Interreg Italy - Croatia MIMOSA

EUROPEAN UNION

# D.4.4.2 ANALYSIS ON THE ENVIRONMENTAL IMPACT OF PASSENGER (CRUISE) SHIPS IN PORT OF ROVINJ

## WP4 – Analysing and piloting new sustainable mobility solutions

## 4.4. Pilot actions for adopting technological

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# Abstract

This report was prepared as part of the working package (WP) “Pilot actions for adopting technological solutions for emissions reducing” under the MIMOSA EU project (Maritime and multimodal sustainable passenger transport solutions and services) contracted by the Rovinj Port Authority, Rovinj, Croatia. An econometric model was built from scratch just for the purpose of the MIMOSA EU project. The econometric model that was developed for this purpose was used in the analysis of the impact of passenger ships (cruisers) on air quality in the port of Rovinj. Our guiding thought was finding a way to separate the effect of passenger ships (cruisers) and emissions given off by these transportation means from the other sources of emissions be it naturally occurring or emitted due to human and connected activities. In order to perform a two-step econometric analysis, the whole analyzed time period is divided into two subsamples - the time period in which the specified passenger vessels (cruisers) are not present T0 (base period – lower frequency period) and the period in which the specified vessels are present T1 (active period - higher frequency period).

In determining the connection between the level of emissions/pollution (according to the parameters mentioned above) and the atmospheric impact, readings from the base period alone are used.

Since for the year 2021 the data was available with a sampling frequency of 4 hours, passenger vessels that entered and/or departed in the times between sampling periods were assigned exponential weights depending on the temporal proximity of the measurement interval, which is also an approximation. For year 2022 where the sampling frequency was 15 minutes the above stated problem of passenger vessels that entered and/or departed in the times between sampling periods is much less pronounced.

In both analysed period, 2021 and 2022, as well as at both sampling frequencies, 4 hours and 15 minutes, there is a statistically significant relationship between the characteristics of the passenger ships docking in the Port of Rovinj and the emissions’ concentration in the air. The current level of all measured and analysed emissions (carbon dioxide (CO2), nitrogen monoxide (NO), nitrogen

dioxide $NO_2$, nitrogen oxides of the general formula $NO_x$ ($x = 0.5$ to 2) ($NO_x$), sulfur dioxide ($SO_2$), particles with an aerodynamic diameter of less than 1 µm (PM1), particles with an aerodynamic diameter of less than 2.5 µm (PM2.5), particles with an aerodynamic diameter of less than 4 µm (PM 4) and particles with an aerodynamic diameter of less than 10 µm (PM 10)) in each active period has been proven to be statistically significantly influenced by their corresponding base values (which were modelled through wind direction, wind speed, atmospheric pressure, air humidity and air temperature).

In addition to their base values, the influence of the gross tonnage and the combination of length and width of passenger vessels docking in Port of Rovinj has also been statistically proven. The size of the influence of the weight of the vessel varies depending on emission being analysed as well as the influence of the vessel's surface.

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# 1. Introduction

This report was prepared as part of the working package (WP) “Pilot actions for adopting technological solutions for emissions reducing” under the MIMOSA EU project (Maritime and multimodal sustainable passenger transport solutions and services) contracted by the Rovinj Port Authority, Rovinj, Croatia.

MIMOSA EU project is focused on changing a low level of cross-border connectivity by developing visible outputs, ranging from multimodal solutions to innovative and smart tools and technologies. It tackles the common challenge of increasing multimodality and reducing the impact of transport on the environment.

MIMOSA project details:

Start Date: 01.01.2020

End Date: 30.06.2023

Total Budget: 7.14 Million Eur

Rovinj Port Authority specific objective in the MIMOSA EU project:

*“4.1 Improve the quality, safety and environmental sustainability of marine and coastal transport services and nodes by promoting multimodality in the Programme area.”*

*D.4.4.2 No. 1 Analysis on environmental impact of passenger ships in Port of Rovinj. Focused on gathering information and relevant data about carbon emissions and particles from passenger ships, being Rovinj a port of call for cruise and passenger liners. Resp. Partner PP14 (M26)*

MIMOSA EU project target groups:

- General public
- Local, regional and national public authorities
- Enterprises, transport operators, including operators of multimodal logistics hubs, infrastructure providers
- Transport associations

Rovinj Port Authority’s role and undertaken actions in the MIMOSA EU project:

In the port of Valdibora, Rovinj, Croatia, as part of the MIMOSA EU project, a metering device was installed to measure emissions from ships during their stay in the Rovinj port. Based on the data obtained from the metering station, this study is made in order to empirically analyse the obtained data, construct a statistical model for identifying and quantifying/measuring the impact of ships’ emissions on the environment and draw conclusions regarding the environmental footprint of passenger ships (cruisers) in the Port of Rovinj.

The metering station/device in question was purchased as part of the implementation of pilot activities, and the goal is to contribute to the development of sustainable travel in the cross-border area.

With the aim of promoting maritime transport, the Port Authority Rovinj acquired and installed a smart bench that provides passers-by and passengers with information about maritime transport timetables.

The project was co-financed with the funds of the European Union, with a total value of Eur 7,140,000.00, of which the Rovinj Port Authority's budget is Eur 240,500.00. The completion of the project implementation is expected in June 2023.

Rovinj Port Authority is conducting 2 pilot activities, one of which is the installation of a device for measuring air quality and the impact of passenger ships on it.

**MIMOSA project work package (WP): Pilot actions for adopting technological solutions for emissions reducing**

**Description of Work package (WP):** With the aim of testing enhanced sustainable transport modalities, piloting the adoptions of technological solutions for reducing transport emissions, act. 4.4 envisages an analysis, a feasibility study, a mapping and a concrete pilot. In particular, in promoting electric mobility solutions in a Maas approach and new low carbon transport solutions at regional level, it must be taken into account that electric sharing services are an important and innovative way for changing transport behaviours (both for tourists and local people) as: users are curious to test electric vehicles; the use of electric vehicles in a sharing mode allows to overcome some psychological barriers nowadays reducing the diffusion of electric vehicles (trust in their reliability, batteries, etc.).Cross-border dimension is proved by the fact that those low carbon vehicles could be used by tourists reaching the Emilia-Romagna Region from Croatia and because those solutions can be easily replicated in other regions.

**(D.4.4.2) No. 1 Analysis on environmental impact of passenger ships in Port of Rovinj. Focused on gathering information and relevant data about carbon emissions and particles from passenger ships, being Rovinj a port of call for cruise and passenger liners. Resp. Partner PP14 (M26)**

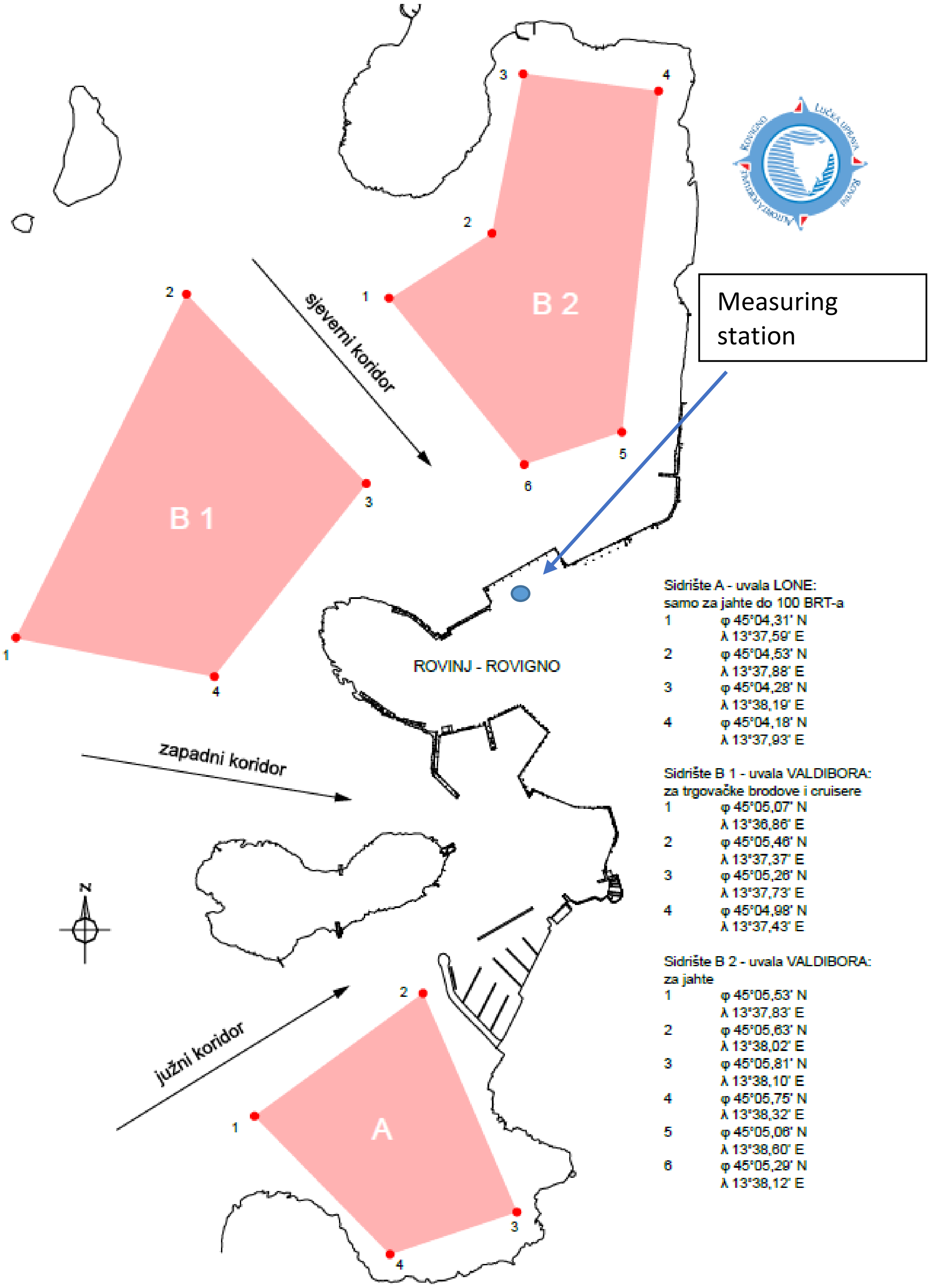
# 2. METHODOLOGY

One very obvious problem and a noteworthy limitation with the current level of performed analysis is that at the moment (and in both years, 2021 and 2022) the emissions' measurements were performed by just one measuring device located on land at Valdibora location of Port of Rovinj, Rovinj, Croatia.

Picture 1: Location of the on land metering device in Port of Rovinj, Rovinj, Croatia

As can be seen from the picture 2 the Port Authority Rovinj covers a significantly larger area for anchorage and for mooring (be it tying the vessel to a buoy, a marina berth pontoon or jetty). Emissions measuring at great majority of these locations cannot be performed by the current type of metering/measurement instrument. For off shore measurement a buoy based measuring devices should be used. Due to quite a large and dispersed anchorage/mooring area several such measuring devices should be used and can be combined with on land measuring devices (such as the current one) and other on land measuring devices such as ACI marina location (lone mooring station). This setup would provide a web of measuring devices that would pick up a more realistic

Picture 2: Port Authority Rovinj mooring/anchorage areas and location of the measuring station



In order to take into account, the influence of passenger vessels that did no use the location just next to the on land metering device we used an average weight of 30% on vessels' characteristics such as gross tonnage (GT), length, width and linear combinations of these measures

An econometric model was built from scratch just for the purpose of the MIMOSA EU project. The econometric model that was developed for this purpose was used in the analysis of the impact of passenger ships (cruisers) on air quality in the port of Rovinj. Our guiding thought was finding a way to separate the effect of passenger ships (cruisers) and emissions given off by these transportation means from the other sources of emissions be it naturally occurring or emitted due to human and connected activities.

We set up the model and the entire econometric analysis in two steps. The analysis was performed in the following way:

1) In the first step, we determined the equation describing the basic state (the state to which we refer to base or lower frequency of activity state) of pollution measured by the level of carbon dioxide (CO2), nitrogen monoxide (NO), nitrogen dioxide NO2, nitrogen oxides of the general formula NOx (x = 0.5 to 2) (NOx), sulfur dioxide (SO2). The was determined for particles with an aerodynamic diameter of less than 1 µm (PM1), particles with an aerodynamic diameter of less than 2.5 µm (PM2.5), particles with an aerodynamic diameter of less than 4 µm (PM 4), particles with an aerodynamic diameter of less than 10 µm (PM 10) in the air in the port of Rovinj. All of the emissions measurements were put in statistical relation to atmospheric parameters such as wind direction (WD), wind speed (WS), atmospheric pressure (PR), air humidity (HU) and temperature (TM), during the time periods when there were no cruisers, yachts, liners and excursion boats in the Port of Rovinj, Croatia.

It is important to note that all vessels of all the analyzed vessel categories use the same type of fuel, that is: Diesel EN 590, with a total sulfur content of up to 10 mg/kg, water up to 200 mg/kg, a minimum cetane number of 51 and a cetane index of 46. They may also contain up to 7% of methyl esters fatty acids (FAME) by volume. This fact eased the whole modelling process to a great extent since the data on type and power of main and auxiliary engines used by the analyzed vessels is not available from the data collected by Port Authority.

In order to perform a two-step econometric analysis, the whole analyzed time period is divided into two subsamples - the time period in which the specified passenger vessels (cruisers) are not present T0 (base period – lower frequency period) and the period in which the specified vessels are present T1 (active period - higher frequency period).

In determining the connection between the level of emissions/pollution (according to the parameters mentioned above) and the atmospheric impact, readings from the base period alone are used.

The setup is the equation for base values (T0):

$$Base\_CO_{2t} = \beta_0 + \beta_1 WD_t + \beta_2 WS_t + \beta_3 PR_t + \beta_4 HU_t + \beta_5 TM_t + u_t$$
$$Base\_NO_t = \beta_0 + \beta_1 WD_t + \beta_2 WS_t + \beta_3 PR_t + \beta_4 HU_t + \beta_5 TM_t + u_t$$
$$Base\_NO_{2t} = \beta_0 + \beta_1 WD_t + \beta_2 WS_t + \beta_3 PR_t + \beta_4 HU_t + \beta_5 TM_t + u_t$$
$$Base\_NO_{xt} = \beta_0 + \beta_1 WD_t + \beta_2 WS_t + \beta_3 PR_t + \beta_4 HU_t + \beta_5 TM_t + u_t$$
$$Base\_SO_{2t} = \beta_0 + \beta_1 WD_t + \beta_2 WS_t + \beta_3 PR_t + \beta_4 HU_t + \beta_5 TM_t + u_t$$
$$Base\_PM1_t = \beta_0 + \beta_1 WD_t + \beta_2 WS_t + \beta_3 PR_t + \beta_4 HU_t + \beta_5 TM_t + u_t$$
$$Base\_PM2.5_t = \beta_0 + \beta_1 WD_t + \beta_2 WS_t + \beta_3 PR_t + \beta_4 HU_t + \beta_5 TM_t + u_t$$
$$Base\_PM4_t = \beta_0 + \beta_1 WD_t + \beta_2 WS_t + \beta_3 PR_t + \beta_4 HU_t + \beta_5 TM_t + u_t$$
$$Base\_PM10_t = \beta_0 + \beta_1 WD_t + \beta_2 WS_t + \beta_3 PR_t + \beta_4 HU_t + \beta_5 TM_t + u_t$$

2) After determining the base (lower frequency) equation and optimized coefficients along with atmospheric parameters, the analysis is performed on time periods and emissions' readings

of values from the active (higher frequency) period (T1). In this second step of modelling passenger vessels' characteristics such as width, length (LE) and tonnage (TO) of the analyzed classes of vessels present in the port of Rovinj are included in the analysis.

Set up for the equations describing the active (higher frequency) period (T1) are composed of underlying base equations with the addition of vessel characteristic parameters:

$$Act\_CO_{2t} = \beta_0 + Base\_CO_{2t} + \beta_1 LE_t + \beta_2 TO_t + u_t$$
$$Act\_NO_t = \beta_0 + Base\_NO_t + \beta_1 LE_t + \beta_2 TO_t + u_t$$
$$Act\_NO_{2t} = \beta_0 + Base\_NO_{2t} + \beta_1 LE_t + \beta_2 TO_t + u_t$$
$$Act\_NO_{xt} = \beta_0 + Base\_NO_{xt} + \beta_1 LE_t + \beta_2 TO_t + u_t$$
$$Act\_PM1_t = \beta_0 + Base\_PM1_t + \beta_1 LE_t + \beta_2 TO_t + u_t$$
$$Act\_PM2.5_t = \beta_0 + Base\_PM2.5_t + \beta_1 LE_t + \beta_2 TO_t + u_t$$
$$Act\_PM4_t = \beta_0 + Base\_PM4_t + \beta_1 LE_t + \beta_2 TO_t + u_t$$
$$Act\_PM10_t = \beta_0 + Base\_PM10_t + \beta_1 LE_t + \beta_2 TO_t + u_t$$

For wind direction analysis we tried 8, 16 and 32-point wind rose but only the 8-point wind rose proved to be statistically significant in the analysis.

