ON-BOARD EMISSION MEASUREMENTS ON SHIPS: LESSONS LEARNED, PRACTICAL CHALLENGES, AND OPPORTUNITIES

ELIAS ALTARRIBA
Logistics and Seafaring, South-Eastern Finland University of Applied Sciences, Kouvola, Finland
Email: elias.altarriba@xamk.fi
ORCID: 0000-0002-9569-2876

MARKO PIISPA
Kymilabs, South-Eastern Finland University of Applied Sciences, Kotka, Finland
Email: marko.piispa@xamk.fi
ORCID: 0009-0006-0456-0277

TARU TANHUANPÄÄ
Logistics and Seafaring, South-Eastern Finland University of Applied Sciences, Kouvola, Finland
Email: taru.tanhuanpaa@xamk.fi
ORCID: 0009-0008-3379-2629

SIRPA RAHIALA
Forest, the Environment and Energy, South-Eastern Finland University of Applied Sciences, Kotka, Finland
Email: sirpa.rahiala@xamk.fi
ORCID: 0009-0007-3329-2360

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Keywords

Emission measurements, maritime transport, ship emissions, voyage data, FuelEU maritime

Abstract

In the future, the need for on-board emission measurements in ships will increase. For example, the FuelEU Maritime regulation obliges certain emission components of renewable fuels to be measured. In some instances, the shipowner can utilize measured emission factors instead of constant values, provided the measurement values are better. This has a growing economic importance in terms of regulations or emissions trading. The same applies to subsequent updates of regulations. The emission measurement laboratory of the South-Eastern Finland University of Applied Sciences called Kymilabs has almost 30 years of experience in measuring ship

emissions. Until now, on-board emission measurements have been conducted in addition to research activities due to the statutory obligations of shipowners or equipment suppliers regarding occasional or system commissioning measurements. The systems of newer ships enable the recording of voyage data on a larger scale, so the usability of the measurement results increases considerably for shipowners or scientists. The emission measurement standards set many boundary conditions. Still, successful measurements in ships also require solving many practical but remarkable challenges related to technical execution, measuring equipment, equipment cleanliness, and the ship as a functional and social environment. The objective of this paper is to analyze the gathered experiences and tacit knowledge about issues that should be considered when implementing emission measurements. This is a crucial factor when planning measurements, analyzing, or learning about the results, and it has a significant impact, e.g., developing regulations or requirements and other boundary conditions based on the research work. This paper creates an overview of the technical, experimental, and social aspects related to the measurement process, with the aim of increasing a comprehensive and holistic understanding of the issues that directly or indirectly affect measurement results.

1 INTRODUCTION

Kymilabs is an accredited emission measurement laboratory at the South-Eastern Finland University of Applied Sciences. The accreditation was carried out by FINAS (T197/SFS-EN ISO/IEC 17025, institution no. NB2450), and thanks to this, the laboratory can issue official certificates of verified emissions to its customers, researchers, and other partners. Most of the measurements are carried out for industrial commissions, the number being about 100 each year. Shipowners are also significant clients; experience with emission measurements carried out on ships has been accumulated over a period of 30 years, and many of the shipowners in the Baltic Sea are regular customers. In addition, the laboratory's emission measurement group has participated in numerous research projects in which ship emissions or the operation of emission abatement systems have been studied in real conditions.

The emissions from marine engines are usually measured on a test bed in laboratory conditions for certification (Khan et al., 2013). However, on-board emission levels can deviate from the certified levels (Chu-Van et al., 2018; Khan et al., 2013) due to, for instance, varying weather conditions (Jahangiri et al., 2018) and depending on the on-board engine loads used (Fan et al., 2023; Yang et al., 2023). Thus, several global and regional environmental provisions require conducting on-board emission measurements. For example, the global NO_X Technical code (IMO, 2008) requires on-board nitrogen oxide emissions to be measured to ensure that the Tier standards are met by ships. The Tier (I–III) standards define limits for on-board NO_X emissions (IMO, 2008). The Baltic Sea, where the Kymilabs laboratory has conducted on-board emission measurements, is a Nitrogen Emission Control Area (NECA), where the strictest Tier III limit applies (IMO, 2023a). Additionally, the EU obliges shipping companies to report on-board CO_2 emissions from ships above 5 000 gross tonnages (GT) under MRV (monitoring, reporting and verification) regulation, which was adopted in 2015 (Monitoring, Reporting and Verification, EU/2015/757).

