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**TNO report**

**TNO 2018 R11500 vs2 | Final report**

# Emissions of black carbon and particulate matter in dependence of SCR and fuel water emulsion during normal operation of a trailing suction hopper dredger

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| Number of pages | 29 |
| Sponsor | Ministry of Infrastructure and Water management |
| Project name | Emissiemeting schip. Zaaknr. 31141694 |
| Project number | 060.35873 |

# Samenvatting


Een meetcampagne met als onderwerp roet (Black Carbon) emissies is uitgevoerd op een baggerschip met verschillende uitlaatgas nabehandeling systemen, namelijk een SCR de$NO_x$ katalysator en een brandstof water emulsie systeem.
Het hoofddoel van het meetprogramma is het ondersteunen van het Ministerie van Infrastructuur en Waterstaat in beleidsontwikkeling met betrekking uitstoot van stof (PM) en roet door maritieme motoren.

Het meetprogramma richt zich op zowel E3 cyclus emissies (typegoedkeuring test cyclus), als op real world sailing emissions (Real Sailing Emissions).

Het geplande test programma, dat was gepland gedurende het reguliere baggerwerk, kon worden uitgevoerd zonder noemenswaardige obstakels. De gerealiseerde vermogenspunten wijken wel af van de theoretische E3 vermogenspunten. Deze afwijking lag tussen 2 en 8 procentpunt.

Met betrekking het effect van de uitlaatgas nabehandeling systemen op roet uitstoot, wordt het volgende geconcludeerd:

- De SCR de$NO_x$ katalysator heeft geen significant effect op de roet emissies. Dit is in lijn met wat verwacht werd.
- Water toevoeging aan de brandstof heeft een sterk reducerend effect op het geobserveerde Filter Smoke Number (FSN). De reductie correleert positief met de hoeveelheid toegevoegd water. Een reductie van 60-80% bij 10-15% water, oplopend tot 80-90% bij 20-35% watertoevoeging.

Met betrekking het effect van de uitlaatgas nabehandeling systemen op $NO_x$ uitstoot, wordt het volgende geconcludeerd:

- SCR heeft een groot effect op de $NO_x$ uitstoot. Het SCR system reduceerde de $NO_x$ uitstoot met gemiddeld ongeveer 90%. Bij een hoog motorvermogen van 100% is de reductie 85% en bij een laag vermogen van 10% wat representatief is voor baggeren is de reductie 87%.
- Na bijmenging van de dieselbrandstof met water was de gemeten $NO_x$ uitstoot lager voor alle motorlastpunten behalve het lage motorlastpunt met 25% motorvermogen. Het verschil na bijmenging bij de hogere motorlastpunten van 50 tot 100% was ongeveer 9 tot 12% voor de lagere bijmengverhoudingen van 10 tot 15% en 23 tot 42% voor de hogere bijmengverhoudingen van 22 tot 35%.

De metingen in dit project hebben een significante afwijking (onderschatting) van de NOx emissiefactor die gebruikt wordt door de Nederlandse emissieregistratie aangetoond. Daarnaast is ook een belangrijke afwijking (overschatting) van de Black carbon emissieregistratie aangetoond. Omdat het hier om meting op 1 schip gaat wordt aanbevolen om metingen op meer schepen uit te voeren ten einde de emissieregistratie beter te onderbouwen.

Het volgende kan geconcludeerd worden bij het vergelijken van de metingen met de Nederlandse emissieregistratie:

- De gemeten NOx emissies zijn rond de 18% lager dan de waarden van de emissieregistratie.
- De gemeten BC emissies zijn tot 90% lager dan de waarden volgens de emissieregistratie.

Geconcludeerd kan worden dat meer metingen nodig zijn om definitieve conclusies te trekken t.a.v. de emissieregistratie (mede vanwege grote verschillen tussen verschillende schepen).

De metingen in dit project hebben nieuw inzichten gegeven in de mogelijke effectiviteit van de toepassing van SCR en fuel water emulsie met betrekking tot de reductie van NOx en Black Carbon. Deze nieuwe inzichten kunnen worden gebruikt om toekomstige emissie inventarisaties te verbeteren.

# Summary


An emissions measurement program focused on Black Carbon (BC) emissions was conducted on a dredging vessel equipped with several emission control technologies, namely an SCR de$NO_x$ catalyst and fuel water emulsion technology.

The main objective of this measurement program is to support the Ministry of I&W in policy development regarding the marine engine fine particles (PM) and black carbon (EC/BC) emissions.

The program was focused on both E3 cycle emissions (type approval test cycle) as well as on real world emissions (Real Sailing Emissions).

The planned test program, which was integrated in the normal dredging work, could be carried out without major difficulties. There was some deviation of the E3 cycle points on board in comparison to the theoretical E3 cycle points. The power deviation ranged from 2 to 8 percentage point.

Regarding the influence of the emission control technologies on Black Carbon emissions,  the following is concluded:

- SCR has no significant effect on the BC emissions. This is also what could be expected. BC emissions are hardly affected by a catalyst.
- Water addition to the fuel has a large positive effect on the observed Filter Smoke Number (FSN). The FSN reduction correlates positively with the amount of water added to the fuel. The reduction ranges from 60% to 80% with 10-15% water added, up to 80-90% with 20-35% water added.

Regarding the influence of the emission control technologies on $NO_x$ emissions, the following is concluded:

- SCR has a large effect on the $NO_x$ emissions. The SCR system reduced about 90% of the $NO_x$ emissions. At full load, the reduction is somewhat lower (85%). At 10% load, representative for a part of dredging work, the reduction is 87%, which is qualified as very good.
- After emulsification of the fuel with water, the $NO_x$ emissions reduced over all engine load points except for the 25% power point. The difference with the baseline was about 9-12% NOx reduction for the lower water contents of 10-15% and about 23-42% NOx reduction for the higher water contents of 22 to 35%.

The following can be concluded, when comparing the measurements with the Netherlands emission inventory values:

- The measured NOx emissions are some 18% higher than the emissions inventory values.
- The measured BC emissions are up to 90% lower compared to the emissions inventory (EC2.5).

From this observation it can be concluded that more measurements are necessary in order to draw definitive conclusions (also taking into account large vessel to vessel differences).

Insights of this measurement campaign with respect of the effectiveness of SCR and fuel water emulsion on the reduction of NOx and BC can be used to improve future emission calculations.

# Contents

# 1 Introduction

Very little is known about the effects of emission reduction equipment intended for $NO_x$-abatement (SCR and fuel water emulsion) on the emissions of particulate matter and black carbon. It is expected that in the near future $NO_x$-abatement equipment and possibly emulsion technology will be used on vessels operating in IMO designated $NO_x$ emission control areas such as the North Sea.
Recent experience with road transport emission reduction measurements has led to the conclusion that on-board emission measurement is a necessary procedure in order to obtain reliable emission factors that are cardinal to construct a reliable emission inventory.
Before this project, little experience was available at TNO with on-board emission measurements on seagoing vessels. A unique opportunity to perform measurements on-board had emerged; a vessel owner had planned an emission measurement campaign on the effectiveness of SCR and emulsion technology on the measurement already. With this opportunity, substantial reduction of operational effort and data retrieval could be realized.
The measurement procedure was harmonized with the vessel operator in order to obtain data not only from the E3-cycle, but also of a wider variation of power settings during normal operation of the trailing suction hopper dredger. Therefore, it may be expected that the emission factors are representative for medium speed engines fueled by low Sulphur marine gas oil.

## 1.1 Objective of the measurement program

The main objective of the measurement project is to support the Ministry of I&W in policy development regarding marine engine fine particles (PM) and black carbon (EC/BC) emissions.