Since there is only one (1) measuring station, passenger vessels that are moored away from Valdibora measuring station or tied by an anchor, i.e. far from the port mooring, were weighted by 30% of their mass, length and width, which represents a rough approximation.

Since for the year 2021 the data was available with a sampling frequency of 4 hours, passenger vessels that entered and/or departed in the times between sampling periods were assigned exponential weights depending on the temporal proximity of the measurement interval, which is also an approximation.

For year 2022 where the sampling frequency was 15 minutes the above stated problem of passenger vessels that entered and/or departed in the times between sampling periods is much less pronounced.

# 3. EMPIRICAL ANALYSIS OF RESULTS FOR THE YEAR 2021

Analysis for 2021 – observation period and frequency of data collection.

- Analysed period from 21/05/2021, 12:00h until 30/10/2021, 20:00h, frequency 4 hours, location Valdibora, Rovinj, Croatia

- T0 (lower frequency of activity)

Analysed period from 21/05/2021, 12:00h until 24/05/2021, 16:00 and from 29/09/2022, 20:00 h until 30/10/2021, 20:00h, frequency 4 hours, location Valdibora, Rovinj, Croatia

- T1 (higher frequency of activity)

Analysed period from 24/05/2021, 16:00h until 29/09/2021, 20:00h, frequency 4 hours, location Valdibora, Rovinj, Croatia

**Descriptive statistics for gases and particles emissions in year 2021**

Emissions values for base period – lower frequency of activity (T0) (values for: CO2 NO NO2 NOX SO2 PM1 PM25 PM4 PM10), period from 21/05/2021, 12:00h until 24/05/2021, 16:00 and from 29/09/2022, 20:00 h until 30/10/2021, 20:00h, frequency 4 hours

| Variable | Obs | Mean | Std. Dev. | Min | Max |
|---|---|---|---|---|---|
| CO2 | 201 | 421.8954 | 9.082611 | 403.91 | 446.51 |
| NO | 201 | 10.14498 | 5.913928 | -.11 | 35.72 |

| | | | | | |
|---|---|---|---|---|---|
| NO2 | 201 | 7.925622 | 2.725063 | 3.15 | 18.25 |
| NOX | 201 | 18.0709 | 7.136534 | 7.17 | 44.62 |
| SO2 | 201 | .2026368 | .5010075 | -.85 | 2.13 |
| PM1 | 201 | 10.98204 | 10.98007 | -.81 | 69.15 |
| PM25 | 201 | 11.48164 | 9.02893 | 2.13 | 63.72 |
| PM4 | 201 | 12.02955 | 7.559058 | 4.23 | 58.12 |
| PM10 | 201 | 14.41398 | 8.715671 | 4.57 | 65.9 |

Emissions values for base period – higher frequency of activity (T1) (values for: CO2 NO NO2 NOX SO2 PM1 PM25 PM4 PM10), period from 24/05/2021, 16:00 until 29/09/2022, 20:00 h, frequency 4 hours

| Variable | Obs | Mean | Std. Dev. | Min | Max |
|---|---|---|---|---|---|
| CO2 | 744 | 412.4235 | 10.20697 | 393.53 | 475.99 |
| NO | 744 | 20.08966 | 41.27399 | -.34 | 620.4 |
| NO2 | 744 | 16.62272 | 7.991529 | 4.1 | 61.23 |
| NOX | 744 | 36.71216 | 45.92006 | 5.93 | 681.63 |
| SO2 | 744 | 1.911304 | 1.465756 | -.49 | 9.4 |
| PM1 | 744 | 10.60908 | 5.839661 | 1.16 | 49.87 |
| PM25 | 744 | 11.17736 | 4.836659 | 3.75 | 46.09 |
| PM4 | 744 | 11.80319 | 4.264677 | 5.4 | 41.55 |
| PM10 | 744 | 15.26864 | 7.206925 | 5.95 | 58.5 |

Emissions values for base period – lower frequency of activity (T0) (values for: CO2 NO NO2 NOX SO2 PM1 PM25 PM4 PM10), period from 21/05/2021, 12:00h until 24/05/2021, 16:00 and from 29/09/2022, 20:00 h until 30/10/2021, 20:00h, frequency 4 hours

| Variable | n | Mean | S.D. | Min | .25 | Mdn | .75 | Max |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| | | | | Quantiles | | | | |
| CO2 | 201 | 421.90 | 9.08 | 403.91 | 414.56 | 421.79 | 427.73 | 446.51 |
| NO | 201 | 10.14 | 5.91 | -0.11 | 6.25 | 9.55 | 12.40 | 35.72 |
| NO2 | 201 | 7.93 | 2.73 | 3.15 | 5.72 | 7.94 | 9.31 | 18.25 |
| NOX | 201 | 18.07 | 7.14 | 7.17 | 13.48 | 16.69 | 21.30 | 44.62 |
| SO2 | 201 | 0.20 | 0.50 | -0.85 | -0.13 | 0.14 | 0.50 | 2.13 |
| PM1 | 201 | 10.98 | 10.98 | -0.81 | 4.19 | 8.42 | 13.02 | 69.15 |
| PM25 | 201 | 11.48 | 9.03 | 2.13 | 5.96 | 9.19 | 13.37 | 63.72 |
| PM4 | 201 | 12.03 | 7.56 | 4.23 | 7.57 | 10.08 | 14.16 | 58.12 |
| PM10 | 201 | 14.41 | 8.72 | 4.57 | 8.92 | 12.16 | 17.88 | 65.90 |

Emissions values for base period – higher frequency of activity (T1) (values for: CO2 NO NO2 NOX SO2 PM1 PM25 PM4 PM10), period from 24/05/2021, 16:00 until 29/09/2022, 20:00 h, frequency 4 hours

| Variable | n | Mean | S.D. | Min | .25 | Mdn | .75 | Max |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| | | | | Quantiles | | | | |
| CO2 | 744 | 412.42 | 10.21 | 393.53 | 405.75 | 410.65 | 416.81 | 475.99 |
| NO | 744 | 20.09 | 41.27 | -0.34 | 7.68 | 12.84 | 20.61 | 620.40 |
| NO2 | 744 | 16.62 | 7.99 | 4.10 | 11.13 | 14.75 | 20.50 | 61.23 |
| NOX | 744 | 36.71 | 45.92 | 5.93 | 18.77 | 27.09 | 40.11 | 681.63 |
| SO2 | 744 | 1.91 | 1.47 | -0.49 | 0.85 | 1.62 | 2.69 | 9.40 |
| PM1 | 744 | 10.61 | 5.84 | 1.16 | 6.39 | 9.11 | 13.97 | 49.87 |
| PM25 | 744 | 11.18 | 4.84 | 3.75 | 7.62 | 9.91 | 14.11 | 46.09 |
| PM4 | 744 | 11.80 | 4.26 | 5.40 | 8.82 | 10.77 | 14.11 | 41.55 |
| PM10 | 744 | 15.27 | 7.21 | 5.95 | 10.52 | 13.56 | 17.79 | 58.50 |

## 1st Step - Baseline model – without clustered standardised errors, frequency 4 hours, 2021

| VARIABLES | (1) **CO2_base** | (2) **NO_base** | (3) **NO2_base** | (4) **NOX_base** | (5) **SO2_base** | (6) **PM1_base** | (7) **PM2.5_base** | (8) **PM4_base** | (9) **PM10_base** |
|---|---|---|---|---|---|---|---|---|---|
| WD8 | -0.067 | 0.456 | 0.007 | 0.462 | -0.010 | 0.350 | 0.269 | 0.189 | 0.118 |
| | [-0.265] | [1.556] | [0.060] | [1.303] | [-0.454] | [0.729] | [0.670] | [0.559] | [0.305] |
| | (0.254) | (0.293) | (0.112) | (0.355) | (0.022) | (0.480) | (0.401) | (0.338) | (0.386) |
| WS | -1.346*** | 0.237 | -0.787*** | -0.551 | -0.206*** | -2.408*** | -1.996*** | -1.654*** | -1.865*** |
| | [-3.830] | [0.585] | [-5.069] | [-1.124] | [-6.838] | [-3.631] | [-3.603] | [-3.537] | [-3.498] |
| | (0.351) | (0.405) | (0.155) | (0.490) | (0.030) | (0.663) | (0.554) | (0.468) | (0.533) |
| PR | 1.069*** | 0.173 | 0.045 | 0.218* | -0.001 | 0.750*** | 0.582*** | 0.443*** | 0.361*** |
| | [11.766] | [1.650] | [1.116] | [1.715] | [-0.104] | [4.373] | [4.062] | [3.666] | [2.621] |
| | (0.091) | (0.105) | (0.040) | (0.127) | (0.008) | (0.172) | (0.143) | (0.121) | (0.138) |
| HU | 0.576*** | 0.224*** | 0.055*** | 0.279*** | 0.012*** | 0.483*** | 0.390*** | 0.332*** | 0.422*** |
| | [15.385] | [5.191] | [3.322] | [5.336] | [3.800] | [6.839] | [6.610] | [6.670] | [7.425] |
| | (0.037) | (0.043) | (0.017) | (0.052) | (0.003) | (0.071) | (0.059) | (0.050) | (0.057) |
| TEMP | -0.532*** | -0.347*** | 0.374*** | 0.027 | 0.035*** | -0.168 | -0.070 | 0.011 | 0.166 |
| | [-5.850] | [-3.313] | [9.291] | [0.209] | [4.432] | [-0.976] | [-0.490] | [0.089] | [1.203] |
| | (0.091) | (0.105) | (0.040) | (0.127) | (0.008) | (0.172) | (0.143) | (0.121) | (0.138) |
| Constant | -693.199*** | -176.364 | -45.995 | -222.274* | 0.089 | -778.343*** | -602.637*** | -458.862*** | -380.403*** |
| | [-7.409] | [-1.636] | [-1.112] | [-1.702] | [0.011] | [-4.407] | [-4.086] | [-3.685] | [-2.680] |
| | (93.566) | (107.792) | (41.364) | (130.567) | (8.040) | (176.614) | (147.505) | (124.519) | (141.956) |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Observations | 201 | 201 | 201 | 201 | 201 | 201 | 201 | 201 | 201 |
| R-squared | 0.736 | 0.173 | 0.427 | 0.167 | 0.359 | 0.356 | 0.336 | 0.325 | 0.340 |

Standard errors in brackets *** p<0.01, ** p<0.05, * p<0.1

**2nd Step - Active model – without clustered standardised errors, frequency 4 hours, 2021**

| VARIABLES | (1)<br>**CO2_act** | (2)<br>**NO_act** | (3)<br>**NO2_act** | (4)<br>**NOX_act** | (5)<br>**SO2_act** | (6)<br>**PM1_act** | (7)<br>**PM2.5_act** | (8)<br>**PM4_act** | (9)<br>**PM10_act** |
|---|---|---|---|---|---|---|---|---|---|
| CO2_base | 0.924*** | | | | | | | | |
| | [23.200] | | | | | | | | |
| | (0.040) | | | | | | | | |
| Tot_GT | 0.000 | 0.003*** | 0.000*** | 0.004*** | 0.000*** | 0.000*** | 0.000*** | 0.000*** | 0.000** |
| | [0.934] | [3.841] | [4.703] | [4.990] | [4.210] | [3.549] | [4.044] | [3.855] | [2.491] |
| | (0.000) | (0.001) | (0.000) | (0.001) | (0.000) | (0.000) | (0.000) | (0.000) | (0.000) |
| NO_base | | -0.954* | | | | | | | |
| | | [-1.658] | | | | | | | |
| | | (0.576) | | | | | | | |
| NO2_base | | | 4.052*** | | | | | | |
| | | | [37.159] | | | | | | |
| | | | (0.109) | | | | | | |
| NOX_base | | | | 1.214 | | | | | |
| | | | | [1.641] | | | | | |
| | | | | (0.740) | | | | | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| SO2_base | | | | | 4.180*** | | | | |
| | | | | | [20.087] | | | | |
| | | | | | (0.208) | | | | |
| PM1_base | | | | | | 0.210*** | | | |
| | | | | | | [5.174] | | | |
| | | | | | | (0.041) | | | |
| PM25_base | | | | | | | 0.191*** | | |
| | | | | | | | [4.413] | | |
| | | | | | | | (0.043) | | |
| PM4_base | | | | | | | | 0.226*** | |
| | | | | | | | | [4.700] | |
| | | | | | | | | (0.048) | |
| PM10_base | | | | | | | | | 0.458*** |
| | | | | | | | | | [6.249] |
| | | | | | | | | | (0.073) |
| Constant | 33.075** | 21.808*** | -28.326*** | 11.985 | -0.305*** | 9.161*** | 9.389*** | 9.382*** | 8.992*** |
| | [2.021] | [5.919] | [-23.644] | [0.970] | [-2.665] | [28.749] | [24.826] | [19.450] | [8.983] |
| | (16.368) | (3.684) | (1.198) | (12.355) | (0.114) | (0.319) | (0.378) | (0.482) | (1.001) |
| Observations | 744 | 744 | 744 | 744 | 744 | 744 | 744 | 744 | 744 |
| R-squared | 0.422 | 0.027 | 0.668 | 0.034 | 0.371 | 0.047 | 0.043 | 0.044 | 0.055 |

Standard errors in brackets, *** p<0.01, ** p<0.05, * p<0.1

## 1st Step - Baseline model – clustered standardised errors, frequency 4 hours, 2021

| VARIABLES | (1) CO2_base_c | (2) NO_base_c | (3) NO2_base_c | (4) NOX_base_c | (5) SO2_base_c | (6) PM1_base_c | (7) PM2.5_base_c | (8) PM4_base_c | (9) PM10_base_c |
|---|---|---|---|---|---|---|---|---|---|
| WD8 | -0.067 | 0.456 | 0.007 | 0.462 | -0.010 | 0.350 | 0.269 | 0.189 | 0.118 |
| | [-0.300] | [1.596] | [0.074] | [1.427] | [-0.542] | [0.832] | [0.790] | [0.676] | [0.370] |
| | (0.225) | (0.286) | (0.091) | (0.324) | (0.018) | (0.421) | (0.340) | (0.280) | (0.318) |
| WS | -1.346*** | 0.237 | -0.787*** | -0.551 | -0.206*** | -2.408*** | -1.996*** | -1.654*** | -1.865*** |
| | [-4.367] | [0.658] | [-5.669] | [-1.274] | [-7.219] | [-5.123] | [-5.297] | [-5.421] | [-5.290] |
| | (0.308) | (0.360) | (0.139) | (0.433) | (0.029) | (0.470) | (0.377) | (0.305) | (0.352) |
| PR | 1.069*** | 0.173* | 0.045 | 0.218* | -0.001 | 0.750*** | 0.582*** | 0.443*** | 0.361* |
| | [11.557] | [1.734] | [1.038] | [1.677] | [-0.099] | [3.508] | [3.084] | [2.683] | [1.922] |
| | (0.093) | (0.100) | (0.043) | (0.130) | (0.008) | (0.214) | (0.189) | (0.165) | (0.188) |
| HU | 0.576*** | 0.224*** | 0.055*** | 0.279*** | 0.012*** | 0.483*** | 0.390*** | 0.332*** | 0.422*** |
| | [14.096] | [4.382] | [3.184] | [4.655] | [3.741] | [6.679] | [6.412] | [6.406] | [7.170] |
| | (0.041) | (0.051) | (0.017) | (0.060) | (0.003) | (0.072) | (0.061) | (0.052) | (0.059) |
| TEMP | -0.532*** | -0.347*** | 0.374*** | 0.027 | 0.035*** | -0.168 | -0.070 | 0.011 | 0.166 |
| | [-6.650] | [-4.665] | [11.289] | [0.294] | [5.578] | [-1.125] | [-0.569] | [0.104] | [1.373] |
| | (0.080) | (0.074) | (0.033) | (0.090) | (0.006) | (0.149) | (0.123) | (0.104) | (0.121) |
| Constant | -693.199*** | -176.364* | -45.995 | -222.274* | 0.089 | -778.343*** | -602.637*** | -458.862*** | -380.403* |
| | [-7.262] | [-1.739] | [-1.035] | [-1.678] | [0.011] | [-3.524] | [-3.090] | [-2.687] | [-1.960] |
| | (95.455) | (101.439) | (44.436) | (132.472) | (8.452) | (220.875) | (194.999) | (170.771) | (194.049) |

| Observations | 201 | 201 | 201 | 201 | 201 | 201 | 201 | 201 | 201 |
|---|---|---|---|---|---|---|---|---|---|
| R-squared | 0.736 | 0.173 | 0.427 | 0.167 | 0.359 | 0.356 | 0.336 | 0.325 | 0.340 |