Environmental regulation in maritime transport is tightening rapidly, which increases the need for on-board emission measurements in the future. In 2024, the MRV regulation will be extended to cover CH_4 and N_2O emissions, in addition to CO_2 emissions (EU/2023/957). This is because maritime transport will be included in the EU Emissions Trading System (EU ETS) starting in 2024. The ETS will include on-board CO_2 emissions beginning in 2024, and CH_4 and N_2O emissions will be included from 2026 onwards. (EU/2023/959.)

Additionally, FuelEU Maritime regulation sets mandatory limits for the greenhouse gas intensity of energy used on board maritime vessels in the EU area. The regulation will apply starting in 2025, and the limits will tighten every five years until 2050. FuelEU Maritime includes emissions during the whole lifecycle of fuels, including fuel production and consumption phases. However, for many fuel types, the emission factors are yet to be defined, highlighting the need for on-board emission measurements. (EU/2023/1805.) The International Maritime Organization has also stated the need for a global pricing mechanism on GHG emissions and global GHG intensity fuel standards. The details of these measures have not been agreed upon yet, but IMO has an ambitious goal that these regulations will enter into force in 2027. (IMO, 2023b.)

The on-board measurements conducted for fulfilling environmental provisions are typically commercial, which means that the emission measurement results are not public, making research on the topic scarce (Chu-

Van et al., 2018; Orovic et al., 2022). For modeling the environmental impacts of maritime traffic more accurately, further research on the on-board measurements is necessary (Agrawal et al., 2010; Chu-Van et al., 2018; Khan et al., 2010; Orovic et al., 2022).

The objective of this paper is to analyze our experiences and tacit knowledge about on-board emission measurements and issues that can occur during the process. The tightening of environmental regulations will increase the need for knowledge about how to measure emissions from marine vessels accurately in real conditions. This paper provides recommendations for this, contributing to the limited literature on the topic.

2 MEASUREMENT OF SHIP EXHAUST EMISSIONS

2.1 Special features

Successful emission measurements require the fulfillment of many general requirements for flue gas measurements. The measurement must be carried out from a point where the flue gas flow is as homogeneous and undisturbed as possible (ISY & VTT, 2007). In the best case, the ship has measurement flanges in the stack designed for this purpose. Nonetheless, their existence does not automatically mean their optimality in terms of measurements—the flanges may have been installed with relatively weak information about the needs of the measurement process, and special attention should be paid to the realization of the homogeneity of the flow. It is also essential to identify the factors affecting the flue gas mixture: Does the exhaust gas come from one engine only? Is it possibly mixed with exhaust gases from auxiliary machines, oil boilers, or waste incinerators? Are there emission abatement systems in the line, or can air bleed into the flue gas mixture before the measurement process?

Linearity, reproducibility, and reliability can suffer due to uncertainties associated with measurements such as follows (ISY & VTT, 2007): In particular, the definition of the field zero value is essential both on ships and in industry, and the calibration of devices with calibration gas on site. Calibration gases, especially gas mixtures, can sometimes have stability problems. To identify any technical problems, measuring device manufacturers declare boundary conditions for their systems and calibration gases, in which case the system can be considered sufficiently reliable, and the necessary maintenance actions must be performed if needed. In all measurements performed at sea, the environmental conditions can vary considerably, and a direct comparison between ships cannot be made due to the different locations of the measurement flanges. The boundary conditions set by the manufacturer regarding permitted measurement temperature, air humidity, vibration, drag, dustiness, and other boundaries must be followed. The measurement results can also be influenced by interfering components and materials, such as, in some cases, the stack materials. The measurer has few opportunities to influence these, but it is worth paying attention to the material selections of the sampling line. Especially if the sampling takes place farther away physically from the measuring devices and the sampling line; therefore, it becomes long.

In the industry sector, flue gases can contain considerable moisture, which directly affects results. Ship exhausts are usually relatively dry (Agrawal et al., 2010; Chu-Van et al., 2018), but drying should be carried out before the measurement process to ensure the reliability of the results. In contrast, the number of particles in the flue gases of diesel engines is high, which easily leads to clogging of measurement devices. Often, clogging happens step-by-step, so it can be challenging to detect its impact on the results. This especially applies to longer-term emission measurements, which are often performed for research purposes. During shorter accredited emission measurements, it is easier to ensure the cleanliness of devices.

