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Environmental Protection Agency

Surveillance of Sulfur Fuel Content in Ships at the Great Belt Bridge 2020

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Summary

Results are reported from stack gas emission measurements of individual ships at the Great Belt Bridge in Denmark. From the data the fuel sulfur content (FSC) used by the ships has been estimated. The project has been carried out on behalf of the Danish Environmental Protection Agency and this report covers the period December 2019 to November 9, 2020. The overall aim of the project was to carry out operational surveillance of ships with respect to the EU sulfur directive that was entered into force in 2015 and which is implemented in the Danish legislation. It requires the usage of low sulfur marine fuel in SECAs (0.10 %) or using abatement technique (e.g. scrubber), The main purpose of the surveillance was to guide further port state control of ships at the destination harbors of the ships, both in Denmark and other ports, and to gather general statistics about compliance rates.

This report describes the technical systems and their performance and discusses the general compliance levels with respect to the EU sulfur directive and Danish legislation. The surveillance measurements were conducted by automatic gas sniffer measurements at the Great Belt Bridge, reporting in real time to a web database. The measurement systems have been developed by Chalmers University of Technology through Swedish national funding and EU projects. The measurement system at the Great Belt Bridge has been in operation since 2015.

In the period December 2019 to November 9, 2020, 3910 valid sniffer measurements of individual ships were carried out at the Great Belt Bridge with medium and good quality. The precision of the fixed sniffer is estimated as 0.04 FSC % (1σ) and therefore only ships running with an FSC of 0.18 % (2σ) or higher can be detected as non-compliant ships with reasonable statistical confidence. The sniffer also has an estimated systematic bias of - 0.077 % FSC for the measurements in 2020, based on comparisons with port state control authorities**.** This bias, together with the measurement precision, is accounted for when determining the non-compliance threshold value. The data for the period December 2019 to November 9, 2020 shows a compliance rate of 98.6 %. This corresponds to 55 non-compliant ships (1.4 %) and out of these only 1 ship (i.e. 0.03 %) was in gross non-compliance, i.e. running with FSC above 0.3 % while the rest had an FSC below 0.14 %. This is slightly lower than in 2019 (4 ships corresponding to 0.075% above FSC 0.3 %) and it can be compared to the corresponding numbers for 2018 when the compliance rate was 95.3 % and 1.8 % of the ships were in gross noncompliance. One reason for the improvements could be that scrubber installations appears to work better in 2019 and 2020 compared to the previous years.

The observed high and improved compliance rate in 2020 is similar to the measurements in 2019 and consistent with other measurement studies in northern Europe during 2019. Airborne mini-sniffer measurements of 600 ships around the coast of Denmark, on behalf of the Danish EPA, shows 50 % less noncompliance between 2018 and 2019, with only 3 ships above FSC of 0.3 %. Sniffer measurements carried out in Belgian waters, in the English Channel, by fixed wing aircraft show that the non-compliance rates of ships with FSC above 0.4% changed from 4.9 % to 0.4 % between 2018 and 2019, with similar values in 2020. Fixed site measurements in the ship channel to Hamburg shows improved compliance rates since 2015 with noncompliance rates less than 1 % in Wedel and Bremerhaven in 2019. Sniffer measurements at the Öresund Bridge by Chalmers University of Technology, on behalf of Swedish transport agency, shows 99.7% compliance rates in 2020 with no ships in gross noncompliance.

Contents

1. Introduction

In 2015 new rules from the IMO and legislation from EU (Sulfur directive) and the US requires ships to run with maximum fuel sulfur content (FSC) of 0.1 % m/m on northern European and North American waters. This has been further implemented in the national legislations of the northern coastal European countries, including Denmark. The extra cost of this fuel is 50 %, or more. To inspect that the legislation is complied with, it is required to carry out on board fuel sampling and this is done by port state control authorities that take the fuel samples of ships at berth. This procedure is time consuming and only a minority of the ships (approx. 4 %) is being controlled, and none while under way on open waters. The high extra cost for low sulfur fuel and the relatively small risk of getting caught, creates a risk that unserious ship operators will run high sulfur fuel. In order to promote a level playing field within the shipping sector there is hence a need for measurement systems that can help make the compliance control effective and guide port state control authorities on which ships the fuel sampling should be carried out.

This report describes the results from ship emission measurements at the Great Belt Bridge in Denmark from December 2019 to November 9, 2020, carried out on behalf of the Danish Environmental Protection Agency. The corresponding measurements have been ongoing since 2015 (Mellqvist 2018.; 2019; 2020).

During the measurement period the fuel sulfur content (FSC) of individual ships was estimated through spot checks of exhaust plumes of individual ships. This was conducted by automatic gas sniffer measurements at the Great Belt Bridge. The data from the fixed system were transmitted in real time to a web database and alarms were triggered for high FSC ships in the form of emails. The objective of the report is to describe the technical systems and their performance, but we will also discuss the general compliance levels of the measured ships.

The measurement systems have been developed in the Swedish project “Identification of Gross-Polluting Ships (IGPS)” (Mellqvist, 2014) and the EU project CompMon (https://compmon.eu/). As part of the CompMon project, fixed measurements were performed at the Göteborg ship channel and Öresund Bridge (Mellqvist et al., 2017b). In addition, airborne ship emission measurements were performed at the SECA (Sulfur emission control area) border in the English Channel (Mellqvist et al., 2017a). Similar systems have been applied by the authors elsewhere including Baltic sea (Beecken et al., 2014a; Berg et al., 2012), Göteborg (Mellqvist et al., 2010 and 2014), Rotterdam (Alfoldy et al., 2011 and 2013; Balzani-Loov et al., 2014), Saint Petersburg (Beecken et al., 2014b) and Los Angeles (Mellqvist et al., 2017c).

2. Method

2.1 Sniffer system

With the sniffer system the FSC is directly obtained by sampling of the gas concentrations in the ship plumes. This is done with several commercially available gas analyzer instruments which in some cases have been modified to match measurement requirements especially concerning the response time and pressure dependence.

The FSC is obtained from the ratio between the pollutants and CO_2 inside of the plume. Eq. 1 shows a more general of this calculation, which is consistent with the on board method described in the MEPC guidelines 184(59).

$$FSC = 0.232 \frac{\int \left[SO_2 - SO_{2,bkg} \right]_{ppb} dt}{\int \left[CO_2 - CO_{2,bkg} \right]_{ppm} dt} \qquad \text{[\% sulfur]} \qquad (1)$$

Here CO_2 and SO_2 corresponds to the gas concentrations expressed in ppm (parts per million) and ppb (parts per billion), respectively. The subscript bkg (background) corresponds to the ambient concentration neighboring the plume. The constant 0.232 corresponds to the sulfur-carbon atomic weight ratio multiplied with a factor of 87 % that relates to the carbon content of the fuel, and a correction for different units.

The FSC as described on Eq.1 can be considered to be directly proportional to the sulfur to carbon content in the fuel, assuming that all sulfur is converted to SO_2. However, this is only partly true since some studies have shown that around 5 % of the sulfur is present as sulfate in particles (Moldanova et al., 2009; Petzold et al., 2008); hence, the apparent FSC obtained from the SO_2 to CO_2 ratio will be somewhat lower than the true FSC. The sniffer also measures NO_x which play an indirect role by correcting the SO_2 measurements, thus improving the accuracy of the FSC estimations. This additional correction will be further explained in the following sections.

In order to identify a particular emitter ship, the gas measurements must also include wind data and positional information. This is achieved through a meteorological station and, by tracking the name, speed and positional information of ships nearby the measurements area through an Automated Identification System receiver (AIS), FIGURE 1.