Robust standard errors in brackets *** p<0.01, ** p<0.05, * p<0.1

### 2nd Step – Active model – clustered standardised errors, frequency 4 hours, 2021

| VARIABLES | (1)<br>**CO2_act _c** | (2)<br>**NO_act _c** | (3)<br>**NO2_act _c** | (4)<br>**NOX_act _c** | (5)<br>**SO2_act _c** | (6)<br>**PM1_act _c** | (7)<br>**PM2.5_act _c** | (8)<br>**PM4_act _c** | (9)<br>**PM10_act _c** |
|---|---|---|---|---|---|---|---|---|---|
| CO2_base_c | 0.924*** | | | | | | | | |
| | [23.168] | | | | | | | | |
| | (0.040) | | | | | | | | |
| Tot_GT | 0.001** | 0.003*** | 0.000*** | 0.004*** | 0.000*** | 0.000* | 0.000** | 0.000** | 0.000* |
| | [1.981] | [3.123] | [3.482] | [3.875] | [2.611] | [1.777] | [1.966] | [1.984] | [1.876] |
| | (0.000) | (0.001) | (0.000) | (0.001) | (0.000) | (0.000) | (0.000) | (0.000) | (0.000) |
| NO_base_c | | -0.954** | | | | | | | |
| | | [-2.571] | | | | | | | |
| | | (0.371) | | | | | | | |
| NO2_base_c | | | 4.052*** | | | | | | |
| | | | [30.027] | | | | | | |
| | | | (0.135) | | | | | | |
| NOX_base_c | | | | 1.214** | | | | | |
| | | | | [2.109] | | | | | |
| | | | | (0.576) | | | | | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| SO2_base_c | | | | | 4.180*** | | | | |
| | | | | | [17.511] | | | | |
| | | | | | (0.239) | | | | |
| PM1_base_c | | | | | | 0.210*** | | | |
| | | | | | | [4.740] | | | |
| | | | | | | (0.044) | | | |
| PM25_base_c | | | | | | | 0.191*** | | |
| | | | | | | | [4.022] | | |
| | | | | | | | (0.048) | | |
| PM4_base_c | | | | | | | | 0.226*** | |
| | | | | | | | | [4.399] | |
| | | | | | | | | (0.051) | |
| PM10_base_c | | | | | | | | | 0.458*** |
| | | | | | | | | | [6.771] |
| | | | | | | | | | (0.068) |
| Constant | 33.075** | 21.808*** | -28.326*** | 11.985 | -0.305** | 9.161*** | 9.389*** | 9.382*** | 8.992*** |
| | [2.030] | [9.763] | [-19.923] | [1.301] | [-2.504] | [24.628] | [21.339] | [17.404] | [9.676] |
| | (16.294) | (2.234) | (1.422) | (9.212) | (0.122) | (0.372) | (0.440) | (0.539) | (0.929) |
| Observations | 744 | 744 | 744 | 744 | 744 | 744 | 744 | 744 | 744 |
| R-squared | 0.422 | 0.027 | 0.668 | 0.034 | 0.371 | 0.047 | 0.043 | 0.044 | 0.055 |

Standard errors in brackets, *** p<0.01, ** p<0.05, * p<0.1

**Explanation of the results of the econometric analysis – influence of passenger vessels' characteristics on emissions (2021, 4h sampling frequency)**

**$CO_2$** – the current level of $CO_2$ in each active period has been proven to be largely and significantly influenced by the base $CO_2$ (which is modelled through wind direction, wind speed, atmospheric pressure, air humidity and air temperature). In addition to the base $CO_2$, the influence (explanatory power) of the tonnage of ships docking in Port of Rovinj has also been statistically proven. The influence of length, width and the combination of length and width of the passenger vessel was not statistically significant. The size of the influence of the weight of the vessel on the $CO_2$ level is 1 ppm for every 1,000 tons of vessel weight (gross tonnage).

**NO** – a large influence of base NO (which is modelled through wind direction, wind speed, atmospheric pressure, air humidity and air temperature) has been proven on the current NO level in each active period. In addition to the base NO, the influence (explanatory power) of the tonnage of ships docking in Port of Rovinj, although small, has also been statistically proven. The size of the influence of the weight of the vessel on the NO level is 3 ppm for every 1,000 tons of vessel weight (gross tonnage).

**$NO_2$** – the current level of $NO_2$ in each active period has been proven to be largely and significantly influenced by the base $NO_2$ (which is modelled through wind direction, wind speed, atmospheric pressure, air humidity and air temperature). In addition to the base $NO_2$, the influence (explanatory power) of the tonnage of ships docking in Rovinj has also been statistically proven. The size of the influence of the weight of the vessel on the $CO_2$ level is 1 ppm for every 1,000 tons of vessel weight (gross tonnage).

**$NO_x$** – the current level of $NO_x$ in each active period has been proven to be largely and significantly influenced by the base $NO_x$ (which is modelled through wind direction, wind speed, atmospheric pressure, air humidity and air temperature). In addition to the base $NO_x$, the influence (explanatory power) of the tonnage of ships docking in Rovinj, although small, has also been statistically proven. The size of the influence of the weight of the vessel on the NOx level is 4 ppm for every 1,000 tons of vessel weight (gross tonnage).

**SO2** – the current level of SO2 in each active period has been proven to be largely and significantly influenced by the base SO2 (which is modelled through wind direction, wind speed, atmospheric pressure, air humidity and air temperature). In addition to the base SO2, the influence (explanatory power) of the tonnage of ships docking in Rovinj, has also been statistically proven. The size of the influence of the weight of the vessel on the SO2 level is 1 ppm for every 1,000 tons of vessel weight (gross tonnage).

**PM1** – the current level of PM1 in each active period has been proven to be largely and significantly influenced by the base PM1 (which is modelled through wind direction, wind speed, atmospheric pressure, air humidity and air temperature). In addition to the base PM1, the influence (explanatory power) of the tonnage of ships docking in Rovinj, although small, has also been statistically proven. The size of the influence of the weight of the vessel on the PM1 level is 1 ppm for every 1,000 tons of vessel weight (gross tonnage).

**PM2.5** – the current level of PM2.5 in each active period has been proven to be largely and significantly influenced by the base PM2.5 (which is modelled through wind direction, wind speed, atmospheric pressure, air humidity and air temperature). In addition to the basic PM2.5, the influence (explanatory power) of the tonnage of ships docking in Rovinj, although small, has also been statistically proven. The size of the influence of the weight of the vessel on the PM2.5 level is 1 ppm for every 1,000 tons of vessel weight (gross tonnage).

**PM4** – the current level of PM4 in each active period has been proven to be largely and significantly influenced by the base PM4 (which is modelled through wind direction, wind speed, atmospheric pressure, air humidity and air temperature). In addition to the base PM4, the influence (explanatory power) of the tonnage of ships docking in Rovinj, although small, has also been statistically proven. The size of the influence of the weight of the vessel on the PM4 level is 1 ppm for every 1,000 tons of vessel weight (gross tonnage).

**PM10** – the current level of PM10 in each active period has been proven to be largely and significantly influenced by the base PM10 (which is modelled through wind direction, wind speed, atmospheric pressure, air humidity and air temperature). In addition to the base PM10, the influence (explanatory power) of the tonnage of ships docking in Rovinj, although small, has also been statistically proven. The size of the influence of the weight of the vessel on the PM10 level is 1 ppm for every 1,000 tons of vessel weight (gross tonnage).
**While significant results were obtained for all of the analysed variables, under both active models – 1 (vessel's length x width as the explanatory variable) and 2 (vessel's tonnage (GT), the vessels' characteristics (the ones that were available to us, namely ship's tonnage, length and width) only had decent explanatory power (measured by R2) on the following measured emission variables: CO2, NO2 and SO2.**

**Limitations of the performed analysis**

Based on the analysed data and its characteristics we can point out a couple of limitations of this analysis as well as suggestions for future data collection:

- It is necessary to analyze data with a much higher frequency, for example 15 or 30 min intervals, in order to better cover the arrivals/departures of ships.
- The installation of new measuring devices is necessary, since the current measuring device covers only the port berth, and there are three more anchorage fields, and for a more precise and robust calculation, it would be necessary to install measuring devices, at least, in those locations as well.
- Better calibration of the device because it reports negative values for certain pollutants in certain periods.

# 4. EMPIRICAL ANALYSIS OF RESULTS FOR THE YEAR 2022

Analysis for 2022 – observation period and frequency of data collection

- Analysed period from 01.05.2022, 00:00h until 30.09.2022, 00:00h, frequency 15 minutes, location Valdibora, Rovinj, Croatia

T0 (lower frequency of activity)

- Analysed period from 01.05.2022, 11:00h until 05.05.2022, 11:00h and from 26.09.2022, 15:30h until 30.09.2022, 00:00h, frequency 15 minutes, location Valdibora, Rovinj, Croatia

T1 (higher frequency of activity)

- Analysed period from 05.05.2022, 11:00h until 26.09.2022, 15:30h, frequency 15 minutes, location Valdibora, Rovinj, Croatia

**Descriptive statistics for gases and particles emissions in year 2022**

Emissions values for base period – lower frequency of activity (T0) (values for: CO2 NO NO2 NOX SO2 PM1 PM25 PM4 PM10), period from 01.05.2022, 11:00h until 05.05.2022, 11:00h and from 26.09.2022, 15:30h until 30.09.2022, 00:00h, frequency 15 minutes, location Valdibora, Rovinj, Croatia

| | | | | Quantiles | | | | |
|---|---|---|---|---|---|---|---|---|
| Variable | n | Mean | S.D. | Min | .25 | Mdn | .75 | Max |
| CO2 | 750 | 406.28 | 12.52 | 384.90 | 397.12 | 405.39 | 414.38 | 448.17 |
| NO | 750 | 9.01 | 4.81 | -2.35 | 6.85 | 9.07 | 10.83 | 46.87 |
| NO2 | 750 | 10.26 | 3.08 | 3.32 | 8.37 | 10.23 | 12.01 | 28.65 |
| NOX | 750 | 19.27 | 6.20 | 2.00 | 16.70 | 19.05 | 21.29 | 61.68 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| SO2 | 750 | 0.08 | 0.60 | -1.46 | -0.31 | 0.02 | 0.44 | 2.86 |
| PM1 | 749 | 10.80 | 10.71 | -0.88 | 2.74 | 10.30 | 13.63 | 119.64 |
| PM25 | 749 | 10.37 | 6.85 | 1.89 | 5.66 | 9.82 | 12.29 | 94.84 |
| PM4 | 749 | 10.80 | 4.94 | 3.90 | 8.03 | 10.20 | 12.05 | 80.76 |
| PM10 | 749 | 12.58 | 5.04 | 4.33 | 10.16 | 11.78 | 13.58 | 85.39 |

Emissions values for base period – higher frequency of activity (T1) (values for: CO2 NO NO2 NOX SO2 PM1 PM25 PM4 PM10), period from 05.05.2022, 11:00h until 26.09.2022, 15:30h, frequency 15 minutes, location Valdibora, Rovinj, Croatia

| | | | | Quantiles | | | | |
|---|---|---|---|---|---|---|---|---|
| Variable | n | Mean | S.D. | Min | .25 | Mdn | .75 | Max |
| CO2 | 13553 | 404.59 | 13.11 | 377.71 | 394.97 | 402.88 | 411.50 | 472.62 |
| NO | 13551 | 19.44 | 15.36 | -2.93 | 10.62 | 14.77 | 23.96 | 306.43 |
| NO2 | 13551 | 19.10 | 9.57 | 1.19 | 12.45 | 16.95 | 23.30 | 142.98 |
| NOX | 13551 | 38.54 | 23.60 | 4.07 | 23.55 | 31.59 | 46.50 | 449.41 |
| SO2 | 13551 | 1.59 | 1.49 | -2.18 | 0.59 | 1.31 | 2.25 | 17.57 |
| PM1 | 13207 | 9.22 | 9.65 | -1.30 | 4.06 | 7.05 | 12.35 | 148.04 |
| PM25 | 13207 | 9.15 | 7.25 | 1.69 | 5.45 | 7.66 | 11.32 | 121.31 |
| PM4 | 13207 | 9.77 | 5.64 | 3.68 | 6.76 | 8.69 | 11.54 | 95.31 |
| PM10 | 13207 | 12.06 | 7.03 | 3.93 | 7.72 | 10.51 | 14.68 | 96.28 |

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## 1st Step - Baseline model – clustered standardised errors, frequency 15 minutes, 2022

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|---|
| *VARIABLES* | *CO2_base* | *NO_base* | *NO2_base* | *NOX_base* | *SO2_base* | *PM1_base* | *PM25_base* | *PM4_base* | *PM10_base* |
| **WD8** | 0.247** | 0.269*** | 0.039 | 0.308** | 0.026** | 0.018 | 0.040 | 0.042 | 0.058 |
| | [2.477] | [2.780] | [0.637] | [2.212] | [2.416] | [0.124] | [0.406] | [0.563] | [0.746] |
| | (0.100) | (0.097) | (0.062) | (0.139) | (0.011) | (0.141) | (0.098) | (0.074) | (0.078) |
| **WS** | -1.410*** | 0.098 | -0.226*** | -0.128 | -0.090*** | -0.811*** | -0.412*** | -0.204*** | -0.065 |
| | [-12.204] | [0.935] | [-4.485] | [-1.060] | [-7.375] | [-4.841] | [-4.112] | [-2.605] | [-0.598] |
| | (0.116) | (0.105) | (0.050) | (0.121) | (0.012) | (0.167) | (0.100) | (0.078) | (0.108) |
| **PR** | 1.019*** | 0.095*** | 0.050*** | 0.144*** | -0.010*** | 0.936*** | 0.599*** | 0.394*** | 0.303*** |
| | [23.998] | [3.166] | [3.262] | [4.229] | [-2.615] | [19.494] | [18.352] | [15.470] | [10.497] |
| | (0.042) | (0.030) | (0.015) | (0.034) | (0.004) | (0.048) | (0.033) | (0.025) | (0.029) |
| **HU** | 0.611*** | 0.151*** | 0.161*** | 0.311*** | 0.035*** | 0.537*** | 0.310*** | 0.213*** | 0.225*** |
| | [17.306] | [4.425] | [13.026] | [8.282] | [11.446] | [9.206] | [9.082] | [8.626] | [8.173] |
| | (0.035) | (0.034) | (0.012) | (0.038) | (0.003) | (0.058) | (0.034) | (0.025) | (0.028) |
| **TEMP** | -1.265*** | 0.051 | 0.602*** | 0.653*** | 0.042*** | 0.302*** | 0.260*** | 0.231*** | 0.302*** |
| | [-18.660] | [0.734] | [13.585] | [6.739] | [5.261] | [3.981] | [5.207] | [6.043] | [6.654] |
| | (0.068) | (0.070) | (0.044) | (0.097) | (0.008) | (0.076) | (0.050) | (0.038) | (0.045) |
| **Constant** | -636.238*** | -98.464*** | -61.223*** | -159.653*** | 7.284* | -972.235*** | -618.305*** | -404.722*** | -313.062*** |
| | [-14.126] | [-3.055] | [-3.760] | [-4.330] | [1.768] | [-19.536] | [-18.161] | [-15.206] | [-10.347] |
| | (45.040) | (32.229) | (16.284) | (36.871) | (4.120) | (49.767) | (34.046) | (26.616) | (30.257) |
| **Observations** | 750 | 750 | 750 | 750 | 750 | 749 | 749 | 749 | 749 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **R-squared** | 0.797 | 0.043 | 0.354 | 0.128 | 0.256 | 0.329 | 0.295 | 0.216 | 0.099 |

**2nd Step – Active model (vessel's length x width as the explanatory variable) – clustered standardised errors, frequency 15 minutes, 2022**

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|---|
| ***VARIABLES*** | ***CO2_act*** | ***NO_act*** | ***NO2_act*** | ***NOX_act*** | ***SO2_act*** | ***PM1_act*** | ***PM25_act*** | ***PM4_act*** | ***PM10_act*** |
| ***LenghtxWidth*** | 0.00017** | 0.00523*** | 0.00165*** | 0.00619*** | 0.00049*** | 0.00073*** | 0.00044*** | 0.00029*** | 0.00034*** |
| | [1.96520] | [32.39881] | [20.70951] | [27.78375] | [30.21651] | [9.77909] | [8.22078] | [7.12271] | [5.83167] |
| | (0.00009) | (0.00016) | (0.00008) | (0.00022) | (0.00002) | (0.00007) | (0.00005) | (0.00004) | (0.00006) |
| CO2_base | 0.86512*** | | | | | | | | |
| | [99.53473] | | | | | | | | |
| | (0.00869) | | | | | | | | |
| NO_base | | 0.44101*** | | | | | | | |
| | | [5.12640] | | | | | | | |
| | | (0.08603) | | | | | | | |
| NO2_base | | | 2.59672*** | | | | | | |
| | | | [81.24165] | | | | | | |
| | | | (0.03196) | | | | | | |
| NOX_base | | | | 3.27311*** | | | | | |
| | | | | [52.04581] | | | | | |
| | | | | (0.06289) | | | | | |
| SO2_base | | | | | 1.12978*** | | | | |
| | | | | | [35.67352] | | | | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | (0.03167) | | | | |
| PM1_base | | | | | | 0.40983*** | | | |
| | | | | | | [34.78955] | | | |
| | | | | | | (0.01178) | | | |
| PM25_base | | | | | | | 0.52921*** | | |
| | | | | | | | [33.62432] | | |
| | | | | | | | (0.01574) | | |
| PM4_base | | | | | | | | 0.70328*** | |
| | | | | | | | | [35.50924] | |
| | | | | | | | | (0.01981) | |
| PM10_base | | | | | | | | | 1.09197*** |
| | | | | | | | | | [37.17066] |
| | | | | | | | | | (0.02938) |
| Constant | 56.54728*** | 11.98454*** | -17.70901*** | -40.74876*** | 1.09895*** | 2.05202*** | 1.21948*** | -0.13428 | -4.96679*** |
| | [16.24805] | [15.24655] | [-42.88244] | [-29.98638] | [83.81068] | [8.85647] | [5.04489] | [-0.48971] | [-10.97651] |
| | (3.48025) | (0.78605) | (0.41297) | (1.35891) | (0.01311) | (0.23170) | (0.24173) | (0.27419) | (0.45249) |
| Observations | 13,553 | 13,551 | 13,551 | 13,551 | 13,551 | 13,207 | 13,207 | 13,207 | 13,207 |
| R-squared | 0.49524 | 0.08107 | 0.54100 | 0.28796 | 0.15441 | 0.05083 | 0.05041 | 0.06319 | 0.08721 |

