate matter (PM) as it was performed for three other ports in Croatia: Zadar, Split and Šibenik [1,2,3]. In that way, the results might be comparable on the national level using the same "bottom-up" [5-9] methodological approach so contributing to the preparation of the National Emission Inventory, [14].

The ships were divided in two different groups based on their length (< 100 m and > 100 m due to different duration of activities) and the results are presented depending on their type.

The ship's data were obtained from the pilot company providing pilotage in the mentioned area and the traffic in-

formation for the year 2017 that were found complete and could thus be used for estimation.

2 Port data and Marine traffic analysis

The port of Rijeka is situated in the Bay of Rijeka, connected with the open sea by the wide strait of Vela Vrata. The strait Vela Vrata represents a border between the Bay of Rijeka and the Kvarner Gulf on the northern side, while the southern side is bounded by Srednja Vrata.

The Port of Rijeka is the most important port in the Republic of Croatia and also the largest international seaport in Croatia with 12,6 million tons of dry cargo handled in 2017 [4]. An important advantage of the Port of Rijeka is its proximity to the neighbouring countries and today finally, due to accession to the EU on 1 July 2013, the mentioned port has equal market conditions as her major competitors (Koper and Trieste).

Ships approach the port basins Rijeka and Sušak, Bay of Bakar basin and Omišalj basin via the strait Vela Vrata, at a reduced speed with mandatory use of diesel fuel

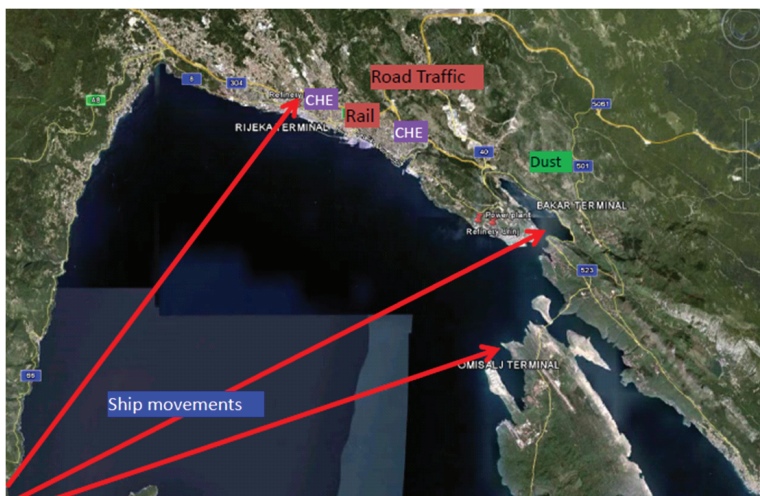


Figure 1 Rijeka port area, without Raša basin

Source: Authors

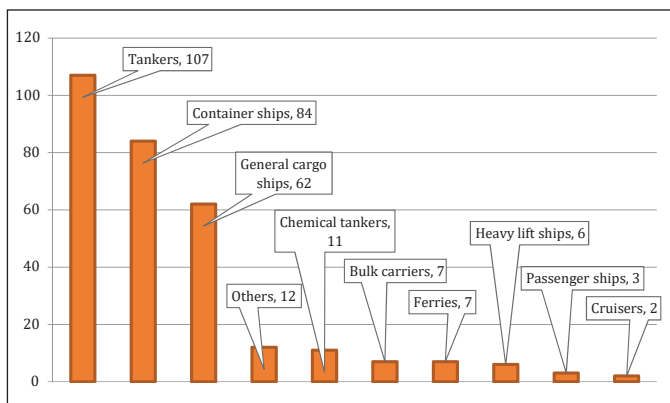


Figure 2 Number of arrivals in 2017

Source: Authors

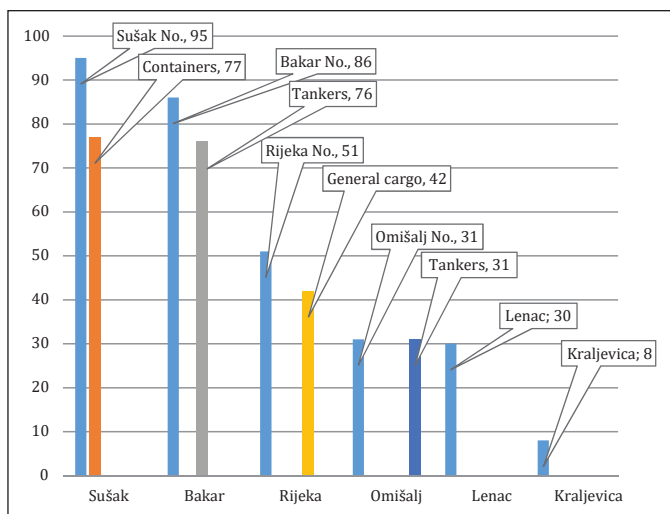


Figure 3 Number of arrivals and number of most frequent type of vessels for individual terminals

Source: Authors

(MDO). Rijeka port area in the Bay of Rijeka is presented on Fig. 1.