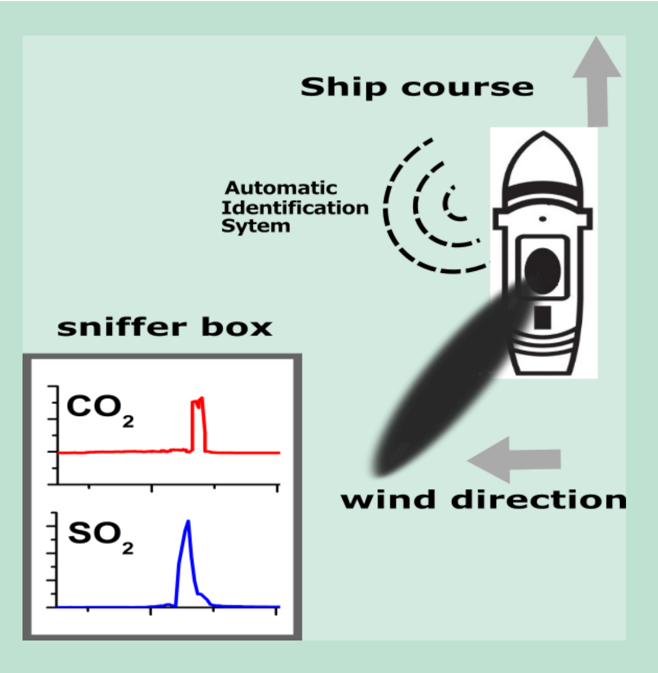

FIGURE 1. Schematic of the sniffer system and ship identification. An emitter ship is identified by combining wind measurements and the transponder signals through the Automatic Identification System AIS.

2.2 Instrumentation and correction for cross interference

The sniffer systems is based on the instruments described in TABLE 1. The sniffer instruments are commercially available as state of the art instruments and they are being used worldwide as reference methods for air quality measurements.

TABLE 1. The instruments employed for ship surveillance. Response time (t_{90}) and measurement resolution uncertainty (σ) is given.

Species	Quantity	Method	Model	t_{90}	1□	Platform
CO_2	Mixing ratio (sniffer)	Cavity ring down spectrometer with custom hardware and sampling (sniffer)	Picarro G-2301m	<1 s	0.1 ppm	Air Fixed
SO_2	Mixing ratio (sniffer)	Fluorescence (modified)	Thermo 43i-TLE	2 s	5 ppb	Air Fixed
NO_x	Mixing ratio (sniffer)	Chemiluminescence (modified)	Thermo 42i-TL	1 s	1 ppb	Air Fixed

The SO_2 analyzer response has cross sensitivity to NO. For example our laboratory test shows that 200 ppb of NO will cause a 3 ppb response in the SO_2 analyzer (Alfoldy, 2014). This may lead to an overestimation of the FSC by up to 0.1 % if not accounted for. To remove the influence of NO on the measurements, the NO_x species are measured in parallel to the SO_2 measurements. However, NO_x consists of the two gas species NO and NO_2 and the SO_2 analyzer only has a cross sensitivity to the former one. One therefore have to assume a certain ratio between NO and NO_2. The calculation of FSC when including the new NO interference is the one given in Eq 2, and here it is assumed that 71 % of the NO_x is present as NO, The latter is based on measurements of the NO to NO_2 ratio at the Great Belt Bridge as part of this project. For more details, see Mellqvist et al. (2018).

$$FSC = 0.232 \frac{\int \left[SO_2 - SO_{2,bkg}\right]_{ppb} dt - 0.0098 \int \left[NO_x - NO_{x,bkg}\right]_{ppb} dt}{\int \left[CO_2 - CO_{2,bkg}\right]_{ppm} dt} \quad \text{[\%sulfur]} \qquad (2)$$

2.3 General Uncertainty

In 2008, a joint study was carried out in Rotterdam with support from the EU (Alfoldy et al., 2011; Alfoldy et al., 2013; Balzani et al., 2014). The objective was to compare methods for the determination of FSC and NOx emission factors based on remote measurements and comparison to direct stack emission measurements on a ferry. The methods were selected based on a review of the available literature on ship emission measurements and they were either optical (LIDAR, Differential Optical Absorption Spectroscopy-DOAS, UV-camera) or sniffer based ones. Using the latter method, three research groups participated with their own SO2 and CO2 instruments and one of the groups used a setup with double instruments measuring at different heights. Our group carried out both DOAS and sniffer measurements using an older instrument setup than the one used in this study (Mellqvist 2010, Berg 2011; Berg et al. 2012, Balzani et al. 2014). The measurements were performed from a land station, a boat and a helicopter together with on board measurements. It was found that the sniffer approach is the most convenient technique for determining mass specific emission factors of both SO2 and NOx remotely. The overall estimated uncertainty for SO2 was 23 % (Alfoldy et al. 2013) at 1 % m/m FSC, based on comparison with on board sampling. In FIGURE 2 results are shown from a comparison between the Chalmers sniffer system measuring from a 3 m mast to a similar sniffer system by the Joint Research Centre (JRC-Ispra) who ran measurements on a 20 m mast. There is a clear correlation between the two systems although there is a 20% systematic difference, similar to the estimated uncertainty. In another study (Beecken et al. 2014a) the measurement precision was estimated from the variability of multiple airborne measurements of the same ship, for a total of 158 different ships. A random uncertainty of ± 0.19 % m/m was obtained for ships with approx. 1 % m/m FSC.

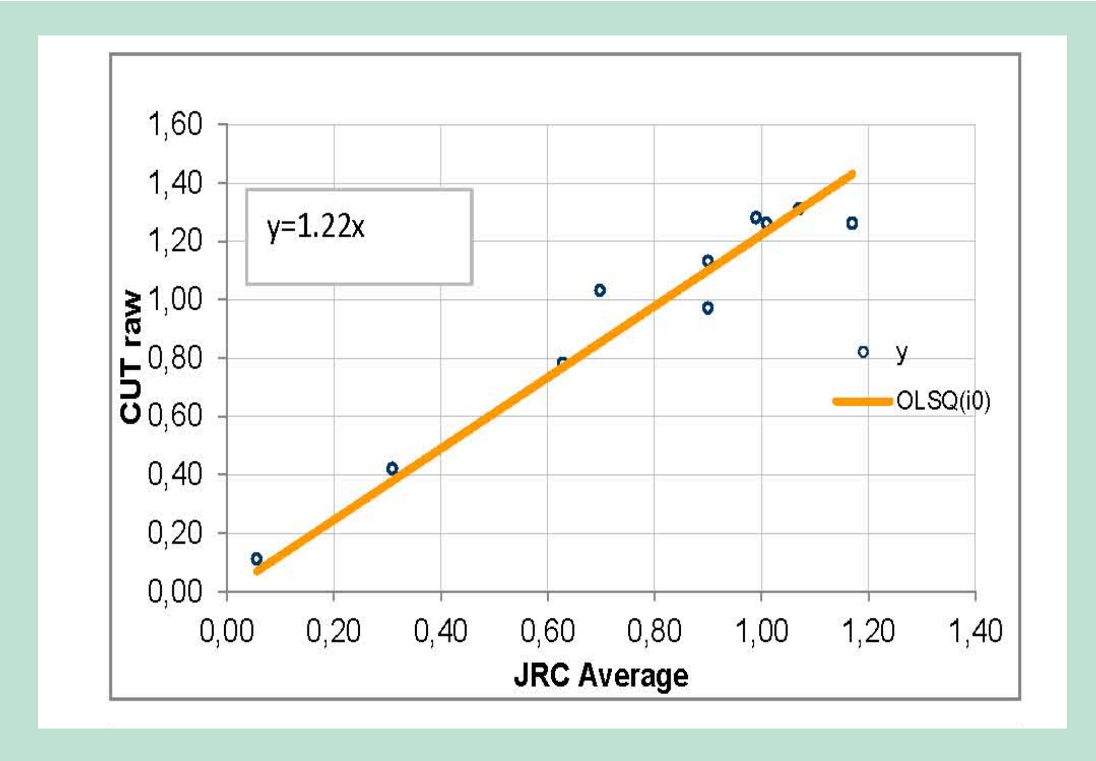

FIGURE 2. Field measurements in Rotterdam measuring individual ships during two days in the ship channel of Rotterdam (Balzani 2013). Two nearby systems, the Chalmers sniffer system(CUT) and the system developed by the Joint Research centre (JRC-Ispra) were compared.

