DOI: 10.5281/zenodo.6974270

Project	GUTTA
Work Package number	5
Work Package title	Demonstrating the change in environmental impact and territorial connectivity
Deliverable number	D 5.1.3
Deliverable title	Report on validation of vessel CO_2 emission model
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Deliverable due date	30-03-2022
Deliverable latest review date	23-06-2022

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Executive Summary

This document reports the comparison and validation of the vessel CO_2 emissions data from the simulated Ro-Pax vessel hosted at the Unizd with the on board Ro-Pax vessels emissions data. The measurement campaign was performed on three similar Ro-Pax vessels and simulation was performed in a joint operation of the Wartsila-Transas engine room and navigational simulators with Ro-Pax vessel models.

1. Introduction

This report corresponds to GUTTA project deliverable D 5.1.3 and documents its execution and the results achieved.

To evaluate the amount of emissions in one shipping area or from a specific type of ship is not an easy task. The most accurate method for estimating ship exhaust emissions is by on board measuring in real conditions with adequate measuring equipment. So far, research studies on the on board emissions measurement, especially in the Ro-Pax segment, are very limited. This problem presents a need for a more relevant on board emission database that will offer the possibility to enhance the estimation of emissions and comparison with the current emission database and current estimation models. The aim of this report is to compare and validate the exhaust gas emissions data from the engine room simulator with the exhaust gas emissions data measured on board Ro-Pax vessels under different engine operating regimes.

The report is organized into a description of the methodology, in Sect.2, and presentation of the results, in Sect.3. The conclusions are drawn in Sect.4.

2. Methodology

On board exhaust gas measurements were carried out on three Ro-Pax vessels. All three vessels have four stroke main engines connected through reduction gearboxes to controllable pitch propellers (CPP). Measurement campaign was carried during multiple voyages in the Adriatic Sea between ports of Croatia, Italy and Montenegro. In order to compare the on board measurement values of the exhaust process with the simulated ones and in addition to perform the validation of the engine room simulator with the measured on board values under a series of different engine operating regimes, the simulated exhaust gas data were also obtained using a Wartsila-Transas simulator model of similar Ro-Pax vessel. The simulated vessel was operated in a joint operation of the engine room and navigational simulators during different weather and engine operating conditions. The basic vessels' and simulator's particulars/parameters are shown in Table 1.

Table 1. Vessel and Engine particulars/parameters

Particulars/Parameters	Vessel I	Vessel II	Vessel III	Simulated Vessel
LOA/Breath/Draft (m)	128.13/19.62/5.73	116.0/18.9/5.2	122.06/18.82/4.83	125.0/23.4/5.3
Service speed (knots)	19.5	17.5	20.0	19.0
Year of build	1973	1993	1979	N/A
Engine type	Stork Werkspoor Diesel 8TM410	Bazan MAN B&W 8L40/54 A	MaK Diesel 8M551AK	MAN B&W 8L32/40
No. of Engines/Propellers	4/2	2/2	4/2	2/2
Engine Power MCR (kW)	3750	3500	3310	4000
Number of cylinders	8	8	8	8
Engine speed (min^{-1}) / propeller speed (min^{-1})	550/250	428/225	425/245	750/175
Bore/stroke (mm)	410/470	400/540	450/550	320/400
Mean effect. pressure (bar)	16.82	18.45	13.3	24.9
Average voyage length (Nm)	136.7	102.6	115.0	N/A
Average vessel speed (kt)	13.4	11.6	12.1	N/A
Average vessel heading: Leg 1 (°) / Leg 2 (°)	260/99	245/65	210/61	N/A

The equipment used for measuring and analysing the exhaust gases on board vessels was Testo 350 Maritime flue gas analyser [1]. This flue gas analyser is used for monitoring exhaust gas temperature and concentrations of CO_2 and O_2 as a percentage in volume of dry exhaust gas, as well as CO, NO_x, SO_x in ppm in dry exhaust gas. It is working in accordance with ISO 8178-4:2020, Marpol Annex VI and NO_x Technical Code 2008. The measurement range and accuracy of the exhaust gas analyser can be found in [2]. The measured raw data files are saved into the analyser internal memory with an option to transfer it to the computer and then use for the analysis. On all three vessels diesel fuel Eurodiesel BS with a maximum of 10 mg/kg of sulphur content was used, which is also in conformity with Regulation 14(1) or 4(a) and Regulation 18(1) of Annex VI [3].

The on board measuring process was carried out during the cruising phase of the voyages. For collecting the exhaust gas samples every few minutes during a period of one hour, the measuring equipment connection point located after the turbine wheel, in the exhaust duct, was used. The probe hole was adjusted with a small ball valve (Figure 1) which was located approximately 0.2 m downstream from the turbocharger. The process has already been explained in the deliverable 3.1.3.

