Ministry of Environment and Food of Denmark
Environmental Protection Agency

Remote sensing of sulphur and particle pollution from ships – from a cost-efficient approach

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Contents

1. Preface

This is the final report in the project with the official title “Cost-efficient technology for surveillance of sulphur and particles in plumes from ships”, co-financed by the Danish Environmental Protection Agency (EPA) under the subsidy scheme MUDP 2015. The project was initiated in December 2015 and finalized in March 2018.

The overall purpose of this project was to develop and identify the potential for using simple and improved cost-efficient methods for monitoring sulphur content in fuel from ships by means of remote sensing techniques.

The project was a partnership between ZenZors A/S, Sund & Bælt A/S, Nordic Tankers Marine A/S, Maersk Maritime Technology, Danish Shipping and Danish Technological Institute.

All pictures and figures shown in the report are produced within the project group unless stated otherwise.

Danish Technological Institute

Aarhus, May 2018

2. Summary and conclusion

On 1 January 2015, the maximum allowed sulphur content in fuel was reduced from 1% sulphur to 0.1% sulphur in SO_x Emission Control Areas (SECAs) according to the International Maritime Organization (IMO). In addition, from 2020 the maximum allowed sulphur content in fuel will be reduced to 0.5 % sulphur globally (except for SECAs). The new IMO regulation will lead to a significant reduction of harmful emissions, which will have a positive effect on the environment and the public health in general. Thus, ship-owners must either use low-sulphur fuel or implement an emission-abatement method, i.e. a scrubber system, which removes the sulphur oxides from the vessel exhaust gas. Either approach will result in significant extra costs for the ship-owners and opens up for possible violations. In order to create a level-playing-field for the ship-owners and a credible risk of being observed when violating regulations, the ships must be monitored. This calls for a simple and robust control method.

Based on the input from the participating ship-owners and Danish Shipping, there is consensus that when considering the significant cost difference between high sulphur and compliant low-sulphur fuels, there is a real need for effective enforcement on a global scale, and also that different technology routes are pursued. With the global IMO regulations on sulphur content in fuel (maximum 0.5 %S), this will especially be the case after 2020.

The main aim of this project was to develop and identify the potential for simple and improved cost-efficient methods for monitoring sulphur content in fuel from ships by means of remote sensing techniques (indicative measurements and classification). The main focus has been on remote monitoring from the Great Belt Bridge.

In the early phase of the project, different CO_2 and SO_2 sensors were identified and evaluated for potential use in our measurements from the Great Belt Bridge for monitoring sulphur content in fuel. Prices range from less than €100 to several tens of thousands of Euros for the raw sensors. The description of the lab development and optimization of selected sensors is evaluated in chapter 5.

In the preliminary part of the project, extensive CFD modelling was carried out in order to determine optimum measurement position(s) at the Great Belt Bridge as well as estimates of gas concentration as function of distance from ship. The CFD modelling had a universal focus in order to be able to generalize the conclusions to cover not only the specific test location on the Great Belt Bridge, but also other bridges, harbor entrances, etc. The modelling results can be summarized as follows:

- No universal position for optimum placement of sensors is possible
- The optimum signal is modelled to be on average ~60 m above sea level (depending on chimney height) during low/normal wind speed conditions which agrees well with the position of the bridge deck on the Great Belt Bridge. Lower plume rise for high wind speed conditions.
- Sufficient CO_2 is available up to 5-600 m from a ship for theoretical use of low-cost sensors, i.e. ~100 ppm above background level.
- A turbulence zone is observed on the lee side of an average ship, which is most pronounced during high wind speed conditions. There is a sort of threshold behavior on wind, hard to define exactly, since this also depends on e.g. engine power, ship dimensions, etc.
- It should be sufficient to place the measurement inlet into the sensors at a vertical distance of 2-4 meters below the bridge deck to avoid turbulence effects.

IR thermography approach as well as visual inspection and photographing on the Great Belt Bridge helped to confirm some of the results from the modelling behavior of the plume, i.e. plume rising to about ~60 m during normal wind speed conditions and less during high wind conditions. During high wind conditions and in case of specific ship designs, part of the plume is also observed being sucked down on the lee side of the ship.

The linearity, precision, range, and response times of all sensors have been measured in a laboratory setting and these have been documented in chapter 5 and Appendix. Based on these results, it is possible to conclude that they fulfill the requirements for the campaigns without compromising the aim of the project for using cost-effective sensor technology and being able to distinguish low-sulphur fuel (0.1 %) from fuel with higher sulphur content (0.5-3 %).

The chosen CO_2 sensors are modified NDIR detectors from GSS, UK with a response time after modification at around 1s (1/e-definition). Two kinds of SO_2 measurement technologies have been used. The most cost-effective technology is the electrochemical sensors, where a pair of SO_2 and NO_2 from Membrapor have been tested showing response times at around 6s. Two sensors are needed, because NO_2 in the plume is also detected on the SO_2 sensor, i.e. there is a cross interference. Finally, the second SO_2 technology is a pulse fluorescence analyzer from ThermoFischer, with the longest response time of 35s. The design of the probe interface has been described in terms of the used materials, the principles of the flow design and the possible measurement positions. Furthermore, it was found that the near optimum measurement position exists at the lantern outlets below the suspension bridge.

The purpose of the first measurement campaign on the Great Belt Bridge (spring 2017) was to evaluate the actual CO_2 concentration available in the plume at the identified optimum measurement locations on the bridge deck. As a result, rough SO_2 concentrations can then be extrapolated. Furthermore, the obtainable hit rate (positively identified ships) and information about the temporal length of the signals was desired. The central node and eastern ship lane marking lamp outlets were used as measurement locations, and a tube of 2-5m was lowered under the deck of the bridge to avoid turbulence effects. At each location, two modified CO_2 sensors as well as logging and communication equipment were installed. A particle detector was also installed in order to achieve positive identification of the ship passages.

Based on the spring 2017 CO_2 campaign of 55 days in total, the following conclusions were drawn:

- The CO_2 signal height above background is on average 50-150ppm, dependent on the method of evaluation and location.
- Signal length and temporal resolution is about 5-20s.
- Hit-rate depends on wind-direction, where up to 50% in the southern wind direction is achieved and in northwestern wind a hit-rate of about 25% is achieved.
- Based on the available data on the ship passages, it was difficult to identify an exact ship if more than one ship passed the bridge within a 5 min. window.
- The found hit rate at the central node is ~21% and at the eastern location ~7%. It is speculated that these numbers may be too optimistic, because they are only based on one working sensor signal.

During autumn 2017, the final measurement campaign with both SO_2 and CO_2 monitoring was carried out. The aim of this campaign was to determine the applicability of the developed cost-effective sensor package for monitoring at the central node of the Great Belt Bridge, which was identified to be the optimum location. The hit rate of positively identified ships was found to be around 3-4%, and the average CO_2 concentration of the peak was about 80ppm above background level. In the data analysis, the system calibration factor was found by assuming that the average sulphur content was about 0.1%S. All %S values are calculated to be below

0.3%S, which indicates that none of the identified ships were using a high sulphur concentration fuel. Statistical analysis of the results show that using the electrochemical sensors allows distinguishing between 0.1%S and 0.5%S. The standard deviation using the pulse fluorescence analyzer is low, hence it is possible to distinguish between 0.1%S and 0.35%S with our developed method.

With a CO_2 concentration around 50ppm above the background, the expected sulphur concentration in the plume is about 22 ppb (0.1%S fuel), which is at the detection limit of both SO_2 sensing technologies. This can explain why the calculated sulphur content has a relatively high noise.

The main challenges for measuring the plumes on the bridge deck are that they are typically diluted to below 50-100ppm CO_2 (above the background level) and that the duration of the plumes is very short ,- typically 5-10s. The additional challenges by using the cost-effective equipment is that highly diluted plumes with CO_2 concentrations <25ppm could not be pinpointed due to the sensor noise. Furthermore, the SO_2 electrochemical sensor is cross-sensitive to NO_2 in the plume, hence this compensating algorithm is needed. The pulse fluorescence analyzer has a rather long response time, which makes it troublesome to use without correcting the time response of the plume.

In conclusion, we have rendered it possible to distinguish between 0.1 and 0.5 %S in fuel using cost-efficient sensors from the Great Belt Bridge. The price for raw sensors, including pumps, casing and tubing is estimated to be below €1,500. Hereto comes expenses for servicing the equipment and software for data analysis, AIS data subscription, reporting, etc., which cannot be estimated with the existing knowledge. The main compromise of using cheap sensor technology, compared to state-of-the-art sensors, is the hit-rate of positively identified ships which in our study lies around 3-4% from the specific measurement position at the bridge deck (central node position). This relatively low number is due to higher noise in the low-cost sensors as compared to using present state-of-the-art sensors. However, continuous sensor improvements with respect to precision and reliability is expected in the future. By installing additional cost-effective sensors at e.g. an eastern and western pylon position, thus covering the entire bridge span, the total hit-rate could also be significantly higher and the hardware cost would still be lower than a state-of-the-art installation.

Besides this particular Great Belt Bridge application, the developed setup could also be used in the future for e.g. harbor entrances or at other bridges with expected similar hit rates, however not possible to define exactly without carrying out specific measurements or evaluating the construction details. In addition, we also predict that the modified CO_2 sensors and measurement approach could have a strong potential for other monitoring applications where short signal duration is a pre-condition.

3. Introduction

3.1 Sulphur emission control areas and IMO regulation

From 2020 ship-owners will face strict requirements regarding fuel sulphur content, both worldwide and as already implemented in Sulphur Emission Control Areas (SECAs) in Northern Europe and North America.

In 2010, the maximum allowed sulphur content in fuel was reduced to 1% in SECAs, and in 2015 the limit was further reduced to 0.1% sulphur content, according to the International Maritime Organization (IMO).[1] As such, ship owners are required to use either low-sulphur fuel or implement an emission abatement method, i.e. a scrubber system, which removes the sulphur oxides from the vessel exhaust gas. The latter makes it possible to continue using fuel oil with high sulphur content if the vessel has the relevant approvals from its flag State in order to document the sulphur equivalent emissions. On a global scale, the sulphur limit will be reduced to 0.5 % sulphur content starting from 1 January 2020 and onwards. This is expected to be both a logistic challenge with availability of compliant fuel and a great challenge with securing sulphur compliance at open sea from a regulatory point of view.

The North European SECA, covering the Baltic and the North Sea area, including the English Channel, can be seen in Figure 1. The SO_x regulations are illustrated in Figure 2. In addition to the North European SECA, there is also the North American SECA, which comprises most of the US and Canadian coast and the US Caribbean SECA.[1] In addition to SO_x regulations, NOx and particulate matter (PM) are also regulated. PM is partly regulated through the sulphur regulative.

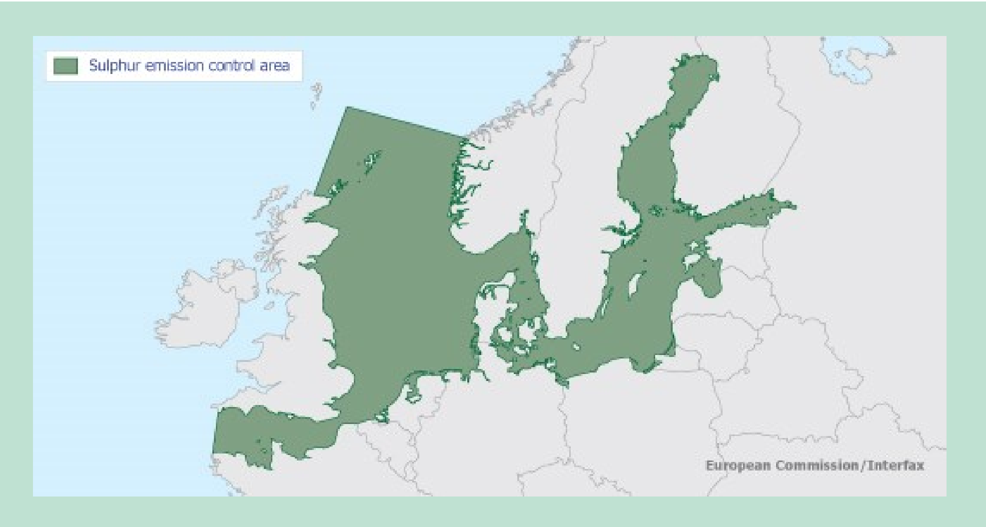

FIGURE 1. Northern European emission control areas (ECAs), covering the Baltic and the North Sea area, including the English Channel (source: European Commission)

Investment in compliant fuel or SO_x scrubber systems will result in significant extra costs for the ship owners and open up for possible violations. In order to ensure the health and environmental benefits and create a level-playing-field for the ship owners with a credible risk of being observed when violating regulations (especially the emission control requirements), the

[1] http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Sulphur-oxides-(SOx)-–-Regulation-14.aspx

ships must be monitored. So far, the relevant authorities primarily control the fuel sulphur content by spot checks of bunker delivery notes, fuel logs and occasional fuel sample analyses when ships are in port. These enforcement methods should not stand alone. Effective enforcement and equal conditions for ship owners call for a simple and robust control method that has the potential to be used worldwide, including at open sea from 2020.

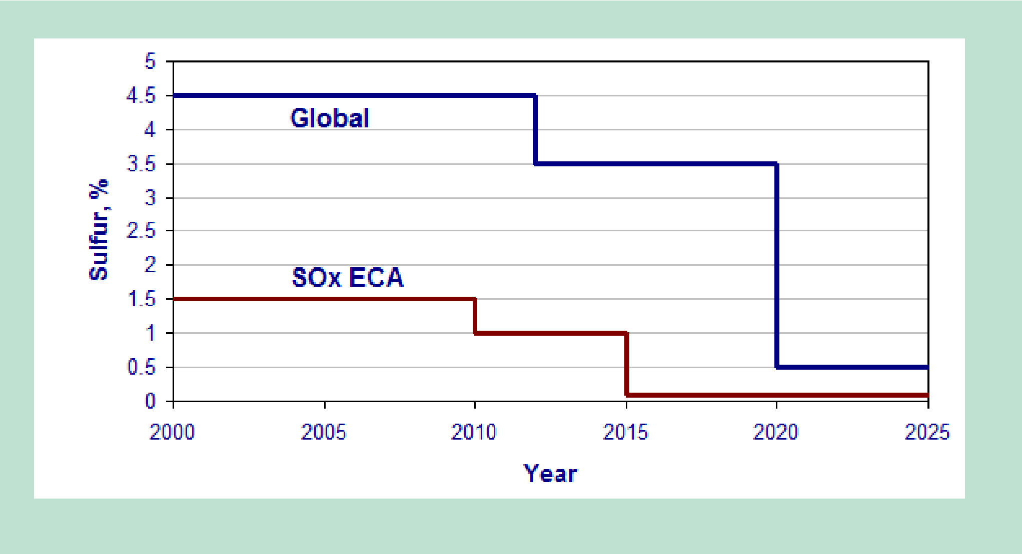

FIGURE 2. Development in SO_x regulations, in the past, present and future regulations as defined by the International Maritime Organization (IMO), MARPOL, Annex VI (source: https://www.dieselnet.com/standards/inter/imo.php)

Different projects have been initiated both nationally and internationally. During the past decade, Chalmers University of Technology in Gothenburg, Sweden, has developed a monitoring platform that makes it possible to measure sulphur concentration both from the air and from fixed installations by using state-of-the-art measuring equipment.[2,3] This allows making quite precise measurements of sulphur concentration. The equipment has been positioned outside Gothenburg for some years in addition to monitoring from the Great Belt Bridge in 2015-2018 (Danish EPA assignment). The Finnish Meteorological Institute (FMI) has also used a similar platform for monitoring in cooperation with Chalmers. Furthermore, there are other initiatives as well primarily across Europe.

In Denmark, a parallel initiative to this project has carried out successful measurements from drones and helicopters, also partly co-financed by MUDP as this project.[4] In combination with our approach, this latter initiative opens up for potential for making a combined and cost-effective monitoring platform from both fixed locations and drones. Now, the primary challenge with drones is that the drone must be within a visual line of sight of the operator, which puts a natural restriction on the applications and range.

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[2] J. Mellqvist and N. Berg, *Identification of gross polluting ships*, Chalmers University of Technology, 2010

[3] Johan Mellqvist, Jörg Beecken, Vladimir Conde and Johan Ekholm, Surveillance of Sulfur Emissions from Ships in Danish Waters, 2017, https://research.chalmers.se/publication/500251/file/500251_Fulltext.pdf

[4] J. Knudsen *et al.*, *Overvågning og tilsyn med svovlemissioner fra skibstrafik ved hjælp af droneteknologi*, Environmental project No. 1833, 2016

The present project is a continuation of a consortium and project initiated in 2013,[5] but here the focus has been laid on concluding on the potential of using cost-efficient sensor technology for remote sensing from fixed installations.

3.2 Project objective

The main objective was to develop and identify the potential for simple and improved cost-efficient methods for monitoring sulphur content in fuel from ships by means of remote sensing techniques (indicative measurement). The main focus has been on monitoring from the Great Belt Bridge. If such a suitable monitoring platform is developed, it will provide the ship owners with the assurance that their investments in low-emission technologies and/or low-sulphur fuels will not cause shortcomings compared to their competitors. In addition, a successful implementation of the sulphur directive will lead to an expected 90% reduction of SO_2 as compared to before 2015 as well as a significant reduction of particulate matter (PM).[6]

The primary focus in the project is the estimation of sulphur content by plume measurements (remote sensing) when ships pass the Great Belt Bridge (proof of concept). Each year, a total of 20-25,000 vessels pass the Great Belt corresponding to about three vessels per hour.[7] In Denmark, the majority of the vessel traffic passes either the Great Belt Bridge or the Oresund Bridge, so by monitoring these strategic locations, a large part of the fleet can be screened quickly.

3.3 Project execution

The project was initiated on 1 December 2015 and finalized on 31 March 2018. Compared to the original time schedule, the project was extended with four months in order to thoroughly complete the project milestones and activities.

The work carried out in the four individual work packages is described in the following chapters.

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[5] M. Køcks *et al.*, *Remote sensing of sulphur and particle emission from ships*, Environmental project No. 1835, 2016

[6] Helge Rørdam Olesen et al. *Ship emissions and air pollution in Denmark 2009,* https://www2.mst.dk/udgiv/publikationer/2009/978-87-92548-77-1/pdf/978-87-92548-78-8.pdf

[7] http://www.statistikbanken.dk/statbank5a/SelectVarVal/Define.asp?MainTable=SKIB25&PLanguage=0&PXSId=0&wsid=cftree

4. Work package 1: Knowledge gathering and plume modelling

4.1 Objective

In this WP, the focus has been on collecting knowledge on existing and cost-effective sensor solutions as well as knowledge sharing between the involved parties. In addition, extensive plume modelling was carried out in the proposed setup on the Great Belt Bridge to identify optimum measurement positions and expected gas concentrations under different physical and meteorological conditions. Finally, general considerations on plume behavior are discussed in order to generalize the simulation results to other potential monitoring locations from other fixed installations.

4.2 The sniffer concept and knowledge gathering

The basic idea when measuring sulphur emissions from a bridge is to monitor SO_2 and CO_2 in the plume and to use the ratio multiplied by a constant to determine the sulphur content. This is an accepted method for calculating sulphur equivalents in exhaust gas, e.g., using SO_x scrubbers.

Sniffer equipment requires a relatively close proximity (within some hundred meters) to the vessel and is restricted by wind conditions. However, the wind conditions can be dealt with by placing measuring equipment on both sides of the shipping lane concerned. One system has been in operation in Gothenburg, Sweden, by Chalmers for some years and is based on standardized, expensive state-of-the-art equipment for air quality monitoring for measuring gases (SO_2, NO_x, CO_2) with a relatively high precision. A similar setup has been installed by Chalmers at the Great Belt Bridge.[8] The sulphur content is then determined from the ratio of SO_2 to CO_2 using the following calculation, which is an accepted method and formula for calculating sulphur equivalents in exhaust gas.[9]

$$\%S \text{ in fuel} = \frac{[\mathrm{SO_2\ (ppb)}]}{[\mathrm{CO_2\ (ppm)\text{-}CO_{2,bagground}\ (ppm)}]} \cdot 0.232\ \%S$$

The formula assumes that all sulphur is oxidized into SO_2 and carbon into CO_2. This is of course an assumption, in particular for SO_2, since sulphur is also emitted as particulates and sulphuric acid, thus further oxidized to sulphates in the stack. According to Chalmers, the error is generally assumed to be quite small and within a few percent.[2] In addition, it is assumed in the formula that SO_2 is unaffected by travelling from vessel stack to monitoring equipment, and it should be noted that SO_2 can also oxidize to / condense as sulphuric acid, in particular during humid conditions – another loss mechanism. Thus, from a monitoring perspective, when having liable SO_2 and CO_2 measurements, in all cases the sulphur content is likely underestimated. Experience from the Chalmers project suggests that the overall error using the formula is approximately 10-15%, considering all losses in their set-up.