2.4 Assessment of the uncertainty of the calculated equivalent sulfur at the Great Belt Bridge

This section describes the aspects taken into account regarding the assessment of the uncertainty and the estimation of the non-compliance threshold for the FSC values obtained using the sniffer method.

The precision of the measurements has been estimated either from multiple measurements of the same ships (fixed station) or from the variability of the data close to the median value (airborne), as described in an earlier report (Mellqvist, 2018).

For instance, for the measurements at the Great Belt Bridge multiple observations (> 9) of 30 individual ships measured during 2015 and 2016 were used. From the square root of the sum of the variances of individual ships we obtained an overall precision (1σ) of 0.04 % in FSC units.

The accuracy of the sniffer measurements has been assessed by comparison to on board sampling by port state control authorities. The Swedish port state authority (pers. comm. Caroline Petrini, Swedish transport Agency) measured 35 vessels in 2019 with median value of 0.06 % m/m and this is lightly larger than in 2015 and 2016 when the median was 0.08%.

Here we assume that the median FSC of the ships passing the Great Belt Bridge and around the waters of Denmark in 2020 is the same as the ships controlled in Swedish ports in 2019, and we have therefore adjusted the noncompliance threshold value accordingly.

For instance, for the sniffer data measured at the Great Belt Bridge in 2019 there is a negative bias of 0.077 % in FSC units for the period December 2019 to November 9, 2020, when compared to port state control data. Note that the negative bias at the Great Belt Bridge has varied between 0.04 % to 0.09% FSC units over the last 5 years. Ships running with an FSC value of

0.1 % in 2020, will hence be measured as having an FSC of 0.023 %. However, since the measurement have random noise, the data will be spread according to a Gaussian distribution with a standard deviation 0.04 %. A ship running with 0.1% FSC will therefore be measured in the FSC interval -0.057 % to 0.103 % (± 2 STD) with 95 % probability. The upper value is used as the *bias and noise corrected noncompliance threshold value*. Individual ships for which the measured FSC exceeds this limit are considered to use non-compliant fuel with a probability of 95 %. The general threshold for compliance can be described according to Eq 3.

$$Compliance\ threshold_{biased} = 0.1\ \% + bias + \ 2\,\sigma \qquad \text{Eq. 3}$$

Here the bias corresponds to the difference between the median FSC value of the sniffer measurements and the median FSC value of port state control data, σ corresponds to the precision obtained as the standard deviation of multiple measurements and 0.1 % is the SECA limit for FSC. We cannot fully explain the reason for the negative bias, but potentially it is compensation of NO_x interference and tubing losses for low levels of SO_2. One could also speculate that a higher proportion of the sulfur could be in particulate form at low levels than at high.

Note that only the compliance threshold is modified to account for the bias in our data, It is however, not the real threshold**,** which is 0.18 %**.** This means that it is not possible to detect non-compliant ships using a FSC in the range 0.1-0.18 %.

The estimated measurement quality parameters are summarized in TABLE 2.

TABLE 2. Estimated overall uncertainty for the sniffer measurements in this study at the 0.1 % FSC limit. All values correspond to the absolute FSC unit.

Error parameter	**Uncertainty FSC units**
Random uncertainty	±0.04%
Systematic bias	-0.077%
Compliance threshold bias corrected (applied for measurements)	0.103%
Real Threshold(2) for the compliance control (95 % probability)	0.18%

(1) Beecken 2014a and other studies, see section 2, (2) Unbiased threshold. (3) Balzani 2014

3. Measurements

3.1 Installation of the sniffer system

The fixed sniffer system is installed at the eastern pylon at the Great Belt Bridge, FIGURE 3. This is an excellent measurement spot in view of the large volume of marine traffic (25000 ships per year) and predominant south westerly wind conditions; thus increasing the chances of detecting the plumes. The gas sensors and its components are installed in a rack inside the control room at the eastern Pylon (#16) of the bridge; while, the AIS antenna, GPS receiver and inlet are mounted on a metallic angle just outside the bridge. The system has it's independent internet link through a 4G modem.

The gas is extracted via a 10 meters long heated Teflon tubing that is connected to a U bent Teflon tube ending with a plastic cone. The total flow speed is approximately 12 lit/min. The sensors are regularly calibrated (typically every month) by injecting reference gases through a 10 m gas tube that is connected to the beginning of the sampling line close to the main inlet to the sniffer system.

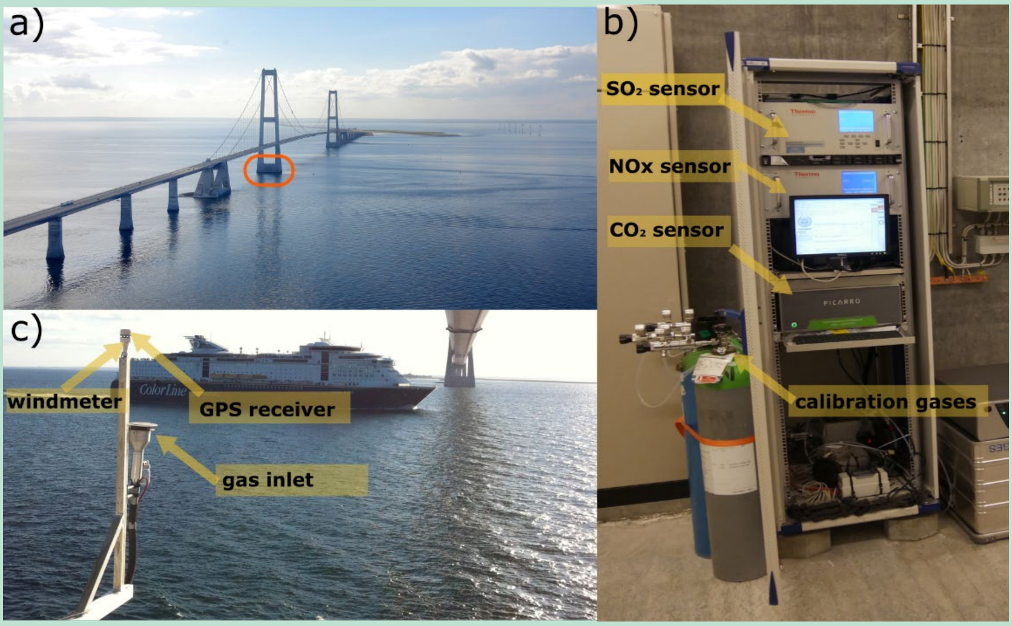

FIGURE 3. Fixed sniffer system installed at The Great Belt Bridge, Denmark. (a) Installation site at the Pylon 16 of the bridge. (b) Instrument racket in the control room. (c) Metallic angle structure holding the GPS receiver and the wind receiver. The gas inlet and the AIS antenna are in the same metallic angle (not showed on the picture).

3.2 Data acquisition system and web data reporting

The optical and sniffer data are handled by a Data Acquisition System (DAS) which is a combination of three custom made software applications running unattended and continuously: TCP-log, IGPSpresent and the IGPS mailer. The software TCPlog has the most critical task which is continuously logging all the available instruments with a sampling period of approximately one second. This includes data from the sniffer and optical sensors, wind meters, AIS receiver and in case of the airborne platform also information from the aircraft.

