

Black Carbon, correlation experiences of measurement methods

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Agenda

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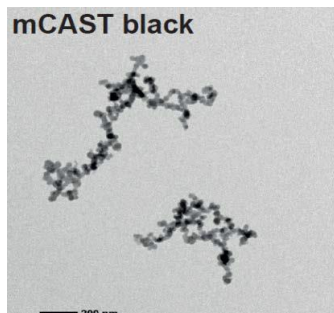
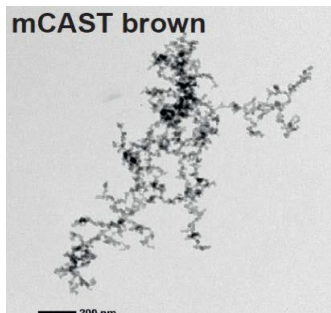
Motivation

EUROMOT measurement **and** reporting protocol

- **EUROMOT developed and proposed a measurement and reporting protocol to be established at IMO to suit all purposes**
- **A scientifically agreed BC standard does not exist**
 - e.g. mini-CAST, spark generator soot, fullerene soot, Printex-U, lamp blacks
 - but soot properties have an effect on measurement result
- **Instruments (FSN & PAS) are calibrated according to an in-house procedure of the instrument manufacturer (e.g. AVL)**
- **When calibrated at identical source -> measurements of instruments correlate**
When calibrated at different sources -> measurements will inevitably differ
- **Correlation of instruments can be / have been established under controlled conditions**
 - reference fuel (e.g. EN-590 or ASTM D 975 for automotive)
 - reference engine operating conditions (test bed)

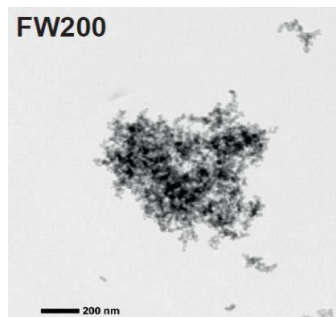
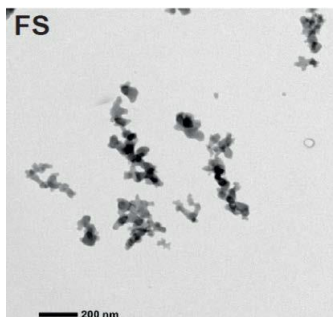
Methods

Black Carbon samples



miniCAST soots with different organic matter content

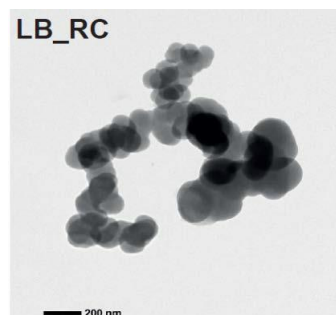
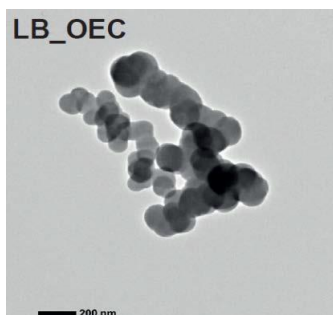
CAST burners are commonly used in automotive as source for particle (number) instrument calibration and (loss-) characterization of sampling



Fullerene soot (FS)

commonly used in aviation

FW200 is an industrial carbon used as surrogate of atmospherically aged soot



Lamp Blacks are frequently used in pigment applications

Source: ETH

Methods

AVL FSN according ISO 10054 / 8178-3 & AVL Photo Acoustic Soot Sensor



AVL 415 SE Smoke Meter

Based on ISO-10054 absorption with highest sensitivity @ 550-600 nm wavelength, light scattering is of no influence due to reflection of scattered light from white reflection plate identical to clean filter

Remark:

Operates on undiluted exhaust gas according to ISO-10054



AVL 483 MSS^{plus} Micro Soot Sensor

Based on photoacoustic principle & measured by microphone, wavelength adjusted to minimize cross-sensitivity (NO_x), sound pressure resonance chamber influenced by temperature, pressure & humidity