This includes the following sub-objectives:
- The validation of the currently used PM/BC/EC emission factors, as function of engine load.
- Determination of the influence of the SCR de$NO_x$ catalyst (main route to comply with ECA Tier III requirements).
- Determination of the influence of a fuel water emulsion technology
- Determination of corresponding engine power which is a direct parameter in the emission factor.

During the preparation phase, it was furthermore decided that it would be important to measure the emissions as much as possible during both the official legislative E3 cycle and normal operation of the trailing suction hopper dredger. Both will be used as key input for the emission factors for the hopper dredger, and for input on other vessels with similar engines and fuels.

# 2 Measurement set-up and program

## 2.1 Vessel & fuel

The vessel on which the measurements took place is a trailing suction hopper dredger. The ship is propelled by 2 identical Caterpillar 3516 Tier I engines. The engines are A-rated (unrestricted continuous), with 1491kW MCR, originally installed in the year 2010. Two months before the measurement campaign, the engines were overhauled, and newly revised propellers were installed. These engines are dedicated for the propulsion, for the dredging pump a different engine is used. The configuration is a diesel direct drive. Each propulsion engine powers a fixed pitch propeller, that is placed in a ducted pod. The electrical load of the ship is supplied by separate generators, and no Power Take Off (PTO) is installed for electricity production. Engine pumps are driven by the engine itself.

One of the propulsion engines is equipped with two emission control systems which can be switched on and off independently. The two systems are:
- A SCR de$NO_x$ catalyst.
- A fuel water emulsification system. This system mixes water with diesel fuel on board of the vessel. The level of water addition can be adjusted. In this case in a range from 10% to 35% of the fuel mass.

The fuel used is a 0.1% Sulphur MGO DMA, ISO 8217. A fuel sample has been collected to be analyzed, see annex A for the analytical report.

## 2.2 Parameters and equipment

The monitoring and measurement equipment were installed with 3 different goals (see Figure 1 for sketch of the engine room):
- Long term permanent installation for continuous monitoring:
    - 2 fuel flow meters per engine, for incoming and return fuel flow. Parameter: consumed fuel flow [liters/hour]
    - Shaft torque and rotational speed by strain gauges on the propeller shaft.
    - Automotive electrochemical $NO_x$ concentration sensor after the SCR.
- Temporary installation for gaseous emissions (in accordance with MARPOL Annex VI/ISO 8178) Horiba PG-350:
    - Gives: dry concentrations of $NO_x$, $CO_2$, $O_2$, $SO_2$ and temperature, placed behind the SCR. Emissions calculation of E[g/kWh] according [TNO 2001][1], $NO_x$ correction according MARPOL annex VI/ISO8178.
- Temporary installation for gaseous emissions (in accordance with MARPOL Annex VI/ISO 8178) Ratfisch RS53-T:

[1] [TNO 2001] Verbeek, R.P., Verfahren zur Messung von Abgasemissionen an Bord von Binnenschiffen, TNO report 01.OR.VM.064.1/RV, 30 October 2001.

  - Gives: wet concentrations of THC. Emissions calculation of THC [g/kWh] according [TNO 2001]
- For Particle Matter (PM) and black carbon:
  - AVL 415 smoke meter. The location of the AVL415 switched between after the turbo, and after the SCR. See Figure 1 for an overview of the engine room and the equipment placement. The smoke meter gives the Filter Smoke Number (FSN) for output. This is converted to black carbon mass concentration using a correlation supplied by the manufacturer.
  - Official gravimetric (ISO 8178) partial matter measurements, including both before and after the SCR. This method filters particle matter from diluted exhaust gasses. The filters are weighted before and after the measurement. Sampling time was 10 minutes exactly. The 10 minutes of the gravimetric PM measurement defines the period of the measurements, as shown in Table 2. Emissions calculation of PM [g/kWh] according [TNO 2001].

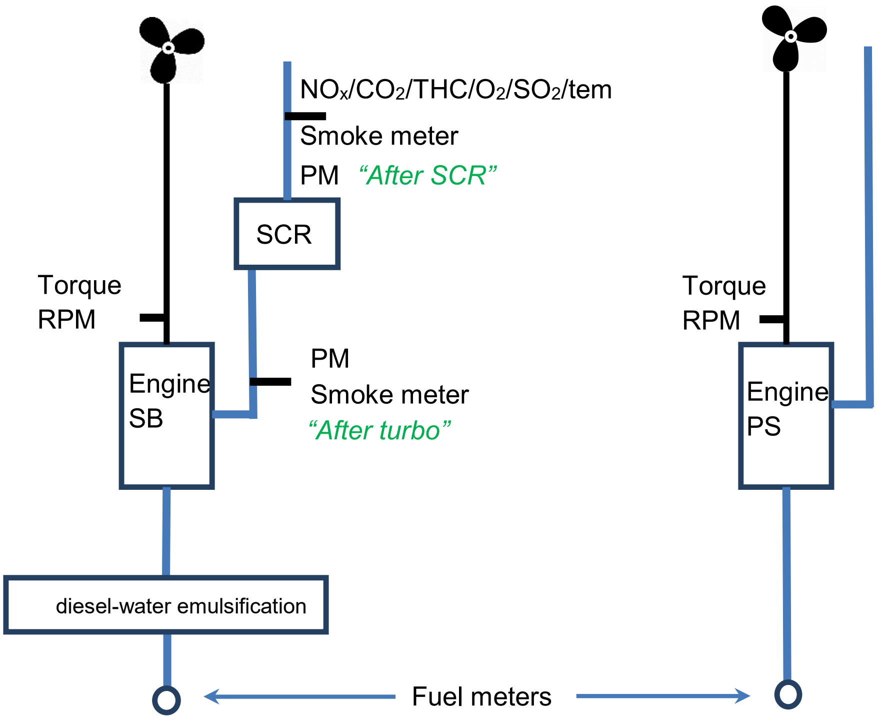


Figure 1: Simplified overview of engines and measurement configurations.

## 2.3 Measurement program

The measurement program was carried out in close cooperation between ship owner, SGS and TNO from 26 to 29 November 2018. The schedule was as follows:
- 26 November: installation of equipment on board of the ship.

- 27 November: baseline measurements and measurements with SCR.
- 28 November: measurements with water addition to the fuel.
- 29 November: removal of equipment from the vessel.

During the measurements, the vessel was working in production. This comes down to dredging, sailing to the dumping area, dumping, and returning. The time distribution was:

- 50 minutes of dredging.
- 50 minutes sailing to dumping area (ship loaded).
- 10 minutes dumping.
- 45 minutes sailing to dredging area (ship empty).

The measurement program was focused on collecting as much as possible data during:

a) The standard ISO8178 E3 test cycle.
b) During normal operation (dredging) conditions.

The weather and sea conditions during the test days (27 and 28 November) were as follows:

Table 1. Weather conditions during the test days. Values taken from KNMI for airport Eelde.

| | 27$^{th}$ of November | 28$^{th}$ of November |
|---|---|---|
| Average temperature | 1.2 Celsius | 3 Celsius |
| Average wind | 2 Bft | 3 Bft |
| Wind direction | 98 degrees (East) | 145 degrees (South East) |
| Sea state (estimated) | 2 | 3 |

The weather conditions were calm with a breeze from the east and south east. Weather conditions in Table 1 were taken from the airport at Eelde, but on the water wind speeds where higher. Nevertheless, waves were small, and swell on the ship was very little.

# 3 Results

## 3.1 Test conditions and sequence

Normally, the E3 cycle is run in a laboratory on a test bed. In that case the theoretical propeller curve can be exactly set by the speed and torque control of the engine dynamometer. In real life margins are built in for rough sea conditions and propeller fouling. Due to these margins, the load or power output at the nominal E3 cycle engine speeds are usually significantly lower than during the exact E3 cycle.

