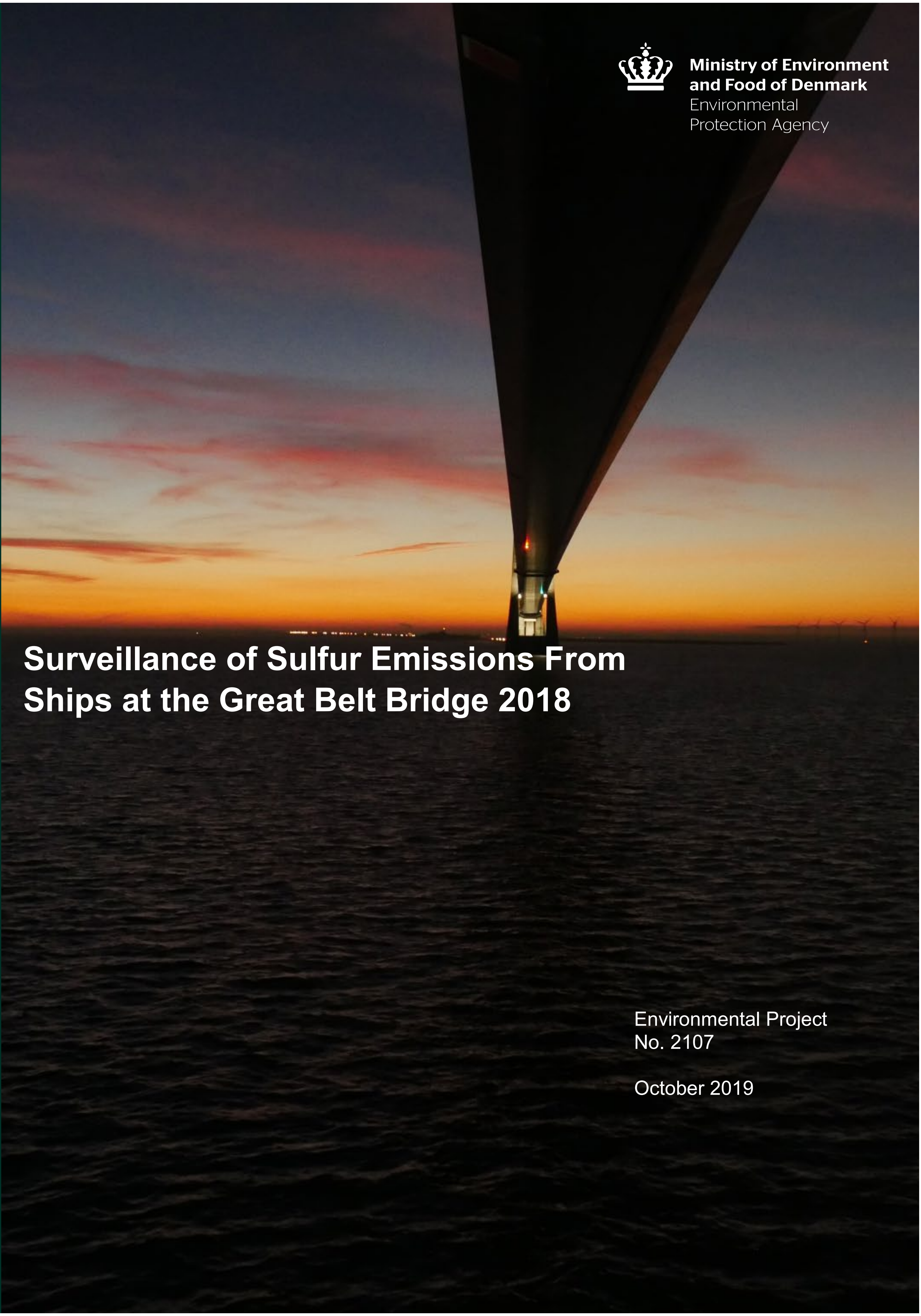

Ministry of Environment and Food of Denmark
Environmental Protection Agency

# Surveillance of Sulfur Emissions From Ships at the Great Belt Bridge 2018

Environmental Project No. 2107

October 2019

Publisher: The Danish Environmental Protection Agency

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ISBN: 978-87-7038-123-9

The Danish Environmental Protection Agency publishes reports and papers about research and development projectswithin the environmental sector, financed by the Agency. The contents of this publication do not necessarily representthe official views of the Danish Environmental Protection Agency. By publishing this report, the Danish Environmental Protection Agency expresses that the content represents an important contribution to the related discourse on Danish environmental policy.

Sources must be acknowledged.

# 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 the contract covers the period March 2018 to December 2018. The measurements reported here cover the period March to November 2018 and in addition we report measurements during January and February 2018, carried out as part of the EU project Envisum. The overall aim of the project was to carry out operational surveillance of ships with respect to the EU sulfur directive and particularly the sulfur limits for marine fuel in SECAs (0.10 %), which entered into force on January 1st 2015, as well as to guide further port state control of ships at the destination harbors of the ships, both in Denmark and other ports

The main objective of this report is to describe the technical systems and their performance, although a discussion about the general compliance levels with respect to the EU sulfur directive is provided as well. 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.