All three vessels sailed overnight back-to-back voyages between ports of Croatia and Italy. Only one vessel had one voyage between Italy and Montenegro. Voyage durations were from 9 to 11 hours and exhaust gas measurements were taken 5-10 times per hour. Vessel 1 has four main engines connected in pair to two controllable pitch propellers. On each voyage vessel operated with only two main engines (one port and one starboard) propelling the both controllable pitch propellers. On the return voyage the engines were replaced with other two that were not running the night before. Vessel 1 exhaust gas measurements were taken during the four back-to-back voyages (8 nights/days) and 235 exhaust gas measurement records were collected for this analysis. The average length of the voyages for Vessel 1 was 136.7 Nm, average speed 13.4 knots, average vessel heading was 260° when sailing from Croatia to Italy and 99° when sailing from Italy to Croatia. During the voyages average absolute wind direction with respect to true North was 128° with the average speed of 8.3 m/s and a sea condition of 5, according to the Beaufort scale.

Vessel 2 has two main engines (port and starboard) each connected to its controllable pitch propeller. On each voyage vessel operated with both main engines propelling the two controllable pitch propellers but for some short periods vessel sailed with only one engine/propeller (port or starboard). Vessel 2 exhaust gas measurements were taken during the one back-to-back voyage (2 nights/days) and 99 exhaust gas measurement records were collected for this analysis. The average length of the voyages for Vessel 2 was 102.6 Nm, average speed 11.6 knots, average vessel heading was 245° when sailing from Croatia to Italy and 65° when sailing from Italy to Croatia. During the voyages average absolute wind direction with respect to true North was 189° with the average speed of 3.2 m/s and a sea condition of 2, according to the Beaufort scale.

Vessel 3 has four main engines connected in pair to two controllable pitch propellers, similar to Vessel 1. On each voyage vessel operated with two main engines connected to only one (port or starboard) controllable pitch propeller. On the return voyage the engines and propeller were replaced with other two engines and (port or starboard) propeller that were not running the night before. Vessel 3 exhaust gas measurements were also taken during the one back-to-back voyage (2 nights/days) and 153 exhaust gas measurement records were collected for this analysis. The average length of the voyages for Vessel 3 was 115 Nm, average speed 12.1 knots and average vessel heading was 210° when sailing from Croatia to Italy and 61° when sailing from Italy to Montenegro. During the voyages average absolute wind direction with respect to true North was 167° with the average speed of 3.0 m/s and a sea condition of 2, according to the Beaufort scale.

The recorded output variables from Testo 350 Maritime flue gas analyser presented in Table 2 were: concentration of CO_2 and O_2 as a percentage in a volume of dry (d) exhaust gas, concentrations of CO and NO_X in ppm in dry exhaust gas and exhaust gas temperature after the turbocharger. The engine shaft power as a percentage of maximum continuous rating (MCR), at which measurements were taken, was calculated according to the parameters collected directly from the instruments in the engine room. Table 2 also shows basic statistics (mean μ and standard deviation σ) of measured and analysed dry exhaust gas quantities for all three vessels and their associated engines with calculated average values. During the voyage the engine speed and main engines load were varied according to the existing weather conditions and/or required vessel speed. All of that influenced the engine shaft power/load.

Table 2. Basic statistics (mean μ and standard deviation σ) of measured and analysed quantities for all vessels and their associated port (P) and starboard (S) engines with calculated average values

Ship	Engine	Stat.	% of MCR	CO_2d (%)	O_2d (%)	NO_xd (ppm)	COd (ppm)	t_{Ex} (°C)
Vessel 1	1 Port	μ	82.98	5.45	13.09	855.61	205.36	386.46
		σ	2.86	0.25	0.34	26.84	34.77	10.73
	1 Stbd	μ	78.21	5.43	13.14	1050.89	139.40	385.99
		σ	3.41	0.15	0.24	55.05	12.08	5.48
	2 Port	μ	69.86	5.47	13.10	1038.81	178.86	392.47
		σ	2.33	0.12	0.16	38.25	29.93	7.52
	2 Stbd	μ	74.86	5.76	12.70	836.78	187.58	411.50
		σ	0.62	0.07	0.10	36.56	17.02	3.93
	Average	$\bar{\mu}$	76.48	5.53	13.01	945.53	177.80	394.11
		$\bar{\sigma}$	2.30	0.15	0.21	39.18	23.45	6.91
Vessel 2	Port	μ	65.43	5.60	13.09	1183.63	149.75	331.72
		σ	0.82	0.05	0.04	22.18	11.56	5.58
	Stbd	μ	77.00	5.89	12.59	1299.23	160.69	354.73
		σ	0.00	0.07	0.06	12.11	9.39	5.70
	Average	$\bar{\mu}$	71.22	5.74	12.84	1241.43	155.22	343.22
		$\bar{\sigma}$	0.41	0.06	0.05	17.15	10.48	5.64
Vessel 3	1 Port	μ	48.00	4.58	14.54	878.77	56.36	361.63
		σ	0.00	0.03	0.03	17.01	3.30	1.85
	2 Port	μ	52.00	4.93	14.05	878.28	68.32	378.03
		σ	0.00	0.06	0.03	5.33	12.89	3.26
	3 Stbd	μ	54.00	5.19	13.64	943.44	49.67	401.56
		σ	0.00	0.05	0.03	13.07	1.69	2.19
	4 Stbd	μ	49.00	4.84	14.18	735.61	52.94	383.90
		σ	0.00	0.02	0.02	8.69	2.36	1.94
	Average	$\bar{\mu}$	50.75	4.88	14.10	859.02	56.82	381.28
		$\bar{\sigma}$	0.00	0.04	0.03	11.02	5.06	2.31
Total average		$\bar{\mu}$	66.15	5.38	13.32	1015.33	129.95	372.87
		$\bar{\sigma}$	0.90	0.08	0.10	22.45	13.00	4.96