The aim is to perform measurements at the load points defined in the E3 cycle (25%, 50%, 75%, 100% load) plus an additional low load point. The low load point represents the dredging conditions. In practice, the high load points (100% and 75% MCR) were aimed to be reached when the ship was fully loaded, and the low points (50% and 25% MCR) with an empty ship. Additional low load points (10-20%) were obtained during dredging. The ship is navigated by the boat master with the engine speed (rpm), therefore the E3 power settings were not exactly matched, but the E3 RPM settings were approximately reached. Measurements commenced when rpm, exhaust gas temperatures and BC emissions were stable.

With respect to the realized PM and BC measurements (Table 2), the following groups of measurements are distinguished:

**Number 1-9:** PM and BC after the turbo for the loads points, both with a full and empty ship. For measurements 6-10 the SCR was switched on, but since the ship was sailing with an empty barge, black carbon measurements were done after the turbo. The reason for this is to obtain points above and below the propeller curve. This is reflected in the spread of the power values at above 1400rpm in Figure 6. Comparing maximum engine load in number 1 and number 8, the difference is 41 rpm, and the FSN numbers 0.128 and 0.141, respectively.
**Number 10:** During this measurement the smoke meter was moved from after turbo to after SCR.
**Number 11-15:** PM and BC after the SCR. The SCR was tuned manually to obtain maximum reduction of $NO_x$, and reach Tier III $NO_x$ emissions.
**Number 16-28:** PM and BC after the turbo with water addition switched on. The water addition level varies between the different measurement. Every measurement was proceeded by a baseline measurement for BC and gaseous emissions. With the fuel water emulsion technology switched on, the starboard engine cannot reach 100% MCR. The maximum power is reduced by the percentage of water in the fuel.

Table 2: Chronological overview of achieved measurements conditions. Values are averaged over a period of 10 minutes, which is required for the PM measurements. FSN values are based on 6 second sample time of AVL415.PM and black carbon results. Corresponding figures for engine speed and power chronologically in Figure 2 Figure 3 Figure 4 Figure 5

| Start | Number | Activity | Duration [s] | Load point | Avg Power [kW] | Speed [rpm] | Engine Speed [%] | SCR on/off | Water content [%] | FSN location | Gas location | FSN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 27-11-2018 09:22 | 1 | full | 600 | 100 | 1459 | 1504 | 94 | off | | Post Turb | Post SCR | 0.128 |
| 27-11-2018 09:56 | 2 | empty | 600 | 50 | 810 | 1248 | 78 | off | | Post Turb | Post SCR | 0.185 |
| 27-11-2018 10:10 | 3 | empty | 600 | 25 | 421 | 1004 | 63 | off | | Post Turb | Post SCR | 0.308 |
| 27-11-2018 10:37 | 4 | dredging | 600 | 10 | 149 | 650 | 41 | off | | Post Turb | Post SCR | 0.19 |
| 27-11-2018 11:25 | 5 | full | 600 | 75 | 1242 | 1425 | 89 | off | | Post Turb | Post SCR | 0.115 |
| 27-11-2018 11:45 | 6 | full | 600 | 50 | 844 | 1264 | 79 | on | | Post Turb | Post SCR | 0.177 |
| 27-11-2018 11:58 | 7 | full | 600 | 25 | 424 | 993 | 62 | on | | Post Turb | Post SCR | 0.306 |
| 27-11-2018 12:51 | 8 | empty | 600 | 100 | 1476 | 1545 | 97 | on | | Post Turb | Post SCR | 0.141 |
| 27-11-2018 13:07 | 9 | empty | 600 | 75 | 1197 | 1430 | 89 | on | | Post Turb | Post SCR | 0.126 |
| 27-11-2018 13:37 | 10 | dredging | 600 | 10 | 146 | 650 | 41 | on | | change | Post SCR | n.a. |
| 27-11-2018 14:21 | 11 | full | 600 | 100 | 1468 | 1509 | 94 | on | | Post SCR | Post SCR | 0.13 |
| 27-11-2018 14:33 | 12 | full | 600 | 75 | 1252 | 1450 | 91 | on | | Post SCR | Post SCR | 0.115 |
| 27-11-2018 15:29 | 13 | empty | 600 | 50 | 813 | 1255 | 78 | on | | Post SCR | Post SCR | 0.189 |
| 27-11-2018 15:45 | 14 | empty | 600 | 25 | 411 | 984 | 62 | on | | Post SCR | Post SCR | 0.331 |
| 27-11-2018 16:16 | 15 | dredging | 598 | 10 | 140 | 649 | 41 | on | | Post SCR | Post SCR | 0.149 |
| 28-11-2018 09:20 | 16 | empty | 600 | 25 | 441 | 1004 | 63 | on | 0 | Post Turb | Post SCR | 0.306 |
| 28-11-2018 09:46 | 17 | empty | 600 | 25 | 430 | 988 | 62 | off | 15 | Post Turb | Post SCR | 0.105 |
| 28-11-2018 10:05 | 18 | empty | 600 | 25 | 442 | 1004 | 63 | off | 30 | Post Turb | Post SCR | 0.04 |
| 28-11-2018 11:18 | 19 | full | 600 | 50 | 854 | 1256 | 79 | off | 0 | Post Turb | Post SCR | 0.208 |
| 28-11-2018 11:35 | 20 | full | 598 | 50 | 847 | 1251 | 78 | off | 15 | Post Turb | Post SCR | 0.057 |
| 28-11-2018 12:16 | 21 | full | 600 | 50 | 850 | 1260 | 79 | off | 35 | Post Turb | Post SCR | 0.018 |
| 28-11-2018 12:52 | 22 | empty | 600 | 25 | 444 | 1004 | 63 | off | 20 | Post Turb | Post SCR | 0.062 |
| 28-11-2018 13:12 | 23 | empty | 600 | 50 | 848 | 1259 | 79 | off | 25 | Post Turb | Post SCR | 0.022 |
| 28-11-2018 14:50 | 24 | full | 600 | 75 | 1267 | 1426 | 89 | off | 0 | Post Turb | Post SCR | 0.138 |
| 28-11-2018 15:29 | 25 | full | 598 | 75 | 1208 | 1429 | 89 | off | 10 | Post Turb | Post SCR | 0.045 |
| 28-11-2018 16:00 | 26 | full | 600 | 75 | 1190 | 1430 | 89 | off | 22 | Post Turb | Post SCR | 0.023 |
| 28-11-2018 16:19 | 27 | empty | 600 | 75 | 1296 | 1478 | 92 | off | 16 | Post Turb | Post SCR | 0.022 |
| 28-11-2018 17:29 | 28 | full | 600 | 80 | 1404 | 1477 | 92 | off | 0 | Post Turb | Post SCR | 0.129 |

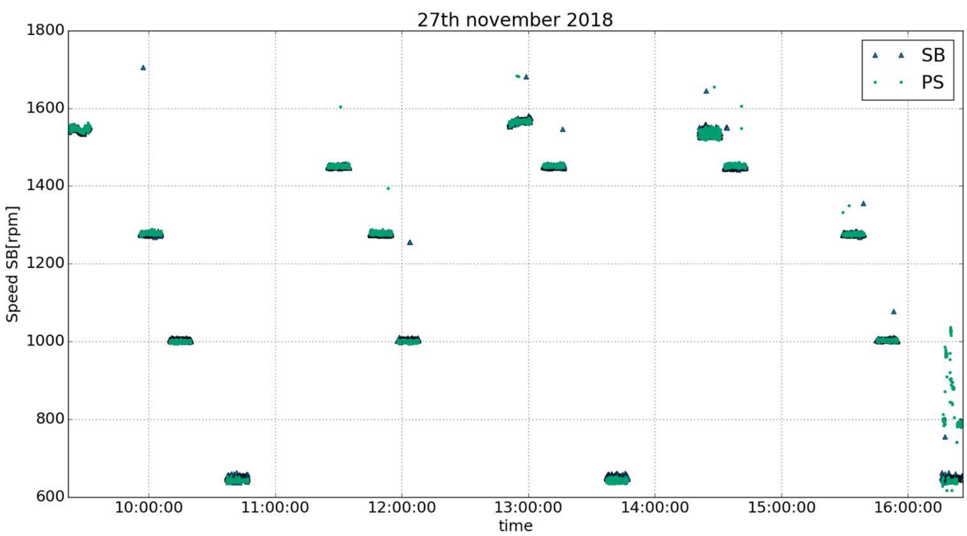


Figure 2: Engine speed for both engines on 27th November 2018. Minimum speed was 650 rpm, maximum around 1575. Engine rated speed is 1600 rpm. On the last measurement, the varying port side engine speed was needed for maneuvering, the starboard engine stayed constant at 650 rpm.