The IGPSpresent program analyses the data in near-real time, namely calculating the FSC through ratio measurements between the concentrations of SO_2 and CO_2. Moreover, the IGPSpresent identifies the presence of ship plumes and its corresponding source of origin. For the fixed station the program initiates a calibration every 5th day, FIGURE 4.
Finally, the IGPSmailer program automatically sends evaluated and compiled measurements to the database at Chalmers University of Technology, see an example in FIGURE 5 from the Älvsborg site in the ship channel of Göteborg obtained in the Compmon project. The database includes the FSC values as well as date, time, position and ship specific data.
The DAS also generates alerts as emails or SMSs when a high emitter ship has been detected, or when there is a possible system malfunction. These alert messages combined with regular remote logging, has been of key importance to ensure reliable measurements.

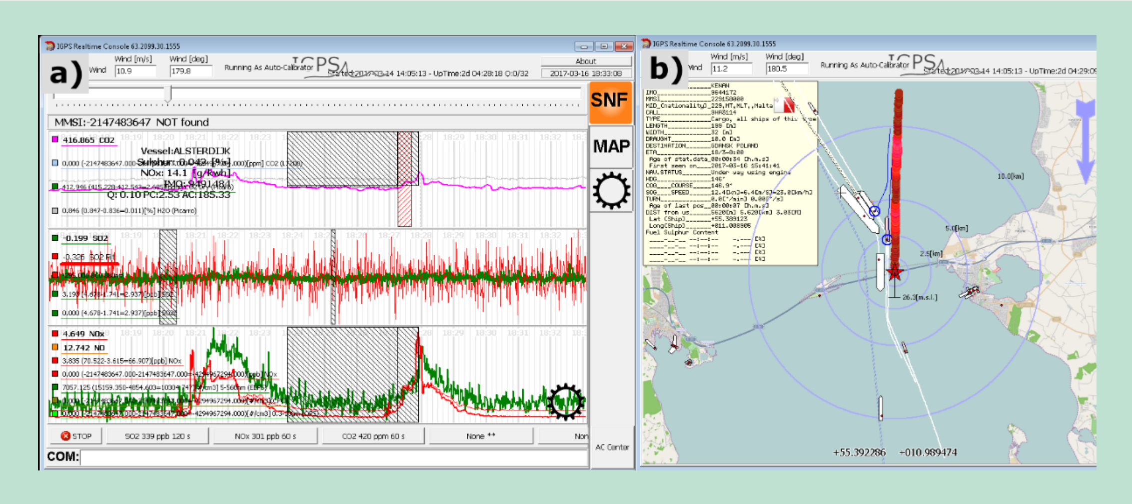

FIGURE 4. Example of the IPGSpresent software while performing a measurement at The Great Belt Bridge. (a) Real-Time series of CO_2, SO_2 and NO_x concentrations. (b) Identification of plumes from the nearby ships. The TCPLog and IGPS mailer are running as background processes.

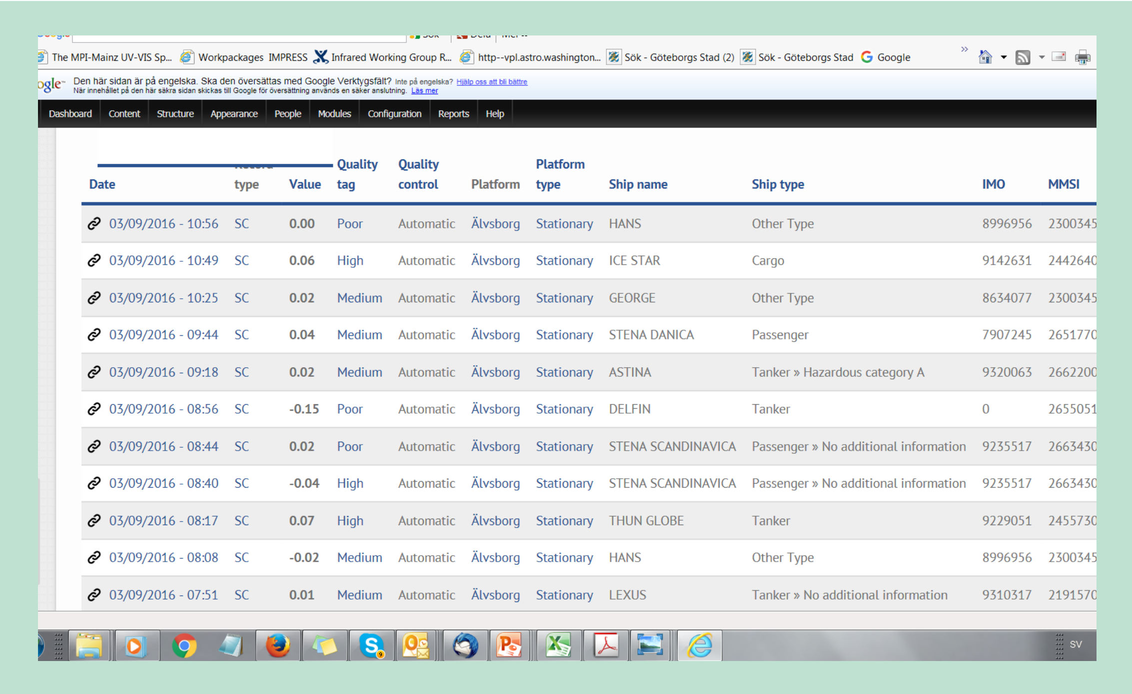

FIGURE 5. Example of database setup from the Älvsborg site in Göteborg.

3.3 Hardware changes and practical problems

In 2020 there were several shorter standstills due to problems with power, internet and software crashes. In addition, there was a longer standstill during July 21 to September 1 due to a malfunctioning SO_2 instrument, TABLE 3. Several faults gradually occurred which were difficult to diagnose, and this required several service trips before being resolved during the summer. In addition, because of COVID-19 there was a problem to get to the site to replace the SO_2 gas calibration cylinder.

TABLE 3. The quality criteria applied for the fixed measurements at the Great Belt Bridge.

Inspection Date	Comments
2020-01-03 to 2020-01-16	Software failure. Logger crashed. It was first believed to be internet problem. Standstill-
2020-04-04 to 2020-04-07	Software failure. Logger crashed. Standstill.
2020-04-08	Filter Change and inspection of erroeneous internet MODEM. SO_2 gas calibration cylinder was empty.
2020-04-29 to 2020-05-05	Power failure at site, standstill
2020-05-10 to 2020-05-19	Internet-Software Failure, standstill
2020-05-20	Installation of wew SO_2 gas calibration cylinder and new internet modem
2020-07-06	SO_2 instrumnet broken. Standstill
2020-07-21	Inspection of SO_2 instrument, Optics Broken. Instrument removed for service.
2020-08-11	Installation of spare SO_2 instrument. This instrumnet broke as well , due to a malfunctining flashdrive we later found out .

2020-08-20	Test of the instrument after service, it was found that theutra-violet lamp of the spare instrument was broken
2020-09-01	Installation of the original SO_2 instrument after service from the support company and hardware calibration Operation started after standstill.
2020-11-26	Changing AIS-GPS receiver and filters

3.4 Calibration

The quality assurance of the sniffer instruments is obtained by periodic calibrations, approx. every month, see FIGURE 6. The instruments at the Great Belt installation site are calibrated by remote control using gas standards diluted in nitrogen or air with values ranging 200-450 ± (5 %) ppb, 210-300 ± (5 %) ppb and 380-420 ± (1 %) ppm for SO_2, NO_x and CO_2 respectively. The calibration gas is injected just after the measurement inlet.

