



Airborne monitoring of compliance to NO_x emission regulations from ocean-going vessels in the Belgian North Sea

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ABSTRACT

Along the worldwide tightening of standards for sulphur emission from ocean going vessels (OGVs) come actions that are also being taken to reduce nitrogen emission. Particularly, as a milestone in this regard, on January 1st 2021 the NO_x Emission Control Area (NECA) for the North Sea and Baltic Sea came into effect. In response to the newly established NECA, the sniffer sensor system on the Belgian coastguard aircraft was modified and extended with a NO_x sensor. Moreover, a methodology was developed to evaluate OGV compliance to the NO_x emission limits through in situ measurements of the plume exhaust. The quality and uncertainty of the measurements demonstrate that it is likely to achieve an effective compliance monitoring of the NO_x emission standards on the sea. Those emission standards are further divided into four tiers depending on the keel laying date. As has been proved by the results, NO_x emissions for Tier II OGVs, contrary to what might be expected, are on average higher than those for Tier I OGVs. What is even more problematic, Tier II OGVs have also more often been found to be non-compliant than Tier I OGVs.

1. Introduction

1.1. Impact NO_x emissions

As is known to all, NO_x has a significant impact on human health, the environment and the climate. Health impact from NO₂ involves mainly cardiovascular conditions and respiratory diseases such as (children's) asthma and Chronic Obstructive Pulmonary Disease (COPD). In addition, NO₂ is also a precursor for ozone (O₃) that causes respiratory illness as well. Due to the fact that nitrogen dioxide reacts with water to give a mixture of nitrous acid (HNO₂) and nitric acid (HNO₃), NO_x is one of the major contributors to acid rain (Zumdahl, 2002) which is responsible for the environmental degradation of forests and coral reefs (Flagan and Seinfeld, 1988; Zumdahl, 2002), for the aggravation of the ocean acidification caused by the emission of CO₂, and even for the damage to structures and artificial surfaces (e.g. historic limestone constructions) (Zumdahl, 2002). Furthermore, NO_x is also a source of eutrophication with significant environmental and monetary impacts (Repka et al., 2021; Turner et al., 2004, 2018).

In the EU, air quality standard for NO₂ limit is 40 µg/m³ annual mean (EU, 2008). Nevertheless, as there is in fact no lower threshold for NO₂, the World Health Organization (WHO) applies a substantial lower standard of 10 µg/m³ (EEA, 2020). Based on the provisional data for 2020, all of the 33 reporting countries, except Malta, reported values above the WHO standard (EEA, 2021). In terms of the situation in Belgium, the WHO standard is even largely breached. For example, a recent citizens science project in 2022 indicates that only 1.7% of more than 3000 measurements points in Brussels met the WHO standard (Meysman, 2022; Vanderstichele, 2022).

1.2. NO_x emissions from maritime transport

Shipping is one of the main contributors of emissions from NO_x on global scale (Corbett et al., 1999). For the period 2007–2012, the NO_x emission from OGVs contributed to 13% of the global anthropogenic NO_x emission, while only representing 3.1% of the CO₂ emission (IMO, 2015). NO₂ data (in molecules/cm²) from the TROPOMI Sentinel 5 satellite (Tack et al., 2021) clearly demonstrate that the maritime sector

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is a substantial source of NO_x emissions, visualizing the maritime transport patterns (Fig. 1).

1.3. NO_x regulations for OGVs

The international NO_x emission standards for OGVs are laid down by the International Maritime Organization (IMO). As the main international convention covering prevention of pollution of the marine environment by ships from operational or accidental causes, the 1973 International Convention for the Prevention of Pollution from Ships (MARPOL), alongside its 1978 Protocol (MARPOL 73/78) (IMO, 1978) was amended by the Protocol of 1997 (MARPOL PROT 1997) and further revised in 2008 (MEPC, 2008a), to include airborne emissions from OGVs in Annex VI. As of 2021, the MARPOL PROT 1997 has been ratified by 101 countries representing 96.75% of the gross tonnage of the worlds merchant fleet (IMO, 2021). At national level, MARPOL Annex VI was adopted in Belgium in 2007 (Royal Decree, 2007).

Regulation 13 of MARPOL Annex VI envisages a gradual decrease of emissions of NO_x and introduces Emission Control Areas (ECAs) where more stringent emission limits for air pollutants from OGVs should be applied (MEPC, 2010). In 2021, the Sulphur Emission Control Area (SECA) in the Baltic Sea, the North Sea and the English Channel was extended with a NO_x Emission Control Area (NECA) and therefore renamed to Emission Control Area (ECA) (MEPC, 2016, 2018) (Fig. 2). Nevertheless, due to the increase in maritime transport, the total NO_x emission from OGVs is still tending to increase (Bencs et al., 2017).

In contrast with the EU sulphur regulations, NO_x emissions from ships are not regulated by an additional EU directive, which means no common European monitoring rules and procedures are in place. As a result, the NO_x inspection data of EU member states are not shared through Thetis EU – the port inspection database managed by the European Maritime Safety Agency (EMSA).

1.4. Marpol Annex VI regulation 13

Unlike the reduction of Sulphur emissions under the EU Sulphur regulations that suffices to limit the sulphur content in the fuel used, reducing NO_x emissions, in accordance with the MARPOL regulatory approach, needs to be achieved through addressing the combustion processes in the engine. Therefore, engines need to be tested and classified according to the NO_x Technical code, MEPC.1/Circ.679 (MEPC, 2008b). Accordingly, in MARPOL Annex VI, the NO_x emission limits in Regulation 13 are also expressed differently from the limits for sulphur emission in Regulation 14. More specifically, the nitrogen content of the fuel is only a small factor in the whole NO_x emission cycle, and therefore the NO_x limits are expressed as the actual weighted amount of NO_x emission (g) per Brake Horse Power (BHP) on the crankshaft (kWh).

1.4.1. Keel laying year

Based on the Keel Laying Year (KLY) of the vessel, as defined as ship constructed (Reg. 2.19), the merchant fleet is divided in 4 tiers in Regulation 13. Tier 0 applies for OGVs with a KLY before 2000 (Reg. 13.7); Tier I concerns ships from 2000 until 2011 (Reg. 13.3); Tier II is for ships from 2011 until 2021 (Reg. 13.4) and Tier III is for ships with a KLY from 2021 onwards (Reg. 13.5). The emission limit per tier is furthermore based on the Engine Rated Speed (ERS or n), which is the point where the engine, expressed in rotations per minute (rpm), produces the maximum power and is defined per engine or engine class. The NO_x emission limits per tier are provided in Fig. 2. For OGVs with Tier 0, with a KLY after 1990, the Tier I regulations apply for ships with a rated engine power output of more than 5000 kWh or with a displacement ≥90 L per cylinder.

1.4.2. Test cycles

An additional complication in Marpol Annex VI Regulation 13 is manifested as a complexity that 5 different test cycles with 4–5 engine

loads and corresponding weighting factors have been described in the NO_x Technical code for the verification of the compliance to the emission limits. The described test cycles are used in order to obtain the Engine International Air Pollution Prevention Certificate (EIAPP) and the International Air Pollution Prevention Certificate (IAPP). The EIAPP is issued during the pre-certification of an engine prior to the installation on board of an OGV, while the IAPP is granted during the certification after installation of the engine on board of an OGV, both of which are addressed by a classification society.

Only test cycles for the main engines fall under the scope of this study. The two test cycles for the main engines (E2 and E3) are both based on the same engine load (Power) and weighting factor (WF) (see Table 1). To verify compliance, the weighted average emission for the 4 engine loads should not exceed the NO_x limit. The results of the engine emission tests are described in Annex 5 of the NO_x Technical Code, as part of the EIAPP and IAPP should be stored onboard. It is also worth noting that all NO_x sensitive components, which are described in the NO_x technical file, must be stored on board together with the EIAPP and IAPP, and all modifications to these components must be recorded in the NO_x technical file (MEPC, 2008a, 2008b).

It is important to highlight that only for Tier III a “not to exceed” limit (NTE) is defined, which states that the emission for any engine load should not exceed the NO_x limit with more than 50% at any of the individual engine loads of the E2 or E3 test cycles (MEPC, 2008b). To comply with the NO_x regulations in the ECA, engine manufacturers and shipowners may resort to several technical solutions. Among those solutions, the two main abatement techniques employed to lower the emission for regular marine diesel engines are Selective Catalytic Reduction (SCR) and Exhaust Gas Reintroduction (EGR). With SCR, urea is added as a reagent to reduce NO_x to N₂ (Papapostolou et al., 2017), which works well to meet Tier III standards, although ammonia slips are a potential risk (Lee, 2017). On the other side, exhaust gasses, in terms of EGR, are injected back in the engine in a controlled manner. This lowers the temperature and oxygen level in the combustion chamber and decreases the NO_x emissions. Although EGR is efficient for NO_x reduction, it is possible to potentially increase the soot and Black Carbon (Zhang et al., 2019). In addition to SCR and EGR, other abatement methods include scavenge air moisturizing (SAM) (MAN, 2022), Miller cycle for 4 stroke engines (Li et al., 2019) and CSNOx (Ecospec, 2022). A shipowner may also decide to opt for new fuels like LNG, but at this moment only about 5% of the OGVs is equipped with an LNG engine (UNCTAD, 2022). In the future, the increasing use of other fuel sources like ammonia or hydrogen might also contribute to a reduction in NO_x emissions from OGVs. With abatement technologies like SCR and EGR, there is a remaining risk for NO_x emission violation in case of technical malfunctioning, negligence or intentional misconduct due to economic gain.

1.5. Surveillance area and time frame for the monitoring operations

The Scientific Service of the Management Unit of the Mathematical Models of the North Sea (MUMM) of the Royal Belgian Institute of Natural Sciences is recognized by the Belgian Law as one of the legally competent authorities for the monitoring and enforcement of MARPOL regulations on the sea. Since 1991, MUMM has been responsible for the airborne surveillance of the Belgian North Sea area and neighboring waters, in the so-called Bonn Agreement (BA) Quadripartite Zone of Joint Responsibility (BAQPZJR) (Fig. 1). From 2015 onwards, MUMM has been conducting airborne surveillance operations for the monitoring of MARPOL Annex VI regulation 14, concerning sulphur emissions from OGVs (Van Roy et al., 2022). Although before 2021 the North Sea was not yet recognized as a NECA, the NO_x monitoring operations covered in this study started in July 2020 and lasted until November 2021.