The emission assessment in this paper includes the coastal area of all mentioned basins in the Port of Rijeka and the port infrastructure, as the ecologically affected area. The assessment emission area has been divided into three separate parts: slow steaming time, manoeuvring, and ship stay at berth (anchorage).

The port emission inventory includes overall international traffic of cargo and passenger ships in the period from January to December 2017. Ships under 500 GT such as fishing vessels, yachts, catamarans and local tourist boats have not been included in the emission inventory.

The marine traffic flow has been systematically arranged and presented on Fig. 2 according to the data provided by the Rijeka pilot.

In the observed period, the highest number of arrivals was recorded with tankers, with a few cruise ships calling at the Port of Rijeka in the same period. The following Fig. 3 presents the number of arrivals and the number of most frequent ship types.

In the period from January to December 2017, Sušak basin had the largest number of ship arrivals. In the same period only eight ships over 500 GT called at the Port of Kraljevica.

3 Methodology

Emissions from the shipping industry account for a significant portion of total emissions, affecting air quality and having a great impact on human health. There are several methods for shipping industry emission assessment and the level of detail achieved within a certain research depends on the approach and the specific purpose of the analysis itself. In general, in case of emissions arising from the shipping industry, two main aspects, namely the quan-

tity and location of emissions produced, should be considered. In that sense, a bottom-up, a top-down approach or a mixture of those two can be applied.

The top-down method calculates total emissions without considering the characteristics of individual ships. Basically, it is based on the data about the total amount of marine fuel sold and the specific fuel emission factor.

The bottom-up method is based on the pollution data of a single ship emission in a specific location. This method takes into consideration all the ship's particulars important for air pollution (main and auxiliary engine power installed, load factor, emission factor) and ship status data (steaming, during manoeuvring, at berth) [5 - 9]. Other methods are generally based on those two main methods. For the purposes of the article, the bottom-up method will be used to estimate the amount of emissions for the considered area to allow comparison with the previously prepared inventories in three other Croatian ports [1-3].

3.1 Emission estimation equations

The emission estimation has been divided into three separate emission categories: slow steaming on arrival and departure, manoeuvring on arrival and departure, and berthed ship. A general approach to estimating emissions from fossil fuels combustion in navigation was provided by the Intergovernmental Panel on Climate Change (IPCC) Guidelines. The basic equation is, [10]:

$$\text{Emissions} = \sum (\text{Fuel Consumed}_{ab} \times \text{Emission Factor}_{ab}) \quad (1)$$

Where:

a - the fuel type (diesel, gasoline, LPG, heavy oil, etc.)

b - the water-borne navigation type (i.e., ship or boat, and possibly the engine type).

Ship's emission depends on the duration of certain ship activities: slow steaming (reduced speed zone - RSZ), manoeuvring and stay in port (berthed ship). The traditional most common ship propulsion consists of one or two main engines (rarely more) and two or more auxiliary engines connected with a generator. The emissions for each ship's activity for the mentioned kind of machinery plant are expressed as follows [5]:

$$Em(\text{steam}) = \frac{D}{v(\text{steam})} * (P_{ME} * L_{ME} * EF_{\text{Steam}} + P_{Ax} * L_{Ax} * EF_{Ax}) \quad (2)$$

$$Em(\text{man}) = tm_{\text{man}} * (P_{ME} * L_{ME} * EF_{\text{man}} + P_{Ax} * L_{Ax} * EF_{Ax}) \quad (3)$$

$$Em(\text{berthing}) = tm_{\text{berth}} * (P_{Ax} * L_{Ax} * EF_{Ax}) \quad (4)$$

Where:

P_{ME} - main engine power (kW)

P_{Ax} - power (kW) of auxiliary engines driving the generators

v - ship's average speed (steaming or manoeuvring) (km/h)

D - distance between cruising and manoeuvring (km)

L_{ME} - main engine load factor (%)

L_{Ax} - the load factor of auxiliary engines driving the generators during steaming, manoeuvring and berthing (%).