In the period January 2018 to November 2018, 3580 valid sniffer measurements of individual ships were carried out at the Great Belt Bridge (medium and good quality). The precision of the fixed sniffer is estimated as ±0.04 FSC % ($1\sigma$) with an estimated systematic bias of - 0.074 % FSC for the measurements in 2018, based on comparisons with port state control authorities. Therefore, only ships running with an FSC of 0.18 % or higher can be detected as non-compliant ships with confidence limit of 95 % by the fixed sniffer system, when accounting for the bias. The data for the period January to November show a compliance rate of 95.3 %. Here 1.1 % of the ships were in gross non-compliance with the EU sulfur directive with values above 0.5 %. Additional 0.8 % of the ships were measured in the FSC interval 0.3-0.5 % while the rest had values below 0.3%. There are differences over time, with the highest values in the summer. On several occasions we encountered one specific ship that was non-compliant with respect to the EU sulfur directive and which was equipped with a scrubber that was being commissioned.

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# 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 US waters. The extra cost of this fuel is 50 %, or more. At present compliance monitoring of ships is carried out by port state control authorities that take fuel samples of ships at berth. This procedure is time consuming and only few ships are being controlled, and none while underway 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 make effective compliance control, without stepping on board the ships.

This report describes the results from ship emission measurements at the Great Belt Bridge in Denmark from March to November 2018 carried out on behalf of the Danish Environmental Protection Agency. In addition, we report measurements for the EU project Envisum carried out during January and February at the same site. This is a continuation of measurement activities carried out at the same site and with the same system during the period June 2015 from 2017 (Mellqvist 2018).

During the measurement period the fuel sulfur content (FSC) of individual ships was estimated by performing 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/). This includes a portable and flight certified version of the sniffer system. 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 at 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.

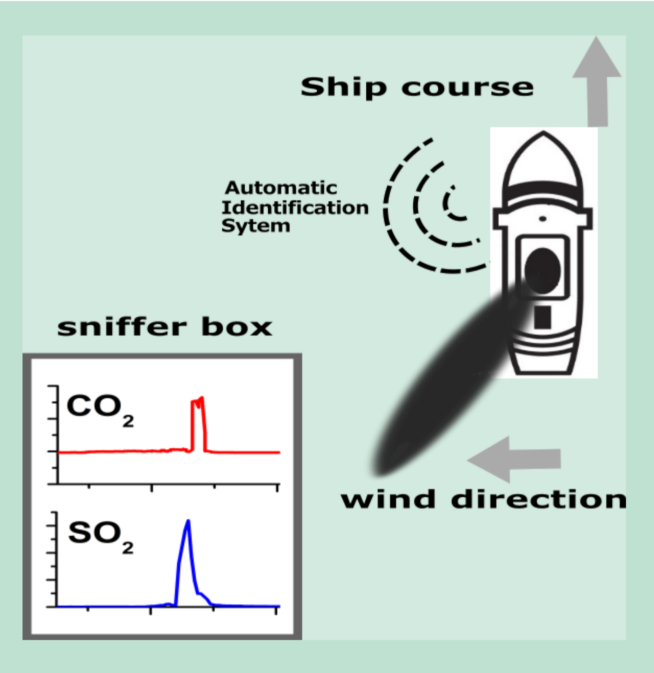



**FIGURE 1.** Schematic of the sniffer system and ship identification. An emitter ship is identified by combining wind measurements and the transponder signals through the Automatic Identification System AIS.

## 2.2 Instrumentation and correction for cross interference

The sniffer systems, respectively, are 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 ($\sigma$) is given.

| Species | Quantity | Method | Model | $t_{90}$ | $1\sigma$ | 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 |
| $CO_2$ | Mixing ratio (sniffer) | Non dispersive infrared instrument, single cell with multiple filters. | LI-COR 7200 | 0.1 s | 0.3 ppm | Air |
| $SO_2$ | 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).

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

## 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 $SO_2$ and $CO_2$ 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 $SO_2$ and $NO_x$ remotely. The overall estimated uncertainty for $SO_2$ 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.

