THE SCIPPER PROJECT

Shipping Contributions to Inland Pollution Push for the Enforcement of Regulations

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Executive summary

The SCIPPER project has studied and field tested methods for onboard and remote sensing of emissions from shipping with a number of methods as well as the impact of ship emissions on air quality using combinations of ship emissions modeling and air quality modeling. Possible future developments of shipping emissions were studied with respect to the consequences for air quality and atmospheric deposition. This considered new technologies and included different options for new regulations as well different degrees of compliance to existing and to new rules. This deliverable lists suggestions on improved policies in the area based on this work. The following policy recommendations are made:

Recommendations on regulations:

Establish a load cycle for nitrogen oxides (NO_X) that better reflects operation during port visits and near coast. The present load cycle used when certifying the NO_X emissions does not reflect real world operation as shown through the results in SCIPPER. This will result in higher emissions of NO_X than was anticipated when the Tier II and Tier III limits were established. SCIPPER recommends that a new test cycle is developed, either as a transient cycle or similar to the present one but with more emphasis on low-load points. The details should be carefully analyzed in a separate study where also the resulting impact on air quality is assessed for different options.

Develop emission limits and test method for number of solid particles and in addition particle mass and black carbon. There are at present no specific limit for emissions of particulate matter from international shipping. The particle emissions are supposed to be limited through the fuel sulphur limitations which is partly correct. However, we argue that also specific limits are required in view of the still high emissions observed when using low sulphur fuels, especially for hybrid fuel oils. In view of the high concentration of volatile particles in emissions from ships' engines we would argue for establishing limits for the number of solid particles in a certain size range. This would also ensure that the types of particles with the highest health risks are regulated. Further, this approach seems to be the most realistic in order to monitor emissions of particles in the exhaust of ships equipped with scrubbers. However, since particle mass is already regulated for diesel engines used for inland shipping in Europe this may also be a way forward, and further, the establishment of limits for black carbon being processed within the IMO since decades, would also be a possibility. We suggest that a project to decide on the most suitable ways to regulate particle emissions from shipping is initiated.

Establish emission limit and test method for ammonia – both for SCR systems and when ammonia is used as fuel. With the Tier III limits the use of SCR for NO_X abatement will be more widespread with a risk of ammonia slip if the systems are not carefully calibrated and maintained; especially transient operations and 'urea mixing issues' could impose ammonia emissions. Further, ammonia is a potential marine fuel for the future and with its use comes a risk of ammonia emissions. Establishing emissions limits at this stage would impose that engine makers produce engines with low emissions.

Establish emission limits for methane - most relevant for liquefied natural gas (LNG) as fuel. LNG was introduced as a marine fuel mainly in order to meet sulphur limits. However, the emission of methane is not regulated and has in several studies been found to be substantial. There are engine types with low methane slip and aftertreatment methods being developed. A regulation on methane slip would speed up the introduction of such technologies.

Establish emission limits for N_2O - most relevant for ammonia as fuel. There is a risk that the potent greenhouse gas N_2O is formed when ammonia is combusted, and the emission should thus be regulated in order to guide the development of ammonia engines.

Establish more nitrogen emission control areas (NECAs). The dispersion modelling performed in SCIPPER has shown that the establishment of NECAs comes with significant benefits for air quality. We therefore suggest that the establishment of NECAs in more sea areas is initiated.

Recommendations on monitoring and enforcement:

Ships install sensor systems for NO_X, SO_X and BC. SCIPPER has shown that it is possible and cost effective to use sensors for monitoring emissions on ships combined with data transfer and a monitoring sensor. It is therefore proposed that all ships should be required to install sensors for SO_X, NO_X and BC in order to monitor that the correct fuel quality is used, and that emissions reach required level. Data should be automatically transferred to a monitoring center e.g., coupled to MRV or the IMO data collection system.

Use remote sensing to detect when fuel with too high sulphur content is used. SCIPPER and other projects have demonstrated that it is feasible and cost-effective to use remote sensing to detect ships using non-compliant fuels. Further, the data from more than 10 years of the remote sensing programs in various locations in Europe indicates that the monitoring contributes to better compliance. It is advised that the existing network for remote sensing is expanded, potentially also to include other pollutants than sulphur, and that all countries develop a strategy for remote monitoring in key maritime locations.

Use remote sensing to identify ships with non-functioning NO_X abatement systems. Preferably the monitoring should include low and high engine power or vessel speed situations. Ships with high emissions should be subject for onboard checks of NO_X emissions.

Use remote sensing data also to exclude ships for fuel sampling and future onboard NO_X compliance checks in order to increase efficiency; develop data strategies.

Establish a not-to-exceed (NTE) limit for NO_X for remote sensing measurements and also a NTE for simple onboard measurements in the exhaust stack applicable to all engine loads. This would imply that during operation, at any engine load, the NO_X emissions may not exceed a certain value, for example 50% above the relevant Tier limit. For a case where this limit is exceeded from an observation using remote sensing, an onboard verification of the NO_X emissions should be required using measurements or other methods. A separate study should be initiated to establish these routines.

For all recommendations it should be carefully considered that when regulations are designed it is done in such a way that practical implementation of monitoring and enforcement is possible. More specifically, legislation should be reviewed based on the principles of enforceability, practicality and fraud-resistance. Current design of, particularly NO_X, emission restriction does not always satisfy these principles limiting accurate and efficient monitoring of compliance

List of abbreviations

AIS – Automatic Identification System
BC – Black Carbon
CEMS - Continuous Emissions Monitoring Systems
CI – Confidence Interval
DOAS – Differential Optical Absorption Spectroscopy
ESC - Electro Chemical Sensors
ECA – Emission Control Area
EGCS – Exhaust Gas Cleaning System
EGR – Exhaust Gas Recirculation
ESMC – Environmental Shipping Monitoring Center
FSC – Fuel Sulphur Content
IMO – International Maritime Organization
ISO – International standardization organization
LNG – Liquefied Natural Gas
MARPOL – International Convention for the Prevention of Pollution from Ships a.k.a. the Marine Pollution Act
MGO – Marine gasoil
MRV – Monitoring, reporting and verification; EU:s database for fuel consumption and CO_2 emissions from ships
NECA – NO_X Emission Control Area
NO_X – Nitrogen Oxides
NTE – Not-to-exceed limit
OBD – On-board Diagnostics
PM – Particulate matter
PM2.5 – Mass of particulate matter with an aerodynamic diameter < 2.5 micrometers
PN – Particulate number
PTI - Periodic Technical Inspections
RDE – Real Driving Emissions
RSE - Real Sailing Emissions
SCR – Selective Catalytic Reduction
SECA – Sulphur Emission Control Area
SFC – Specific fuel consumption
SO_X – Sulphur oxides

Contents

Figures

Tables

1 Introduction

Shipping is the bloodstream of the international economy and is typically a fuel-efficient way to transport freight over large distances. However, shipping has also been associated with high emissions of air pollutants like nitrogen oxides, sulphur oxides and particulate matter contributing to problems with health risks, acidification and eutrophication. Compared to other modes of transport the emission regulations for ships have been, and still are, rather weak. The emission regulations are discussed in SCIPPER D5.1 and will only be briefly mentioned here.

Emissions of sulphur oxides is limited through the maximum allowed sulphur content in marine fuels which is 0.5% from 2020 and 0.10% m/m in special sulphur emission control areas, e.g., the North and Baltic Seas from 2015 and the Mediterranean Sea starting in 2025. As an alternative to use low-sulphur fuel, abatement measures, so-called scrubbers, can be applied to reach the corresponding reduction of sulphur oxides.

Emissions of nitrogen oxides are regulated in a tiered system where allowed emissions depend on the year of construction of the engine and also the engine speed. Worldwide the Tier II limits apply since 2011 and the more stringent Tier III apply to the NO_X emission control areas in the North and Baltic Seas since 2021. To reach the Tier III limits, abatement measures such as selective catalytic reduction or exhaust gas regeneration must normally be applied. However, certain engines using natural gas (LNG) as fuel can reach Tier III without after-treatment.

Particulate matter emissions are not specifically regulated for international shipping. However, the sulphur regulations are intended to reduce the emissions of particles due to the relation between fuel-sulphur content and emissions of particulate matter (see e.g., SCIPPER D4.1). Both the NO_X and the sulphur limits will help to reduce secondary particles.

These emission regulations are of course in place to limit harmful effects of air quality to human health and environment. For this reason, it is important that the regulations are efficient, monitored and enforced to ensure the reduction of emissions. Further, for the shipping industry, regulatory clarity is essential to avoid bad investments in technologies which may not meet future standards.