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[8] Johan Mellqvist, Jörg Beecken, Vladimir Conde and Johan Ekholm, Surveillance of Sulfur Emissions from Ships in Danish Waters, 2017, https://research.chalmers.se/publication/500251/file/500251_Fulltext.pdf

[9] IMO's guidelines for scrubbers, MEPC.259(68)

Also, other scientific equipment, like particle analyzers, can be added to the sniffer system, and software for ship tracking and identification (AIS) should be implemented alongside calibration procedures for instrumentation.

The total cost for one state-of-the-art installation is estimated to 100 k€ in pure instrumental hardware – in addition to this comes installation and running costs. This high cost is the main reason for carrying out this project, where we aim for a total price less than 1/20 of the described hardware cost with the trade-off being precision accepting a more indicative classification of ships. This must then be followed by further inspections by the relevant authority which today always is the case anyway. We suspect that the present price for a system is inhibiting the broadening of remote sensing solutions from fixed installations.

4.2.1 Enforcement

There is consensus among Danish ship-owners that when considering the significant cost difference between high sulphur and compliant low-sulphur fuels, there is a real need for effective enforcement on a global scale. This will not least be the case after 2020. Another challenge is the logistics concerning the 2020 global sulphur regulations and whether there will be enough compliant fuel from 2020. This challenge is, however, not directly addressed in this project but should also be targeted in combination with enforcement in order to secure sufficient available compliant fuel.

The Danish Ship owners' Association has conducted a small scale study on highlighting the placement of active *sniffers* around the world. Thus, *sniffers* are identified in Denmark, Sweden, Finland, Germany, Belgium and Holland.

In 2016, the Swedish Chalmers University of Technology deployed a high-end sensor package on the Great Belt Bridge to monitor the fuel sulphur content of the northbound ships. The installation was placed at the eastern pylon platform, and this monitoring was continued in the first half of 2017 alongside with our present initiative. Airborne monitoring in Danish waters was also continued in the second half of 2017 by the company Explicit A/S with monitoring from helicopters.

Maersk works dedicatedly to ensure a level playing field, also when sulphur regulations enter into force on the high sea. For example, Maersk conducts an ongoing project about in-stack CEMS (continuous emission monitoring system) on the individual ships. However, the specific technology used by Maersk needs to mature in order to be able to provide reliable results on compliance. Nordic Tankers is also involved in other initiatives than our present project, including on-board CEMS trials with another technology partner. Both ship-owners are interested in pursuing different technology roads and evaluate options for best possible enforcement of the new sulphur directive, not the least following 2020.

4.2.2 Cost-efficient sensor options

In the early phase of the project, different CO_2 and SO_2 sensors were identified and evaluated for potential use for our measurements. The identified sensors are listed below, and the lab development/optimization part is evaluated in the next chapter:

The potential CO_2 sensors are:

- SprintIR from GSS (UK) modified to be flow-through using NDIR detection
- SenseAIR CO_2 Engine K30 using NDIR detection
- Licor LI820 using NDIR detection
- Picarro G2301 using Cavity ring-down spectroscopy

The identified SO_2 sensors are:

- SO_2/C-1 from Membrapor that is an electrochemical sensor
- SO4-D2 from Alphasense which is also an electrochemical sensor
- SO_2 analyzer from Thermo Fischer which uses UV pulse fluorescence

The price of the CO_2 NDIR sensors from GSS and SenseAir is less than €100 for the raw sensor. The Licor NDIR sensor has a price below €4,000, whereas the Piccaro has a price above €60,000. Each electrochemical sensor including electronics has a price below €250 and a pulse fluorescence analyzer is in the price range of €10,000.

4.3 Plume modelling

The purpose of this work was to determine how the plumes from ships are diluted and where it makes the most sense to physically measure the chemical content of the plumes. This involves building a reliable computer model and obtaining physical-meaningful results. The key outcome is how the plumes are diluted with distance and the height of the center of the plume with distance. Furthermore, insight into the dominating flow mechanism is desired.

4.3.1 Method and models

In this project, the ANSYS CFX CFD-software is applied. In previous study,[5] the plume has been simulated near the Great Belt Bridge, but currently a more general understanding of the plumes is desired. The following models are built and their purposes are:

- Plumes in free flow
  - To simulate the gas dilution and height of plumes with distance
- Plumes from an obstacle (“ship-like” object)
  - To investigate the influence of a ship/structure on the behavior of the plume
- Flow around the bridge deck
  - To find an optimum vertical placement of the measuring inlet under the bridge deck

Chosen common input parameters are:

- Gas exhaust: 90,000 kg/h (25 kg/s) which corresponds approximately to a 10.5MW engine (Based on MAN Diesel &Turbo 5S60ME-C8.5)
- Exhaust temperature: 250 °C
- CO_2 fraction of exhaust: 7 % (After the simulations were carried out, the CO_2 fraction was discussed and a more appropriate value for a 2-stoke marine engine is closer to 4-5%. This correction does not influence the simulations, but the quantitative results can be corrected by multiplying the identified values with ~0.7.)
- Chimney diameter: 2.5m
- The simulations are the so-called steady-state, i.e. the ship/source is not moving.

In the free flow model, the following domain and parameters are used:

- Exhaust height: 10m
- Domain size: 600x60x70m (LxWxH)
- Wind speed: 8 m/s

In the model, where the exhaust is located on an obstacle, the following domain and parameters are used:

- Symmetry axis in the middle of the exhaust and obstacle is used
- Exhaust height: 25m
- Domain size: 500x240x90m (LxWxH), hence the simulated width is 120m
- Obstacle size: 25x25x24m (LxWxH)
- The obstacle is an at angle of 45° to the wind
- Chimney height: 1m
- Wind speeds: 4, 6, and 8 m/s

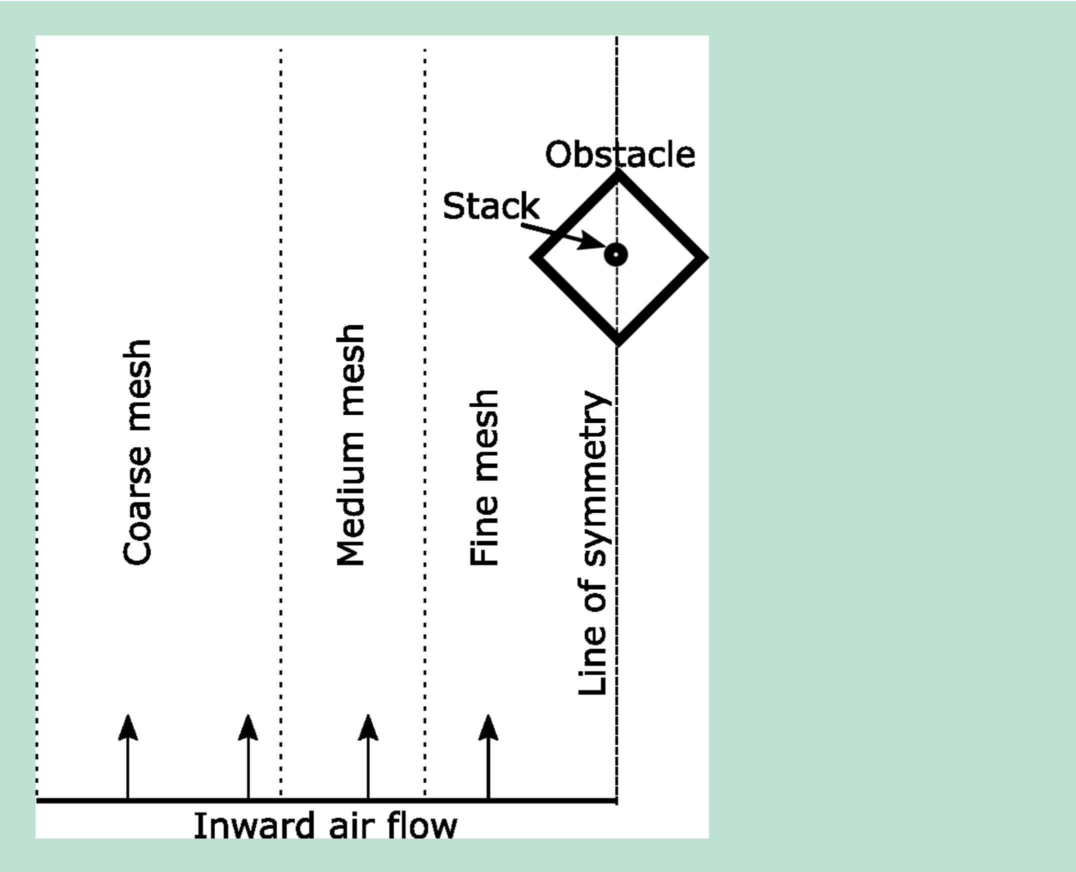

FIGURE 3. The sketch of the model with an obstacle. Note that the symmetry of the problem is used, so only half of the stack and obstacle is modelled (the mirror line goes through the middle of them). The domain is structured in a way that the discretization mesh is finest close to the obstacle and coarsest at the border of the domain.

In the model of the bridge deck, no exhaust is modelled, hence only the wind speed (4 and 8 m/s) and the angle between the wind direction and the length of the bridge deck (25° and 50°) are varied. Detailed diagrams/plans from A/S Storebælt have been used as input for modelling the bridge deck, see Figure 4 and 5.

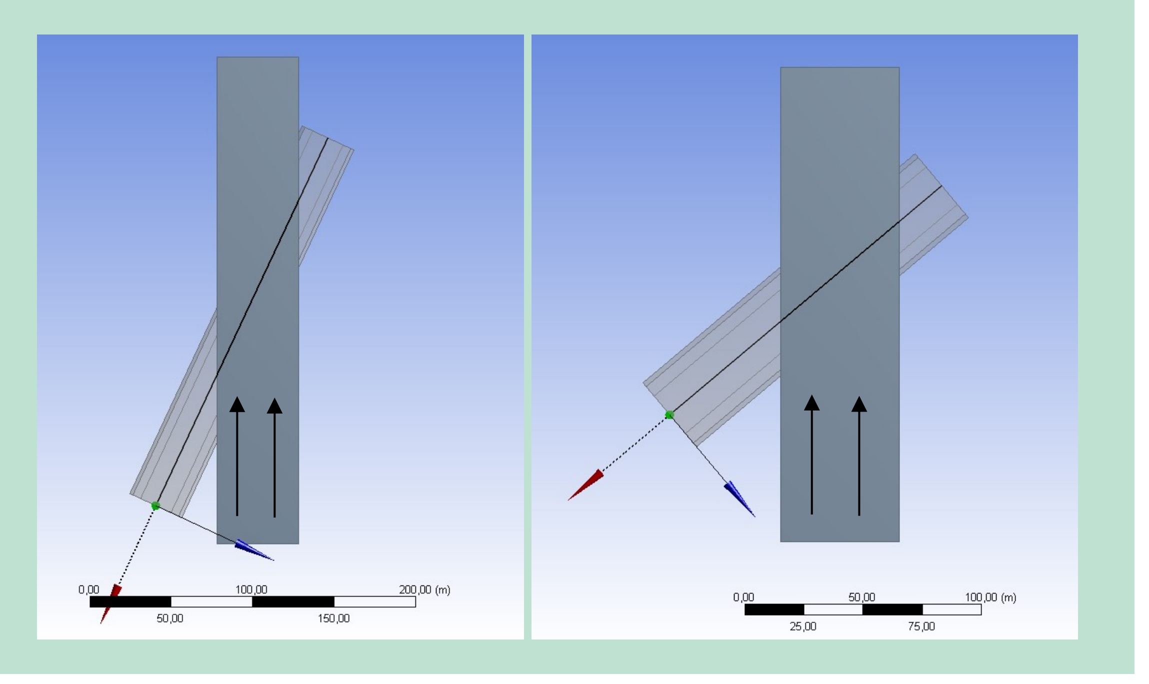

FIGURE 4. Bridge at an angle of 25° to the wind direction (left) and bridge at an angle of 50° to the wind direction (right).

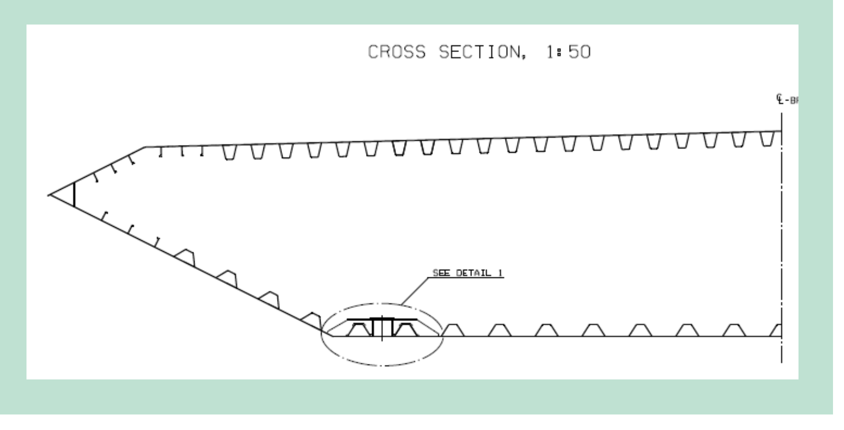

FIGURE 5. Cross section of the bridge deck, where the measurement inlet is at the marked detail. Source: Sund og Bælt A/S.

4.3.2 Results and discussion

In the following, the results of the models will be presented and discussed.

4.3.2.1 Plumes in free flow

In this model, the exhaust is originating from a horizontal surface "hanging" in free air and no other objects are present. The Figures 6-10 and their caption describe the general findings.

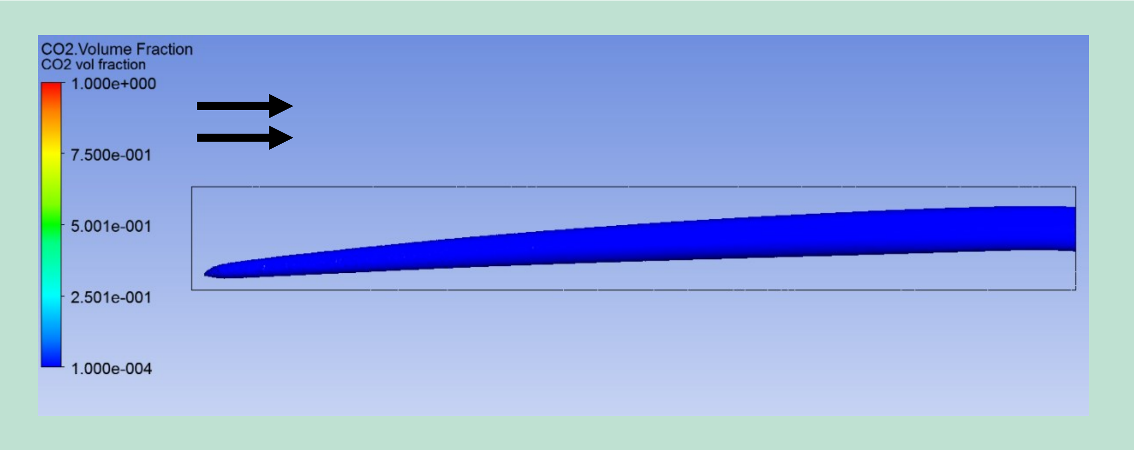

FIGURE 6. The plume is shown as the surface/volume of the CO_2 containing air at a concentration of 100 ppm (above background) or higher. The wind speed is 8 m/s from the left side. The plume is spreading in the axial direction and is rising to more than 50 m height with the distance of 590m.

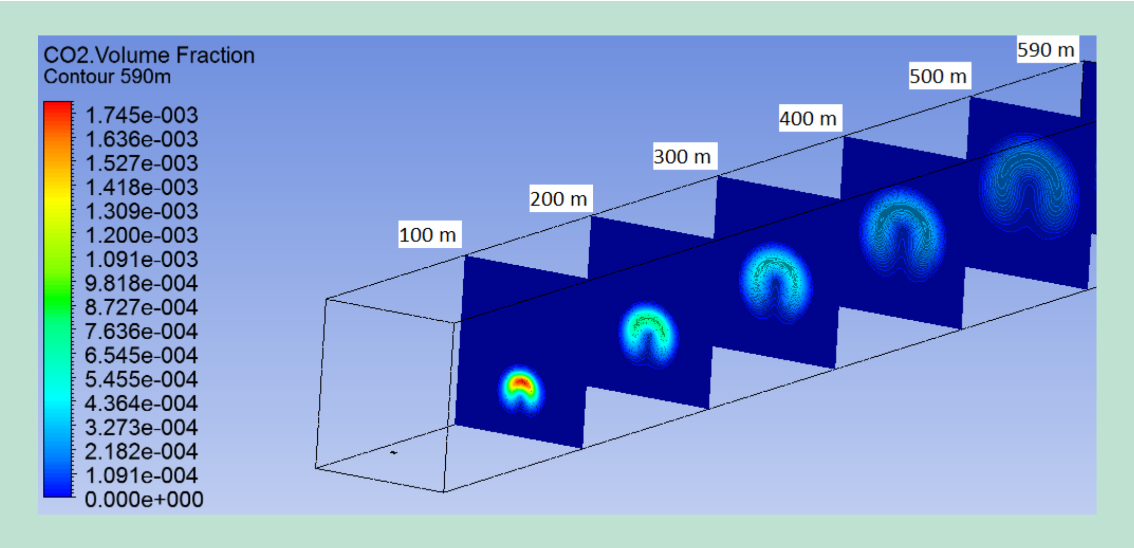

FIGURE 7. The plume is illustrated using cross-sections, where the distribution of the CO_2 can be seen at each surface. It is distributed as a reverse U-shape due to the buoyance of the hot exhaust**.**

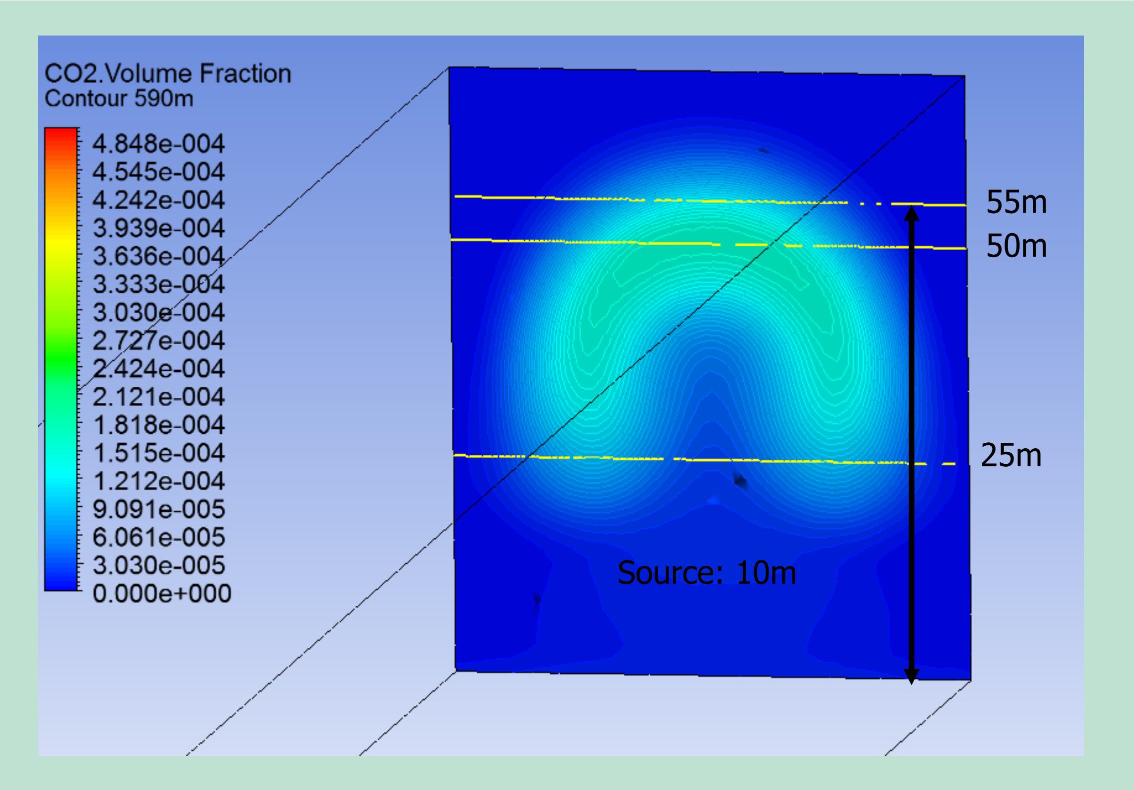

FIGURE 8. The reverse U-shape distribution of the CO_2 590m down-stream. The lines are included to show the height. CO_2 distribution along these lines is shown below.