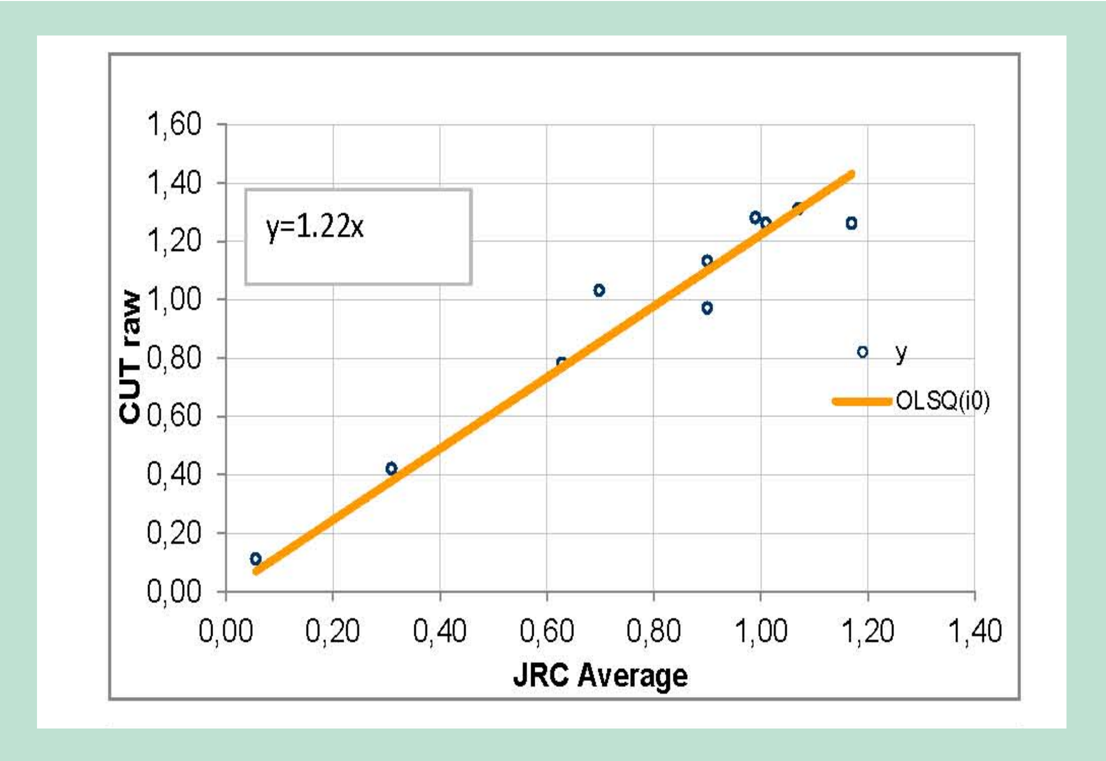



**FIGURE 2.** Field measurements in Rotterdam measuring individual ships during two days in the ship channel of Rotterdam (Balzani 2013). Two nearby systems, the Chalmers sniffer system (CUT) and the system developed by the Joint Research centre (JRC-Ispra) were compared.

## 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 ($1\sigma$) 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 440 vessels in 2015 and 178 vessels in 2016 with the same median value on both years (0.08 % m/m). The same average value was obtained from 316 fuel samples in Danish ports in 2015 and 2016 (pers. comm. Dorte Kubel, Danish EPA). It is rather likely that the median FSC of the ships passing the Great Belt Bridge and around the waters of Denmark is the same also in 2018, or higher, as the port state control data and we have therefore adjusted the threshold for compliance accordingly.

For instance for the sniffer data measured at the Great Belt Bridge in 2018 there is a negative bias of 0.074% in FSC units for the period January to November 2018, when compared to port state control data. Ships running with an FSC value of 0.1 %, will hence be measured as having a FSC of 0.026%, on average. However, since the measurement have random noise associated with them corresponding to a precision with standard deviation 0.04 %, the data will be spread out according to a Gaussian distribution. Most of the data (95 %) will be within 2 standard deviations from the 0.026 % value; this gives an upper value of 0.11 % FSC units and this is the bias corrected compliance threshold used in our evaluation. Individual ships with FSC measured above this limit are considered to use non-compliant fuel with 95 % confidence limit. The general threshold for compliance can be described according to Eq 3,

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

where the bias corresponds to the difference between the median value of port state control data and the median value of sniffer measurements, $\sigma$ corresponds to the precision obtained as the standard deviation of multiple measurements and 0.1 % is the SECA limit for FSC. We can not explain the reason for the negative bias and potentially it is caused by 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 the compliance threshold is modified to account for the bias in our data, so it can be used to calculate compliance levels. It is however, not the threshold for the real data, since in this case one should use the real FSC threshold of 0.1% , taking into account only the 4% variability for the data % . For instance, in the case of the Great Belt Bridge the real threshold, at 95 % confidence limit 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 |
|---|---|
| Random uncertainty abs FSC unit | ±0.04% m/m |
| Systematic bias | -0.074% |
| Threshold(2) for compliance limit (95 % confidence limit) | 0.18% FSC |

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

# 3. Measurements

## 3.1 Installation

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 its 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 (every 5$^{th}$ day) by injecting reference gases through a 10 m gas tube that is connected in the beginning of the sampling line close to the main inlet to the sniffer system.

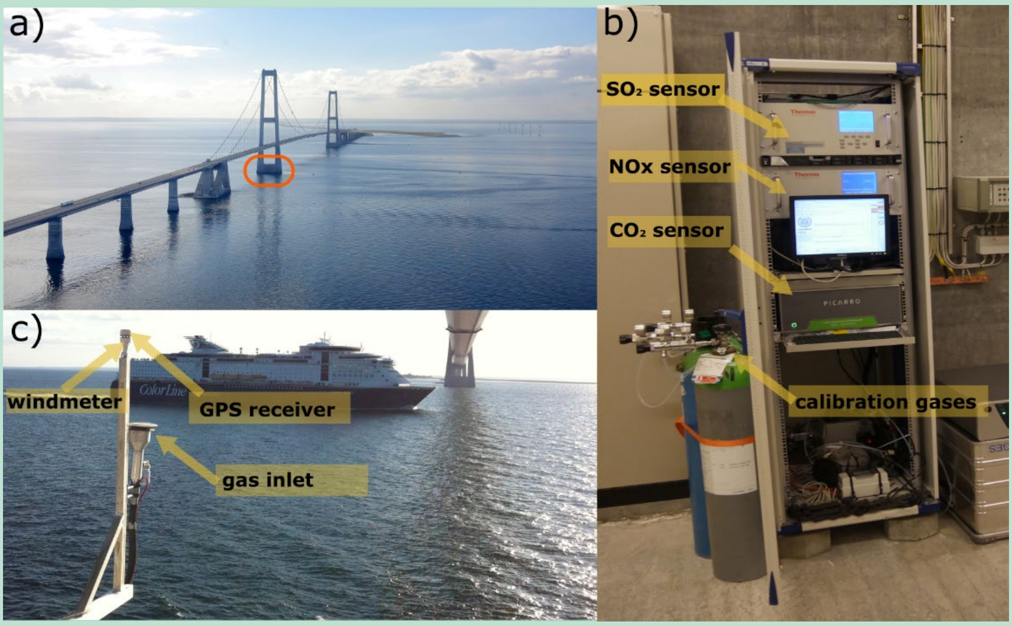



**FIGURE 3.** Fixed sniffer system installed at The Great Belt Bridge, Denmark. (a) Installation site at the Pylon 16 of the bridge. (b) Instrument racket in the control room. (c) Metallic angle structure holding the GPS receiver and the wind receiver. The gas inlet and the AIS antenna are in the same 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.

