Atmospheric
Chemistry
and Physics

*Supplement of*

# Measurement report: Inland ship emissions and their contribution to $NO_x$ and ultrafine particle concentrations at the Rhine

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**Supplement**

**Table S1:** Emission limits set by the CCNR (CCNR, 2022) and the EU (European Union, 2016) in comparison with mean emission factors from this study (measured at BRI).

| Emission standard | Valid from year | NO$_x$ limit (g kWh$^{-1}$) | $E_{NOx}$ (this study) | PM limit (g kWh$^{-1}$) | $E_{PM}$ (this study) | PNC limit ($10^{12}$ particles kWh$^{-1}$) |
|---|---|---|---|---|---|---|
| none | ≤ 2003 | none | | none | | none |
| CCNR I | > 2003 | 9.2 | 8.9 ± 3.2 | 0.54 | 0.35 ± 0.21 | none |
| CCNR II | > 2007 | 6 | 8.7 ± 3.2 | 0.2 | 0.41 ± 0.20 | none |
| Euro IIIa | > 2007 | 6 | 7.0 ± 2.5 | 0.2 | 0.44 ± 0.28 | none |
| Euro V[a] | > 2020 | | 0.6 ± 0.5 | | 0.01 ± 0.02 | |
| IWP/IWA | | 1.8 | | 0.015 | | 1 |
| NRE, P<560kW | | 0.4 | | 0.015 | | 1 |
| Euro VI marinized | | 0.4 | | 0.01 | | 0.8 |

5   [a]Subcategories according to EU 2016/1628: IWP/IWA = motors certified for inland ships. NRE = motors for non-road mobile machines.

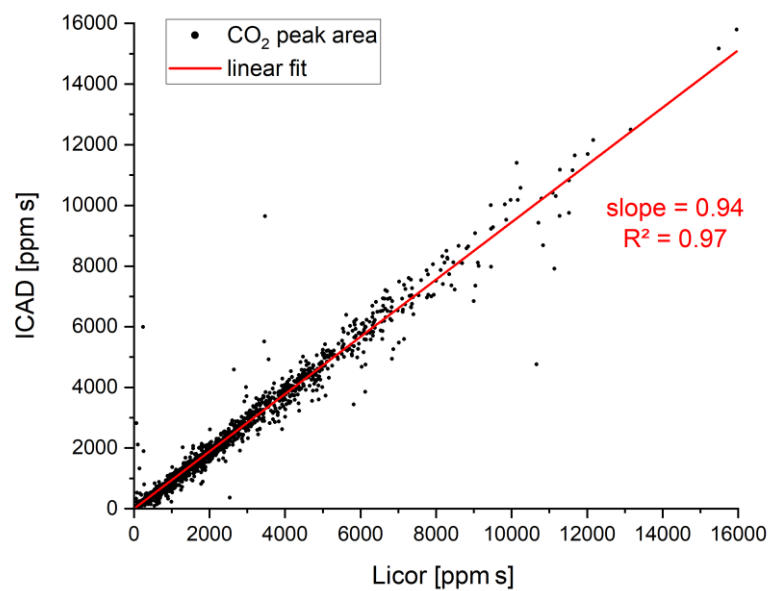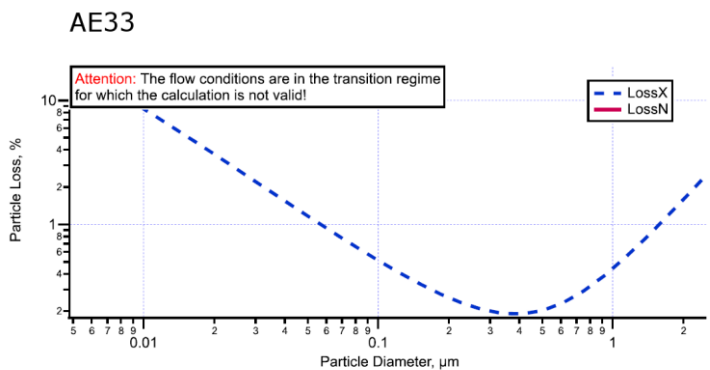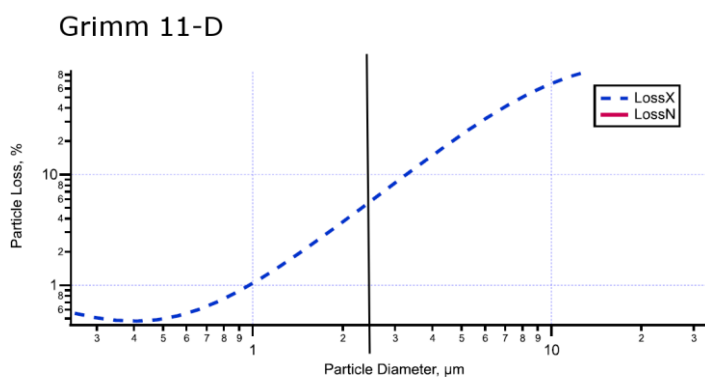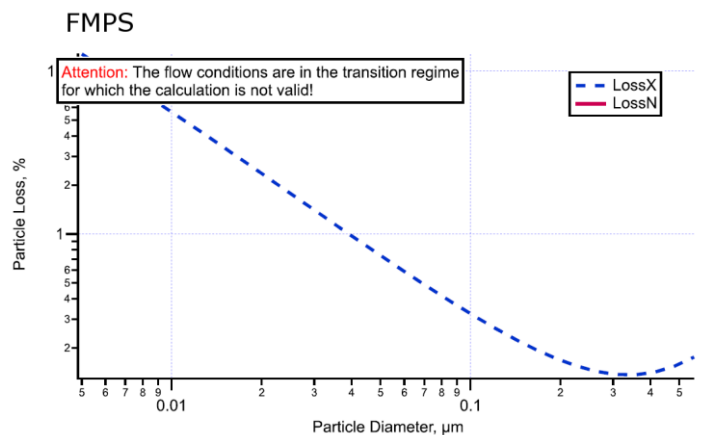Marinized = marinized motors from heavy-duty vehicles.