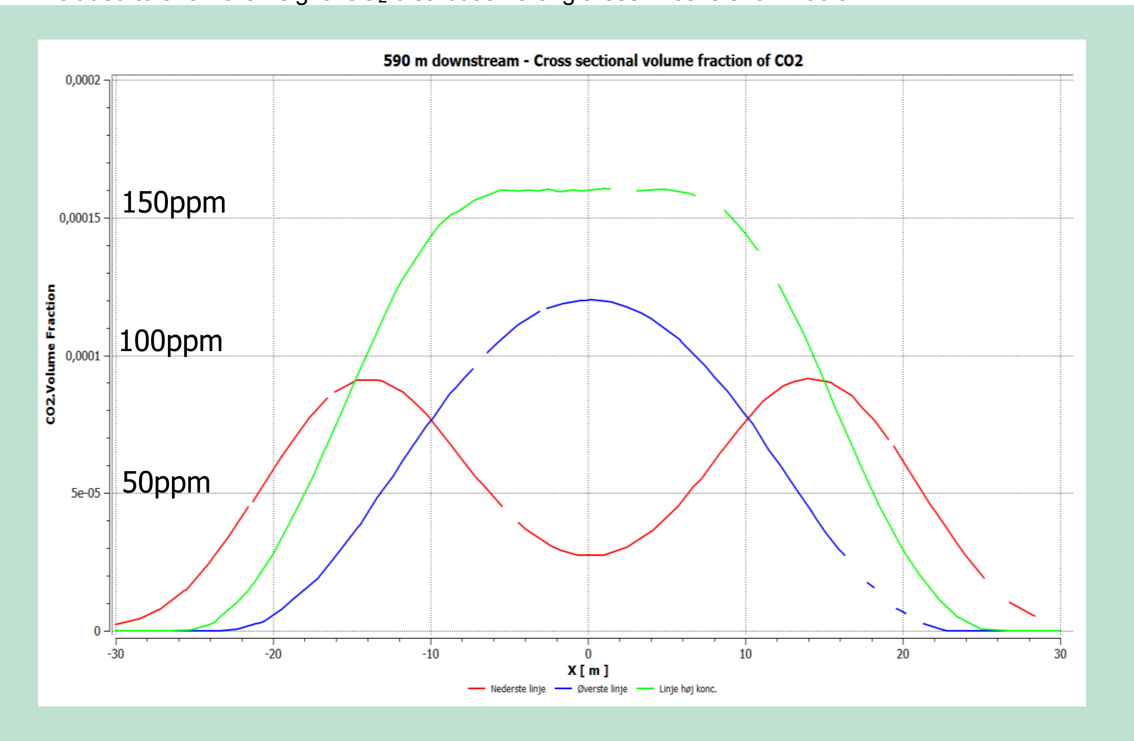

FIGURE 9. The CO_2 distribution 590m down-stream along horizontal lines at 25m (red), 50m (green), and 55m (blue). In this simulation, the source is in 10m height. Note, the values refer to CO_2 concentration above the background concentration of ~400 ppm. It can be seen that the width of the distribution is maximum 50 m.

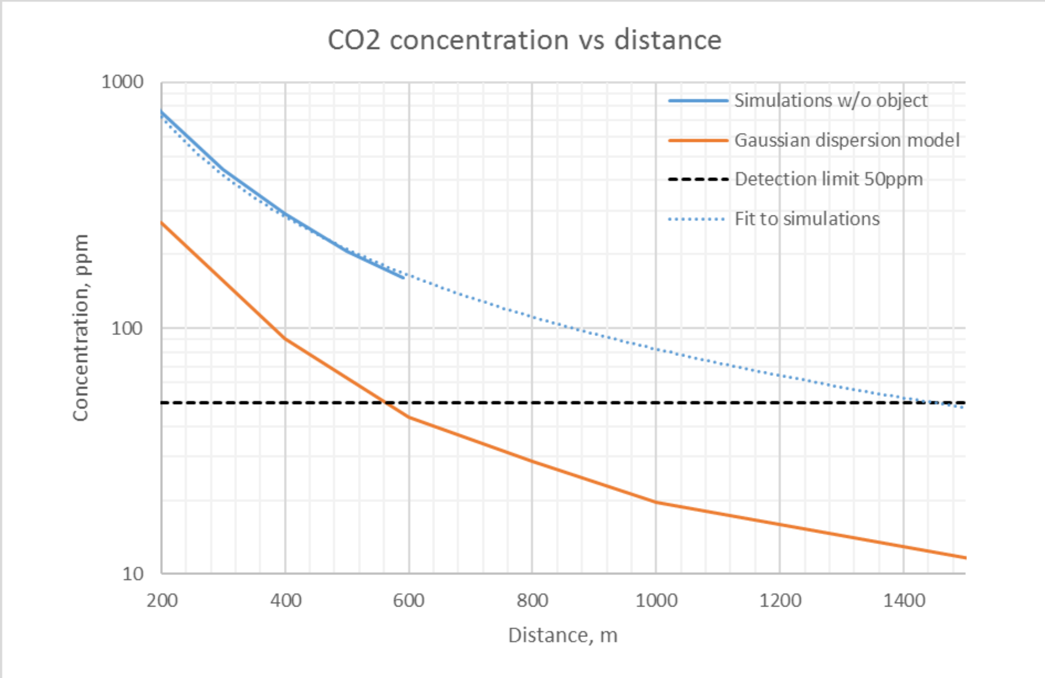

FIGURE 10. The figure shows the calculated maximum CO_2 concentration (blue line) along the distance from the exhaust. Note that the concentration is on a logarithmic scale. A power fit to the data is made to predict the dilution at longer distances. This fit should only be understood as a rough estimate, and is needed because the computational requirements for simulating a longer distance were higher than the one available.

A result from a Gaussian dispersion model is also included (See reference: Annex 5.1 Urban dispersion models by European Environment Agency, 2008). This model is used for predicting plumes, e.g. from industrial chimneys and models a certain distribution of the plume that is spreading with distance.

By comparing the simulation with the Gaussian model, it is observed that the Gaussian model concentration prediction is around 2-4 times lower than the simulation result. Within the uncertainties of the models, the results are in fairly good agreement. In the simulations, it was found that by refining the mesh the concentration would dilute at a slower rate, hence a refined simulation could show even higher values.

The displayed detection limit of 50 ppm (dotted black line) is more a guideline to indicate where the sensors must be positioned to achieve a good signal. Based on the results in Figure 10 it can be estimated that the sensors need to be positioned within 600-1400m from the ship. These distances fit well with an installation at the Great Belt Bridge where the distance typically will be 500-1200m.

Note that if the engine power is increased from the modelled 10MW to e.g. 30 MW, then the concentration is expected to be tripled because a larger absolute amount of exhaust gasses is generated. This should not be confused with the fact that the concentration (in percent or ppm) of CO_2 and SO_2 in the exhaust gas is about the same regardless of the size of the engine.

4.3.2.2 Plumes from obstacle

The above model does not consider any objects that can disturb the flow of the exhaust. This is not accurate because the exhaust from ships is emitted from a small chimney of a few meters' height. In order to simulate, the implications of this a square box (25x25x24m) are included, which is a rough representation of the accommodation unit on a ship. The results are shown in Figure 11. It was found that, in the simulation, depending on wind speed, the plume is pulled to the water surface, and therefore the three different wind speeds of 4, 6, and 8 m/s are used.

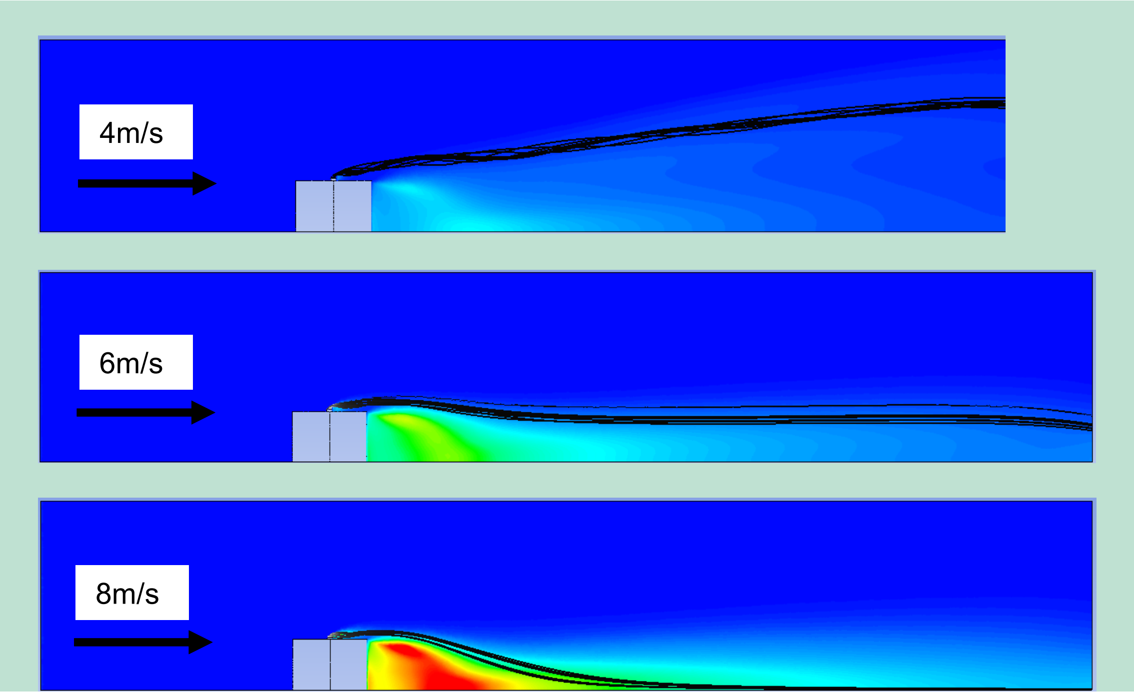

FIGURE 11. The plume path at a wind speed of 4m/s, 6m/s and 8m/s. The background shows the turbulent kinetic energy where blue is no turbulence, green is "medium" turbulence, and red is high turbulence. The lines are stream-lines that show the path of the plume. At 6m/s, the plume is affected by the turbulent zone to the right of the object resulting in the plume being kept at a height of 20-25m. At 8m/s, the plume is dragged into the turbulent zone to the right of the object and results in that the plume is sucked to the water level.

4.3.2.3 Discussion of input parameters

The results above show that the object (the accommodation unit of ship) has a large influence on how the CO_2 is distributed when exiting the ship. This can be explained by the turbulent zone behind the object that can drag down the exhaust and is affected by the wind speed. Thus, a threshold-like behavior is very likely present here, which is also highly dependent on the wind speed.

It is important to state that this behavior is not only dependent on the wind speed, but also on other selected input parameters such as the engine power, height of chimney, design of ship, march speed of the ship etc. Therefore, this is not expected to be a generic result for all ships, where the plume raises at 4 m/s and it is sucked to the water level at 8 m/s.

Based on the physics, it is expected that this threshold is *increased* by: increasing engine power, increasing the height of the chimney, increasing the exhaust gas temperature, and in case of a more aerodynamic chimney and ship design. If further simulations are to be carried out, it could be interesting to look into more details on these parameters. Due to the costs for carrying out simulations, this was not pursued further in the present project, where real world results as well as plume marking experiments (e.g. thermography) were the next steps.

4.3.2.4 Flow around the bridge deck

This project is based on placing a measurement inlet on the bridge deck to be able to measure the height, where the highest concentration of the plume is expected to occur (under some circumstances). However, the deck structure generates turbulence, and it needs to be outside of the turbulent zone to ensure that the measurement instruments to function correctly. Therefore, the bridge deck has been simulated with in-flow wind speed of 4 and 8 m/s at 25° and 50°angles. Figure 12 below shows a cross section of the bridge deck.

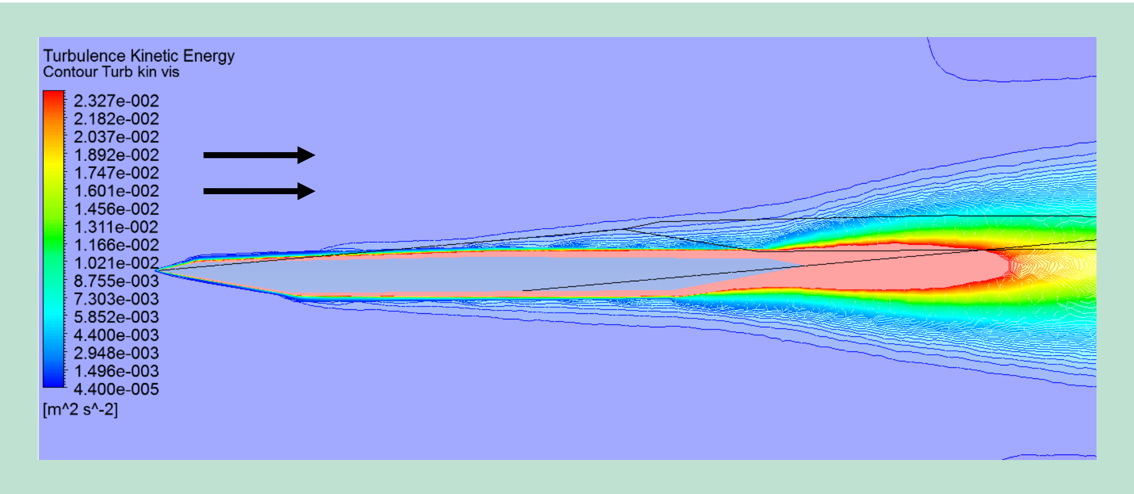

FIGURE 12. The turbulent kinetic energy (a measure of the turbulence) around the bridge deck for a 25° angle at an input wind speed of 8 m/s.

A turbulent zone is generated downstream, where the upper and lower air flows meet. The amount of turbulence is limited below the bridge deck at relevant positions (close to the edges of the lower horizontal part) for measurement inlet.

Based on the simulations at 8 m/s, it is indicated that the measurement inlet position should be 2-4 m below the horizontal surface of the deck to avoid turbulence. At a wind speed of 4 m/s, the turbulence is much lower than at 8 m/s, and hence turbulence is practically non-existent >1 m below the deck.

These results indicate that the down-stream position is influenced by the turbulence zone most. Furthermore, the turbulent zone is more pronounced at an angle of 25° rather than at 50°, due to the longer path length of air travelling.

4.3.3 Conclusion and outlook – plume modelling

In this work, we have attempted to include the most important parameters in the modelling. When concluding, it is important to keep in mind that the following assumptions are made:

- The ship is not moving
- It is not possible to simulate all ships, therefore a "standard" ship is chosen:
  - The used engine power is fairly small (10.5MW)
  - The size of the accommodation unit (the object) can be much smaller and much bigger, but represents an average size.
  - The used exhaust parameters apply best to those of a two-stroke marine engine
- The amount of detail on the ship was minimal in order to be able to simulate the long distances that a plume must evolve
- The maximum modelled distance was limited to 600m
- The used discretization (the digital mesh) was a compromise between accuracy and simulation time. Initial studies indicated that a finer mesh lead to lower dilution than presented here.

We conclude the following on plume behavior, based on the above assumptions:

Plumes in free flow:

- The plume rises slowly with distance and flattens out after approximately 500m
- The shape of the plume is as a reverse U-shape with the highest concentration at the top
- At ~600m from the source, the CO_2 is distributed within a 30m diameter, and the height is 30-45m above the height of the source
- The CO_2 dilution with distance was compared to a Gaussian model and found to differ by a factor of 2-4.
- Based on both models, the distance where the CO_2 concentration is 50 ppm higher than the background, is between 600-1400m.

Plumes from an obstacle:

- An object (the accommodation unit of ship) has a large influence on how the CO_2 is distributed when exiting the ship. This can be explained by a turbulent zone behind the object that can drag down the exhaust.
- At higher wind speed (8m/s), the present model shows that the plume is mainly sucked towards the water level
- At lower wind speed (4m/s), the present model shows that the plume raises almost unperturbed-like in the free flow model
- This threshold behavior is dependent on the wind speed and other chosen input parameters such as the engine power, height of chimney, design of ship, march speed of the ship etc.

The following tendencies of the turbulence were observed around the bridge deck:

- A turbulent boundary layer of a few meters' thickness is generated under the deck.
- At a 25°angle , the turbulent zone is more pronounced than at 50°
- The turbulence is most pronounced where the upper and lower flows meet, but is also present across the entire surface of the deck.
- It should be sufficient to place the measurement inlet at a vertical distance of 2-4 meters below the deck.

4.4 IR camera thermography

In addition to modelling, an infrared camera technology was used to visualize the plume by the thermal signature. The equipment used was FLIR 320 to capture passages of Mols-Linien in Aarhus Harbor on 27 May 2016.

Four ship passages were recorded within the basin of the Harbor. During the day of the measurement, the wind speed changed from low (ca. 4 m/s) to high (ca. 8 m/s). This enabled us to deduce the effect of the wind speed. Based on the estimate of the height of the ship, the elevation of the plume could be deduced. The plume exit height was about 20 m. The ship can be seen in Figure 13.

At low speed, the plume rose approx. 2.5-3 times the height of the ship (see Figure 14), whereas at high wind speed the plume can only be registered at about 2 times the height of the ship (see Figure 15). Therefore, the total plume height is somewhere between 40 m and 60 m at high and low wind speed, respectively.
Two of the videos are published on YouTube and can be watched by clicking on these hyperlinks:

- "High" wind speed: https://youtu.be/zQtIuuTyQ2g
- "Low" wind speed: https://youtu.be/gDU06XFcSYg

FIGURE 13. Picture of one of the ships photographed by a digital camera.

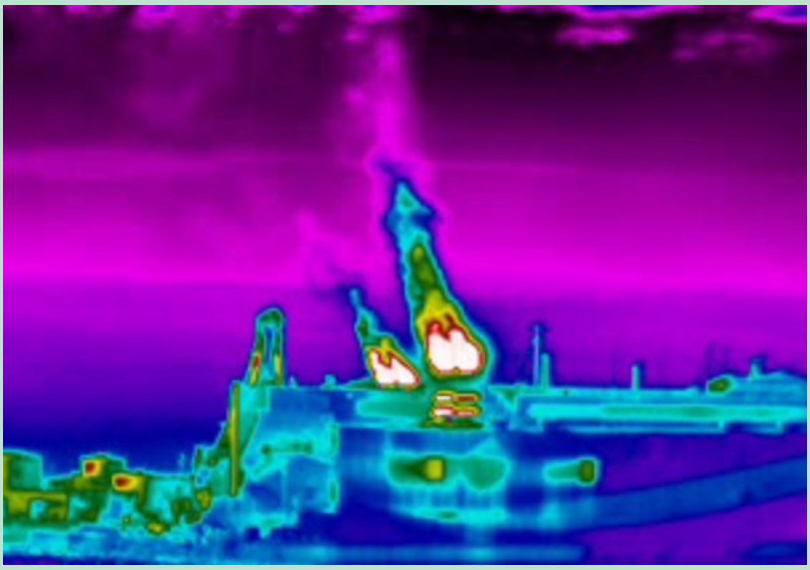

FIGURE 14. Plume rises at maneuvering during low wind speed.

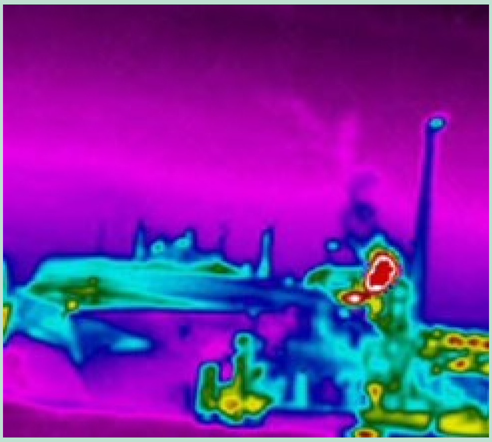

FIGURE 15. Plume rises at maneuvering during high wind speed.

4.5 Photographs of plume marking at the Great Belt Bridge

On 19 September 2016, several photographs of ships passing the Great Belt Bridge were captured, among others a military ship (HDMS Iver Huitfeldt). At the time of taking the pictures, the wind speed was around 6-8 m/s. Figure 16 shows a photograph of a ship during maneuvering, where the colors are adjusted to enhance the nuances of the plume. It can be observed that the plume rises to more than 2 times the ship height. In Figure 17, the ship is passing the Great Belt Bridge. By comparing of the height of the ship and the height of the bridge, it can be deduced that in the case the plume would be quite concentrated at a sensor position just below the deck of the Bridge.