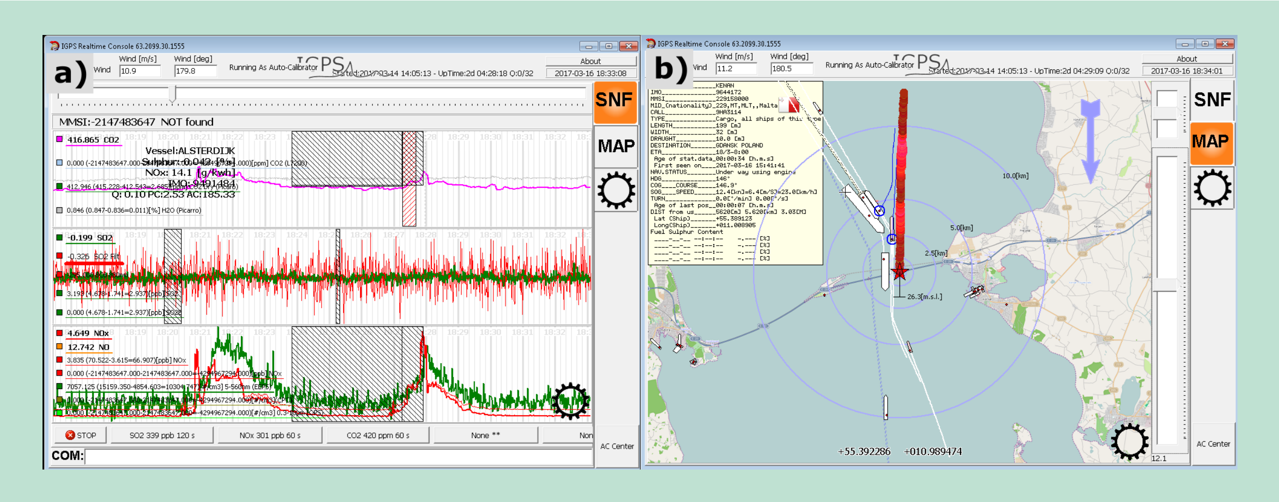
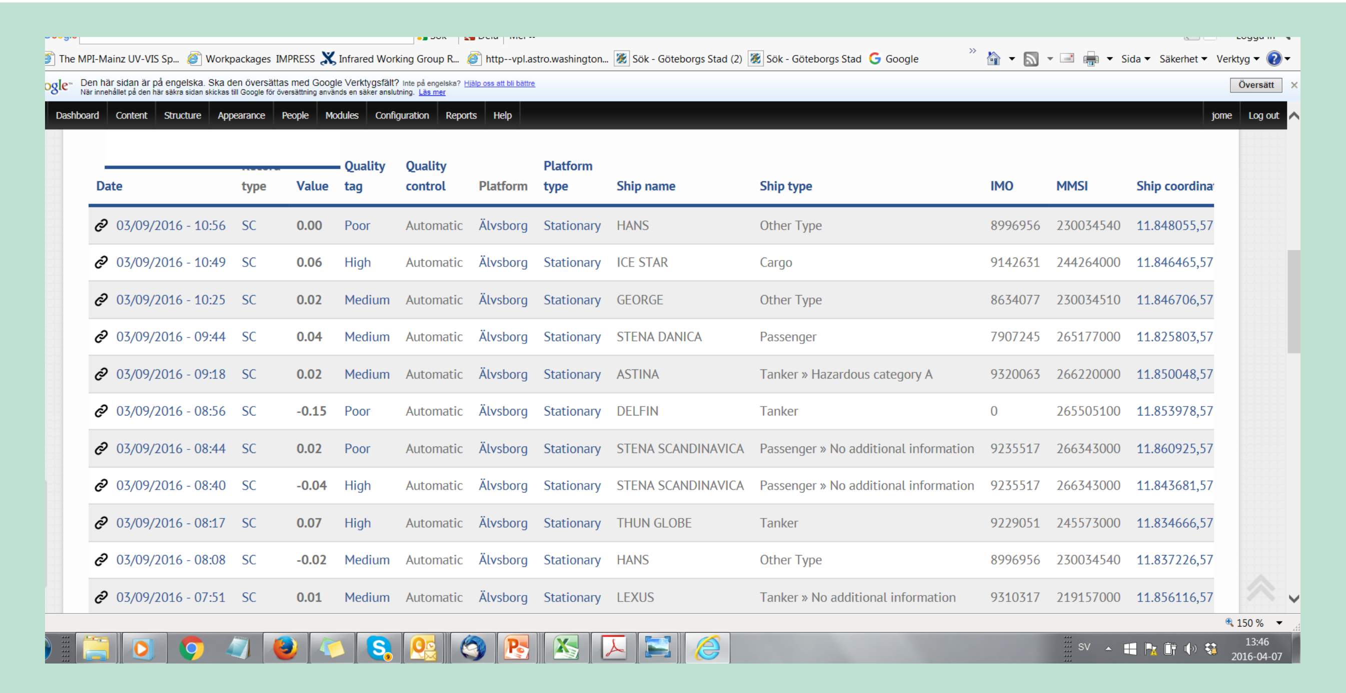



**FIGURE 4.** Example of the IPGSpresent software while performing a measurement at The Great Belt Bridge. (a) Real-Time series of $CO_2$, $SO_2$ and $NO_x$ concentrations. (b) Identification of plumes from the nearby ships. The TCPLog and IGPS mailer are running as background processes.