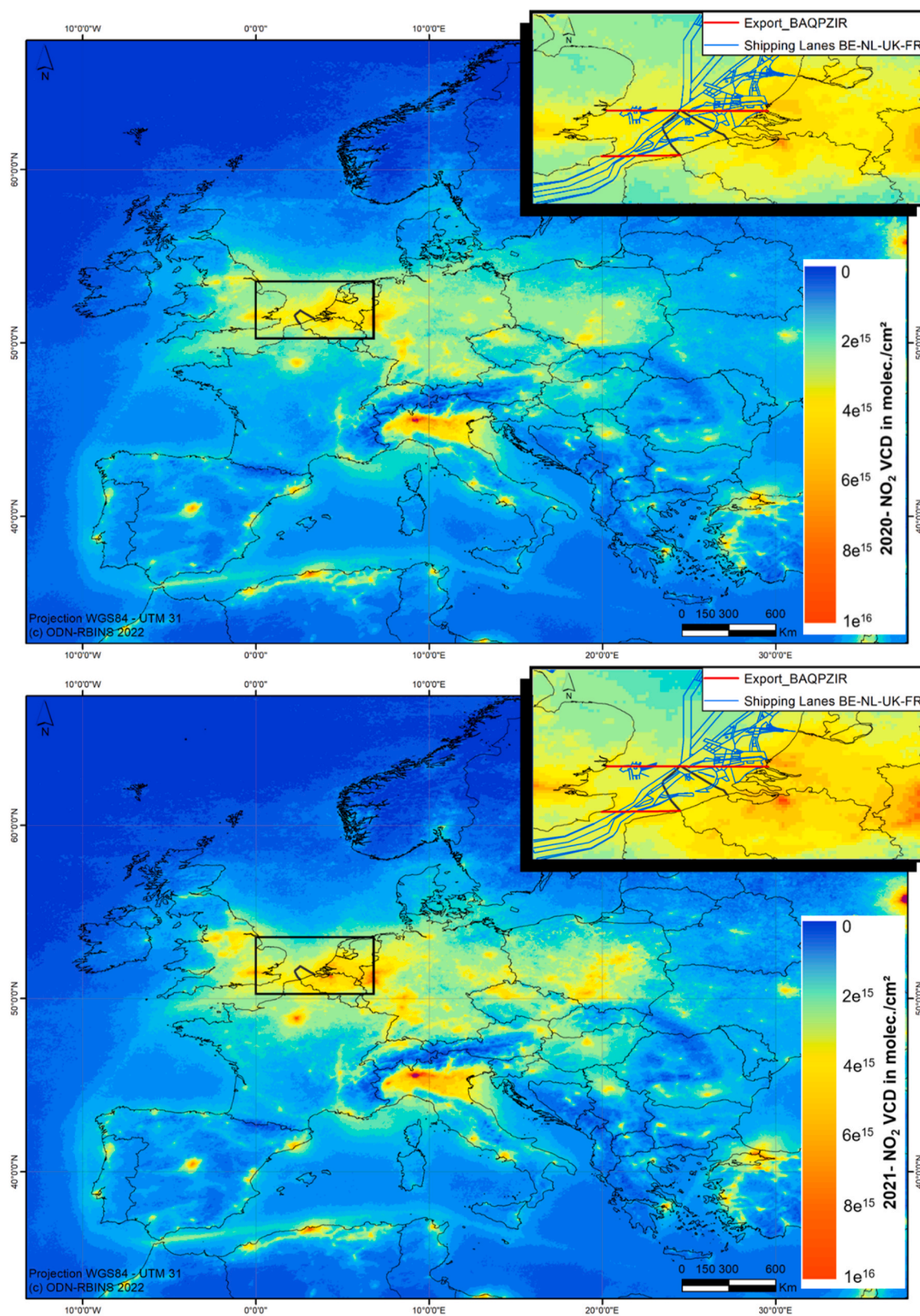


Fig. 1. Annual average observed NO₂ molecules/cm² VCD (Vertical Column Density) for 2020 (upper) and 2021 (lower) from TROPOMI Sentinel 5 (compiled data provided by BIRA).

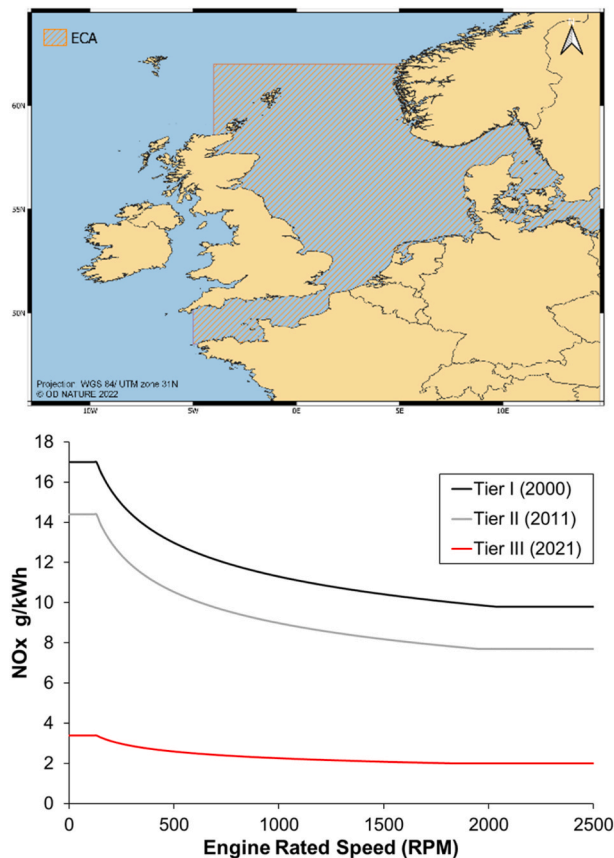


Fig. 2. Upper: Emission Control Area (ECA) as defined by MARPOL Annex VI. Lower: NO_x emission limits according to MARPOL Annex VI Regulation 13.

Table 1
Test cycles and weighting factors according to the NO_x Technical code (MEPC, 2008b).

E2	Speed	100%	100%	100%	100%
	Power	100%	75%	50%	25%
E3	WF	0.2	0.5	0.15	0.15
	Speed	100%	91%	80%	63%
	Power	100%	75%	50%	25%
	WF	0.2	0.5	0.15	0.15

2. Methods and materials

2.1. Belgian coastguard aircraft

The Belgian coastguard aircraft, a Britten Norman Islander (BN2), was used for this study. Characterized as a Short Take Off and Landing (STOL) aircraft with low stall speed (40 kts), this high wing aircraft has a large wing surface (15 m width for 11 m length), suiting this type of operations. More importantly, the aircraft is equipped with modern avionics, a remote sensing system from Optimare and a sniffer sensor from FluxSense was also purchased in 2015 for the airborne measurement of SO₂.

2.2. NO_x sensor

An Ecotech Serinus 40 NO_x sensor, which was purchased from Chalmers University and installed in June 2020, measures its gaseous concentration through using the chemiluminescence characteristics of NO. This sensor can operate in either the “NO_x mode”, the “NO mode” or the “All mode” that calculates the NO₂ based on the average NO_x and NO over a chosen time (min 15 s). Specifically, for the measurement of NO_x,

the sample passes through an ozone converter that transforms all the NO₂ in the sample flow to NO. While, for the NO_x monitoring operations, the sensor was set to NO_x mode with a sample time of 1 s.

2.3. Sniffer sensor system modification

The sniffer sensor system on board of the Belgian coastguard aircraft (Van Roy et al., 2022) was modified and extended in order to include the NO_x sensor. The same air supply probe was used as for the other gas analyzers in the sniffer sensor, but the NO_x sensor was kept outside of the pressurized loop as the NO_x requires a deeper vacuum and lower airflow (1 l/min). On the one hand, a custom build KNF vacuum pump (modified N022) was installed to provide the airflow. On the other hand, an additional exhaust probe, due to the ozone production, was further installed for the sniffer sensor (Figure S.1.).

The sniffer software (IGPS presenter and TCP log) was modified by Chalmers University to include the NO_x data. In addition, a yearly updated list all KLYs and MMSI information of 49,327 OGVs larger than 70 m was obtained from EMSA. This number of OGVs comes near to the global merchant fleet. This list was linked through the software so that KLY information is available to the operator during flight. Furthermore, on request of MUMM, an entry for the Specific Fuel Consumption (SFC) was added in the SNF menu (Fig. 3).

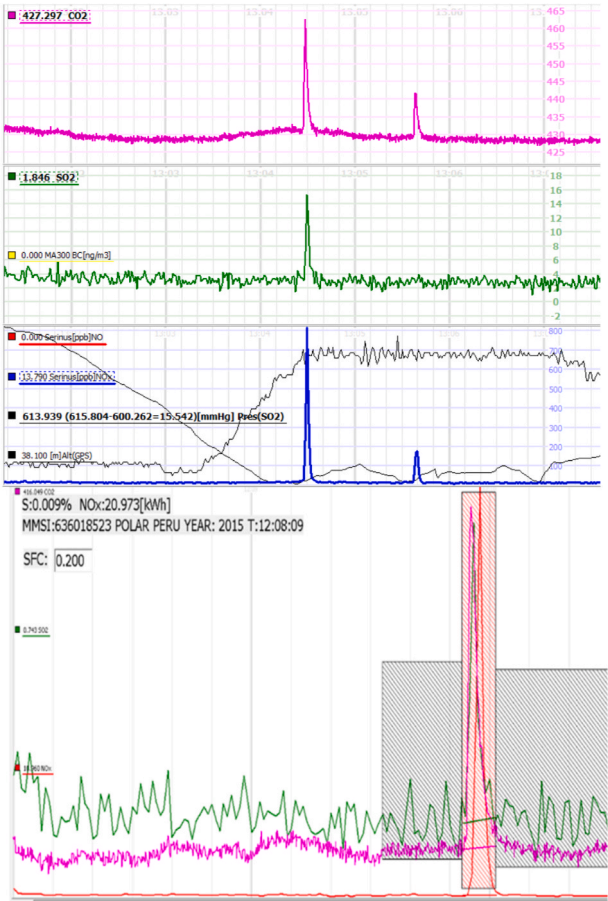


Fig. 3. Upper: print screen of the “SNF” view with the CO₂ concentration (in ppm) in magenta, SO₂ concentration (in ppb) in green and the NO_x concentration (in ppb) in blue. Lower: graph selection view, the start and end of the peak (red striped area) and the background before and after the peak (black striped areas) can be set by the operator to get a high-quality measurement. The NO_x emission is displayed immediately together with the Fuel Sulphur Content (FSC) (upper left side), the SFC is per default set at 0.2 kg/kWh but can be entered manually (snapshots from the IGPS software, developed by Chalmers University).