The measurement of nitrogen oxides has long been a subject of interest in shipping emissions. The amount of nitrogen oxides varies based on operating conditions and engine type, which is why their observation is possible mainly by on-board measuring (Tschoeke et al., 2010). The TIER classes that limit nitrogen oxide emissions also consider the engine rotating speed, leading to well-known challenges in the official control and monitoring of nitrogen oxide emission levels. As a substance to be measured, nitrogen oxides are quite easy to measure. Under shipboard conditions, nitrogen oxides hardly react with other substances, so their measurement can usually be performed without any significant disturbances. NO_2 is water soluble, but it also does not usually present challenges such as SO_2 (Liu et al., 2020).

Particle measurements contain several special features compared to gas measurements. This especially applies to measurements where the particle level is measured with a one-time sampling. The representativeness of the sample is, therefore, much more critical. Due to bends or other structures, the number of particles in the flue gas flow can vary significantly on different sides of the stack, so special attention must be paid to the sampling point locations. The engine must also run smoothly and predictably. If the equipment enables continuous particle flow monitoring, it is easier to ensure the representativeness of the results. However, special attention must be paid to the tightness of the sampling line to eliminate sample dilution. The suction effect of the measuring probe nozzle must be minimized because of negative pressure, and the nozzle must not touch the stack walls. In addition to this, the temperature of the nozzle, probe, and filter must be monitored continuously. The sample is also dried before the measurement process.

2.2 Measurement devices and methods

There are several types of measurement devices available on the market for performing exhaust gas measurements (ISY & VTT, 2007). It is worth paying attention to the choice of methods and equipment because the exhaust gas flow from diesel engines is a challenging measurement target (Tschoeke et al., 2010). The particles tend to clog the devices, and the temperature levels of the gases are often relatively high. Purpose also matters—many cheaper devices are mainly intended for a quick check of emission levels, for example, after system adjustments, in which case their technical durability is not necessarily sufficient for long-term measurements (ISY & VTT, 2004a). Also, not all measuring devices are intended for measuring diesel engine flue gases but for heating boilers or similar systems, including continuous combustion processes (ISY & VTT, 2004b). In addition, especially for research purposes, there can be a need to perform long follow-up measurements (e.g., an entire day or several days-long measurement processes), which requires considerably more from the measuring devices and their on-board maintenance compared to quick inspections.

On ships, stack decks and structures are often cramped, so the compact size of the equipment is a big advantage. On RoRo and RoPax vessels, the emission measurement team can usually take a van on board to facilitate equipment logistics. Even so, this is not possible on many other ship types, in which case the carrying distances will be even longer. The electrical connection (230 V) is practically a prerequisite for the operation of the devices, and it should be found close enough to keep the doors in sea lock mode closed. If the ship also carries passengers, closing the doors is also essential in terms of public safety.

Table 1 summarizes measuring methods and related standards that we are applying in our measurement processes. Flue gas measurements can also be carried out with other approaches (ISY & VTT, 2007), such as applying systems based on electrochemical gas detectors (for O_2, CO, NO_X, and SO_2, and CO_2, it often requires using the IR method). Devices based on electrochemical cells are usually very compact and cheaper to purchase. Still, gas driers are typically not included in the system, and often, long-term measurements produce contamination problems. Another advantage of the methods presented in Table 1 is that NO_X, O_2, and TVOC are measured with separate methods compared to SO_2, CO, and CO_2. Different methods provide more certainty to reduce measurement errors. NO_X measurements based on chemiluminescence (SFS-EN 14792/2017) are reliable, and residual oxygen data is essential when calculating the amount of gas exchange in the engine (SFS-EN 14789/2017). The focus of the substance measurements based on the infrared method is often to define CO_2 concentration (ISO 12039/2019), but the method is also applied to measure the SO_2 concentration (CEN/TS 17021/2017). High CO values can cause a small error in SO_2 values as well (SFS-EN 15058/2017). For example, an LNG ship operating under partial engine load often produces a lot of CO, meaning that the measured SO2 values can be slightly higher correspondingly. This is an observed measurement error in practice, but in some situations, it could lead to wrong conclusions. In all measurement processes, it is essential to recognize the effect of different variables on the results.

Compound	Measurement method	Standard
SO_2	Infrared	CEN/TS 17021/2017
NO_X	Chemiluminescence	SFS-EN 14792/2017
CO	Infrared	SFS-EN 15058/2017
CO_2	Infrared	ISO 12039/2019
O_2	Paramagnetic	SFS-EN 14789/2017
TVOC	Flame ionization detector	SFS-EN 12619/2013

Table 1 Measurement methods and standards followed.