EF_{Steam} - main engine emission factor in steaming (g/kWh),

EF_{man} - main engine emission factor in manoeuvring (g/kWh),

EF_{Ax} - emission factor of engines driving generators in steaming, manoeuvring and berthing (g/kWh).

Modern cruise ships are equipped with diesel-electric machinery and gas-electric machinery which ensure the ship propulsion and provide electrical power for the operation of all ship's systems.

3.2 Types of fuel

The quality and type of fuel used has a great impact on emission factors and exhaust emissions. The estimation of SOx and CO₂ emissions depends on the content of sulphur and carbon in fuel. According to [5], fuel carbon content for all marine distillate fuels is 86.7 %, while sulphur content is regulated by EU Directive 2016/802 which requires the use of low-sulphur fuel (0.1%) for all inland waters and EU ports, [11]. MEPC 74 (May 2019) adopted the resolution MEPC.323(74) on encouraging voluntary cooperation between the port and shipping sectors to contribute to the reduction of GHG emissions from ships for member states [12]. The mentioned resolution includes regulatory, technical, operational and economic actions, such as the provision of Onshore Power Supply (preferably from renewable sources), safe and efficient bunkering of alternative low-carbon and zero-carbon fuels, incentives promoting sustainable low-carbon and zero-carbon shipping. This resolution also provides support in the optimization of port calls including facilitation of just-in-time arrival of ships.

3.3 Engine particulars

The data for the main and the auxiliary engines (ME and AE) of some vessels calling at the Port of Rijeka were obtained from the pilot company providing pilotage in the mentioned area. The data on the installed main and auxiliary engine power of other vessels that entered the Port of Rijeka were obtained by searching through the available database. A detailed database of vessel characteristics and performance was supplied by Lloyd's Register - Fairplay. Lloyd's Register is the principal source of vessel characteristics covering a great share of the world's merchant fleet over 100 gross tons [13]. This includes data as to the size and engine type of individual ships combined with such

information as fuel consumption. For some ships, the data for the main engines were assessed on gross tonnage basis and the power of auxiliary engines was determined on basis of main engine power. [5–7]

3.4 Engine load and emission factors

The importance of engine load in ship's emission has been the focus of many researchers. The load factor may be defined as a percentage of the current load in relation to the maximum continuous rating of the main and auxiliary engines. It depends on the activity of the ship (slow steaming, manoeuvring, and berthing). Auxiliary engine load factor depends on ship type and activity, whereas auxiliary engines are considered to be running at all times. For cruise ships, the load factor is higher during manoeu-

vring due to the use of bow thrusters and the supply of other electricity consumers on board the ship. [8]

For each of the three different activities for ship operation (slow steaming, manoeuvring and berthing), several assumptions regarding engine load operation were necessary in order to determine corresponding emission factor. At the Viktor Lenac shipyard, the ships are supplied with on-shore power and the ship's engine propulsion plant is shut down.

Whenever the load factor of the main engines was not available, it was assumed to be 80% while cruising, 20% during manoeuvring and stopped in port (except for tankers where it was assumed to be 20% due to the usage of pumps), [5]. Load factors for auxiliary engines are presented in table 1.

Table 1 The auxiliary engines load factors, adopted from [8]

| Type of vessel | Cruising | RSZ | Manoeuvring | Berthing |
|----------------|----------|------|-------------|----------|
| General cargo | 0.17 | 0.27 | 0.45 | 0.22 |
| Bulk cargo | 0.17 | 0.27 | 0.45 | 0.22 |
| Container | 0.13 | 0.25 | 0.50 | 0.17 |
| Cruise ships | 0.8 | 0.8 | 0.8 | 0.8 |
| Tankers | 0.13 | 0.27 | 0.45 | 0.67 |
| Refrigerated | 0.20 | 0.34 | 0.67 | 0.34 |
| RO-RO | 0.15 | 0.30 | 0.45 | 0.30 |

The emission factors are selected from [6] (main engine – ME – Table 2, and auxiliary engines – AE – Table 3).