**2nd Step – Active model (vessel's tonnage (GT) as the explanatory variable) – clustered standardised errors, frequency 15 minutes, 2022**

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|---|
| ***VARIABLES*** | ***CO2_act*** | ***NO_act*** | ***NO2_act*** | ***NOX_act*** | ***SO2_act*** | ***PM1_act*** | ***PM25_act*** | ***PM4_act*** | ***PM10_act*** |
| ***Tot_GT*** | 0.0003* | 0.00066*** | 0.00022*** | 0.00080*** | 0.00007*** | 0.00007*** | 0.00004*** | 0.00003*** | 0.00008*** |
| | [1.66422] | [18.80526] | [12.39860] | [17.02898] | [20.35943] | [4.91633] | [3.76237] | [3.52579] | [5.59697] |
| | (0.0002) | (0.00004) | (0.00002) | (0.00005) | (0.000004) | (0.00001) | (0.00001) | (0.00001) | (0.00001) |
| CO2_base | 0.86359*** | | | | | | | | |
| | [100.35610] | | | | | | | | |
| | (0.00861) | | | | | | | | |
| NO_base | | 0.51569*** | | | | | | | |
| | | [5.98075] | | | | | | | |
| | | (0.08622) | | | | | | | |
| NO2_base | | | 2.71529*** | | | | | | |
| | | | [85.42269] | | | | | | |
| | | | (0.03179) | | | | | | |
| NOX_base | | | | 3.57544*** | | | | | |
| | | | | [56.58350] | | | | | |
| | | | | (0.06319) | | | | | |
| SO2_base | | | | | 1.21002*** | | | | |
| | | | | | [37.30634] | | | | |
| | | | | | (0.03243) | | | | |
| PM1_base | | | | | | 0.41019*** | | | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | [34.73384] | | | |
| | | | | | | (0.01181) | | | |
| PM25_base | | | | | | | 0.53452*** | | |
| | | | | | | | [33.64690] | | |
| | | | | | | | (0.01589) | | |
| PM4_base | | | | | | | | 0.71303*** | |
| | | | | | | | | [35.59663] | |
| | | | | | | | | (0.02003) | |
| PM10_base | | | | | | | | | 1.10554*** |
| | | | | | | | | | [37.71967] |
| | | | | | | | | | (0.02931) |
| Constant | 57.22309*** | 13.66800*** | -18.61786*** | -44.92776*** | 1.28602*** | 2.39995*** | 1.36172*** | -0.12706 | -5.07100*** |
| | [16.64850] | [17.43707] | [-44.72602] | [-32.74382] | [103.50316] | [10.90092] | [5.75846] | [-0.46396] | [-11.18641] |
| | (3.43713) | (0.78385) | (0.41626) | (1.37210) | (0.01242) | (0.22016) | (0.23647) | (0.27387) | (0.45332) |
| Observations | 13,553 | 13,551 | 13,551 | 13,551 | 13,551 | 13,207 | 13,207 | 13,207 | 13,207 |
| R-squared | 0.49519 | 0.02171 | 0.52856 | 0.25636 | 0.10965 | 0.04767 | 0.04832 | 0.06171 | 0.08692 |

**Explanation of the results of the econometric analysis – influence of passenger vessels' characteristics on emissions (2022, 15 minutes sampling frequency)**

**CO2** – the current level of CO2 in each active period has been proven to be largely and significantly influenced by the base CO2 (which is modelled through wind direction, wind speed, atmospheric pressure, air humidity and air temperature). In addition to base CO2, the influence (explanatory power) of tonnage and the combination of length and width of ships docking in Rovinj has also been statistically proven. The size of the influence of the weight of the vessel on the CO2 level is 0.3 ppm for every 1,000 tons of vessel weight (gross tonnage), i.e. 0.2 ppm per 1,000 m2 of vessel surface (length x width).

**NO** – the current level of NO in each active period has been proven to be largely and significantly influenced by the base NO (which is modelled through wind direction, wind speed, atmospheric pressure, air humidity and air temperature). In addition to the base NO, the influence (explanatory power) of tonnage and the combination of length and width of ships docking in Rovinj, although small, has also been statistically proven. The size of the influence of the weight of the vessel on the NO level is 0.7 ppm for every 1,000 tons of vessel weight, i.e. 5.2 ppm per 1,000 m2 of vessel surface.

**NO2** – the current level of NO2 in each active period has been proven to be largely and significantly influenced by the base NO2 (which is modelled through wind direction, wind speed, atmospheric pressure, air humidity and air temperature). In addition to the base NO2, the influence (explanatory power) of the tonnage and the combination of length and width of ships docking in Rovinj has also been statistically proven. The size of the influence of the weight of the vessel on the CO2 level is 0.2 ppm for every 1,000 tons of vessel weight, i.e. 1.7 ppm per 1,000 m2 of vessel surface.

**NOx** – the current level of NOx in each active period has been proven to be largely and significantly influenced by the base NOx (which is modelled through wind direction, wind speed, atmospheric pressure, air humidity and air temperature). In addition to the base NOx, the influence (explanatory power) of the tonnage and the combination of length and width of ships docking in Rovinj has also been statistically proven. The size of the influence of the weight of the vessel on the NOx level is 1 ppm for every 1,000 tons of vessel weight, i.e. 6.2 ppm per 1,000 m2 of vessel surface.

**SO2** – the current level of SO2 in each active period has been proven to be largely and significantly influenced by the base SO2 (which is modelled through wind direction, wind speed, atmospheric pressure, air humidity and air temperature). In addition to the base SO2, the influence (explanatory power) of tonnage and the combination of length and width of ships docking in Rovinj has also been statistically proven. The size of the influence of the weight of the vessel on the SO2 level is 0.1 ppm for every 1,000 tons of the vessel's weight, i.e. 0.5 ppm per 1,000 m2 of the vessel's surface.

**PM1** – the current level of PM1 in each active period has been proven to be largely and significantly influenced by the base PM1 (which is modelled through wind direction, wind speed, atmospheric pressure, air humidity and air temperature). In addition to the base PM1, the influence of the tonnage and the combination of length and width of ships docking in Rovinj, although small, has also been statistically proven. The size of the influence of the weight of the vessel on the PM1 level is 0.1 ppm for every 1,000 tons of vessel weight, i.e. 0.7 ppm per 1,000 m2 of vessel surface.

**PM2.5** – the current level of PM2.5 in each active period has been proven to be largely and significantly influenced by the base PM2.5 (which is modelled through wind direction, wind speed, atmospheric pressure, air humidity and air temperature). In addition to the base PM2.5, the influence of the tonnage and the combination of length and width of ships docking in Rovinj, although small, has also been statistically proven. The size of the influence of the weight of the vessel on the PM2.5 level is 0.1 ppm for every 1,000 tons of vessel weight, i.e. 0.4 ppm per 1,000 m2 of vessel surface.

**PM4** – the current level of PM4 in each active period has been proven to be largely and significantly influenced by the base PM4 (which is modelled through wind direction, wind speed, atmospheric pressure, air humidity and air temperature). In addition to the base PM4, the influence of the tonnage and the combination of length and width of ships docking in Rovinj, although small, has also been statistically proven. The size of the influence of the weight of the vessel on the PM4 level is 0.03 ppm for every 1,000 tons of vessel weight, i.e. 0.3 ppm per 1,000 m2 of vessel surface.

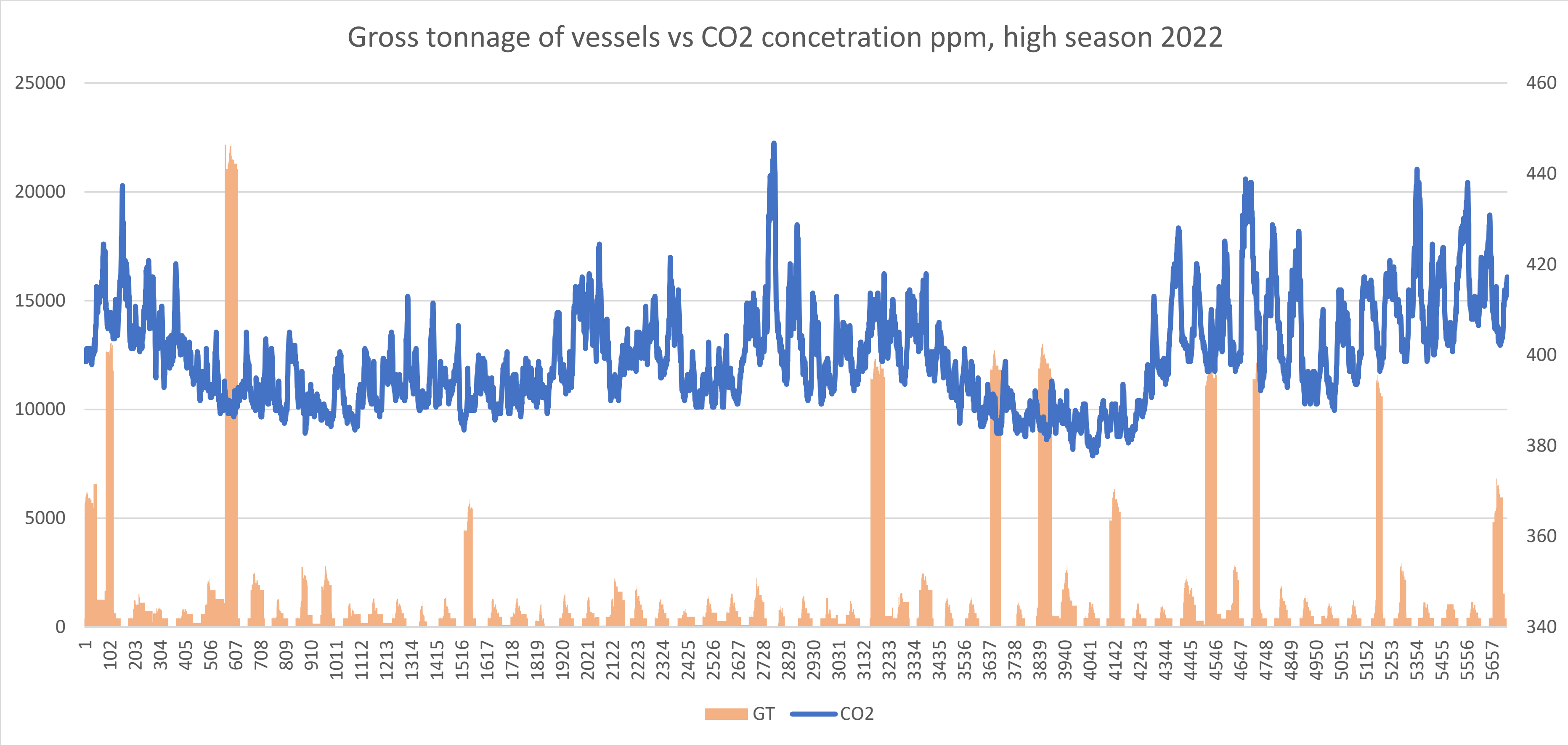
**PM10** – the current level of PM10 in each active period has been proven to be largely and significantly influenced by the base PM10 (which is modelled through wind direction, wind speed, atmospheric pressure, air humidity and air temperature). In addition to the base PM10, the influence of the tonnage and the combination of length and width of ships docking in Rovinj, although small, has also been statistically proven. The size of the influence of the weight of the vessel on the PM10 level is 0.1 ppm for every 1,000 tons of vessel weight, i.e. 0.34 ppm per 1,000 m2 of vessel surface.

**While significant results were obtained for all of the analyzed variables, under both active models – 1 (vessel's length x width as the explanatory variable) and 2 (vessel's tonnage (GT), the vessels' characteristics (the ones that were available to us, namely ship's tonnage, length and width) only had decent explanatory power (measured by R2) on the following measured emission variables: CO2, NO2, NOx and SO2.**

**Limitations of the performed analysis**

Based on the analyzed data and its characteristics we can point out a couple of limitations of this analysis as well as suggestions for future data collection:

- The installation of additional measuring devices is necessary, since the current measuring device covers only the port berth, and there are three more anchorage fields, and for a more precise and robust calculation, it would be necessary to install measuring devices, at least, in those locations as well.
- Better calibration of the device because it reports negative values for certain pollutants in certain periods.


Gross tonnage of vessels vs CO2 concetration ppm, high season 2022
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20000
15000
10000
5000
0
460
440
420
400
380
360
340
1
102
203
304
405
506
607
708
809
910
1011
1112
1213
1314
1415
1516
1617
1718
1819
1920
2021
2122
2223
2324
2425
2526
2627
2728
2829
2930
3031
3132
3233
3334
3435
3536
3637
3738
3839
3940
4041
4142
4243
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4445
4546
4647
4748
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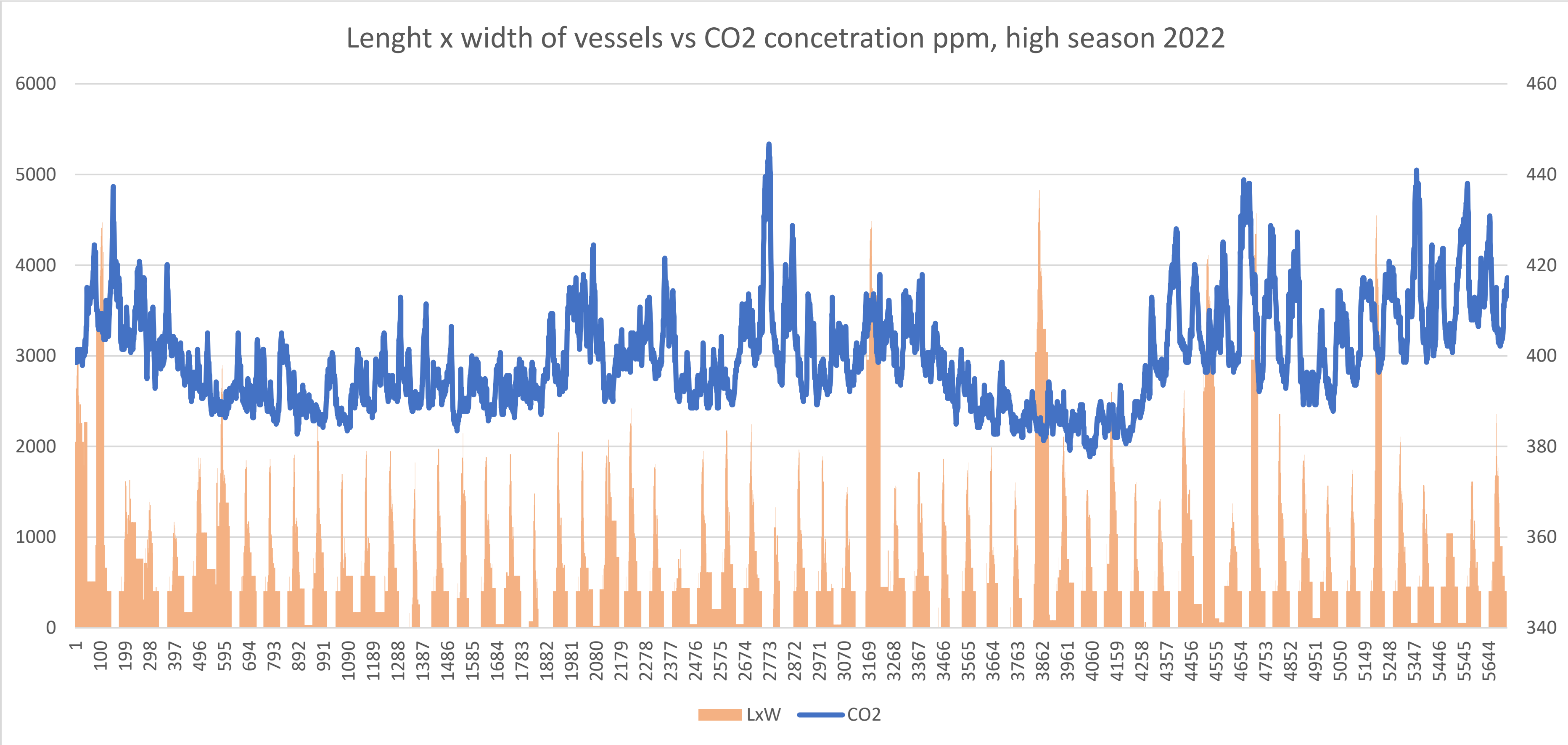
4950
5051
5152
5253
5354
5455
5556
5657
GT
CO2


