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Klimaschutz im Seeverkehr

Black Carbon-Messkampagne auf einem Motorenprüfstand: drei IMO-Submissionen zur Veröffentlichung der Ergebnisse

Abschlussbericht zum Vorhaben: „Analyse und Weiterentwicklung von Klimaschutzmaßnahmen im Seeverkehr unter Berücksichtigung der aktuellen Entwicklungen auf internationaler und europäischer Ebene“

von

Dr. Brigitte Behrends
Marena Ltd., Jever

Dr. Martin Cames, Friedhelm Keimeyer
Öko-Institut e.V., Berlin

Dr. Jasper Faber, Dagmar Nelissen
CE Delft, HH Delft, Die Niederlande

Dr. Volker Wichmann
Universität Rostock

Öko-Institut e.V., Berlin
Schicklerstraße 5-7
D-10179 Berlin

Im Auftrag des Umweltbundesamtes

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Kurzbeschreibung

Im Rahmen des hier dargestellten Projektes ist eine Black Carbon (BC)-Messkampagne an der Universität Rostock erfolgreich ausgeführt worden. Die Messkampagne wurde vom 11. bis zum 22. Juli 2016 von der Universität Rostock, dem National Research Council Canada (NRC), dem Helmholtz Zentrum München und AVL durchgeführt – unterstützt durch Marena Ltd., CE Delft und das Öko-Institut.

Die Messungen sind an dem Motorenprüfstand im Labor der Universität Rostock unter Verwendung eines einzylindrigen Dieselmotors mit Direkteinspritzung (1VDS18/15CR), sechs BC-Messinstrumenten (PAX, LII-1, LII-2, TOA, AVL 415SE und MSS), unter Verwendung drei verschiedener Treibstoffe und bei verschiedenen Motorleistungen durchgeführt worden.

Nach der Messkampagne sind die Messergebnisse analysiert und in drei Submissionen beim Unterausschuss für die Verhütung und Bekämpfung der Meeresverschmutzung (PPR) der Internationale Seeschiffahrts-Organisation (IMO) veröffentlicht worden; zwei Submissionen zur vierten Sitzung des PPR in 2017 (PPR4/INF9, PPR4/9/4) und eine Submission zur fünften Sitzung des PPR in 2018 (PPR 5/INF.10). Diese Submissionen sind gemeinsam von Kanada und Deutschland eingereicht worden. Sie wurden in Zusammenarbeit von Marena Ltd., dem NRC Canada, der Universität Rostock, AVL, dem Umweltbundesamt und den zuständigen Ministerien der beiden Staaten erarbeitet.

In der Submission PPR4/INF.9 „Technical details of a multi-instrument Black Carbon measurement campaign“ sind die technischen Details der Messkampagne und in der PPR4/9/4 Submission „Results of a multi-instrument Black Carbon measurement campaign“ sind die Ergebnisse der BC-Messungen dargestellt worden. In der dritten Submission PPR 5/INF.10, „New findings of a multi-instrument Black Carbon measurement campaign“ sind nach weiteren Analysen der Messdaten weitere Ergebnisse präsentiert worden.

Abstract

In the here presented project, a Black Carbon measurement campaign was successfully performed at the University of Rostock. The measurement campaign was carried out from 11th to 22nd July 2016 by University of Rostock, National Research Council Canada (NRC), Helmholtz Centre Munich and AVL, and was supported by Marena Ltd., CE Delft and Öko-Institute.

The BC measurements were carried out with an engine test bed in the lab of University of Rostock on a single cylinder diesel engine with direct injection (1VDS18/15CR), six BC measuring instruments (PAX, LII-1, LII-2, TOA, AVL 415SE and MSS), and three different fuels under different engine loads.

Following the measurement campaign, the results have been analyzed and were published in three submissions to the sub-committee pollution prevention and response (PPR) of the International Maritime Organization (IMO); two submissions to the fourth meeting of PPR in 2017 (PPR4/INF9, PPR4/9/4) and one submission to the fifth meeting of PPR in 2018 (PPR 5/INF.10). These submissions were jointly prepared by Canada and Germany with the support of Marena Ltd., NRC Canada, University of Rostock, AVL and the corresponding ministries.