Table 2 ME emission factors (g/kWh), at sea, during manoeuvring and in port, [6]

| At sea | | | | | | |
|---------------------|----------------------------------|---------------------------------|-----------------|-----------------|-----|-----|
| Type of engine/fuel | NO _x (before 2000) | NO _x (after 2000) | SO ₂ | CO ₂ | VOC | PM |
| SSD/MGO | 17.0 | 14.1 | 0.7 | 588 | 0.6 | 0.3 |
| SSD/MDO | 17.0 | 14.1 | 5.6 | 588 | 0.6 | 0.3 |
| MSD/MGO | 13.2 | 11.0 | 0.8 | 645 | 0.5 | 0.3 |
| MSD/MDO | 13.2 | 11.0 | 6.2 | 645 | 0.5 | 0.4 |
| GT/MGO | 5.7 | 4.7 | 1.2 | 922 | 0.1 | 0.0 |
| GT/MDO | 5.7 | 4.7 | 8.7 | 922 | 0.1 | 0.0 |
| Manoeuvring/In port | | | | | | |
| SSD/MGO | 13.6 | 11.3 | 0.8 | 647 | 1.8 | 0.9 |
| SSD/MDO | 13.6 | 11.3 | 6.2 | 647 | 1.8 | 1.2 |
| MSD/MGO | 10.6 | 8.8 | 0.9 | 710 | 1.5 | 0.9 |
| MSD/MDO | 10.6 | 8.8 | 6.8 | 710 | 1.5 | 1.2 |
| GT/MGO | 2.9 | 2.4 | 1.3 | 1014 | 0.5 | 0.5 |
| GT/MDO | 2.9 | 2.4 | 9.6 | 1014 | 0.5 | 0.7 |

SSD (slow speed diesel engine), MSD (medium speed diesel engine), GT (gas turbine), MGO (marine gasoil), MDO (marine diesel oil).

Table 3 AE emission factors (g/kWh) at sea, during manoeuvring and in port, [6]

| Type of engine/fuel | NO _x (before 2000) | NO _x (after 2000) | SO ₂ | CO ₂ | VOC | PM |
|---------------------|----------------------------------|---------------------------------|-----------------|-----------------|-----|-----|
| M/H SD/MGO | 17.0 | 14.1 | 0.7 | 588 | 0.4 | 0.3 |
| M/H SD/MDO | 17.0 | 14.1 | 5.6 | 588 | 0.4 | 0.4 |
| M/H SD/RO | 14.7 | 12.2 | 12.3 | 722 | 0.4 | 0.8 |

M/H SD (medium/high speed diesel engine), RO (residual oil).

3.6 Duration of the activities

The quantification of ship's emissions includes the analysis of ship's activities (slow steaming, manoeuvring and berthing). Slow steaming zone is defined as the distance from the beginning of the end of sea passage (EOP) point to the commencement of the manoeuvring regime in the port during the arrival and also on their departure from the end of the manoeuvring regime to full away on passage (FAOP). The EOP on arrival and FAOP on departure has been calculated from the area of the strait Vela Vrata for ships calling port basins Rijeka and Sušak, Bay of Bakar basin and Omišalj basin (bay on the island of Krk). Manoeuvring zone

is defined as the activity in which ship is steaming in manoeuvring regime during proceeding to/from the berth (anchorage). Berth (anchorage) implies the time spent at berth (on anchorage). Slow steaming time is calculated according to the ratio of the trip's length (in kilometres) and the ship's arithmetic average speed in slow steaming zone (km/h). The speed calculated for cargo ships in slow steaming amounts to 10 knots (18.52 km/h), for container ships and cruise ships 11 knots (20.37 km/h). Manoeuvring time and time spent at berth (anchorage) were determined according to the data obtained by the pilot organization. Estimated average time of each activity for the terminals of Rijeka port are presented in the following tables (Tables 4–9).

Table 4 Estimated average time for **Bakar** terminal for different types of vessels

| Type of vessel | Steaming time (h) | Manoeuvr (h) | Loading/Unloading (h) | At Port (h) |
|----------------------------------------|-------------------|--------------|-----------------------|-------------|
| Bulk carriers (LOA<100 m) | 3 | 1 | 8 | 9 |
| Bulk carriers (LOA≥100 m) | 4 | 3,5 | 160 | 165 |
| Oil tankers (LOA≥100 m) | 4 | 2 | 47 | 49 |
| Oil tankers (LOA<100 m) | 3 | 1,5 | 13 | 15 |
| General cargo (LOA<100 m) | 4 | 2,5 | 365 | 370 |
| General cargo (LOA≥100 m) | 3 | 1,25 | 125 | 128 |
| Chem. tankers/gas carriers (LOA≥100 m) | 2,5 | 1,25 | 18 | 19 |

Source: Authors

Table 5 Estimated average time for **Omišalj** terminal for different types of vessels

| Type of vessel | RSZ (h) | Manoeuvr (h) | Loading/Unloading (h) | At Port (h) |
|-------------------------|---------|--------------|-----------------------|-------------|
| Oil tankers (LOA≥100 m) | 4 | 3 | - | 30 |