2.4. NO_x emission measurements

The NO_x emission factor (EF_{NO_x}) in g NO_x/kg fuel can be calculated by using the NO_x and CO₂ concentrations. When crossing the exhaust plume, NO_x and CO₂ concentrations will increase and create peaks compared to the background [value] (bkg) before and after the peak. The surface area of these peaks above the background of the respective concentration plots is used for the calculation of the NO_x emission factor. In terms of the calculation of the amount of kg burned fuel, the amount of carbon (C) is multiplied with the carbon content in the fuel. And with regard to marine fuels, a carbon content of 87% is used (Beecken et al., 2014, 2015).

$$EF_{NO_x} = \frac{MNO_2 \frac{g}{mol}}{MC \frac{g}{mol}} \times 1000 \times \frac{\int [NO_x - NO_{x,bkg}]_{ppm} dt}{\int [CO_2 - CO_{2,bkg}]_{ppm} dt} \left[\frac{g}{kg_{fuel}} \right] \quad (1)$$

$$EF_{NO_x} = 3.33 \times \frac{\int [NO_x - NO_{x,bkg}]_{ppm} dt}{\int [CO_2 - CO_{2,bkg}]_{ppm} dt} \left[\frac{g}{kg_{fuel}} \right] \quad (2)$$

According to Regulation 13 of MARPOL Annex VI, the molecular weight of NO₂ is used for the calculation of the NO_x emission factor. For the calculation of the NO_x emission in g NO_x/kWh, the NO_x emission factor (g NO_x/kg fuel) is multiplied by the Specific Fuel Consumption (SFC).

$$SFC = \frac{kg_{fuel}}{kWh_{BHP}} \quad (3)$$

$$EF_{P,NO_x} = EF_{NO_x} \times \left(\frac{kg_{fuel}}{kWh_{BHP}} \right) \quad (4)$$

Based on literature and public engine data, the SFC can generally be found between 0.16 kg/kWh and 0.24 kg/kWh (Acomi and Cristian Acomi, 2014; Asariotis et al., 2020; Balzani Lööv et al., 2014; Berg et al., 2012; Cheng et al., 2017; Faber et al., 2021; MAN, 2014a, 2014b; Pirjola et al., 2014; WINGD, 2016, 2017).

2.5. Sniffer Quality Management System

A Sniffer Quality Management System (SQMS) has been set up with Standard Operational Procedures (SOPs) (Van Roy et al., 2022) to guarantee a high reliability of emission measurements on spatial and temporal level and to ensure that the airborne monitoring missions are executed efficiently, safely and in accordance with standardized measurement procedures. This SQMS system consists of three parts: (i) the operational procedures are described in the OPS manual, (ii) the quality assurance (QA) protocols are described in the QA manual, and (iii) the data management is described in the data manual. The updated three parts, including the NO_x emission monitoring, are described in the sections below.

2.5.1. Operational procedures

For the selection and sampling of the exhaust plumes of the OGVs, the same procedures were applied as for the monitoring of SO₂ (Van Roy et al., 2022), which means that both the NO_x emission limit from MARPOL Annex VI Regulation 13 and the FSC limit as described in MARPOL Annex VI Regulation 14 were monitored at the same time. As soon as the aircraft sampled the OGV exhausts, gas concentrations of CO₂, SO₂ and NO_x were immediately plotted on the SNF graphs on the IGPS software. The manual calculation of the NO_x emission by aerial operators was done together with the calculation of the FSC by selecting the area before/after the peak (background) and the area of the peak itself.

For the initial NO_x emission calculation, an SFC of 0.2 kg/kWh was used. The KLY was displayed together with the NO_x emission. When this

first measurement with the default SFC showed a value exceeding a predefined threshold, marine VHF radio contact was made with the vessel to request the actual fuel consumption of the main engine (in metric tons/hour) and the current main engine power (in kW), to be calculated and provided by the chief engineer. A special radio communication checklist was therefore created for this purpose. For simplification, it was chosen to ask the total main engine power output as the provision of the crankshaft power output may not always be possible, reliable or as fast as the main engine total power output. The total power output will always be slightly higher than the break power at the crankshaft due to friction losses and losses for additional auxiliary systems connected to the main engine. The obtained NO_x emission factor was therefore always an underestimation of the actual NO_x emission factor. Based on the information obtained through radio communication, the SFC was calculated and entered in the IGPS software. Moreover, a second exhaust plume sampling was executed and the NO_x emission factor was determined with the actual SFC. It is also worth noting that NO_x emission factor measurements taken with the default SFC could also be recalculated in case the SFC was only obtained after both measurements occurred.

$$Corrected\ EF_{P,NO_x} = \frac{Initial\ EF_{P,NO_x}}{Default\ SFC} \times Actual\ SFC \quad (5)$$

Whenever it was not possible to contact the OGV due to, for instance, other operations on board of the OGV (e.g. piloting or maneuvering) or when the chief engineer was not available, a lower end SFC of 0.16 kg/kWh was applied as it was preferred to avoid false positives over false negatives. In case the recalculated NO_x emission factor was still higher than the Tier threshold, the OGV was considered as non-compliant and reported to PSC. In case the recalculated NO_x emission fell below the threshold, the OGV was not reported. In the database the calculation of the NO_x emission factors for OGVs without a confirmed SFC however were all based on an SFC of 0.2 kg/kWh for standardization purpose. In case the second measurement confirmed a NO_x emission factor exceeding the Tier threshold, a flight report was drafted and sent to the port inspection authorities of the country of destination (in case this was an ECA port), who could decide whether or not to board for an inspection in the next port of call.

Based on a dataset from IHS Markit, it was demonstrated that the majority of OGVs equipped with two stroke slow speed engines have engine rates below 130 rpm (Winnes et al., 2015). This is especially the case for tankers (60%), container OGVs (74%), vehicle carriers (75%) and bulk carriers (81%). On the other hand, Roll On Roll Off OGVs (RORO) (17%), cruise OGVs (2%) and ferry's (1%) are not often equipped with slow speed engines but rather with medium speed engines (with engine rates of 500–750 rpm) and high speed engines (with engine rates >1000 rpm) (Winnes et al., 2015). Four stroke high speed engines are often to be found for auxiliary applications on all vessel types. Furthermore, the IMO greenhouse Study 2020 demonstrated that the majority of the OGVs with a Dead Weight Tonnage (DWT) larger than 20 kt have an engine rate under 130 rpm, which was partly based on the IHS Markit dataset and a regression algorithm from the University Maritime Advisory Services (UMAS) for the missing datapoints (see Figure S.2, upper) (Faber et al., 2021). Based on a cross referencing of the airborne dataset from 2015 to 2020 with a dataset of 1500 OGVs calling Belgian ports in 2019 (data provided by SPF Mobility), this DWT of 20 kt corresponded to an OGV length of minimum 172.9 m (Figure S.2, middle).

Ignoring the engine rate, it was decided to focus on operational efficiency due to two reasons: firstly, the focus of the airborne monitoring was the larger segment of the merchant fleet (>100m); secondly, auxiliary systems fall outside the scope of the monitoring. This meant that a fixed limit was applied per Tier level, being the (highest) NO_x limit for engine rates ≤130 rpm, not taking into account the lower NO_x emission limit for OGVs with engine rates >130 rpm. The Tier I limit was therefore set to 17 g NO_x/kWh and the limit for Tier II ships was fixed at

14.4 g NO_x/kWh.

For Tier 0 OGVs, that were built after 1990 with a power output ≥ 5000 kWh, the same rules apply as for Tier I OGVs. Based on the IMO GISIS online database (IMO, 2020), 173 m was found to be the absolute maximum length for ships with a power output as low as 5000 kWh (see Figure S.2, lower). Thus, all Tier 0 OGVs with a KLY after 1990 and a length >175 m were considered to be subject to Tier I emission limitations. As a result, limiting the workload for the operators that otherwise needed to look up engine parameters during flight for all Tier 0 OGVs built after 1990. For Tier 0 OGVs built after 1990 with a power output >5000 kWh but with a size smaller than 175 m, a manual check of the engine power output (on Thetis-EU) was still required, but those ships were only observed occasionally (2.7% of the observed OGVs).

OGVs sailing at an engine load lower than 25% were considered “off cycle”, which means that they fall outside the regulated emission “spectrum”. Due to the fact that it was not possible to request the engine load information for every individual measurement, a cut off speed of 10 kts was applied. Below this speed a higher threshold level was applied for the initial evaluation. The speed of 10 kts was chosen based on operational criteria. This was a very rough selection criteria, owing to the large variation in loads for different ship types and ship loads. For example, the average speed of bulk carriers and tankers for 2018 was 8–13 kts, for bulk carriers 9–12 kts, while for containers this was 13–17 kts (Faber et al., 2021). As such it is likely that several OGVs were included with engine loads $<25\%$, but a speed higher than 10 kts (type I). In addition, it is not possible to guarantee that all observed OGVs with a speed lower than 10 kts had engine loads lower than 25% (type II) and may therefore be wrongly excluded. For type I errors (false positives), the engine power output derived from the radio communication was used to calculate the actual load, thus assessing if the load was below 25%. Accordingly, type I errors could be completely excluded. Aiming to avoid important type II errors (false negatives), a higher threshold was applied for OGVs with a speed <10 kts, which meant that high polluting OGVs would still have been noted and reported to the port authorities.

2.5.2. Maintenance and calibration procedures

The Quality Assurance Manual consists of all detailed maintenance and calibration procedures. This part was updated with maintenance and calibration procedures for the NO_x sensor that was calibrated using a zero (synthetic air) and span gas of 300 ppb NO in N₂. The respective calibration gases were connected to the NO_x sensor directly to reset the sensor background (offset) and to set the calibration factor (slope). The span gas and zero gas mixtures were tested on regular intervals by the ISO certified air quality laboratory of the Brussels Environmental Agency (BIM). The NO concentration was very stable over time with an average variation of 2.3%. The calibration interval was therefore set at 3 months (together with the SO₂ span gas).

2.5.3. Data management

All NO_x measurement data, together with the collected data on the fuel consumption, engine loads, SFC and NO calibration factors, were included in the sniffer database. The sniffer data management procedures were updated to include the NO_x data. A similar presentation was achieved to present the NO_x emission measurement data and relevant engine data, besides the FSC data. The data management was also adopted with the procedures for the annual collection of the KLY from EMSA and its application on the IGPS software.

2.6. Statistical analysis

A Kolmogorov Smirnov test was used to assess the normality of the NO_x emission measurement data, showing that the NO_x data did not follow a Normal distribution ($P < 0.05$), which was the reason why non-parametrical tests were used. As the NO_x emission data is continuous, the Kolmogorov Smirnov test was chosen over the Mann-Whitney U test to compare the emission distribution of different groups (Years, Tiers,

OGV type, region). Distributions were found to be significantly different when $P < 0.05$ (Jay and Devore, 2011). To determine a difference in compliance levels between groups (Tier level, OGV Type, Year), a two-sided Chi Square test was used. Statistical significance was defined when $P < 0.05$ (Gardner and Altman, 1988; Sprinthall, 2011).

3. Results and discussion

3.1. Description of the sampled OGVs

During a total of 78 flights and 127.2 operational flight hours performed in the period 2020–2021, NO_x emissions of 1407 OGVs were successfully measured together with the measurement of the FSC. This comes down to an average number of successful emission measurements of 11.2 OGVs per flight hour. This is roughly the same amount of measurements per flight hour as the overall 10.4 inspected OGVs per hour for FSC monitoring for the period 2015–2019, but notably lower than the 12.9 average number of monitored OGVs for FSC monitoring for the year 2019 (Van Roy et al., 2022). Some improvement might be possible for the following years due to experience gained. Nevertheless, it can be concluded that by including NO_x emission in the airborne OGV emission monitoring program, the absolute number of monitored ships decreased by almost 15%.