The SCIPPER project has investigated means to monitor that the emission regulations are followed using remote sensing techniques and on-board sensors. Further, the impact of emissions from shipping on air quality has been investigated using measurement data and modelling.

This report contains a short review of gaps in policies identified early in the project, an assessment of methods for compliance monitoring, results from air pollution modelling of non-compliance scenarios, a discussion on quality assurance in monitoring and finally a list of recommendations for potential policy changes.

2 Summary of identified gaps in regulation

In deliverable SCIPPER D5.1 early in the project we assessed gaps in the policies regulating emissions from shipping through discussions within the project, literature searches and input from stakeholders. Here the findings are summarized together with some comments on related work that has taken place in SCIPPER.

A number of fuels where residual oils is mixed with distillates to reach the sulphur limits are on the market. This may lead to additional problems in the case of oils spills and further the emissions on PM may be higher for distilled fuels. More specific definitions of these fuel are suggested, regarding e.g. content of aromatics.

Regulated limits of PM and of emission of the non-volatile particulate fraction BC are lacking. The fuel sulphur limits were put in place to both limit the emissions of SO_X and the emissions of PM, the latter motivated by the observed connection between PM emissions and FSC. However, there will still be high emissions of primary PM even with MGO as fuel. In SCIPPER different ways to monitor emissions of particles have been applied (SCIPPER D1.6 and D2.3) as well as a summary of emission factors (SCIPPER D4.1). It is clear that the emissions of PM from ship engines are high also when using low-sulphur fuels (SCIPPER D4.1, SCIPPER D1.1). Further, there is a lack of standards for how to measure particle emissions for marine engines using residual oils with relatively high sulphur content.

Regulations of negative side effects of EGCS are lacking. This applies to scrubbers which can be used to reduce the emissions of SO_X and therefore to meet the sulphur regulations. This is investigated thoroughly in the H2020/EMERGE project where emissions to air and impact on the marine environment from the use of scrubbers are studied.

Regulatory approaches to use of remote sensing and cost-effective technologies for ensuring compliance at sea are lacking. There is a need to develop approaches for remote sensing techniques and data handling for these to be used for identifying ships violating the sulphur regulations. This is discussed in SCIPPER D2.3 and in Chapter 5 in this report. The need for onboard systems is described in SCIPPER D5.3 and in Chapter 3.

It was identified that the limited geographical scope of the NECAs and the fact that the Tier III limits only applies for ships keel-laid from 2021 (for northern Europe) may cause a slow introduction of abatement techniques. In SCIPPER we have found that the NECAs have large benefit when it comes to air pollution (see SCIPPER D4.3 and SCIPPER D5.4). There are ships keel-laid before 2021 equipped with NO_X abatement systems, such as SCR, to meet the North American NECA, which do not have to use this equipment in Europe. Observations indicate that those ships often do not use the equipment in Europe, because it is not required.

For approval of engines regarding NO_X emissions there are different test cycles to be followed with fixed engine load points. We pointed out in SCIPPER D5.1 that the use of such a cycle can lead to higher emissions from operating ships than the different Tier limit values. For main engines the E2 and E3 test cycles apply with four load points and weighting factors as shown in Table 2-1.

Table 2-1. Weighting factors for the E2/E3 cycles (ref MEPC.177(58)).

Power	100%	75%	50%	25%
Weighting factor	0.2	0.5	0.15	0.15

There is no load point below 25% and the weighting is biased towards the higher loading points. For Tier III there is a limit that the emissions in any load point may not exceed 50% over the weighted Tier III – limit; there is no such limitation for Tier II or Tier I. Figure 2-1 shows two examples of NO_X emissions vs load that meet the Tier III limit but showing significantly different emissions at loads below 75%. At low loads the emissions may be high because the most common aftertreatment methods, SCR, is usually not in use at low loads since the exhaust temperature may be too low for the catalytic reaction (see further SCIPPER D5.1). Improvements may be possible, but this is currently not required because of the test procedure. Possible improvements may include increase of exhaust gas temperature at low load, by better air-excess control and/or engine-controlled regeneration cycles to restore catalyst efficiency at low load.

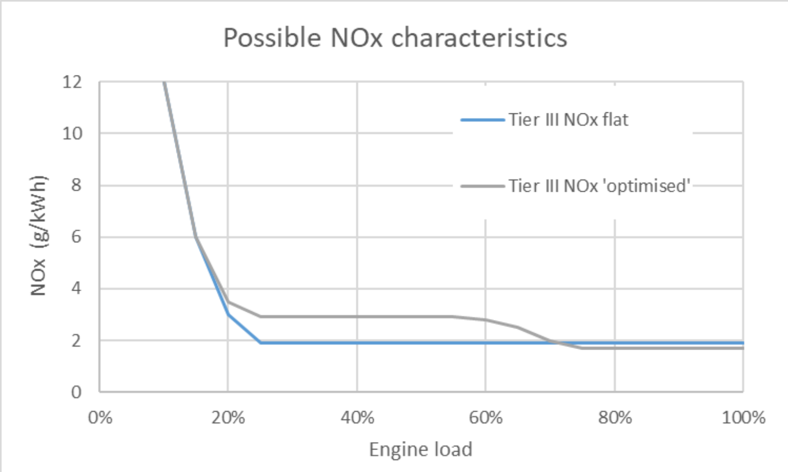

Figure 2-1. Possible NO_X characteristic, both with E2/E3 cycle average of 1.9 g/kWh. Lowering NO_X to 1.7 g/kWh for high load points, makes it possible to increase NO_X to almost 3 g/kWh up to 70% load.

As will be discussed in Chapter 4 the potential high specific emissions at low loads may contribute to air pollution problems over land since ships often operate at low speeds, and thus low engine loads, close to shore. Figure 2-2 shows an example of collected average load profiles on the North Sea outside the Netherlands; as can be seen the ships operate at low engine loads for a large fraction of the time, especially when inside the 12-mile zone. Within the Port of Rotterdam, the engine power as calculated from AIS data is at least 40% of the time below 25% engine power and about 80% of the time below 30% engine power.

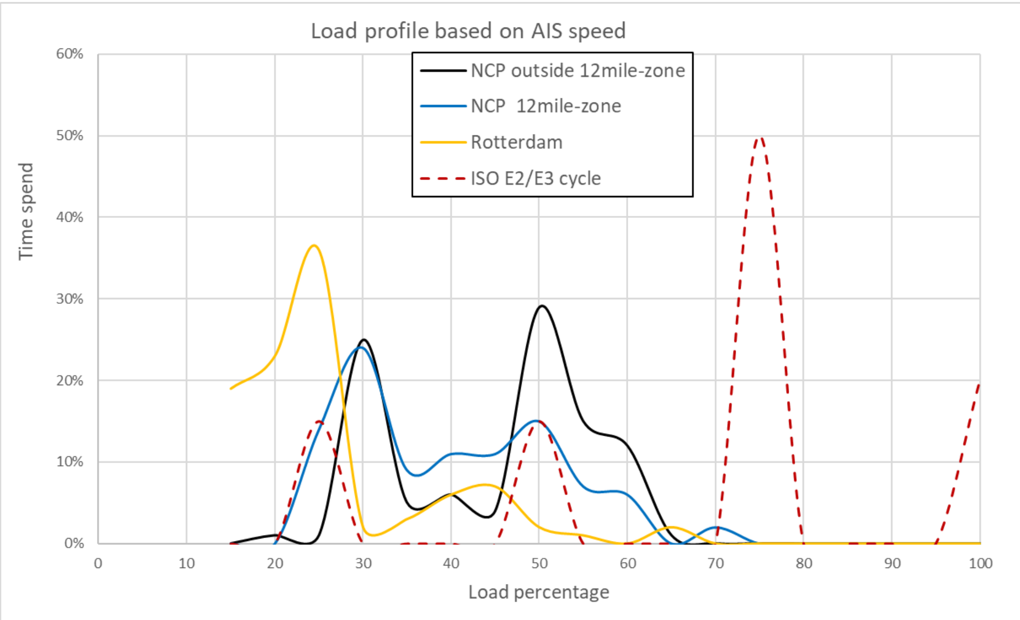

Figure 2-2. Projected average load profile on the North Sea, Netherlands Continental Plat. Source TNO, 2019.