Source: Authors

Table 6 Estimated average time for **Rijeka** terminal for different types of vessels

| Type of vessel | RSZ (h) | Manoeuvr (h) | Loading/Unloading (h) | At Port (h) |
|---------------------------|---------|--------------|-----------------------|-------------|
| | 3 | 1,75 | 158,25 | 163,25 |
| General cargo (LOA<100 m) | 2 | 1,25 | 52 | 55 |
| General cargo (LOA≥100 m) | 3 | 2 | 171 | 176 |

Source: Authors

Table 7 Estimated average time for **Sušak** terminal for different types of vessels

| Type of vessel | RSZ (h) | Manoeuvr (h) | Loading/Unloading (h) | At Port (h) |
|----------------------------------|---------|--------------|-----------------------|-------------|
| Passenger ship (LOA≥100 m) | 3 | 1,25 | - | 10 |
| General cargo (LOA<100 m) | 2 | 1,5 | 167 | 172 |
| General cargo (LOA≥100 m) | 3 | 1,75 | 390 | 395 |
| Container ship (LOA≥100 m) | 3 | 1,5 | 14,5 | 15,5 |
| RO-RO container ship (LOA≥100 m) | 3 | 1,5 | 12 | 13 |
| RO-RO container ship (LOA<100 m) | 2 | 1,0 | 3 | 4 |

Source: Authors

Table 8 Estimated average time for **Kraljevica** shipyard for different types of vessels

| Type of vessel | RSZ (h) | Manoeuvr (h) | Loading/Unloading (h) | At Port (h) |
|----------------------------------|---------|--------------|-----------------------|-------------|
| RO-RO Passenger ship (LOA≥100 m) | 3,5 | 1,0 | - | 480 |
| RO-RO Passenger ship (LOA<100 m) | 1,0 | 1,0 | - | 250 |
| General cargo (LOA<100 m) | 2,5 | 2,0 | - | 350 |

Source: Authors

Table 9 Estimated average time for **Viktor Lenac** shipyard for different types of vessels

| Type of vessel | RSZ (h) | Manoeuvr (h) | Loading/Unloading (h) | At Port (h) |
|-------------------------------------|---------|--------------|-----------------------|-------------|
| General cargo (LOA<100 m) | 2,0 | 2,0 | - | 101 |
| General cargo (LOA≥100 m) | 3,0 | 3,5 | - | 363 |
| Container ship (LOA≥100 m) | 3,0 | 2 | - | 212 |
| RO-RO Passenger ship (LOA≥100 m) | 3,0 | 1,5 | - | 750 |
| RO-RO Passenger ship (LOA<100 m) | 2,0 | 1,5 | - | 240 |
| Off shore supply vessel (LOA≥100 m) | 2,0 | 3,25 | - | 54 |
| Oil tankers (LOA≥100 m) | 3,0 | 3,0 | - | 504 |
| Oil tankers (LOA<100 m) | 2,0 | 1,25 | - | 48 |

Source: Authors

4 Results

CO2 emission

The total emissions of CO₂ exhaust gases from the combustion of fuels from ships in the port of Rijeka in 2017 amounted to 14519.37 tons. CO₂ emissions (tons) and percentage of total emissions for different types of ships (year 2017) are shown on Fig. 4 and emissions for each terminal (tons/year 2017) with respect to different activities are presented on Fig. 5. Numerical values are as follows:

Terminal: RSZ + manoeuvring + in port = total

Omišalj: 686.16 + 274.34 + 2716.8 = 3677.3 t

Lenac: 246.42 + 121.76 + 0 = 368.18 t

Kraljevica: 115.38 + 22.58 + 0 = 137.96 t

Rijeka: 247.06 + 87.34 + 1025.82 = 1360.22 t

Bakar: 522.42 + 161.06 + 2762.92 = 3446.4 t

Sušak: 2896.35 + 810.99 + 1821.97 = 5529.31 t

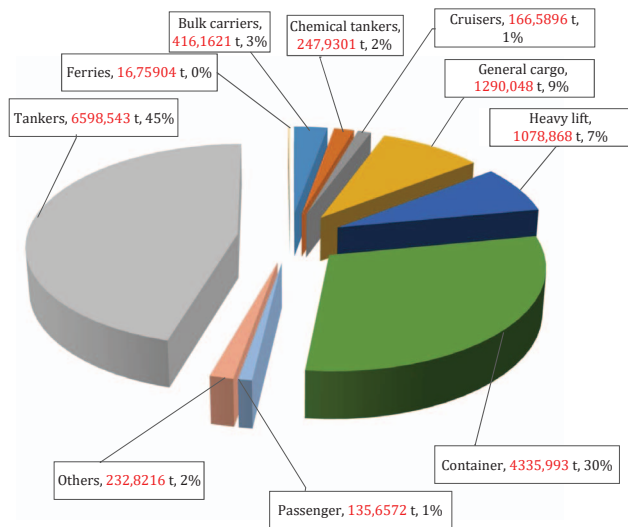


Figure 4 CO₂ emissions (t) and the percentage of total emissions for different types of ships (year 2017)

Source: Authors

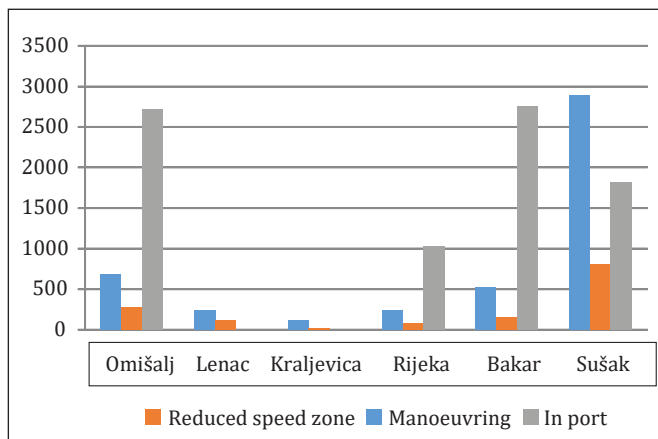


Figure 5 CO₂ emission (t/yr 2017) for terminals with respect to different activities

Source: Authors

NOx emission

The total emission of NOx gases in 2017 was 325.91 tons. NOx emissions (tons) and the percentage of total emissions for different types of ships (year 2017) are shown on Fig. 6 and emissions for each terminal (tons/year 2017) with respect to different activities are presented on Fig. 7. Numerical values are as follows:

Terminal: RSZ + manoeuvring + in port = total
 Omišalj: 19.31 + 5.70 + 56.12 = 81.13 t
 Lenac: 6.72 + 2.49 + 0 = 9.21 t
 Kraljevica: 3.13 + 0.44 + 0 = 3.57 t
 Rijeka: 6.17 + 1.66 + 20.66 = 28.49 t
 Bakar: 13.40 + 3.59 + 52.60 = 69.59 t
 Sušak: 80.51 + 16.71 + 36.70 = 133.92 t

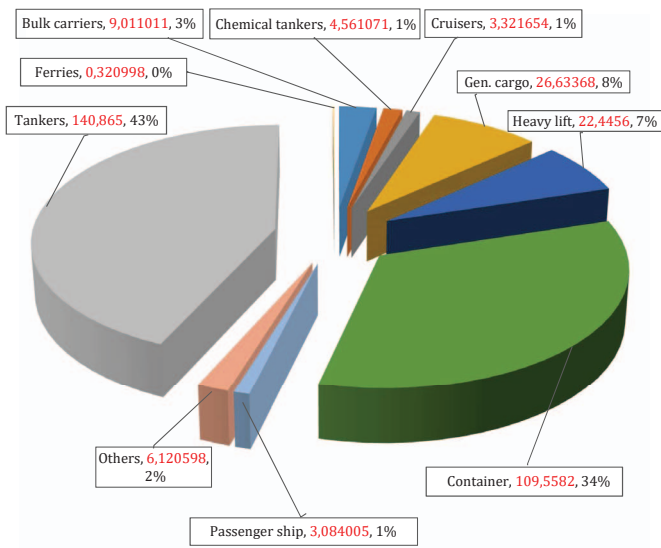


Figure 6 NOx emissions (t) and the percentage of total emissions for different types of ships (year 2017)