3.2. Efficiency of flight operations

On the one hand, when assessing the monitored compliance to different MARPOL Annex VI regulations, there is a vast improvement. Up until 2020 only FSC was monitored, hence the number of monitored MARPOL Annex VI regulations equaled the number of monitored OGVs. From 2020 onwards, by including NO_x monitoring, this was increased to a total average amount of 22.4 monitored MARPOL Annex VI regulations per flight hour (see Figure S.3).

When assessing the ratio of the successfully measured OGVs, after a small decrease in 2020, due to additional flight time that was spent to setup the NO_x measurement methodology, the success rate did increase back to 97%. This means that adding the NO_x emission monitoring did not significantly affect the number of failed attempts.

3.3. Emission measurements

3.3.1. Temporal analysis

NO_x emission levels were measured for 1407 OGVs, of which 403 in 2020 and 1004 in 2021. The lower number of OGVs for 2020 was a consequence of the impact of the Covid19 pandemic on the number of flight hours. Of these OGVs, 11% belonged to Tier 0, 53% was Tier I and 36% was Tier II. So far, neither Tier III OGVs nor significant difference in the distribution of Tier 0, Tier I and Tier II OGVs between 2020 and 2021 ($P = 0.683$) have been observed. Although the KLY dataset for 2022 only contains 445 Tier III OGVs ($<1\%$), this does not mean that no new OGVs have been constructed in 2021. In fact, the KLY database contains 1426 OGVs that have a built year from 2021 but a KLY before 2021, corresponding to 76% of the ships built ≥ 2021 , as well as 8 OGVs that have even a KLY <2011 . When looking at the 1055 OGVs built in 2021 that have length larger than 70 m and are larger than 5000 Gross Tonnage (GT), only 138 had a KLY in 2021 (13%). Ship builders have prepared numerous keels in the years before 2021, which are used for the construction of new OGVs and to avoid the much stricter Tier III emission limits. Also, in the following years a large section of the newly built OGVs will still have a KLY <2021 , hence delaying the impact of the emission regulations. Zhang et al. (2021) have estimated that the implementation of the Tier III limits would prevent up to 33,300 (30, 100–36,4000) premature deaths as from 2021. By evading the implementation of the Tier III standards by 87% of the OGVs built in 2021, 29,000 (26,200–31,7000) premature deaths were therefore not avoided. As for the following years still a large section of the newly built OGVs will

have a KLY <2021, the overall impact of the delay of the effective implementation of the Tier III standards on the non-avoided premature deaths is expected to be a multiple of this figure.

For all Tier 0 OGVs with a KLY ≥ 1990 the engine power was looked up in the Thetis-EU database (Figure S.4). Based on a linear regression, on average, OGVs with a length from 117.9 m have an engine power above 5000 kWh ($R^2 = 0.74$). The maximum OGV length corresponding to an engine power lower or equal to 5000 kWh was 160 m, and it was therefore chosen to adjust the limit of 170 m–160 m. In total 81% of the Tier 0 OGVs was subject to the Tier I emission limits, these OGVs are referred as Tier 0(I). The other 19% Tier 0 OGVs had either a KLY before 1990 or a total engine power <5000 kWh, and are referred as Tier 0 OGVs.

The average measured NO_x was 13.0 g/kWh, which was lower than the NO_x emission limit for Tier I and Tier II ships with engine rates below 130 rpm. In comparing the average NO_x emission between 2020 and 2021, it can be noted that the average NO_x emissions were not significantly different but were remarkably higher for 2021 (13.1) compared to 2020 (12.6) ($P < 0.1$). This is counterintuitive, since the ECA was not yet in place in 2020. The average speed of the observed OGVs was marginally lower in 2020 (12.6 kts), compared to 2021 (12.7 kts) with no significant difference ($P > 0.1$), while the median speed was slightly higher for 2020 (12.6) compared to 2021 (12.5).

3.3.2. Analysis per tier

When comparing the average NO_x emission per tier, it was assumed that Tier II OGVs would have a lower NO_x emission than Tier I OGVs, as the NO_x emission limit for Tier II OGVs is lower than for Tier I. However, it was witnessed that the average NO_x emission for Tier II OGVs (13.5 g/kWh) was higher than the average NO_x emissions for Tier I (12.6 g/kWh) and even comparable to the overall NO_x emission of Tier 0(I) (13.5 g/kWh) (Fig. 4).

The emission distributions per Tier were compared statistically. There were no significant differences observed in NO_x emission distributions between Tier 0(I) and Tier I for the year 2020 ($P > 0.1$) and the year 2021 ($P > 0.1$). In contrast, during the overall period 2020–2021, a significant difference was observed ($P < 0.025$). When comparing the NO_x emission distributions between Tier I and Tier II, the distributions were found to be significantly different for the year 2020 ($P < 0.005$), the year 2021 ($P < 0.001$) and for the overall period 2020–2021 ($P < 0.001$). This finding confirms the observed higher average NO_x emission for Tier II OGVs for all time periods. For NO_x emission distributions between Tier 0(I) and Tier II, there was no significant difference observed for the period 2020, 2021 or the overall period ($P > 0.1$). This phenomenon can be interpreted as a finding that the Tier II OGVs did not significantly emit lower NO_x emissions compared to Tier 0(I) OGVs. The

average higher NO_x emission levels for Tier II OGVs were also observed by the Danish EPA, although those measurements were performed by reanalyzing historic data from before the ECA came into force (Knudsen et al., 2022).

These findings are in clear contrast with the assumption that the average NO_x emission for Tier II OGVs would be lower than for Tier I and Tier 0 OGVs. Based on the emission limits, an emission reduction of 15.3% by Tier II OGVs would be expected compared to Tier I. However, on average the observed Tier II OGVs emit in fact 7.4% more than the observed Tier I OGVs. A possible explanation for the higher observed actual NO_x emissions in the Belgian and neighboring waters lies in the fact that the average speed of the OGVs passing in the North Sea is low compared to the average OGV cruising speed, the overall average observed speed was 12.7 kts. As the cruising speed strongly depends on the OGV type and the operational mode, a closer look was taken on the speed of container OGVs. The average speed for all container OGVs that were en route in the northern shipping lanes was 13.7 kts (Figure S.5 upper), whereas the most optimal speed, the slow steaming speed for container OGVs is 18–20 kts, the minimum cost speed for container ships is 12–15 kts, these speeds are commercially not efficient at the high seas (Notteboom and Cariou, 2009), however it seems that these speeds are used by OGVs passing in the North Sea.

Lower sailing speed lead subsequently to lower engine loads corresponding to lower weighting factors. Whereas for Tier 0(I) and Tier I OGVs the NO_x emissions tend to be more stable over different engine loads, Tier II OGVs have a different NO_x emission profile (Cheng et al., 2017). Engine manufacturers design their Tier II engine to optimize fuel efficiency. As fuel efficiency conflicts with NO_x emissions reduction, a trade-off needs to be made. By taking advantage of the weighting factors per engine load, engine manufacturers are able to design engines in such way that NO_x emissions in lower loads are higher than for the higher loads. Nevertheless, the overall weighted average NO_x emission approaches the limit and thus optimizes fuel consumption. As a result, Tier II OGVs may consume less fuel, but emit more NO_x, which is especially the case for engine loads of 25% and 50% that occur during coastal operations, which can be illustrated by an example of a test result for a Tier II engine (1945 kW and ERS of 1000 rpm). The weighted average is just below the limit while the unweighted average is above the limit (Figure S.5 lower).

3.3.3. Results per OGV type

The OGV type was first derived from the MMSI number obtained through AIS. Of the observed OGVs, the majority were cargo OGVs (66.3%) followed by tankers (29.9%). The rest were other vessel types (1.5%); ROROs and passenger OGVs (1.4%), dredgers (0.6%), military OGVs (0.1%), fishery OGVs (0.1%). For 0.2% of the OGVs, no vessel type could be assigned due to missing or incomplete AIS data. As a result of the limited categories in the MMSI data protocol, based on AIS information, it is not possible to differentiate between various types of cargo OGVs. Accordingly, container OGVs, bulk carriers, general cargo OGVs and vehicle carriers are considered as cargo OGVs. When comparing the NO_x emission distributions per vessel type, a higher average value was found for cargo OGVs (13.7 g NO_x/kWh) compared to tankers (11.7 g NO_x/kWh) (Fig. 5, upper). This difference was found to be significant ($P < 0.001$). The other vessel types were not compared due to the low number of observations per vessel type. When comparing the different NO_x distributions per Tier level for tankers and cargo OGVs, a higher average NO_x emission was observed for Tier II. Based on statistical analysis, it was showed that Tier 0(I) and Tier I were not significantly different for cargo OGVs and tankers. However, Tier II was significantly different from Tier I for both cargo OGVs and tankers ($P < 0.005$). When comparing Tier II with Tier 0(I), no significant difference was observed for neither cargo OGVs nor tankers ($P < 0.01$) (see Fig. 5, middle). The ratio of the amount of tanker OGVs and container OGVs did not differ from each other significantly between 2020 and 2021 ($P = 0.062$).

In addition to this first analysis, for the large majority of the observed

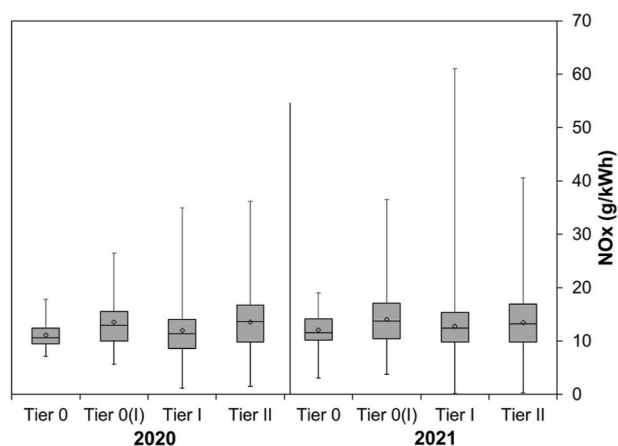


Fig. 4. Box plot of NO_x emissions (g/kWh) per Tier level for the period 2020–2021, with 25% and 75% percentiles, median, and average (◆).