The flue gases of diesel engines contain little moisture. If the analyzer can measure moist gases and the practical measurement arrangements allow for the sample to be led to the analyzer being hot and moist, this is the recommended approach in general (Laeeq, 2005). The drying process always causes substances to transfer to the condensed water. Typical drying methods include a refrigerator, jet flow, or permeation dryer. Each of these has its advantages and disadvantages (ISY & VTT, 2007). In the refrigerator dryer, the sample gas passes through the piping bathed in the refrigerant, and the condensed water is directed to a separate container. When measuring emissions from ships, the advantage of the refrigerator dryer is its good tolerance of even large amounts of particles. The dryer does not clog easily, but a small number of substances are always removed with condensed water. The jet flow dryer models are quicker, aiming to minimize the contact time of the condensing water and sample gas. This reduces the risk of absorption of sample gas substances to condense water.

The permeation dryer consists of ion exchange membrane tubes that let water molecules through, producing a dried flow of sample gas. No water condensation tank is needed, and the process is optimal for water-soluble components such as SO_2 or NO_2. However, the permeation dryer clogs easily if the sample gas contains many particles, which is the situation with marine diesel engines. In addition, certain gases, such as ammonia, can react with the membrane, causing measurement distortion. This issue is essential to notice, especially when measuring ships equipped with selective catalytic reduction treatment systems. Poorly functioning catalyst processes can cause significant ammonia emissions.

In Figures 1 and 2, the portable emission measurement equipment mainly used by Kymilabs is introduced. In addition, calibration gas and a variety of other accessories must also be included for mobilized storage.

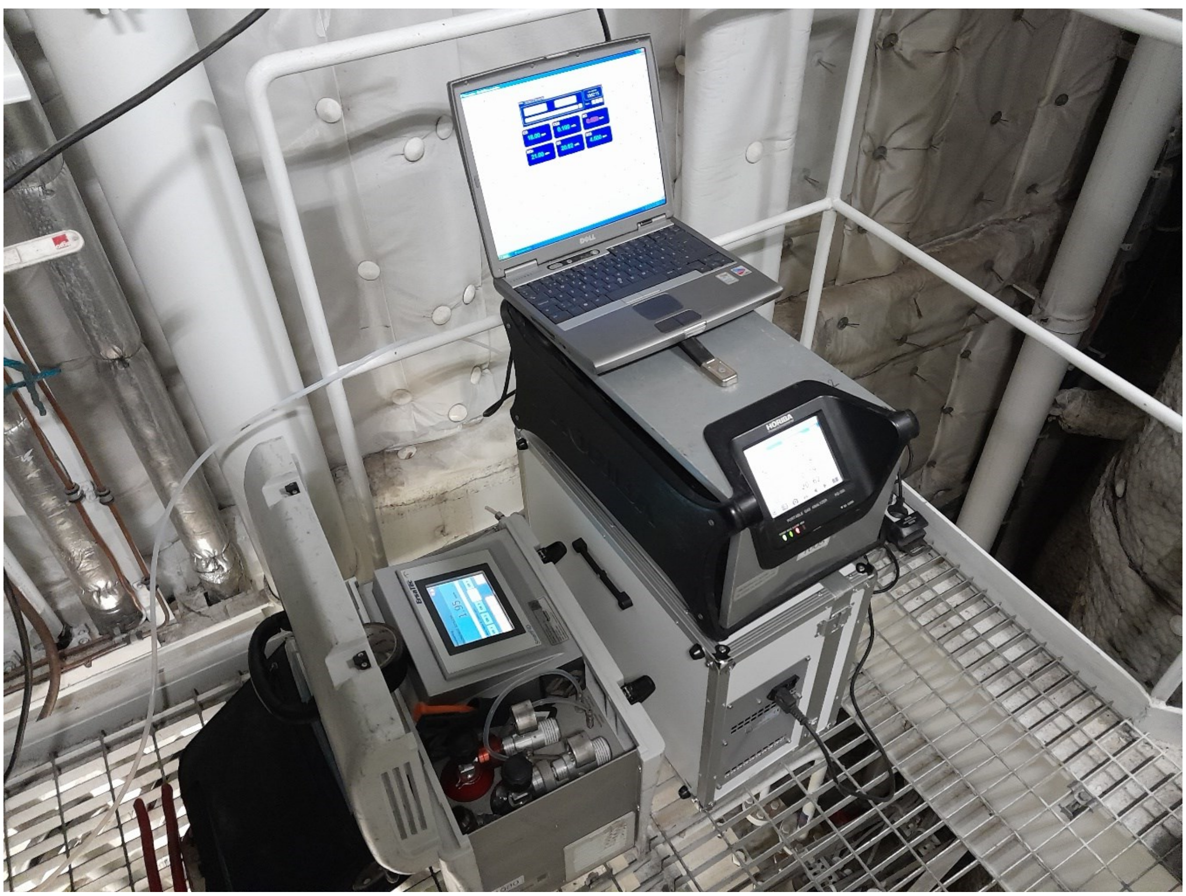

Fig. 1 Portable emission measurement equipment (CO, CO_2, NO_X, SO_2, O_2, and TVOC)

