IN-SERVICE-MONITORING FOR NRMM USING SEAMS, PARAMETER AND REPORTING OPTIONS

Ruud Verbeek, Norbert Ligterink

2nd annual Emission Control Forum for Non-Road Mobile Machinery, Frankfurt, 7 & 8 September 2017
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› Introduction
› SEMS measurement system
› Long term monitoring
   › PROMINENT inlet ships
   › Rail locomotive
› Conclusions
INTRODUCTION

Reference numbers / Emission Factors for IWT

Monitoring data

In Service Monitoring

Alternative certification

(Proof of) True average environmental performance

Tools development Driveline / efficient navigation

http://www.prominent-iwt.eu/

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INTRODUCTION

- Formal In Service Monitoring (EU 2017/655) is only applicable to categories V5 and V6 land based engines

<table>
<thead>
<tr>
<th>In Service Monitoring</th>
<th>EU 2017/655 - PEMS</th>
<th>SEMS (sensor based)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Main Parameters</strong></td>
<td></td>
<td></td>
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<tr>
<td>Gas analysers for NOx, HC, CO Exhaust Flow Meter (EFM)</td>
<td>NOx/O₂, NH3 sensors Fuel flow / carbon balance</td>
<td></td>
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<tr>
<td><strong>Averaging / visualisation</strong></td>
<td>Work and CO₂ based windows</td>
<td>Long term averaging, binning Work and CO₂ based windows</td>
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SEMS: Smart Emissions Measurement System

Aqua Myra

Arese: 135m, ARA + Rhine + Danube

TNO SEMS

NOx, fuel, rpm, temperatures, gps

prominent
SEMS MEASUREMENT SYSTEM

- **In-house developed**
- **Flexible**
- **Connected to TNO database**

**Standard components**

- **3x CAN bus interfaces**
  - OBDII or WWH-OBID
  - J1939
  - Additional CAN

- **GPS**
  - 5Hz speed, altitude and position

- **SD-card memory**
  - Up to 160,000 hours

- **NOx / O2 Lambda automotive sensor**
  - [ppm] and [v%]

- **K-type thermo couples**
  - 2 pieces standard

- **GPRS Modem**
  - Remote data reading

**Main unit**

- **12V / 24V power supply**

**Optional**

- **NH3 automotive sensor**
  - [ppm]

**Future option**

- **PM/PN automotive sensor(s)**

**Post-processing**

- Calculated values like:
  - Mass flow of NOx, NH3, CO2, fuel in [g/s]
SEMS MEASUREMENT SYSTEM
Data processing:
- Screening
- Filtering
- Periodic inspection and calibration of sensors
- Tables with averaging and visualisation

Data access of partners / clients (secured)
SEMS MEASUREMENT SYSTEM

SEMS compared to PEMS concentrations

R.J. Vermeulen, N.E. Ligterink, et.al.
Transport and Air Pollution TAP 2012.

TBM NRMM forum, Frankfurt, 7 & 8 September 2017
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## CALCULATION & PARAMETER OPTIONS

<table>
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<tr>
<th>Calculation Options</th>
<th>Main Parameters</th>
<th>NOx in</th>
</tr>
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<tr>
<td>NOx mass flow based on exhaust or air flow</td>
<td>NOx, CO₂ concentrations</td>
<td>g/kWh</td>
</tr>
<tr>
<td></td>
<td>Exhaust or inlet air flow</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Power</td>
<td></td>
</tr>
<tr>
<td>Carbon balance method</td>
<td>NOx, CO₂ concentrations</td>
<td>g/kWh</td>
</tr>
<tr>
<td>Used in PROMINENT</td>
<td>Fuel flow (re-calibrated)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Power</td>
<td></td>
</tr>
<tr>
<td></td>
<td>fuel flow → Power</td>
<td></td>
</tr>
<tr>
<td>Exhaust concentrations only</td>
<td>NOx, CO₂ concentrations</td>
<td>‘g/kg’</td>
</tr>
<tr>
<td></td>
<td>CO₂</td>
<td>CO₂</td>
</tr>
</tbody>
</table>

According to EU 2017/655

More practical alternatives for ships

Refer to PROMINENT deliverable D5.8: [http://www.prominent-iwt.eu/](http://www.prominent-iwt.eu/) (end 2017)
Data until December 2016
STANDARD REPORTING FORMAT

Exhaust gas temp.

Vessel 1 Container 110m
2005
Power[kW] 1492
Num. engines 1
Brand Caterpillar
Type 3516
Features CCNR 1-SCR / DPF
Area Antw./Rot.
DWT 3200
Modelled Temp.
Hours 924

Sailing speed and fuel consumption

g/kWh / power binning

NOx in g/km
REPORTING FORMAT OPTIONS

Power binning

Container vessel 110m

CCNR I + SCR/DPF

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REPORTING FORMAT OPTIONS

- 1-hour average of NOx and power versus time
  
  ![Graph showing specific NOx emissions and power over time]

  Engine ~ 1500 kW  
  CCNR I + SCR/DPF

Total error of on-board monitoring is quite reasonable: ± 6 to 8% (similar to PEMS)