By comparing the nominal gas standard value with the measured one, a calibration factor is calculated for each species. The calibration procedure also includes measuring the offset of each instrument (zero calibration) by utilizing the other gases. For instance, the SO_2 and NO_x instruments are zero calibrated using the CO_2 calibration gas while the CO_2 instrument is zero calibrated using either the NO_x or SO_2-calibration gas. When the instrument response deviates too much from the nominal value a hardware recalibration of the instruments is carried out and then the calibration factors are reset to approx. 1. However, in most cases the instruments are not recalibrated and instead the output from the instruments are validated and post-corrected by multiplying the measured values with the calibration factors, after correction for the offset.

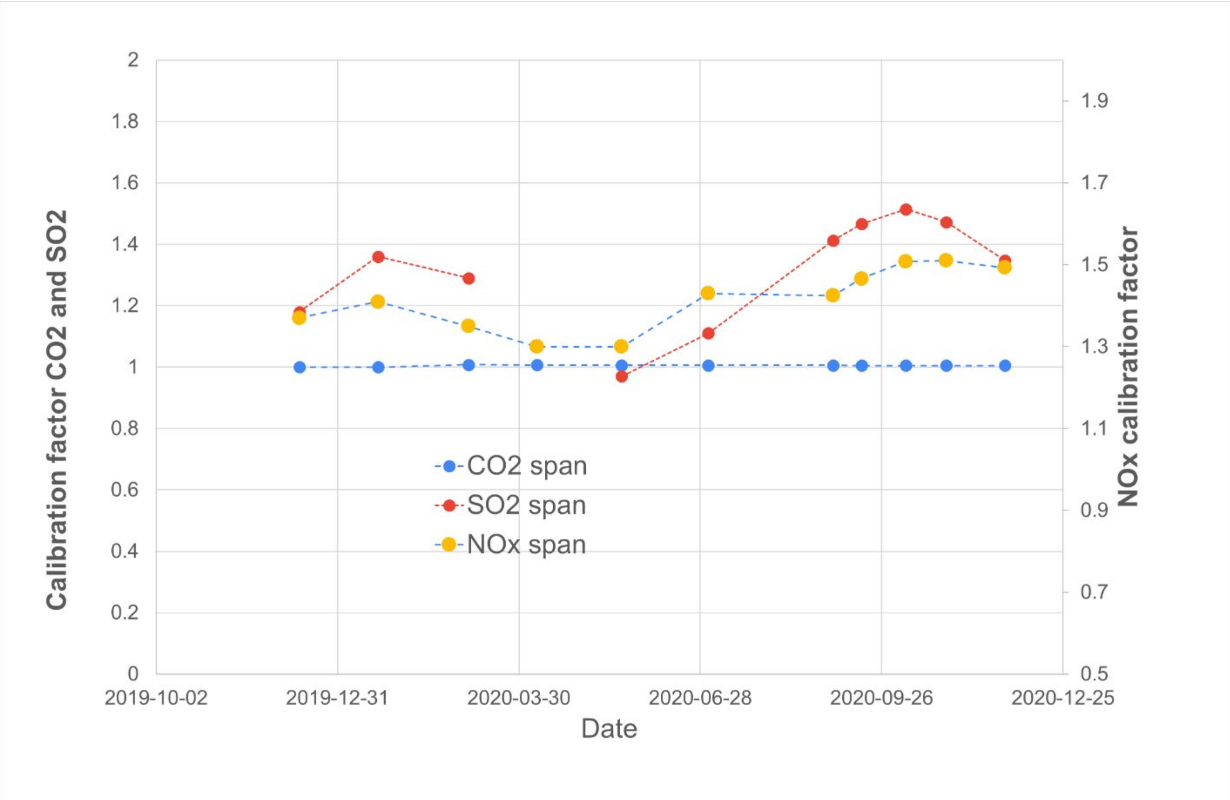

FIGURE 6. The calibration factors obtained during 2020 through measurements of gas standards from Air Liquide.

3.5 Quality assessment of data

In the data evaluation the quality of the measurements is expressed through a quality flag that can alternate between the following levels: HIGH, MEDIUM, and POOR. This assessment is based on the parameters in TABLE 4 for the fixed station at the Great Belt. As can be seen in the tables the quality flag is a combination of measured parameters such as CO_2 peak signal and empirical observations of conditions when the measurements are more certain. One important consideration here is the comparison of CO_2 in the ship plume against the variation of the ambient background CO_2, which comprises both variations of the background (upwind fixed source like a city) and the noise of the instrument. The quality level may also shrink if different hardware warning flags are raised while the instruments are operating. These flags are mostly associated to issues related to high/low temperature, low voltages, flow interruptions, etc. Moreover, though the CO_2 signature play a critical role for assessing the quality level of the measurements. In general, the automatic data retrieval performed satisfactorily for high and medium quality measurements and therefore the data with poor quality are uncertain.

TABLE 4. The quality criteria applied for the fixed measurements at the Great Belt Bridge.

Criteria	Comment	High	Medium	Poor
Normal operation	Warning flags for the hardware not set, such as high/low temperature, low voltages etc	Required	Required	Depends
□CO_{2Max} in plume	Peak height	>3 ppm	>2 ppm	0.5 ppm
□$CO2_{integrated}$	Integration of plume	>50 ppms	>25 ppms	3> ppms
□t_{CO2} in plume	Time duration in plume	<100 s	<150 s	<240 s
Wind direction	Wind relative to ship movement	± 30°	± (30-60°)	± (30-60°)
Wind speed		3-8 m/s	2-3 m/s or 8-10 m/s	1-2 m/s or 10-12 m/s
No of ships with overlapping plumes		1	1	1
FSC	Filtering out low values	>-0.2	>-0.2	>-0.2

4. Results

The period of this project covers December 2019 to November 9, 2020. The system was in operation during 75 % of this time (253 out 347 days) and during 40 % of the measurement days the weather conditions allowed for measurements. The obtained data set correspond to a total of 6145 ship plumes, FIGURE 7 and FIGURE 8, divided into 3 qualities, based on the criteria in TABLE 4.

In FIGURE 9 the frequency distribution of all FSC measurements is shown, corresponding to 3910 individual ship measurements of good or medium quality. *Note that a ship is counted twice if the measurements are carried out on separate days*. The FSC data has a measured median FSC value of -0.018 %, average value of -0.0172% and standard deviation of 0.047 % in FSC units. This is consistent with an earlier study (Mellqvist, 2018) in which the precision was obtained from the variability of 30 different individual ships that were measured multiple times (more than 9). Here it was assumed that for each individual ship the FSC was constant and since the sulfur content of fuel deliveries may vary there is no guarantee that the same ship will have the exact same sulfur emission each time it passes the sniffer. The measured variability is for this reason *our best upper estimate of the real precision* of the sniffer measurements.

The median FSC value of the sniffer measurements can been compared to the corresponding value obtained through on board measurements by the port state control authorities, as described in section 2.4. From here it is indicated that the sniffer measurements have a negative bias of 0.077 % in FSC units, as discussed in section 2.4. In our analysis we take this bias into account when calculating the bias corrected threshold for noncompliance as illustrated in FIGURE 9 and several figures below.

In FIGURE 10 a histogram is shown of the number of ships with different FSC levels for the Great Belt Bridge sniffer data. Since negative data points are non-physical and caused merely by noise or systematic over corrections we have assigned all these FSC value to 0 % in FSC. In addition, the histogram data for FSC levels above 0.1 % is shown separately, corresponding to the non-complying ship.