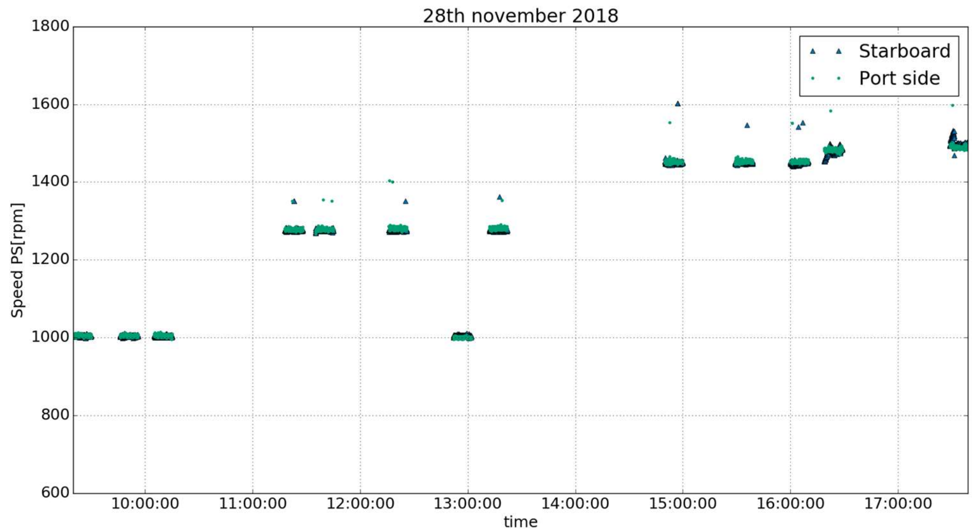


Figure 3: Engine speed for both engines during 28th November 2018. Minimum speed was 1080 rpm, maximum around 1575. Engine rated speed is 1600 rpm.

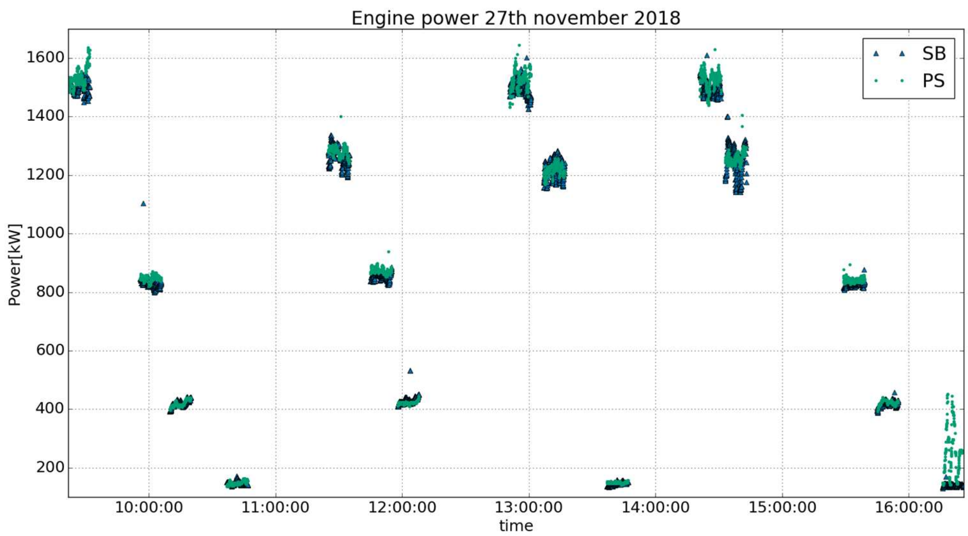


Figure 4: Measured shaft power for both propulsion engines during the 27th of November 2018.

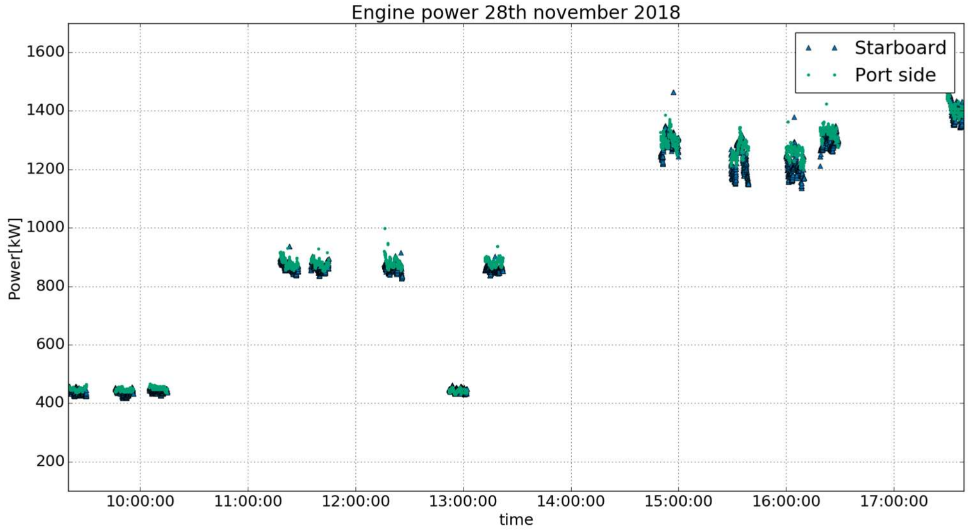


Figure 5: Measured shaft power for both propulsion engines during the 28th of November 2018.

Power values were obtained from the torque meter on the propeller shaft. The installed equipment delivers data at a frequency of 0.5 Hz. Because the torque measurements had a frequent variation of 15% around a clear mean value, a moving average of 1 minute was taken to smooth out the deviations (resulting power in Figure 4 and Figure 5). As a feasibility check, the registered shaft powers are shown in Figure 6. The propeller and maximum power curve are shown as given by the manufacturer for this specific engine.

In general, the observed powers are above the propeller curve, for both sailing with a full and empty barge. This may be caused by fairway conditions and/or a heavy running propeller. At high engine speeds, the delivered power overshoots the max power curve. During the measurement campaign, it was noticed that the engine management system showed a fuel consumption of 369L/h to 383 L/h, while at 100% MCR a fuel consumption of 359.6 L/h is maximum. An overshoot of the 100% MCR limit may have occurred here.
Unfortunately, these fuel consumptions cannot be verified with the fuel meters, because these measurements were discarded because of suspected imprecision of the readings. Large differences up to 30% from the expected fuel consumption from the engine specification charts and between the 2 engines where observed.
In conclusion, the shaft torque and speed measurements seem consistent and accurate and are used in this report as realized power for the E3 cycle.