Fig. 2 Measuring probe installed in the stack (another measuring flange is found in the background)

2.3 Voyage data

It is always essential to compare the results of emission measurements with at least the actual fuel consumption of the ship; otherwise, the data does not provide much value. Considering the objectives of the measurements, information about the engine's load level is usually required as well in TIER accredit**ed** measurements, including engine rotation speed. Automatic data collection on ship systems has increased dramatically over the past 20 years (Perera & Mo, 2017). In the past, the systems were fully analog, in which case the essential information was recorded manually in the engine logbook by staff. The first generation of computer-aided control systems often automatically stored a pretty limited amount of data because the memory capacity was also limited. In technically modern ships, the amount of data that is automatically stored is enormous (Zeng & Chen, 2021). In practice, often, all variables monitored by the control system remain in the system's memory, at least for a while. Therefore, very detailed running data on the variables related to engines is often stored. Over the years, many older ships have also been updated, so data collection possibilities provided by these systems can also surprise.

Recorded voyage data forms a typical big data entity containing all five characteristics of big data: Volume, variety, velocity, value, and veracity (Emani et al., 2015). Volume refers to the amount of stored data, which is often the key to how comprehensive and generalizable the analyzed results can be understood. As the time step is short (e.g., 1 sec), inevitably, the amount of data produced by the ship's systems increases substantially. The variety of data varies by ship. Often, the ship contains several different control systems, which different suppliers produce. These systems may not have any technical interaction with each other. The technical age of the systems often varies as well. The variety of the stored data can, therefore, vary from unstructured raw data to a structured or even partially analyzed form, even on the same ship. As automatically recorded data, the accumulation velocity is often high and happens in real-time. The value of the data depends on the stored variables and the purpose of use. Shipowners have often been more interested in "big lines," e.g., fuel consumption per voyage.

On the other hand, there have been limited opportunities for more detailed analysis in the past. The veracity of the data varies too: Part of the stored data is produced by analog sensors, whose calibration may never have been done, or the sensor is not intended for high-quality data collection at all. The power line system also must be considered. For example, quite different readings can be obtained from the torsion sensors depending on whether they are installed in the crankshaft or the propeller shaft and whether the system contains shaft generators, compressors, or other auxiliary devices. In addition, some parts of the data can be based on completely calculated values, such as on the control signal set by the software of the engine control unit for the fuel supply. Getting certainty can be challenging—often, these are unique issues that the engine staff have never had to figure out.

However, the voyage data contains a lot of information that could be very useful in terms of maritime transport research, regulation development, and the competitiveness of shipping companies (Liu et al., 2020). Voyage data is the property of the shipowners, which is why it is sometimes complicated to obtain for research purposes (Chen et al., 2023). Obstacles can be social, commercial, technical, or often all of these. A reference point for usability can be found in the openly available AIS data, which is widely used for maritime traffic research at present day (Yang et al., 2019). The available on-board voyage data from a ship would be a much more valuable data set.

3 PRACTICAL IMPLEMENTATION: LESSONS LEARNED

3.1 General issues

In emission measurement processes guidance, the focus is often laid on technical execution (CEN/TS 17021/2017; ISY & VTT, 2007; ISY & VTT, 2004a; ISY & VTT, 2004b; ISO 12039/2019; SFS-EN 12619/2013; SFS-EN 14789/2017; SFS-EN 14792/2017; SFS-EN 15058/2017). This is essential to ensure the quality of measurements. However, a successful process also requires the implementation of many other requirements as well. This chapter discusses these features. Comprehensive technical documentation is available from the manufacturers of the measuring devices.