Submission PPR4/INF.9 „Technical details of a multi-instrument Black Carbon measurement campaign“ contains only the technical details, whereas PPR4/9/4 „Results of a multi-instrument Black Carbon measurement campaign“ contains the first results of the measurement campaign. In third submission PPR 5/INF.10 „New findings of a multi-instrument Black Carbon measurement campaign“ the results of further analysis of the data were presented.

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Abkürzungsverzeichnis

BC	Black Carbon
CO₂	Kohlendioxid
EC	Elementarer Kohlenstoff (Elemental Carbon)
eBC	Äquivalentes Black Carbon (equivalent Black Carbon)
FSN	Filter Rußzahl (Filter Smoke Number)
ICCT	International Council on Clean Transportation
IMO	Internationale Schifffahrtsorganisation (International Maritime Organization)
IPCC	Zwischenstaatlicher Ausschuss für Klimaänderungen (Intergovernmental Panel on Climate Change)
LII	Laser Induzierte Inkandescenz (Laser Induced Incandescence)
NRC	National Research Council, Kanada
MAAP	Multiwinkel Absorptionsspektroskopie (Multi Angle Absorption Photometry)
MEPC	IMO-Umweltausschuss (Marine Environmental Protection Committee)
OC	Organischer Kohlenstoff (Organic Carbon)
PAS	Photoakustische Spektroskopie (Photo Acoustic Spectroscopy)
PPR	IMO-Unterausschuss für die Verhütung und Bekämpfung der Meeresverschmutzung (Pollution Prevention and Response)
rBC	refraktäres Black Carbon (refractory Black Carbon).
S	Schwefel
TOA	Thermo-Optische Analyse (Thermo-Optical Analysis)

Klimaschutz im Seeverkehr – Black Carbon-Messkampagne

Im Rahmen des Projektes „Klimaschutz im Seeverkehr“ (FKZ 3715 41 101 0) ist als ein Arbeitspaket eine Black Carbon (BC)-Messkampagne an der Universität Rostock erfolgreich durchgeführt worden. Nach der Messkampagne sind die Messergebnisse analysiert und in drei Submissionen beim Unterausschuss für die Verhütung und Bekämpfung der Meeresverschmutzung (PPR) der Internationalen Seeschiffahrts-Organisation (IMO) veröffentlicht worden.

Die drei IMO Submissionen wurden in englischer Sprache für das Forschungsvorhaben „Klimaschutz im Seeverkehr“ verfasst. Die Zusammenfassungen liegen in Deutsch und Englisch vor.

1 Klimaschutzmaßnahmen auf IMO-Ebene mit Schwerpunkt Black Carbon

1.1 Einleitung

Schiffe transportieren weltweit ca. 80% (Volumen) aller Güter.¹ Dabei emittieren sie - bezogen auf die Transportleistung – im Vergleich zu anderen Transportsektoren deutlich weniger Treibhausgase. Dennoch trägt die Schifffahrt, auch durch den Zuwachs in der Branche, zunehmend zu den Kohlendioxid (CO₂-) und Black Carbon- (BC-) Emissionen bei. Black Carbon findet sich in den Rußpartikeln der Schiffsabgase und entsteht bei der unvollständigen Verbrennung von Treibstoffen. Wegen seiner Licht-absorbierenden Wirkung wurde BC als Schadstoff in Schiffsabgasen seitens der Internationale Seeschiffahrts-Organisation (International Maritime Organization, IMO) definiert.

BC ist klimaschädlich und beschleunigt das Abschmelzen von arktischem Eis. BC hat zudem einen schädlichen Einfluss auf die Gesundheit von Menschen und Ökosystemen. BC führt zu Lungen- und Herzkrankheiten und stellt auch eine Gefahr für die Umwelt dar. Schiffsemissionen tragen zunehmend zu den BC Emissionen bei. Prozentual gesehen trägt die Schifffahrt bisher nur 0,7 bis 1,1% an den globalen BC Emissionen bei (PPR5/INF.16), allerdings nimmt dieser Anteil durch das Wachstum der Schifffahrt kontinuierlich zu. Diese Zahlen werden gewichtiger, wenn man bedenkt, dass die meisten Schiffsemissionen in unmittelbarer Küstennähe entstehen und weit ins Landesinnere getragen werden¹. Besonders dramatisch stellt sich das Problem der BC-Emissionen in Hafenstädten dar.