| Date | Record type | Value | Quality tag | Quality control | Platform | Platform type | Ship name | Ship type | IMO | MMSI | Ship coordina |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 03/09/2016 - 10:56 | SC | 0.00 | Poor | Automatic | Älvsborg | Stationary | HANS | Other Type | 8996956 | 230034540 | 11.848055,57 |
| 03/09/2016 - 10:49 | SC | 0.06 | High | Automatic | Älvsborg | Stationary | ICE STAR | Cargo | 9142631 | 244264000 | 11.846465,57 |
| 03/09/2016 - 10:25 | SC | 0.02 | Medium | Automatic | Älvsborg | Stationary | GEORGE | Other Type | 8634077 | 230034510 | 11.846706,57 |
| 03/09/2016 - 09:44 | SC | 0.04 | Medium | Automatic | Älvsborg | Stationary | STENA DANICA | Passenger | 7907245 | 265177000 | 11.825803,57 |
| 03/09/2016 - 09:18 | SC | 0.02 | Medium | Automatic | Älvsborg | Stationary | ASTINA | Tanker » Hazardous category A | 9320063 | 266220000 | 11.850048,57 |
| 03/09/2016 - 08:56 | SC | -0.15 | Poor | Automatic | Älvsborg | Stationary | DELFIN | Tanker | 0 | 265505100 | 11.853978,57 |
| 03/09/2016 - 08:44 | SC | 0.02 | Poor | Automatic | Älvsborg | Stationary | STENA SCANDINAVICA | Passenger » No additional information | 9235517 | 266343000 | 11.860925,57 |
| 03/09/2016 - 08:40 | SC | -0.04 | High | Automatic | Älvsborg | Stationary | STENA SCANDINAVICA | Passenger » No additional information | 9235517 | 266343000 | 11.843681,57 |
| 03/09/2016 - 08:17 | SC | 0.07 | High | Automatic | Älvsborg | Stationary | THUN GLOBE | Tanker | 9229051 | 245573000 | 11.834666,57 |
| 03/09/2016 - 08:08 | SC | -0.02 | Medium | Automatic | Älvsborg | Stationary | HANS | Other Type | 8996956 | 230034540 | 11.837226,57 |
| 03/09/2016 - 07:51 | SC | 0.01 | Medium | Automatic | Älvsborg | Stationary | LEXUS | Tanker » No additional information | 9310317 | 219157000 | 11.856116,57 |

**FIGURE 5.** Example of data base setup from the Göteborg site Älvsborg

## 3.3 Hardware changes and practical problems

The system worked well during the measurements period, with only a few stop due to a malfunctioning internet part, power interruption due to work at the bridge and an electronic card for the automatic calibration.

## 3.4 Calibration

The quality assurance of the sniffer instruments is obtained by repeated calibrations through the reported period. The instruments at the Great Belt installation site were remotely calibrated using gas standards diluted in nitrogen 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. In most cases the instruments were not recalibrated and instead the output from the instruments were validated and after-corrected using the calibration factors. However, when the instrument response deviated too much from the nominal value a hardware recalibration of the instrument was carried out.

## 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 3 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 poor quality data are uncertain

**TABLE 3.** The quality criteria applied for the fixed measurements at the Great Belt Bridge. Some of the criteria suggested for future use are also given

| 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 |
| $\Delta CO_2$ in plume | Peak height | >3 ppm | >2 ppm | 0.5 ppm |
| $\Delta CO2_{plume}$ | | >50 ppms | >25 ppms | 3> ppms |
| $\Delta t_{CO2}$ in plume | Time duration in plume | <100 s | <150 s | <240 s |
| Wind direction | Wind relative to ship movement | ±30° | ±60° | ±60° |
| Wind speed | | 3-8 m/s | 2-10 m/s | 1- 12 m/s |
| No of ships with overlapping plumes | | 1 | 1 | 1 |
| FSC | Filtering out low values | >-0.2 | >-0.2 | >-0.2 |
| $\Delta SO_2$ in plume | Peak height | NI | NA | NA |
| | | | | |
| $\Delta SO_2/(1.5\%*\Delta NO)$ | Interference effect, If interference dominates uncertainty increases | NA | NA | NA |

# 4. Results

The period of this project covers from March 1 to November 18, 2018. However, since the sniffer measurements at the Great Belt Bridge were on-going also during January to February as part of the EU interreg project Envisum we include also these data here. The system was in operation during 296 days out of 320 days (92.5% availability) from January to November 2018. Here 181 days had appropriate wind conditions. The obtained data set correspond to a total of 6177 ship plumes, Figure 6, divided into 3 qualities according to Figure 7.

In Figure 8 the frequency distribution of all FSC measurements between January to November 2018 is shown, corresponding to 3580 individual ship measurements of good or medium quality. *Note that a ship is counted twice if the measurements are on separate days*. The FSC data has a measured median value of 0.006 %. It also shows that a Gaussian distribution can be fitted to the data, with a width corresponding to a standard deviation of approx. 0.04 % 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, 0.006 % 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 0.074 % in FSC units. In our analysis we take this bias into account when calculating the bias corrected threshold for noncompliance as shown in Figure 8 and several figures below.

In Figure 9 a histogram is shown of the number of ships with different FSC levels for the Great Belt Bridge sniffer data for January to November 2018. Here all negative data points were assigned a FSC value of 0 %. In addition, the histogram data above 0.11% are shown corresponding to non-complying ship.