Lenght x width of vessels vs CO2 concetration ppm, high season 2022
6000
5000
4000
3000
2000
1000
0
460
440
420
400
380
360
340
1
100
199
298
397
496
595
694
793
892
991
1090
1189
1288
1387
1486
1585
1684
1783
1882
1981
2080
2179
2278
2377
2476
2575
2674
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3169
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3565
3664
3763
3862
3961
4060
4159
4258
4357
4456
4555
4654
4753
4852
4951
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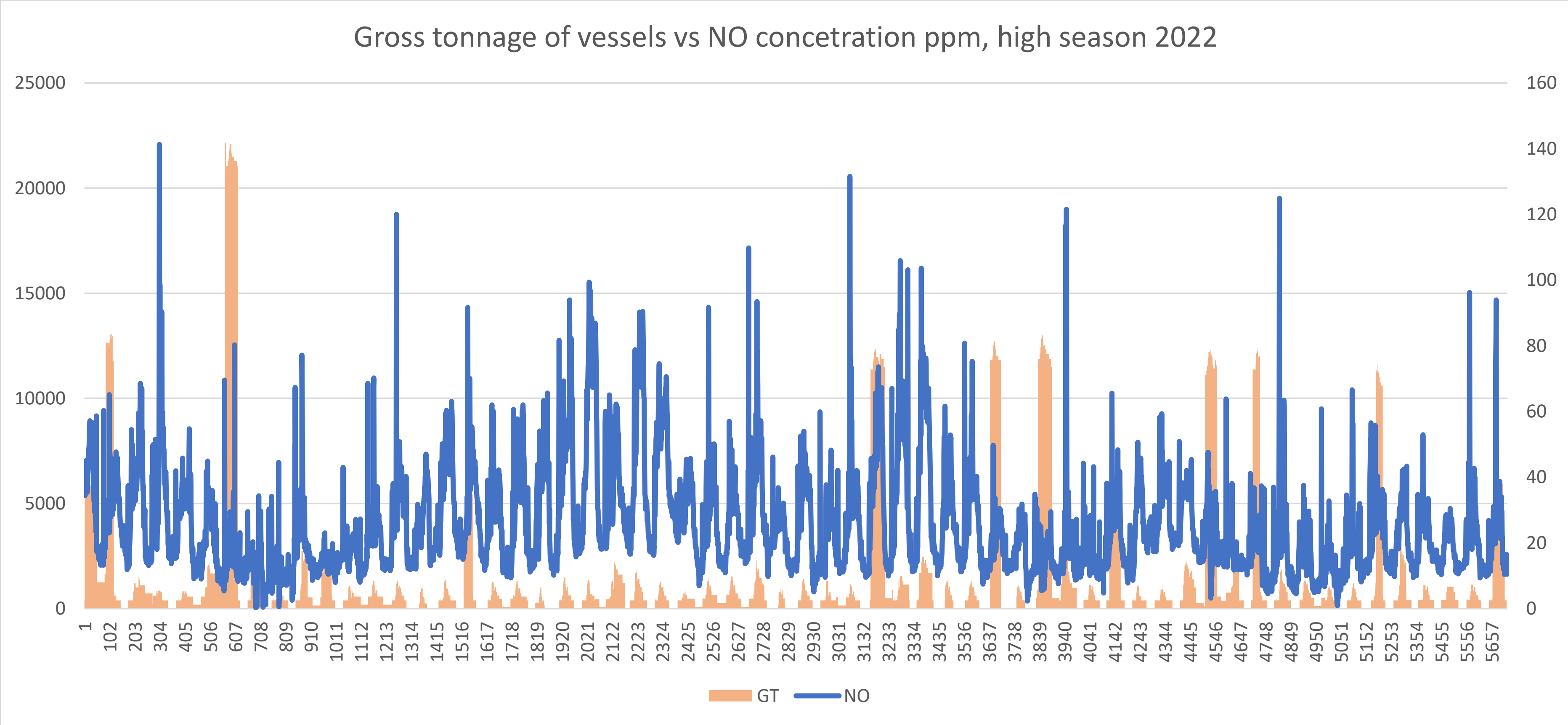
5545
5644
LxW
CO2


Gross tonnage of vessels vs NO concetration ppm, high season 2022
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20000
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10000
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0
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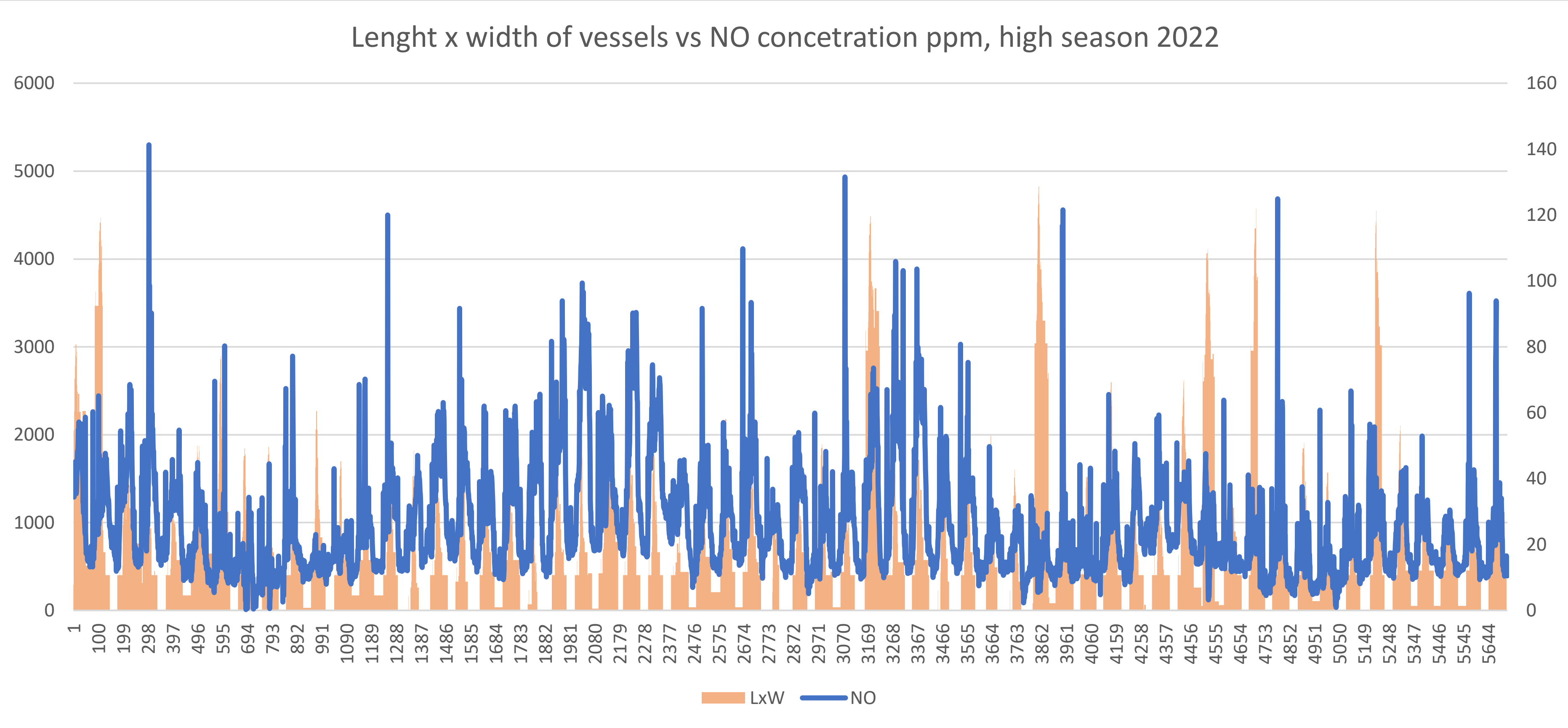
140
120
100
80
60
40
20
0
1
102
203
304
405
506
607
708
809
910
1011
1112
1213
1314
1415
1516
1617
1718
1819
1920
2021
2122
2223
2324
2425
2526
2627
2728
2829
2930
3031
3132
3233
3334
3435
3536
3637
3738
3839
3940
4041
4142
4243
4344
4445
4546
4647
4748
4849
4950
5051
5152
5253
5354
5455
5556
5657
GT
NO


Lenght x width of vessels vs NO concetration ppm, high season 2022
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5000
4000
3000
2000
1000
0
160
140
120
100
80
60
40
20
0
1
100
199
298
397
496
595
694
793
892
991
1090
1189
1288
1387
1486
1585
1684
1783
1882
1981
2080
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3565
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4258
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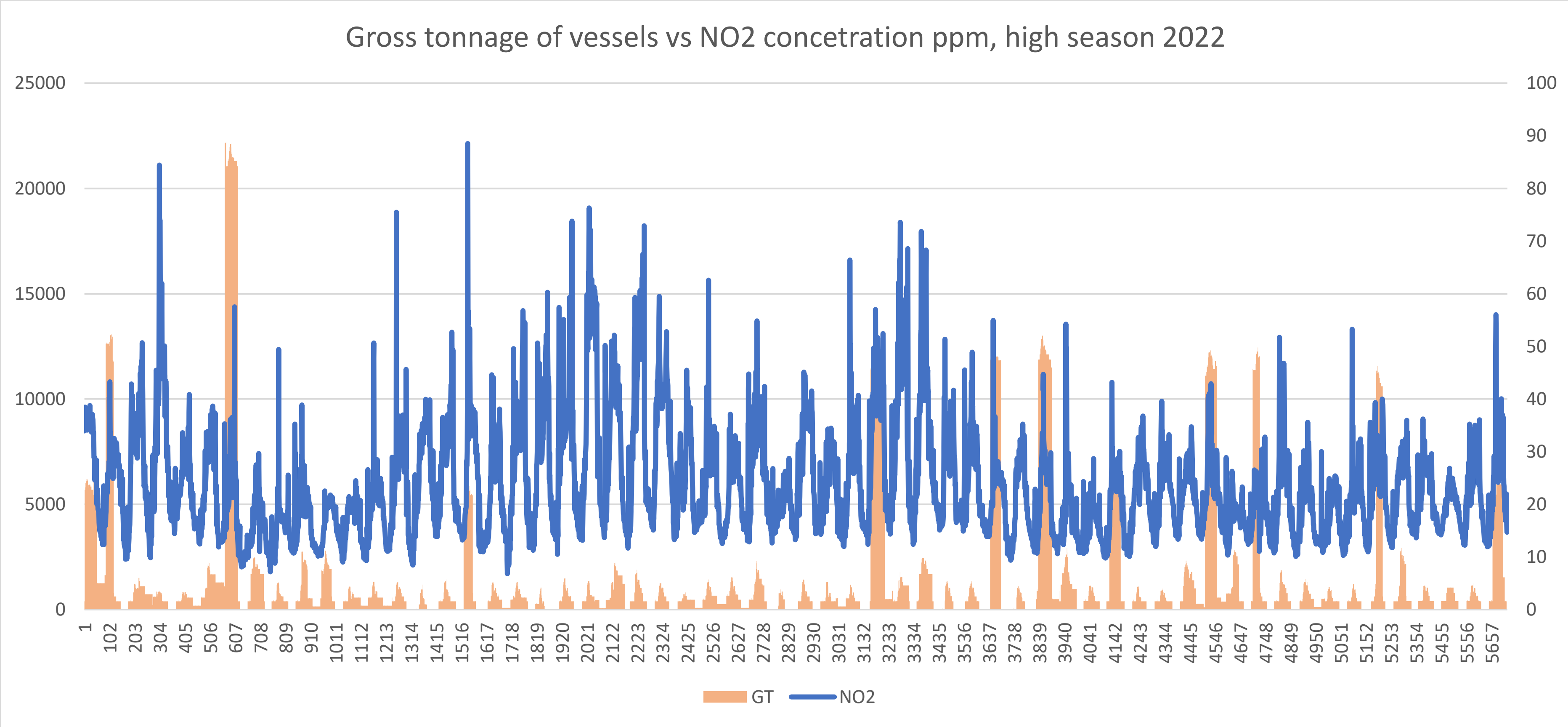
4654
4753
4852
4951
5050
5149
5248
5347
5446
5545
5644
LxW
NO


Gross tonnage of vessels vs NO2 concetration ppm, high season 2022
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20000
15000
10000
5000
0
100
90
80
70
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50
40
30
20
10
0
1
102
203
304
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506
607
708
809
910
1011
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4142
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5152
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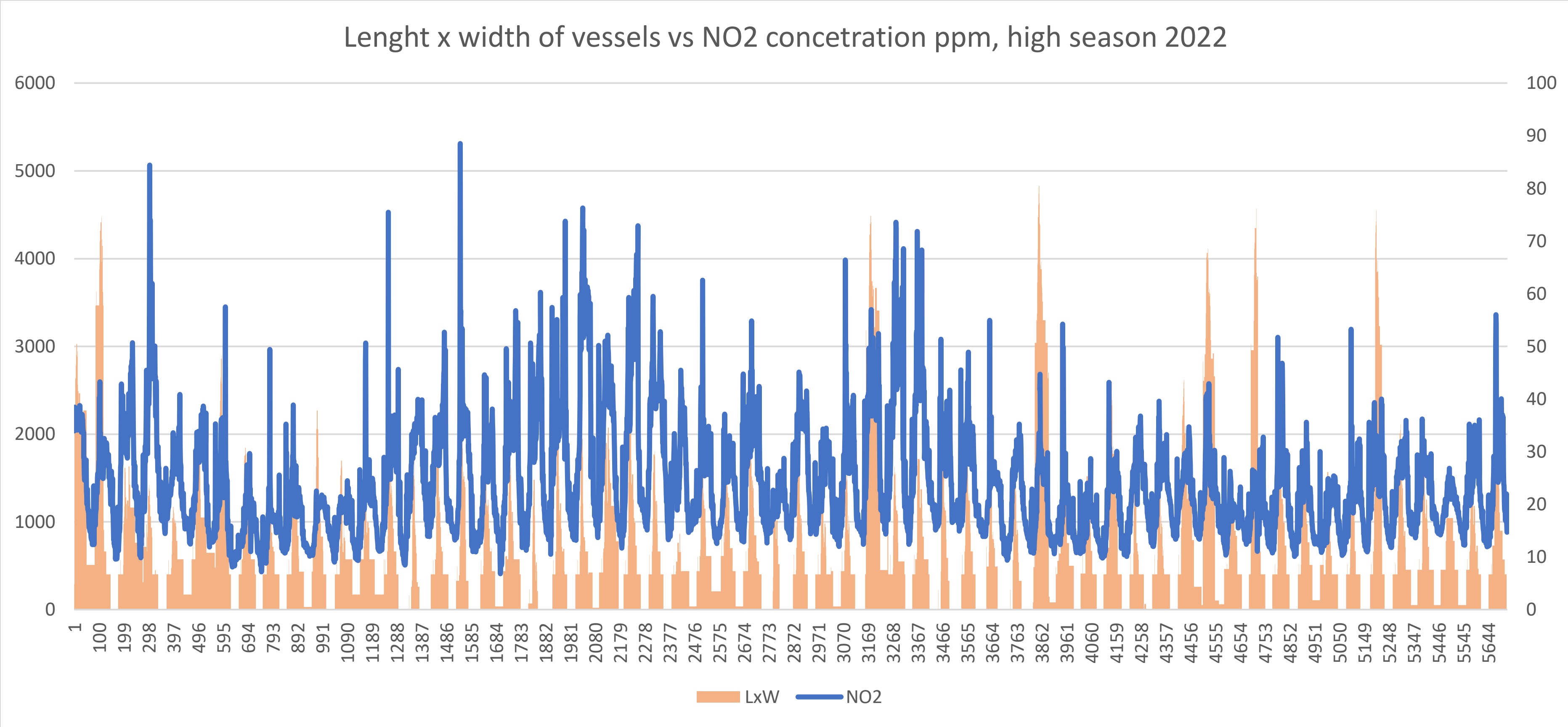
5354
5455
5556
5657
GT
NO2