Each shipping company and every ship is a unique social environment. Based on our experience, there can be a surprising amount of variation in the operating culture, even on ships owned by the same shipping company. It affects how, for example, environmental issues are approached in practice and how much they are willing to invest in emission reduction technologies, both in terms of capital and maintenance. Are things handled in such a way that "there is no evidence of illegalities," "the regulations are fulfilled, but the spirit of the legislation is not necessarily," or so that "the spirit of the legislation is also taken into account," or is the shipping company ready to act proactively? Especially when considering the company's non-core operations, it is quite typical that many things can be poorly managed and handled. It is also common for new employees to be given responsibilities that no one else wants to handle. This is not only an issue in maritime transport but a matter that appears in industrial activities as well. If these issues are related to the ship's emission reduction technologies, the new employee may have a surprising amount of influence over the emissions produced.

The on-board accommodation of measurement staff is one practical issue to be resolved. On passenger ships, the issue is often easy to arrange, but on cargo ships, the number of cabins suitable for accommodation can be limited. Especially if the ship is undergoing maintenance or something similar at the same time and there are more maintenance specialists on board than usual. The necessary passage permits must be arranged for movement in the port area, and keys, necessary access cards or codes are also needed to move around on board. Regarding ships in non-EU traffic, the necessary notifications to the destination port and entry legislation and customs clearance practices of that country must be considered. This especially applies if the measurement voyage ends at that port. On RoRo/RoPax ships, measurement staff can often take a van on board (reservation of a parking space is needed), but on other types of ships, a parking space must often be arranged at the port. This complicates practical arrangements, especially if the ship does not return to the same port. Particularly in research-oriented emission measurements, the challenges mentioned in this paragraph easily focus research projects on more reachable ships.

Before agreeing on the emission measurement voyage, it is essential to ensure that engines and other on-board systems work correctly. Faulty or malfunctioning systems should not be measured, and the date should not be scheduled at the same time as engine overhauls or other maintenance procedures. Therefore, it is essential to ensure the following: Are all engines and emission abatement technologies operating normally? Has the necessary maintenance been performed for the different systems? Has the sufficiency of additives (e.g., urea) been ensured, and is there space in the wastewater tanks of the closed-loop scrubbers? If the measurements are performed using different fuel types, are there enough of these in the tanks? It is also essential to note the need to adjust the systems: Can it be performed by staff on board, or are experts from equipment suppliers needed? In addition, scheduling a measurement session for urgent voyages known in advance should be avoided (challenges regarding the operation of the required power ranges).

3.2 Special characteristics of accredited emission measurements

Accredited emission measurements are usually performed because the shipowner must demonstrate compliance in accordance with regulations (EU/2023/957; EU/2023/1805). Similar measurements can also be carried out during the commissioning of installed systems or inspections carried out by the authorities. However, the initiative to perform accredited emission measurements comes from the shipowner or the ship. Practices vary—in some shipowner companies, the ship inspector (or similar) may have a greater role, while in others, these matters are the responsibility of the chief engineer. Self-initiative is essential: For example, CSI (clean shipping index) does not require precise dates for emission measurements, but in some cases, the reporting date can be a significant issue.

Even if the shipowner gives general instructions, the actual ordering of the emission measurements is usually done by the chief engineer. The content of the performed measurements varies according to the customer's wishes and needs. A quality-conscious customer is aware of their needs and orders the measurements they really need and does not say, "Let's take it all," just in case. The motive for performing the measurements affects the selection of the compounds to be measured and sets the boundary conditions for the practical performance of the measurement process. The motive can be, for example, an inspection of the conditions of the ship's systems, system accreditation, CSI, or similar certification, a desire to use one's own verified emission factors to fulfill FuelEU Maritime regulations (EU/2023/1805) etc. In addition, which entity can carry out the required measurements must be verified, depending on the purpose of the use of measurement data. For instance, those who carry out the emission measurements must have sufficient accreditations.

In the accredited emission measurements, the special goal is practically always to get emission values as good as possible under boundary conditions set by regulations (CEN/TS 17021/2017; ISO 12039/2019; SFS-EN 12619/2013; SFS-EN 14789/2017; SFS-EN 14792/2017; SFS-EN 15058/2017). The systems are usually serviced before measurements, and last-minute adjustments or maintenance may also be performed during the measurement process. In accredited emission measurements, many boundary conditions, such as power ranges and the length of measurement periods, are usually precisely defined in the regulations. Acceptable deviations may also be defined in the regulations, which in some situations may be possible to use to achieve slightly better emission values; for instance, increasing engine load according to "navigational conditions," with the fundamental goal of reducing NO_X emissions. Depending on the route, the measurements are scheduled in such a way that it is possible to use the required power ranges, and, if necessary, adjustments and emission measurements can be carried out intermittently with the aim of optimal emission values.