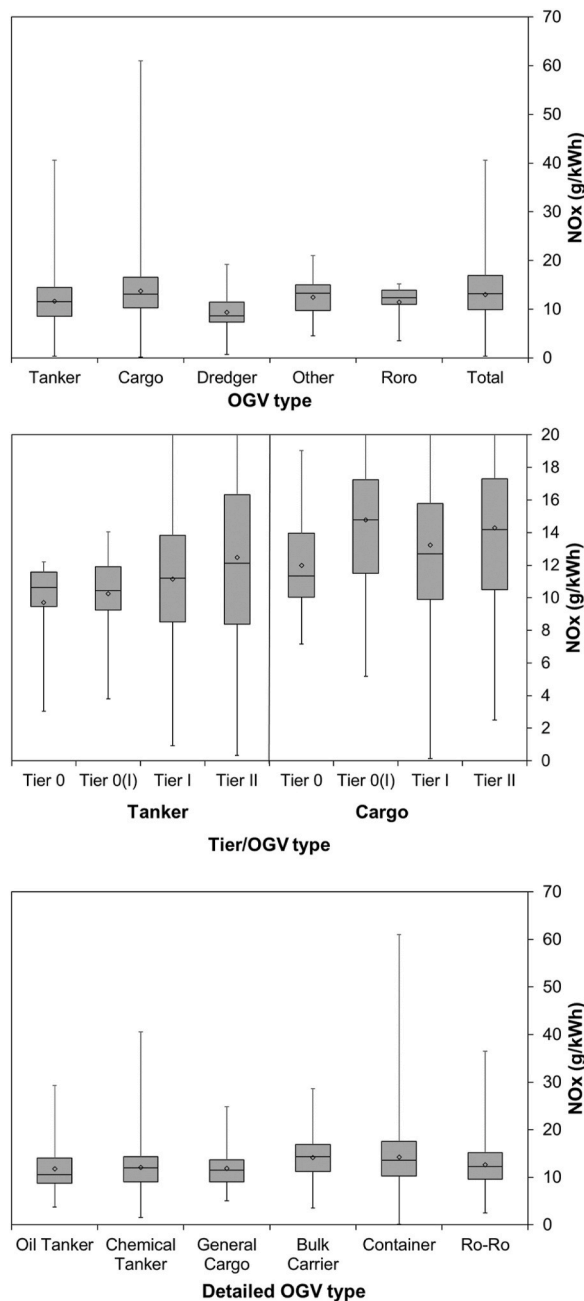


Fig. 5. Upper: Box plot for the NO_x emissions for different OGV types. Middle: Boxplot of different tiers for cargo and tanker OGVs. Lower: Box plot for detailed vessel type (Ro-Ro and vehicle carriers were combined to Ro-Ro). With 25% and 75% percentiles, median, and average (◆).

OGVs, the detailed vessel type could also be obtained by cross referencing with the GISIS database (99%). The higher average NO_x emission for cargo OGVs is apparently due to the significant higher NO_x emissions for container OGVs and bulk carriers ($P < 0.001$) (Fig. 5, lower). Moreover, a significant difference was also observed between oil tankers and chemical tankers ($P < 0.05$).

3.4. Specific fuel consumption

Fuel consumption was collected for 42 OGVs. Analysis showed that SFC values were observed from 100 g/kWh up to 350 g/kWh, with an average of 201/kWh (standard deviation $\text{SD} = 46$ g/kWh), confirming that the SFC of 200 g/kWh used per default was representative. To avoid

under- or overestimations of the NO_x emissions due to unreliable information received by marine VHF, it was decided to define an acceptance limit for the SFC. All values falling outside the 95% confidence interval ($\text{average} \pm 1.96 \times \text{SD}$), which means that values below 100 and above 300 will not be accepted. In those cases, the 200 g/kWh standard was used. No correlation could be made between the SFC versus the OGV length nor OGV type (Figure S.6). When comparing the SFC between OGV types or Tier level, no clear patterns were observed ($P < 0.1$), although this dataset was largely insufficient for an in-depth analysis.

3.5. Engine loads

Based on the obtained information and the engine characteristics from the EMSA Thetis-EU database (EMSA, 2020), engine loads were derived for all OGVs that were contacted. According to this analysis, the average load of the observed OGVs was 34%, ranging from 6% up to 77% (Figure S.7, upper). The loads were all rounded to 5% and divided in 4 categories (0–25%, 25–50%, 50–75% and 75–100%). The category that was most observed was the 25–50% load (60% of the measured OGVs), but on the second place was the 0–25% category (23% of measured OGVs). As no limits are defined for the 0–25% category, it probably means that compliance of these OGVs could not be technically determined. When comparing the difference in engine load per Tier, it was observed that Tier II OGVs sail generally at lower engine loads compared to Tier I (24% versus 14%), although this effect, due to the low amount of data, could not be proven statistically ($P = 0.643$). When comparing the 2 lower categories (0–50%) with the two higher categories (50–100%), the relative difference becomes less profound, with 84% of Tier II OGVs and 71% of the Tier I OGVs in the 0–50% engine load category. Again, this was not found to be statistically significant ($P = 0.451$).

Based on the comparison of the engine load with the OGV speed (Figure S.8, upper), it could be demonstrated that both were strongly correlated ($R^2 = 0.83$). In accordance with the propeller law, the engine load can also be derived from the maximum speed and the actual speed (Faber et al., 2021; Goldsworthy and Goldsworthy, 2015; Knudsen et al., 2022; Mackay et al., 2015; Yau et al., 2012).

$$\text{Modelled load} = \left(\frac{\text{actual speed}}{\text{Maximum speed}} \right)^3 \times CF \quad (6)$$

A modelled load was calculated and compared to the actual load (Figure S.8, lower), which indicated a good correlation ($R^2 = 0.778$). Through employing the least square method, the correction factor (CF) was determined for the Belgian North Sea area ($CF = 1.28$). Nevertheless, due to some potential large differences, instead of relying solely on the modelled load by default, it was decided to continue with the marine radio communication procedure to obtain the actual engine load. In case no radio communication could be established, the modelled load was used to determine the engine load.

When examining the distribution of a sub dataset for which the modelled load was calculated (Figure S.7, lower), roughly the same distribution was observed as for the actual load, with a majority (46%) of the modelled engine loads in the 25–50% category and 26% in the 0–25% category. However, the amount of Tier II OGVs in the 0–25% category (24%) is lower than the amount of Tier I OGVs (28%). The same is observed in the 0–50% category where Tier II represent 68% compared to 76% for Tier I. As is manifested in the result, based on this dataset, it cannot be argued that Tier II OGVs sail at lower engine loads and therefore are not more off cycle compared to Tier I OGVs.

When the NO_x emission is expressed in function of the engine load only, a weak correlation is observed. Remarkably, when comparing this relation per Tier level a stronger decrease (slope -5.06) of the NO_x emission is observed in function of the engine loads for Tier II compared to Tier 0(I) and Tier I OGVs (slope -0.5) (see Figure S.9). This confirms the assumption that the higher observed NO_x emissions for Tier II are

most likely related to the higher emissions of Tier II engines on lower engine loads. As a result of the lower weighting factors for the 25% and 50% load, emission load profiles for Tier II OGVs indicate that this is indeed the case (Cheng et al., 2017).

3.6. Measurement quality

Similar as for the FSC measurements (Van Roy et al., 2022), it was chosen not to calculate a quantitative quality indicator. Instead, it was decided to assess if a NO_x met the quality standards, based on a set of qualitative requirements. For high quality NO_x measurements, firstly, the NO_x and CO₂ gas sensors should have comparable response times; secondly, the NO_x measurements should have a good signal to noise ratio (SNR). These restrictive conditions are in addition to the common requirements that also count for the FSC measurements: (i) plume could be successfully linked to an OGV; and (ii) no interference from land pollution or other sources.

3.6.1. Response time

As the flow is split before the pressure and flow regulators, the NO_x sensor has with 1 l/min a substantial lower flow than the CO₂ sensor. Thanks to a change from single-headed to a two-headed pump, the flow in the CO₂ sensor was increased from 6 l/min to 8 l/min. The responding time of both the CO₂ and NO_x sensors were determined by using the calibration gas mixtures. For the NO_x sensor, the NO gas calibration with a concentration of 273 ppb NO was used, which corresponds to a concentration-difference (ΔC). A span gas with a concentration of 479 ppm was used for the CO₂ sensor. These differences with the respective CO₂ and NO_x concentration in the environment correspond from small to medium peaks. The responding time was found by determining the time difference (ΔT) between 10% of the beginning (C_b) and end concentration (C_e).

$$\Delta T = T_{90} - T_{10} \quad (7)$$

where

$$\Delta C = C_2 - C_1 \quad (8)$$

$$C_1 = C_b + 0.1 \times \Delta C \quad (9)$$

$$C_2 = C_e - 0.1 \times \Delta C \quad (10)$$

For the determination of the T_{10} and T_{90} , a linear interpolation was employed based on the concentrations before and after the C_1 and C_2 concentrations.

$$C_i = C_{i-1} + \frac{C_{i+1} - C_{i-1}}{2} \quad (11)$$

$$T_i = T_{i-1} + (T_{i+1} - T_{i-1}) \times \frac{C_{i+1} - C_i}{C_{i+1} - C_{i-1}} \quad (12)$$

The curve between the start and end concentration was however not linear but followed a sigmoid curve. For CO₂, the time resolution was 0.2 Hz, whereas the time resolution for the NO_x sensor was only 1 Hz (similar to the SO₂ sensor), which means that the curve, for the CO₂ signal, between T_{i-1} and T_{i+1} follows approximately a linear shape. The difference between the T_{90} based on linear interpolation is therefore very similar to the T_{90} for nonlinear interpolation. For the NO_x signal, the time between two measurements was ca. 1.0 s and the error from the linear interpolation could be significant. Accordingly, a nonlinear interpolation was used for the determination of T_i . The nonlinear interpolation between T_{i-1} and T_{i+1} showed a very desirable fit, which can be drawn as a conclusion that no additional S-curve fitting was required. Based on a nonlinear interpolation, the T_{90} time of the NO_x sensor was 2.3 s (Figure S.10, upper). For the CO₂ sensor, the T_{90} was 2.7 s, although slightly higher than NO_x sensor. Yet, it is worth noting that both sensors provide a very comparable response time (Figure S.10,

lower).

3.6.2. Signal to noise ratio

The signal to noise ratio is a quality measure for a signal, by comparing the power of the signal, or the peak amplitude (A_{plm}) to the background noise (A_{bkg}) (Serway and Jewett, 2004).

$$SNR = \frac{A_{plm}}{A_{bkg}} \quad (13)$$

The amplitude of the noise (A_{bkg}) of the CO₂ sensor depended on the sensor measurement resolution and the background conditions, which was calculated by looking at the standard deviation of the background concentration over 60 measurements. The background conditions over sea were more stable, resulting in lower CO₂ noise (standard deviation SD = 0.25 ppm) as over land (SD = 1.6 ppm). For CO₂, the minimum peak height to provide high quality exhaust plumes was established at 5 ppm (Van Roy et al., 2022), which corresponds to a SNR of 20, whereas 15 is considered as the minimum SNR for high quality peaks. The amplitude of the background was determined by the standard deviation of the background concentration over sea (before and after exhaust plumes were sampled). For NO_x the amplitude of the background is relatively low (0.58 ppb) when a SNR of 20 is applied. This demonstrates that the minimum peak height for a high-quality measurement is 11.6 ppb, which is much lower than the average observed peak height of 198.7 ppb, thus corresponding to an SNR of 341. A minimum peak height for NO_x was set at 15 ppb, although this minimum peak height, for the vast majority of the measurements, was easily met when the peak height for CO₂ was more than 5 ppm. Only for three measurements, the CO₂ peak height was higher than 5 ppm while the NO_x peak was below 15 ppb, and these concerned all three gas tankers.