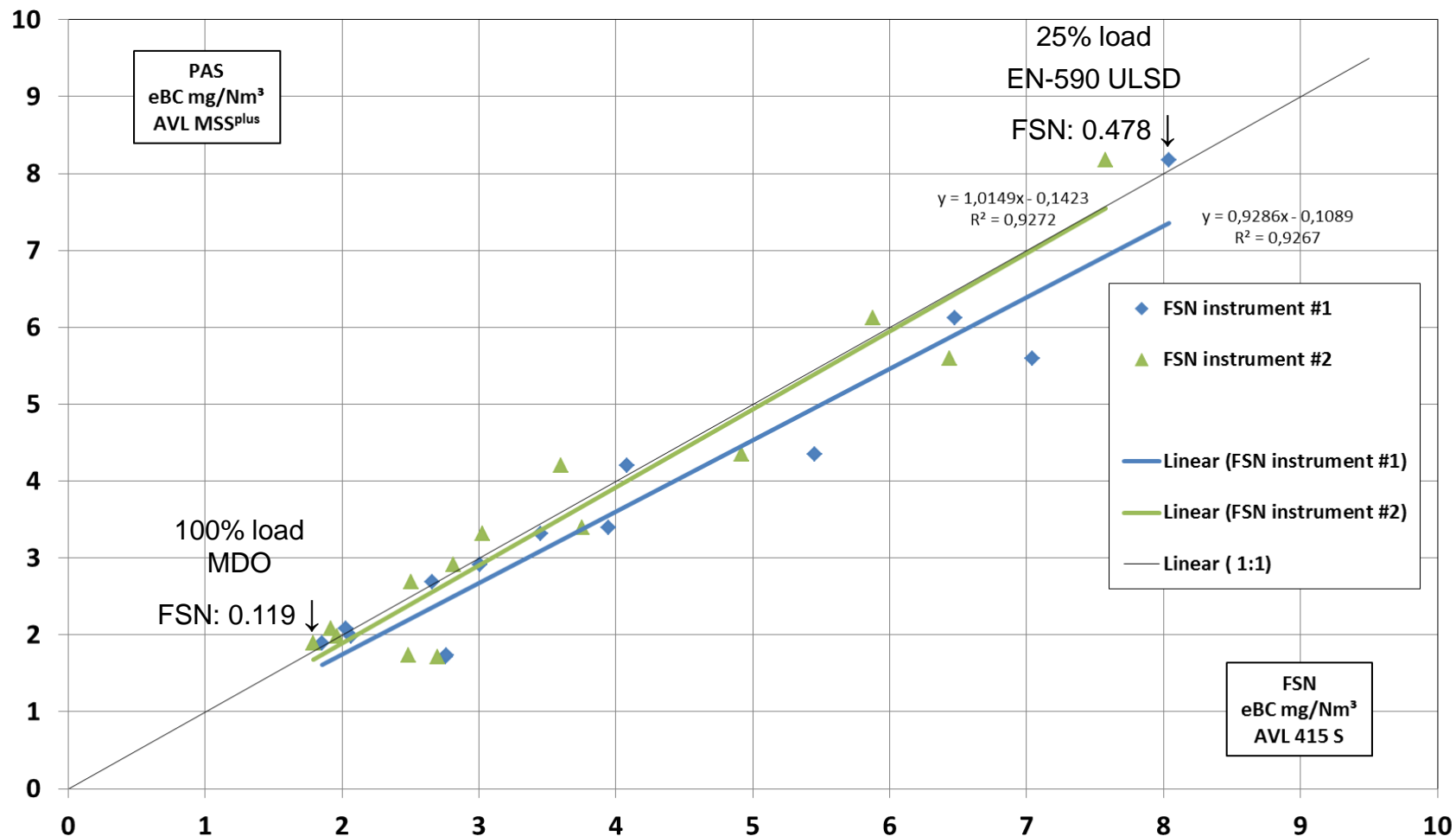
Remark:

Operates on diluted exhaust gas, incorporates a thermophoretic loss compensation

Results

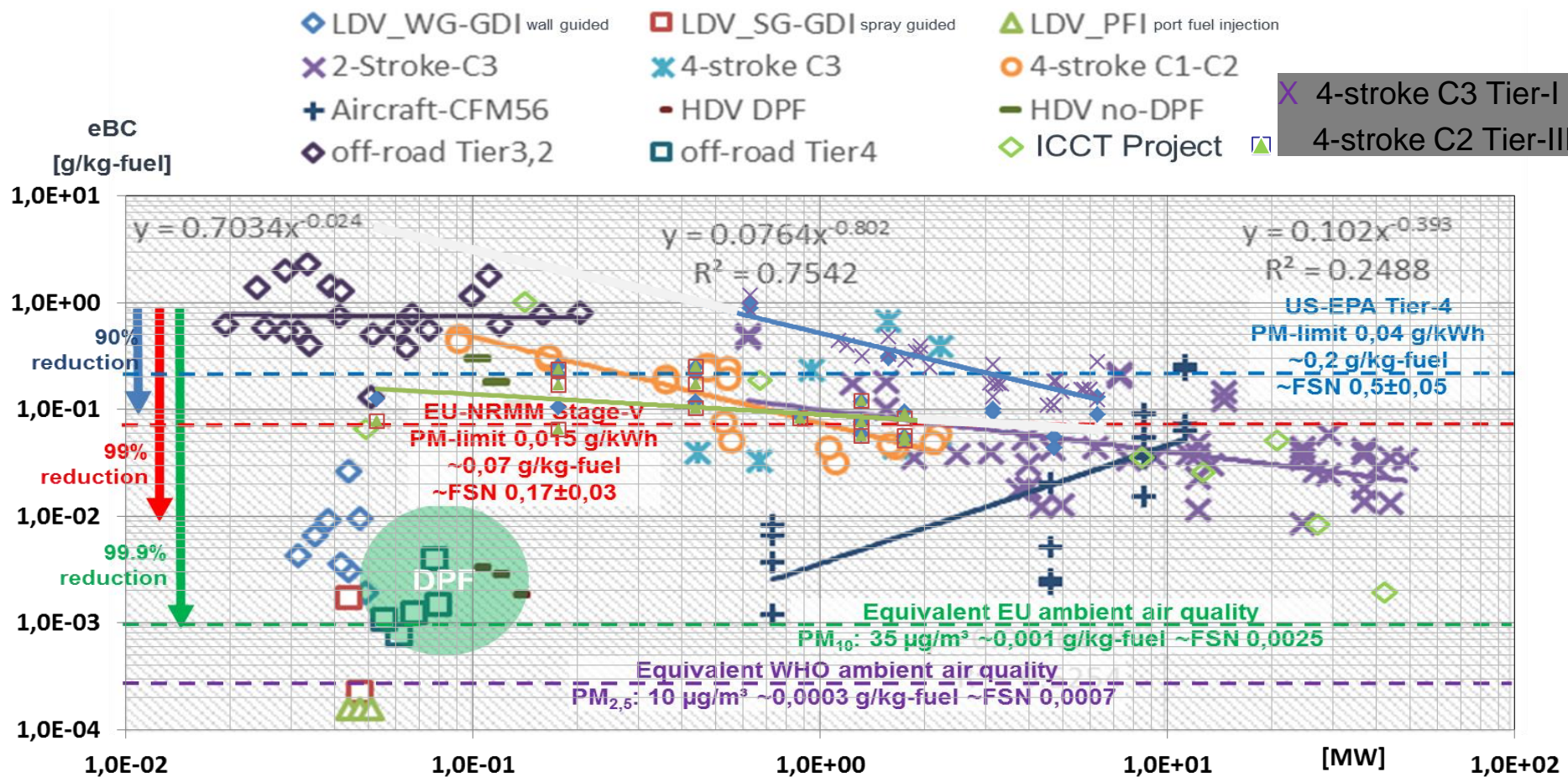
Instrument comparison FSN vs. PAS 8L21/31 EN-590 & MDO

