Emission factors of gases and particles from ships observed by remote measurements from fixed and airborne platforms

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Some research questions

• Ships must operate on low sulfur fuel oil (0.1%) in the Sulfur Emission Control Area (SECA) in northern Europe since 2015
  • How well do the ships comply with the requirements (harbors - open sea)?
  • Is there improvement in the emissions also of particles and NOx?
  • How well does the new abatement technique work?

• Impact of shipping on port cities by combining measurements, AIS-modelling and air quality modelling
  • How do the real world emission of particles (PM, PN, BC), NOx and SO2 vary during different modes of operation- chase studies
Activities

Airborne

IGPS 2008 – 2014
a) Development of a fixed, automated system for sulfur compliance measurements.
b) Building and certifying a permanent airborne system, CompMon 2014-2016
CEF project on Sulfur Compliance monitoring in Europe, (Älvsborgsfästning, Öresundsbron, English channel
IGPS - Denmark 2015-2017
Sulfur Compliance measurements at Great Belt bridge and Aircraft around Denmark
Envisum (BSR Interreg) 2016-2019
New ship emissions of gases and particles, compliance (Baltic sea, Gdansk Gdyna, Göteborg, Sankt Petersburg)
Ship emission in LA basin 2015-2016
Variability in different modes of operation and impact on air quality
# Instrumentation

<table>
<thead>
<tr>
<th>Short description</th>
<th>Measured species resp. purpose</th>
<th>Response time ($t_{90}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-dispersive infrared analyzer</td>
<td>CO₂ and H₂O</td>
<td>&lt; 0.1 s</td>
</tr>
<tr>
<td>Cavity ring-down spectrometer</td>
<td>CO₂, CH₄ and H₂O</td>
<td>&lt; 1 s</td>
</tr>
<tr>
<td>Fluorescence analyzer</td>
<td>SO₂</td>
<td>2 s/60 s</td>
</tr>
<tr>
<td>Chemiluminescence analyzer</td>
<td>NOₓ</td>
<td>1 s</td>
</tr>
<tr>
<td>Electrostatic particle sizer EEPS</td>
<td>Size-distribution 5.6 to 560 nm</td>
<td>0.5 s</td>
</tr>
<tr>
<td>Optical particle sizer OPS</td>
<td>Size-distribution 0.3 to 10 µm</td>
<td>2 s</td>
</tr>
<tr>
<td>Condensation particle counter CPC</td>
<td>Total number concentration &lt;1 µm</td>
<td>&lt; 0.3 s</td>
</tr>
<tr>
<td>Aethelometer Magee 33</td>
<td>BC</td>
<td>1 s</td>
</tr>
<tr>
<td>UV Spectrometer</td>
<td>SO₂, NO₂</td>
<td>1 s</td>
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</tbody>
</table>
Airborne measurements (combination of optical and sniffer technique)

a) Aircraft crosses above or through plume. An **optical** measurements of the ratio of SO2 and NO2 is carried out at higher altitude.

b) If the ratio is high a **sniffer** measurement of SO2 and CO2 is done at lower altitude. The SO2/CO2 ratio is proportional to fuel sulfur content.
Example of ship measurements outside Island of Gotland

Emission factor in g/kg\textsubscript{fuel} of various species obtained from measured $X$/CO\textsubscript{2} ratios
$X=\text{SO2, NOx, PM, PN, BC}$
Airborne monitoring from Roskilde during 2015-2016

Navajo Piper with 6 h endurance, 6-10 ship measurements per hour, 700 ships.

Flag FSC
Red > 0.3 %
Yellow 0.17-0.3 %
Green <0.17 %
Fraction of ships using compliant fuel for airborne measurements of SO₂/CO₂ from 700 ships. These measurements show that 10% of the ships are using non-compliant fuel. Similar measurements at SECA border show 84% compliance rate.
Fixed measurements using sniffers (smoke drifts over station)

Great Belt bridge, since 2015, 4000 inspections per year

Ship channel of Göteborg since 2014, 4000 inspection per year

Öresund bridge, 3 months Dec 16
Fraction of ships using compliant fuel obtained from the fixed measurements of SO2/CO2 at Great belt. These measurements show that **5% of the ships are using non-compliant fuel**. 4000 ships were measured,
Malfunctioning scrubber has been encountered on several occasions. Here two scrubber ships measured at Great Belt. One of them had problems with ANTIFOULING.
Results regarding compliance rate

- Around Denmark and southern Baltic the compliance rate is 95 % at great Belt bridge and 90 % from airborne.
- Close to the SECA border the compliance level was 84 %, with non compliance dominated by ships leaving the SECA.
- Some specific shipowners/lines are often encountered high (flag less important).
- Several ferry lines have been operating with malfunctioning scrubbers, (partly) due to malfunctioning sensors.
- A cruiser line, flagged in a European non SECA state, has been measured high both from the air, Great Belt bridge and onboard inspection. They have one scrubber installation on one out of 4 engines for a 18 month test period, approved by the flagstate.
- Ships that are only occasionally in the SECA have higher emissions.
- Ship going to non SECA harbors have higher emissions.
Influence of ship emissions on air quality in port cities

- Ports of Gdynia/Gdansk, LA and Göteborg
- Emission factors of SO2, NOx and particulates (PM, PN, BC) in g/kg at different modes of operation (chase studies).
- Investigate the influence of ships on the air quality (See Borkowski AP04)
Example from Gdynia chasing a ship from open sea to full stop

CO₂, BC, SO₂, CH₄

NOₓ, PM₁₀, P₂.₅, PN
Overall emission factor results from individual ships often manuevring together with tugs in port of LA

<table>
<thead>
<tr>
<th>No of Plumes / Ships</th>
<th>EF(NO\textsubscript{x}) g/kg\textsubscript{fuel}</th>
<th>EF(SO\textsubscript{2}) g/kg\textsubscript{fuel}</th>
<th>EF(PM) g/kg\textsubscript{fuel}</th>
<th>EF(BC) g/kg\textsubscript{fuel}</th>
<th>EF(PN) 10\textsuperscript{16}/kg\textsubscript{fuel}</th>
</tr>
</thead>
<tbody>
<tr>
<td>median (25\textsuperscript{th}</td>
<td>36.3 (24.9</td>
<td>52.6)</td>
<td>0 (-0.23</td>
<td>0.16)</td>
<td>PM0.5: 0.42 (0.23</td>
</tr>
<tr>
<td>75\textsuperscript{th} percentile)</td>
<td></td>
<td></td>
<td></td>
<td>PM1: 0.46 (0.25</td>
<td>0.76)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>PM2.5: 0.61 (0.31</td>
<td>1.21)</td>
</tr>
</tbody>
</table>

- The PM2.5 emission factors were lower than other studies
- A surprisingly large fraction of the measured PM2.5 mass was Black carbon (70-80 %).
- The emission factors of BC versus ship speed varies within a factor of 2 and they show high and variable values for speeds between 0 and 4 knots which then decrease at higher ship speed. The pattern for the PM0.5 measurements is similar.
- The NO\textsubscript{x} was generally lower than used in inventories
The Danish paper "Berlingske tider" about our sniffer measurements at the Great belt (20160622)

You probably have to put out your cigarette, Rene'.

https://www.tveast.dk/artikel/sniffer-er-vigtigt-redskab-i-kampen-mod-miljoesyndere
https://www.facebook.com/Miljoestyrelsen/videos/1822810627745962/
https://www.youtube.com/channel/UCvUmGhGY_8XKbGHeDqQQPVYYA