Tier III in the European NECAs applies to ships keel-laid after 2021 and this in practice means new ships coming into operation late in 2021 or 2022. There is thus a limited number of new ships, in addition to the existing SCR installations, following Tier III in Europe at this stage. However, we have collected data from the SCIPPER partners on emissions of NO_X from Tier III ships operating in the Northern Europe NECA during 2022. The data for individual ships are presented in Chapter 5. A high fraction of the ships showed emissions of NO_X high above the Tier III limit indicating that the abatement systems were not in use. The data collected also showed that ships that meet the Tier III standard, but keel laid before 2021 do most often not use the abatement equipment while operating in the North European NECA, because they are not required to do so. Further, for Tier II ships there are many observations of emissions higher than the Tier II limit, especially for ships operating at low engine load (Knudsen et al. 2022).

There is identified a need for control measures to discover if SCR systems have become deactivated and thus do not reduce NO_X as expected as well as to limit the potential slip of ammonia. The impact on air pollution from ammonia emissions is investigated in SCIPPER D5.4.

It was also identified that there is no specific limit for emissions of methane. This is a problem mainly with LNG-fueled ships where the so-called methane slip from engines often is significant (See SCIPPER D4.1).

3 Assessment of cost-effective methods for compliance monitoring

In Europe the enforcement of the IMO MARPOL Annex IV legislation is focused on fuel sulphur content (FSC). Each European port should take fuel samples of at least 10% of the vessels visiting the port on an annual basis. In addition to this, a number of European countries are operating remote, plume sensing options via fixed plume sensing stations or via aerial vehicles or patrol vessels.

3.1 Remote measurements of FSC and pollutant emissions

The fixed plume sensing stations are usually continuously operational but have limited range, while the mobile options can survey larger sea areas but are typically limited to spot check campaigns lasting a limited number of weeks or months a year. Combined, the various techniques offer an array of survey options which have proven to be effective in both deterring non-compliance and monitoring impacts from ship emissions under various operational conditions.

The sniffer measuring technology is quite robust since the ratio between the pollutant emission and CO_2 is used as a basis. In that way the pollutant mass is directly related to the fuel mass, and the emissions are expressed in g/kg fuel. For FSC this can directly be compared to the requirement. For NO_X the legal requirement is based on gram emissions per kWh mechanical engine work (shaft power x time), but it is also a weighted emission across four engine load points (ISO 8178, E2 and E3 cycles). The remote NO_X monitoring can give a good impression of the real-world NO_X emission of the ships, but legal comparison with the IMO MARPOL Annex VI requirements is challenging. Some practical guidelines can however be given. In Table 3-1, an overview is given of three engine load conditions and the corresponding practical legal requirements. The weighting of the four test cycle load points leans heavily towards the two highest load points (see Chapter 2). These two points, which represent 75% and 100% engine power, determine 85-90% of the final result of the test. As a consequence, the NO_X measured above 50% engine load should directly be in line with the Tier III limit value (SCIPPER D2.3), otherwise it will not pass the E2/E3 test. Thus, it is important that also sufficient monitoring is being done on open sea at nominal vessel speeds. For example, this can be done with a patrol vessel at the entrance of a NECA or with aerial vehicles. In port areas, the engine load will often be at or below 30% engine power (Figure 2-2). The 25% engine point should stay below 150% of the E2/E3 cycle average NO_X for Tier III engines. This can be verified with remote sensing, although there is always some uncertainty about the precise engine load since this is not reported by the vessel as part of AIS data. Below 25% engine power, the NO_X will gradually go up to a relatively high value for ships using SCR, because the urea dosage for the SCR catalyst is diminished (gradually or sudden) to zero when further reducing the engine power. Under those conditions, any remote sensing will probably confirm that the Tier III legislation (including the test cycles) is not effective in significantly reducing NO_X emissions in port areas. A further additional complexity is that any remote sensing will monitor the NO_X/CO_2 ratio, while the limit value is in g/kWh. The NO_X/CO_2 ratio can simply be converted to a NO_X value in g/kg fuel, if the specific fuel oil consumption is known, to make the transfer to g/kWh. For the SFC often the load dependent empirical curves of the IMO fourth GHG study are used (Faber et al. 2020). It is recommended to carry out an onboard inspection when the limit values shown in Table 2-1 are exceeded. The onboard inspection can include monitoring data of NO_X emissions analyzers if available and/or monitoring data of urea dosage in relation to engine power. The urea dosage can be compared to engine specific or generic urea quantity requirements depending on the engine type.

Thus, remote sensing can effectively be used to monitor the compliance with the fuel sulphur limitations since measurements of CO_2 and SO_2 gives the FSC. The only limit is the sensitivity of the systems (See Chapter 5). For NO_X the remote systems can in the same way monitor the emissions. To assess compliance is more complicated since it both involves a conversion to specific emissions and must account for the test cycles applied when engines are certified.

In SCIPPER D2.3. most focus was on testing remote sniffer methods. However, optical remote sensing measurements using sky-DOAS were also tested and this technique was found to be useful for detecting ships running on high sulphur fuel, but with larger uncertainties than the sniffer method. Other techniques tested in the project include infrared passive measurements. Remote optical sensing has the advantage that it does not require the sensor to be in contact with the ship emission plumes. This is of large advantage when making airborne measurements, and in a fixed setup these measurements could be less dependent on the wind direction since it is possibly point towards the source. Another advantage is that the remote sensing measurements are contactless which makes it easier to measure sticky species, such as ammonia, which can be difficult for a sniffer sensor. It is hence advised that remote optical techniques are further developed and validated as a tool for complementary compliance monitoring.

Table 3-1. Practical NOx compliance limit values depending on engine load.

Engine power	Location	Practical limit value for compliance
> 50%	Open sea	Tier III limit value
Around 25%	Port area	150% of Tier III limit value
< 25%	Port area	No clear legal limit

3.2 Sensor-based onboard monitoring

In the SCIPPER project five different sensor systems were tested for continuous monitoring (SCIPPER D1.6, SCIPPER D5.3). These sensor systems are characterized by their low costs since they are based on automotive sensors or low-cost air quality sensors. The monitoring emissions parameters include NO_X, NO, NO_2, SO_2 NH_3, PM, BC, CO_2 and O_2. Continuous Emissions Monitoring Systems (referred to as CEMS) are also already available from commercial suppliers like ABB, Danfoss, Sick, Siemens and others. These systems generally make use of infrared or ultraviolet analyzers, but also electro chemical sensors (ESC) are used in some cases (De Jong, 2018).

The overall SCIPPER system for onboard monitoring includes also continuous data transmission via satellite and the reporting of the emission in an Environmental Shipping Monitoring System (ESMC). This centre offers different kinds of reporting, for example detailed reporting for ship owners, and more aggregated monitoring for authorities.

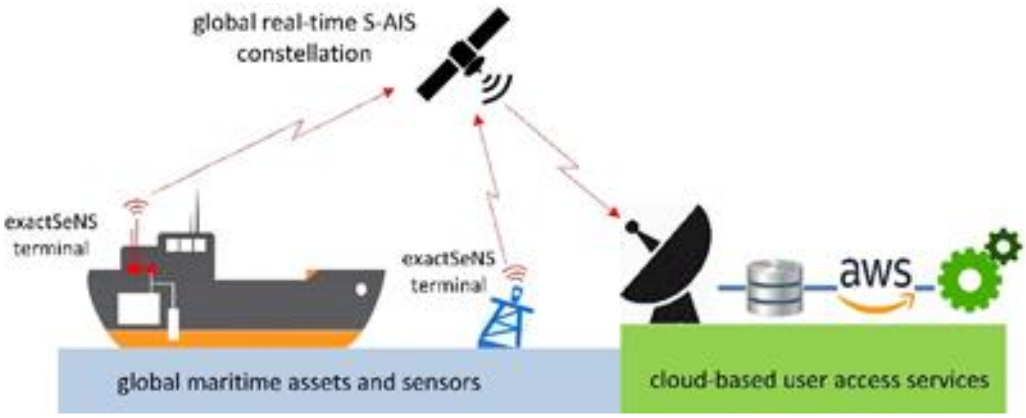

Figure 3-1. A schematic showing the end-to-end emissions reporting service - from ship-to-shore and then to the cloud-based user access services

The SCIPPER work included developments of standards for data transmission and for reporting (SCIPPER D1.6). The reporting would include (historic) daily average emissions, area specific emissions (e.g., port area) and (monthly) maps as function of engine power or vessel speed. Maintenance, calibration and lifetime of the sensors are key parameters. The NO_X sensors were tested on two vessels for 3 to 4 months, and mostly worked fine. The other sensors systems were tested for 1-2 weeks. The sensor lifetime can be extended by a dilution system with intermitted exposure or via an air shield. Also with these measures, annual sensor replacement is probably still necessary, but also feasible. For the NO_X sensors it is generally sufficient to calibrate them before installation, and optionally a calibration check when replaced after one year.