Test bed measurements presented at 4th ICCT workshop

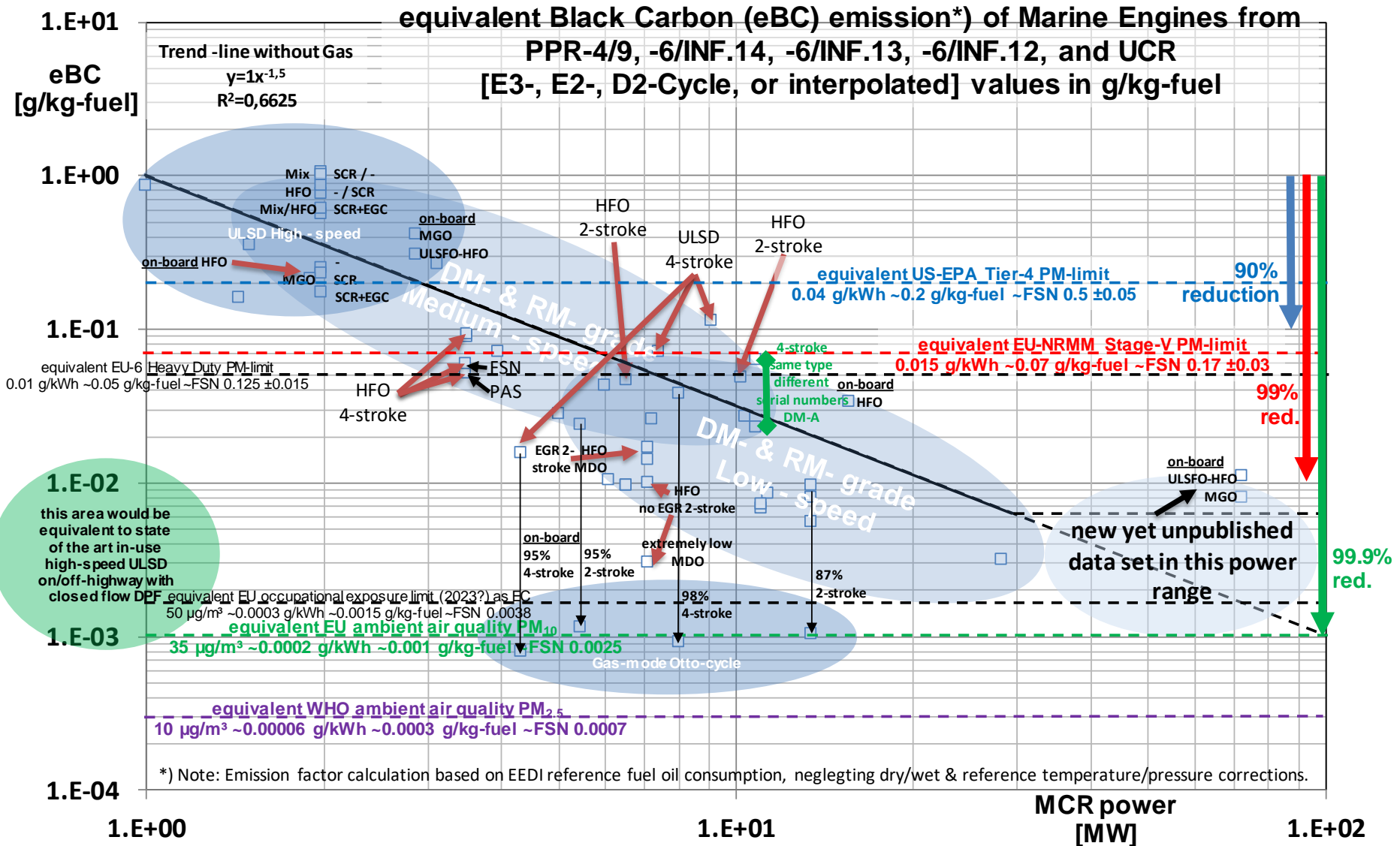


Results

eBC in g/kg fuel UCR-ICCT database with MAN data added and put into regulatory context, presented at 4th ICCT workshop



eBC in g/kg fuel IMO and UCR data put into regulatory context



Discussion

EUROMOT measurement **and** reporting protocol

- With the existing EUROMOT measurement and reporting protocol, correlations between FSN and PAS can be established under controlled conditions (test bed, EN-590 fuel)
- BC from marine engines covers a range of 3 orders of magnitude
- BC emission levels of marine engines are nowadays competitive to light/heavy duty vehicles and the majority of BC emission factors from large marine engines operating on distillates as well as on residual grade fuels are below existing state of the art LDV/HDV applications*
- The BC scatter band is at least 1 order of magnitude, but can be up to 2 orders of magnitude
 - requires conformity factors depended on the measurement purpose

***) PM from LDV/HDV & off-road consist almost exclusively of BC due to ULSD use**

Discussion

Normative status of FSN according to ISO 8178-3:2019(E)

Annex B (informative)

Overview particulate and soot measurement methods

In much of the scientific literature the terms soot, black smoke, black carbon (BC) and elemental carbon (EC) are used interchangeably, although soot, black smoke, BC and EC commonly have operational and source-based definitions, respectively, notwithstanding that reliable reference samples and aerosol standards do not exist for either one.