Zudem ist BC im Vergleich zu CO₂ klimaschädlicher und trug z.B. in 2015 zu 5 bis 8% in Kohlendioxid-Äquivalenten an den klimaschädlichen Emissionen der Schifffahrt bei (International Council on Clean Transportation, ICCT, 2017).¹ ICCT hat einen Anstieg des prozentualen Anteils auf 16% für die nächsten 100 Jahre vorausgesagt.

1.1.1 Hintergrund

Bei der 62-ten Sitzung (MEPC 62, 2011) des Umweltausschusses der IMO (Marine Environmental Protection Committee, MEPC) einigten sich die Mitgliedstaaten auf einen Arbeitsplan, um den Einfluss der Black Carbon Emissionen der internationalen Schifffahrt auf die Arktis zu prüfen und unterwies den Unterausschuss für flüssige und gasförmige Massengüter (Bulk Liquids and Gases, jetzt Pollution Prevention and Response, PPR) diese Arbeit in folgenden Schritten durchzuführen: eine Definition für Black Carbon zu entwickeln, die passendsten BC-Messmethoden für die internationale Schifffahrt zu identifizieren und mögliche Kontrollmechanismen zu prüfen. Bei MEPC 68 einigte man sich auf die von dem Unter-Komitee PPR vorgeschlagene Definition von Bond et al., (2013).² Darüber hinaus nahm

¹ Comer, B., Olmer, N., Mao, X., Roy, B. and Rutherford, D. (2017). Black Carbon Emissions and Fuel Use in Global Shipping, 2015; ICCT Report.

² Bond, et al. (2013). "Bounding the role of black carbon in the climate system: A scientific assessment". J. Geophys. Res. Atmospheres. 118: 5380–5552.

man weiteren Forschungsbedarf zur Kenntnis. Dies umfasst die Entwicklung von Protokollen, weiterführenden Studien zur Sammlung von Daten und zur Identifizierung der geeignetsten Messmethode für BC-Emissionen der internationalen Schifffahrt (MEPC 68/21).

1.1.2 Definition von Black Carbon

Beim Start des Projektes in 2015 hatte man sich bei der IMO lediglich auf die wissenschaftliche Definition von Black Carbon von Bond et al. (2013) geeinigt:

„Black Carbon ist ein bestimmter Typ von kohlenstoffhaltigem Material, welches sich nur in Flammen bei der Verbrennung von Kohlenstoff-basierten Treibstoffen bildet. Es ist unterscheidbar von anderen Formen von Kohlenstoff und Kohlenstoffverbindungen, die in atmosphärischen Aerosolen enthalten sind, weil es eine einmalige Kombination der folgenden physikalischen Eigenschaften hat:

1. es weist eine starke Lichtabsorption im sichtbaren Bereich auf mit einem Massen-Absorptionsquerschnitt von mindestens $5 \text{ m}^2 \text{ g}^{-1}$ bei einer Wellenlänge 550 nm,
2. es ist refraktär, was bedeutet, dass es seine grundlegende Form bei sehr hohen Temperaturen beibehält; mit einer Verdampfungstemperatur nahe 4000 K,
3. es ist unlöslich in Wasser, in organischen Lösemitteln inklusive Methanol und Aceton, und in anderen Komponenten von atmosphärischen Aerosolen, und
4. es besteht aus einem Aggregat von kleinen Kohlenstoffkügelchen.“