Source: authors

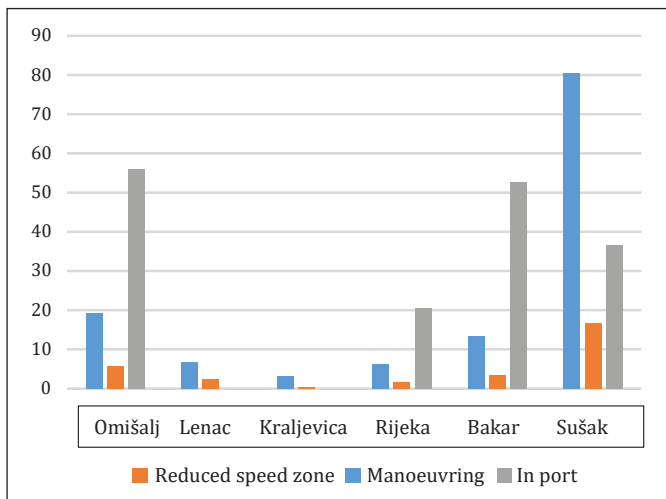


Figure 7 NOx emission (tons/year) for terminals with respect to different activities (year 2017)

Source: Authors

SOx emissions

The total emission of SOx gases in 2017 was 91.19 tons. SOx emissions (tons) and the percentage of total emissions for different types of ships (year 2017) are shown on Fig. 8 and emissions for each terminal (tons/year 2017) with respect to different activities are presented on Fig. 9. Numerical values are as follows:

Omišalj: 4.31 + 1.73 + 17.10 = 23.14 t
 Lenac: 1.56 + 0.78 + 0 = 2.34 t
 Kraljevica: 0.73 + 0.14 + 0 = 0.87 t
 Rijeka: 1.56 + 0.55 + 6.39 = 8.50 t
 Bakar: 3.30 + 1.02 + 17.35 = 21.67 t
 Sušak: 18.21 + 5.11 + 11.35 = 34.67 t

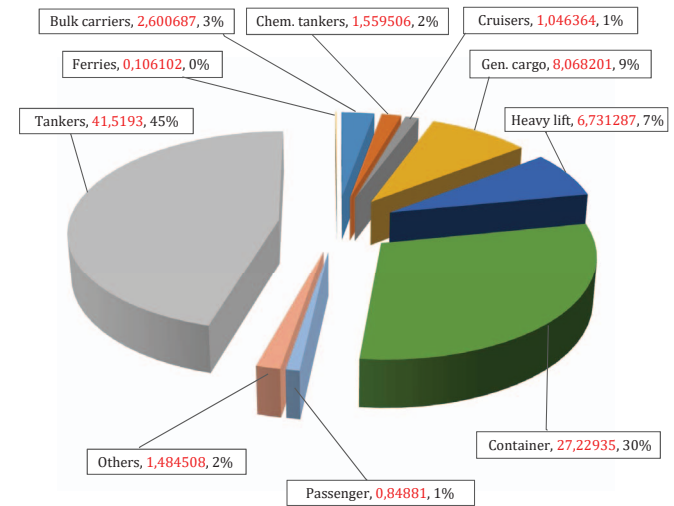


Figure 8 SOx emissions (t) and the percentage of total emissions for different types of ships (year 2017)

Source: Authors

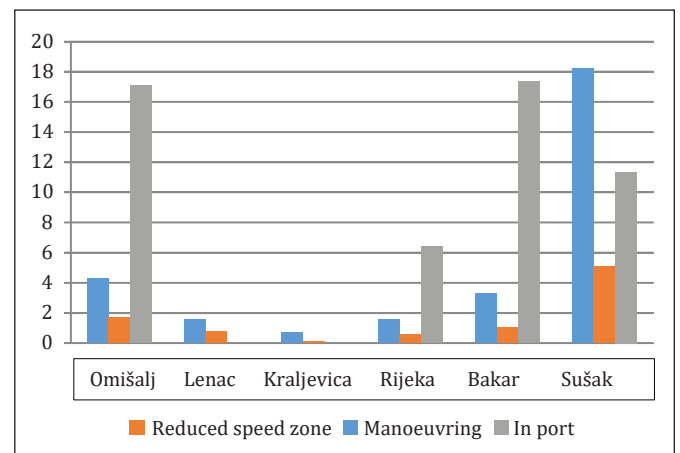


Figure 9 SOx emission (tons/year) for terminals with respect to different activities (year 2017)

Source: Authors

PM emissions

The total emission of PM in 2017 was 10.21 tons. PM emission (tons) and the percentage of total emissions for different type of ships (year 2017) are shown on Fig. 10 and emission for each terminal (tons/year 2017) with respect to different activities are presented on Fig. 11. Numerical values are as follows:

Omišalj: $0.35 + 0.31 + 2.70 = 3.36$ t
 Lenac: $0.12 + 0.13 + 0 = 0.25$ t
 Kraljevica: $0.06 + 0.02 + 0 = 0.08$ t
 Rijeka: $0.12 + 0.09 + 0.45 = 0.66$ t
 Bakar: $0.25 + 0.17 + 2.32 = 2.74$ t
 Sušak: $1.45 + 0.88 + 0.79 = 3.12$ t