**Figure S1:** Correlation plot of $CO_2$ peak areas derived from Licor and ICAD measurements at BRI.

## FMPS



## Grimm 11-D



## AE33



**Figure S2:** Calculated overall transmission losses with ~ 5 m sampling line for the instruments FMPS (flow rate 10 lpm), Grimm 11-D (flow rate 1.2 lpm) and AE33 (flow rate 5 lpm), derived using the Particle Loss Calculator Tool (von der Weiden et al., 2009). To carry out calculations in the transition regime between laminar and turbulent flow (2000<Re<4000) laminar equations were extended to this regime. The results marked with an info box have a lower precision but still provide useful estimates of occurring losses.
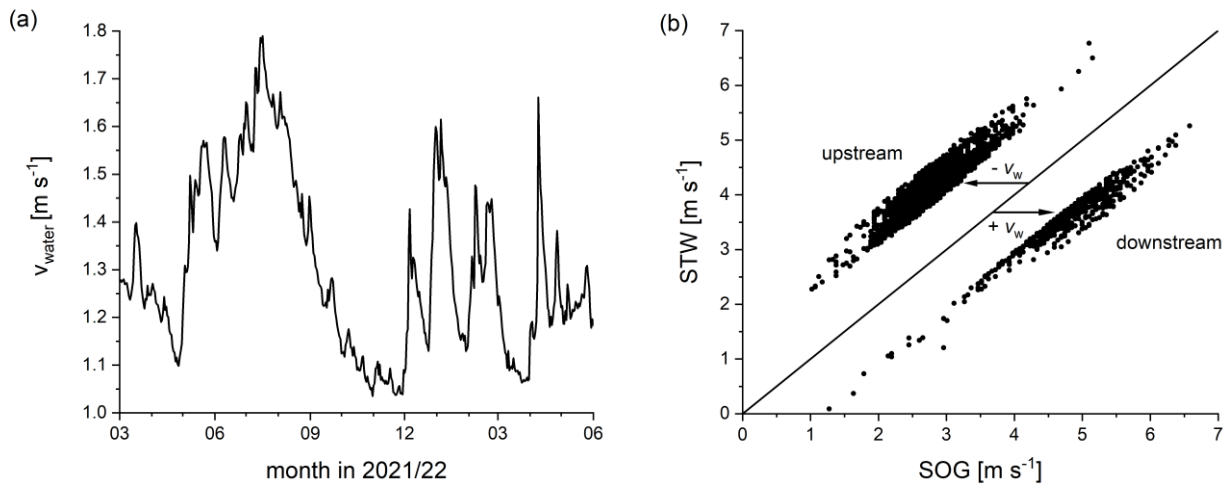
**Figure S3:** (a) Evolution of the velocity of the Rhine ($v_{water}$) within the measurement period. (b) Comparison of SOG and STW for ships travelling upstream and downstream.