In several SCIPPER reports, we have concluded that monitoring and enforcement of especially NO_X, but in the future probably also PM and BC, is difficult since limit values are based on a weighting of different engine load points, and values are based on mechanical engine work, g/kWh values. Specifically for monitoring and enforcement, it is recommended to also define limit values for real-life use, and also implement this within the MARPOL Annex VI legislation. It is recommended to implement this in the form of a Not-to-Exceed (NTE) limit value in g/kg fuel. This NTE value could be engine load or vessel speed dependent. This has several big advantages:

- The dependency on load is significantly reduced. At lower loads the emissions in g/kWh increases quickly due to the relatively high internal engine work (friction). This is not the case for g/kg fuel values as is also demonstrated for NO_X in for example SCIPPER D2.3.
- Compliance checks with remote sensing become feasible, since g/kg fuel values can be based on only emissions concentration values and fuel properties.
- Onboard monitoring becomes more robust, because often uncertain engine parameters such as engine power, are not needed. Also, independent verification of the correct working of the monitoring system becomes quite simple, for example with raw monitoring data checks or with hand-held emissions analyzers.

The NTE emission limits can also be engine type dependent. This is currently the case with Tier III NO_X limits, which are dependent on the maximum engine speed. In the long run, it can be argued whether limit values should be engine type dependent. For example, for heavy duty road transport, this is not the case. Limit values are independent of the engine size and type. Also, with active NO_X emission control systems such as SCR (and EGR) low NO_X emissions are generally feasible by improving the design. For example, for trucks 95% NOx reduction is achieved with very compact SCR systems.

In Europe, the emission legislation for cars and trucks includes specific test procedures and limit values for so-called Real Driving Emissions (RDE) and In Service Conformity (ISC). These procedures are based on driving on the road in normal traffic situations. This consequently can impose additional requirements to the engine, which are not directly required by the formal test procedure in an engine or vehicle laboratory. It is recommended to take the procedures for road vehicles as an example for defining the test or monitoring procedure and NTE limit values for ships (SCIPPER D5.3).

As mentioned before, it is recommended to include the monitoring and enforcement procedure within the IMO MARPOL Annex VI legislation. It is also recommended to install a technical working group to work out further details on monitoring parameters, averaging and options for limit setting. The implementation could start on a voluntary basis and there could also be a monitoring period without actual limit setting.

Further development and demonstration of the sensor systems are needed. For sensors operating in raw exhaust (automotive sensors) a protection system leading to reduced exposure time is needed. For sensors used in combination with a dilution system, a simple, robust dilution system needs to be developed. This should include a clear guideline on the dilution factor, especially for particulate matter. Sufficient quantity of emissions monitoring data is essential in monitoring the effectiveness of legislation and other measures to reduce pollutant emissions of ships. Also, because the relative contribution of maritime emissions to air emissions is increasing compared to other sources.

The proposed solutions to some of the identified gaps in SCIPPER D5.1 are summarized in Table 3-2. This is based on the SCIPPER onboard monitoring as well as remote sensing work. The table mostly contains regulatory gaps as well as one technical gap.

Table 3-2 Identified gaps (SCIPPER D5.1) in regulation related to pollutant emissions and proposed solutions.

GAP	Possible solution(s)
Regulated limits of PM and of emission of the non-volatile particulate fraction BC are lacking.	Regulate the emissions of particles specifically
Regulations of negative side effects of EGCS can be improved	Implement a specific directive with limit values and measuring procedure for scrubber water, NH_3 and N_2O.
Regulatory approaches to use of remote sensing and cost-effective technologies for ensuring compliance at sea are lacking	Implement a specific directive for monitoring and enforcement including simple, robust measurement and calculation procedure.
- Difference between test cycle and real sailing emissions - SCR and EGR functioning in port areas and other close to shore locations are not well covered by the regulation	Options: - Adapt test cycle or - expand NTE requirements or - implement Real Sailing Emissions (RSE) requirement and procedure
- Control procedures to discover SCR deactivation or EGR system malfunction are missing	Implement requirement for continuous monitoring or periodic measurements for both

- Regulation on ammonia slip is missing	NOx and NH_3
Knowledge of NOx sensor performance over time.	- Replace frequently (once or twice per year) - Position NO_X sensor in diluted gas - Limited exposure time of NO_X sensor by intermittent sampling - Calibration & standardization of sensors
No regulation limits the methane slip from LNG engines	- Implement methane emissions in legislation (GHG requirement) - Monitor methane emissions continuously or periodically

3.3 Onboard and remote monitoring costs

In SCIPPER D5.3, the annual costs for six typical short-sea vessels are calculated. This was also done for five different sensor configurations:

- Option A: Only s-AIS data transmission and reporting
- Option B: Automotive sensors per each engine: NO_X, NH_3 and O_2
- Option C: Air quality sensors per each funnel
- Option D: Option C plus PM or BC sensor
- Option E: Plume and background sensor boxes

The annual costs for these options ranged from about 2500€ to about 9500€, depending on the option and the vessel size. This includes all costs such as depreciations, maintenance, calibration and service fees. This also includes a service fee of 2000€ per year for the ESMC, based on the rather small number of 250 participating vessels. These costs will likely go down with a larger number of participating vessels. The costs might be split between the ship owners and the authorities. For example, the authorities may take the cost of the ESMC as proposed in Table 3-2. It would make sense to develop the monitoring centre compatible with the EU-MRV or the IMO data collection system. This was also one of the conclusions of the stakeholders meeting in October 2022. It is logical to combine the monitoring of air pollutants with GHG emissions monitoring.

In SCIPPER D5.3, the monitoring costs are compared to the external costs and also to the emissions abatement costs. It appeared that the monitoring costs varied from below 1% to around 2% of the external costs and similar numbers for the part of the abatement costs. The annual external costs of emissions ranged from some 450,000€ to some 4 million € depending on the vessel type and sailing area. So even though the annual costs can be significant, they are small in relation to the external costs or the abatement costs.

The costs of remote monitoring are extensively investigated in SCIPPER D5.3. An overview of the costs for different types of remote sensing techniques and also for onboard sensor monitoring is presented in Table 3-3 below. The table shows that the costs of remote monitoring options are significant, but not exceptionally high. Especially the costs of an onshore permanent monitoring station, with an approximate annual cost of 300,000 € seem acceptable, especially if this is compared with the costs of onboard inspections including analysis of fuel samples and specific data checks or measurements for NO_X emissions. The fact that a high fraction of vessels will be monitored, will stimulate the ship operators to comply with the FSC and NOx regulations, for example via proper maintenance and monitoring or periodic measurements. The remote monitoring with aerial vehicles or patrol vessels can be more expensive. For that reason, it is often limited to periodic campaigns of several weeks. The actual costs can be lower if these campaigns are combined with other activities such as general marine pollution surveillance, oil spill detection, SAR operations, fishery control, FRONTEX operations etc. The monitoring costs should also be compared to the external costs of emissions. The external costs of typical short sea vessels in Europe range from some 450,000€ to some 4 million annually per vessel, depending on the vessel type and sailing area (SCIPPER D5.3).

Table 3-3. Indication of total costs for onboard monitoring (row 2) and typical cases of remote monitoring (row 3-7). Source SCIPPER D5.3

Monitoring	Ship owners	Authorities
Onboard monitoring – per year	Per vessel (excl. ESMC*): 500 – 7500 €** per year	Total ESMC*: 500,000 € per year
Sniffer station onshore (full year operation one system)		300,000 € per year, or 20 – 770 € per vessel-pass
Small drone campaign		140 - 350 € per vessel-pass
Large drones campaign (3 months)		400-1000 € per vessel-pass
Manned aircraft campaign		200 - 870 € per vessel-pass
Satellite (globally)		1 – 5 million € per year 100 € per vessel (both indicative)

* Environmental Shipping Monitoring Centre: estimate based on 250 participating vessels, 2000 € per vessel
** All engines are monitored. Costs depend on monitoring option including number of sensors (parameters) and number of engines onboard of the ship.