Lenght x width of vessels vs NO2 concetration ppm, high season 2022
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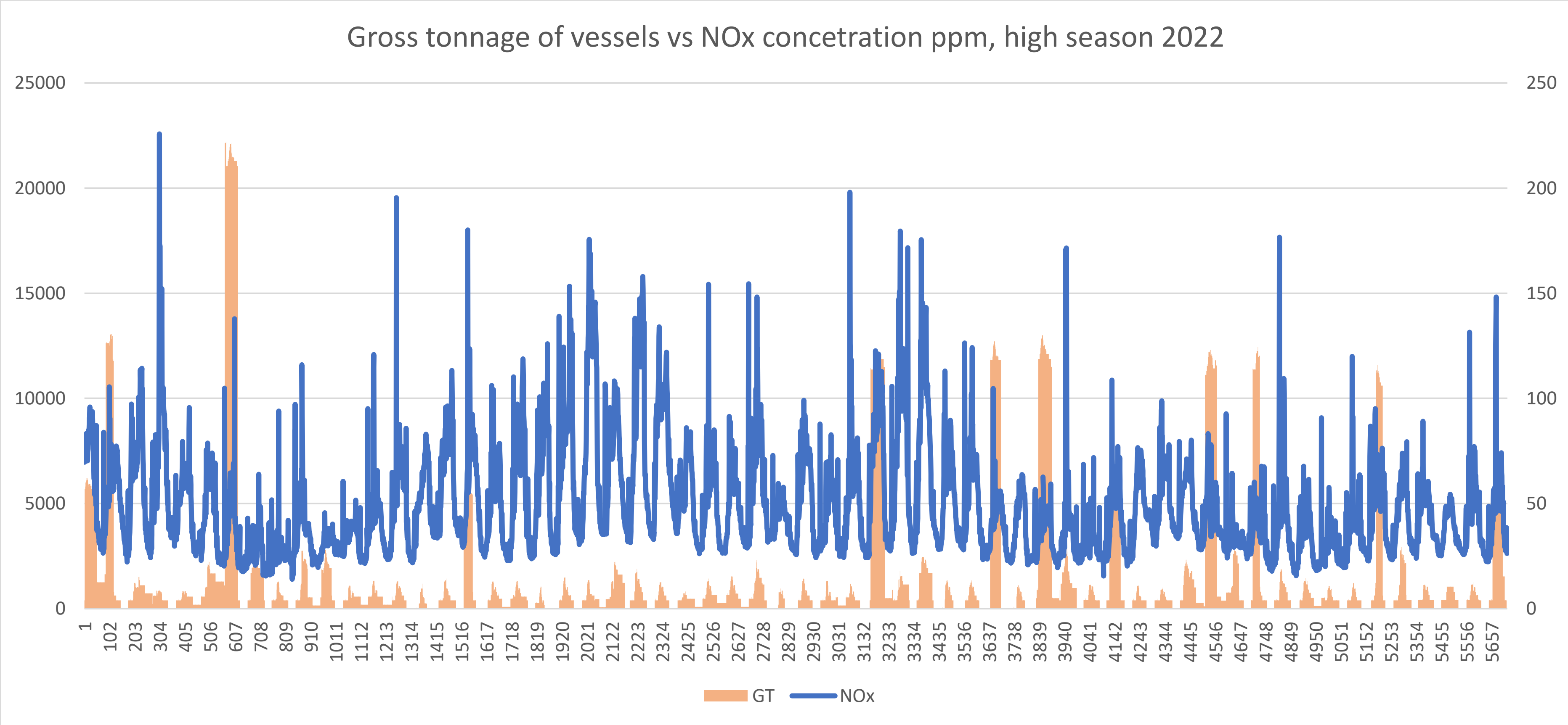
4000
3000
2000
1000
0
100
90
80
70
60
50
40
30
20
10
0
1 100 199 298 397 496 595 694 793 892 991 1090 1189 1288 1387 1486 1585 1684 1783 1882 1981 2080 2179 2278 2377 2476 2575 2674 2773 2872 2971 3070 3169 3268 3367 3466 3565 3664 3763 3862 3961 4060 4159 4258 4357 4456 4555 4654 4753 4852 4951 5050 5149 5248 5347 5446 5545 5644
LxW
NO2


Gross tonnage of vessels vs NOx concetration ppm, high season 2022
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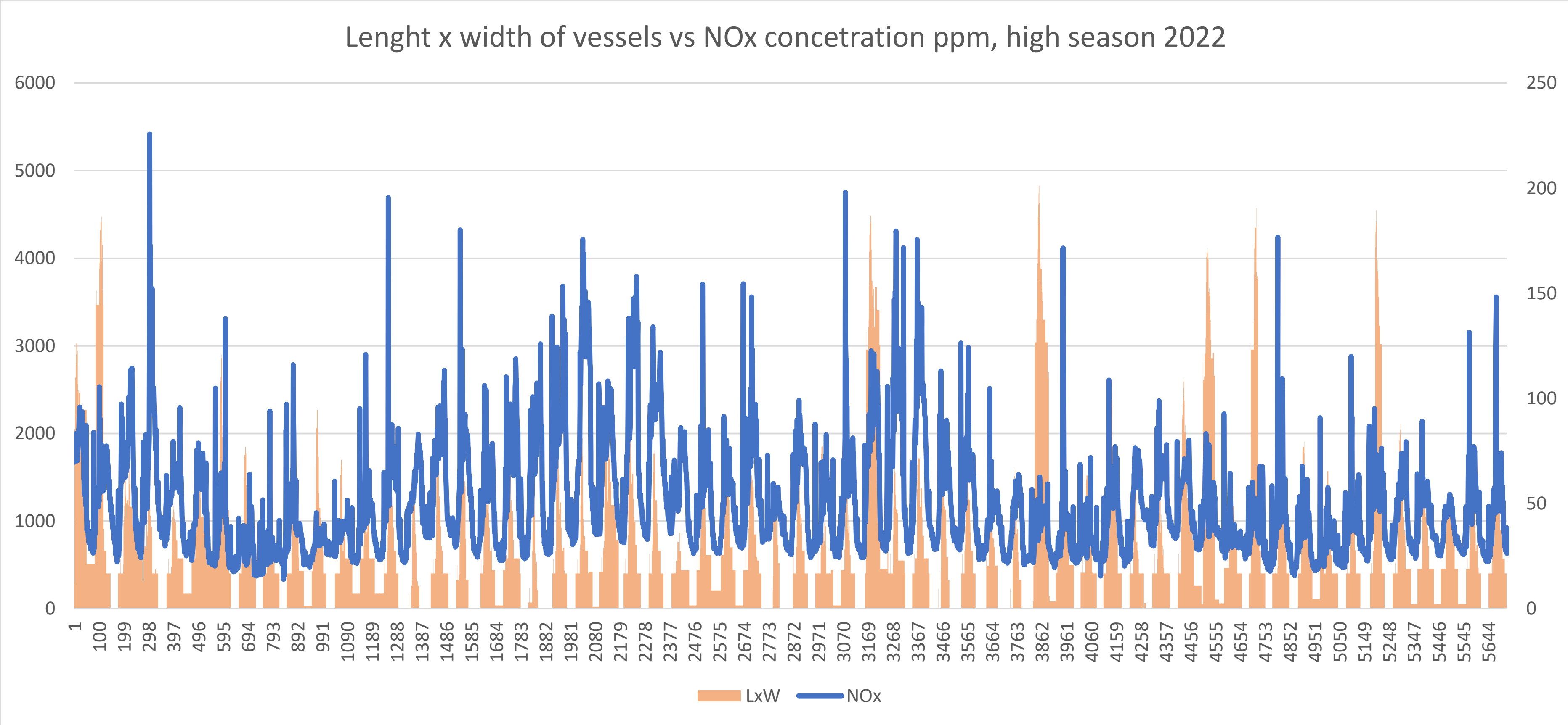
15000
10000
5000
0
250
200
150
100
50
0
GT
NOx


Lenght x width of vessels vs NOx concetration ppm, high season 2022
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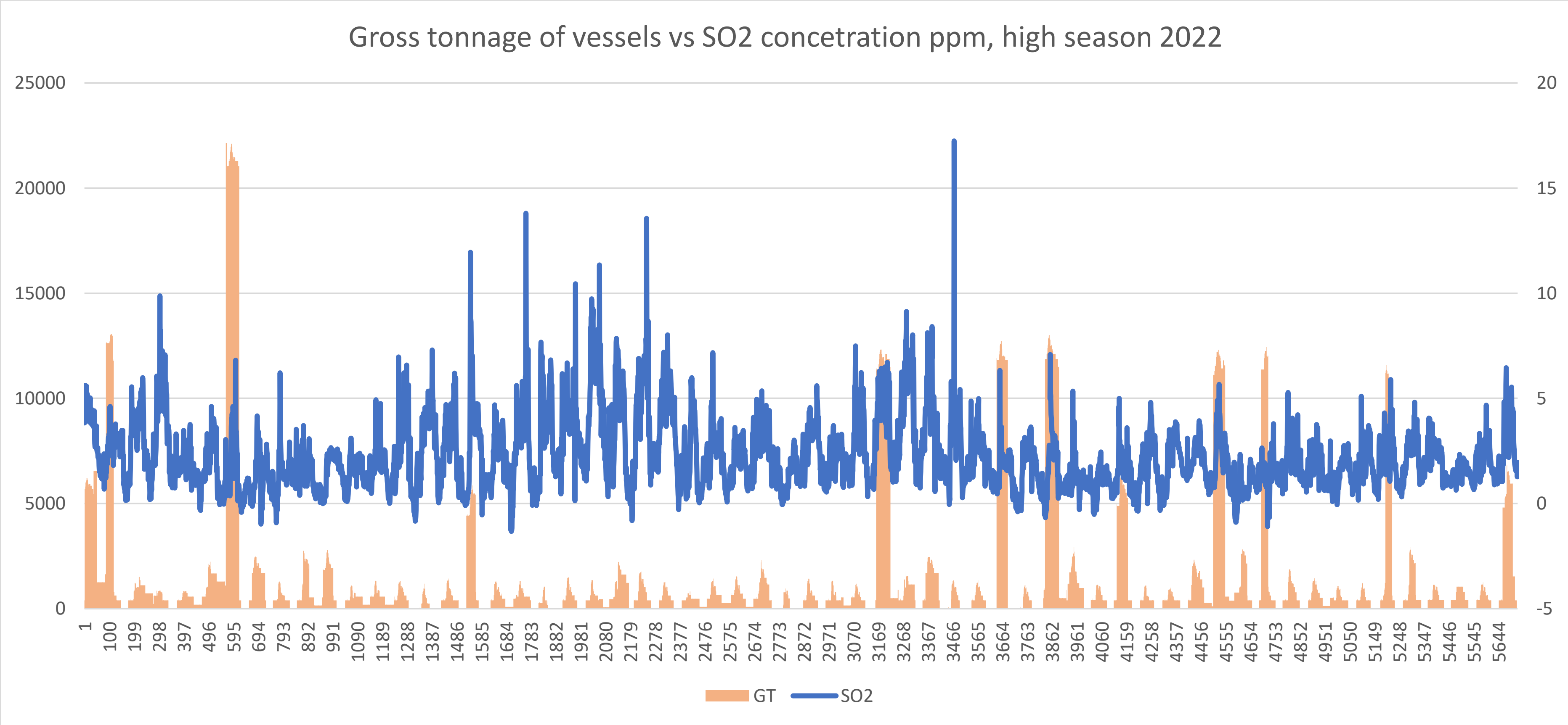
4000
3000
2000
1000
0
250
200
150
100
50
0
1 100 199 298 397 496 595 694 793 892 991 1090 1189 1288 1387 1486 1585 1684 1783 1882 1981 2080 2179 2278 2377 2476 2575 2674 2773 2872 2971 3070 3169 3268 3367 3466 3565 3664 3763 3862 3961 4060 4159 4258 4357 4456 4555 4654 4753 4852 4951 5050 5149 5248 5347 5446 5545 5644
LxW
NOx


Gross tonnage of vessels vs SO2 concetration ppm, high season 2022
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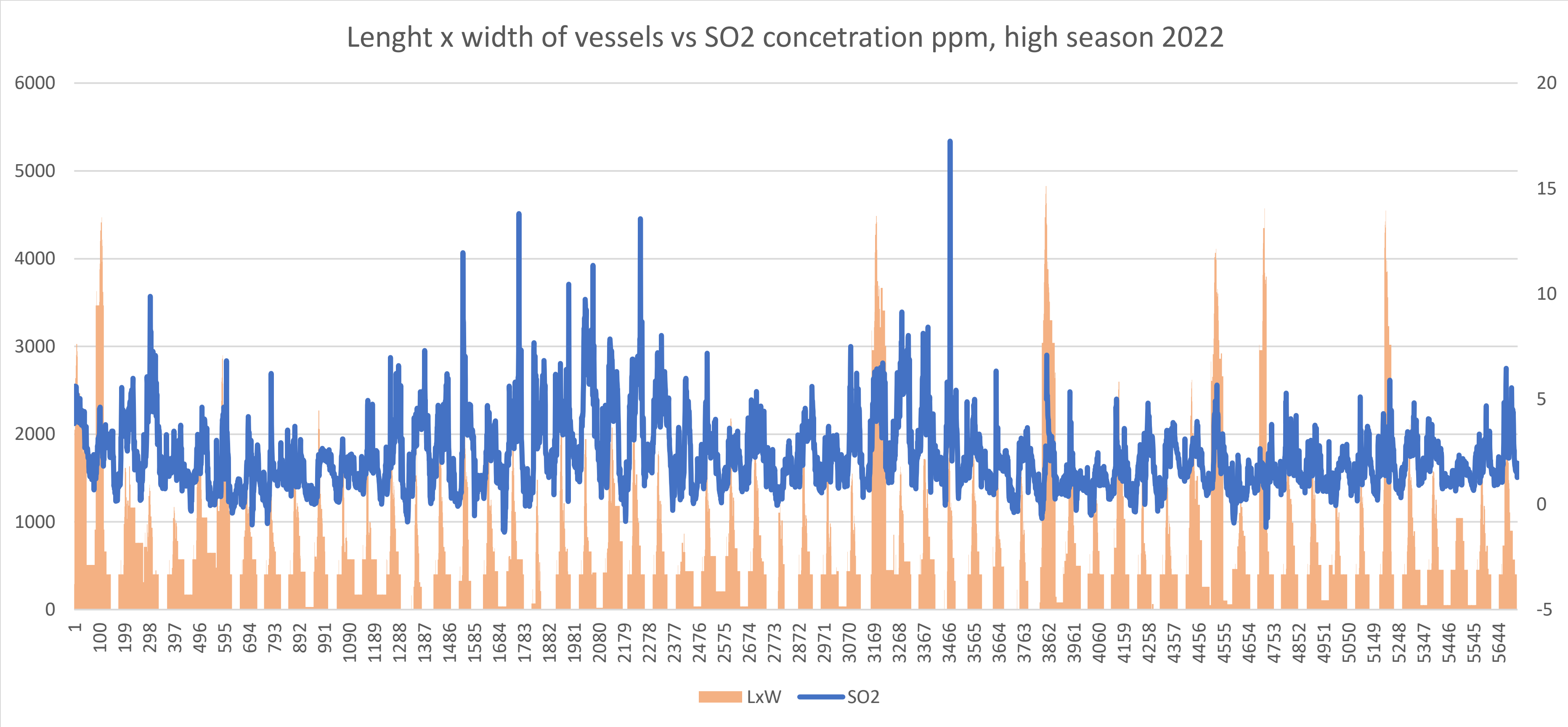
15000
10000
5000
0
20
15
10
5
0
-5
GT
SO2


Lenght x width of vessels vs SO2 concetration ppm, high season 2022
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100
199
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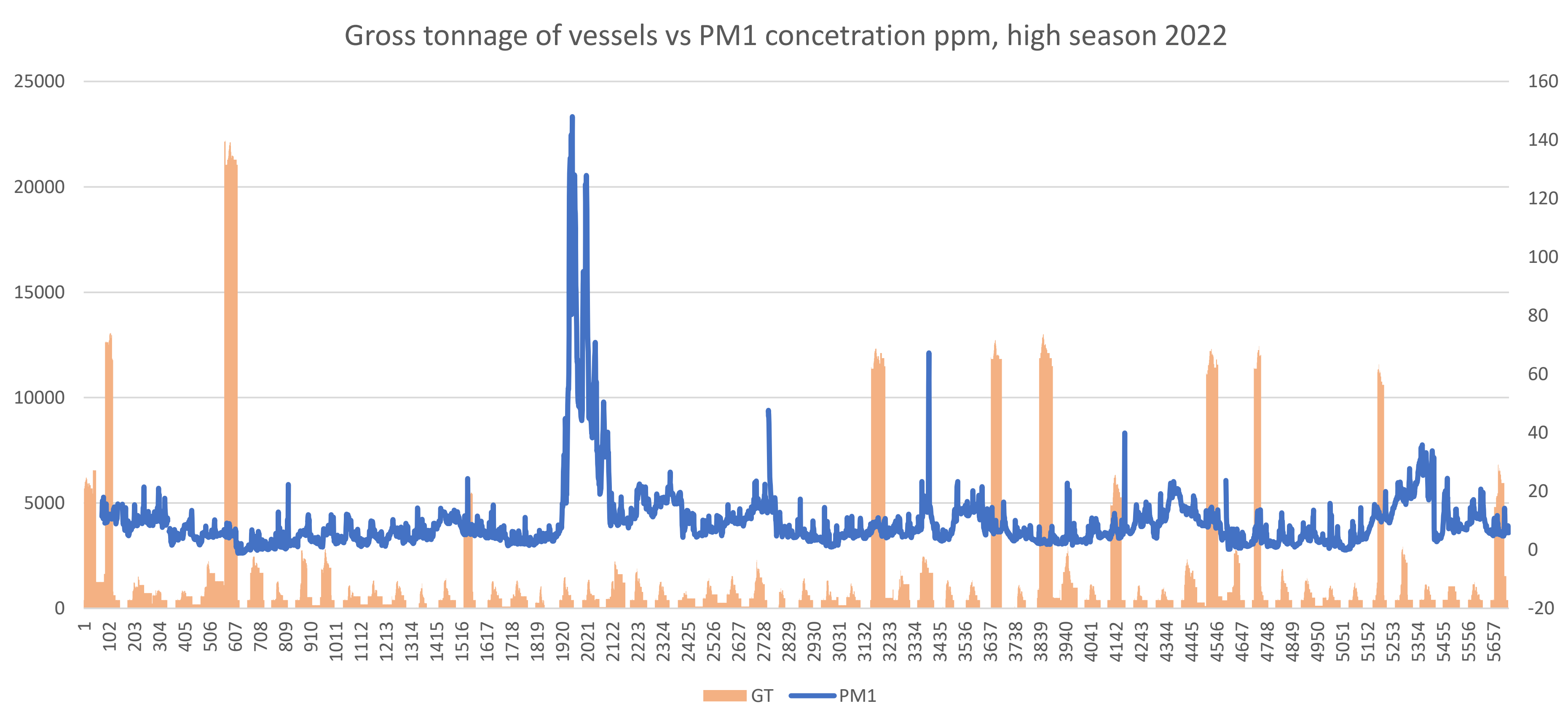
5446
5545
5644
LxW
SO2