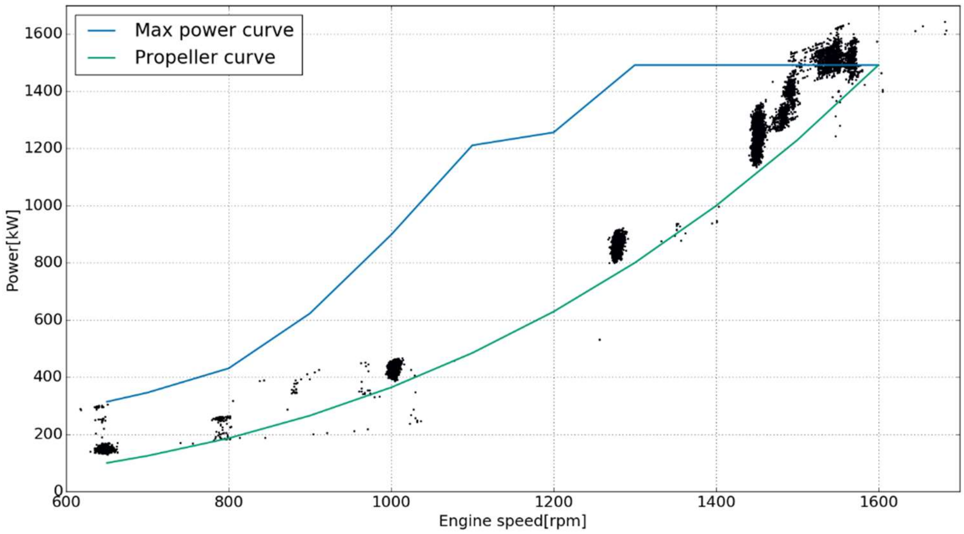


Figure 6: Shaft power measurements for at points in Table 2. All observations are found above the propeller curve (ignoring incidental outliers). During the tests, 100%MCR power was obtained before maximum rpm was reached. This may be explained by a heavy running propeller.

In Table 3 the theoretical and achieved load (power) percentages are shown. The table shows that the deviations range from 2 to maximum 8 percent point. It is expected that with a Tier 1 engine, this does not lead to significant differences in emission levels, because these engines generally have smooth emission maps.

Table 3. Achieved average test conditions of E3 test cycle

| | Official E3 power | Achieved E3 power points | Official E3 rpm | Achieved E3 rpm |
|---|---|---|---|---|
| 1 | 100% | 98% | 100% | 92% |
| 2 | 75% | 83% | 91% | 78% |
| 3 | 50% | 57% | 80% | 81% |
| 4 | 25% | 30% | 63% | 63% |

The following can be concluded regarding the achieved test conditions, (on board) equipment and test program:

- There was some deviation of the E3 cycle points on board in comparison to the theoretical E3 cycle points. The power deviation ranged from 2% to 8%.
- The on-board fuel meters showed large deviations compared to values which should be expected in relation to the engine power level. For that reason, shaft power measurements are used instead of fuel consumption for data processing.
- The planned test program could be carried out without major difficulties.

## 3.2 Baseline emissions

### *3.2.1 E3 cycle results – engine out emissions*

The table below shows the FSN results during the ISO8178 E3 test cycle. It shows also how well the E3 cycle could be approached on the ship. The NOx engine out results are presented in section 3.3.2.

Table 4. Baseline - engine out - FSN of starboard engine

| mode | Power % E3 | Power actual % | Power [kW] | FSN | BC from FSN [mg/m$^3$] | BC from FSN [mg/kWh][2] |
|---|---|---|---|---|---|---|
| 1 | 100% | 98% | 1460 | 0.128 | 1.6 | 9 |
| 2 | 75% | 83% | 1238 | 0.115 | 1.5 | 8 |
| 3 | 50% | 57% | 850 | 0.185 | 2.4 | 13 |
| 4 | 25% | 30% | 447 | 0.308 | 4.2 | 22 |
| Additional | 80% | 80% | 1193 | 0.129 | 1.7 | 17 |
| Additional | 10% | 10% | 149 | 0.190 | 2.5 | 9 |

The FSN ranges from about 0.115 FSN at high load to 0.308 FSN at low load. The FSN are also shown in gravimetric BC density in mg/m$^3$ in the exhaust gasses. The manufacturer provides the following empirical formula for this:

BC concentration: beck (mg/m$^3$) = 4.95 FSN exp(0.38*FSN) / 0.405.

The BC density is compared with the values presented in Aakko-Sakso 2017[3]. This corresponds quite well. Aakko-Sakso shows BC densities of about 2 mg/m$^3$ at 75% load and about 12 mg/m$^3$ at 25% load. This was basically for a medium speed engine using the ECA 0.1% fuel (MDO DMB). So, for this 'high speed' engine, the values are somewhat lower.

### *3.2.2 Emissions during dredging cycle*

A typical dredging cycle consists of dredging, transit loaded, dumping and transit empty. The emissions of the starboard propulsion engine during those four load points were measured in order to get a good insight of the emissions during a normal dredging cycle. The dredging pump, sand pump and generator sets were not measured and are not considered here. In general, the dredging cycle depends on the type of sediment being dredged, the waterway conditions and the distance to the dumping area. The dumping time and emissions depend on the dumping method, where opening the bottom doors is fast, while dumping by pumping to the shore costs more time and fuel for the pump engine.

During this measurement campaign, sludge was dredged in a fairway, and dumping was performed by opening the bottom doors. In table 5, the power levels and the

[2] [TNO 2001] Verbeek, R.P., Verfahren zur Messung von Abgasemissionen an Bord von Binnenschiffen, TNO report 01.OR.VM.064.1/RV, 30 October 2001.

[3] P. Aakko-Saksa, et.al. „Black carbon emissions from a ship engine in laboratory (SEA-EFFECTS BC WP1)," VTT-R-02075-17, 2017.

FSN emissions are shown during a typical dredging cycle for this dredging project. It should be noted that the dredging cycle is very dependent on the conditions. Main factor for transit time is the distance to the dumping area, currents and shallowness of the waterway. Emissions during the dredging mainly come from the separate engines driving the dredging pump and sand pump.

Table 5. Power (load) and FSN emissions of the propulsion engines during a typical dredging cycle. Emissions of sand pump not measured.

| mode | Power % | Duration (min) | Power main propulsion engines (kW) | FSN starboard engine |
|---|---|---|---|---|
| Dredging | 10 | 50 | 300 | 0.19 |
| Transit loaded | 80 | 50 | 2400 | 0.115 |
| Dumping | 10 | 10 | 300 | 0.19 |
| Transit empty | 65 | 45 | 2000 | 0.155 |
| Weighted Average | 49 | 155 | 1470 | |

## 3.3 Effect of emission control technologies on emissions

The propulsion engine was equipped with the two emission control technologies which could be switched on and off independently. In the table below, the FSN (Filter Smoke Numbers) are presented for four conditions:

- Baseline engine out (or post turbo).
- With SCR (post SCR).
- With 10% to 15% water added to the fuel (medium level).
- With 20% to 35% water added to the fuel (high level).

### *3.3.1 Effects on black carbon emissions*

The effects of the emission control technologies SCR and fuel water emulsion on the FSN are presented in Table 7.

Table 6. Influence of SCR aftertreatment and water emulsion on the FSN emissions during the E3 cycle

| Mode | Power % | Power actual % | Baseline / engine out | With SCR | water 10%-15% | water 20%-35% |
|---|---|---|---|---|---|---|
| 1 | 100% | 98% | 0.128 | 0.130 | - | |
| 2 | 75% | 83% | 0.115 | 0.115 | 0.045 | 0.023 |
| 3 | 50% | 57% | 0.185 | 0.189 | 0.057 | 0.018 |
| 4 | 25% | 30% | 0.308 | 0.331 | 0.105 | 0.041 |
| Additional | 80% | 81% | 0.129 | | 0.022 | |
| Additional | 10% | 9% | 0.190 | 0.149 | | |

The results from Table 6 are graphically presented in figure 7.