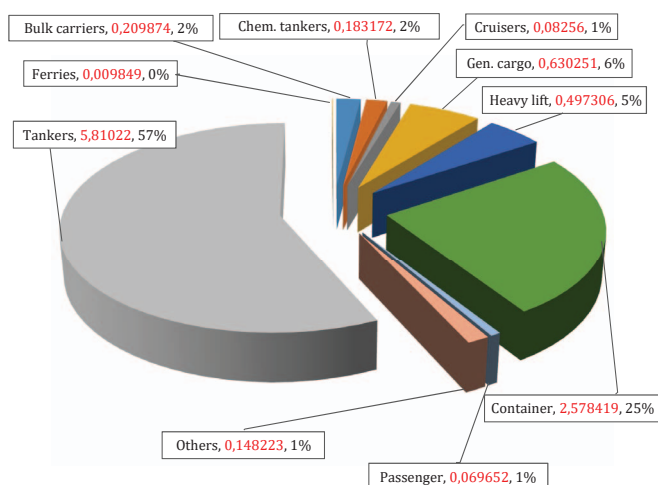


Figure 10 PM emissions (t) and the percentage of total emissions for different types of ships (year 2017)

Source: Authors

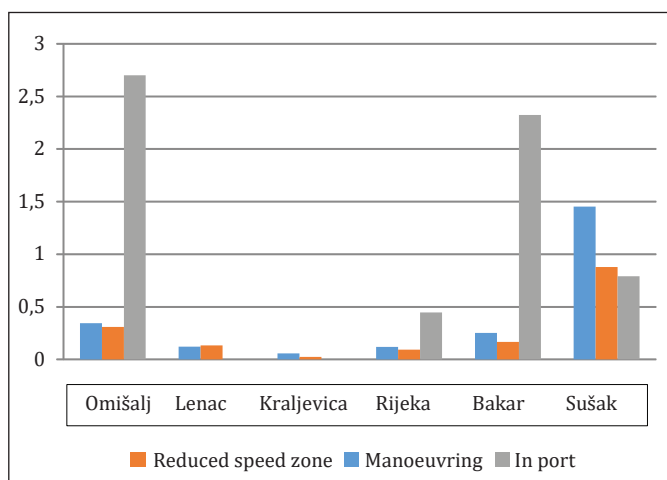


Figure 11 PM emission (tons/year) for terminals with respect to different activities (year 2017)

Source: Authors

5 Discussion

Total emissions for the Port of Rijeka in the year 2017 are: 14519.37 tons of CO₂, 325.91 tons of NO_x, 91.19 tons of SO_x and 10.21 tons of PM.

The greatest emissions are caused by tankers (45% of CO₂, 43% of NO_x, 45% of SO_x and 57% of PM) while berthed (Omišalj and Bakar) and from container ships (30% CO₂, 34% of NO_x, 30% of SO_x and 25% of PM) while approaching the berth at Sušak (RSZ and manoeuvring). The emissions from vessels approaching Kraljevica and Lenac shipyard are almost negligible.

However, such results were expected when taking into consideration the number of arrivals and the fact that those terminals are the busiest in the Port of Rijeka.

Taking into consideration the expansion in cruising industry, there is a possibility that Rijeka port basin will contribute more to total emission depending on the rise in the number of large cruiser arrivals.

6 Conclusion

The Port of Rijeka includes several berthing locations as port basins Rijeka and Sušak, Bay of Bakar basin, Omišalj basin (bay on the island of Krk) and Raša basin (located in Istria, so excluded from this research). It is the most important port in the Republic of Croatia and also the largest international seaport in Croatia.

The aim is to prepare the basic records for estimation and further monitoring with respect to changes in ongoing environmental legislation on international and national levels.

This port emission inventory includes overall international traffic of cargo and passenger ships in the year of 2017. Ships under 500 GT such as fishing vessels, yachts, catamarans and local tourist boats were excluded from the calculation of the emission inventory.

The bottom-up method (that starts from the ship characteristics and her activities) was used to estimate the amount of emission for the considered area and to allow comparison with previously prepared inventories in three other ports in Croatia, so contributing to the National Ships Emissions Inventory.

The results show that tanker and container terminals are the candidates for continuous monitoring of emission that might be included in the future strategic plans, both on the local and national level.

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