Gross tonnage of vessels vs PM1 concetration ppm, high season 2022
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10000
5000
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160
140
120
100
80
60
40
20
0
-20
1
102
203
304
405
506
607
708
809
910
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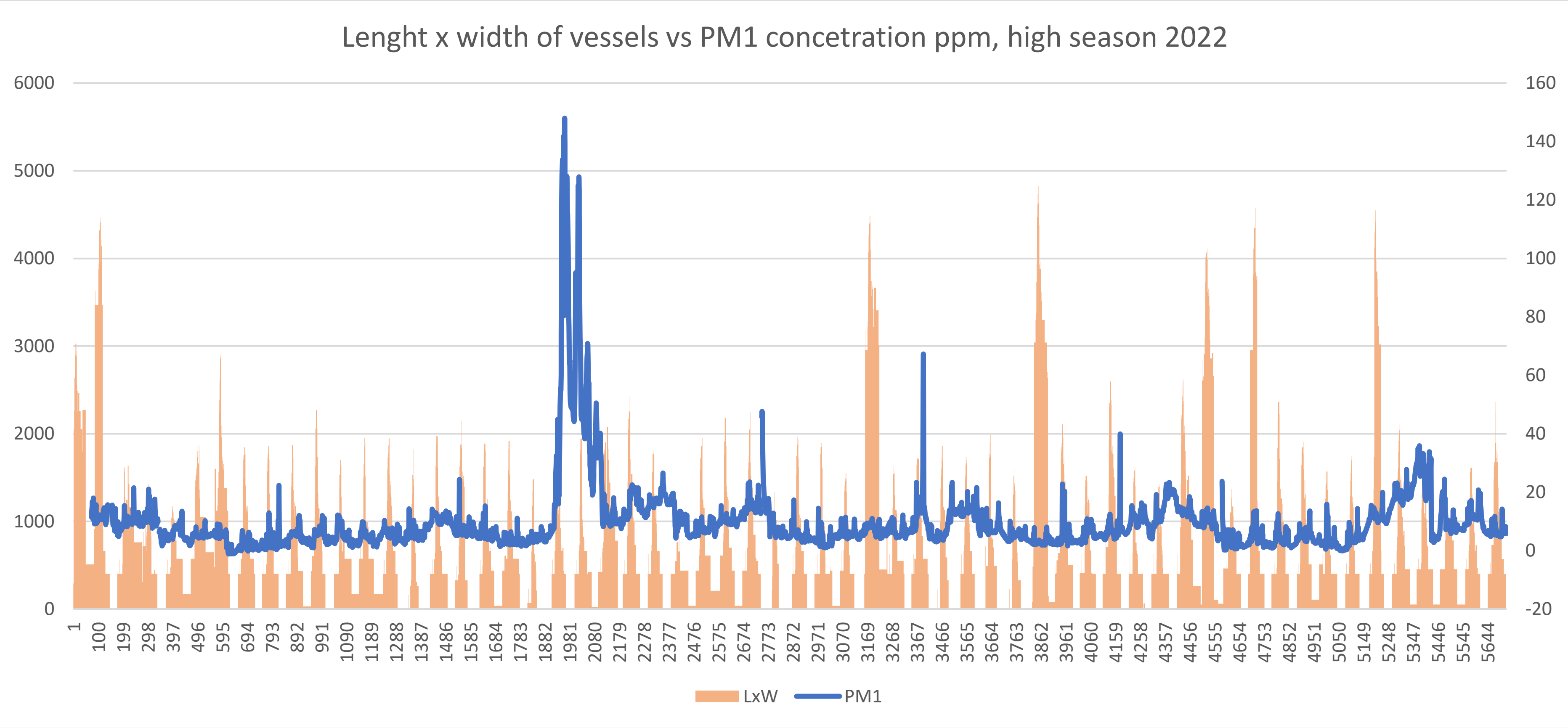
GT
PM1



Lenght x width of vessels vs PM1 concetration ppm, high season 2022
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4000
3000
2000
1000
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140
120
100
80
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40
20
0
-20
1
100
199
298
397
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991
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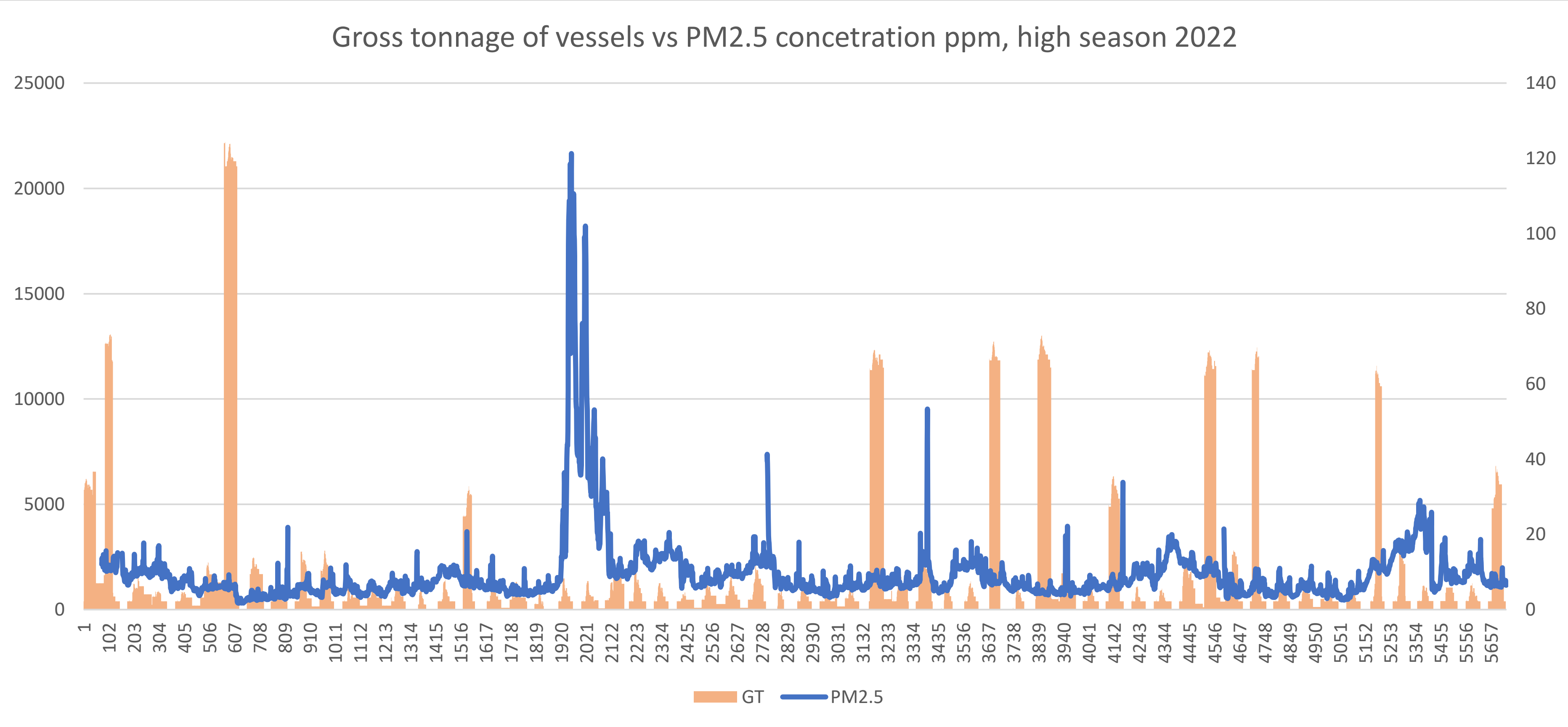
5644
LxW
PM1


Gross tonnage of vessels vs PM2.5 concetration ppm, high season 2022
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15000
10000
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100
80
60
40
20
0
1
102
203
304
405
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708
809
910
1011
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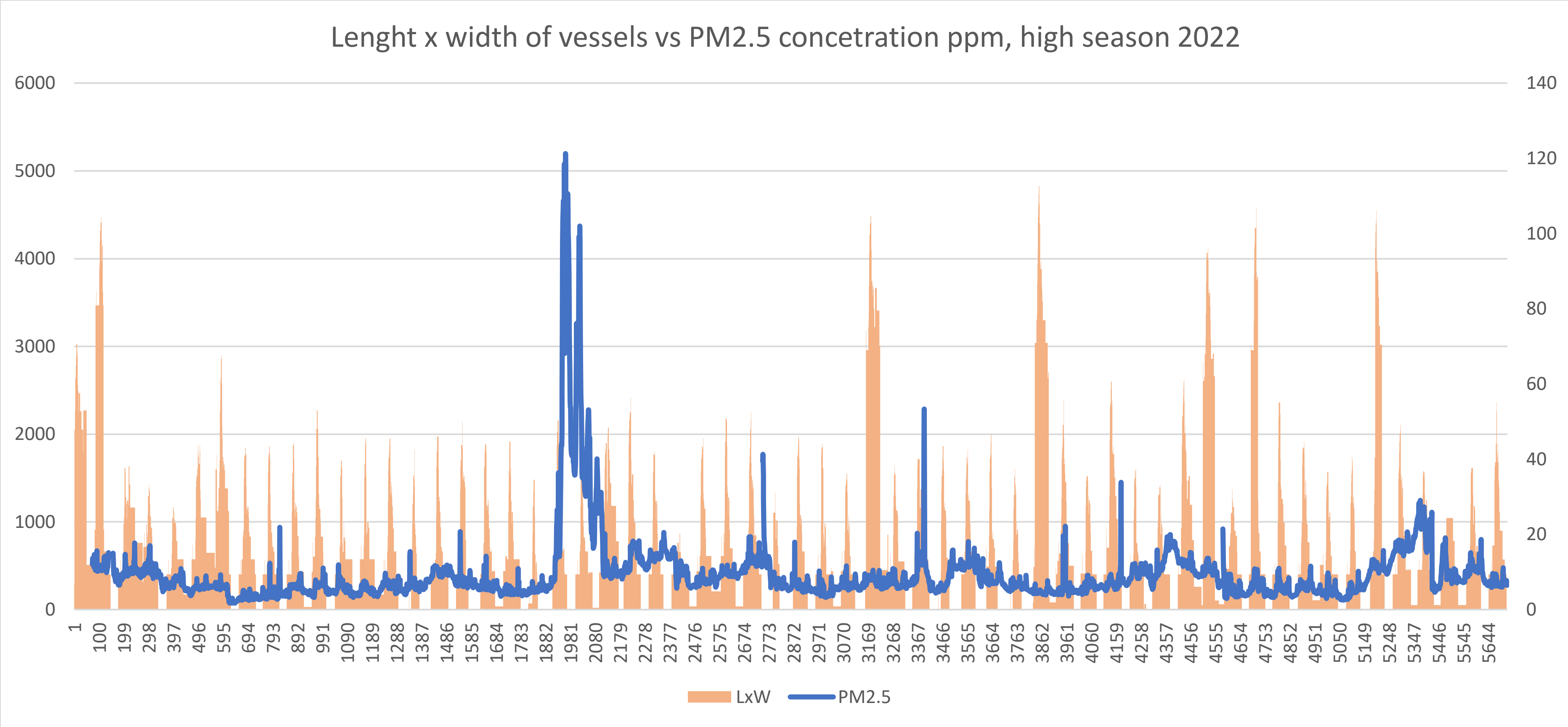
5354
5455
5556
5657
GT
PM2.5


Lenght x width of vessels vs PM2.5 concetration ppm, high season 2022
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5000
4000
3000
2000
1000
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120
100
80
60
40
20
0
1
100
199
298
397
496
595
694
793
892
991
1090
1189
1288
1387
1486
1585
1684
1783
1882
1981
2080
2179
2278
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2674
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2872
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3169
3268
3367
3466
3565
3664
3763
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3961
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4159
4258
4357
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4555
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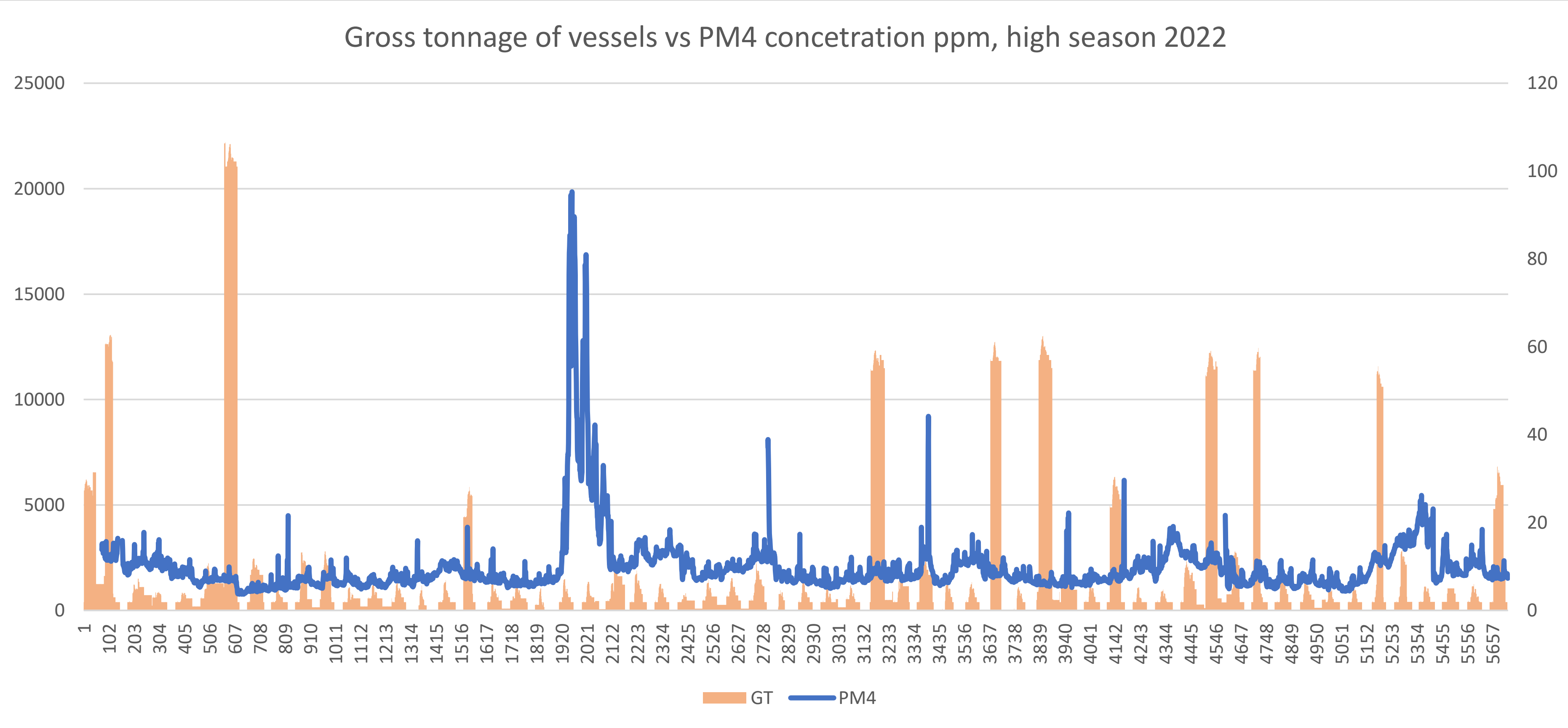
4951
5050
5149
5248
5347
5446
5545
5644
LxW
PM2.5