Standard deviation σ used in this analysis is based on a normalization factor of N, i.e. it can be defined as:

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2}, \tag{1}$$

where N denotes a number of measurements for the associated measurement sample, x_i is the i-th measurement, and μ represents the mean value defined as:

$$\mu = \frac{1}{N}\sum_{i=1}^{N} x_i. \tag{2}$$

Figures 2, 3 and 4 show individual vessel and engine exhaust gas measurements and parameters with calculated average values. Red squared points show the mean value and blue lines above and below the red points show the standard deviation of each measured or analysed value.

The simulators used for this research were Wärtsilä-Transas Marine NTPro 5000 navigational simulator and Wärtsilä ERS-LCHS 5000 TechSim engine room simulator [4, 5], also described in deliverable 3.2.2. The simulated vessel type was a Ro-Pax ferry with two main four-stroke engines each connected to its controllable pitch propeller via reduction gearbox, similar to Vessel 2. Other simulator vessel and engine particulars/parameters are provided in Table 1. Simulated Ro-Pax vessel was operated in a joint operation of the engine room and navigational simulators. This means that simulators are synchronously connected and operated as one vessel which enables simultaneous recordings and later analysis of simulated vessel parameters i.e. both from navigational and marine engine room point of view. The simulator was operated with various simulation scenarios of different weather and engine operating conditions typical for the Adriatic Sea [6] in order to record vessel and engine parameters. The simulator data obtained from these scenarios were partially used for the research published by Mannarini et al. [7] and were also used for this analysis in order to compare exhaust emissions from on board measurements with simulated values. The simulated vessel was operated with varying the wind speed from 0-34 m/s, significant wave height from 0-4 meters, wind and wave relative direction to vessel heading from 0-180°, and engine telegraph lever position from 70-100. The total number of different simulation scenarios was 287 and each simulated scenario was recorded during the time frame of 25 minutes (also described in deliverable 4.1.1). Initial transient dynamics, during the first two minutes, were pruned and the remaining parameters were averaged although it should be noted that simulated signals behave as stationary ones with very low variance. The recorded simulator output variables presented in Table 3 were: engine shaft power as a percentage of maximum continuous rating (MCR) at which measurements were taken, concentration of CO_2 as a percentage in a volume of dry exhaust gas, concentrations of NO_x and CO in ppm in dry exhaust gas, exhaust gas temperature t_{Ex} after the turbocharger in °C, and specific fuel oil consumption (SFOC) in g/kWh. Values of oxygen O_2 as a percentage in volume of dry exhaust gas and the amount of excess air λ could not be modelled/simulated so they were post-calculated. These values were calculated with the assumption that the used marine diesel oil has sulphur content in fuel less than 0.10 % by mass, which is defined by EU directive 2016/802 for all EU ports and inland waters, and that emission conversion factor for marine diesel oil is 3.206 kg of CO_2 in exhaust gases per 1 kg of burned marine diesel oil, which is defined by International Maritime Organization (IMO) [8, 9].