1.1.3 Black Carbon-Messmethoden sowie Mess- und Berichtsprotokoll

Ebenfalls bei PPR 2 (Bericht von PPR 2 an MEPC (PPR 2/21, Absatz 8.5.3)) wurden vier verschiedene Messmethoden identifiziert, die BC entsprechen der Bond et al. (2013) Definition messen können: Photoakustische Spektroskopie (Photo Acoustic Spectroscopy, PAS), Multiwinkel Absorptionsspektroskopie (Multi Angle Absorption Photometry, MAAP), Laser Induzierte Inkandescenz (Laser Induced Incandescence, LII) und Filter Rußzahl (Filter Smoke Number, FSN). Die Messverfahren PAS, MAAP und FSN messen äquivalentes BC (eBC), LII misst refraktäres BC (rBC). Weitere Informationen über die verschiedenen Definitionen von BC finden sich z.B. in Lack et al., 2014³. Des Weiteren wurde in der hier beschriebenen Messkampagne Thermo-Optische Analyse (Thermo-Optical Analysis, TOA) angewandt, welches oft als Referenzanalyse dient. TOA misst elementaren Kohlenstoff (elemental carbon, EC).

Während der Projektlaufzeit wurde zur Verbesserung des von EUROMOT entwickelten Mess- und Berichtsprotokoll (Measurement Reporting Protocol) beigetragen. Bis jetzt, nach derzeitigem Wissensstand, gibt es jedoch noch keine nationalen oder internationalen Regelungen zu den BC-Emissionen der Schifffahrt. Aus diesem Grund hat der IMO-Unterausschuss PPR 2015 in seinem Bericht an das MEPC (PPR 2/21) konstatiert, dass ein Bedarf an Studien besteht, in denen BC-Emissionen von Schiffsmotoren gemessen werden, um Erfahrungen mit der Anwendung der BC-Definition und den BC-Messmethoden zu sammeln. Damit sollte ein Vergleich der Messmethoden ermöglicht werden, um mögliche Abweichungen in den erfassten Daten bewerten zu können. Darum hatte der PPR-Ausschuss interessierte Mitgliedstaaten und internationale Mitgliedsorganisationen dazu aufgerufen, auf freiwilliger Basis BC-Messstudien durchzuführen.

³ Lack, D.A., Moosmüller, H., McMeeking, G.R., Chakrabarty, R.K. and Baumgardner, D. (2014). Characterizing elemental, equivalent black, and refractory black carbon aerosol particles: a review of techniques, their limitations and uncertainties. *Anal Bioanal Chem* (2014) 406:99–122.

1.2 Black Carbon-Messkampagne

Im Rahmen des vorliegenden Projektes ist eine solche BC-Messkampagne erfolgreich an dem Motorenprüfstand im Labor der Universität Rostock ausgeführt worden. An dieser Messkampagne waren Wissenschaftler von der Universität Rostock und vom National Research Council (NRC) aus Kanada, vom Helmholtz Zentrum München sowie von AVL – einem österreichischen Hersteller von BC-Messgeräten – beteiligt. Dadurch konnte die Vielfalt an BC-Messgeräten deutlich erhöht werden. Die Ergebnisse der BC-Messkampagne wurden unter Beteiligung von Marena Ltd., NRC, AVL und der Universität Rostock ausgewertet und in Zusammenarbeit mit den zuständigen deutschen und kanadischen Ministerien sowie dem Umweltbundesamt 2017 und 2018 in drei IMO PPR Submissionen (PPR4/INF.9, PPR4/9/4 und PPR5/INF.10) veröffentlicht.

1.2.1 Veröffentlichung der Ergebnisse der Black Carbon-Messkampagne

In der Submission PPR4/INF.9 „Technical details of a multi-instrument Black Carbon measurement campaign“ wurden die technischen Details der Messkampagne dargestellt. Die Submission enthält Informationen über die sechs benutzten BC-Messinstrumente (PAX, LII-1, LII-2, TOA, AVL 415SE und MSS), die Messungen unter verschiedenen Motorenlasten und die verwendeten Treibstoffe. Des Weiteren wurden die Erfahrungen mit dem von EUROMOT erstellen Measurement Reporting Protocol erörtert.