FIGURE 16. Plume visualization during maneuvering by adjusted image colors.

FIGURE 17. The ship passes through the Great Belt Bridge.

4.6 Conclusion

Based on the input from the ship-owners and Danish Shipping, there is consensus that when considering the significant cost difference between high sulphur and compliant low-sulphur fuels, there is a real need for effective enforcement of the regulations on a global scale – and also that different technology routes should be pursued. This will not least be the case after 2020 when the global IMO regulations on sulphur content in fuel (maximum 0.5 %S) come into force. Both Maersk and Nordic Tankers have initiated their own investigations (mainly in-stack measurements) in order to test and validate equipment for on-board documentation of enforcement of these regulations. It is necessary to mature the in-stack technology in order to be able to provide accurate results on documenting compliance. Both ship-owners are interested in pursuing different technology roads and evaluate options for best possible enforcement of the new sulphur directive, not least after 2020.

In the early phase of the project, different CO_2 and SO_2 sensors were identified and evaluated for potential use for our measurements from the Great Belt Bridge. Prices for the raw sensors range from less than €100to several tens of thousands Euros. The description of the lab development and optimization of selected sensors is evaluated in chapter 5.

In order to determine optimum measurement position(s) at the Great Belt Bridge as well as estimates of gas concentration as function of distance from ship, extensive CFD modelling was carried out in the preliminary part of the project. The main emphasis has been on CFD modelling in order to be able to generalize the conclusions to cover not only the specific test location at the Great Belt Bridge, but also other bridges, harbor entrances, etc. The modelling results can be summarized as follows:

- No ”universal” position for optimum placement of sensors is possible
- The optimum signal is modelled to be on average ~60 m above sea level (depending on chimney height) during low/normal wind speed conditions which agrees well with the position of the bridge deck at the Great Belt Bridge. Lower plume rise for high wind speed conditions.
- Sufficient CO_2 is available up to 5-600 m from a ship for theoretical use of low-cost sensors, i.e. ~100 ppm above background level.
- A turbulence zone is observed on the lee side of an average ship, most pronounced during high wind speed conditions. There is a sort of threshold behavior on wind, hard to define exactly, since this also depends on e.g. engine power, ship dimensions, etc.
- It should be sufficient to place the measurement inlet to the sensors at a vertical distance of 2-4 meters below the bridge deck to avoid turbulence effects.

The application of IR thermography approach , visual inspection at the Great Belt Bridge and photographing helped to confirm some of the results from the modelling behavior of the plume, i.e. plume rising to about ~60 m during normal wind speed conditions and less during high wind conditions. At specifically high wind conditions and in case of ship designs, a part of the plume can also be observed being sucked down on the lee side of the ship.

5. Work package 2: Characterization of cost-efficient sensors and development of probe interface

5.1 Objective

In this WP, the focus has been on laboratory experiments with sensors and probe interface in a controlled environment and with controlled measurement conditions. The results from WP 1 have been used for optimum choice of sensor principles and probe considerations.

5.2 Sensor selection

Currently, the Swedish Chalmers University of Technology has, as described earlier, deployed a high-end sensor package at the Great Belt Bridge to monitor the sulphur content of the north-passing ships. The installation is positioned at the eastern pylon platform 20-25m above sea level. Based on their data from October 2015 and data from the first MUDP project (phase I),[5] we are able to put forward guidelines for the requirements to sensors at the following location:

- The signal durations are in the range of ~30-100 s
- CO_2 concentrations are typically a few ppm and up to 30 ppm (tentatively 50 ppm) above the background concentration
- SO_2 concentrations are typically a few ppb and the highest was 20 ppb (in October 2015).

These requirements should be understood as indicative because locations on the bridge closer to the center of the exhaust plumes will be less diluted and hence have higher concentrations.

According to the results from the simulations in WP1, a slightly different set of requirements can be put forward for measurements from the bridge deck:

- CO_2 concentration above 50ppm (above ambient) can be found within 600-1400m from the source
- The plume is diluted to a width of approx. 40m at a distance of 600m from the source. As the vessel speed is typically 10 knots or 5m/s, the calculated transit time is 8s. The signal of this short duration requires a temporal resolution and response time of the sensors of preferably below 1s.
- The optimal height of the sensors depends on the wind speed, but can range from 0-60m at high and low wind speeds, respectively.

One of the main aims of this project was to test the usability of cost-effective sensor technology, and this has limited the choice of the sensors to a few listed in section 4.2.2. The other and more expensive ones were kept as a fall back solution in the project.
The cost-effective SO_2 sensors identified with sufficient specifications are based on electrochemical reaction. However, possible cross interference from other gases is problematic with this technology. Another more expensive solution will be to use UV pulse fluorescence tech-

nology. In order to directly compare the two sensing technologies of SO_2, it was later decided to use both in some parts of the test campaign.

The most important sensor parameters are the linearity, the sensitivity, and the response time. Another interest in in this project is on the long term stability, the variation with ambient temperature, and robustness to the harsh environment at the bridge. Additional measurements of the sensors are included in Appendix 1.

5.3 CO_2 sensors

During this project, 7 SprintIR CO_2 sensors of UK manufacture Gas Sensing Solutions have been tested. A setup has been constructed to be able to calibrate and measure the linearity, the detection limit, and the response time of the sensors.
The results on the unmodified sensors showed that the response time (t90%) is around 45-60 s. Upon further investigations, it turned out that the sensor response time was severely limited by the time it takes for the air to diffuse into the measurement volume of the sensor. Therefore, a modification has been carried out where the air flow is forced into the sensor. The first edition of the modified sensor is shown in Figure 18. First results were very promising and indicated that the response time can be reduced to below 4s. Furthermore, experiments show that the noise level of the sensors is also kept low, so that the detection limit is in the desired range.
For this kind of sensor, the noise of the sensor is highly dependent on the integration time (time averaging). Therefore, using longer measurement times results in lower noise level.However, the response time might be compromised by too long averaging times. It was decided to record the data at the highest sampling rate possible, namely 20Hz, which is the raw signal from sensing cell. In the data treatment, a moving average is applied to reduce the measurement noise by a factor of 5-10.
The noise of the sensors at 1s averaging time was found to be around 10ppm (standard deviation), which approximately leads to a precision of 30ppm (3 times the standard deviation). By increasing the averaging time to 2s, the standard deviation is reduced to 4ppm.

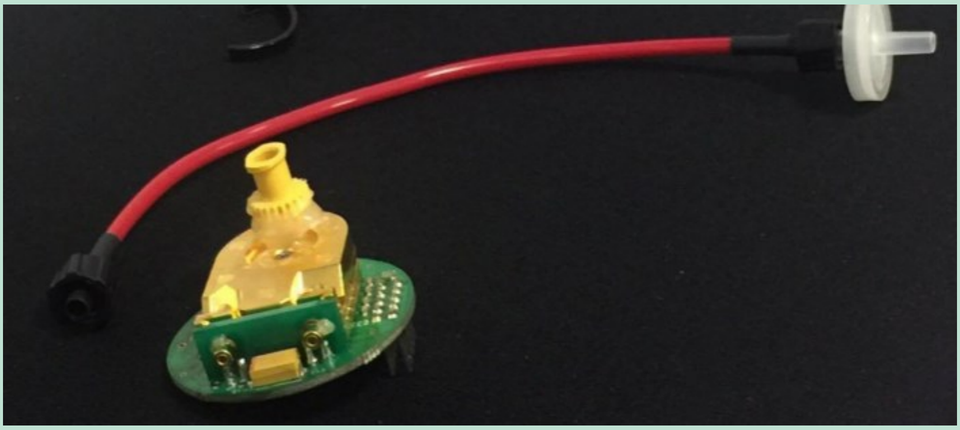

FIGURE 18. Modified CO_2 sensor with forced airflow to increase the response time

5.3.1 Response time of CO_2 sensor

The characterization of the sensor response time is of high importance in this project. To make valid measurements, the setup used for these measurements must be carefully designed because the sensors and their pumps are sensitive to the inlet pressure which can easily be affected when changing gasses. The switching from low concentration gas to high concentration gas must therefore be carried out without disturbing the inlet pressure. For the CO_2 sensors, this was done by sucking from one bag with low concentration CO_2 through a t-piece with the last port blocked. When switching is completed, the last port of the t-piece is opened to a bag of high concentration CO_2 followed by closing the port to the low concentration CO_2 bag. The response time is then found by fitting the data to a 1st order system to find the time constant t_0:

$$f(t) = f_0 + k \cdot \left\{1 - e^{-t/t_0}\right\}$$

The t_0 value indicates when the sensor has reached 63% of the high concentration value. To calculate the response time at the 90% value, then it is 2.3 times t_0. The modified CO_2 sensors were found to have an average response time around 1s (see Figure 19). This value is also estimated to be the response time of the experimental setup. Hence, the actual response time of the CO_2 sensor might be lower than 1s.

The gas cell of the CO_2 sensors has an estimated volume of 0.3mL, which at the flow of approx. 400mL/min means that gas cell volume is exchanged more than 20 times per second. This also points to the fact that the response time of the CO_2 sensors is lower than 1s.

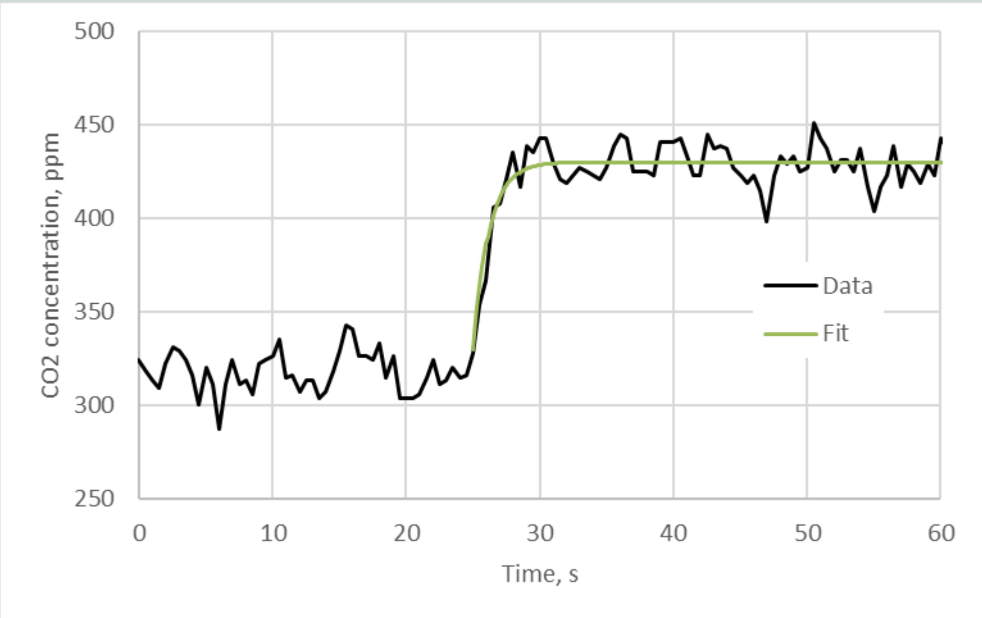

FIGURE 19. Response time of modified CO_2 sensors. The fit finds a time constant of 1.2 s in this measurement.

5.4 Electrochemical SO_2 and NO_2 sensors

In this project, the electrochemical sensors were chosen to fulfill the target of testing cost-effective technologies. In the recent years, the sensitivity of the sensors has been increased, so that concentrations at the ppb-level can also be quantified.

The electrochemical sensors function by either oxidizing or reducing the target gas, which then generates an electrical current. The resulting electrical current is measured and is directly proportional to the specific gas concentration.

The SO_2 sensor from MEMBRAPOR, Switzerland, was tested due to their market leading sensitivity. The SO_2 sensor should always be paired with NO_2 sensor due to a high degree of cross-sensitivity. It is not feasible to filter NO_2 from the SO_2 molecules, and since a negative signal from the NO_2 is obtained at the SO_2 sensor, it is necessary to calculate the correct SO_2

concentration from the superimposed signals. The specifications of each SO_2 and NO_2 sensors are shown in Figure 20.
The sampling rate was 1.25Hz. The noise of the raw signal was about 8-9mV. When using the proportionally factor for SO_2 found in Appendix 1 of approx. 1.8mV/ppb, the precision (3 times the standard deviation) is approx. 13ppb, which fit well to the datasheet.

SO2/C-1

Sulfur Dioxide Gas Sensor in Compact Housing

MEASUREMENT

Operation Principle	3-Electrode Electrochemical
Nominal Range	0 – 1 ppm
Maximum Overload	10 ppm
Inboard Filter	–
Output Signal	4000 ± 1500 nA/ppm
Resolution (Electronics dependent)	< 0.01 ppm
T90 Response Time	< 20 sec
Typical Baseline Range (pure air, 20°C)	< 0.05 ppm
Maximum Zero Shift (+20°C to +40°C)	N.D.
Repeatability	< 2 % of signal
Output Linearity	Linear
Gain	–

NO2/C-1

Nitrogen Dioxide Gas Sensor in Compact Housing

MEASUREMENT

Operation Principle	3-Electrode Electrochemical
Nominal Range	0 – 1 ppm
Maximum Overload	10 ppm
Inboard Filter	–
Output Signal	-2500 ± 1000 nA/ppm
Resolution (Electronics dependent)	< 0.02 ppm
T90 Response Time	< 60 sec
Typical Baseline Range (pure air, 20°C)	< 0.05 ppm
Maximum Zero Shift (+20°C to +40°C)	-0.1 ppm
Repeatability	< 2 % of signal
Output Linearity	Linear
Gain	–

FIGURE 20. Specifications of the electrochemical sensors from Membrapor.

5.4.1 Building the electrochemical sensor setup

The electrochemical sensors were mounted on a custom-made Teflon (PTFE) plate. The plate was made by drilling a hole from one edge to the other as a passage for the air to be pumped through. Two chambers matching the size of the sensors were drilled from the top, and the sensors were then fastened with screws. O-rings made sure that it was airtight.

FIGURE 21. The build of the flow through setup for the electrochemical sensors. The white block is PTFE (Teflon) in order to be chemically resistant to the plume gas.

5.4.2 Response time of SO_2 sensor

The time response for the electrochemical sensors were tested abruptly administering or cutting off a high concentration inlet flow without changing the flow or inlet pressure. The experiment was repeated several times and an average response time of 6.8s was found. An example of the response time measurement is shown in Figure 22.

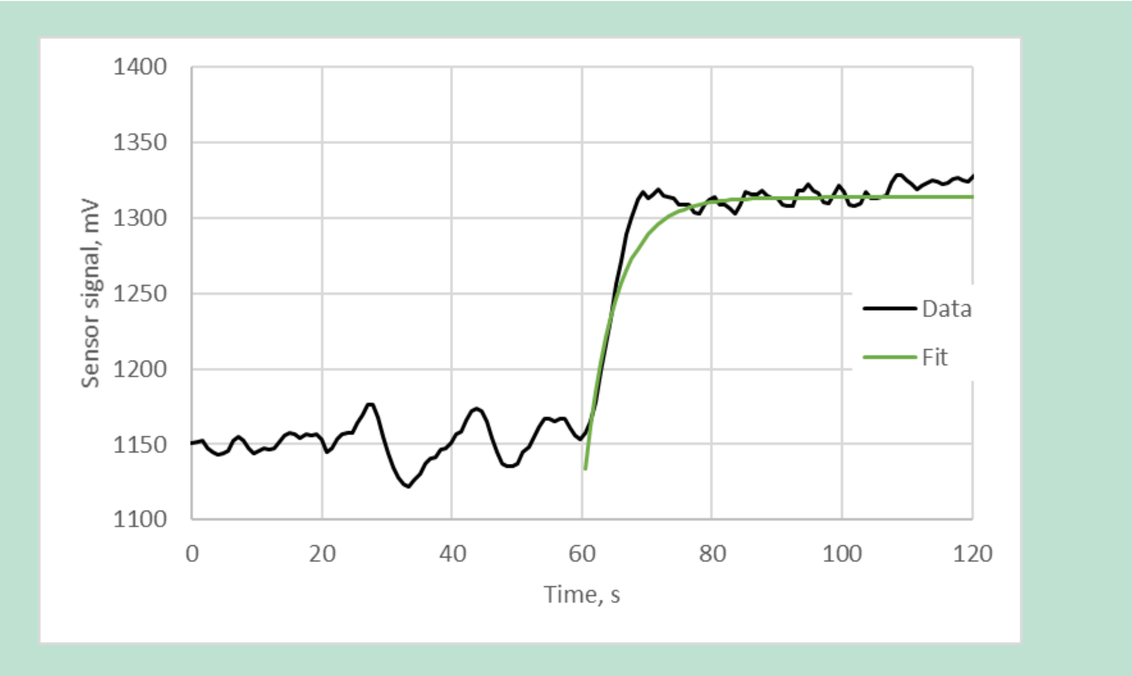

FIGURE 22. SO_2 sensor response and fit to calculate response time, which in this measurement is 4.8s.

5.4.3 NO_2 compensation of SO_2 electrochemical sensor

As the SO_2 electrochemical sensor also reacts to the NO_2 gas present in the plume, it is necessary to include a NO_2 electrochemical sensor. To analyze this cross interference, both sensors were in turn exposed to a gas mixture of about 500 ppb of NO_2 and clean laboratory air. The results are shown in Figure 23, where the background level of both sensors is indicated together with the signal level resulting from the NO_2 gas. The SO_2 sensor reacts with a negative signal to the NO_2 gas, hence the signal drops in the figure when the NO_2 gas is exposed to the sensor. The compensation factor was found to be about 1.4 mV/mV (SO_2/NO_2). Note that the response times of the two sensors are very similar.

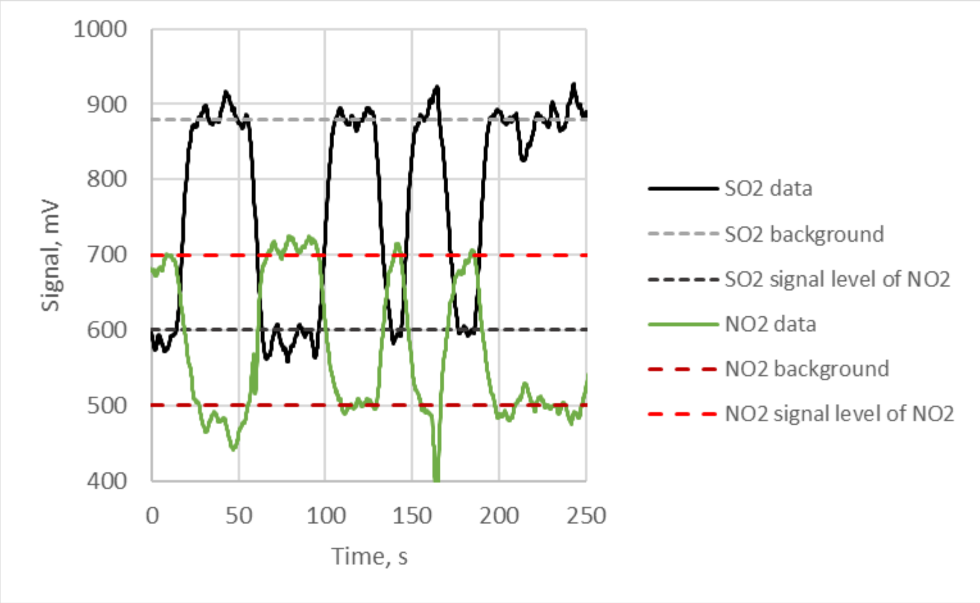

FIGURE 23. Determination of compensation factor of NO_2 gas on SO_2 sensor. The factor on raw signal (mV/mV) is found to be around 1.4.

5.5 SO_2 analyzer based on pulse fluorescence

An SO_2 analyzer, model 43i from ThermoScientific rented from Air Monitors Ltd (UK), was also used for measuring the SO_2. The analyzer functions by exciting SO_2 molecules with an ultraviolet light pulse in a sample chamber. The following emission of light from decaying SO_2 will have a higher wavelength, i.e. fluorescence decay. The amount of light emitted from SO_2 is detected and translated into a SO_2 concentration. The SO_2 analyzer 43i can detect concentrations at a range down to 10s of ppb.
The so-called hydrocarbon kicker is normally installed in the analyzer to remove a potential cross interference if the sampling gas contains a moderate concentration of hydrocarbon gasses. This device was removed in the rented instrument to obtain a shorter response time, something deemed necessary to catch the momentary signals from the ships passing by.
The sampling rate of the instrument was about 1 Hz, and an intern moving average of 5 seconds was applied to reduce noise.