In Figure 10 the fraction of ships below a certain FSC level are shown for the period January to November 2018. The fraction below the bias corrected compliance threshold of 0.11 % is 95.3 %. Hence 4.7 % of the ships are running on non-compliant fuel with a confidence limit of 95 %. Here 1.1% the ships were operating on fuel with SFC levels above 0.5% while 0.8 % of the ships operated on fuel with FSC level between 0.3-0.5 %. The rest of the non-complying ships had FSC values below 0.3%.

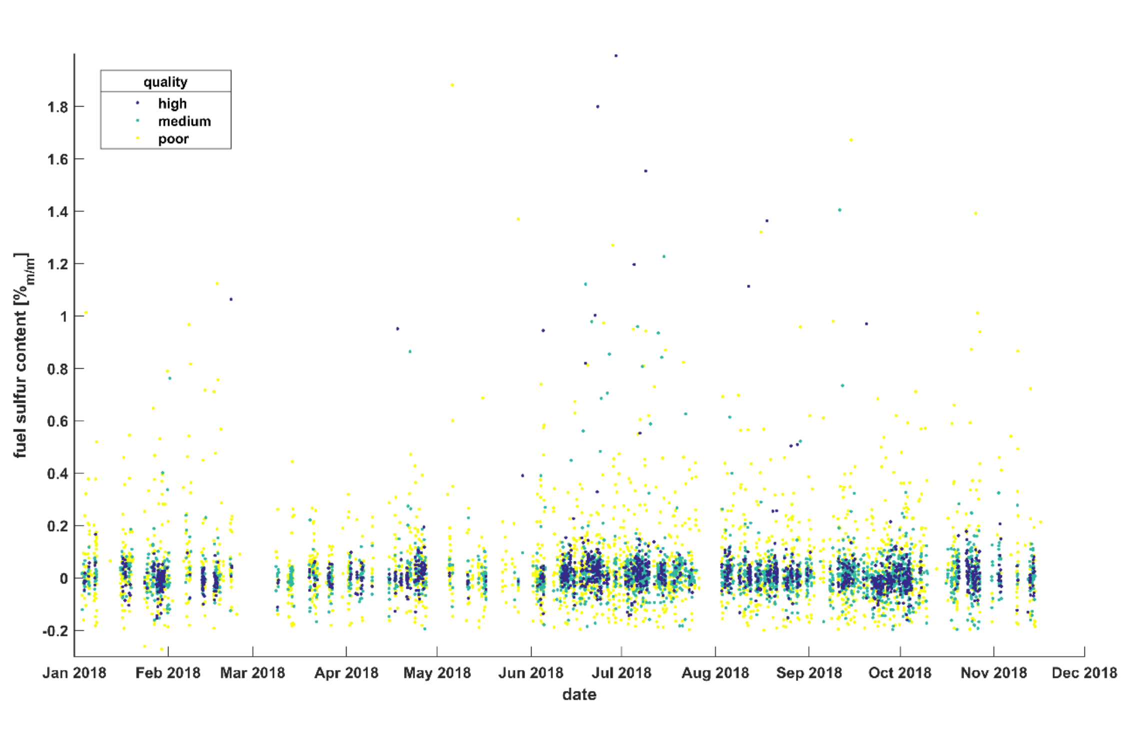



**FIGURE 6.** Sniffer measurements at the Great Belt Bridge between January and November 2018.

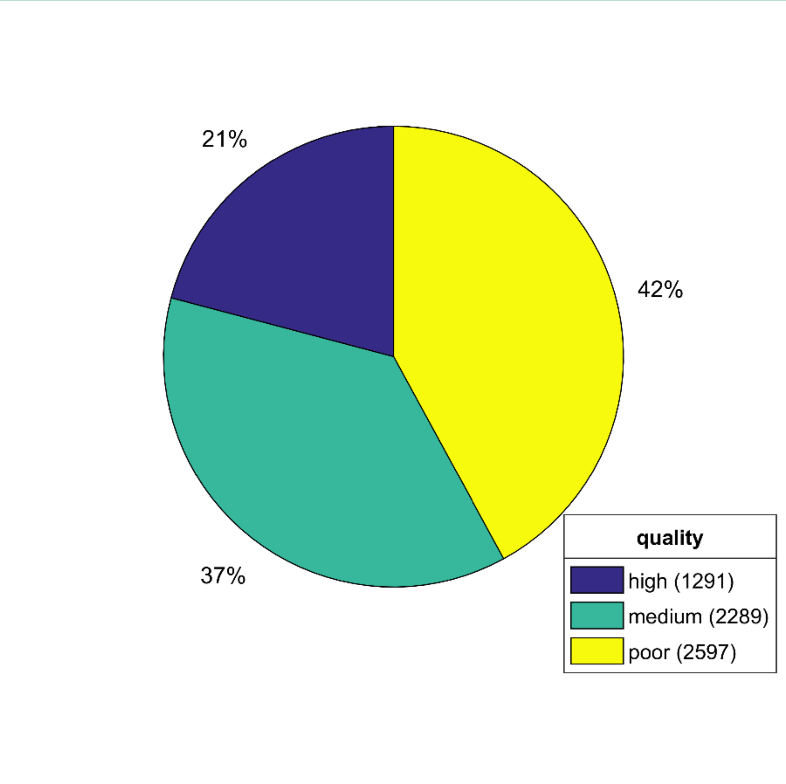



**FIGURE 7.** Statistical distribution of measurements quality at Great Belt Bridge and number of ships for the period January to November 2018.