Die Ergebnisse der BC-Messungen wurden in einer separaten Submission (PPR4/9/4 „Results of a multi-instrument Black Carbon measurement campaign“) dargestellt. Die sechs verwendeten Messinstrumente deckten vier verschiedene Messmethoden für BC ab: PAS, LII, TOA und FSN. Ein Vergleich der gemessenen BC-Konzentrationen der verschiedenen Messinstrumente zeigte, dass das PAX (PAS), das LII-1 (LII), der MSS (PAS) und das AVL415SE (FSN) sehr gut übereinstimmen mit einer Streuung der Ergebnisse von $\pm 7\%$ für Dieselkraftstoff, $\pm 14\%$ für das Marinedestillat und $\pm 15\%$ für Schweröl. Das LII-2 stimmt besser mit dem TOA überein, weicht aber deutlich von den anderen Messergebnissen ab, wobei der Grund für diese Abweichung nicht genau ermittelt werden konnte.

Ferner wurden in der Submission Verbesserungsvorschläge für das von EUROMOT vorgeschlagene Measurement Reporting Protocol gemacht. Insbesondere für ausgedehnte Messkampagnen, sollte das Protokoll vereinfacht werden, indem bestimmte Kapitel pro Messinstrument und Treibstoff nur einmal ausgefüllt werden müssen.

Außerdem wurde weiterer Forschungsbedarf zum Thema BC-Messungen aufgezeigt, um eine zuverlässige und einfache Messmethode für den Schiffseinsatz zu identifizieren.

Während der PPR4-Sitzung war sich die Mehrzahl der Delegationen einig, dass weiterer Forschungsbedarf zum Thema BC -Messungen besteht, damit der IMO-Unterausschuss PPR Entscheidungen hinsichtlich der besten BC-Messmethode treffen kann. Insbesondere sollten auch im Hinblick auf das globale Schwefelgrenzwertes für Kraftstoffe von Seeschiffen, das ab 2020 gelten wird, vermehrt Treibstoffe mit 0,5% Schwefelgehalt untersucht werden. Des Weiteren sollten vornehmlich langsam laufende Motoren untersucht werden, da sie in der Welthandelsflotte weit verbreitet sind. Die Überarbeitung des Measurement Reporting Protocols wurde ebenfalls von der Mehrheit unterstützt. Überdies wurde eine Korrespondenz-Gruppe zum Thema BC-Messungen einberufen, damit die Diskussionen zu dem Messprotokoll und den Messmethoden zwischen den Sitzungen weitergeführt werden können.

Wegen des weiteren Forschungsbedarfs wurden die in diesem Projekt erhobenen BC-Messdaten, durch Berechnung von Emissionsfaktoren sowie durch Erstellung von Korrelationsmatrizen, weiter analysiert und unter dem Titel „New findings of a multi-instrument Black Carbon measurement campaign“ (PPR5/INF.10) zusammen mit Kanada zur PPR-5-Sitzung im Februar 2018 eingereicht. Die wesentlichen Erkenntnisse waren, dass die Verbrennung der Treibstoffe Diesel (0,00063% S) und marines Destillat Grad A (0,087% S) die gleiche Größenordnung an BC-Emissionsfaktoren zur Folge

hatten. Hingegen verursacht die Verbrennung von Schweröl (2,3% S) ca. 10-fach höhere BC-Emissionsfaktoren, je nach Motorlast. Die Korrelationen der Messdaten zeigten, dass sich alle Instrumente linear verhielten und dass der Treibstoff Diesel, mit dem geringsten Schwefelgehalt, die höchsten Korrelationskoeffizienten ergab. Eine Ursache dafür könnte ein Einfluss von Schwefel oder ein hoher Anteil von organische Substanzen auf die BC-Messinstrumente sein, indem sie mit dem Messsignal interferieren.

Des Weiteren wird in der Submission ein Bedarf an einer einheitlichen Kalibrationsmethode für die verschiedenen BC-Messinstrumente vorgeschlagen. Dadurch könnten Differenzen der Messdaten vermindert werden. Es ist bisher unklar, wo die zukünftigen BC-Messungen durchgeführt werden sollen. Möglich wären Messungen auf dem Prüfstand im Labor während der Zertifizierung des Schiffsmotors oder an Bord von Schiffen im laufenden Betrieb. Auch der geplante Ort der Messung (also die Platzierung der Messgeräte an Bord) hat einen Einfluss auf die mögliche Auswahl der geeigneten Messmethode(n).