5.5.1 Response time of SO_2 pulse fluorescence analyzer

The response time of the pulse fluorescence analyzer has been carried out in the same manner as the other sensors described above. In Figure 24, the SO_2 signal at an abrupt addition of SO_2 gas of 150ppm is observed. The average time constant was determined to be 35s.

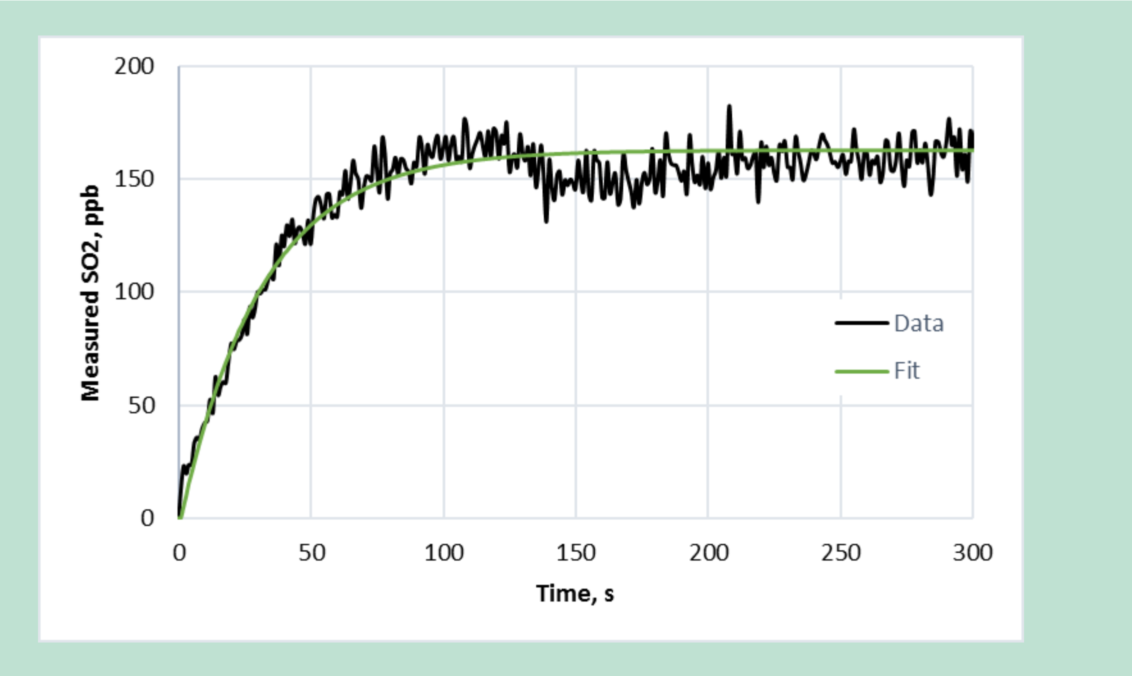

FIGURE 24. SO_2 analyzer and fit to calculate response time, which in this measurement is 30 s.

5.6 Expected gas concentrations and sensor precision

It is assumed that the CO_2, SO_2 and NO_2 content of the plume is constant independent of the type of ship and engine. In Table 1 the concentration of CO_2, SO_2 and NO_2 is calculated at the stack, at a dilution factor of 256 to 200ppm CO_2 above the background and at a dilution factor of 1026 to 50ppm CO_2 above background.

TABLE 1. Expected gas concentrations in diluted and concentrated plumes

Gas	0.1%S at the stack	0.1%S at sniffer	0.5%S at sniffer	2.8%S at sniffer	0.1%S at sniffer	0.5%S at sniffer	2.8%S at sniffer
CO_2, ppm	51.300	200	200	200	50	50	50
SO_2, ppb	22.000	86	429	2.339	21	107	585
NO_2, ppb	100.000	390	390	390	97	97	97

the table above shows that the precision of the CO_2 sensor is about 30ppm (1s averaging), the precision of the electrochemical SO_2 sensor is approx. 13ppb, and the precision of the pulse fluorescence SO_2 analyzer is about 10ppb. By comparing Table 1 with these numbers, it can be concluded that at a dilution to 200ppm CO_2 both the CO_2 sensor and SO_2 sensor have in principle the necessary precision to distinguish between 0.1%S and 0.5%S. When the plume is diluted to 50ppm CO_2 and the used fuel is 0.1%S, the SO_2 concentration approaches the limit for detection of both the electrochemical and pulse fluorescence analyzer. However, at the same dilution and 0.5%S fuel or higher, the concentration is well within the measurement range of the sensors.

5.7 Probe interface

The purpose of the probe interface is to ensure that the measured gas is representative to the actual content of the plume. The chemical behavior of SO_2 is of particular importance, because it is known to be “sticky” in the sense that it is easily adsorbed on surfaces and can be dis-solved in many materials. In order to overcome this, the highly chemically resistant polymer PTFE (Teflon) is used for tubing, and only stainless steel is used for connections. The sampling system of the SO_2 is arranged in a way that the tube lengths are reduced to the necessary length, and the sensor cells are positioned upstream of the sampling pumps. In this way, the various polymer materials inside the pumps are not in contact with the sampling plume before the actual measurement.

The focus of the installation process and laboratory validation, has been on eliminating potential leak that would dilute the plume gas and thereby lead to erroneous measurements. In all steps of laboratory and setting up, the flow of in-take and flow-out air is measured with a reference flowmeter (EMlab Defender 510).

In the first campaign, where only CO_2 was measured, the aim was to examine the influence of the length of the tube below the bridge deck on the measured CO_2 concentration. This could answer the question if the sampling inlet was free of turbulence on the bridge deck as the simulations have indicated. Furthermore, the plume can be at various heights depending on the wind and cruise speed, the height of the stack, and engine power. For this reason, it was desired that the tubes of each CO_2 sensor had different lengths. The length of the tubes under the bridge at the eastern location was about 2.5m and 4.5m under the deck of the bridge. At the central node, the length of the tube was determined with a precondition that it does not obstruct the free-pass height of the bridge, and therefore about 2.2mwas the max. possible length.

In the final SO_2 test campaign, it was decided to use a single sampling tube out of the lamp outlet, and the sampling is then split towards the instruments using T-splitters. This means that the sampling gas originates from exactly the same plume volume at any given time. It was also ensured that the flow to different sensors was approximately the same (within 25%).

Initially in the project, it was also considered to develop a specific type of distributed measurement probe with a number of gas intakes (holes) along a sample line in order to cover the relatively wide possible spatial spread of plumes from different ships when measured from a distance. This would theoretically enable us to achieve a higher hit rate of positively identified ships when being able to cover a number of different plume propagations. After some discussions in the group, we did however not seek this approach further, mainly due to the following observations/limitations met quite early in the project:

- The approach would require a rather high gas concentration, since the gas is severely diluted along the line with a number of gas intakes. Early lab experiments and modelling suggested that it was impossible to dilute the necessary factor of 5-10 for this work approach, and still positively identify a signal using low-cost sensors;
- on the Great Belt Bridge, it was not possible to place many sensors or a long measurement sample line outside the bridge for a longer period, It might have been possible for a short period of time within the project, but would have had no future perspectives after the project termination;
- CFD modelling in the early part of the project, as well as later CO_2 measurements, suggested a near optimum measurement position at the lantern outlets, thus no obvious need for further initiatives since simplicity is also highly preferred.

5.8 Conclusion

This section provides a description of the sensors used in the measurement campaigns. The linearity, precision, range, and response times of all of these sensors have been measured in a laboratory setting, and the most important findings have been documented in this section and in Appendix 1. The results indicate that these sensors fulfill the requirements for the campaigns without compromising the aim of the project on using cost-effective sensor technology.

The CO_2 sensors are modified NDIR detectors from GSS, UK, and after the described modifications their response time is around 1s (1/e-definition).

Two kinds of SO_2 measurement technologies have been used. The most cost-effective technology is by far the electrochemical sensors. A pair of SO_2 and NO_2 from Membrapor, S, CH, have been tested, and their response times are around 6s. Two sensors are needed, because NO_2 in the plume is also detected by the SO_2 sensor, i.e. cross interference. Finally, the second SO_2 technology is a pulse fluorescence analyzer from ThermoFischer, US. This device has the longest response time of 35s.

The design of the probe interface has been described in terms of the used materials, the principles of the design of the flow and the possible measurement positions. Furthermore, it turns out that near optimum measurement position exists at the lantern outlets below the bridge deck.

6. Work package 3: Selection of measurement positions

6.1 Objective

This work package focuses on dedicated experiments at the Great Belt Bridge. The generic potential for using cost-efficient sensor technology was originally also to be evaluated by these test campaigns. Upon agreement with the Danish EPA, his project has however focused exclusively on this location (Great Belt Bridge), and other locations have not been covered as originally mentioned in the project application, e.g. roadside monitoring.

6.2 Development of the setup for the Great Belt Bridge

The Great Belt Bridge is an enormous structure and is very suitable for ship plume monitoring due to several reasons:

- It is a fixed installation
- The amount of ship passages is among the highest in Denmark with around 50 passages per day.
- The north- and southbound ship lanes are quite narrow, so the traffic is concentrated within 500-1000m width.
- The pylons are quite close to the ship lanes as can be seen in Figure 25.
- The deck of the bridge is at a height of 65-70m above the water surface, hence much of the plumes are expected to be detectable at this height.
- The distance to other large combustion engines/stacks is quite long, so ambient noise is generally low.
- The main alternative route from the Baltic Sea to the North Sea (and beyond) is through Øresund which has a depth limit of around 10m.

Based on these advantages, it is obvious that the Great Belt bridge is ideal for placing a plume monitor (sniffer). However, the location is remote, the environment is rough and thus special precautions must be taken when operating at the structure.

In order to optimize the outcome of the measurement campaigns, the following steps are taken:

- The sensors are duplicated, when possible, to avoid missing data due to a single sensor malfunction.
- An internet connection is established to enable remote control, debug, restart of the equipment, and the data can be transferred, so it is not only locally stored on the measurement PC.
- The equipment is tested thoroughly in the laboratory to ensure that the stability is sufficient.
- The tube for sampling the air is securely fixed and has more than sufficient strength.
- The equipment must be able to handle high humidity and condensing conditions.
- Since the exact requirements to the sensitivity and response times are not known, as much raw data as possible is collected.
- The data recording software is optimized for long-term operation for several months of autonomous operation.

Based on the analysis in WP1 and from the former MUDP project,[5] it was clear that the eastern pylon platform (also the location of the Chalmers monitoring station) was not the obvious choice due to a relatively low CO_2 signal from the ships of typically below 30ppm above ambient. In order to obtain higher signals, it was decided to use locations at the bridge closer to the ship lanes to measure less diluted plumes. In Figure 25, the cross section of the bridge is shown with arrows indicating the lamp outlets. In addition to the lamp outlet of the central node and the eastern lamp outlet marking the shipping lane, there were also a similar lamp outlet marking at the western edge of the shipping lane, but this has not been indicated.

The predominant wind direction at the Great Belt Bridge is western wind direction. Except for the western wind, the wind directions are fairly evenly spread except from north to north-east wind, which is uncommon. The installation of sensing equipment at the central node will enable monitoring of southbound ships in west wind and northbound ships in eastern wind. The eastern lamp outlet will predominantly enable monitoring northbound ships in western wind directions, and the western lamp outlet will predominantly enable monitoring of southbound ships in eastern wind directions. However, there will be some deviations from these guidelines, because it is, e.g. possible for a northbound ship to pass the bridge in the western part of the shipping lane if no southbound ships are passing.

The lamp outlets are chosen as the location based on modelling results as well as due to the fact that it requires much preparation and permissions to make additional outlets in the bridge. The position of the lamp outlets were sufficiently separate and almost ideal locations. From the lamp outlet, it is also possible to extend a soft sampling tube of desired length. The only limitation of the tube is not to interfere with ship transits under the bridge in any way.

In the initial CO_2 campaign, it was chosen to setup two CO_2 sensing packages; one at the central node and one at the eastern lamp outlet. The aim of this was to point out the location with the highest success rate for identification of ships, and quantify the difference in terms of signal magnitude and signal length.

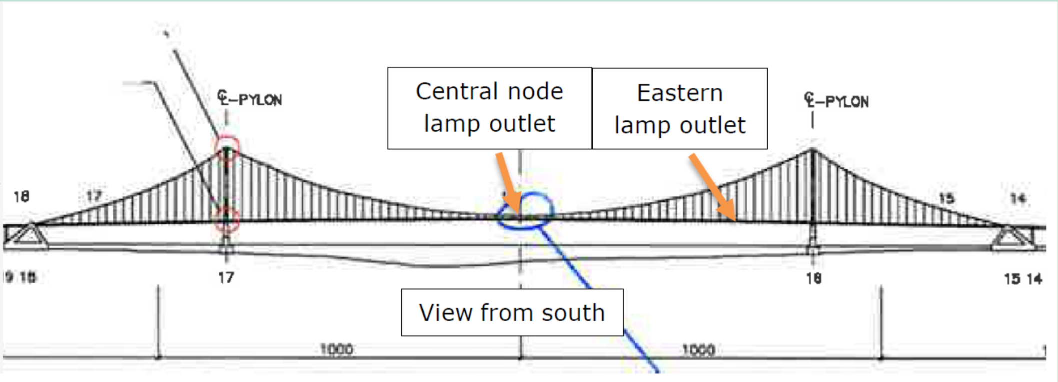

FIGURE 25. Schematics of the Great Belt bridge layout as seen from the south. The locations of two used lamp outlets (the central node and the eastern) are shown. Source: Sund og Bælt A/S.

6.3 Installation at the Great Belt Bridge

The sensor packages where installed at the lamp outlet on the bridge over a few visits. In Figure 26, pictures of the lamp outlet are shown as seen from the inside and outside of the bridge. The lamp itself is mounted on a disc, and by ensuring that the sampling tube is well below this disc the sampling air will not be affected by the turbulence from the structures.

The inside of the bridge is suited for installation of equipment quite well as seen in Figure 27. Through the bridge, a 230/400V system is available and around the lamp outlet a 3G/4G wireless signal is present for easy data communication.
At each measurement location, two modified CO_2 sensors with dedicated pumps and separate sampling tubes were installed below the bridge. At the eastern lamp outlet, the two tubes were about 2m and 5m below the deck of the bridge, respectively.
A particle detector, a diffusion size classifier (DiSCmini) from Testo AG, was also used, because the project group had had good experience with identifying the plume by the particle signal before.
In addition to the sensors, a PC and a 4G modem was set up in order to log and transmit the measured data during the campaigns.

FIGURE 26. Lamp outlet seen from inside the deck of the bridge and seen from below.

FIGURE 27. Measurement setup at the central node lamp outlet during the CO_2 campaign

6.4 CO_2 measurement campaign results

The objective of the CO_2 campaign was to point out the location with the highest success rate for identification of ships and quantify the signal in terms of magnitude and length.
The overview of the campaign period is shown in Table 2. It is split into three periods; two with a focus on the eastern location (one with and one without particle measurements, and one with data from central node).

In general, the CO_2 campaign was very successful, taken into account that this was the first long-term in-situ test of the sensors. However, the particle detector malfunctioned on the 17th day of the campaign, and thus no successful particle measurements were recorded at the central node. Furthermore, only one of the two CO_2 sensors at each location provided useful measurement data due to unexpectedly high level of random noise, probably due to a sensitivity to inlet pressure variation due to fluctuating wind speed. Finally, a hardware problem at the central node caused that during the last part of the period the uptime was about 60%.

TABLE 2. Overview of the CO_2 campaign

Period	Days	East location	Central node	Particles
1/5 – 17/5 2017	17	Yes	No	Yes
17/5 – 22/5 2017	6	Yes	No	No
26/5 – 27/6 2017	32	Yes	Yes	No

The CO_2 signal was analyzed as the peak value (after 2s averaging) and as an integrated value around the approximate width of the signal. The statistical values are shown in Table 3. Note that the displayed CO_2 values has been subtracted the ambient CO_2 background of around 400 ppm. The CO_2 signal has therefore a typical value of 50-100 ppm at the east location and 100-150ppm at the central node, depending on the way of evaluating the peak.

TABLE 3. Summary of CO_2 values at the CO_2 campaign

Value	East location	Central Node
Average peak value, ppm	90	159.7
Median peak value, ppm	86	155
Maximum peak value, ppm	200	295
Average integrated peak, ppm	55.7	97.5
Median integrated peak, ppm	51	94
Maximum integrated peak, ppm	122	236

The signal length is typically between 5-20s with an average of about 10s, and no clear difference between the two locations was observed.
It turned out to be quite challenging to identify the ships unambiguously for several reasons; Firstly, quite often ships pass the bridge within a window of about +/-10min. Secondly, CO_2 data contain some random noise peaks, which in terms of length and height, are similar to the signals seen from the ship. Only with a corresponding particle signal, it is possible to positively identify a ship.

The hit rates, i.e. how many of the passages during the periods are identified in the data, have also been found. Table 4 shows the number of ships identified for the central node position, and Table 5 shows the number of ships for the east location. At the central node, the detected number of ships is almost 21%. At the east location, the total number of ships for this period is almost 7%. If the data are split in the first (1/5 – 17/5 2017) and the second period (17/5 – 22/5 2017), with and without positive identification of the plume by the particle signal, then the numbers are different. The first period resulted in a hit rate of 4.4%, whereas the second is more than three times higher at 15%. This cannot be explained by that the weather conditions are more optimal; hence the hit rate is probably overestimated.

TABLE 4. Summary of the number of ships identified at the central node

Central node	Number of ships
Total in the period	891
CO_2 peak identified	186
Percentage identified	20.9%

TABEL 5. Summary of the number of ships identified at the eastern location

Eastern lamp outlet	Number of ships	First period with CO_2 and particles	Second period with only CO_2 sensor
Total in the period	1100	850	250
CO_2 peak identified	75	37	38
Percentage identified	6.8%	4.4%	15%

It is obvious that the hit rate also depends on the wind direction, especially at the eastern location. Figure 28 shows the wind-dependent hit rate, which is calculated as a percentage of identified ship passages at each wind direction (split into 16 directions) in relation to the total number during the time period with that given wind direction. It is assumed that both measurement locations are used and that they measure independently of each other. This results in hit rates between 30-60% in southern wind directions and 15-30% in western wind directions. During the campaign period, an inadequate amount of data was collected with wind in the eastern/north-eastern wind direction, and was omitted as a result.

Based on the collected data, it was not possible to find a specific window of operation regarding the wind speed for the measurement.

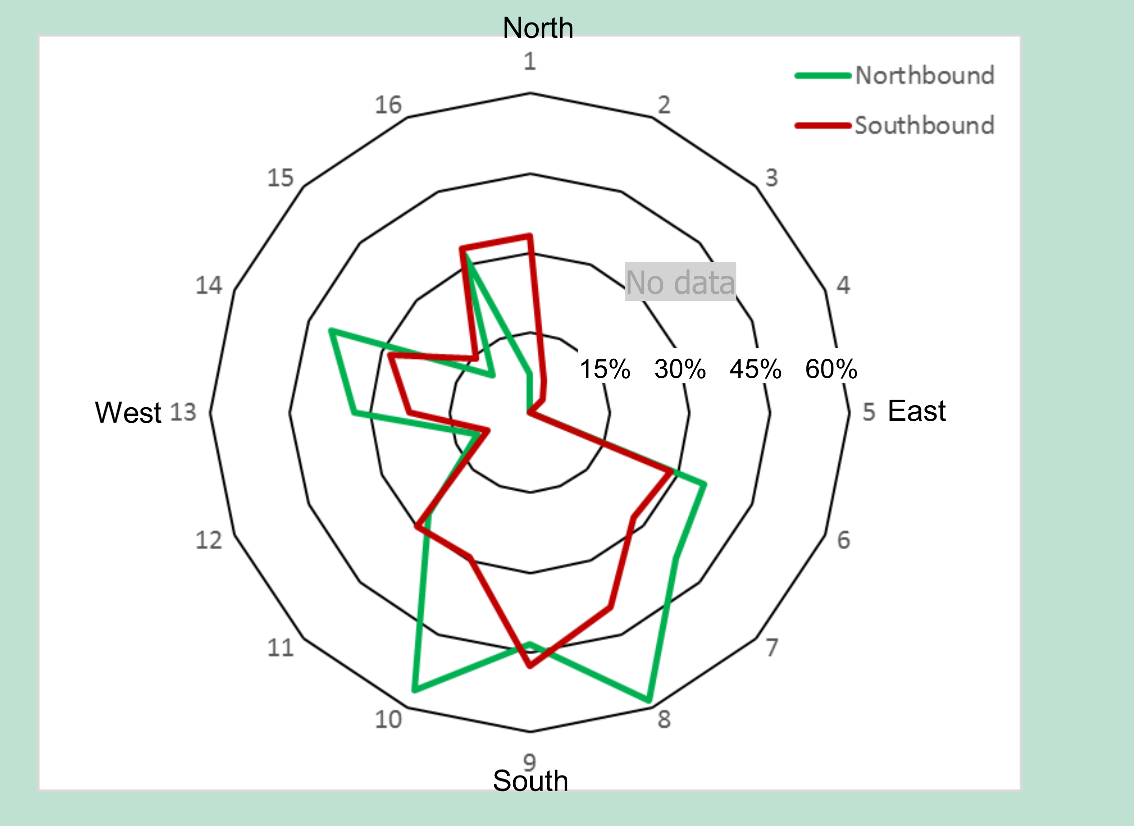

FIGURE 28. Hit rate as a function of the measured wind direction at ship passage. It is assumed that both measurement locations are used and that they measure independent of each other. The hit rate is split into northbound and southbound ships. At wind directions 2-5 (Northeast - East), no valid statistics could be produced due to not insufficient amount of data.