The filter-type smoke measurement method is used for the measurement of visible black smoke emissions. The measurement results (FSN) evaluated in accordance with this document, are different from the results obtained with the particulate-measurement methods described in ISO 8178-1 or in other standards and regulations.

There is a distinct difference between the results of this smoke measurement method and the results obtained with the measurement of opacity as described in ISO 8178-9. Whereas an opacimeter measures the fraction of light that traverses the exhaust gas a filter type smoke meter measures the light which is reflected by a filter blackened by exhaust gas.

Opacity based on light extinction (given by the absorption and the scattering of light) is sensitive to any kind of exhaust gas component which is absorbing and/or scattering the light passing the exhaust gas. It measures the components from the black, brown, blue and white smoke.

The FSN is sensitive to particulates which are blackening a filter and therefore it detects components which are absorbing light. These components are mainly elemental carbon.

For information about components and related measurement methods refer to [Figure B.1](#).

| Components | | Smoke Types | | Measurement Methods |
|-----------------------------|-----------------|-------------|----------------------------------|---------------------|
| sulfate associated water | seml - volatile | white smoke | PM incl. condensables ISO 8178-1 | ! ^a |
| sulfates [SO ₄] | | blue smoke | | ! ^a |
| organic carbon | | blue smoke | | ! ^a |
| elemental carbon (EC) | non - volatile | black smoke | PM without condensables ISO 9096 | FSN ISO 8178-3 |
| ash fuel oil | | | | ! ^a |
| ash lube oil | | | | ! ^a |
| abrasion/wear | | | | ! ^a |
| NO ₂ | volatile | brown smoke | Opacity ISO 8178-9 | |
| NO | | | | |
| SO ₃ | | blue smoke | | ! ^a |
| SO ₂ | | | | ! ^a |
| H ₂ O | | white smoke | | ! ^a |
| CO ₂ | | | | |
| CO | | | | |
| O ₂ | | | | |
| N ₂ | | | | |

Key

! contribution possible

^a Contribution can be minimized or even eliminated by use of appropriate fuel and lube oil.

NOTE Particle number and its measurement methods are not included in the figure. For more information refer to ISO 8178-1.

Discussion

Normative status of PAS & LII

- **Status of standardization process of either PAS method or LII method for combustion engine exhaust gas application is currently unknown.**