3.7. Measuring uncertainty and compliance thresholds

Similarly as for FSC (Van Roy et al., 2022), the total NO_x uncertainty measurement (U) can be described as a combination of the measurement bias (b) and the standard deviation ($\underline{u}_{tot}$):

$$U = |b| + \sigma \cdot \underline{u}_{tot} \quad (14)$$

In contrast to the FSC, where fuel samples from port inspections were used to calculate the bias (Van Roy et al., 2022), no reference data is available for NO_x. Nevertheless, it can be assumed that there is a negative systematic error for several reasons. The first is the difference between indicated power of the main engine, which is requested through radio communication and the brake power which is used in the NO_x technical code. The brake power is measured at the crankshaft using a brake dynamometer. For conformity and simplification, the indicated power is requested when contacting an OGV. As the indicated power is always higher due to friction losses of the shaft and auxiliary systems connected with the main engine. The ratio between indicated power and brake power is expressed as mechanical efficiency (N_m) that is in the order of magnitude of 95% at full power but can be as low as 75% at rated speed (Heywood, 2018; Hyvönen et al., 2006; Lewander et al., 2009; Stanton, 2013; WINGD, 2016, 2017). The use of the indicated power instead of the brake power means an overrating of the power output in the SFC formula, which will result in an underestimation of the SFC and NO_x emissions by ca. 15%.

The next factors are the temperature and a humidity correction. The NO_x Technical Code describes that a correction should be applied for the air intake temperature and humidity.

$$k_{hd} = \frac{1}{1 - 0.0182 \times (H_a - 10.71) + 0.0045 \times (T_a - 298)} \quad (15)$$

In the Belgian part of the North Sea, the annual average temperature is 11.9 °C (maximum 14.5 °C) with an average humidity of 5.6 g/kg dry air. The corresponding combined average negative correction is 3.4%

with a range between 2 and 4% (see Figure S.11).

The last factor is the impact from auxiliary engines and generators. These are generally four stroke engines with a higher ERS and have therefore lower emission limits. As only OGVs that are en route are measured, the impact of the exhausts of these engines on the emission measurements of the main engine is limited. Nevertheless, due to a dilution effect, main engine exhaust with higher NO_x/CO₂ ratios might be mixed with lower auxiliary engine exhaust with lower NO_x/CO₂ ratios, creating a negative bias. The part of the auxiliary exhausts in the total OGV exhaust is impossible to determine in flight, nevertheless auxiliary engine(s) can take up to 10–15% of the used fuel on the total journey. This amount can be even higher when the ship is sailing at very low speeds (DNV-, 2015; Heywood, 2018). Auxiliary engine emission limit corresponds to circa 58–64% of the limit of main engines (ERS ≥ 1000 rpm), the negative bias is therefore estimated to be in the order of magnitude of 4–6%. As a result, the combined negative systematic error is estimated to be 15–25%. The NO_x Technical Code provides a margin of 10% to account for the simplified measurement methods as described in Chapter 6 and an additional 10% allowance for the use of non-residual marine (non-RM) graded fuel (ISO8217:2005) such as distillates like Marine Gas Oil (MGO) (MEPC, 2008b), although the combined allowance should not exceed 15%. For this reason, the negative systematic error was not used to correct the measurement data for reporting to PSC, which was mostly eliminated by the 15% allowance.

The second part of the uncertainty is described by the standard deviation of the measurements. When comparing the results of repeated measurements, it was observed that in most cases the measurement data correlated strongly ($R^2 = 0.84$) (Figure S.12, upper). Furthermore, no strong relative effect is observed on the difference between both values, although the difference between two measurements is clearly smaller for lower NO_x values than for higher measurement values (Figure S.12, lower).

The standard deviation u_{tot} can be calculated based on the intra reproducibility coefficient CV_{RW} and the sum of all additional supplementary uncertainty factors (u_{sup}) (Royal Decree, 2014).

$$u_{tot} = \sqrt{(CV_{RW})^2 + \sum (u_{sup,i})^2} \quad (16)$$

$$CV_{RW} = \frac{1}{\sqrt{2}} \sqrt{\frac{\sum_{i=1}^n \left(\frac{x_{i1} - x_{i2}}{0.5(x_{i1} + x_{i2})} \right)^2}{n}} \times 100(\%) \quad (17)$$

To calculate the standard deviation, three intra reproducibility coefficients have been calculated for three different ranges of NO_x emission values: 0–10 g NO_x/kWh, 10–20 g NO_x/kWh and ≥ 20 g NO_x/kWh. The CV_{RW} values are displayed in Table S.1.

The supplementary uncertainty factors are listed in Table S.2. For the reported indicated power, an uncertainty of 6.8% was used (Kowalak, 2015); while for the provided fuel consumption, 10% was used (Hunsucker et al., 2018), although this does not include an uncertainty due to human errors during reporting. Of the 43 contacted OGVs, 16% provided unreliable data, for which the standard SFC of 200 g/kWh was used. With the bias and total uncertainty values, the combined uncertainty was calculated for the three NO_x emission levels.

3.8. Compliance thresholds

As for FSC, a color flag system that was composed does not only incorporate the measurement uncertainty, but also reflects on the level of non-compliance (Van Roy et al., 2022). The compliance threshold (T) was defined as the NO_x emission measurement value from which the OGV is considered to be non-compliant and would therefore be alerted to PSC authorities. The Threshold is reached as soon as the NO_x emission minus the measurement uncertainty is higher than the Tier limit (L) plus the NTE.

$$L_{Tier_i} + NTE = T - U_T \quad (18)$$

$$T = \frac{L_{Tier_i} + NTE}{1 - \sigma \times u_{to}} \times (1 + b) \quad (19)$$

3.8.1. Tier I and Tier II

The lowest alert level (the yellow flag color) uses a 68% confidence interval (CI), which is not to exceed the limit (NTE) of 15%, corresponding to the 15% margin of the NO_x Technical Code. The medium alert level (the orange flag color) uses a 95% CI with a NTE limit of 20% for Tier I. The red flag is used for high non-compliance alerts, with a CI of 99% and a NTE limit of 50%. The NTE levels for the orange and red flags are higher to take into account a tolerance level for the weighting factors.

3.8.2. Tier III

As no data yet exists for Tier III, the uncertainty for this measurement range could not yet be calculated. Nevertheless, it can be assumed that this would be comparable to the uncertainty of Tier I and Tier II. For the Yellow flag, a 50% NTE limit was used corresponding to the NTE limit of the NO_x Technical Code. For the Orange and Red flag, a NTE of 60% and respectively 65% was used to incorporate an additional tolerance due to the low emission limit and unknown uncertainty.

3.8.3. Operational thresholds

For operational use, the thresholds were further rounded up to 5 g NO_x/kWh for Tier I and Tier II and to 1 g NO_x/kWh for Tier III. Thus, it is convenient for the operators to create operational thresholds (T_{ops}) (Table 2) that are memorized and applied in flight. The determination of the initial T_{ops-21} was based on test measurements from 2020. Although the initial uncertainties differed only slightly from the updated uncertainties, several T values decreased with the uncertainty calculation from the complete 2020–2021 data. Therefore, the T_{ops-22} were lowered for the compliance monitoring operations from 2022 onwards.

3.9. Compliance rate comparison

3.9.1. Temporal compliance comparison

The measurements were evaluated in flight according to the T_{ops-21} thresholds. There are several different situations discussed below. In case a possible non-compliant OGV was observed, radio contact was established to retrieve the engine parameters to calculate the SFC and a second measurement was conducted. If no radio contact could be established due to pilot operations on board of the OGV, an SFC of 160 g/kWh was applied. In case, the data was unreliable (in 15% of the cases), an SFC of 200 g/kWh was applied. On the condition that the second measurement did not confirm the initial value, the lowest of the two values was used and the OGV was therefore not reported as non-compliant. In case the second measurement confirmed the first measurement, both values were reported. In the last situation that the two measurements were assigned with two different color flags, the lower of the two was used to avoid reporting false positive alerts.

In 2020, 16 OGVs were observed with NO_x emissions exceeding the

Table 2
NO_x Color flag thresholds per Tier level.

Tier	L_{Tier}	Color flag	NTE	σ	T	T_{ops-21}	T_{ops-22}
Tier I*	17	Yellow	15%	1	21.2	25	25
		Orange	20%	1.96	31.8	35	35
		Red	50%	2.576	53.2	60	55
Tier II	14.4	Yellow	15%	1	17.9	20	20
		Orange	20%	1.96	26.9	30	30
		Red	50%	2.576	45.0	50	45
Tier III	3.4	Yellow	50%	1	5.4	7	6
		Orange	60%	1.96	7.5	9	8
		Red	65%	2.576	8.9	12	9

operational thresholds (T_{ops-22}). But as the NECA was not active yet in 2020, the OGVs were not reported. In 2021, there were 43 possible non-compliant OGVs observed – among which, 23 were reported, while the other 20 concerned OGVs without Tier information at the moment of the measurement were not reported. The overall compliance rate was 95.9% in 2020 (according T_{ops-22}) and 95.6% in 2021, with an overall compliance of 95.7 (Fig. 6). No difference in compliance was observed between 2020 and 2021 ($P = 0.814$).

3.9.2. Compliance per Tier

When comparing the compliance rate between Tier levels, no difference in compliance was observed between Tier 0(I) and Tier I for 2020 ($P = 0.833$) and 2021 ($P = 0.702$). However, Tier II had a significantly higher non-compliance rate than Tier I for 2020 ($P = 0.000$) and 2021 ($P = 0.000$). Tier II was even found to have a significantly higher non-compliance rate than Tier 0(I) for 2021 ($P = 0.0102$), although this was not the case for 2020 ($P = 0.2035$). This finding confirms the significantly higher observed average NO_x emission for Tier II OGVs, which is in contradiction to the objectives of MARPOL Annex VI Regulation 13.

This does not necessarily mean that all Tier II OGVs on a global scale have a lower compliance rate compared to Tier I OGVs. But for the fleet composition and navigation parameters of the maritime traffic in the southern North Sea area, this seems to be the case. It is clear that the lower compliance rate for Tier II OGVs in the southern North Sea must be tackled to ensure the effective implementation of the emission reduction regulations and to reduce the impact of air pollution from the maritime sector for the North Sea coastal communities.

It must be noted that the use of rounded thresholds (T_{ops}) for operational reasons inevitably results in false negatives. In total, 103 OGVs had a NO_x emission between T and T_{ops} (7%). As no confirmation measurements were made for these OGVs, the exact number of false negatives could not be established. To estimate the number of potential false negatives, the NO_x emission values were recalculated with an SFC of 160 g NO_x /kWh. Based on this SFC, the number of potential false positives was only 7 OGVs (or 0.5%). Hence the number of potential non-compliant OGVs that were not reported to PSC was fairly limited. In addition, this number is largely insignificant compared to the operational advantage of using rounded T_{ops} values. Furthermore, this shows the importance of obtaining the actual SFC value for the NO_x compliance monitoring. By using the higher-end SFC value of 200 g/kWh for the initial measurement, more false positives can be avoided than by using the unrounded T values.