From the studies performed in SCIPPER it is clear that the installation of onboard systems to monitor emissions with sensors is feasible and economically viable. The signal from the sensors and additionally needed engine data can be transmitted for continuous monitoring of emissions. Precise measured engine power is not needed according to the SCIPPER monitoring proposal, just a power setting and RPM are sufficient. Fuel consumption is desired to additionally report CO_2 emissions. For calculation of g/kg fuel emissions only emissions and CO_2 concentrations in exhaust gas are needed; g/kWh emissions are consequently calculated by multiplication with the SFC (SCIPPER D1.6).

Even though, the monitoring costs and enforcement costs are low in comparison to the abatement costs and the external costs, the total costs of monitoring and enforcements still must be covered. It can be debated who should bear these costs: the industry and/or public bodies. For road transport the vehicle pays for the obligatory OBD system in its vehicle and for the Periodic Technical Inspections (PTI). On the other hand, ministries generally pay for in-use compliance programs. It is not strange that ship operators bear the costs of onboard monitoring and periodic inspections. Basically, this should be done to minimise the external costs of pollutants for the society, which are large also when ships are perfectly compliant. Society can also be considered to bear the costs of certain compliance monitoring on a European level. For example, several EU countries would benefit from remote monitoring of emissions close to the entrances of environmental zone's (North and Baltic Seas and Mediterranean Sea) or other strategic points.

3.4 Conclusions

The conclusions regarding monitoring and enforcement are summarized below. In general, compliance monitoring and enforcement are much more difficult for NO_X than for FSC because the regulatory requirements are based on engine work and averaging over different engine load points.

Conclusions regarding regulatory gaps:

- The NO_X Tier III legislation is not very effective for vessels operating at low or medium speed, because test requirements are primarily met with test points above 50% load.
- Effective compliance monitoring is only possible if this compliance monitoring is implemented within the NO_X regulations. Most desirable are Not-to-Exceed levels for exhaust gas quality (g/kg fuel limit values) for real sailing emissions. This applies to NO_X, but also to possible future requirements for NH_3, PM and BC.

Conclusions regarding continuous onboard sensor monitoring:

- Continuous onboard monitoring is essential to get a grip on malfunction of emission control systems. Malfunctioning could be related to insufficient maintenance of SCR, EGR or SOx scrubber systems.

- Sensor based monitoring is possible but proper system design and annual maintenance including sensor replacement are needed. A robust data format for satellite data transmission is possible and demonstrated in SCIPPER.

Conclusions regarding the costs of onboard and remote monitoring:

- The annual costs of onboard monitoring range from 500 to 9500 € per vessel depending on the monitoring option and the vessel type.
- These costs are generally below a few percent of the (SOx and NOx) abatement costs. The costs are also lower than a few percent of the external costs of the emissions.
- The emissions and external costs increase by factors if the vessels are not compliant and a reason why it is advised to pursue continuous onboard emissions monitoring, which is already common for much smaller emitters such as road vehicles.
- Remote monitoring at selected locations is needed to independently check for emissions compliance of ships and also to verify the validity of onboard monitoring systems.
- The costs for onshore or mobile remote monitoring ranges from 20 to 1000€ per vessel-pass, depending on the monitoring option and shipping density. Both fixed as well as mobile remote monitoring are recommended in order to monitor the ships at different engine load conditions as well as during expected and unexpected cases.

The costs for onboard monitoring as well as remote sensing are fully reasonable compared to the external environment and health costs they are aimed to prevent.

4 Air pollution impact in policy and compliance scenarios

Despite an expected further increase of global trade, emissions from shipping need to be reduced in the future. This concerns emissions of greenhouse gases as well as those of other air pollutants like sulphur oxides, nitrogen oxides, and particulate matter. The effects of future ship emissions, that are in accordance with the IMO goals to reduce GHG emissions and that consider growth and modernization of the shipping fleet as well as potential new regulations and a certain non-compliance to these regulations, can be studied with a combination of ship emission models and atmospheric chemistry transport models (see SCIPPER D4.3 and D4.4). Possible future emissions from shipping as well as from other land-based sources are combined in emission scenarios, which describe alternative future developments of ship emissions. A number of scenarios were investigated in SCIPPER to analyze the contribution of shipping to air pollution in Europe. The studies were made with 2040 and 2050, respectively, as target year. The shipping emission scenarios are based on projections for certain fuel mixes published by DNV (2020) in their Maritime Forecast to 2050. Selected scenarios are analyses using emissions and dispersion modeling. In this Chapter some of the results are highlighted.

4.1 Developments until 2040

Based on projections by DNV (2020) for their main scenario, shipping fuels will shift towards the use of LNG and partly also ammonia in order to reach the IMO goals of at least 50 % reduction of GHG emissions from shipping (compared to 2008). The scenario considers a high growth in transported cargo. The described global developments in cargo volumes were assumed to be valid for shipping in Europe, too. Details can be found in the DNV Maritime forecast to 2050 (2020 report) and in SCIPPER D5.4. Land-based emissions play a role for the results of the chemistry transport model simulations because of interactions between the pollutants emitted from different sources. In SCIPPER, high ship emission reduction for Europe was assumed in 2040.

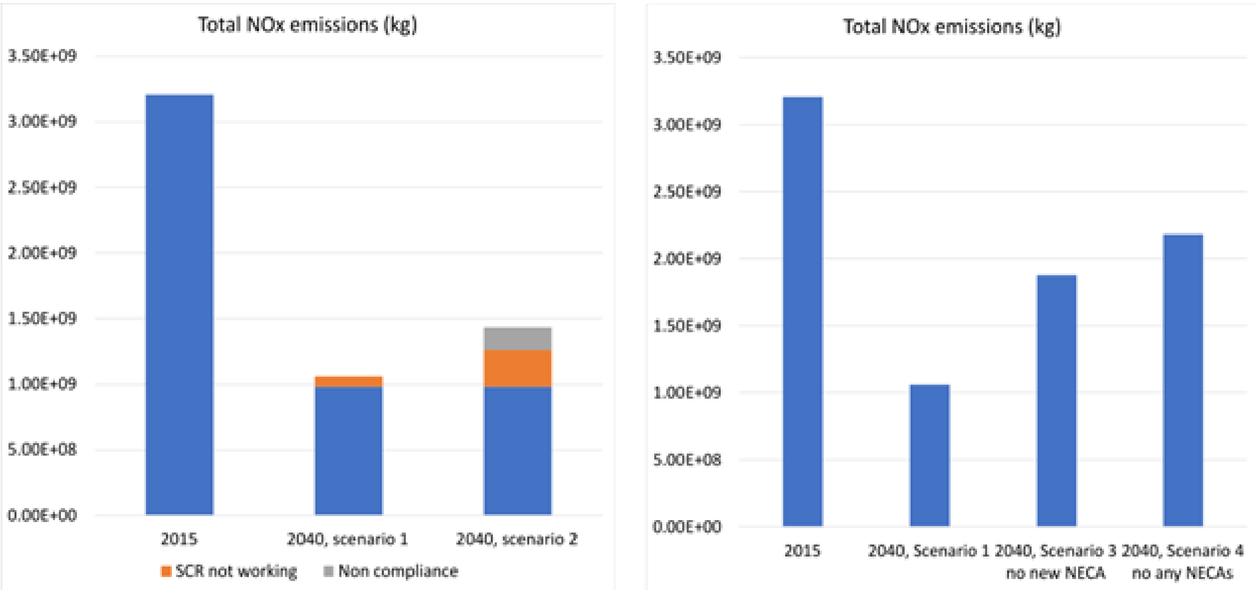

Figure 4-1 Total emissions of nitrogen oxides (NO_x) from shipping in Europe in 2015 and 2040 under different regulatory scenarios simulated using the STEAM model (from SCIPPER D5.4).

The modeled scenarios indicate that almost independent from the fuel used, the already implemented NECA in the North and Baltic Seas will lead to significantly reduced NO_X emissions from shipping (Figure 4-1, scenario 1). Combination of malfunctioning SCRs and non-compliance to newly established NECAs may increase the total NO_X emissions by up to 40%, however, this is still less than the total NOx emissions for the case that no new NECA will be implemented outside the North and Baltic Seas (Figure 4-1, scenario 3). The existing ECAs in the North and Baltic Seas contribute to an emission reduction of approx. 20% for entire Europe (Figure 4-1, difference between scenarios 3 and 4).

Consequently, NO_2 and O_3 concentrations related to shipping emissions will be reduced in 2040 compared to 2015 in all of these scenarios. If Tier III regulations (NECA) will be implemented in entire Europe (200 nm zone), reductions in NO_2 from shipping can be expected at western and southern European coastlines, similar to what can be seen in the North and Baltic Seas. As a consequence of Tier III regulations in Europe, ozone concentrations will be reduced in most parts of Europe except the SW North Sea. Here, NO_X emission reductions will lead to increased ozone concentrations because of the complex ozone chemistry that is different in formerly highly polluted regions like the South-West part of the North Sea.