Even though accredited emission measurement can yield better emission values compared to the ship's actual operating profile, their advantage is at least periodic maintenance and system adjustment. In a modern ship, many emission components are monitored on board, so at the same time, the functionality of the ship's emission observation systems can be verified, at least at a general level, even if this is not the purpose and goal of the measurements and certifications etc., for this would not be granted. At the same time, the crew's awareness of the emissions produced and the effect of the adjustments and maintenance on the composition of the emissions increases.

Accredited emission measurements are usually of short duration, so the technical durability of the measuring devices and equipment usually does not cause problems. Clogging problems caused by particles are also easy to manage because there are several natural interruptions to the measurement process (changes of engines to be measured, adjustment procedures etc.). Cooperation with the ship's crew is also usually relatively smooth. However, the mutual interest shared by both parties is that the measurement process can be performed successfully. Regarding cooperation, it must be stated that every ship is a unique social environment. Even between ships of the same shipowner, there can be surprisingly large differences in operating methods and practices.

3.2 Special characteristics of research-oriented emission measurements

Research-oriented emission measurements differ from accredited emission measurements in many ways, although the goal of both is to measure emissions (Khan et al., 2013). One significant difference is time span: Whereas in accredited emission measurements, the goal is to carry out a spot-type emission measurement as required by regulations, in scientific research, longer-term emission levels are usually the subject of interest. This creates numerous practical challenges. In long-term emission measurements, special attention must be paid to the equipment's durability and functionality. In addition, in longer measurements, the measurement personnel must allocate considerable time to carry out the measurements, and accommodation must be found on the ship.

Which routes and ships are chosen to be measured depends on the purpose, but due to the large number of ships, resources must be allocated to a sample relevant to the research aims. Often, in maritime traffic (depending on the route), it has been the norm to operate on the high seas with a steady engine load (Ni et al., 2020). Nowadays, this is not always certain; slow steaming has become more common to save fuel, and intelligent routing aims to find the ship's optimal speed, considering the time window to arrive at the destination port. However, slow steaming changes the ship's emission profile and lower carbon dioxide emissions are only one output of this operating profile. The emissions formed during port maneuvering and port operations are particularly interesting because they are usually emitted in the immediate vicinity of communities. In practice, the measurement of maneuvering emissions requires being on board the ship until reaching the destination port, even if the interest is only focused on port maneuvering emissions.

In research-oriented measurements, the aim is often that the ship operates as realistically as possible. This applies to both operation and system maintenance. Systems maintenance is a complicated issue in terms of emission measurements—newly serviced systems can give an overly positive impression of the ship's actual emissions. On the other hand, measuring faulty systems is often not meaningful. In real conditions, the efficiency of the systems is usually somewhere in between. Long-term emission measurements would produce valuable results, but performing them is often challenging due to resource reasons. The data stored by the systems (if it is available to researchers) can be a valuable information source when evaluating the level at which the ship's emissions are set on average.

There is, for the most part, more freedom with measurement arrangements compared to accredited emission measurements, where the procedures are often precisely defined in advance. In general, there are variations in the arrangements depending on what emission components are measured and whether the purpose is to examine emission levels over a short or long period or a certain period on the route. Arrangements can and often have to be adjusted also according to what kind of voyage data can be downloaded from the control systems of the ship and what kind of goals are set for the ongoing research project (Agrawal et al., 2010; Khan et al., 2013; Liu et al., 2020).

When considering the matter on a large scale, it can be assumed that this leads to research bias**:** Cooperative shipping companies are usually the kind where things are generally in order, and blatant violations are avoided. If there is a considerable variation in the technical condition of the shipowner's fleet, a "problem nest" is less often chosen as a cooperation vessel for brand reasons. However, the matter is not explained to researchers this way. The measurement of the ship in question "just will not work this time for some reason."

Practical cooperation on board depends a lot on the attitudes of engine control room personnel. Researchers often bring "extra work" to the engineers, which may be perceived negatively. Some of them may be very willing to cooperate and excited that there will be a change in their daily working life. However, the working days of the engine room staff often resemble each other in a relatively closed work environment. In particular, the personnel's ability to cooperate dramatically affects access to voyage data recordings. Some of the shipowners do not allow data to be handed over, but even if permission is granted, the crew is not necessarily familiar with data downloading. At that time, it can often be easier to state that "this is technically impossible" if there is no motivation to assist researchers. However, real technical surprises and obstacles have been encountered from time to time—firewalls, USB ports closed for data security reasons, computers completely disconnected from the internet, separate applications or utilities needed for downloading etc.