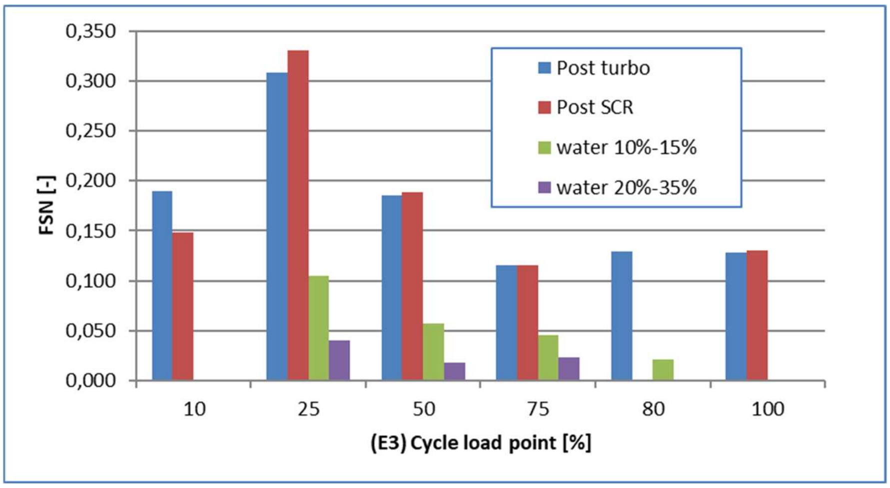


Figure 7. Influence of SCR aftertreatment and water emulsion on the filter smoke number(FSN) during the E3 cycle

Looking at these results, the following can be observed:

The FSN is the highest at 25% load and is reduced when going to higher loads. At 75% to 100% load, the FSN is about threefold lower than at 25% load. These are quite normal results. With total / gravimetric PM emissions, we normally see an increase at low load.  It should be noted that the exhaust flow rate at 25% is about a factor 3 lower than at 75% load, so the total BC emissions in terms of mass per hour would be about constant.

Regarding the influence of the emission control technologies, the following can be noted:

- SCR has no significant effect on the BC emissions. This is also what was expected. BC emissions are hardly affected by a catalyst. It can have some positive influence on the gravimetric PM emissions, but then the non-BC part, such as OC (organic carbon) is then reduced.
- Water addition causes large reductions of the observed Filter Smoke Number (FSN). The FSN reduction correlates positively with the amount of water added to the fuel. The reduction ranges from 60% to 80% with 10-15% water added, up to 80-90% with 20-35% water added.

The FSN can be translated to a gravimetric eBC (equivalent BC) density in the exhaust gasses. The manufacturer provides the following empirical formula for this:

BC concentration:  eBC (mg/m$^3$)  =  4.95 FSN exp(0.38*FSN) / 0.405

The results of this calculation are shown in figure 8.

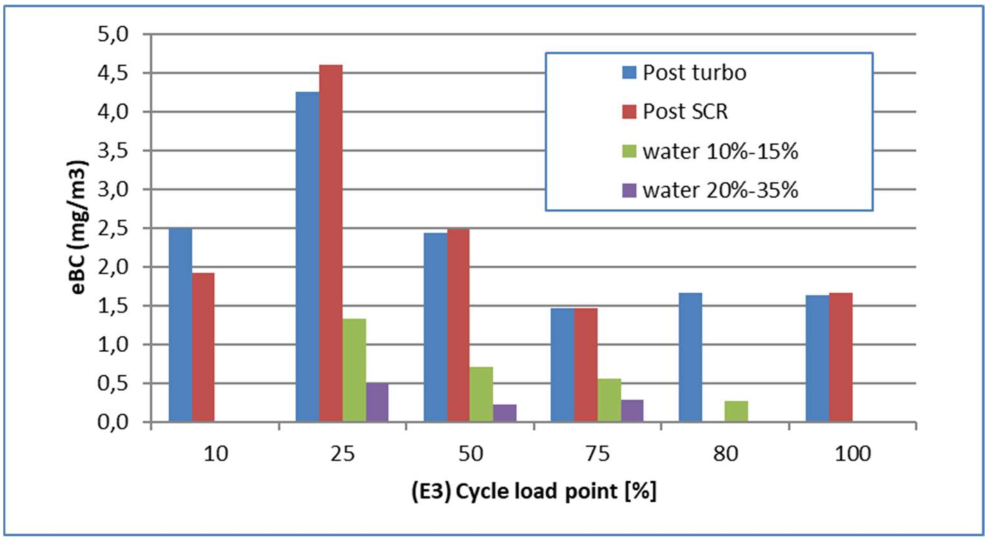


Figure 8. Influence of SCR aftertreatment and water addition on the eBC emissions during the E3 cycle

### 3.3.2 *Effect of SCR emission control technology on $NO_x$ emissions*

NOx emissions were measured after the SCR with the SCR inactive and inactive Presented $NO_x$ emissions in Table 7 are not corrected for humidity and temperature with exception of the 'E3 corrected' NOx emissions .

Table 7: results of $NO_x$ emissions measured before the SCR (engine out) and after the SCR (with SCR) in g/kWh over the tested mode points and as weighted over the E3 cycle.

| Mode | Power % | **$NO_x$ [g/kWh] Baseline, SCR off** | $NO_x$ [g/kWh] with SCR | Difference with baseline [%] |
|---|---|---|---|---|
| 1 | 100% | **10.1** | 1.5 | -85% |
| 2 | 75% | **10.3** | 1.1 | -89% |
| 3 | 50% | **11.3** | 1.0 | -91% |
| 4 | 25% | **10.6** | 0.8 | -92% |
| E3 | | **10.3** | 1.2 | -89% |
| E3 corrected[1] | | **9.5[1]** | 1.1 | -89% |
| E3 Marpol Annex VI $NO_x$ limit | | **10.3 (Tier 1)** | 2.1 (Tier 3) | |
| Additional | 80% | **9.4** | 0.9 | -90% |
| Additional | 10% | **15.1** | 2.0 | -87% |

[1]Corrected for humidity and temperature according IMO.

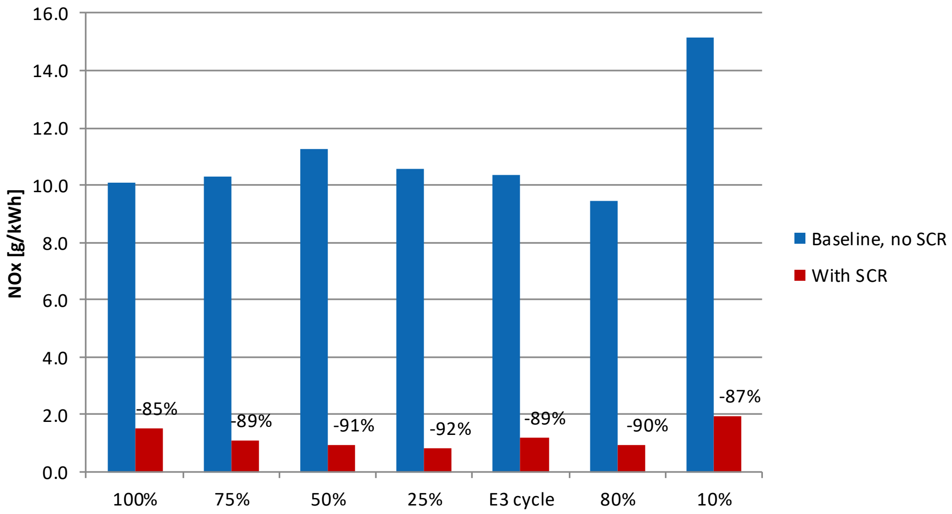


Figure 9: results of $NO_x$ emissions measured without SCR (no reagent dosage) and with SCR active, in g/kWh over the tested mode points and as weighted over the E3 cycle. $NO_x$ emissions results are not corrected for temperature and humidity.