6.5 Conclusion

The purpose of the first measurement campaign was to evaluate the actual CO_2 concentration in the plume at the identified measurement locations. Furthermore, the obtainable hit rate and information about the temporal length of the signals was desired.
The relevant properties of the bridge in relation to the sampling locations are described together with the setup. The central node and eastern ship lane marking lamp outlets are used as measurement locations, and a 2-5m tube of is lowered under the deck of the bridge to avoid turbulence effects. At each location, two modified CO_2 sensors, logging and communication equipment were installed. A particle detector is also installed for positive identification of ship passages.
Based on the in total 55 day CO_2 campaign, the following conclusions can be made:

- The CO_2 signal height above background is on average 50-150ppm, depending on the method of evaluation and location.

- Signal length and temporal resolution is about 5-20s.
- Hit-rate depends much on wind-direction, but up to 60% in the southern wind and about 25% in northwestern wind
- Based on the available data of the ship passages, it was problematic to identify an exact ship if more than one ship passed through the bridge within a 5 minute. window.
- The identified hit rate at the central node is 21% and 7% at the eastern location. It is speculated that this number is likely to be too optimistic, because it is only based on one sensor signal, and during the period with working particle detector, which added additional requirement for the identification, the hit rate was lower.

It can be concluded that the central node is the most suitable location for the final SO_2 campaign, which is described in the next section.

7. Work package 4: Demonstration and evaluation of developed sensor package

7.1 Objective

In the final WP, the developed sensor platform has been tested at the Great Belt Bridge in a final measurement campaign with the aim to determine the sensor precision and robustness.

7.2 Final SO_2 measurement campaign

Based on the typical CO_2 concentration found in the CO_2 campaign of 50 ppm above ambient, it is possible to calculate the expected SO_2 concentration of the different sulphur-containing fuels using the formula given in section 4.2. This is shown in Table 6, and concentration of the SO_2 is expected to be 20ppb for 0.1%S fuel. This is the limit of detection for both SO_2 sensor technologies, but it seems promising with less diluted plume or plumes with a higher sulphur fraction.

TABLE 6. Expected gas concentrations in diluted and concentrated plumes

Gas	0.1%S at the stack	**0.1%S at sniffer**	0.5%S at sniffer	2.8%S at sniffer
CO_2, ppm	51.300	**50**	50	50
SO_2, ppb	22.000	**21**	107	585
NO_2, ppb	100.000	**97**	97	97

Some of the CO_2 sensors in the CO_2 campaign showed problems with noise and hardware instability. These were excluded from the SO_2 campaign, and only the stable CO_2 sensors and electronics were used.

Before the campaign, the CO_2 sensors were calibrated, and the linearity was tested at different realistic temperatures. The electrochemical sensors were mounted in a PTFE flow cell as described in section XX, and they were tested thoroughly. The pulse fluorescence analyzer was leak-tested and calibrated before the installation.

Due to the higher concentration and hit rates at the central node, it was decided to focus this campaign only on this location. A schematic illustration of the total installation is shown in Figure 29, and a picture is shown in Figure 30.

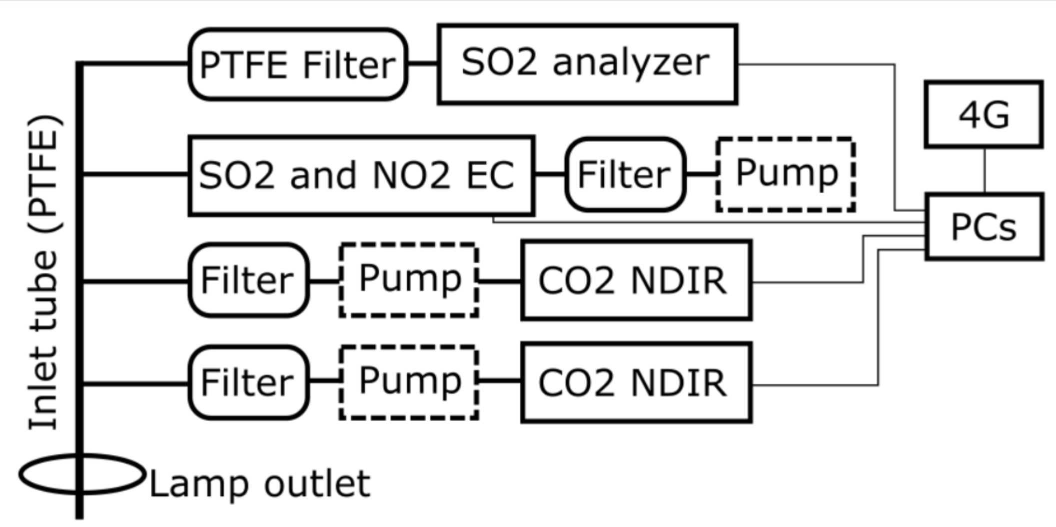

FIGURE 29. Schematics of the setup in the SO_2 campaign.

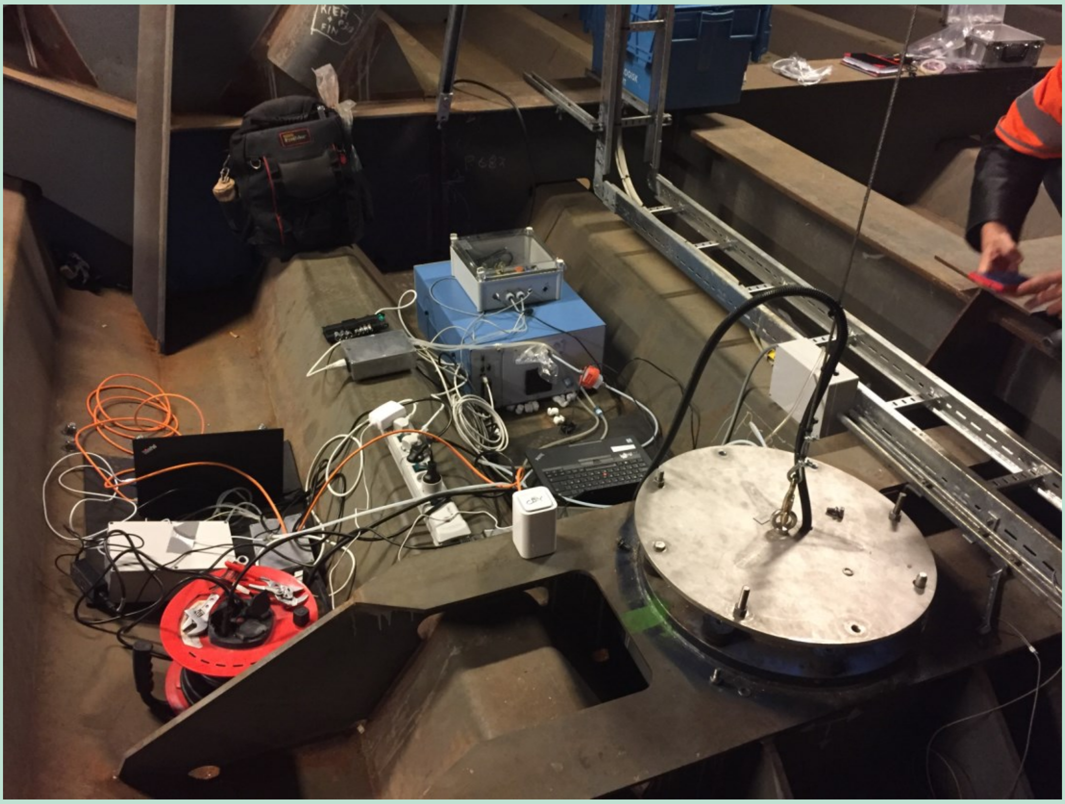

FIGURE 30. Setup of the SO_2 campaign inside the bridge deck.

7.3 Results of SO_2 campaign

The overview of the period of the SO_2 campaign is displayed in Table 7. It is divided into three periods, which are characterized by the length of the sampling inlet tube under the bridge. The following results are based on the first 24 days with a tube length of 2.2 m. The hit rate in the second period is estimated to be similar to the first period. During the second period, the pulse fluorescence analyzer stopped working correctly. In the third period, the length of the tube was reduced to less than 1 m in order to see if the turbulence effects of the bridge could increase the duration of the plume. Unfortunately, due to the turbulence the inlet pressure fluctuation caused the noise of the electrochemical sensors to increase by orders of magnitude, and obstructed the measurement of SO_2 data for this third period.

TABLE 7. Overview of the SO_2 campaign

Period	Days	Length of tube under bridge	Ship data (VTS)	Pulse fluorence analyzer
24/10 – 17/11 2017	24	~2.2m	Yes	Yes
17/11 – 7/12 2017	20	~4m	No	Partly
7/12 – (11/1 2018)	35	<0.5m	No	No

In the SO_2 campaign, the number of sensors have increased compared to the CO_2 campaign. This means that the signal identification routine could be further developed, so that it requires several signals in order to positively identify a ship; CO_2 signals are needed from both two CO_2 sensors and signal on SO_2 and NO_2 electrochemical sensors. This also leads to a reduction of the acceptable time shift from a ship passing to a detected signal to +/- 2 min.

It was chosen to use peak values of the signals in the analysis, and the used CO_2 value is the average of both CO_2 sensors.

The peak values of CO_2 signals are shown in Table 8 in order to make a direct comparison of the measured CO_2 values of the two campaigns. The average and median values from the central node are in generally lower by a factor of 2-3. The maximum value is higher by a factor of 2.

TABLE 8. Summary of CO_2 value in the first period of the SO_2 campaign (24/10-17/11 2017)

Value	CO_2 sensor 1	CO_2 sensor 2
Average peak value, ppm	84.5	80.2
Median peak value, ppm	63	61
Maximum peak value, ppm	404	402

The overall summary of the hit rate of the SO_2 campaign is shown in Table 9. The electrochemical sensors had a better hit rate than the pulse fluorescence analyzer. This could be due to the fact that SO_2 sensor is sensitive to NO_2, which is present in the plume at a concentration up to an order of magnitude higher than the SO_2 concentration. The SO_2 pulse fluorescence analyzer has a significantly longer response time, so the most diluted and shortest plumes cannot be detected.
Based on the CO_2 campaign, the overall hit rate of 3-4% was lower than expected at the central node of 21%, however that number was also likely too high as discussed in former chapter.

TABLE 9. Overall summary of the first period of the SO_2 campaign (24/10-17/11 2017)

Central node SO_2 campaign	Number of ships
Total in the period	1188
CO_2 peak identified	42
Identified with electrochemical sensors	3.5%
Identified with pulse fluorescence analyzer	2.7%

During the period (24/10 – 17/11 2017), the weather conditions varied significantly. In Figure 31, the wind direction at the time of all ship passages has been shown together with the ones that have been detected by the sensors. The identified passages are split into northbound and southbound ships. The southbound ships are normally positioned in the western ship lane, and in western wind direction the plume will therefore blow towards the central node. In this figure, it can be seen that southbound ships are predominantly identified in western wind, which was expected and is a nice validation of the identified signals. The opposite applies to northbound ships.
The total number of identified ships in the period is only 42, so the calculation of the wind direction dependent hit rate was not included as in the CO_2 campaign.

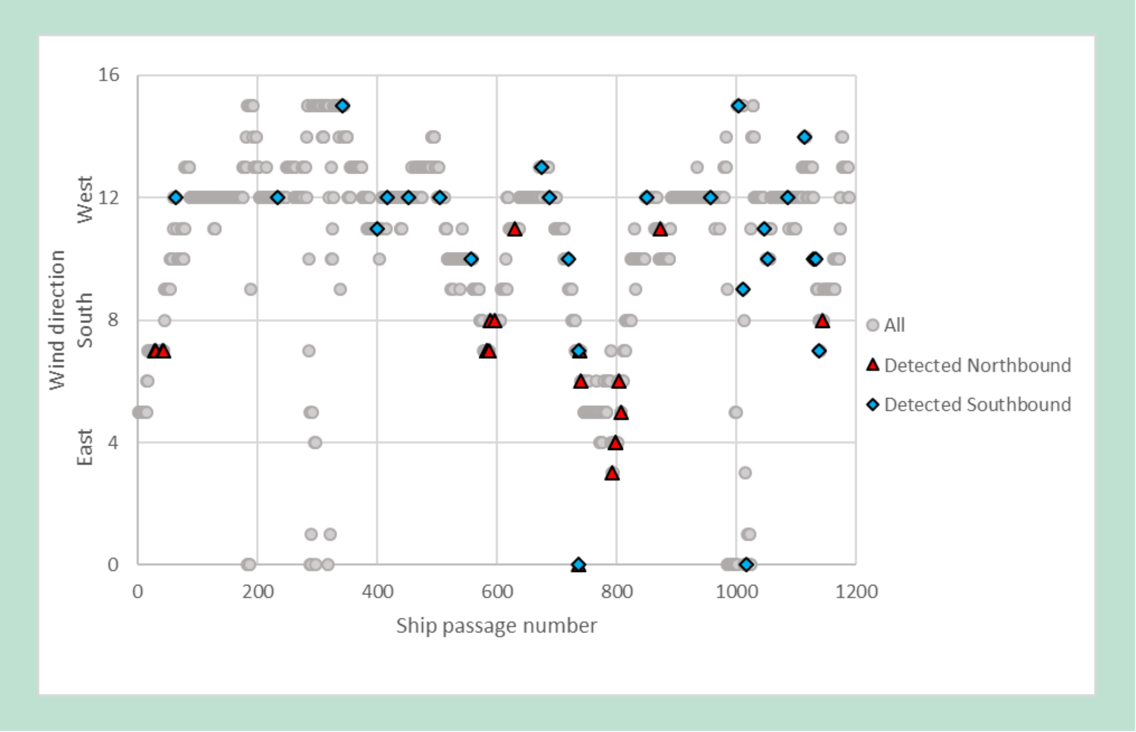

FIGURE 31. Plot of all and identified ships as function of the wind direction

In Figure 32, the wind speeds at all passages are shown. The variation is quite large: from almost 0m/s to more than 25m/s. The ship identified at the highest wind speed is about 14m/s, but typically the maximum wind speed for positive identification seems to be around 11m/s.

The CO_2 signals in the final SO_2 campaign are also compared to the length of the ships, the wind speed and the wind direction, see Appendix 1.

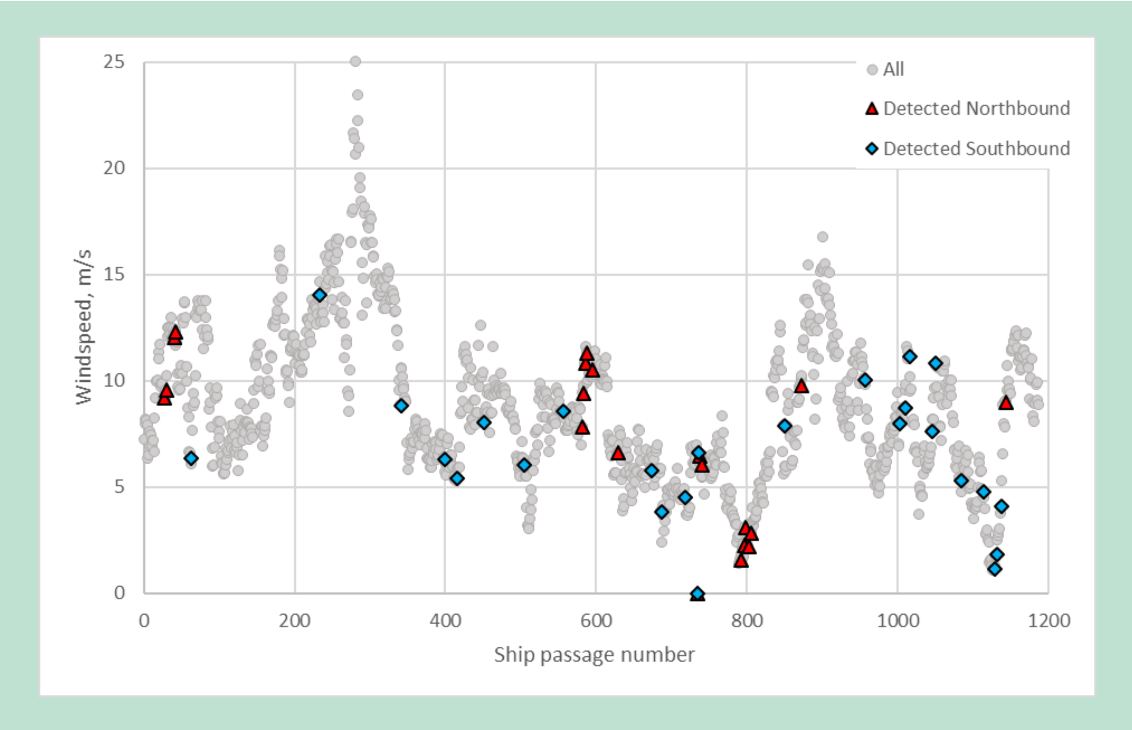

FIGURE 32. All and identified ships as function of the wind speed

7.4 Estimation of the %S

In this section, the measurements are used to calculate the sulphur content of the burned fuel. In principle, it should be sufficient to use the formula:

$$\%S \text{ in fuel} = \frac{[SO_2 \text{ (ppb)}]}{[CO_2 \text{ (ppm)-}CO_{2,\text{bagground}} \text{ (ppm)}]} \cdot 0.232\ \%S$$

However, a few corrections are needed for both SO_2 measurement technologies to quantify the SO_2 concentration.

The SO_2 electrochemical sensor reacts to the NO_2 in the plume, and the SO_2 signal must be compensated by the signal measured by the NO_2 sensor. The SO_2 calibration factor and the compensation factor were identified in the laboratory. By using these factors, the %S turned out to be mainly negative which does not make physical sense. This can probably be explained by the fact that the gas mixes used in the laboratory are too simplified compared to the complex composition in the plume (e.g. SO_2, SO4, NO_2, NO, CO, particles, unburned fuel, humidity etc.). Furthermore, the factor was determined on a long time scale, but the plume signal is very short.

In order to evaluate the precision of the evaluated %S from the electrochemical sensors, a new set of calibration and compensation factor was found assuming that the average fuel sulphur content is around 0.1%S and that only a few negative values are allowed. By doing so, the estimated sulphur content foundin the campaign is shown in Figure 33. All %S values are below 0.3%S, which means that high probability no ships were identified to be using a high sulphur concentration fuel. The standard deviation is around 0.06%S, which is quite large compared to the mean value of 0.1%S. This can be explained by the fact that the sulphur concentration in the sampled plume is very close to the limit of detection.

The pulse fluorescence SO_2 analyzer directly outputs the SO_2 concentration to be used in the formula above, however a correction is needed to take into account that plume signals are much shorter than the response time of the analyzer. This means that the plume is already gone before the measurement cell is filled with the sampling gas of the plume. To compensate this, a correction factor dependent of about 4 is suggested based on the data, response time and signal length, and so the mean is also close to 0.1%S. The results are shown in Figure 34.