3.9.3. Compliance per OGV type

Based on the AIS OGV type category, the only OGV types that were observed to be non-compliant were tankers and cargo OGVs. Figure S.13 illustrates that overall a higher non-compliance rate was observed for cargo OGVs (10.1%) compared to tankers (3.5%) and this difference was

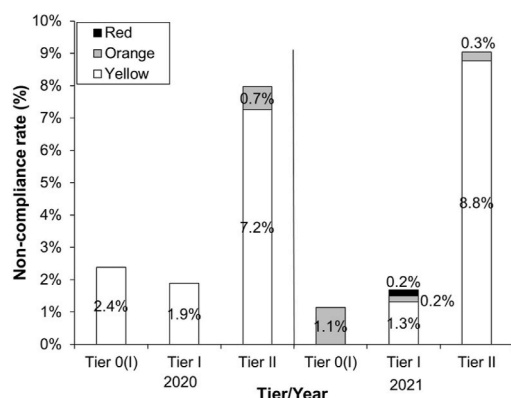


Fig. 6. Compliance levels according to T_{ops-22} per Tier per year.

found to be significant ($P = 0.0155$). By comparing compliance rate per detailed vessel type, it was observed that container OGVs had a significantly higher non-compliance compared to all other types ($P < 0.05$), while no significant difference was observed in compliance between the other types of cargo vessels ($P > 0.05$).

When comparing the compliance rate between cargo vessels and tankers per tier, only a significant difference was observed for Tier II ($P = 0.0187$). For Tier 0(I) and Tier I OGVs, the difference in compliance is not significant ($P = 0.06$). However, when comparing the compliance rate between Tiers per vessel type, Tier II OGVs for both cargo and tanker OGVs have a significant higher non-compliance rate ($P < 0.001$ for cargo and $P = 0.0092$ for tanker), indicating that the higher Tier II emissions are not restricted to one OGV type.

3.9.4. Engine rated speed

As compliance levels were based on an evaluation according to the NO_x emission limits for OGVs with an ERS <130 rpm, some OGVs with higher rpms were possibly wrongfully considered to be compliant (false negative). Therefore, a set of thresholds was defined for OGVs with an ERS of 500 rpm (Table S.3).

To evaluate the number of possible false negatives, the OGVs were identified as exceeding the 500 rpm thresholds (T_{ops-5}) but were classified as compliant. This concerned 201 OGVs and for those, the actual ERS was looked up. The OGVs with an ERS between 130 and 500 rpm were very close to 130 rpm (146,160 and 167 rpm). For these OGVs, the NO_x limit is not much different, and applying the exact NO_x limit would not have resulted in a different evaluation. For the OGVs with and ERS ≥ 500 rpm, it was assessed if these could be potential false negatives. According to the procedures for alerts without radio contact, an SFC of 160 g/kWh was applied and the NO_x emission values were recalculated. After this correction, only one of the OGVs with an ERS ≥ 500 rpm was found to exceed the T_{ops-5} , a Tier II (dredger) OGV with a NO_x emission of 17.1 g NO_x /kWh.

In addition, for the OGVs with an ERS of 600 and 700 rpm, an ERS specific threshold rounded up to 5 g NO_x /kWh ($T_{OPS-ERS}$) was calculated. Based on these thresholds, the OGV with an ERS of 750 rpm (a Tier I chemical tanker) would have exceeded its specific threshold (19.1 g NO_x /kWh). This means that in total 2 potential OGVs (or 0.15%) were wrongfully assigned as negative due to not incorporating the lower emission limits for higher ERS and applying a rounded threshold level (Table S.4). In addition to the 201 OGVs searched for the determination of the potential false negatives, ERS data was acquired for 157 additional OGVs. Of this total of 358 OGVs, 16% had an ERS >130 rpm and 11% had an ERS >500 rpm. It was observed that higher ERS values were mainly observed for OGVs with a length <200 m, 25% of the OGVs with a length <200 m had a ERS >130 (Table S.3). When looking only at OGVs with a length >200 m, the amount of OGVs with an ERS >130 rpm was reduced to 4%. It was observed that the OGV type played the most important role as indicator for higher ERS values, with ROROs, dredgers, cruise liners and gas tankers having a higher likelihood to have an ERS >130 rpm (on average 54%) compared to general cargo (29%), tankers (15%), containers (5%) and bulk carriers (4%) ($P < 0.001$).

When assessing the Tier level, it was observed that the amount of OGVs with an ERS >130 was significantly higher for Tier 0(I) (30%) and Tier I (25%), compared to Tier II OGVs (10%) ($P = 0.001$). The same effect was observed for ERS >500 rpm ($P = 0.001$). When the data are restricted to OGVs >200 m, the number of Tier II OGVs with an ERS >130 rpm (2%) are no longer significantly lower than for Tier I OGVs (4%) ($P = 0.0518$). As the OGV type appeared to be a decisive factor, the fleet compositions of the Tier I and Tier II subsets were further examined, which showed a very comparable amount of OGV types. On average, the amount of OGVs with an ERS <130 RPM was rather comparable between Tier I and Tier II, with 85% for Tier I and with 87% slightly higher for Tier II. However, when looking only at container and tanker OGVs, Tier II OGVs were found to have a significantly higher amount of OGVs with an ERS <130 rpm ($P = 0.001$). Hereafter, based on

this dataset, it can be concluded that container and tanker Tier II OGVs have a significantly higher amount of OGVs with an ERS <130, which further indicates that the intentional downrating of the main engine may be used as strategy to increase the emission limits for Tier II OGVs.

Consequently, it can be concluded that the inclusion of specific thresholds according to the ERS in the SOPs would not result in a significant higher number of observed non-compliant OGVs. Nevertheless, due to the higher ERS that were mainly found with passenger OGVs and RORO OGVs, it was decided to use the T_{Ops-5} for all ROROs, ferries, passenger OGVs <200 m as the threshold for the initial measurement. In addition, the ERS will be requested during the radio communication, together with the correct SFC, which can reduce the potential number of false negatives, without too much additional workload for the operators in flight.

3.9.5. Off cycle engine load

As no limits are available for engine load below 25%, it is important to avoid reporting OGVs with engine loads under 25% as these OGVs are considered to be “off cycle”. Based on the reported engine power and the available total indicated power, it was observed that relatively more OGVs were classified as non-compliant with low engine loads. The amount of compliant OGVs increased with the engine loads, for the engine loads >75% almost all OGVs were classified as compliant (97%). When comparing the compliance rate for OGVs with engine loads <50% with OGVs with engine loads >50%, a significant lower compliance rate was observed for OGVs sailing at low engine loads ($P = 0.0241$).

For the engine load <25%, technically there are no limits in place. Nevertheless 3 OGVs with an engine load <25% were observed to be over the lowest reporting threshold. As their speed was just over 10 kts, these OGVs were not withheld and reported to the PSC, which can therefore be considered as possible false positives. To avoid reporting false positives as of 2022, the engine load will be requested during the radio communication. If no communication is established, a calculated

load will be used based on the propeller law (see sect. 3.4). In addition, as of 2022, a threshold speed of 8 kts, on the one hand, will be used for RORO and passenger OGVs; on the other hand, a threshold speed of 12 kts will be used for cargo and tanker OGVs. It is also worth noting that only red and orange flag color alerts will be reported for OGVs sailing at lower speeds.

3.10. Geospatial analysis

3.10.1. NO_x emissions in North Sea between 2020 and 2021

When looking at the difference in NO_2 between 2020 and 2021 based on the TROPOMI Sentinel 5 data, it was found that the NO_2 emissions over land were substantially lower in 2020 compared to 2021. The difference was most profound in densely populated areas like Belgium, the northern part of France, the eastern side of Germany the southern part of the Netherlands and the central and southern part of the United Kingdom (Fig. 7). The lower levels of NO_2 over land in 2020 compared to 2021 can largely be attributed to the public measures to control the Covid19 pandemic in 2020. These lower emission levels for NO_2 in 2020 were also observed for other areas (Stavrakou et al., 2021). However when looking at the shipping lanes in the North Sea, the Mediterranean Sea and the Atlantic Ocean, these lower NO_2 emission for 2020 were much less profound. In fact for the northern part of the North Sea the emissions actually decreased noticeably between 2020 and 2021. It remains unclear if this reduction in NO_2 between 2020 and 2021 is significant and can be attributed to the implementation of the NECA in 2021 or if other factors play a role as well.

3.10.2. Spatial distribution compliance

The map in Fig. 8 visualizes all monitored ships according to the flag color. When assessing the non-compliant OGVs on a geospatial basis, no clear patterns can be observed at first sight, although more red flags were observed in the inland Westerschelde estuary and the Westhinder

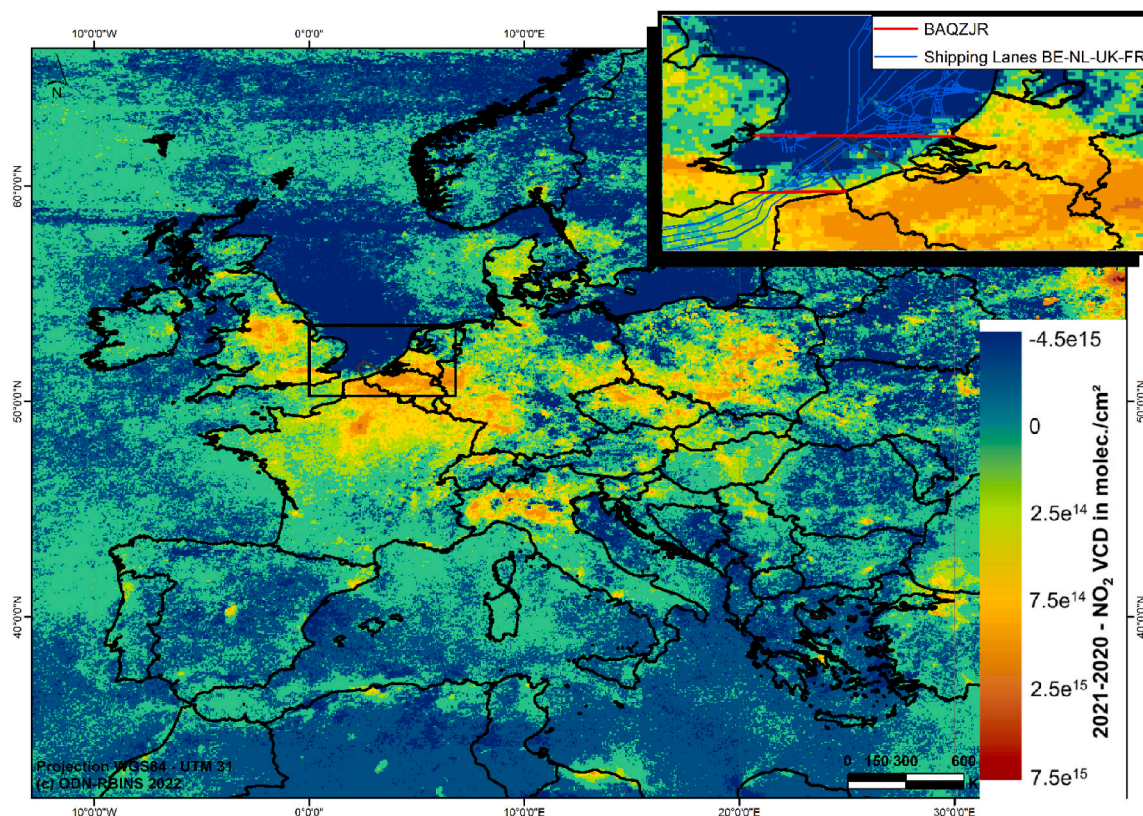


Fig. 7. Difference between the annual average observed NO_2 in 2021 and the annual average observed NO_2 in 2020 (in molecules/cm² VCD) from TROPOMI Sentinel 5 (based on data provided by BIRA).