In FIGURE 11 the fraction of ships below a certain FSC level are shown for the measurement period. The fraction below the bias corrected compliance threshold of 0.103 % is 98.6 %. Hence 1.4 % of the ships were running on non-compliant fuel with 95 % measurement probability. This corresponds to 55 non-compliant ships in the FSC interval 0.103% to 0.14 % and 1 ship (0.03%) that were in gross non-compliance with FSC of 0.4 %, FIGURE 12.

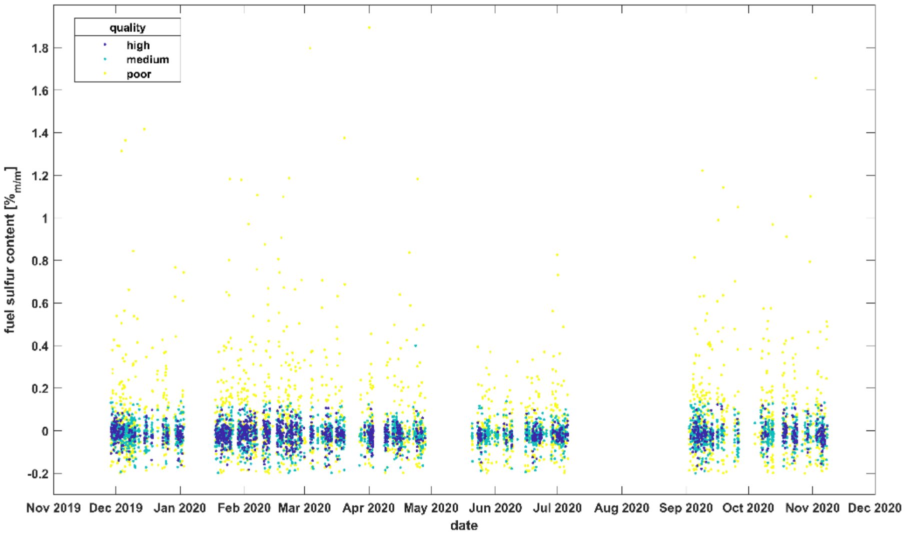

FIGURE 7. Sniffer measurements at the Great Belt Bridge between December 2019 to November 9, 2020.

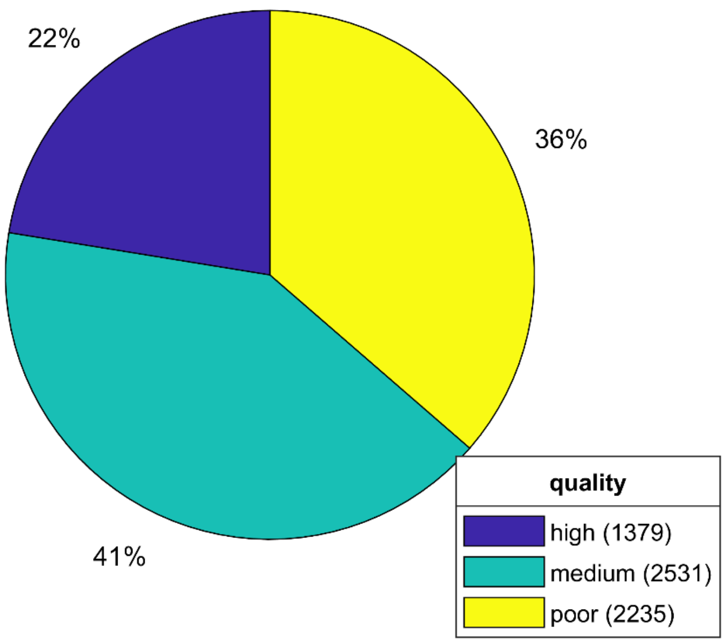

FIGURE 8. Statistical distribution of the measurement quality at Great Belt Bridge and number of ships for the measurement period.

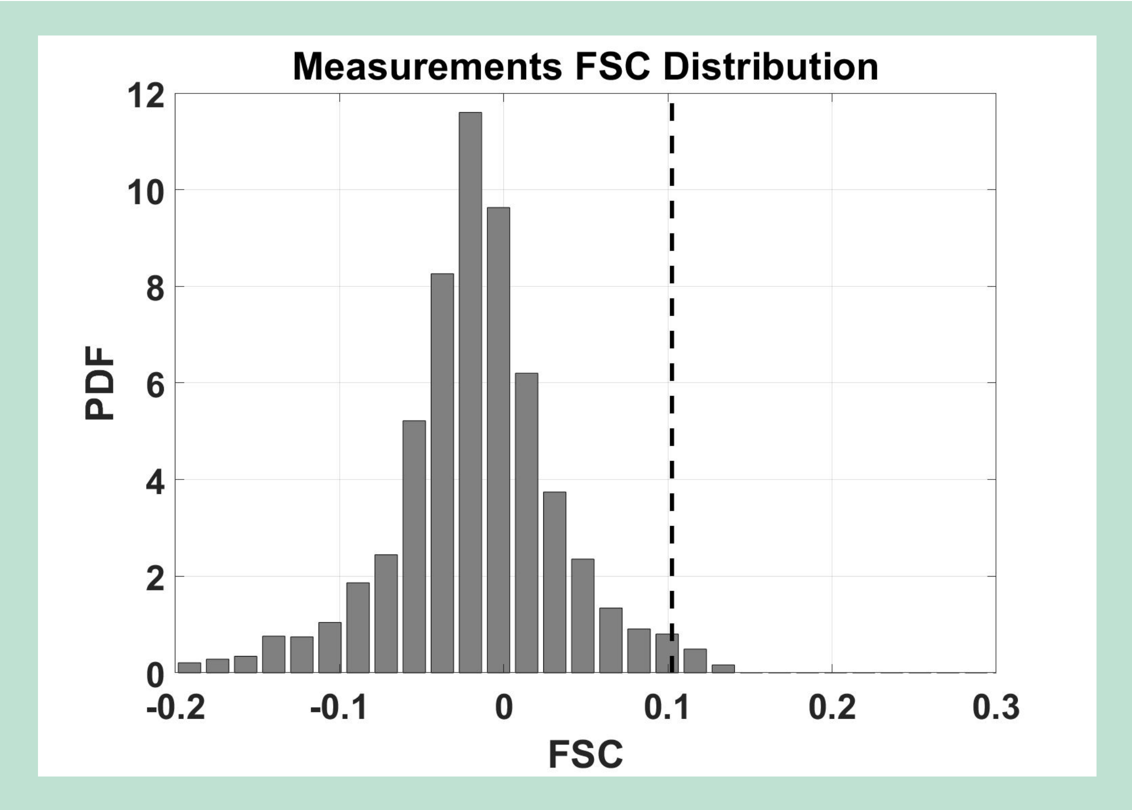

FIGURE 9. Statistical distribution (probability density function) of the measured FSC, corresponding to individual ships measured with sniffer at the Great Belt Bridge (3910 ships, medium and high quality). The dotted line is the estimated non-compliance limit for which the instrument errors (precision and bias) have been accounted for. The measured data set has a median and average FSC values of -0.018% and -0.0172 %, respectively. The standard deviation is 0.047 % and the 75th and 90th percentiles are 0.009% and 0.042 % in FSC units, respectively.