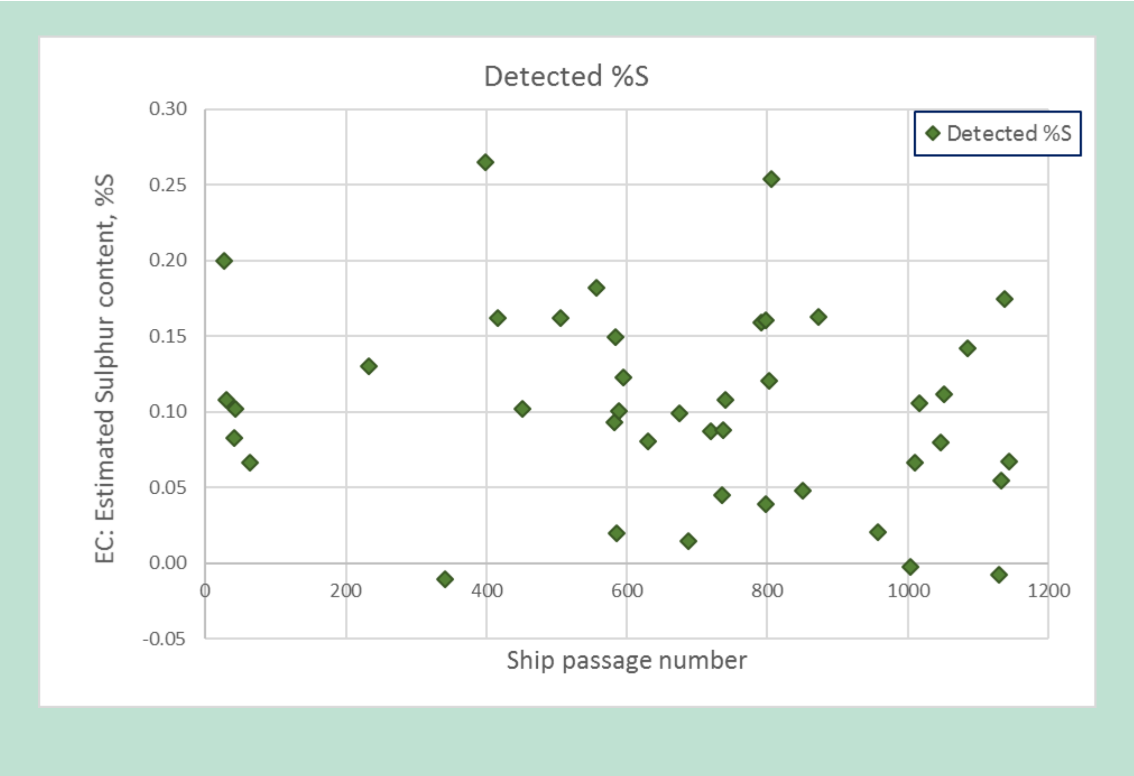

FIGURE 33. Estimated sulphur content %s of the identified ships using the signal from the electrochemical sensors.

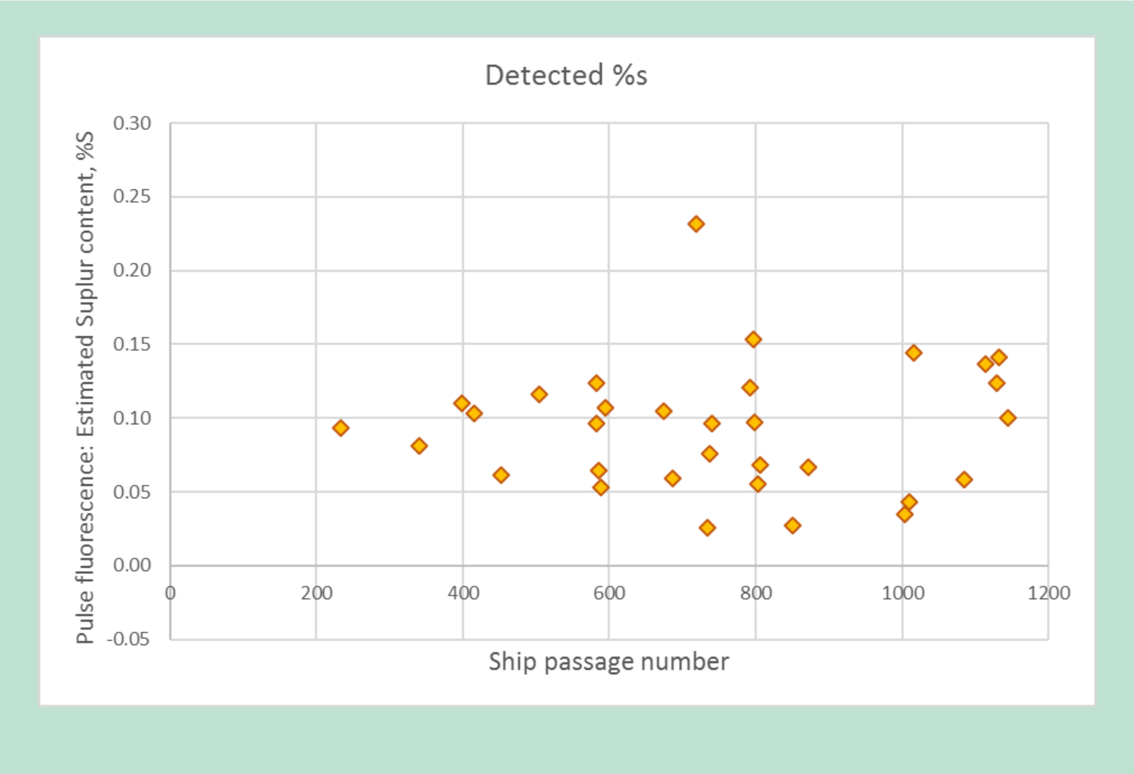

FIGURE 34. Estimated sulphur content %S of the identified ships using the signal from the pulse fluorescence analyzer

The two methods for measuring the SO_2 are compared in Figure 35. Ideally, the linear relationship between the two should have a slope of unity, and it is found to be 0.96 which is rather close to the ideal value. However, there is a large spread in the data points which reflects the uncertainty in the measurements.

Finally, the estimated sulphur content, %S, is plotted against the CO_2 concentration at the given signal in Figure 36. At higher CO_2 concentrations, the noise of the SO_2 signal becomes less dominating, which means that the %S values should also have lower noise.

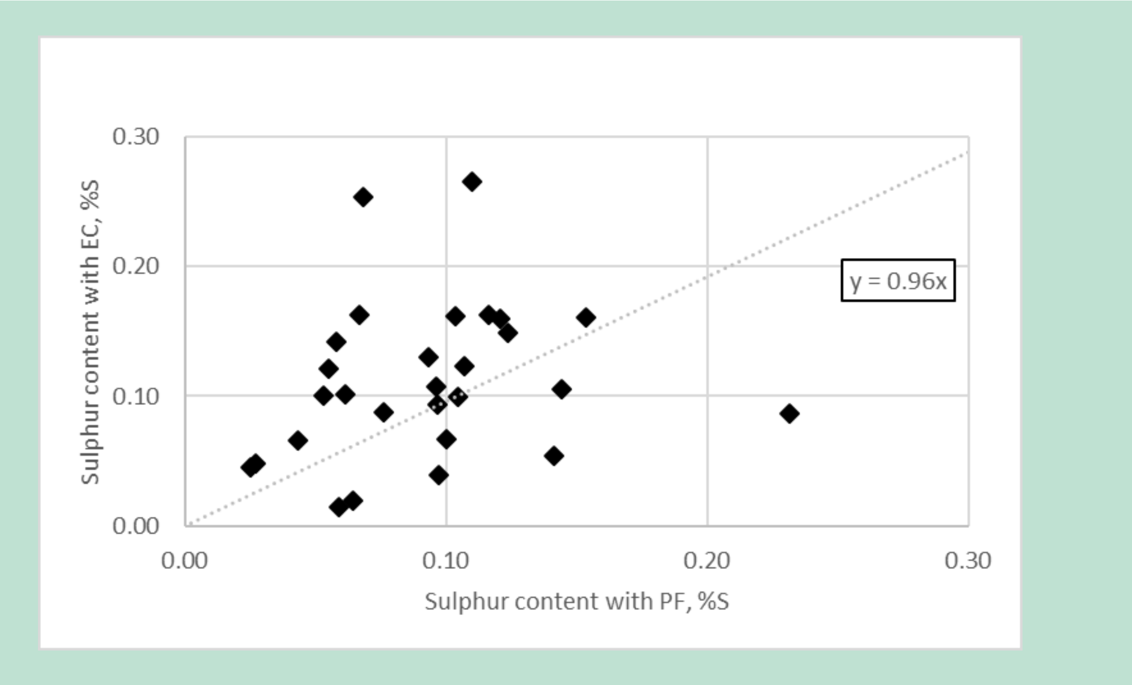

FIGURE 35. Correlation between the two methods for evaluating the suphur content (electrochemical sensors (EC) and pulse fluorescence (PF)).

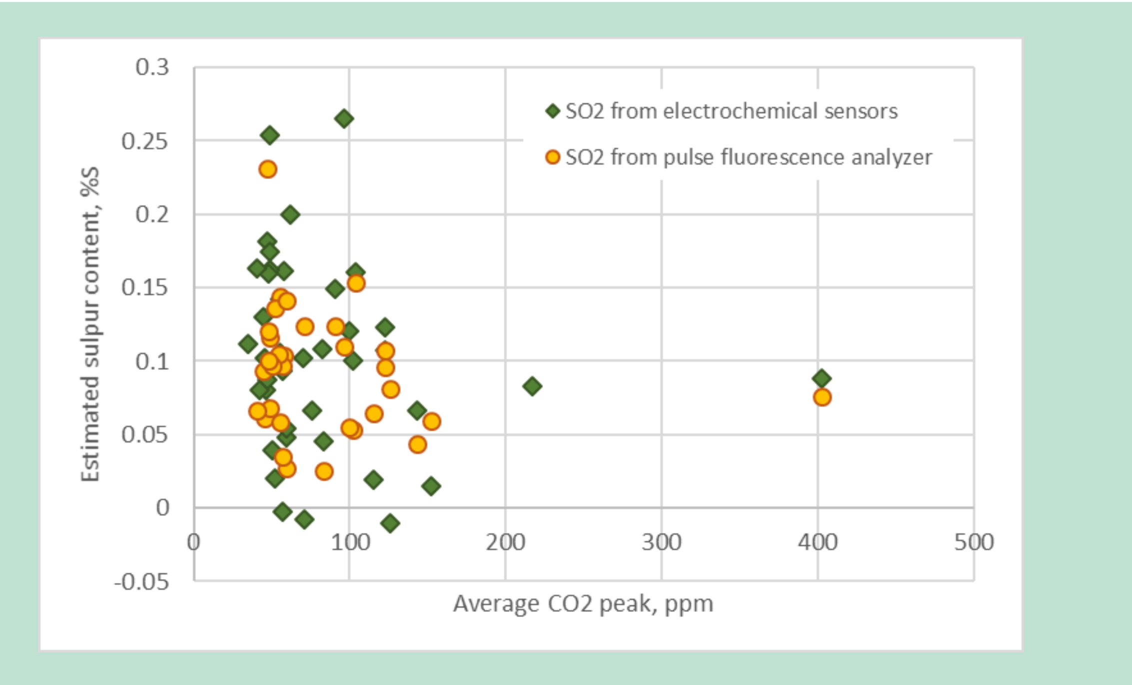

FIGURE 36. The estimated sulphur content displayed as function of the CO_2 peak value (average of both sensors). The lowest value of the CO_2 is 33 ppm, the average is 84ppm, the median is 63ppm. Higher CO2 content indicates less dominating noise.

7.4.1 Estimate of the accuracy of the sensing system

The aim of the sensing system is to identify ships that do not comply with the existing regulations. It is therefore important to identify the accuracy at which the system can report the sulphur content in the fuel (or the equivalent in case of ships with scrubber). The statistical analysis of the data is shown in Table 10, which is based on the fitted calibration and compensation factors by assuming that the average sulphur content is 0.1%S. In order to be able to distinguish a 0.1%S fuel signal with very high probability from one with a higher percentage fuel, a 6 times the standard deviation is added to the mean value of the 0.1%. This results in that when using the electrochemical sensors it is possible to distinguish 0.1%S and 0.5%S. The standard deviation of the pulse fluorescence analyzer is low, hence it is possible to distinguish between 0.1%S and 0.35%S.

TABLE 10. The statistically evaluated properties of the data for the electrochemical sensors and the pulse fluorescence analyzer

Statistical property	Electrochemical sensors	Pulse fluorescence
Mean value, %S	0.103	0.093
Standard deviation (STD), %S	0.064	0.043
Precision (Mean -/+ 3 STD), %S	-0.090; 0.295	-0.036; 0.222
Distinguishable limit (0.100+6 STD), %S	0.100 vs. 0.500	0.100 vs 0.350

7.5 Conclusion

The aim of this SO_2 campaign was to determine the applicability of the cost-effective sensors for monitoring at the central node of the Great Belt Bridge. The hit rate of the identified ships was found to be around 3-4% at the specific measurement position, and the average CO_2 concentration of the peak was about 80ppm. In the data analysis, the system calibration factors was found by assuming that the average sulphur content was about 0.1%S. All %S values are below 0.3%S, which means that in our campaign no ships were identified likely to be using a high sulphur concentration fuel. Statistical analysis of the results prove that using the electrochemical sensors it is possible to distinguish between 0.1%S and 0.5%S. The standard deviation using the pulse fluorescence analyzer is lower, hence it is possible to distinguish between 0.1%S and 0.35%S.

Given that the CO_2 concentration around 50ppm above the background, the expected sulphur concentration in the plume is about 22ppb (0.1%S fuel), which is at the detection limit of both SO_2 sensing technologies. This can explain why the calculated sulphur content has relatively high noise.

The challenges for measuring the plumes at the bridge deck are that the plumes are typically diluted to CO_2 concentration below 50-100ppm (above the background level) and that the duration of the plumes is very short - typically 5-10s. The additional challenges when using the cost-effective equipment is that highly diluted plumes with CO_2 concentrations <25ppm could not be pinpointed due to the noise of the sensors. Furthermore, the SO_2 electrochemical sensor is cross-sensitive to NO_2 in the plume, hence this compensating algorithm is highly needed. The pulse fluorescence analyzer has a rather long response time, which makes it difficult to use without correcting the duration time of the plume.

By installing the cost-effective sensors at several measurement points the total hit-rate could be higher and the hardware cost would still be lower than a state-of-the-art installation. In order to increase the sensitivity of the system more costly sensors could also be installed.

Appendix 1. Sensor linearity, temperature dependence and additional data

Appendix 1.1 Overview of measurements in Appendix

In this appendix, the linearity and the temperature dependence of the linearity of the applied sensors is presented. In addition to this, plots of the raw data from the bridge are shown. The CO_2 signals in the final SO_2 campaign are also compared to parameters of the ships, the wind speed and the wind direction.

Appendix 1.2 Linearity and temperature variation of CO_2 sensor

Linearity was verified by administering known concentrations of CO_2 to the two sensors and then compared with the collected data. Even though the sensors were supposed to measure at a one to one ratio, both showed minor offsets, but in opposite directions with one being slightly lower and the other almost equally higher.

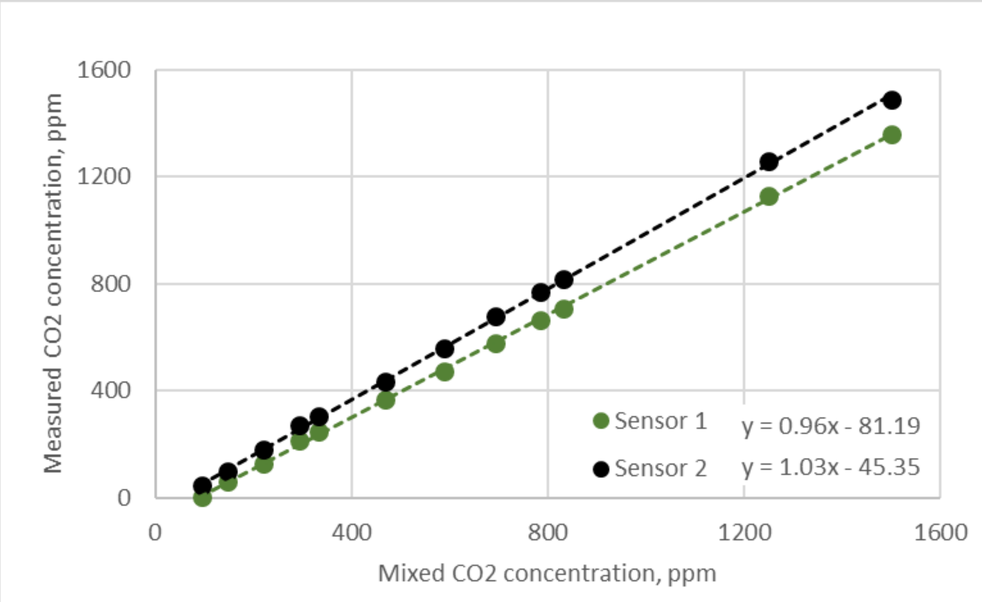

FIGURE 37. Linearity of two of the used CO_2 sensors

The CO_2 sensors were tested for temperature drift by placing them in a temperature controlled environment and running the linearity experiment at two different temperatures, where the selected temperatures were 5 and 20 degrees Celsius.
The temperature affected the sensors, but the linearity was stable.

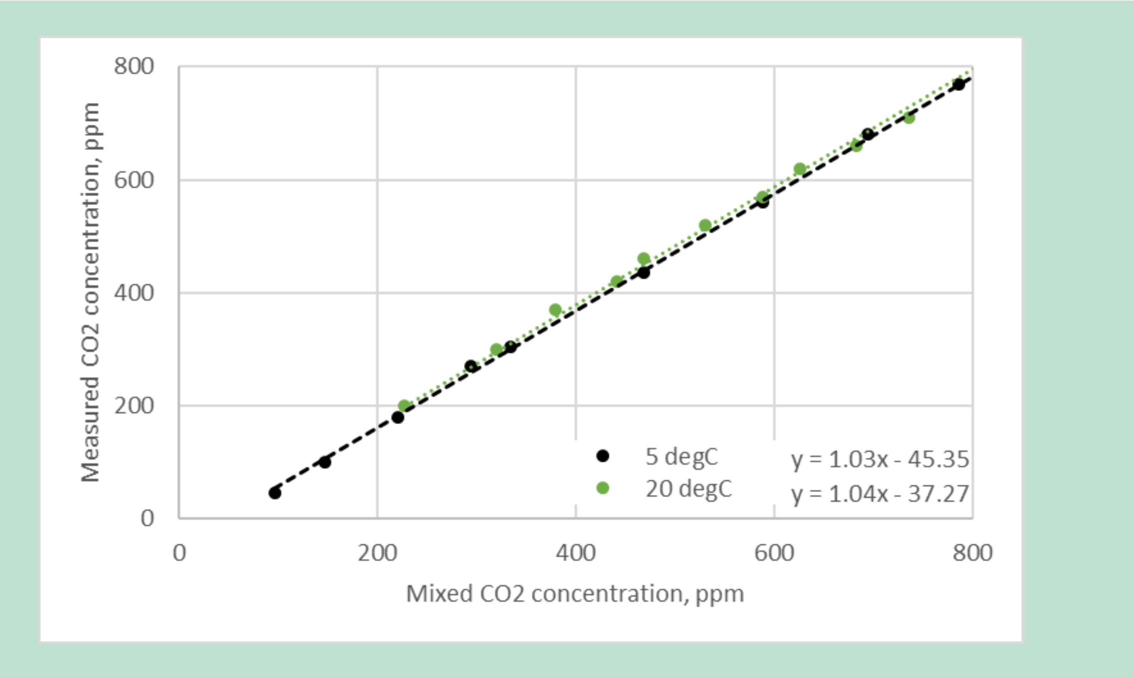

FIGURE 38. Linearity of CO_2 sensor 1 at two temperature extremes.

Appendix 1.3 Linearity and temperature variation of SO_2 electrochemical sensor

The linearity of the sensors was tested by a step-by-step administering of a known concentration of the target gas. Unfortunately, the exact proportion between the electric signal and its corresponding SO_2 concentration in ppb have a large uncertainty. Therefore, in Figure 39, SO_2 concentration is the best estimate and gives a proportionality factor of 1.83mV/ppb.