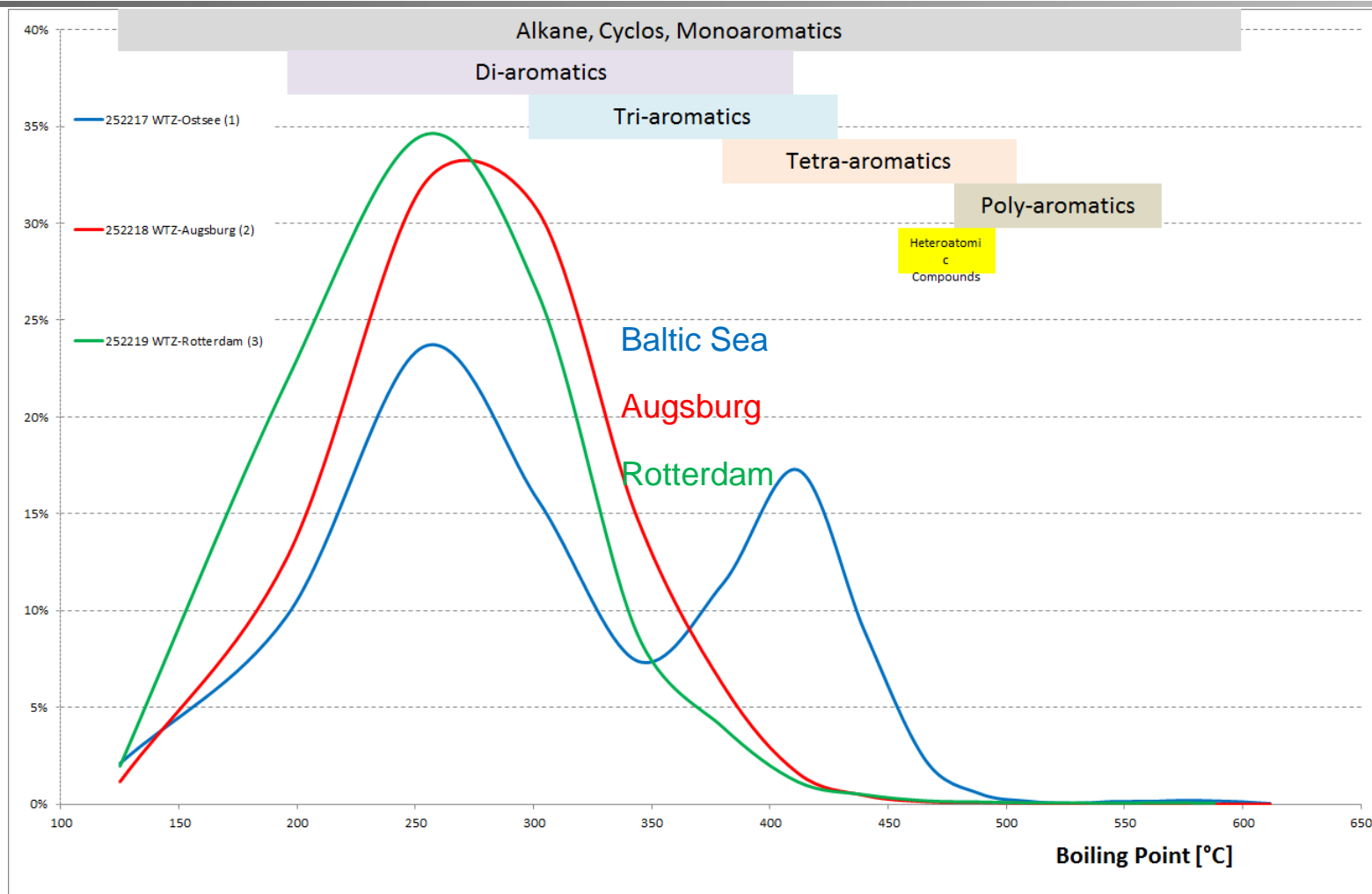
Discussion

BC influencing parameters automotive vs. marine

- **(Future) marine fuel oil qualities are relatively undefined besides their sulfur content**
 - **Limitation of (poly-)aromatic content in marine fuel is missing (EN-590: max 8%)**
 - **IP541 fuel combustion analyzer (estimated cetane number ECN specified between 5 - 40) better suited as Cetane number or CCAI for combustion quality especially for hybrid fuels**
- **Marine lube oil qualities are undefined besides their base number and related ash content**
 - **Selective/specific evaporation behavior of lube oil is missing**
 - **Evaporation loss of a lubricating oil by the NOACK volatility test method, see ACEA for automotive**
- **Renewable future carbon neutral fuels (non-fossil based): PtX, gas, liquid, ammonia...???**
- **Sensitivity of low speed engines is different to medium and high-speed engines**
- **Time between overhaul (TBO) and maintenance status of engines is critical**