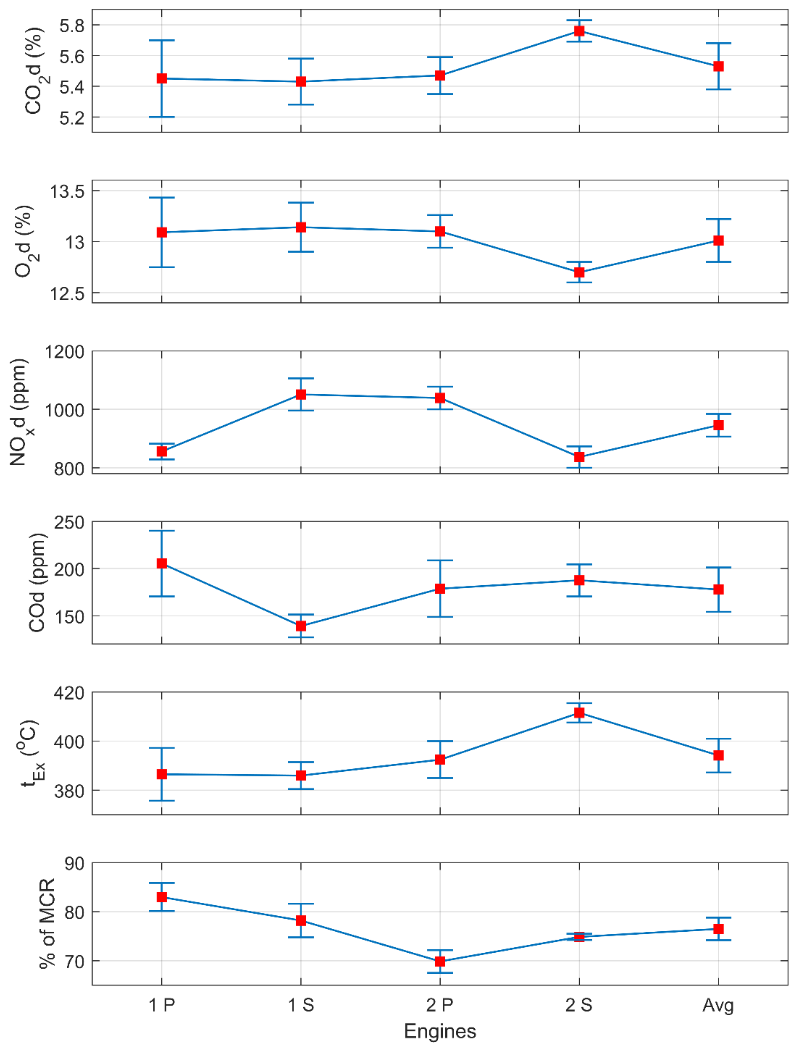

Figure 2: Mean μ and standard deviation σ of measured and analysed parameters for Vessel 1 and its associated port (P) and starboard (S) engines with calculated average values

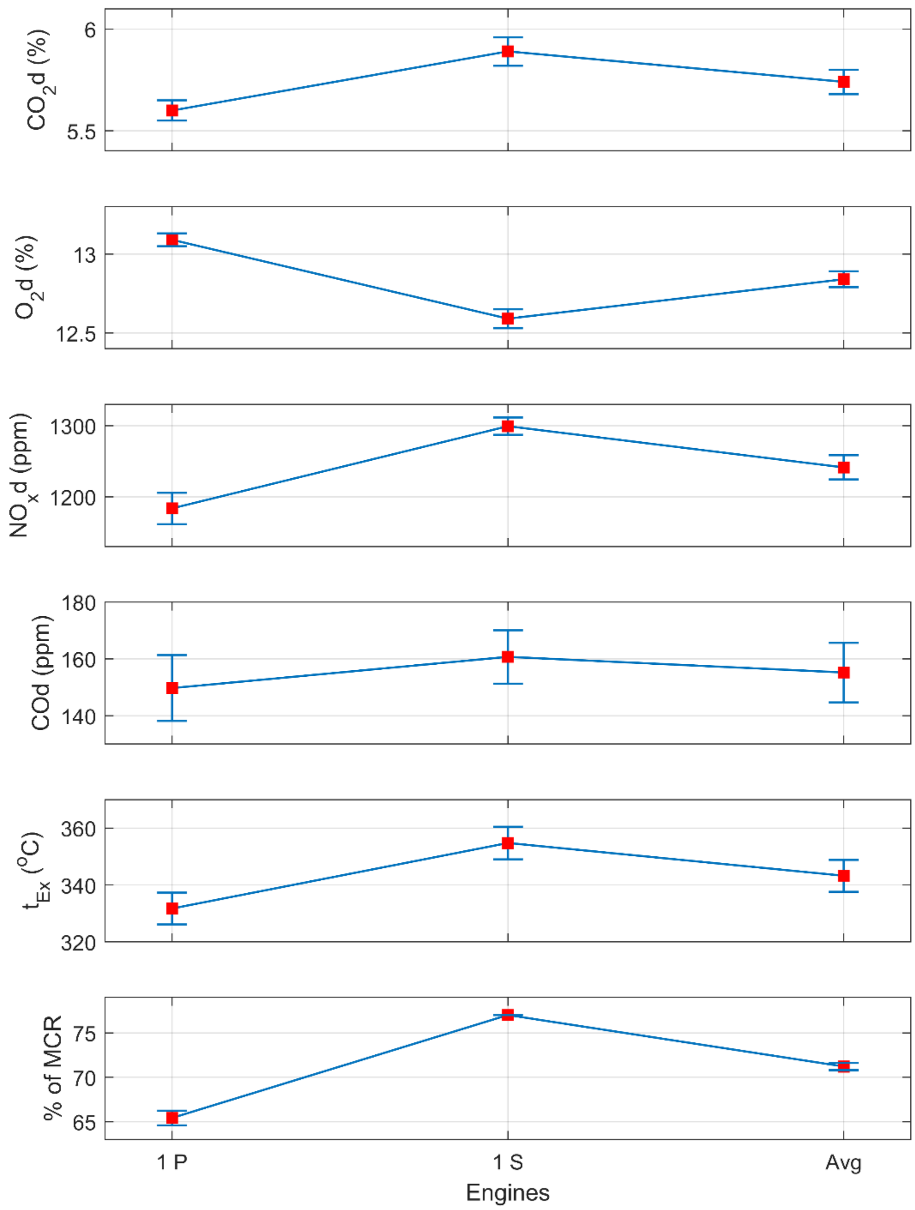

Figure 3: Mean μ and standard deviation σ of measured and analysed parameters for Vessel 2 and its associated port (P) and starboard (S) engines with calculated average values