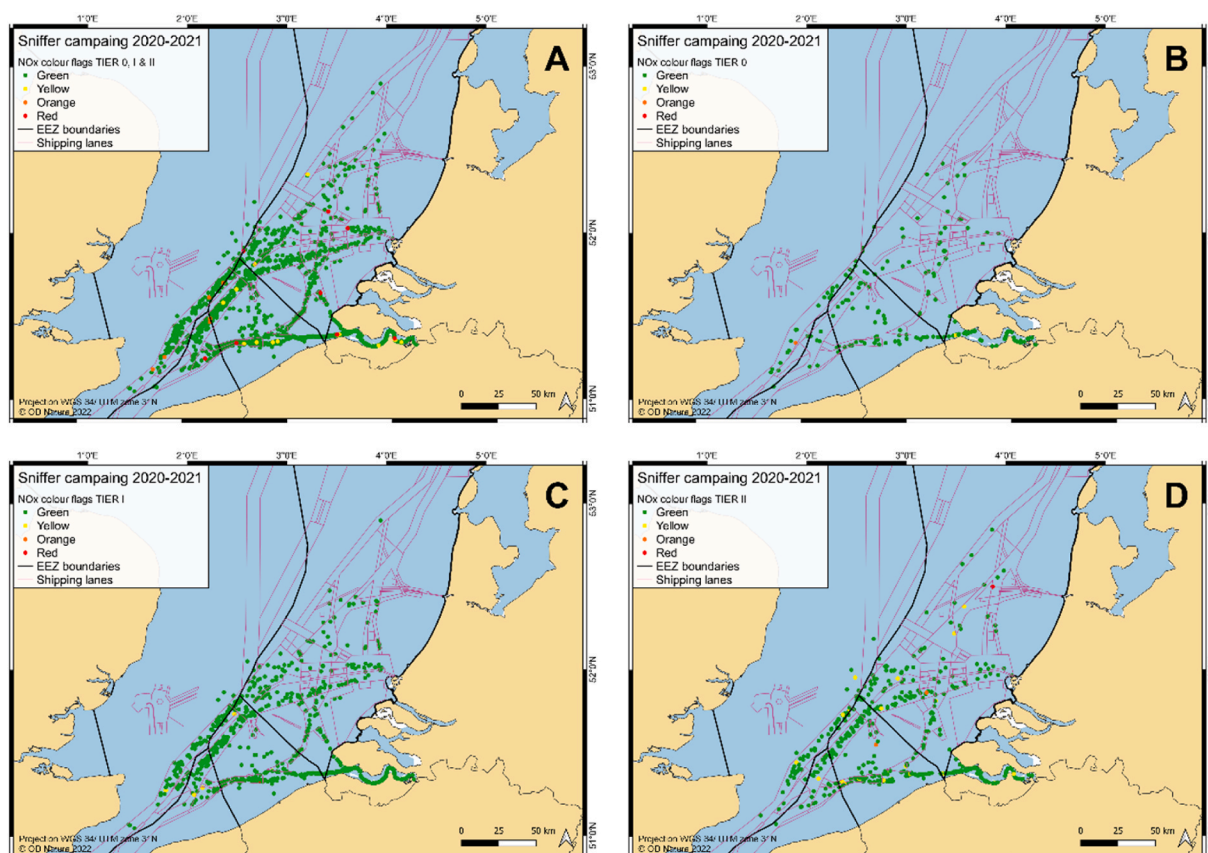


Fig. 8. Geographical visualization of the monitored OGVs with the NO_x color flags, for all Tiers (A), Tier 0(I) OGVs (B), Tier I OGVs (C) and Tier II OGVs (D).

Traffic Separation Scheme (WHTSS) in and nearby coastal waters. In the North Hinder Traffic Separation Scheme (NHTSS) further offshore, no red flags were observed. This could possibly be explained by the fact that on average OGVs have a higher speed in the NHTSS and consequently also have a higher engine load with a resulting lower NO_x emission, further confirming the impact of the higher NO_x emissions for the lower engine loads for Tier II.

The surveillance area was divided in 5 sub areas: NHTSS, WHTSS, Rotterdam area, Inter Rotterdam-WHTSS and Westerschelde. The average NO_x emission was compared between these areas but were not found to be significantly different ($P = 0.6498$). When comparing the NO_x emission distributions per Tier level for the different sub-areas, Tier II was found to be significantly different from Tier I for the WHTSS ($P < 0.005$) and the NHTSS ($P < 0.001$). However, for the other areas, no significant difference was observed, although for these other zones, only a limited number of observations per Tier were available (Figure S.14).

For the inland Westerschelde area the NO_x emissions from OGVs have the most drastic impact on human health. The average observed NO_x emission in this zone is higher (13.34 g/kWh) than the other areas (12.9 g/kWh), although not statistically significant ($P > 0.1$).

When comparing the compliance rate per zone, a higher non-compliance rate was observed for the WHTSS, but this was not found to be significant. When examining the Tier level of the non-compliant vessels, the higher non-compliance level for Tier II is again clear and present for all areas. For the WHTSS and NHTSS, this was even found to be significant ($P = 0.005$ and $P = 0.001$); while for the other areas, the number of Tier II observations was too low to compare the frequencies (Figure S.15).

4. Conclusion

The enforcement of NO_x emission regulations in seaports is limited to

documentary inspections. In this paper, it is demonstrated that the airborne sniffer monitoring methodology based on compliance thresholds for NO_x emission measurements in an operational setup is scientifically proven and reliable. The methodology thus provides opportunities for the enforcement of real-life NO_x emissions from OGVs on the sea. The sniffer sensor system on board of the Belgian coastguard aircraft was modified and extended to include the NO_x sensor. The measurement quality on spatial and temporal level is assured based on the Sniffer Quality Management System that has been set up with Standard Operational Procedures. For every Tier level, specific thresholds have been defined taking into account (i) the measurement uncertainty; (iii) the confidence interval, and (ii) a tolerance for the effect of the weighted average.

Analysis of TROPOMI Satellite data showed a notable reduction of NO₂ levels in the northern part of the North Sea in 2021 compared to 2020. Although this reduction coincides with the introduction of the NECA, it is however still unclear if this reduction is directly related to the NECA implementation as laid down by MARPOL Annex VI Regulation 13.

During the timeframe of the operations (2020–2021), NO_x emissions of 1407 OGVs were successfully measured with an average NO_x emission of 13 g/kWh. The average NO_x emission factors are not significantly different between 2020 and 2021, thus demonstrating that shipowners did not notably change their behavior since the entry into force of the North Sea NECA in 2021. In 2020, although 16 OGVs were observed with NO_x emissions exceeding the operational thresholds, those OGVs were not reported, due to the fact that the NECA was not active yet in 2020. In 2021, 43 possible non-compliant OGVs were observed, of which 23 OGVs were reported, with the overall compliance rate: 95.7%.

NO_x pollution from OGVs is considered as an import factor for human health in Belgium and neighboring countries, due to the high shipping density in the North Sea, the close proximity of the shipping

lanes and the already high anthropogenic NO_x pollution. Unfortunately, the monitoring operations demonstrate that the standards for Tier II OGVs, as described in MARPOL Annex VI Regulation 13, miss their target in reducing the NO_x emissions from OGVs. The predetermined emission reductions from OGVs are, at least for the Southern North Sea, not realized.

When comparing the average NO_x emission per Tier, it was assumed that Tier II OGVs would have a lower NO_x emission than Tier I OGVs as the NO_x emission limit for Tier II OGVs is lower than for Tier I. However, it was noted that the average NO_x emissions for Tier II OGVs was significantly higher than the average NO_x emissions for Tier I. Furthermore, Tier II OGVs were not only observed to have a higher average NO_x emission, but were also often found to be non-compliant significantly.

Engine manufacturers design their Tier II engine to optimize fuel efficiency. As fuel efficiency conflicts with NO_x emissions reduction, a trade-off needs to be made. The use of weighting factors per engine load creates a legal loophole to allow for higher NO_x emissions. Engine manufacturers are able to design engines in such way that NO_x emissions in lower loads are higher than the higher loads, nevertheless the overall weighted average NO_x emission approaches the limit for optimizing fuel consumption. For engine loads below 25%, no limits are even defined by MARPOL Annex VI Regulation 13. As a result, although consuming less fuel, Tier II OGVs may emit more NO_x, which is especially the case for engine loads of 25 and 50% that occur in the maritime traffic in the Southern North Sea. An improvement of the NO_x emission reduction impact of the standards could be achieved by defining NTE limits for Tier I and Tier II, applicable for the whole engine load spectrum like for Tier III.

The definition of emission limits according to the age of the OGV is the backbone of MARPOL Annex VI Regulation 13. Unfortunately, by applying the KLY instead of the year built in the regulations, another legal loophole is exploited, as many OGVs have been built since 2021, but yet have a KLY before 2021. Therefore, the effective favorable impact of Tier III standards in the field, and thus on the environment and public health, will be delayed by several years. This is demonstrated by the fact that only 13% of the OGVs with a length >70 m and a Gross Tonnage > 5000 GT with a built year in 2021 had a KLY in 2021. The use of this legal loophole, resulted in an estimated 29,000 premature deaths in 2021, these premature deaths could have been avoided if Tier III standards would have been applied for all OGVs built in 2021, a figure which is expected to rise substantially in the following years.

Last but not least, the ERS plays an import aspect in MARPOL Annex VI Regulation 13. For the vast majority of the observed OGVs, the ERS is lower than 130 rpm, which allows the use of (higher) linear values thus creating another legal loophole for higher NO_x emissions. Tier II OGVs have been found to be significantly more often rated at an ERS <130 rpm, which take advantage of the highest NO_x emission limit. Nevertheless, for ROROs, passenger OGVs and OGVs <200 m, there is a higher probability for ERS above 130 rpm. The compilation of an additional ERS dataset could further improve the monitoring methodology and lower the number of false negatives.

The airborne monitoring dataset is available on: <https://doi.org/10.24417/bmdc.be:dataset:2687>.

Credit author statement

Ward Van Roy: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration, Funding acquisition, Kobe. Scheldeman: Investigation, Resources, Project administration, Funding acquisition, Writing – review & editing, Benjamin Van Roozendaal: Investigation, Resources, Visualization, Writing – review & editing, Annelore Van Nieuwenhove: Investigation, Resources, Writing – review & editing, Ronny Schallier: Writing – review & editing, Laurence Vigin: Visualization, Frank Maes: Supervision, Writing – review & editing.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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