Besides these positive developments resulting from new regulations on NO_X emissions from shipping, non-compliance to Tier III rules as well as exhaust gas cleaning (i.e., SCRs) that do not work properly at low loads (< 30%) may deteriorate NECA achievements. NO_X emissions from ships may be approx. 50% higher when 20% of the ships are non-compliant and SCRs do not work properly at low loads. For this case, the effect of malfunctioning SCRs is more important than that of non-compliance. Harbour cities may be most affected by malfunctioning SCRs because ships run at low loads when they approach the port.

The effect of shipping on PM2.5 will decrease by more than 80% compared to 2015 because of global sulphur regulations, low use of diesel fuels, a new SECA in the Mediterranean Sea and Tier III regulations for NO_X. SECA and Tier III regulations decrease PM2.5 from shipping by more than 90% compared to 2015. However, any non-compliance to new SECA rules in the Mediterranean will increase SO_2 emissions from ships in 2040. STEAM ship emission model results show a 22% increase of SO_X emissions for 6% non-compliance rate.

4.2 Developments until 2050

In another set of emission scenarios, the effects on air quality of new fuel mixes that could be established until 2050 were investigated. Again, the fuel mixes follow the DNV Maritime forecast to 2050 (2020 report) for a scenario with high growth in trade volume, see SCIPPER D4.3 for more details. In this case, prerequisite for the described developments was that no additional regulations concerning air pollutants will be implemented, i.e., North Sea and Baltic Sea are ECAs for nitrogen oxides and sulphur oxides and global sulphur rules apply outside ECAs.

Based on 4 different projections by DNV for high growth in cargo volumes, NO_X emissions will decrease by 0 -30% compared to 2015, depending on fuel mix (Figure 4-2). Highest reductions can be achieved for fuel mix dominated by LNG (DNV fuel mix 5).

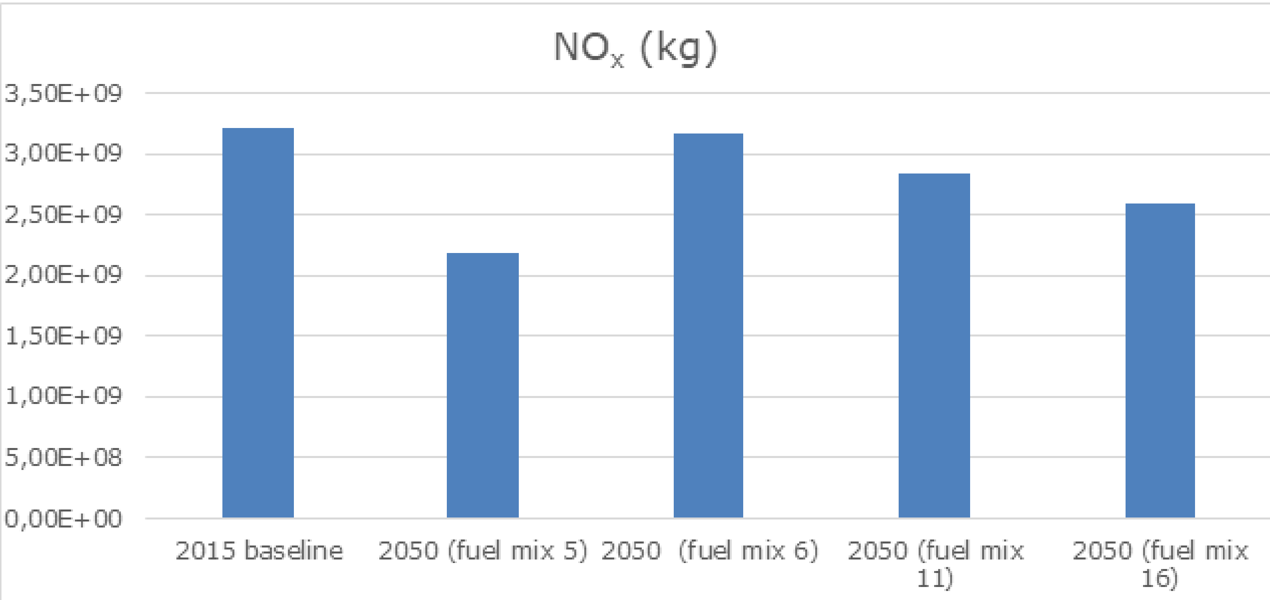

Figure 4-2 Total shipping emissions in 2050 compared to 2015 for CO_2 (top) and NO_x (bottom) for the DNV fuel mix scenarios 5, 6, 11, and 16 (from SCIPPER D4.3).

For a fuel mix with high shares of e-ammonia and LNG (DNV fuel mix 11), IMO goals for CO_2 emissions can be reached, however, emissions of methane and N_2O reduce the climate benefit because these components are strong greenhouse gases. In addition, NO_X emissions will not be much lower than in 2015 for this fuel mix, given the prescribed high growth in shipping. In the case of high ammonia and NO_X emissions from ammonia engines, the relative impact of shipping on NO_2 concentrations will increase in regions outside ECAs. However, total NO_2 from shipping will decrease.

Shipping will also contribute to increased ozone concentrations, with a relative impact of 0-15% on annual average. Highest contributions are expected in the Mediterranean, where solar radiation promotes ozone formation.

Unregulated emissions of NH_3 and NOx from ammonia engines will lead to significant changes in particle chemical composition towards increased formation of ammonium nitrate.

4.3 Conclusions

The SCIPPER ship emission scenarios show the potential of emission reductions of important air pollutants in line with the decarbonization pathways for international shipping. However, large increases in traded volume and consequently in number and size of ships might work against the emission reductions generated by permanent ship renewal and the use of cleaner fuels. New emission control areas for nitrogen and sulphur compounds from shipping will have significant positive effects on further emission reductions until 2040. Non-compliance of up to 20% of the fleet to Tier III rules might increase NO_X emissions from shipping in Europe by 18%, however, the effects of SCRs not working at low loads (below 30% load in scenario 2) will have bigger effects on NO_X emissions with an increase by 29%. Ammonia-driven engines might contribute to reduced GHG emissions from shipping until 2050, if the ammonia is produced from green hydrogen. Ship engines running on ammonia without additional exhaust after-treatment will increase the formation of ammonium nitrate particles, thereby deteriorating air quality in coastal areas.

5 Quality assurance and harmonized reporting of remote ship emission measurements

5.1 Introduction

One of the objectives in SCIPPER was to harmonize measurement procedures, including reporting of measurement uncertainty, for remote sniffer measurements of Fuel Sulphur Content (FSC) and future emission measurements of NO_X and particles. Details on this work are provided in SCIPPER D2.3.

A suite of different sensors was considered, including both optical remote sensing and sniffer type measurements. Since the latter techniques are more mature, most of the focus was on these. Three types of sniffer techniques were included, ranging from compact and light-weight ones on drones, to more complex high sensitivity ones operate from fixed stations or patrol vessels. The conclusions were underpinned by validation studies in SCIPPER D2.3, in which side-by-side measurements of ships were compared to known emissions.

It was concluded in the project that ship emission data should be reported with expanded uncertainty, corresponding to 95 % confidence intervals (CI 95 %). However, for triggering on-board inspections the standard uncertainty, corresponding to 68 % confidence intervals should instead be used, and this uncertainty should be subtracted from the measured results before assessing whether a ship is operating on compliant fuel or not. It is suggested to continue the harmonization work started in SCIPPER D2.3 and develop a full standard for remote measurements of FSC and other emissions.

5.2 Fuel Sulphur Content

From validation measurements it is estimated that the FSC in by-passing ships can be detected with remote measurements with a typical uncertainty between 0.03 to 0.08 % S m/m for ships operating at an FSC level of 0.1 % S m/m, depending on system. Here compact sensors on drones typically have an uncertainty between 0.03 to 0.08 % S m/m while standard fixed sensors, operated on several fixed sites in Europe, have an uncertainty of 0.08 % S m/m, and high-sensitive fixed sensors, based on lasers, have an uncertainty of 0.03-0.05 % S m/m. At higher FSC levels, at 1 % S m/m, the uncertainty (CI 95 %) appears to increase to about 0.2 % S m/m. The accuracy of the remote measurements is generally not high enough to detect ships which are close to the IMO SECA limit, i.e., below 0.15% S m/m. Such levels are often encountered at port for ships that have carried out late fuel switching after having operated on non-compliant fuel. Hence, remote sensors need to be further improved in accuracy and in some cases precision. Nevertheless, the remote methods can easily detect ships which operate fully on non-compliant fuel and can automatically provide ship emission data of up to thousands of ships per month (in busy locations) for ships in real traffic in ports and open sea. Such measurements therefore provide a complement to regular port state control on board fuel sampling and can be used to guide the port-state sampling. Within the SCIPPER project more than 17000 FSC measurements have been collected with high compliance rates (>96%) for all locations (SCIPPER D2.5 and D2.6). Here the poorest compliance was found in the English-channel near to the SECA border.