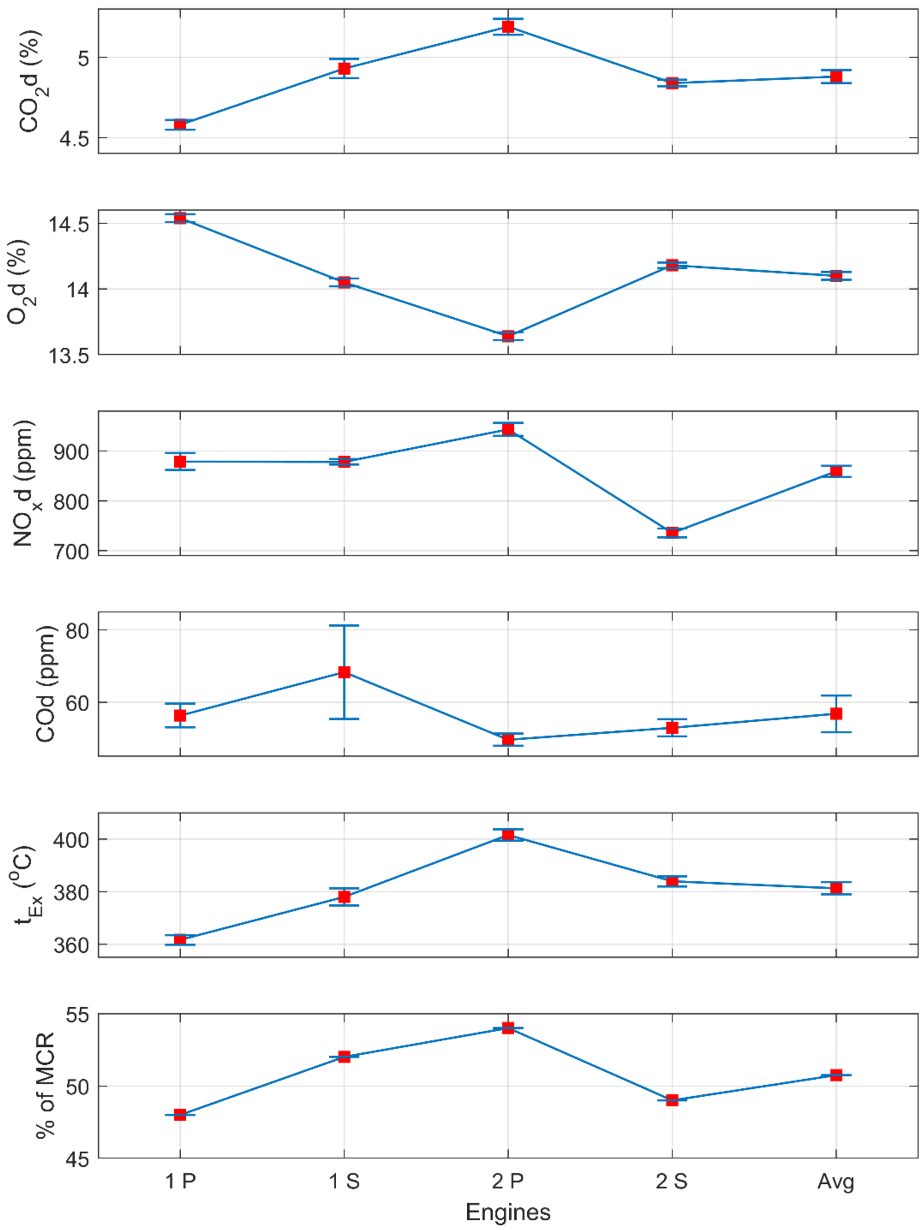

Figure 4: Mean µ and standard deviation σ of measured and analysed parameters for Vessel 3 and its associated port (P) and starboard (S) engines with calculated average values

Table 3. Simulated Ro-Pax vessel engine operating and exhaust gas simulated values

% of MCR	CO_2d (%)	O_2d (%)	NO_xd (ppm)	COd (ppm)	t_{Ex} (°C)	SFOC (g/kWh)	λ
85	6.09	12.85	1025	94	350.01	190	2.477
83	6.00	12.97	992	94	346.99	191	2.513
80	5.97	13.01	980	95	341.28	191	2.526
77	5.93	13.07	968	97	335.43	191	2.543
74	5.90	13.10	955	99	331.92	191	2.555
72	5.88	13.13	954	99	330.22	191	2.564
70	6.70	12.03	884	99	404.27	193	2.258
68	6.64	12.11	860	99	404.50	193	2.277
67	6.66	12.09	855	99	404.12	193	2.271
60	6.75	11.96	816	104	399.83	194	2.241
55	6.60	12.17	747	104	392.00	195	2.291
50	6.60	12.17	740	109	381.67	195	2.291

3. Results

During the on board measurement process environmental loads, vessel speed and voyage duration influenced the engines shaft power/load. Engines shaft power proportionally changes with the change of the environmental loads and engine speed and influence the exhaust gas measured parameters. Vessel 1 sailed under the longest averaged distances, had the highest averaged vessel speed and heaviest weather conditions when compared to other vessels. Vessel 2 and 3 sailed with similar averaged vessel speeds and weather conditions on voyages with similar averaged distances.