**Table S2:** Standard parameters for the peak identification algorithm which were chosen individually for each instrument.

| Parameter | Default | 2B NOx | 2B NO₂ | O₃ | ICAD NOx | ICAD NO₂ | ICAD CO₂ | Licor CO₂ | BC | FMPS PNC | 11-D PNC | EDM PNC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Filter method[a] | **F, p, T** | | | - | | | | | | | | |
| Typ. noise[b] [$x$] (1σ) | | 4 | 4 | 1 | 0.4 | 0.4 | 1 | 0.3 | 0.4 | | | |
| Time resolution [s] | | 5 | 5 | 2 | 2–3 | 2–3 | 2 | 2–3 | 1 | 1 | 1 | 6 |
| Window size[c] [min] | **10** | | | | | | | | | | | |
| Threshold interval[d] [s] | **30** | | | | | | | | | | | |
| Threshold factor[e] [σ] | **4** | | | | | | | | | | | |
| Max threshold[f] [$x$] | | 50 | 40 | 20 | 50 | 20 | 20 | 20 | 5 | 20 000 | 40 | 20 |
| Points above thres[g] [s] | **3** | | | | | | | | | | | |
| Time below thres[h] [s] | **20** | | | | | | | | | | | |
| Mininum peak height [$x$] | | 50 | 20 | 10 | 50 | 10 | 10 | 10 | 2 | 10 000 | 20 | 20 |
| Peak duration [s]: | **10–240** | | | | | | | | | | | |
| Offset between peak and ship passage[i] [s]:<br>  BRI<br>  RIV | **-30 to 120**<br>**-60 to 240** | | | | | | | | | | | |

[a]Prior to analysis the raw instrument data was screened for flow rate (F), pressure (p) and temperature (T) conditions not in the range specified by the manufacturer. [b]Typical instrumental noise. $x$ = unit depending on component, i.e. ppb for $NO_x$, $NO_2$ and $O_3$; ppm for $CO_2$; µg m$^{-3}$ for BC; particles cm³ for PNC. [c]Window size for background calculation (running median). [d]Interval length before peak start for calculation of the standard deviation to filter out periods with high atmospheric variability. [e]Number of standard deviations (σ) to determine the threshold for peak detection from the threshold interval. [f]Maximum permitted threshold value to filter out periods with increased atmospheric variability. [g]Minimum consecutive data points above the threshold to define the beginning of a peak. [h]Minimum time span below the threshold to define the end of a peak. [i]Temporal offset between the observed peak and the corresponding ship passage determined via AIS position (positive for peak occurring after ship passage).
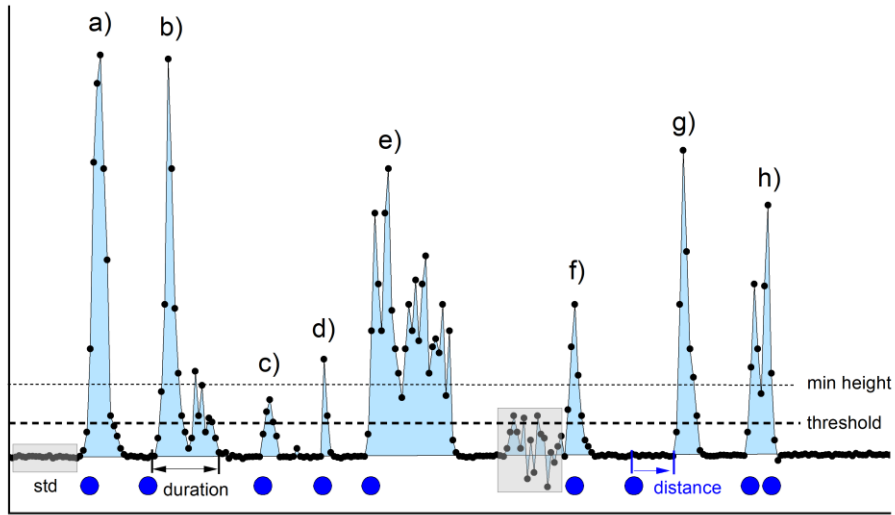
**Figure S4:** Exemplary peaks illustrating certain criteria of the peak identification algorithm according to Sect. 2.3.1 in the manuscript. A description of cases (a) to (h) is given in Table S2 below.

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**Table S3:** Exemplary cases (a) to (h) belonging to Fig. S4.

| Peak | All criteria fullfilled | peak > minimum height | 3 points or more > threshold | peak duration < 4 min | low atmospheric background noise | distance between ship passage and deteced peak < 120 s | not more than 1 ship present within 120 s |
|------|------|------|------|------|------|------|------|
| a) | **yes** | yes | yes | yes | yes | yes | yes |
| b) | **yes** | yes | yes | yes | yes | yes | yes |
| c) | **no** | no | yes | yes | yes | yes | Yes |
| d) | **no** | yes | no | yes | yes | yes | Yes |
| e) | **no** | yes | yes | no | yes | yes | yes |
| f) | **no** | yes | yes | yes | no | yes | yes |
| g) | **no** | yes | yes | yes | yes | no | yes |
| h) | **no** | yes | yes | yes | yes | yes | no |

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**Table S4:** Emission factors (in g per kg fuel), NO$_2$-to-NO$_x$ ratio (calculated for the initial time of emission), geometric mean diameter (GMD) and mode diameter ($D_{mode}$) for stations BRI and RIV.