Die drei Submissionen sind als Anlagen in englischer Sprache beigelegt. Die Formatierungen entsprechen den Standards der IMO.

Climate Protection in Maritime Transport – Black Carbon measurement campaign

As part of the project "Climate protection in Maritime Transport" (FKZ 3715 41 101 0) a Black Carbon measurement campaign was successfully performed at the University of Rostock. Following the measurement campaign, the results have been analyzed and were published in three submissions to the sub-committee pollution prevention and response (PPR) of the International Maritime Organization (IMO). The three submissions were written in English for the German Federal Environment Agency (UBA) as part of the project entitled research project „ Climate Protection in Maritime Transportation“.

2 Greenhouse gas emission reduction targets for international shipping

2.1 Introduction

Ships approximately transport worldwide ca. 80% (by volume) of all cargo.¹ However, compared to other transport sectors, they emit much less greenhouse gases related to their transport capacity. However, as shipping is a growing sector, the contribution of shipping to carbon dioxide (CO₂) and Black Carbon (BC) emissions will increase. Black Carbon is a constituent of soot particles in ships' exhaust gas and results from incomplete combustion of fuels. Due to its light-absorbing property, BC has been defined by the International Maritime Organization (IMO) as pollutant in ships' exhaust gas.

BC is climate damaging and accelerates the melting of Arctic ice. BC also has a damaging effect on human health and ecosystems. BC causes lung and heart diseases and is also a danger for the environment. Ship emissions increasingly contribute to the BC emissions. The percentage of BC emissions as compared to global BC emissions is relatively low with 0.7 – 1.1% (PPR5/INF.16), however, this proportion will rise in future due to the growth of shipping. These relatively small numbers appear in a different light, when taking into account that most ship emissions are generated in coastal areas and affect the air of the inland.¹ The impact of BC-emissions is very dramatic in seaports.

Furthermore, BC is more climate damaging as compared to CO₂ and contributed e.g. in 2015 to 5 – 8% carbon dioxide equivalents to the climate damaging emissions of shipping (International Council on Clean Transportation, ICCT, 2017).¹ ICCT predicts an increase of this share to 16% in the coming 100 years.

2.1.1 Background

At the 62nd meeting of the Marine Environmental Protection Committee (MEPC 62, 2011) the member states agreed to a work plan to consider the impact on the Arctic of Black Carbon emissions from international shipping and instructed the Sub-Committee on Bulk Liquids and Gases (BLG now PPR) to undertake this work by: developing a definition of Black Carbon (BC); identifying the most appropriate measurement method(s) for international shipping; and investigating appropriate control measures. MEPC 68 approved the Bond et al. (2013)² definition of BC proposed by PPR 2 and noted the need for the development of protocols and further study to collect data in order to identify the most appropriate measurement method(s) of BC emissions from international shipping (MEPC 68/21)

¹ Comer, B., Olmer, N., Mao, X., Roy, B. and Rutherford, D. (2017). Black Carbon Emissions and Fuel Use in Global Shipping, 2015; ICCT Report.

² Bond, et al. (2013). "Bounding the role of black carbon in the climate system: A scientific assessment". J. Geophys. Res. Atmospheres. 118: 5380–5552.

2.1.2 Definition of Black Carbon

At the start of the presented project in 2015 only the definition of BC according to Bond et al. (2013) had been agreed upon.

"Black Carbon is a distinct type of carbonaceous material, formed only in flames during combustion of carbon-based fuels. It is distinguishable from other forms of carbon and carbon compounds contained in atmospheric aerosol because it has a unique combination of the following physical properties:

1. it strongly absorbs visible light with a mass absorption cross section of at least $5 \text{ m}^2\text{g}^{-1}$ at a wavelength of 550 nm;
2. it is refractory; that is, it retains its basic form at very high temperatures, with vaporization temperature near 4000 K;
3. it is insoluble in water, in organic solvents including methanol and acetone, and in other components of atmospheric aerosol; and
4. it exists as an aggregate of small carbon spherules."