For SO_2, the standard sniffer sensor, using UV-fluorescence technique, works reasonably well. It has a detection limit of around 2 ppb, but it is cross-sensitive to NO, and it has long response time (t90=30 s) and the typical FSC uncertainty is around 0.08% S m/m. It needs frequent calibrations (bi-monthly) or a combination of less frequent calibrations and the use of a permeation source to validate sufficient performance. Part of the measurement uncertainty is caused by systematic uncertainties causing a negative bias. It is advised that these are further investigated.

A new type of laser sensors tested in SCIPPER D2.2 and D2.3 showed improved performance in terms of detection limit (80 ppt), insignificant cross-sensitivity and response time (1s) and the uncertainty was then improved to 0.05% S m/m, dominated by systematic uncertainties. This sensor does not require calibrations. In SCIPPER D2.3 it was observed that nearly all tested sniffer sensor showed a negative bias which increased with higher relative humidity. The accuracy would improve significantly if these systematic uncertainties could be better understood and corrected for, and it is advised to work with this further. The compact sensors, used on drones, work relatively well and tests in SCIPPER showed that the sensors were relatively stable over time. However, they have cross sensitivity to other species and a rigid quality control scheme is used. In SCIPPER D2.3 the uncertainty varied between 0.03 to 0.08 % S m/m using these sensors and the uncertainty was primarily random with no obvious bias.

5.3 NO_X emissions

The results in SCIPPER D2.3 shows that fuel-mass specific emission of NO_X (g/kg fuel) of by-passing ships can be remotely detected with an estimated uncertainty (CI 95 %) of 8 - 17 g/kg fuel (17 % - 40 %). The measurements can further be converted to brake specific emissions (g/kWh) by multiplying with the specific fuel oil consumption (SFC) and then compared to the IMO legislation. The SFC is ship and engine load dependent and it is estimated that there is an uncertainty of 10-20 % in this value when using data from a ship emission inventory. To improve the accuracy in the calculation of the brake specific emissions (g/kWh), going forward for the purpose of NO_X compliance monitoring, it is advised that the SFC value could be reported to the authorities by the shipping companies or that limits are set as fuel-based emissions g/kg fuel).

In SCIPPER D2.3 it is shown that the fuel-mass specific NO_X emission, and the brake specific one, varies relatively little with engine load, above 50 % engine loads for Tier I and Tier II ships. Since the emission value limit in the NO_X technical code is heavily weighted towards higher engine loads this means that the remote measurements can be used to assess and control this value. For engine loads below 50 % more care must be taken when assessing whether a ship complies with the IMO rules for its specific Tier. For Tier III the already existing implementation, when doing type approval of engines, of a Not-To-Exceed limit (NTE) of no more than 50 % above the applicable NOx emission limit (max 3.4 g/kWh) at any load point means even low loads (<50 %) have a regulatory 'cap' which may be monitored via remote measurements.

In Figure 5-1, results from remote measurements of Tier III ships are shown from different projects, obtained from fixed measurements at the Great Belt bridge (13 ships, Chalmers, SHIPTRASE) and Wedel (1 ship, BSH, SCIPPER) and airborne measurements in Danish and French waters (10 ships, Explicit, French Maritime Authority) and just before port entrance of Rotterdam (73 ships, TNO, SCIPPER and ILenT.). Clearly, a high fraction of the ships corresponds to brake specific NO_X emissions which exceed the Tier III limit with more than 50 %. The figure shows that the NO_X emission of many ships is far above the Tier III level. The sailing conditions represent normal sailing speeds in the ECA areas.

For NO_X, the sniffer sensors work well. Using the chemiluminescence technique in terms of detection limit (0.5 ppb), insignificant cross sensitivity to other species and response time (1s). This sensor requires frequent calibration (bi-monthly) or a combination of less frequent calibrations and the use of a permeation source to validate sufficient performance. It is challenging to calibrate it for NO_2, since this gas is difficult to store and keep stable in gas cylinders. It is advised to test also other types of sensors, for instance optical ones, that can measure both NO and NO_2 directly and do not require field calibrations. The compact sensors, used on drones, may be used but quality assurance is challenging in the corresponding manner as explained in section 5.2 for FSC measurements.

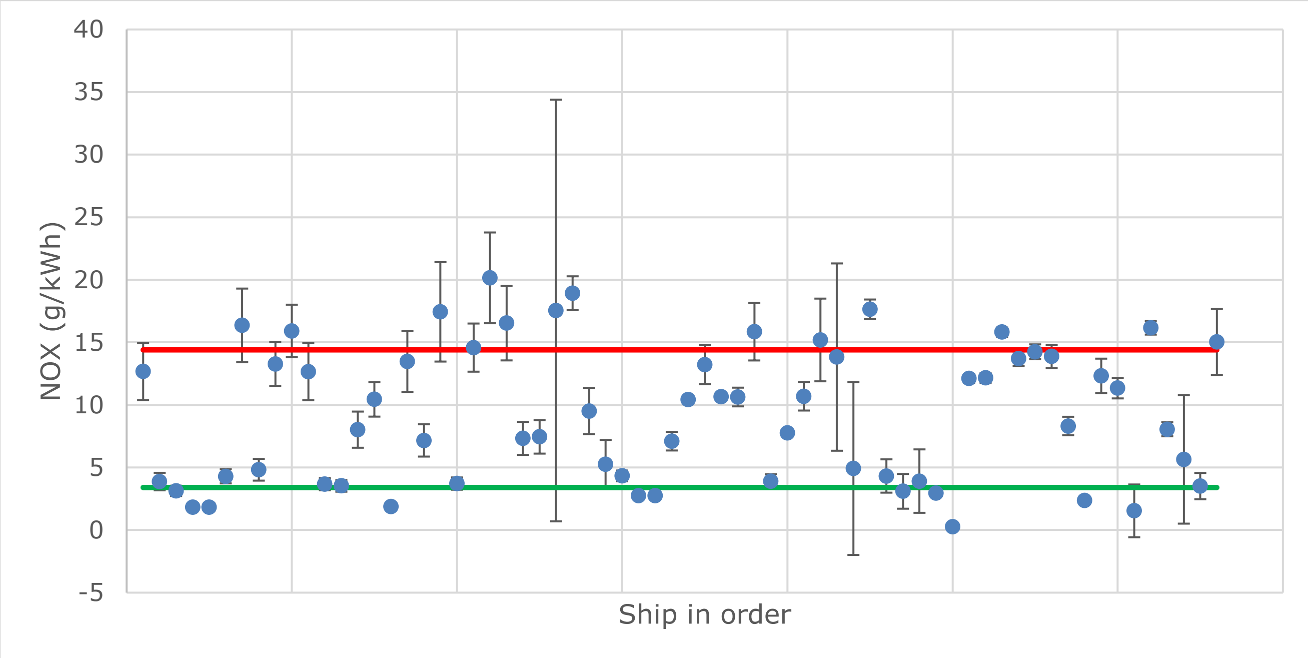

Figure 5-1. Remote sensing observations of Tier III ships keel laid from 2021 within the North European NECA. The measurements were carried out in different projects by fixed remote measurements at Great Belt bridge (13 ships, Chalmers, SHIPTRASE), and Wedel (1 ship, BSH, SCIPPER) and by airborne measurements in Danish and French waters (10 ships, Explicit, French Maritime Authority) and in Rotterdam (73 ships, TNO). The green line shows the Tier III limit value (all ships have slow speed engines); the red line shows the Tier II limit value.

5.4 Particulate matter

In SCIPPER D2.3 fuel-mass specific particulate emissions were derived by side-by-side remote measurements using a suite of different sensors. In contrast to the gaseous species, the particle measurements are difficult to compare since different instruments measure different properties of the particles (such as different ranges of particle sizes and properties like electro-mobility or optical properties of particles). Nevertheless, a satisfactory agreement was found with differences in the derived particle number- and mass concentration ranging from far below 10 % to maximum 35 %.