4 DISCUSSION

The need to measure emissions in the maritime sector will probably increase in the future. Environmental issues are increasingly being paid more attention to. In new regulations, such as FuelEU Maritime, it is possible to use shipowner's coefficients within certain frameworks if emission measurements have proved their validity. The proliferation of emission abatement systems also increases the periodical need for emission measurements. The development of new regulations and research on emissions produced by the maritime sector increases the number of emission measurements performed for scientific research needs.

Transitioning away from fossil fuels is currently the primary goal of global environmental policy to limit climate change. Nonetheless, other emissions produced by marine engines are equally harmful, and their reduction often requires emission aftertreatment systems (Ni et al., 2020). Catalytic converters have proven to be an effective method of reducing nitrogen oxides, and EGR systems may also be seen alongside them in the future. Even so, catalytic converters may not work at low loads due to low exhaust temperatures. Recently, a study showed that NO_X levels were higher than expected in measurements in the North Sea and that ships meeting Tier III were not necessarily using the cleaning methods they had in place (Fridell et al., 2023). The use of high-sulfur fuel is still allowed if the ship is equipped with sulfur scrubbers. Both technologies need to be controlled dynamically and, therefore, require automatic monitoring of emission levels.

From this point of view, the ship's emission abatement systems are a good investment, as well as from the perspective of developing the environmental sustainability of operations. This is a growing competitive advantage for the shipowner year after year. However, in addition to investments, it is essential that the system is serviced, maintained, and calibrated periodically. Of course, the equipment should be in use, even if ships are not required to do so. A poorly adjusted catalyst converter not only weakly reduces nitrogen oxides but also increases ammonia emissions due to additive feeding. Ammonia is an environmental poison, which puts unnecessary strain not only on the environment but also on the components of the stack. Correspondingly, poorly functioning sulfur scrubbers do not fulfill the task that has been set for them. The operating profiles of ships vary and affect the need for maintenance, which can be optimized using measured emission levels.

In addition to the automatic control of emission abatement systems, it is essential to note the possibility of deliberate non-optimization. Regarding sulfur scrubbers, there can be two motivational factors for this. The energy needed by the scrubber is reflected in a slight increase in fuel consumption. Wastewater is generated in the closed-loop scrubbers, which must be emptied either into the sea (if allowed) or at the port. Especially the latter often forms a cost item for the shipowner. Correspondingly, the urea additive needed by the catalytic converters is an additional expense for the shipping company. Inevitably, this does not mean turning off the system but running it underpowered so that the original purpose of the system is unfulfilled, but the costs are significantly reduced. However, there is little surveillance at sea, and the risk of getting caught is minimal.

Not all issues are caused by negligence: For example, in the emission measurement results, we presented in the paper (Altarriba et al., 2023), an unexpected peak in sulfur emissions occurred when the sulfur scrubbers were being turned off. The sulfur-containing substance left in the scrubber was vaporized by the hot exhaust gases, causing sulfur emissions to be momentarily high when the ship arrived at port. It is essential to note that the shipowner operated in full compliance with regulations. The scrubbers had to be turned off when reaching the restricted area, and the fuel had been changed to low-sulfur oil much earlier. This is an example of a technology-related phenomenon that can only be detected by emission measurements.

It would be of considerable benefit to decision-making and maritime transport emissions research if, in the future, on-board continuous emission measurement systems following an international standard, including open data transport protocol (such as AIS on the navigation side), were available on ships. Also, remote monitoring has been proposed to tackle the issue (Fridell et al., 2023). Shipowners' responsibility for sharing fuel consumption information has increased with both the EU's MRV regulation and the IMO's reporting obligation, so perhaps someday, this level of cooperation could be reached.

5 CONCLUSIONS

This is a review-type article about experiences of on-board emission measurements on ships. The importance of emission measurements will probably increase in the future, as more precise monitoring of emission levels and their reduction forms the core of FuelEU Maritime regulation and the EU ETS as well. The article provides an overview of the issues to be considered in emission measurements related to equipment and practical implementation. The latter is particularly emphasized, as documents dealing with technical execution usually do not consider these issues, which can be of great importance to the success of the measurements or in the selection of measurement targets. In addition, the paper compares the procedural differences between accredited and scientific emission measurements. The discussion deals with experiences in relation to tightening emission regulation and the spread of emission reduction technologies. The need for emission measurements will probably increase in the future.

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