Discussion

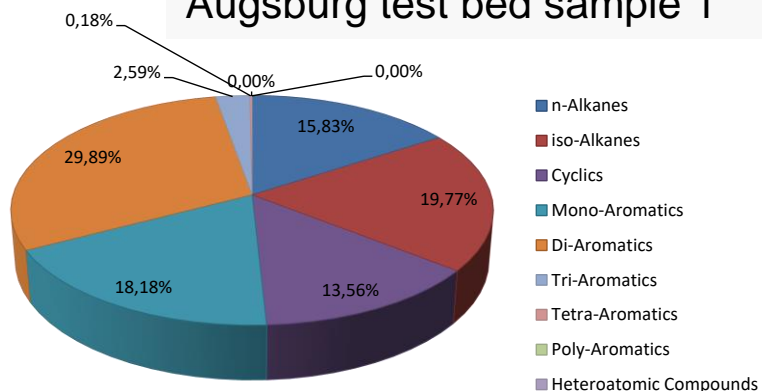
Fuel influence various HFO examples



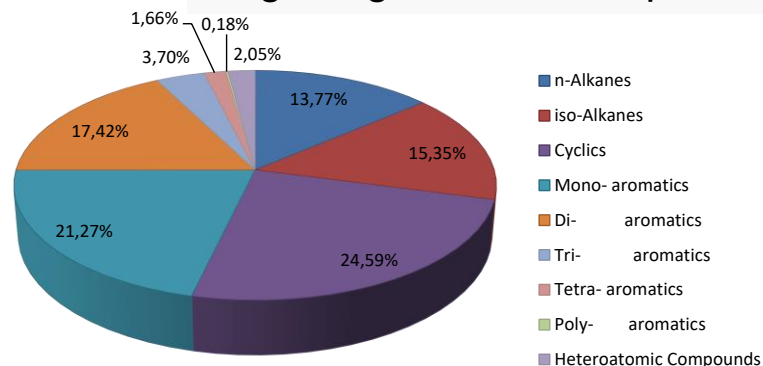
Discussion

Fuel influence various HFO examples

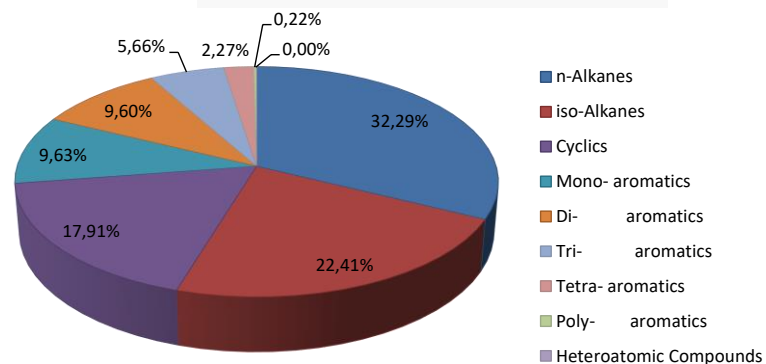
Augsburg test bed sample 1



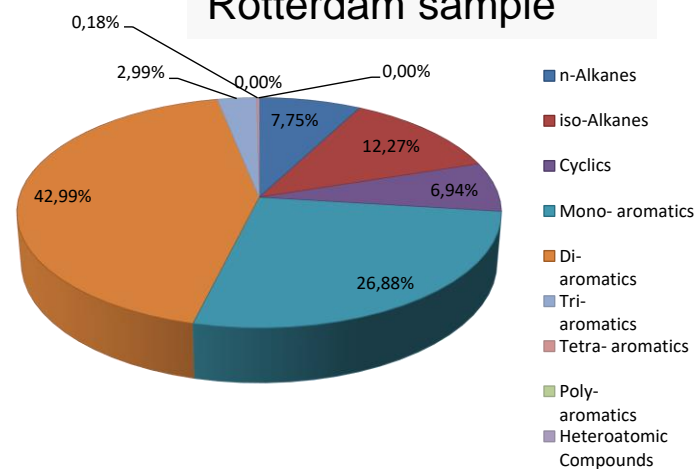
Augsburg test bed sample 2



Baltic Sea sample



Rotterdam sample



Conclusions

Measurement methods, conditions & fuels

- **FSN and PAS measurement correlate at test bed under reference conditions while only the FSN method is standardized**
- **FSN does not require sampling preconditioning, whereas in PAS it is incorporated**
- **No references for LII measurements available at EUROMOT-member companies**

Acknowledgements & References

- **AVL 415 SE:** <https://www.avl.com/-/avl-smoke-meter>
- **AVL 483 MSS^{plus}:** <https://www.avl.com/-/mssplus-avl-micro-soot-sensor>
- **Printex-U:** Orion Engineered Carbons, Printex-U regular color gas (RCG), size 25 nm, BET surface area 92 m²/g, <https://www.orioncarbons.com/index.php>
- **ETH:** Soot Aerosols as a Source for Ice Nucleating Particles in the Cirrus Regime, the Role of Soot Particle Properties, Fabian Mahrt, 22th ETH Conference on Combustion Generated Nanoparticles, 2018
- **UCR:** UCR, Measure Marine BC Emissions, ICCT 3rd Workshop, 2016
Kent Johnson, Marine BC EF, ICCT 2nd Workshop, 2015
Evaluation of modern Tier-2 ocean going vessel on 2 fuels, 2019 (yet unpublished)
Evaluation of modern Tier-2 ocean going vessel with scrubber, 2018 (yet unpublished)

Acknowledgements & References

- **MO PPR 3/8:** **Proposal for a measurement protocol for voluntary Black Carbon measurement studies, Germany & EUROMOT submission**
- **IMO PPR 4/9:** **Measurement data derived from the application of the draft Black Carbon Measurement Reporting Protocol – Summary, EUROMOT submission**
- **IMO PPR 6/INF.12:** **Emissions of an in-use, natural-gas-powered dual-fuel commercial ferry operated in Vancouver, Canada submission**
- **IMO PPR 6/INF.13:** **Evaluation of the effect of SCR, EGC and sulphur limit solutions on Black Carbon emissions from ships using three Black Carbon measurement methods, Canada & Denmark submission**
- **IMO PPR 6/INF.14:** **Evaluation of the effect of EGR on Black Carbon emissions from ships and the effect of sampling conditions on two Black Carbon measurement methods, Canada & Denmark submission**

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All data provided in this document is non-binding.