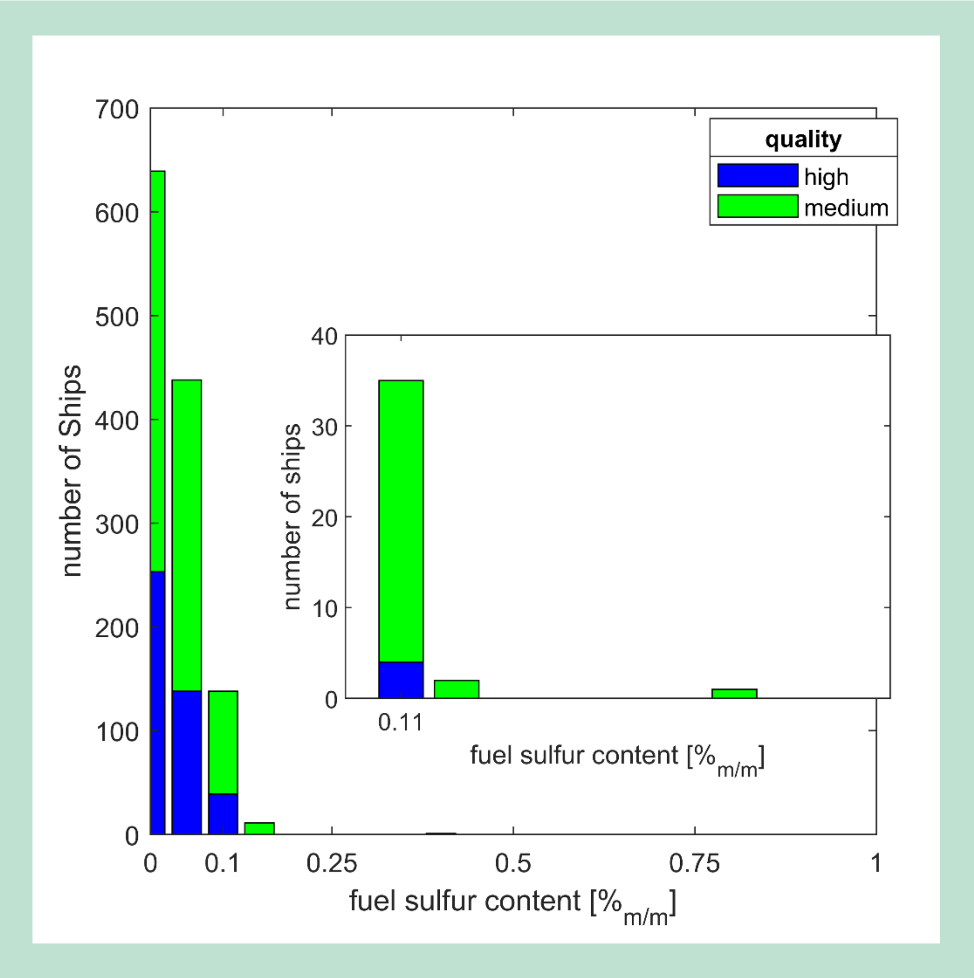

FIGURE 10. Histogram of fuel sulfur content shown for different measurement qualities. The distribution of fuel sulfur contents above 0.103% is highlighted in the inset, i.e. the bias corrected compliance limit threshold.

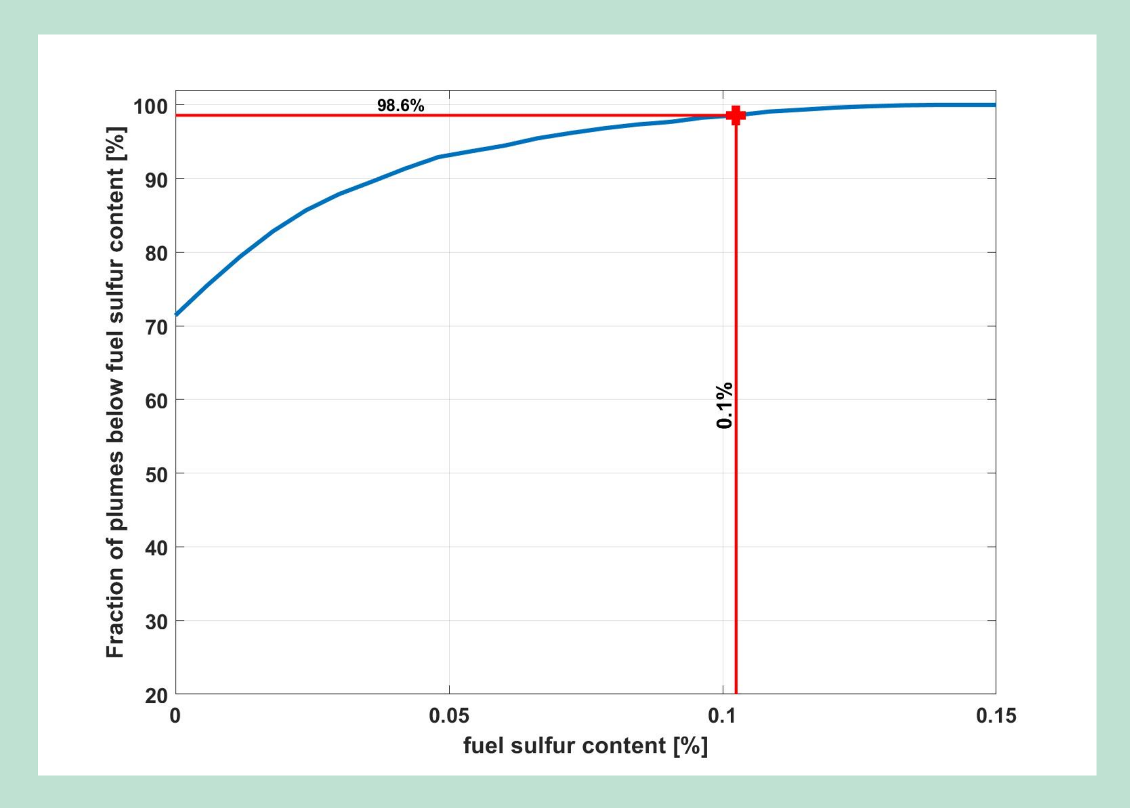

FIGURE 11. The fraction of ships that were measured below a certain FSC level at the Great Belt Bridge for the measurement period. In addition, the biased and noise corrected compliance limit threshold is shown.

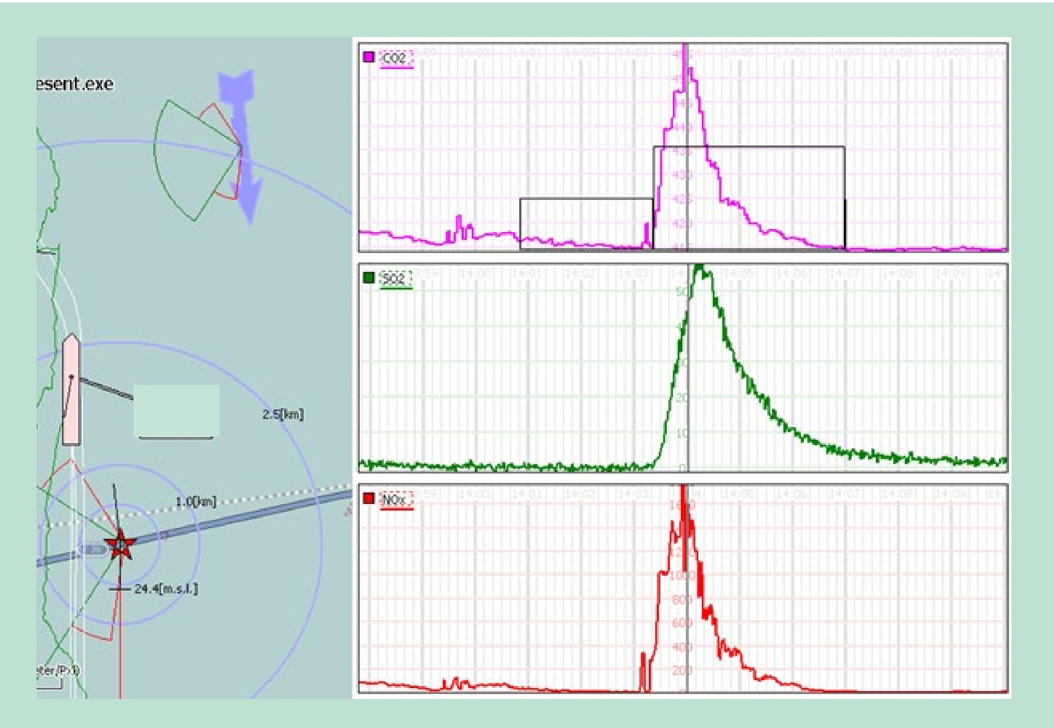

FIGURE 12. Measurement of a non compliant ship passing Great Belt Bridge in April 2020.