Looking at these results, the following can be observed:

- The engine out $NO_x$ emissions level is around 10 g/kWh and increases at the lowest measured engine load point. This is as expected. At a low engine power, the effective work of the engine decreases until at idle operation effectively no work is produced, while $NO_x$ is still emitted.
- The engine out corrected $NO_x$ emissions level over the E3 cycle is 9.5 g/kWh and lies just below the Marpol Tier 1 limit of 10.3 g/kWh that is applicable for the tested engine.
- SCR has a large effect on the $NO_x$ emissions. The $NO_x$ emissions after the SCR are 85% to 92% lower. At the highest load point (100%) the $NO_x$ emissions is 85% lower. In practice, the given vessel almost never sails at this full load point. Remarkably, also at the lowest power point, 10% power, the $NO_x$ conversion is very good with a reduction of 87%. This is usually a difficult point for $NO_x$ conversion, due to the lower exhaust gas temperatures.
  The reagent dosage (urea water solution) amount was adjusted such that about 90% of the $NO_x$ emissions would be reduced for this engine type. The results are well in line with this.

### 3.3.3 *Effect of fuel water emulsion on $NO_x$ emissions*

Emissions were measured with different levels of water emulsion, i.e. water content added to the fuel. The water emulsion system supplier defined several water contents to be used for the different load points of the engine. For these load points the consecutive water contents was increased from zero (baseline) stepwise to a certain maximum that is defined by the supplier for each mode point. This enabled sampling emissions under comparable sailing conditions, while water content was changed stepwise and allows a more accurate comparison of the different settings of the water content. For each load point emissions of $NO_x$ and FSN were allowed to stabilize in response to the different water content of the preceding point.

Table 8: results of $NO_x$ emissions measured without water and with different levels of water content emulsified with the diesel fuel over the tested mode points and as weighted over the E3 cycle.

| E3 Mode | Power [%] | **$NO_x$ Baseline pre water test point [g/kWh]** | $NO_x$ @ 10% water [g/kWh] and difference with baseline | $NO_x$ @ 15% water [g/kWh] and difference with baseline | $NO_x$ @ 22 and 25% water [g/kWh] and difference with baseline | $NO_x$ @ 35 and 30% water [g/kWh] and difference with baseline |
|---|---|---|---|---|---|---|
| 1 | 100 | **n.a.** | Not possible due to decrease of maximum power due water addition to the fuel | | | |
| Additional | 80 | **9.4** | | 8.3/-12% | | |
| 2 | 75 | **9.7** | 8.8/-9% | | 7.4/-23% | |
| 3 | 50 | **10.9** | | 9.6/-12% | | 6.3/-42% |
| 4 | 25 | **9.8** | | 9.9/1% | 10.7/10% | 11.7/20% |

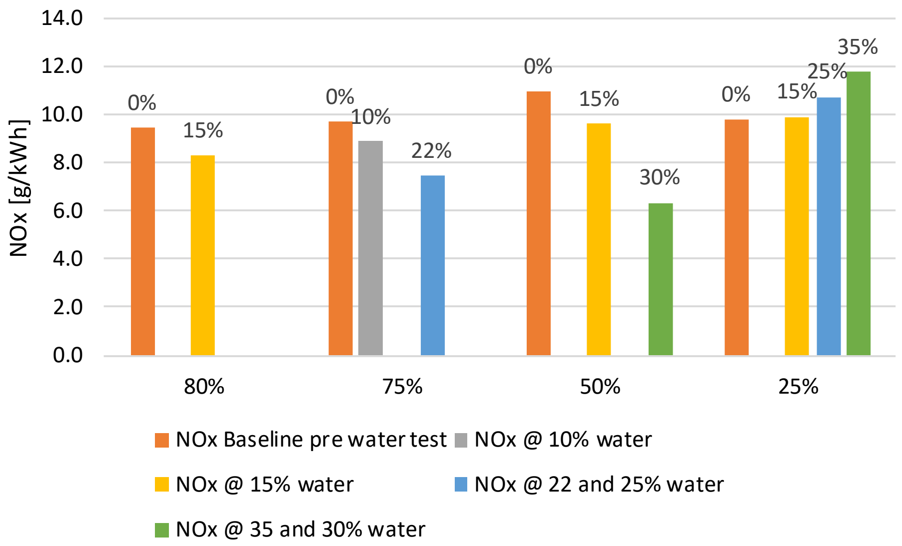


Figure 10: results of $NO_x$ emissions measured without water and with different levels of water content emulsified with the diesel fuel over the tested mode points.

The effect of fuel-water emulsion on $NO_x$ emissions are as follows:

– After water addition, lower $NO_x$ emissions were observed for all but the 25% engine power setting. The highest reduction of the $NO_x$ emission was observed with the highest water content. For the 25% power the $NO_x$ emissions seem to increase. Differences (reductions) were observed of 9 to 12% for the water content in the fuel of 10-15% and 23 to 42% $NO_x$ reduction for the two load points where the water content was higher (22 and 35%). The results are in line with the rule of thumb, that each percent of water addition leads to about 1% $NO_x$ reduction.

# 4 Application of results for Netherlands emission inventory

Below the measurement results of the dredging vessel are compared to the values according to the Netherlands emission inventory.

## 4.1 NOx emission factor

A comparison was made between the measured NOx baseline emission factors (Table 9 column C) with emission factors that are applied by the current Netherlands emission inventory (Table 9 column A).

Table 9 NOx Emission factors measured (column C) compared to emission factors applied in the Netherlands emission inventory (column A).

| power% | correction factor | A<br>EF inventory<br>(10.3*0.87)<br>* correction factor<br><br>(g/kWh) | B<br>EF limit<br>(10.3)<br>*correction factor<br><br>(g/kWh) | C<br>EF measured dredging vessel<br>(g/kWh) | Measured/used with base correction(0.87) | Measured/used w.o. base correction |
|---|---|---|---|---|---|---|
| 10% | 1.34 | 12.0 | 13.8 | **15.1** | 26% | 10% |
| 25% | 1.06 | 9.5 | 10.9 | **10.6** | 12% | -3% |
| 50% | 1 | 9.0 | 10.3 | **11.3** | 26% | 10% |
| 75% | 0.98 | 8.8 | 10.1 | **10.3** | 17% | 2% |
| 80% | 0.97 | 8.7 | 10.0 | **9.4** | 8% | -6% |
| 100% | 0.97 | 8.7 | 10.0 | **10.1** | 16% | 1% |
| Average difference% | | | | | 18% | 2% |

From Table 9, it can be concluded that the emission factors of the current Netherlands emission inventory underestimate the emission factors of the measured vessel with about 18%. The basic NOx emission factors are derived from a big number of test values coming from EIAPP certificates of marine vessels with medium/high speed engines. From the analysis of this certificates it was concluded that the average emission factor could be estimated 87% of the emission limit values of IMO Tier I. From the measurements of this particular vessel it can be concluded that when not using the correction of 87% of the limit value an emission factor (Table 9 column B) results that on average is rather close to the measured values. Because this measurement concerns only one value it is not possible to conclude that current emission factors in the Netherlands emission inventory are too low. However the results of the measurements suggest that more measurements are needed to get a better picture of the average situation.

## 4.2 BC emission factor

A comparison was made between the measured BC baseline emission factors (Table 10 column C) with emission factors of EC2.5 that are applied by the current Netherlands emission inventory (Table 10 column A). The definition of Black carbon and EC (elementary carbon) is different. However it may be expected that the results could be very close.