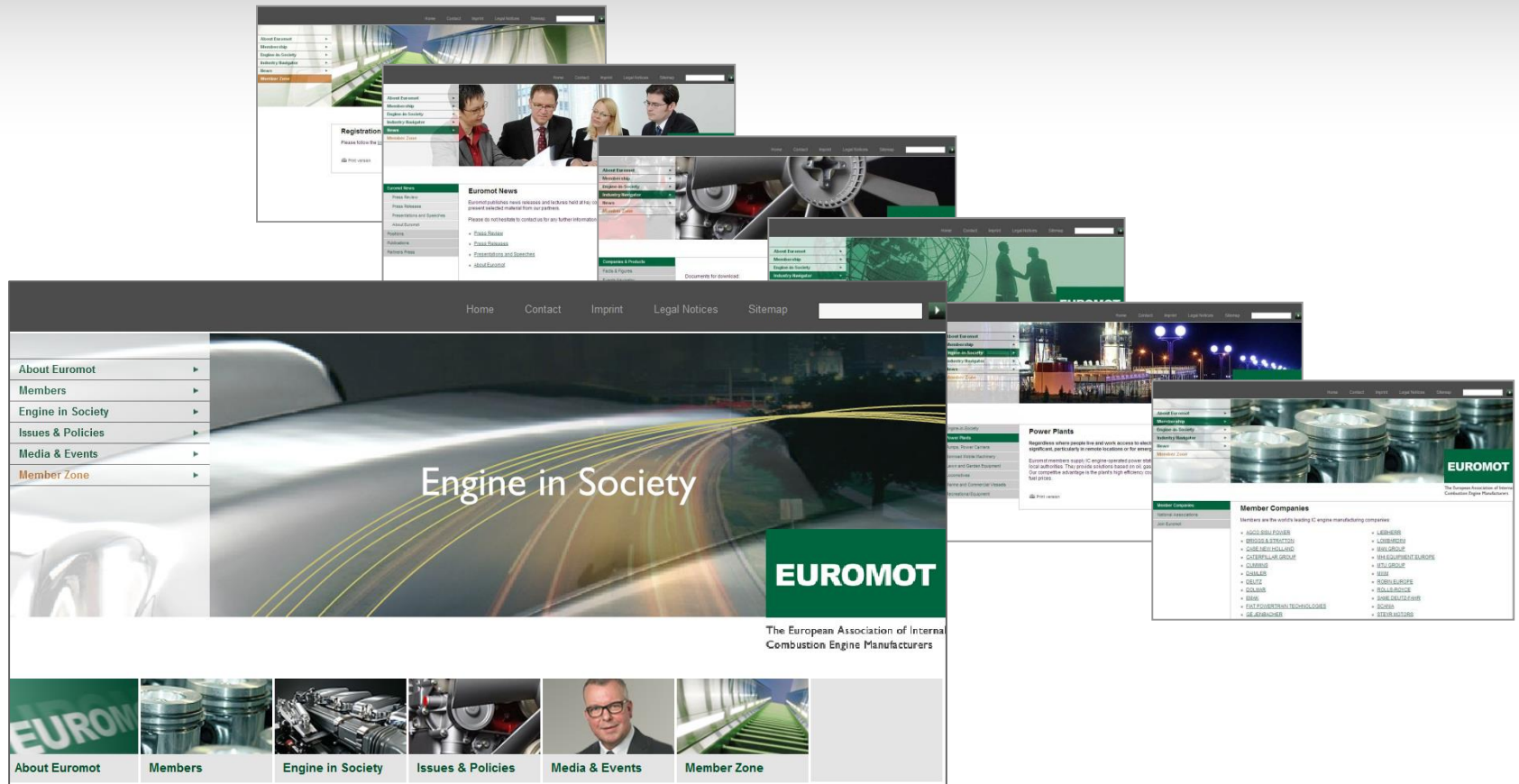
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