- Other options: one day, one week, one month averages versus time
## PROMINENT

### Rhine ships: average emissions

**1000-2000 hrs**  

**Period:** Refer to PROMINENT deliverable D5.7 & D5.8 (end 2017): http://www.prominent-iwt.eu/

<table>
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<tr>
<th>Engine technology</th>
<th>Inland vessels</th>
<th>Container 110m</th>
<th>Container 135m</th>
<th>Dry Bulk 135m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max power[kW]</td>
<td>1500</td>
<td>1050</td>
<td>850</td>
<td></td>
</tr>
<tr>
<td>NOx[g/kWh]</td>
<td>4.1</td>
<td>5.4</td>
<td>8.6</td>
<td></td>
</tr>
<tr>
<td>NOx/CO(_2)[g/kg]</td>
<td>6.3</td>
<td>8.2</td>
<td>12.3</td>
<td></td>
</tr>
<tr>
<td>NOx[g/km]</td>
<td>171</td>
<td>515</td>
<td>281</td>
<td></td>
</tr>
<tr>
<td>CO(_2)[kg/km]</td>
<td>27</td>
<td>63</td>
<td>23</td>
<td></td>
</tr>
</tbody>
</table>
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Diesel locomotive:
› 656 hours of monitoring December 2016 – February 2017
› Netherlands – Nordrhein-Westfalen

NOx emissions:
› Normal operation: 12 g/kg NOx/CO₂ (Comparable Euro I)
› Idling: 35 g/kg NOx/CO₂
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CONCLUSIONS

- Continuous monitoring of emissions is possible and useful for many purposes:
  - Insight in long term environmental performance
  - Complementary as low costs alternative to PEMS measurements
  - Non-working events can be separated in several ways
  - The total life span emissions may replace ISM / ISC testing in the future

- Fuel flow or inlet air flow form excellent alternatives to exhaust mass flow, in order to calculate mass emissions (also for ISC/ISM)

- Extremely long idle periods with relatively high NOx emissions are seen with rail. This creates a gap between real-world emissions and ISM results.
THANK YOU FOR YOUR ATTENTION

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- Ruud.Verbeek@tno.nl
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SPARE SHEETS
CALCULATION & PARAMETER OPTIONS

Consider alternative to g/kWh for ISM:

- Monitor NOx/CO$_2$ ratio based on concentrations only
- Conversion to g/kg CO$_2$ with molecular masses:
  \[ \frac{NO_x^{ppm}}{CO_2\% \cdot 10} \cdot \frac{M_{NO_x}}{M_{CO_2}}. \]
- Plot NOx/CO$_2$ as a function of engine speed, indicative power or exhaust gas temperature. Determine limit value in g/kg CO$_2$.

Advantages:
- Stable relation with NOx in g/kWh
- Less susceptible to errors
- No amplification of values at low power
CALCULATION & PARAMETER OPTIONS

› Carbon balance method

› Following steps: NOx in g/kWh, g/kg CO₂ or g/km
CALCULATION & PARAMETER OPTIONS

Power based on fuel consumption

- Either per engine or for a group of engines

\[
\begin{align*}
P_{\text{engine}} &= \frac{3600}{\text{BSFC}} \cdot m_{\text{fuel}} \\
\text{BSFC}(\text{LFE}) &= a \cdot \left( 1 + 0.1 \cdot \left( \frac{b}{m_{\text{fuel}}} \right) \right)
\end{align*}
\]
DATA PRESENTATION OPTIONS

Data checks

P_BSFC

NOx [g/s]

Vermogen (kW)

RPM [L/min]

Engine Power [kW]

engine with SCR
**ACCURACY ESTIMATION**

<table>
<thead>
<tr>
<th></th>
<th>g/h NOx</th>
<th>g/kWh NOx</th>
<th>g/kg CO2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ISO 8178 laboratory</td>
<td>On-board monitoring</td>
<td>ISO 8178 laboratory</td>
</tr>
<tr>
<td>NOx concentration</td>
<td>2%</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td>02/CO2 concentration</td>
<td>2%</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td>calibration gas</td>
<td>2%</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td>cross sensitivity NH3, NO/NO2 ratio</td>
<td>2%</td>
<td>3%</td>
<td>2%</td>
</tr>
<tr>
<td>measuring point NOx inhomogienity</td>
<td>1%</td>
<td>3%</td>
<td>1%</td>
</tr>
<tr>
<td>pressure sensitivity</td>
<td>2%</td>
<td></td>
<td>2%</td>
</tr>
<tr>
<td>Engine speed</td>
<td></td>
<td></td>
<td>1%</td>
</tr>
<tr>
<td>Engine torque /power</td>
<td></td>
<td></td>
<td>2%</td>
</tr>
<tr>
<td>Engine power</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air</td>
<td>2%</td>
<td></td>
<td>2%</td>
</tr>
<tr>
<td>Fuel flow</td>
<td></td>
<td>4%</td>
<td></td>
</tr>
<tr>
<td>BSFC/engine efficiency</td>
<td>3%</td>
<td></td>
<td>3%</td>
</tr>
<tr>
<td>Fuel carbon content</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td><strong>Total accuracy</strong></td>
<td>± 4%</td>
<td>8%</td>
<td>5%</td>
</tr>
</tbody>
</table>

Refer to PROMINENT deliverable D5.7 & D5.8: http://www.prominent-iwt.eu/ (end 2017)