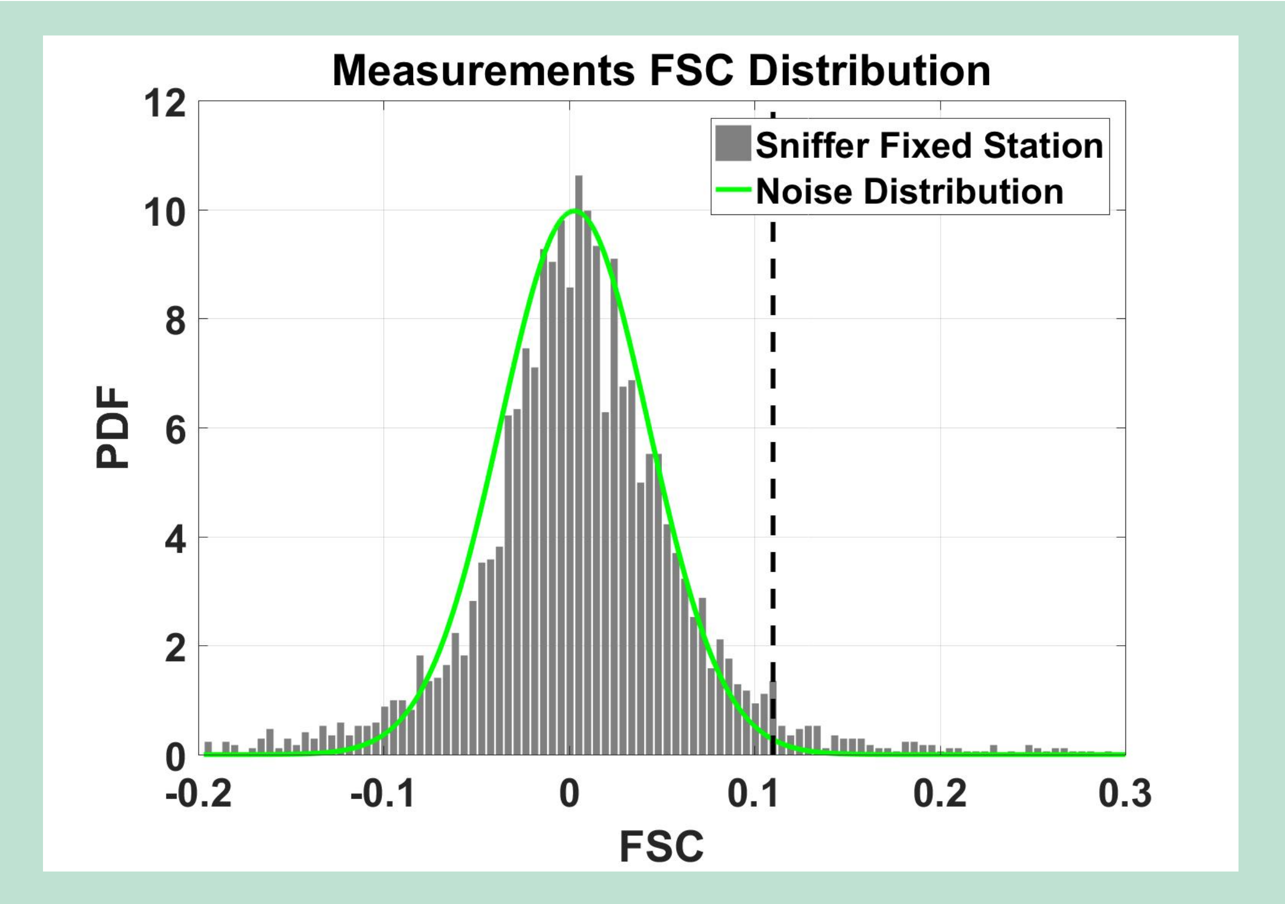



**FIGURE 8.** Statistical distribution (probability density function) of the FSC corresponding to individual ships measured with sniffer at the Great Belt Bridge. The data covers the period January to November 2018. The green curve corresponds to the random noise distribution (precision) of the measurements obtained from multiple measurements of single ships. The dotted line is the estimated non-compliance limit for which the instrument errors (precision and bias) have been accounted for.