Data presented in Table 2 show that Vessel 1 sailed with the highest averaged engine shaft power (or load) on engines compared to other vessels. Averaged load on Vessel 1 engines was 76.48 % and the lowest averaged engine load was 50.75 % on Vessel 3. This higher load on Vessel 1 was caused due to the heavier weather and higher vessel speed due to the longer distances of the voyages. Averaged concentrations of CO_2 and O_2 in dry exhaust gases were similar on Vessel 1 and Vessel 2 which is normal due to almost similar engine loads. These engines were working with sufficient excess air quantity in order to enable complete combustion process in the cylinders and have a certain concentration of O_2 in exhaust gases. Vessel 3 operated with lower CO_2 and higher O_2 concentrations in the dry exhaust gas, compared to the other vessels, which is typical for lower engine loads. The standard deviation for all averaged concentrations of CO_2 and O_2 in dry exhaust gases on all three vessels was very small. Highest averaged concentrations of CO in dry exhaust gases were on Vessel 1 because of the higher engine loads and engine speed and the lowest on Vessel 3 for the opposite reasons. Highest averaged NO_x concentrations were recorded on Vessel 2 and the lowest on Vessel 3. The formation of NO_x concentration in exhaust gases is influenced with high combustion temperatures, pressures and the duration of the combustion process [10]. Engines on all three vessels were built before 1st January 2000 (Pre-2000 Engines) so the IMO emission standards, commonly referred to as Tier I, II and III standards, do not apply to these engines [11].

Figure 4 shows measured data and differences on all 4 main engines on Vessel 1. The standard deviation of all measured values is higher compared to other vessels because of the influence of heavier weather on main engines during the voyages. For Port engines (1 P and 2 P) and 1 Starboard (1 S) engine the averaged concentrations of CO_2 and O_2 in dry exhaust gases were similar except for the engine 2 Starboard (2 S) where concentrations of CO_2 were higher and O_2 lower. Also, for engine 2 S, averaged concentrations of NOx were the lowest, the exhaust gas temperatures after the turbocharger the highest and concentrations of CO the second highest. All of this can indicate the retarded injection timing or prolonged duration of the combustion process. Engine 1 S had the lowest averaged concentrations of CO, lowest exhaust gas temperatures and highest averaged concentrations of NOx, which can indicate the best combustion process among all engines. Higher NOx concentration, which results from higher combustion temperatures, should satisfy Tier I, II or III emission levels for engines built after the 1st January 2000.

Figure 5 shows measured data and differences on port and starboard main engines on Vessel 2. Starboard main engine had a higher averaged load than the port main engine and consequently higher exhaust gas temperatures after the turbocharger, higher averaged values of CO_2 and NO_x and slightly higher values of CO. Averaged concentrations of O_2 in dry exhaust gases were lower on the port main engine compared to starboard engine. This data difference is normal for engines working at such different engine loads. Averaged concentrations of NO_x on Vessel 2 are the highest when compared to other vessels which should be investigated further.

Figure 6 shows measured data and differences on all 4 main engines on Vessel 3. Main engine 2 Port (2 P) had the highest percentage of averaged load compared to other engines. That resulted with the highest averaged values of exhaust gas temperatures, concentrations of CO_2, NO_x and lowest values of averaged data for concentrations of O_2 and CO in dry exhaust gases. All four engine data presented in Figure 6 follow the same line pattern as previously explained. As the averaged load increases the exhaust gas temperatures, averaged concentrations of CO_2 and NO_x increase (except for CO data for engine 2 P) and averaged data for concentrations of O_2 and CO decrease (and vice versa).

Data presented in Table 3 show averaged simulator engine parameters during the engine shaft power/load change in percentage of MCR. Other values that are not provided by the simulator were post-calculated, as explained in the previous section. Engine loads, during simulation process, varied from 50-85 % which are usual loads on board vessels during the voyages and were also during the measurement processes. The data in the table can be divided in two parts, engine parameters lower and higher than 70 % of MCR. The data in the table follow the previously mentioned pattern (with the minor exception at lower loads, at 60 % and 67 %). When the engine load increases, the exhaust gas temperatures, concentrations of CO_2 and NO_x increase and concentrations of O_2 and CO decrease. At engine loads higher than 70 % of MCR the turbocharger operates more efficiently and the exhaust gas temperature after the turbocharger decreases from 404 °C to 330 °C. This causes suction of more combustion air quantity into the cylinder (excess air λ is higher). As the engine load again increases (more than 72 % of MCR), the simulated data follow the previously mentioned pattern.

In order to compare the on board measured values with simulated data, table 4 was created. It shows a comparison of exhaust gas measurements and engine operating parameters from Vessel 1, Vessel 2 and simulated Ro-Pax vessel at the same loads. Vessel 1 engine data was compared with simulator data at 80 % and 74 % of MCR and Vessel 2 engine data was compared with simulator data at 67 % and 77 % of MCR. These were the cases during the measurement process where both controllable pitch propellers were connected to two main engines at specified engine load. Vessel 1 and 2 data for SFOC were taken from the engine instruction manuals [12, 13] and excess air λ was calculated in the same manner as for the simulator data.