In general, it was found that 85 % of the emitted particles from vessels had a diameter between 10 and 80 nm and 70 % of the emitted particle mass comes from particles with a size between 40 and 200 nm. It is therefore suggested, for possible future regulations on the reduction of particle emissions from seagoing vessels, that the emission of very small particles should be considered (down to 10 nm and 40 nm for particle number- and mass concentration, respectively). These regulations should set limits such as particle number or particulate mass per kg of fuel burned, to make potential violations easier to detect by remote measurement than for NO_X. To monitor particle emissions, sufficiently sensitively and fast, instruments must be used to cover the above given size ranges. Total particle emission factors were found to be in the range from $0.8 \cdot 10^{16}$ to $1.5 \cdot 10^{16}$ particles/kg fuel on average, but with significantly different emission behaviours for different kind of vessels. However, further studies are needed to validate the found conclusions and to investigate effectiveness of the recommended further actions.

5.5 Other species

Other species which are relevant to monitor by remote measurements includes methane (CH_4) from ships with gas engines as demonstrated by Grönholm et al., (2021), (b) ammonia slip from SCR ships and N_2O from ammonia fueled ships. For measurements of the two latter cases, further instrument development is needed.

5.6 Conclusions

Remote measurements of FSC should be carried out from fixed or mobile platforms (drones, aircraft, patrol vessels) to identify ships running on non-compliant fuel and it is advised that countries develop a strategy for remote monitoring focusing on key maritime locations to support and optimize in-port enforcement efforts. The remote sensing data should be reported to the same database in a common format, including measurement uncertainties. The data can be used directly, taking the reported measurement uncertainties into account, or to guide on board sampling by port state control authorities. The procedure for remote ship emissions measurements, data reporting and quality assurance should be standardized. SCIPPER and other projects have demonstrated that it is feasible and cost effective to use remote sensing to detect ships using non-compliant fuels. The combination of mandatory on-board inspections and remote sensing efforts has produced significant amounts of data on compliance behaviour of ships in and/or near port. Further, compliance levels are high and have increased in the past years. The work within the SCIPPER project has not studied in detail the factors leading to compliant behaviour, nonetheless inspection efforts as driver for the observed compliant behaviour is a plausible explanation. To identify ships that run slightly above the 0.10% limit (>0.13% S m/m) the uncertainties of the remote FSC sensors needs to be decreased, by better understanding of systematic uncertainties and correction for these. However, for ships running at higher FSC levels the sniffer techniques work well. It is advised to continue working with quality assurance and potentially find sensors based on other types of detection principles, such as laser absorption.

Remote measurements of mass-fuel specific NO_X emissions (g/kg fuel) and brake specific emission (g/kWh) should be carried out of ships in real operation from fixed or mobile platforms (drones, aircraft, patrol vessels) to identify ships with non-functioning NO_X abatement systems. Preferably, the monitoring should include low and high engine power or vessel speed situations.

At engine loads above 50 % it is straightforward to detect ships for which the abatement is not in proper operation. In order to simplify future NO_X compliance monitoring by remote measurements also at lower loads it is suggested to establish not–to-exceed limits for different tiers. It would also be useful to introduce as scheme in which individual ships reported their SFC to the authorities or define NTE limits in fuel-based units, which would simplify compliance monitoring and reduce the uncertainty involved in unit conversions.

It is advised to develop emission limits and test method for particles on number of solid particles and possibly in addition PM and BC. There are at present no specific limit for emissions of particulate matter from international shipping. The emissions are supposed to be limited through the fuel sulphur limitations which is an indirect way to regulate particulates. However, we argue that also specific limits are required in view of the high emissions observed when using low sulphur fuels, especially for hybrid fuel oils. In view of the high concentration of volatile particles in emissions from ships' engines we would argue for establishing limits for the number of solid particles in a certain size range. This would also ensure that the types of particles with the highest health risks are regulated. Further, this approach seems to be the most realistic to monitor emissions of particles in the exhaust of ships equipped with scrubbers. However, since particle mass is already regulated for diesel engines used for inland shipping in Europe, this may also be a way forward, and further, the establishment of limits for black carbon being processed within the IMO since decades, would also be a possibility. We suggest that a project to decide on the most suitable ways to regulate particle emissions from shipping is initiated.

Remote measurements of mass-fuel specific CH_4 emissions (g/kg fuel) should be carried out of ships in real operation. Optical Remote sensing techniques should be further developed and validated as a tool for complementary compliance monitoring from aircraft and other applications.

6 Recommendations aimed at improving both monitoring and regulations for enforcement

This chapter formulates recommendations that are based on the work and findings of SCIPPER. These recommendations aim to:

- repair gaps in current legislations
- identify upcoming risk areas based on future technology use in shipping
- improve effectiveness of monitoring and enforcement efforts

For any policy to be implemented it must not only be tested on the societal benefit of the policy but also be tested for the ease with which it can be monitored and enforced. For the latter legislation needs to satisfy the requirements of being enforceable, practical and fraud-resistant.

Enforceable entails that compliance can be both practically determined and also be sanctioned. As an example, the current implementation of NO_X regulations is only in part enforceable. An inspector can determine on-board if the relevant certificates are available and valid. However, to determine if the engine actually operates as stated in the certificate is nearly impossible to verify. This matter is also a considerable limiting factor when deploying remote sensing technologies. The emission constraint is formulated in grams per unit of power, but the power delivered is not known by the remote sensor, only the emission in grams per fuel used. An estimate of fuel efficiency (specific fuel oil consumption) is therefore required to calculate an emission factor, hence limiting the accuracy of remote sensing operations.

The requirement of *practicality* means that executing the task of verification can be performed efficiently and effectively. Given the high intensity of shipping in many ports and shipping lanes, physical on-board inspections are infeasible given the amount of capacity required to perform inspections. Legislation should therefore allow and facilitate for targeting mechanisms and large-scale pre-screening of targets for example through remote sensing. There are several options to make remote sensing more effective. One way would be to implement in legislation an NTE limit in g/kg fuel independent of load (applicable to all engines onboard). Another option would include remote access to all emission sensor data onboard but should for example also include easy access to engine load dependence of the specific fuel oil consumption. Apart from facilitating remote sensing evaluation, it would also increase enforceability as now it is complex to evaluate compliance of individual remote sensing results when NO_X vs load engine specifications are not remotely available.

The requirement of *fraud-resistance* is perhaps best explained through the example of the here recommended installment of on-board sensor systems with the obligation to continuously report measurement data. This must be done in such a way that reported data are true measurements of the emissions and cannot be manipulated or even falsified. Fraud resistance of reported data is why our recommendations include a combination of investment in on-board and remote measurements. While less accurate the fraud-proof remote measurement allows for large scale screening for anomalies in the reported emissions from the on-board systems, that can be followed up by a more detailed investigation in the reported emissions which may be subject to fraud or other issues.

<u>Recommendations on regulations:</u>

- Establish an emission cycle for nitrogen oxides that also reflects operation at low loads typical for port visits and near coast operation. Also implement a test, possibly as Not-to-Exceed limit for in-service conformity and enforcement. Preferably implement such a limit in g/kg fuel which is much less dependent on engine load and easier to enforce.
- Develop emission limits and test method for particles on number of solid particles and possibly in addition particle mass and black carbon.

- Establish emission limit and test method for ammonia – both for SCR systems and when ammonia is used as fuel.
- Establish emission limits for methane - most relevant for liquefied natural gas (LNG) as fuel.
- Establish emission limits for N_2O - most relevant for ammonia as fuel.
- Establish more nitrogen emission control areas (NECAs).

Recommendations on monitoring and enforcement:

- Ships should install sensor systems for NO_X, SO_X and BC.
- Sensor data should be automatically transferred to a monitoring center
- In addition to onboard techniques, use the remote sensing options to detect when fuel with too high sulphur content is used. It is advised that all countries develop a strategy for remote monitoring.
- Remote sensing should further be used to identify ships with non-functioning NOx abatement systems. Ships with high emissions should be subject for onboard checks of NO_X emissions.
- Remote sensing should also be used to exclude ships for fuel sampling and future onboard NO_X compliance checks, develop strategies.
- Establish a not-to-exceed limit for NO_X for remote sensing measurements and also a NTE for simple onboard measurements in the exhaust stack.
- Develop routines for remote sensing measurements, simple onboard data checks and measurements and legal actions.

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