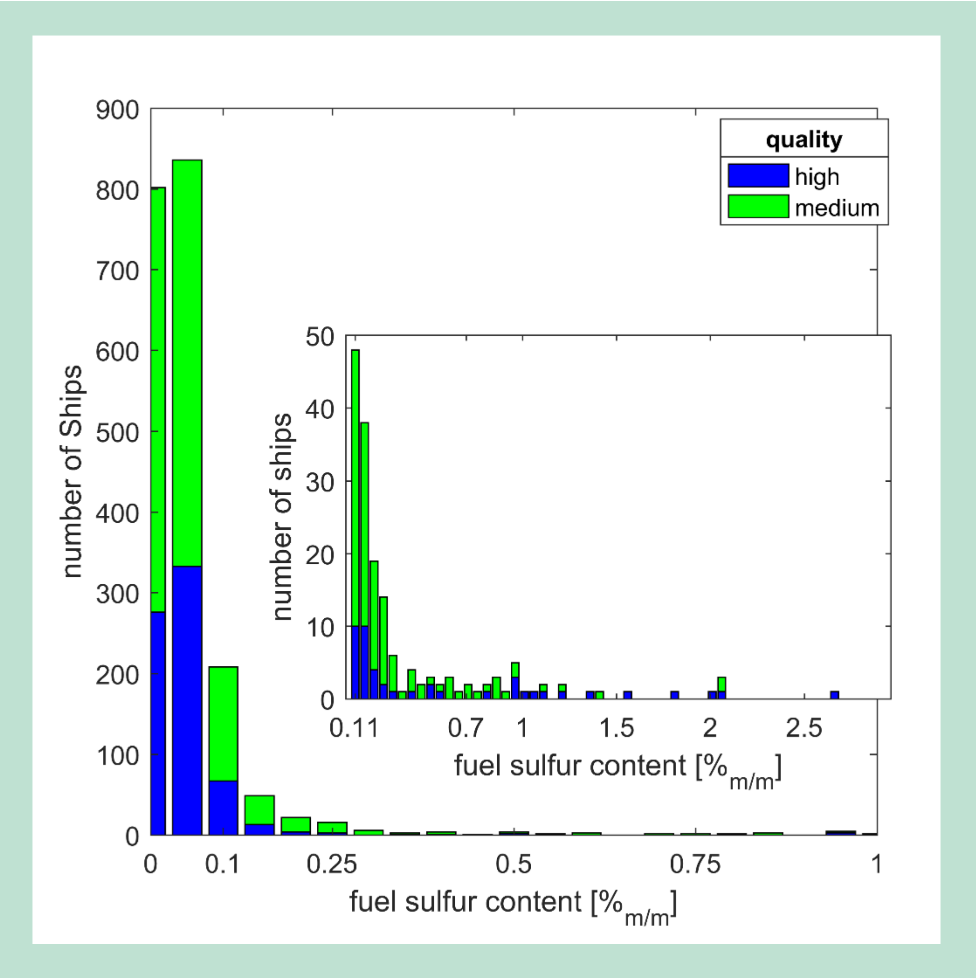



**FIGURE 9.** Histogram of fuel sulfur content shown for different measurement qualities. In the inset the distribution of fuel sulfur contents above 0.11 is highlighted, i.e. the bias corrected compliance limit threshold. The data correspond to 3580 ships measured between January to November 2018.

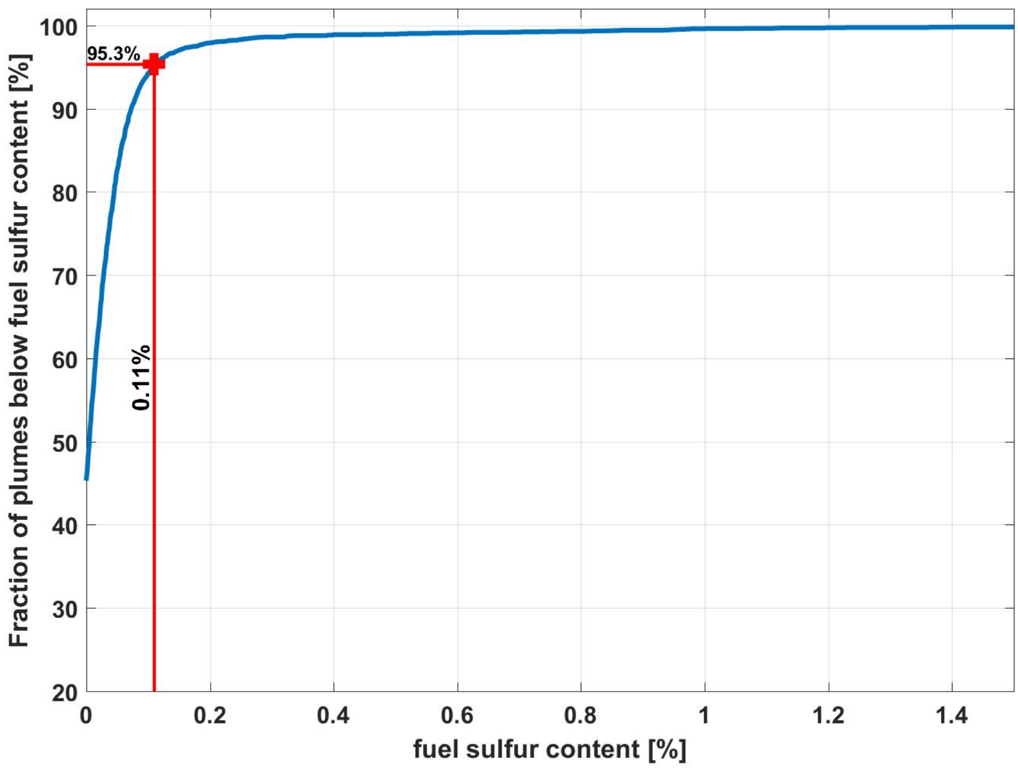



**FIGURE 10.** The fraction of ships that were measured below a certain FSC level at the Great Belt Bridge for the period January to November 2018. In addition, the biased corrected compliance limit threshold is shown.

# 5. Discussion

During the period January 1 to November 18, 174 individual ships were measured at the Great Belt Bridge to have non-compliant FSC out of 3580. Note that in this report a ship is counted twice if the measurements are done 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. Most of the non-complying cases seemed to occur during the summer season.

Several of the ships operating in the SECA area are equipped with scrubbers which remove the $SO_2$ from the flue gas. The ships are in this manner able to operate on high sulfur fuel. In the past there were several examples in the dataset of scrubber ships that were measured above the compliance threshold (Mellqvist 2018), During 2018 one ship was commissioning a scrubber with some technical difficulties which later were solved.

# 6. Acknowledgment

The project was carried out for the Danish Environmental Protection Agency corresponding to the tender: 2017/S 234-486297. We also acknowledge the EU interreg project EnviSum for providing additional data to this project. Oscar Isoz is acknowledged for support.

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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 Emissions From Ships at the Great Belt Bridge 2018**
Chalmers University of Technology has prepared the report for the Danish Environmental Protection Agency (DEPA). It outlines the results of the sniffer monitoring of sulfur emissions from ships from the Great Belt Bridge in 2018 as part of the DEPA's maritime sulfur enforcement effort.

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