Table 4. Comparison of exhaust gas measurements and engine operating parameters from Vessel 1, Vessel 2 and simulated Ro-Pax vessel

Vessel / Engine	% of MCR	CO_2d (%)	O_2d (%)	NO_xd (ppm)	COd (ppm)	t_{Ex} (°C)	SFOC (g/kWh)	λ
Vessel 1/ Engine 1P	80	5.20	13.46	866	167	376.44	213	2.891
Vessel 1/ Engine 1S	80	5.45	13.10	1114	135	391.54	213	2.761
Simulator / Engine	80	5.97	13.01	980	95	341.28	191	2.526
Vessel 1 / Engine 2 P	74	5.67	12.87	1006	184	404.29	216	2.657
Vessel 1/ Engine 2 S	74	5.79	12.70	789	198	411.22	216	2.603
Simulator / Engine	74	5.90	13.10	955	99	331.92	191	2.555
Vessel 2 / Engine P	67	5.65	13.15	1218	166	331.32	205	2.666
Simulator / Engine	67	6.66	12.09	855	99	404.12	193	2.271
Vessel 2 / Engine S	77	5.83	12.59	1314	165	356.58	203	2.585
Simulator / Engine	77	5.93	13.07	968	97	335.43	191	2.543

At almost all compared engine loads the measured averaged concentrations of CO_2 and O_2 in dry exhaust gases were similar except for the Vessel 2 / Engine Port when compared to simulated values. As explained earlier, this is because simulated engines' turbocharger operates less efficiently at loads lower than 70 % of MCR. This can be seen if the exhaust temperatures of simulated engines are observed. Only at 67 % of MCR the exhaust temperature of simulated engines was higher than during the on board measurements. Excess air λ depends on turbocharger efficiency and engine/turbocharging system design. The value of excess air directly influences on CO_2 and O_2 percentage in exhaust gases. Averaged concentrations of CO on simulated engines were lower than measured on board vessels which is normal for newer versions/designs of engines. Averaged concentrations of NO_x were similar when comparing Vessel 1 and simulated engine. Vessel 2 had the highest averaged concentrations of NO_x and for that reason fuel injection system/equipment on that vessel should be checked for proper operation. All above mentioned differences between measured and simulated values can be even better explained when comparing SFOC data. Simulated engines have significantly lower specific fuel oil consumption when compared to Vessel 1 and 2 engines. Vessels 1 and 2 were built in 1973 and 1993, respectively, with much lower mean effective pressure (mep) inside the cylinders, lower engine speed and engine power (Table 1). Simulator engines are a replica of modern and efficient MAN B&W 8L32/40 type engine that enables operation in different load ranges with low fuel oil consumption. All other advantages of the latest type of this engine can be found in [14].

Ro-Pax vessels and simulated Ro-Pax vessel can be compared during one example voyage which duration is set to 8 hours. The energy consumption E_{cons} [kWh] is calculated according to:

$$E_{cons} = P_{prop} \cdot t_{voyage} \tag{3}$$

where P_{prop} is the propulsion power [kW] generated with all active engines and t_{voyage} is the voyage duration [h].

The propulsion power P_{prop} is calculated according to:

$$P_{prop} = N_{eng} \cdot \%\ of\ MCR \cdot MCR \tag{4}$$

where N_{eng} is the number of engines that are used for propelling the vessel.

Fuel oil consumption FO_{cons} [t] could be then calculated according to the equation:

$$FO_{cons} = E_{cons} \cdot \frac{SFOC}{10^6} \tag{5}$$

where $SFOC$ is the specific fuel oil consumption [g/kWh].

For Vessel 1, with two main engines and engines load equal to 74 % of MCR, the fuel oil consumption will be:

$$FO_{cons} = P_{prop} \cdot t_{voyage} \cdot SFOC \cdot 10^{-6}$$

$$= (2 \cdot 0.74 \cdot 3750)\ [\mathrm{kW}] \cdot 8\ [\mathrm{h}] \cdot 216 \cdot 10^{-6}\ [\mathrm{g/kWh}]$$

$$= 9.59\ [\mathrm{t}].$$

For Simulated vessel, with two main engines and engines load equal to 74 % of MCR, with the same energy consumption, the reduced voyage duration $t_{voyage,red}$ and reduced fuel oil consumption $FO_{cons,red}$ will be:

$$t_{voyage,red} = \frac{E_{cons}}{P_{prop}} = \frac{(2 \cdot 0.74 \cdot 3750)\ [\mathrm{kW}] \cdot 8\ [\mathrm{h}]}{(2 \cdot 0.74 \cdot 4000)\ [\mathrm{kW}]} = 7.5\ [\mathrm{h}]$$

$$FO_{cons,red} = (2 \cdot 0.74 \cdot 4000)\ [\mathrm{kW}] \cdot 7.5\ [\mathrm{h}] \cdot 191 \cdot 10^{-6}\ \left[\frac{\mathrm{g}}{\mathrm{kWh}}\right] = 8.48\ [\mathrm{t}].$$