| **BRI** | NO$_x$ | NO$_2$/NO$_x$ (initial) | PM$_1$ | BC | PNC ($\times 10^{15}$ #) | UFP ($\times 10^{15}$ #) | GMD (nm) | $D_{mode}$ (nm) |
|---|---|---|---|---|---|---|---|---|
| Mean ± std | 36.8 ± 15.7 | 0.08 ± 0.07 | 1.7 ± 1.1 | 0.5 ± 0.3 | 3.5 ± 5.5 | 3.2 ± 5.6 | 52 ± 23 | 66 ± 35 |
| Median | 33.8 | 0.07 | 1.6 | 0.4 | 1.5 | 1.0 | 55 | 81 |
| 25-75% | 26.3 – 43.9 | 0.06 –0.09 | 0.9 – 2.3 | 0.3 – 0.7 | 1.0 – 3.3 | 0.7 – 2.9 | 31 – 70 | 26 – 93 |
| IQR | 17.6 | 0.03 | 1.4 | 0.4 | 2.3 | 2.2 | 39 | 67 |
| min-max | 1.5 – 184 | 0 – 1 | 0 – 13 | 0 – 3.8 | 0 – 92 | 0 – 92 | 8 – 114 | 6 – 143 |
| N$_{peaks}$ | 3123 | 885 | 1780 | 1895 | 1780 | 1780 | 2010 | 2010 |
| **RIV** | NO$_x$ | NO$_2$/NO$_x$ (initial) | PM$_{2.5}$ | BC | PN$_{2.5}$ ($\times 10^{15}$) | PN$_{UFP}$ ($\times 10^{15}$) | GMD (nm) | $D_{mode}$ (nm) |
| Mean ± std | 39.0 ± 15.7 | - | - | - | - | - | - | - |
| Median | 43.9 | - | - | - | - | - | - | - |
| 25-75% | 29.4 – 47.6 | - | - | - | - | - | - | - |
| IQR | 18.2 | - | - | - | - | - | - | - |
| min-max | 8.7 – 81 | - | - | - | - | - | - | - |
| N$_{peaks}$ | 47 | - | - | - | - | - | - | - |

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**Table S5:** Ship classification scheme according to Krause et al. (2022) with emission factors derived in Krause et al. (2022) (converted with suggested fuel consumption scenario) together with $E_{NOx}$ (in g kg$^{-1}$) and $E_{PNC}$ (in particles kg$^{-1}$) measured at BRI.

| Ship class | length [m] | width [m] | $N$ (this study) | $E_{NOx}$ (this study) [g kg$^{-1}$] | $N$ (Krause et al.) | $E_{NOx}$ (Krause et al.) [g kg$^{-1}$] | $N$ (this study) | $E_{PNC}$ (this study) [$10^{15}$ particles kg$^{-1}$] |
|---|---|---|---|---|---|---|---|---|
| All | - | - | 3123 | $37 \pm 16$ | | | 1780 | $3.5 \pm 5.5$ |
| I | $\leq 39$ | $\leq 6$ | 13 | $36 \pm 14$ | 469 | $45 \pm 3$ | 8 | $4.9 \pm 6.5$ |
| II | $\leq 56$ | $\leq 7$ | 19 | $39 \pm 21$ | 49 | $44 \pm 9$ | 14 | $4.8 \pm 5.9$ |
| III | $\leq 68$ | $\leq 9$ | 27 | $42 \pm 17$ | 258 | $39 \pm 3$ | 9 | $10.9 \pm 9.3$ |
| IV | $\leq 86$ | $\leq 10$ | 330 | $40 \pm 19$ | 2608 | $47 \pm 1$ | 181 | $5.3 \pm 7.2$ |
| Va | $\leq 111$ | $\leq 12$ | 1550 | $36 \pm 15$ | 5377 | $50 \pm 1$ | 850 | $3.1 \pm 4.2$ |
| Vb | $\leq 136$ | $\leq 12$ | 412 | $36 \pm 16$ | 1548 | $49 \pm 1$ | 260 | $3.3 \pm 5.7$ |
| Jowi | $\leq 136$ | $\leq 18$ | 185 | $35 \pm 14$ | 1343 | $52 \pm 2$ | 110 | $3.9 \pm 6.1$ |
| VIa | $\leq 173$ | $\leq 12$ | 125 | $39 \pm 16$ | 285 | $57 \pm 3$ | 79 | $2.1 \pm 2.2$ |
| VIb | $\leq 194$ | $\leq 23$ | 408 | $37 \pm 15$ | 906 | $58 \pm 2$ | 243 | $3.7 \pm 7.5$ |
| VIc | $\leq 194$ | $\leq 35$ | 7 | $38 \pm 11$ | 280 | $47 \pm 3$ | 3 | $1.1 \pm 0.9$ |

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