Table 10 eBC Emission factors measured (column C), compared to EC2.5 emission factors applied in the Netherlands emission inventory (column A).

| power% | correction factor | A<br>EF inventory (200) (EC2.5) (33.25%) of PM10<br>*<br>correction factor<br>(mg/kWh) | B<br>EF POSEIDON (BC) (20%) of PM10<br>*<br>correction factor<br>(mg/kWh) | C<br>BC from FSN measured dredging vessel<br><br>(mg/kWh) |
|---|---|---|---|---|
| 10% | 1.63 | 108 | 65 | **9** |
| 25% | 1.12 | 74 | 45 | **22** |
| 50% | 1.01 | 67 | 40 | **13** |
| 75% | 0.98 | 65 | 39 | **8** |
| 80% | 0.98 | 65 | 39 | **17** |
| 100% | 0.97 | 65 | 39 | **9** |

From Table 10, it can be concluded that BC emission factors measured on the vessel (Table 10 column C) are very low compared to emission factor as applied by the Netherlands emission inventory (Table 10 column A). It is known that PM and BC emission factors show large variations between different vessels. The measured values are 50% to 90% lower.
The emission factors within the Netherlands emission inventory are estimated by taking 33% of the PM emission factors. The PM emission factors measured within this measurement campaign are not available in the current version of this report. Within the TNO POSEIDON model (used by PBL for prognosis of future shipping emissions) BC is estimated by taking 20% of the non-Sulphur part of PM-emission. Using the relations between BC and PM to estimate PM-emissions the PM-emission could be estimated between 50 and 100 mg/kWh, which can be rated as a low value for this type of engine.
No conclusion about eBC emission factors used by the Netherlands emissions inventory can be drawn, since the eBC measurement concerns only one vessel.

## 4.3 Implications of the effectiveness of SCR and fuel water emulsion

Below an overview is given regarding the Implications of the effectiveness of SCR and fuel water emulsion with respect of the Netherlands emission inventory.

a. Future NOx emissions and SCR

The measurements have shown that SCR is very well able to reduce emission factors of NOx below the IMO tier III emission limit value covering the whole power range of the measured vessel. From this observation it can be concluded that proper installation and operation of SCR (in future tier III certified vessels with SCR) can reduce NOx emissions as may be expected from the emission limit values. However it is known that proper installation and operation may not always be practiced. Therefore it is advised to monitor actual emissions of future tier III certified vessels.

b. Future BC emissions and SCR

From the measurement it is clear that no BC-reduction may be expected from SCR equipped vessels in the future

c. Future NOx emissions and fuel water emulsion

It is not to be expected that fuel water emulsion will be applied on a large scale in the near future. Implications for the emission inventory are not to be foreseen. When this technique will be applied on significant scale, the rule of the thumb of 1% reduction of NOx by 1% of water may be applied.
Possibly fuel water emulsion technique may be combined with EGR on slow speed engines to comply with tier III. In such case combined effects are to be taken into account.

d. Future BC emissions and fuel water emulsion

It is not to be expected that fuel water emulsion will be applied on a large scale in the near future. Implications for the emission inventory are not to be foreseen. When this technique will be applied on significant scale the BC or EC emission factors should possibly be adapted according to the percentage of water that will be added (depending on combined effects of EGR and fuel water emulsion).

# 5 Conclusions

An emissions measurement program was conducted to determine the level of the Black Carbon (BC) emissions, Particulate Matter emissions and $NO_x$ emissions on a dredging vessel. Also, the programme aimed to determine the effect of two emission control technologies on the tail pipe emissions, namely an SCR de$NO_x$ catalyst and a fuel water emulsion technology. For the programme E3 cycle (type approval test cycle) load points as well as a few additional load points were measured to determine real world emissions (Real Sailing Emissions).

The planned test program was integrated in the normal dredging work and could be carried out without major difficulties. There was some deviation of the E3 cycle engine load points on board in comparison to the theoretical E3 cycle points. The power deviation of those points ranged from 2 to 8 percentage point.

For the main propulsion engine of the dredging vessel, the engine out $NO_x$ emissions are around 10 g/kWh for the E3 load points (25%-100% load). At 10% load, which is representative for certain part of the dredging cycle, the specific NOx emissions increase to about 15 g/kWh. This is a normal characteristic at very low load points.
The weighted and corrected E3 test cycle result is 9.5 g/kWh and lies below the applicable Marpol tier 1 limit of 10.3 g/kWh.

Regarding the influence of the emission control technologies on Black Carbon emissions, the following is concluded:

- SCR has no significant effect on the BC emissions. This is also what could be expected. BC emissions are hardly affected by a catalyst.
- Emulsification of the fuel with water leads to a reduction of the observed Filter Smoke Number(FSN). The FSN reduction correlates with the amount of water added to the fuel; at higher water contents the reduction of the FSN is larger. The reduction ranges from 60% to 80% with 10-15% water added, up to 80-90% with 20-35% water added.

Regarding the influence of the emission control technologies on $NO_x$ emissions, the following is concluded:

- SCR has a large effect on the $NO_x$ emissions. The SCR system reduced about 90% of the $NO_x$ emissions. At full load, the reduction is somewhat lower (85%). At 10% load, representative for dredging, the reduction is 87%, which is qualified as very good.
- After emulsification of the fuel with water, the $NO_x$ emissions reduced over all engine load points except for the 25% power point. The difference with the baseline was about 9-12% NOx reduction for the lower water contents of 10-15% and about 23-42% NOx reduction for the higher water contents of 22 to 35%.

The following can be concluded, when comparing the measurements with the Netherlands emission inventory values:

- The measured NOx emissions are some 18% higher than the emissions inventory values.

- The measured BC emissions are up to 90% lower compared to the emissions inventory (EC2.5).

From this observation it can be concluded that more measurements are necessary in order to draw definitive conclusions (also taking into account large vessel to vessel differences).
Insights of this measurement campaign with respect of the effectiveness of SCR and fuel water emulsion on the reduction of NOx and BC can be used to improve future emission calculations.

# 6 Signature

Delft, 27 December 2018

TNO

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Review

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Approval

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# A Glossary

| | |
|---|---|
| BC | Black Carbon (according to Bond definition) |
| deNOx | Removal technology of NOx from exhaust gas |
| DWT | Dead weight tonnage (maximum allowable total weight of a vessel) |
| E3-cycle | IMO-defined test cycle with weighing procedure for emission measurement results for maritime propulsion engines |
| eBC | Equivalent black carbon (Black carbon measured by indirect measurement like FSN) |
| EC | Elemental Carbon (refractory part of black carbon) |
| ECA | IMO designated Emission Control Area concerning SOx or NOx |
| FSN | Filter Smoke Number (well defined measure of filter opacity measurement) |
| FWE | Fuel Water Emulsion, NOx-removal technology |
| IMO | International Maritime Organisation (part of United Nations) |
| MCR | Maximum Continuous Rating (power) of a engine |
| MGO DMA | Marine Gas Oil with defined specification |
| NOx | Nitrogen Oxides calculated as $NO_2$ |
| PTO | Power take off (Power delivered by main engine for other purposes than propulsion) |
| RPM | Revolutions per minute (engine speed) |
| SCR | Selective catalytic reduction, Nox-abatement technology |
| SOx | Sulphur oxides |
| Tier III | NOx abatement standard defined by IMO (third step) |
| Turbo | Mechanical Diesel Aspiration technology |

# B Test fuel

**ANALYTICAL REPORT SR-6677.01.A01** P.1/2

| | |
|---|---|
| grade | DIESEL |
| sample 001 | Sample received from client<br>Sample packed in plastic, quantity approx. 0.25L<br>Sample marked as EZMO 2018-06-006 28-11-2018<br>Diesel Shoalway |
| date received | 03.12.2018 |

| | 001 |
|---|---|
| ° Calorific value, gross, MJ/kg (ASTM D 240) | 45.955 |
| Calorific value, nett, MJ/kg (ASTM D 240) | 43.090 |
| ° Carbon, % wt (ASTM D 5291) | 86.3 |
| ° Hydrogen, % wt (ASTM D 5291) | 13.5 |
| Nitrogen, % wt (ASTM D 5291) | 0.14 |
| Sulphur, mg/kg (ASTM D 2622) | 425 |