With the same voyage duration and energy consumption, reduced two engines load expressed as the % of MCR and fuel oil consumption will be:

$$\%\ of\ MCR = \frac{E_{cons}}{t_{voyage} \cdot MCR} = \frac{(2 \cdot 0.74 \cdot 4000)\ [\mathrm{kW}] \cdot 7.5\ [\mathrm{h}]}{8\ [h] \cdot 4000\ [\mathrm{kW}]} = 2 \cdot 0.694\ [\%\ \mathrm{of\ MCR}]$$

$$FO_{cons} = (2 \cdot 0.74 \cdot 4000)\ [\mathrm{kW}] \cdot 7.5\ [\mathrm{h}] \cdot 193 \cdot 10^{-6}\ \left[\frac{\mathrm{g}}{\mathrm{kWh}}\right] = 8.57\ [\mathrm{t}].$$

The reduction of fuel oil consumption will be 1.11 tons or 1.02 tons per voyage. When multiplied with an emission factor of 3.206 kg of CO_2 in exhaust gases per 1 kg of burned marine diesel oil it will be 3.56 tons of CO_2 or 3.27 tons of CO_2 less per voyage. A similar calculation can be done with other vessels parameters.

Presented results show that exhaust gas concentrations acquired during the on board measurements and from the simulation process, with the same engine loads, are similar and can be compared. Differences in excess air quantities and specific fuel oil consumption originate from differences in engine models and year of built. Newer engines have lower specific fuel oil consumptions which, as a result, will have reduced vessel's fuel oil consumption and CO_2 emission. Engine complete fuel oil combustion process and optimal point of operation are influenced by many parameters that could be used in different fuel efficiency and pollution minimization optimisation procedures.

In some cases, it is very difficult, expensive or impossible to measure on board exhaust gas emissions and also to acquire engine room and navigational simulators. Results show that exhaust gas data from one source can be used to validate the data from the other source in order to reduce the research expenses and help creating relevant emission database. Acquired data can be also used for creating exhaust gas emissions models, engine and vessel optimization models, ship routing models [15] and similar.

4. Conclusions

The recorded simulator output variables, which were similar to the on board measured parameters, were compared to the exhaust gas emissions and engine operating parameters of Vessels 1, 2 and 3 engines. Comparison of the simulated data with the data measured on board vessels showed that concentrations of exhaust gas components were similar for all engine loads and measured averaged concentrations. Presented analysis shows that significant fuel oil and CO_2 emission reduction per voyage could be accomplished by voyage and/or engine operation optimization. Finally, it should be noted that the values presented in Table 3 can be further used for the data-driven modelling with the purpose of exhaust gases estimation with respect to different engine operating conditions.

Research studies on exhaust gases on board Ro-Pax vessels are very limited. Thus, measured data presented in this research will help creating more relevant on board emission database and offer the possibility to enhance the estimation of emissions and comparison with the current emission database. Measured and simulated data can be used for root cause analysis, creating engine optimization and exhaust emissions models, ship routing models and similar. Results of this analysis could be of interest to shipowners, ship operators, environmentalists and all other in reducing the fuel oil consumption and emissions of greenhouse and harmful exhaust gases into the atmosphere.

References

1. https://www.testo.com/hr-HR/testo-350-maritime/p/0563-3503 (accessed on 17 March 2022).

2 Testo-350-Maritime-Instruction-Manual.pdf; https://static-int.testo.com/media/30/a7/476842882400/testo-350-maritime-Instruction-manual.pdf (accessed on 17 March 2022).

3. Internal company document: Bunker delivery note.

4. https://www.wartsila.com/voyage/simulation-and-training/technological-simulators (accessed on 17 March 2022).

5. https://www.wartsila.com/voyage/simulation-and-training/navigational-simulators, (accessed on 17 March 2022).

6. Farkas, A.; Parunov, J.; Katalinić, M.: Wave statistics for the middle Adriatic Sea. Pomor. Zb. 2016, 52, 33–47.

7. Mannarini, G.; Carelli, L.; Orović, J.; Martinkus, C.P.; Coppini, G.: Towards Least-CO2 Ferry Routes in the Adriatic Sea. J. Mar. Sci. Eng. 2021, 9, 115. https://doi.org/10.3390/jmse9020115.

8. IMO. MEPC.1/Circ.684 Guidelines for Voluntary Use of the Ship Energy Efficiency Operational Indicator (EEOI); Technical Report; International Maritime Organization: London, UK, 2009.

9. IMO: Fourth Greenhouse Gas Study 2020; Available online: https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Fourth%20IMO%20GHG%20Study%202020%20-%20Full%20report%20and%20annexes.pdf, (accessed on 30 March 2022).

10. European Maritime Safety Agency (EMSA): Possible Technical Modifications on Pre-2000 Marine Diesel Engines for NOx Reductions, 2008, Available online: http://www.emsa.europa.eu/tags/download/1017/604/23.html, (accessed on 30 March 2022).

11. US Environmental Protection Agency: Regulatory update - Overview of EPA's Emission Standards for Marine Engines, August 2004.

12. Internal company document: Instruction manual for Stork Werkspoor Diesel 8TM410 engine.

13. Internal company document: Instruction manual for Bazan MAN B&W 8L40/54 A engine.

14. MAN B&W: L+V32/40 Project Guide – Marine Four-stroke diesel engines compliant with IMO Tier II, Available online: https://man-es.com/applications/projectguides/4stroke/manualcontent/L32-40_GenSet_TierII.pdf (accessed on 30 March 2022).

15. https://www.gutta-visir.eu (accessed on 30 March 2022).