5. Discussion

The high efficiency of remote ship measurements by sniffer technique for compliance control of FSC has been demonstrated in this project at the Great Belt Bridge. During the period December 2019 to November 9, 2020, 3910 ships were measured with good quality and out of these 55 individual ships (1.4%) were measured to use FSC above the compliance threshold. Only 1 of these were in gross non-compliance, i.e. running with FSC above 0.3 %. Note that in this report a ship is counted twice if the measurements are done on separate days. The measurements with high and medium quality measurements of non-compliant ships have been flagged in the EU database THETIS-EU by the Danish EPA and this information is used by the port state control authorities when making decisions on board inspections.

The compliance rates for 2020 can be compared to the corresponding measurements between 2015 and 2019 (Mellqvist, 2019). This is shown in Table 4 in which the compliance levels for several years are shown at the Great Belt Bridge or surrounding Danish water (Mellqvist, 2018). For instance, in 2018 the compliance rate was 95.3 %, and 1.8 % of the ships were using fuel with FSC 0.3 % or higher. The higher noncompliance levels during the first years after the introduction of lower FSC limits in the SECA in 2015 were to some degree caused by the presence of technical problems in scrubber installations of the ships (Mellqvist, 2018 and 2019). There is potentially only one such occasion in 2020 and in general it appears as if the technical problems were overcome in 2019 and 2020. This is noteworthy since the number of scrubber ships within the SECA has increased strongly during the recent years. The observed high and improved compliance levels in 2020 and 2019, compared to 2018, is consistent with other measurement studies in northern Europe. For instance Airborne mini-sniffer measurements of 600 ships around the coast of Denmark (Explicit 2020) in 2019, on behalf of the Danish EPA, shows 50 % less noncompliance compared to 2018 with only 3 ships above FSC of 0.3 %. Sniffer measurements carried out in Belgian waters, in the English Channel, by fixed wing aircraft (Ward Van Roy, 2019) show that the non-compliance rates of ships with FSC above 0.4% changed from 4.9 % to 0.4 % between 2018 and 2019, with similar values also in 2020 (Mellqvist 2020). Fixed site measurements in the ship channel to Hamburg (Andreas Wedel, 2019) shows improved compliance rates since 2015 with noncompliance rates less than1 % in Wedel and Bremerhaven in 2019. Sniffer measurements at the Öresund Bridge by Chalmers University of Technology, on behalf of Swedish transport agency, shows a compliance rate of 99.7% in 2020 with no ships in gross noncompliance, i.e. above 0.3%. In 2018 the corresponding compliance rate was 99%.

TABLE 5. Compliance levels at Great Belt Bridge and Danish waters during several years, carried out by Chalmers University of Technology (Mellqvist 2018; 2019; 2020).

	2015	**2016**	**2017**	**2018**	**2019**	**2020**
	Airborne	Fixed	Fixed	Fixed	Fixed	Fixed
No of ships	820	1691	4155	3580	5458	3910
Compliance level	94 %	94.6 %	98.6 %	95.3 %	98.6 %	98.6%
Ships >FSC_{lim}: 0.3 % 0.5 %	 NA 2 %	 NA 1 %	 NA NA	 1.8 % 0.7 %	 0.075 % 0.02 %	 0.03% 0%

6. Recommendation for the future

Compliance monitoring of ships will continue to be important in the next couple of years to monitor the effects of the IMO global cap for FSC of 0.5 % which came into effect January 2020 with an additional ban on carrying high FSC oil in the ship fuel tanks. In the long run, when the Pandemic has diminished, this may change fuel price and availability, general usage of fuel oil and implementation of scrubbers.

It will also be interesting to investigate whether the high compliance levels in 2019 and 2020 will remain 2021 and investigate whether ships adapt to being controlled at the bridge, i.e. carry out fuel switching before and after passing the bridge to avoid being caught. This can be controlled by comparison to airborne measurements carried out by the Danish EPA.

It would be advantageous to improve the sensitivity of the sniffer measurements to be able to monitor ships running with FSC between 0.1 % to 0.18 %, which today is below the measurement sensitivity. Some of the noise and measurement bias is caused by interference of and it could be improved by measuring NO instead of NO_x; this will be investigated in 2020. As part of a parallel project (Scipper, EU Horizon 2020) Chalmers has just tested in a field campaign in Hamburg a new high sensitivity system for SO_2 which has 30 times higher sensitivity than the present one and according to preliminary results this fills the measurement gap between 0.1 and 0.18% FSC. It is planned to test this instrument at the Great Belt Bridge during 2021.

In 2021, new IMO legislation requires that new built ships follow tier III standard for NO_x emissions. However, the technical NO_x code refers to an emission factor corresponding to g NO_x per kWh of axial power at 4 different engine loads. It is today possible to measure the NO_x emission factor with the present sniffer-system but it will be necessary to assess the uncertainties in the measurements when compared to the requirements in the NO_x technical code. During the next couple of years the number of Tier III ships will increase with a need to assess whether they utilize their abatement technique.

Emission factors (g emission per kg fuel) can also be measured for other species, such as CH_4 and particles. Even though no present regulation for these species have been implemented by IMO yet, it is still interesting to use such measurements to assess the efficiency and sustainability of new propulsion and abatement techniques such as LNG (Liquefied Natural Gas).

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Appendix 1. Acronyms

AIS	Automatic Identification System
IGPS	Identification of Gross Polluting Ships
DEPA	Danish Environmental Protection Agency
FSC	Fuel Sulfur Content in mass percentage (m/m)
IMO	International Maritime Organization
MEPC	Marine Environment Protection Committee
MARPOL	Marine Pollution
PSC	Port State Control (authority)
SECA	Sulfur Emission Control Area

Surveillance of Sulfur Fuel Content in Ships at the Great Belt Bridge 2020

The project has been carried out by Chalmers University of Technology, on behalf of the Danish Environmental Protection Agency (DEPA). Chalmers University of Technology is hired by DEPA to estimate the fuel sulfur content (FSC) of ships at the Great Belt bridge in Denmark. The measurements is conducted by automatic gas sniffer measurements at the Great Belt Bridge.

This report describes the technical systems for the gas sniffer measurements and their performance, and discusses the general compliance levels with respect to the EU sulfur directive and Danish legislation. The work described in the report is a part of DEPA's inspection task on this field. The survey contains of 3.910 valid sniffer measurements of ships from the period December 2019 to November 9, 2020.

Dette projekt er blevet udarbejdet af Chalmers Tekniska Högskola, på vegne af Miljøstyrelsen. Chalmers Tekniska Högskola er hyret af Miljøstyrelsen til at beregne indholdet af svovl i udstødningsgasserne for skibe ved Storebæltsbroen. Målingerne er udført med automatiske gas "sniffers" placeret på Storebæltsbroen.

Denne rapport beskriver det tekniske system for gas "sniffer" målingerne samt deres ydeevne, og diskutere den generelle overholdelse med EU svovl direktivet og den danske lovgivning. Arbejdet der er beskrevet i rapporten er en del af Miljøstyrelsens tilsynsopgave inden for området. Overvågningen indeholder 3.910 gyldige "sniffer" målinger for skibe, i perioden december 2019 til d. 9 november 2020.

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