Gross tonnage of vessels vs PM4 concetration ppm, high season 2022
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10000
5000
0
120
100
80
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40
20
0
1
102
203
304
405
506
607
708
809
910
1011
1112
1213
1314
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1819
1920
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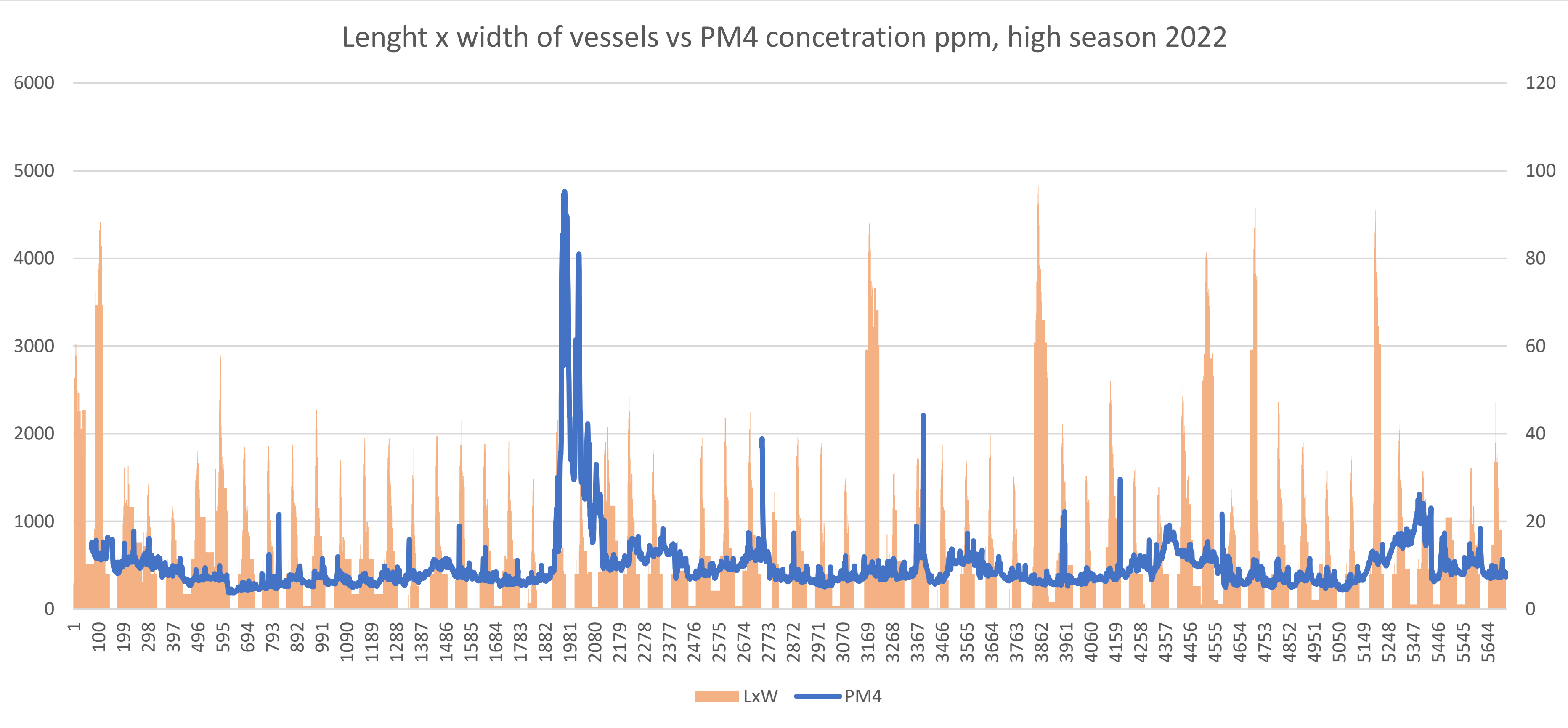
5354
5455
5556
5657
GT
PM4


Lenght x width of vessels vs PM4 concetration ppm, high season 2022
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5000
4000
3000
2000
1000
0
120
100
80
60
40
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0
1
100
199
298
397
496
595
694
793
892
991
1090
1189
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1585
1684
1783
1882
1981
2080
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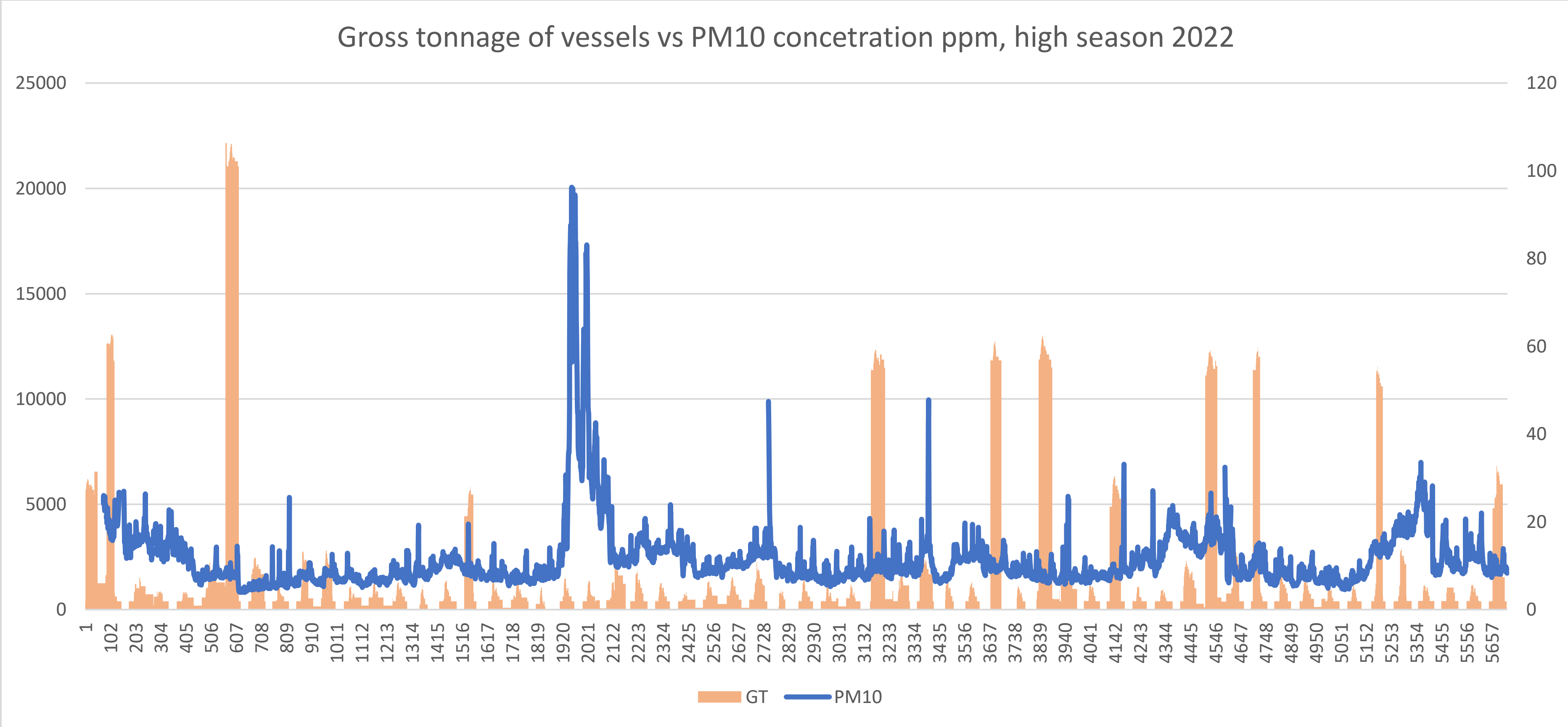
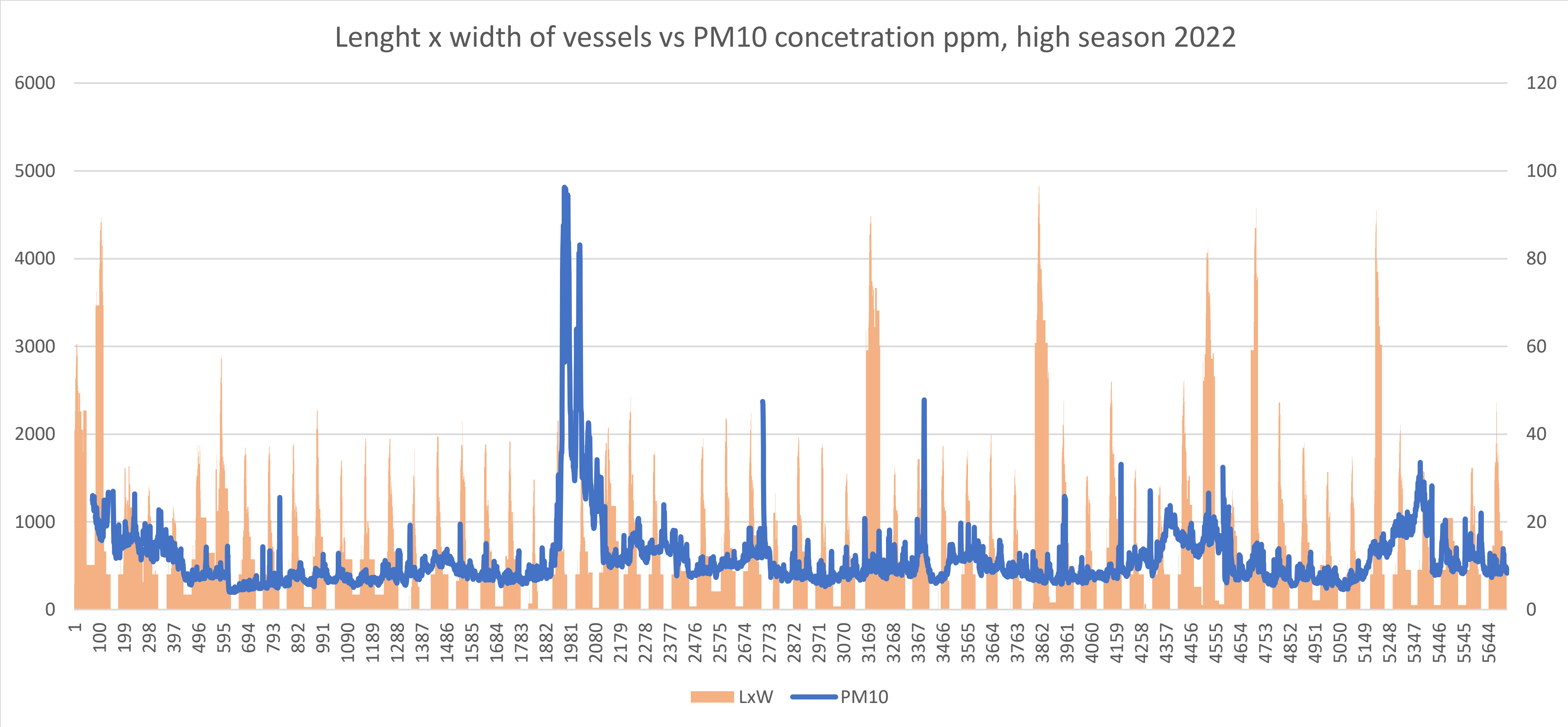
3664
3763
3862
3961
4060
4159
4258
4357
4456
4555
4654
4753
4852
4951
5050
5149
5248
5347
5446
5545
5644
LxW
PM4


Gross tonnage of vessels vs PM10 concetration ppm, high season 2022
25000
20000
15000
10000
5000
0
120
100
80
60
40
20
0
GT
PM10


Lenght x width of vessels vs PM10 concetration ppm, high season 2022
6000
5000
4000
3000
2000
1000
0
120
100
80
60
40
20
0
1
100
199
298
397
496
595
694
793
892
991
1090
1189
1288
1387
1486
1585
1684
1783
1882
1981
2080
2179
2278
2377
2476
2575
2674
2773
2872
2971
3070
3169
3268
3367
3466
3565
3664
3763
3862
3961
4060
4159
4258
4357
4456
4555
4654
4753
4852
4951
5050
5149
5248
5347
5446
5545
5644
LxW
PM10

The general trend of comovement between some explanatory and response variables (particularly this is the case for $NO_2$, $NO_x$ and $SO_2$) is visible at plain sight. As can be seen from the presented graphs and tables, our findings indicate that the analysed variables yielded statistically significant results under both active models (model 1 and model 2), which featured the vessel's length, width and tonnage (GT) as the explanatory variables, respectively. However, the aforementioned available characteristics of the vessels exhibited only moderate explanatory power, as visible from the recorded $R^2$ values. Notably, out of the examined emission variables, only $CO_2$, $NO_2$, $NO_x$ and $SO_2$ were found to be more substantially impacted by the measured vessel characteristics (length, width and tonnage) at the 15 minutes' measurement intervals during 2022. The situation for 2021 and 4-hour measurement intervals is similar insofar as out of the examined emission variables, only $CO_2$, $NO_2$ and $SO_2$ were found to be more substantially impacted by the measured vessel characteristics (length, width and tonnage).

# 5. CONCLUSION

A new econometric model was developed for the purpose of analysing the impact of passenger ships (cruisers) on air quality in the port of Rovinj under the EU MIMOSA project. Our goal was to separate the effect of passenger ships (cruisers) and emissions given off by these transportation means from the other sources of emissions, be it naturally occurring or emitted due to human and connected activities.

In order to perform a two-step econometric analysis, the whole analysed time period was divided into two subsamples - the time period in which the specified passenger vessels (cruisers) are not present T0 (base period – lower frequency period) and the period in which the specified vessels are present T1 (active period - higher frequency period).

In determining the connection between the level of emissions/pollution (according to the parameters mentioned above) and the atmospheric impact, readings from the base period alone are used. After determining the base (lower frequency) equation and optimized coefficients along with atmospheric parameters, the analysis is performed on time periods and emissions' readings of values from the active (higher frequency) period (T1). In this second step of modelling passenger vessels' characteristics such as width, length (LE) and tonnage (TO) of the analysed classes of vessels present in the port of Rovinj are included in the analysis.

Since for the year 2021 the data was available with a sampling frequency of 4 hours, passenger vessels that entered and/or departed in the times between sampling periods were assigned exponential weights depending on the temporal proximity of the measurement interval, which is also an approximation.

For year 2022 where the sampling frequency was 15 minutes the above stated problem of passenger vessels that entered and/or departed in the times between sampling periods is much less pronounced.

In both analysed period, 2021 and 2022, as well as at both sampling frequencies, 4 hours and 15 minutes, there is a clear and statistically significant relationship between the characteristics of the passenger ships docking in the Port of Rovinj and the emissions' concentration in the air. The current level of all measured and analysed emissions (carbon dioxide (CO2), nitrogen monoxide (NO), nitrogen dioxide NO2, nitrogen oxides of the general formula NOx (x = 0.5 to 2) (NOx), sulfur dioxide (SO2), particles with an aerodynamic diameter of less than 1 µm (PM1), particles with an aerodynamic diameter of less than 2.5 µm (PM2.5), particles with an aerodynamic diameter of less than 4 µm (PM 4) and particles with an aerodynamic diameter of less than 10 µm (PM 10)) in each active period has been proven to be largely and significantly influenced by their corresponding base values (which were modelled through wind direction, wind speed, atmospheric pressure, air humidity and air temperature).

In addition to their base values, the influence of the gross tonnage and the combination of length and width of passenger vessels docking in Port of Rovinj has also been statistically proven. The size of the influence of the weight of the vessel varies depending on emission being analysed as well as the influence of the vessel's surface.

Our research findings reveal that both active models, model 1 and model 2, which utilized the vessel's length, width, and tonnage (GT) as the explanatory variables, generated statistically significant results for the analyzed variables (emission values). However, the available vessel characteristics demonstrated only a moderate level of explanatory power, as demonstrated by the recorded R2 values. During the measurement intervals of 15 minutes in 2022, it was observed that the vessel characteristics (length, width, and tonnage) had a more substantial impact on the following emission variables: CO2, NO2, NOx, and SO2. A similar situation was observed during 2021 and the 4-hour measurement intervals, where the vessel characteristics had a meaningfully significant impact on CO2, NO2 and SO2, out of the examined emission variables.

Looking at the obtained results we can conclude that 15-minute reading give a much higher quality of results and the obtained results from a 15-minute frequency sampling interval can be treated as more trustworthy and statistically significant, both due to the higher amount of data and the almost complete disappearance of problems connected to passenger vessels that entering and/or departing in the times between sampling periods.

In order to get higher quality data and more conclusive results and better policy implications it is a necessity to install additional measuring devices, since the current measuring device covers only the port berth, and there are three more anchorage fields, and for a more precise and robust calculation, it would be necessary to install measuring devices, at least, in those locations as well.

The combination of length and width of ships docking in Rovinj has also been statistically proven" while (if we got it correctly), it seems that we have an $R^2$= 0.02171 in relation to tonnage. This means that only 2% of the variation in pollutant concentration appears to be linked to the variation in the presence of tonnage of vessels. This indicates a very weak correlation obtained and could actually mean the absence of a significant relationship between the two quantities

While significant results were obtained for all of the analysed variables under both active models – 1 (vessel's length x width as the explanatory variable) and 2 (vessel's tonnage (GT) as the explanatory variable), only $CO_2$, $NO_2$, $NO_x$ and $SO_2$ have a decent explanatory power (measured by $R^2$)