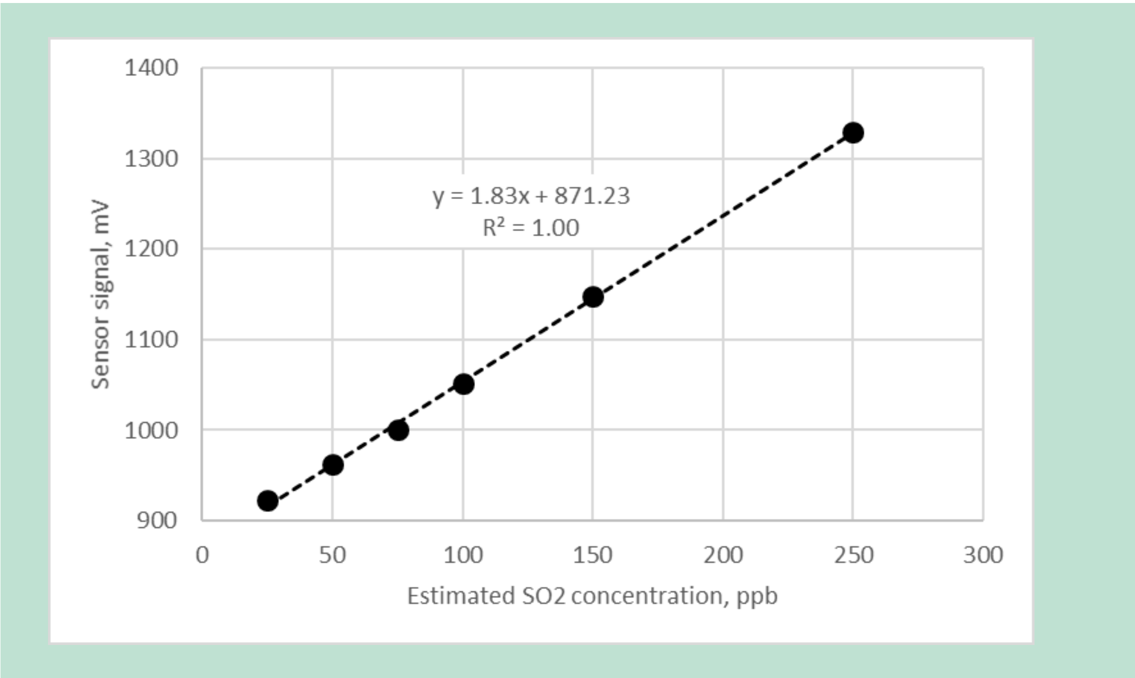

FIGURE 39. Linearity of the SO_2 sensor.

The temperature stability of the sensors was tested by repeating the linearity experiments, while exposing the sensors for varying temperatures. Temperatures being 5, 13 and 20 degrees C.
It was found that the operating temperature had a significant effect on the signal output. Even though no exact linear relationship was established, there was a tendency to record a higher signal at lower temperatures.

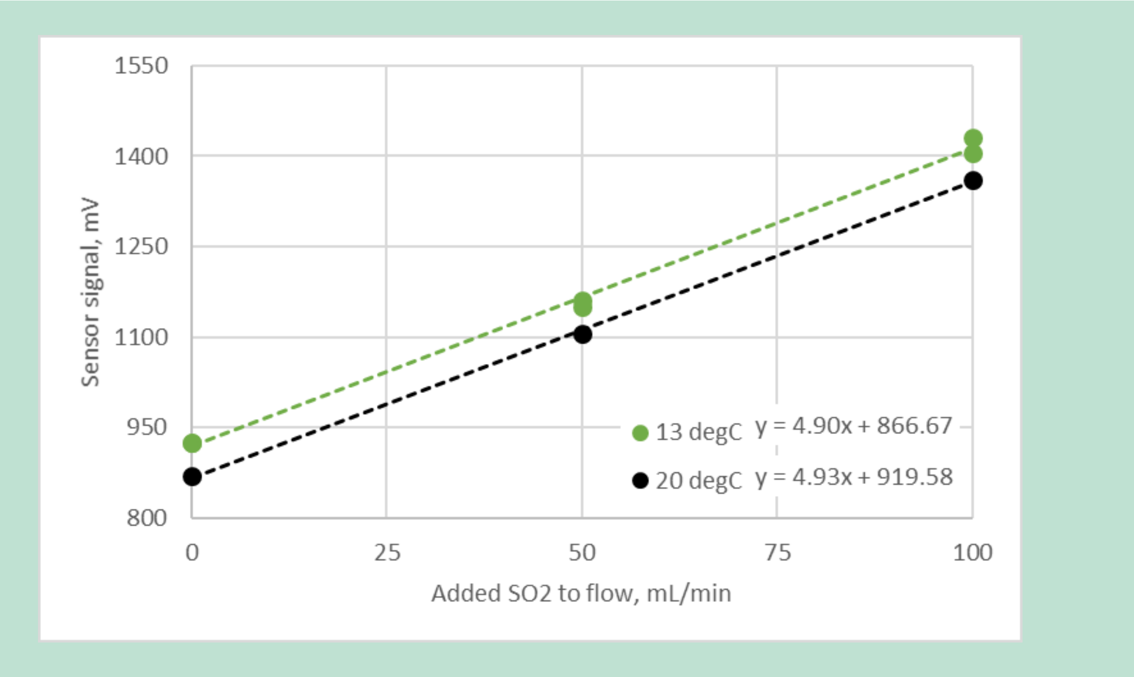

FIGURE 40. Linearity at two temperatures:13 and 20 C. An offset is seen but the linearity is sufficiently stable

Appendix 1.4 Linearity of pulse fluorescence analyzer

Linearity was tested by a step-by-step administering of a known concentration of gas to the SO_2 analyzer. The gas had to be delivered at atmospheric pressure, so a bypass from the flow-controller was made. The total flow was measured with a Defender flow meter, and the dilution factor is used to calculate the SO_2 concentration in ppb.

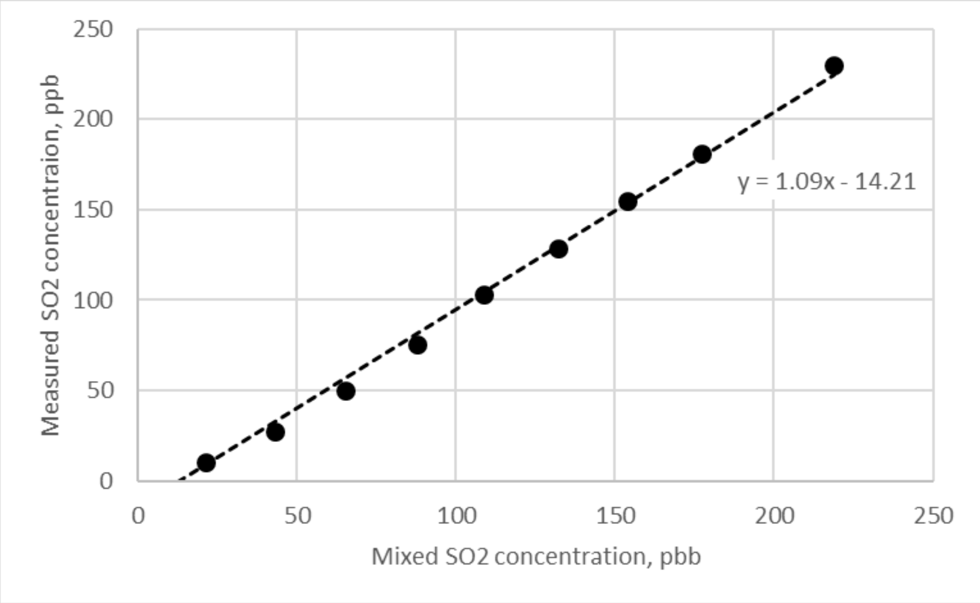

FIGURE 41. SO_2 pulse fluorescence analyzer linearity

Appendix 1.5 Raw signals from the SO_2 campaign

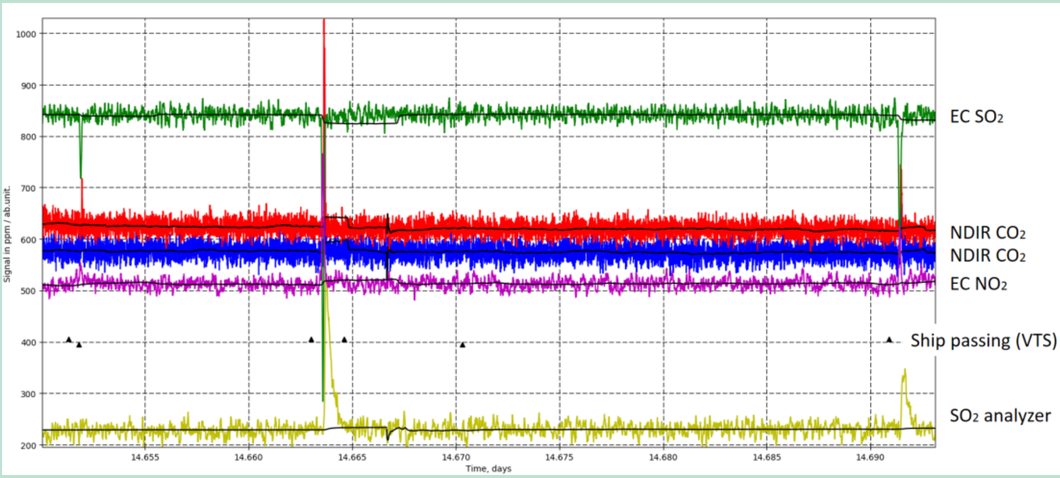

FIGURE 42. Raw signals for a period of approximately 2 hours. 6 ship transits were registered, where 2 can be seen clearly on all sensors and one on all sensors except the SO_2 analyzer.

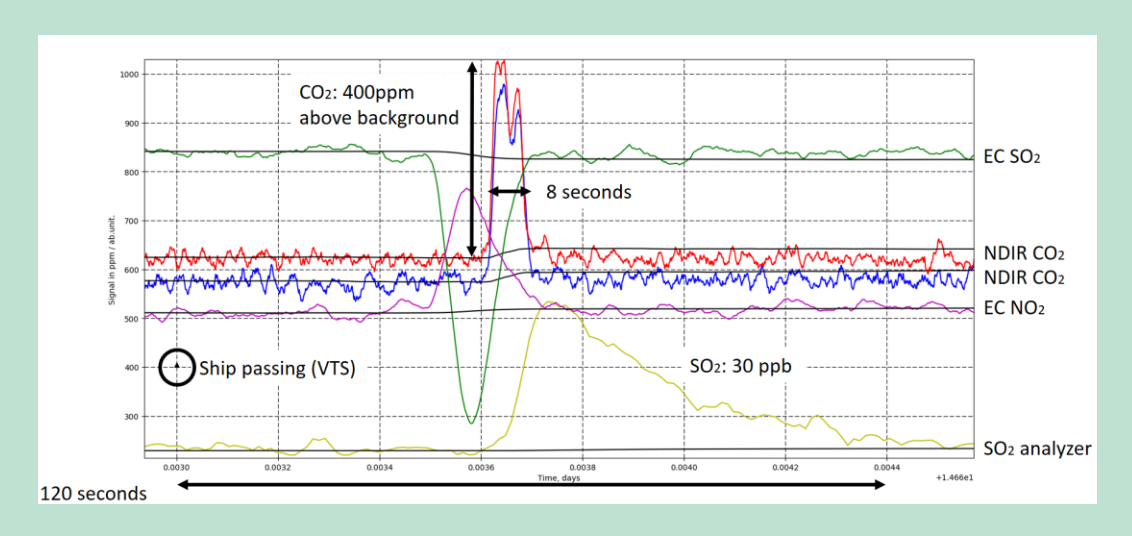

FIGURE 43. Raw signals for single ship passage. Curves in the plot is assigned to the sensor list of sensors to the right. The total time period is about 2 minutes. The down-slope of SO_2 from the pulse fluorescence could indicate VOCs in the sample caused by the missing kicker. The down slope should be equal to the up-slope on the pulse fluorescence signal as the signals from for EC and CO_2 sensors have no indication of remaining sample. VOCs have a higher tendency to stick to the materials used in the sampling system than the inorganic compounds.

Appendix 1.6 Correlation of ship data, weather, and CO_2 results in SO_2 campaign

The volumetric rate of CO_2 emitted from a ship is dependent on the instantaneous engine power, which cannot be evaluated easily. But the length of the ship can be approximated to the designed engine power, and therefore the CO_2 signal peaks are plotted as function of the length of the ship, see Figure 44. There is no clear correlation, but the tendency is that signals below 50ppm are observed for all ship lengths, and there might be a dependence for a signal higher than 100ppm.

The CO_2 signal magnitudes are also plotted as a function of wind speed and wind direction respectively, as shown in Figure 45 and 46. In general, a baseline around 50ppm can be seen. Above a concentration of 50ppm the signals are more or less randomly distributed.

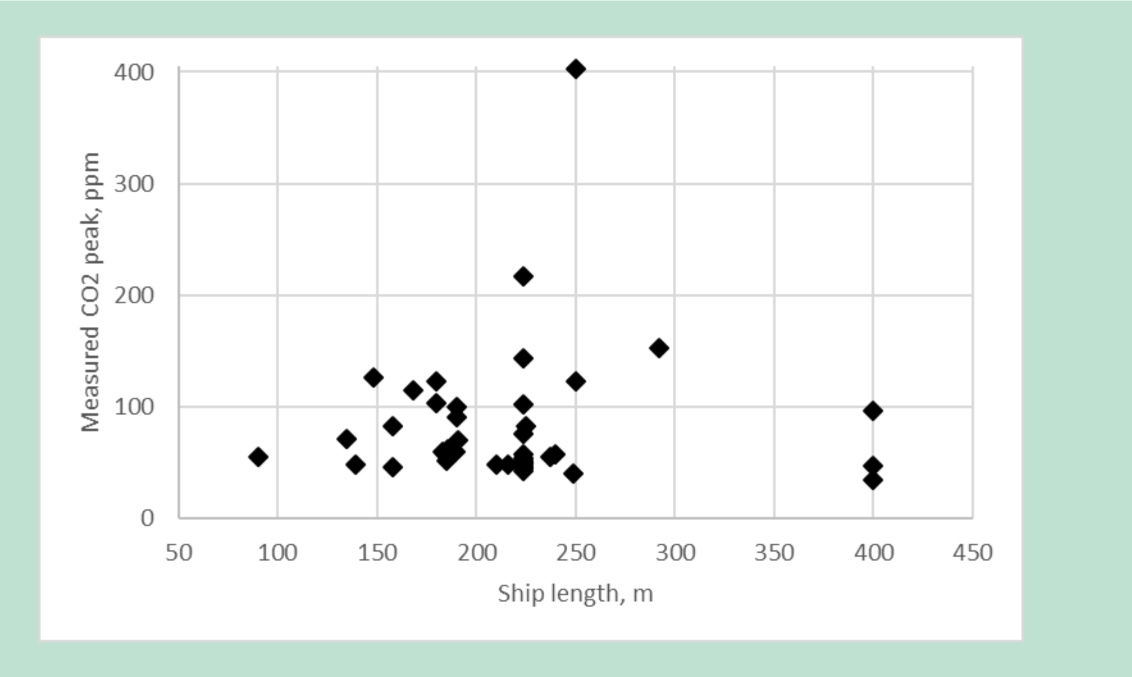

FIGURE 44. The measured CO_2 peak is plotted as function of ship length, which presumably is correlated to the engine power and therefore also the exhaust volumetric rate.

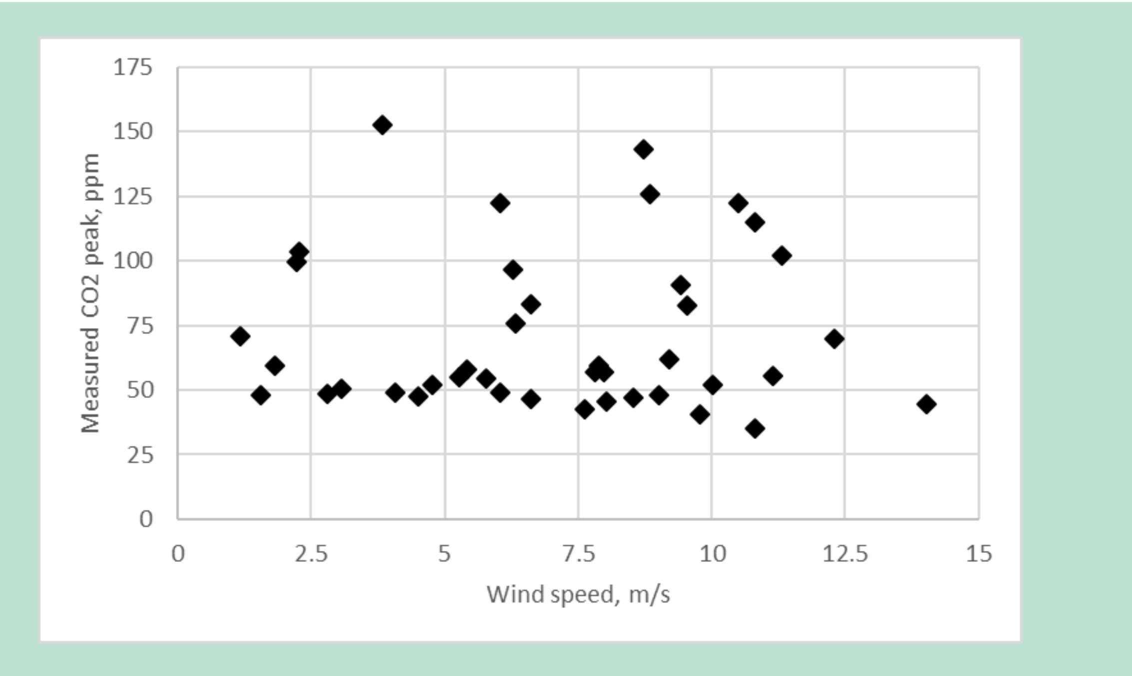

FIGURE 45. The measured CO_2 peak value is plotted as function of the wind speed at the time of the ship passage.

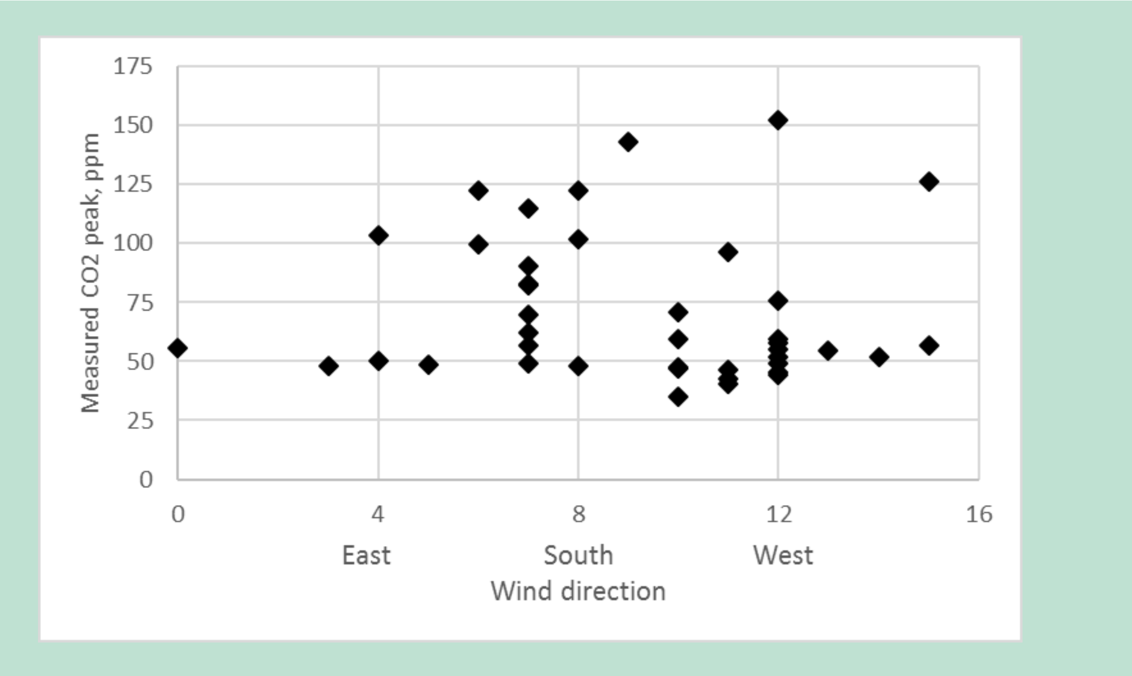

FIGURE 46. The measured CO_2 peak value is plotted as function of the wind direction at the time of the ship passage.

Remote sensing of sulphur and particle pollution from ships –a cost-efficient approach

The main aim of this project has been to identify and develop the potential for simple and improved cost-efficient methods for monitoring sulphur content in fuel in ships by means of remote sensing techniques. The main focus has been on remote monitoring from the Great Belt Bridge.

In the project, we rendered it probable to distinguish between 0.1 and 0.5 %S in fuel using cost-efficient sensing from the Great Belt Bridge. A raw sensor price, including pumps, casing and tubing is estimated to be below €1,500, hereto comes expenses to servicing the equipment and software for data analysis, reporting, etc. The main challenge for using cheap sensor technology, as compared to state-of-the-art sensors, is the hit-rate of positively identified ships, which in our study is around 3-4% measured from the specific position on the bridge deck. This relatively low number is due to higher noise in the low-cost sensors as compared to using present state-of-the-art sensors. However, continuous sensor improvements with respect to precision and reliability is expected in the future. By installing the cost-effective sensors at several measurement points, the total hit-rate could also be significantly higher and the hardware cost would still be lower than a state-of-the-art installation.

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