2.1.3 Black Carbon Measurement Methods and Measurement Reporting Protocol

Also, at PPR 2 (Report of PPR 2 to MEPC (PPR 2/21, paragraph 8.5.3) four different measurement methods were identified, which can measure BC according to the Bond et al. (2013) definition: Photo Acoustic Spectroscopy (PAS), Multi Angle Absorption Photometry (MAAP), Laser Induced Incandescence (LII) and Filter Smoke Number (FSN). PAS, MAAP and FSN measure equivalent BC (eBC), LII measures refractory BC (rBC). More information about the definition of the different BC types can be found e.g. in Lack et al., 2014.³In the here presented BC measurement campaign, additionally a Thermo-Optical Analysis (TOA) was carried out, an often-used measurement method which measures elemental carbon (EC).

During the run-time of this project, the project team contributed to the improvement of the EUROMOT Measurement Reporting Protocol. So far, as to our current knowledge, no national or international legislation exists regarding BC emissions of shipping. For this reason, the sub-committee PPR in its report to MEPC in 2015 stated that there is a need of further BC studies, which measure BC emissions from marine engines to gain experience with the BC definition and the BC measurement methods. This would enable to compare the different measurement methods and to assess possible variations in the measured data. Therefore, the PPR sub-committee invited member states to carry out BC measurement campaigns on a voluntary basis.

2.2 Black Carbon measurement campaign

In the here presented project, a BC measurement campaign was successfully carried out at an engine test bed at the University of Rostock. The National Research Council (NRC) from Canada, the Helmholtz Centre Munich and AVL – a manufacturer of BC measuring instruments – from Austria, joined the BC measurement campaign. Thereby, the variety of BC measuring instruments could be increased significantly. The results of the BC measurement campaign were analyzed by Marena Ltd, NRC, AVL and University of Rostock and jointly published by the German and Canadian ministries and the Federal Environment Agency in 2017 and 2018 as three IMO submissions (PPR4/INF.9, PPR4/9/4 und PPR5/INF.10).

³ Lack, D.A., Moosmüller, H., McMeeking, G.R., Chakrabarty, R.K. and Baumgardner, D. (2014). Characterizing elemental, equivalent black, and refractory black carbon aerosol particles: a review of techniques, their limitations and uncertainties. *Anal Bioanal Chem* (2014) 406:99–122.

2.2.1 Publication of the results of the Black Carbon measurement campaign

The submission PPR4/INF9 „Technical details of a multi-instrument Black Carbon measurement campaign“ contained only the technical details of the measurement campaign like information about the six applied BC measuring instruments (PAX, LII-1, LII-2, TOA, AVL 415SE und MSS), the measurements under different engine loads and the different fuels. Further, the experience made with the EUROMOT Measurement Reporting Protocol were discussed.

The results of the BC measurements were described in a separate submission (PPR4/9/4 „Results of a multi-instrument Black Carbon measurement campaign“). The six applied BC measuring instruments covered four different measurement methods for BC: PAS, LII, TOA und FSN. A comparison of the measured BC data showed that the results of the PAX, the LII-1, the MSS and the AVL415SE were very consistent with a data scattering of $\pm 7\%$ for Diesel, $\pm 14\%$ for marine distillate and $\pm 15\%$ for heavy fuel oil. The LII-2 data coincided better with the TOA data, but deviated significantly from the other measurement results. The reason remained unclear.

The submission further contained suggestions for improvement of the by EUROMOT proposed Measurement Reporting Protocol. The protocol should be simplified especially for large measurement campaigns by reporting several chapters only once per measuring instrument and per fuel.

A further need for BC measurement research was expressed to find a reliable and simple measurement method for use on board of ships.

The majority of delegations during the PPR4-Meeting agreed that further research with emphasis on BC measurements is required to enable the IMO sub-committee PPR to make decisions regarding the most appropriate BC measurement method. Especially, in the light of the global sulfur cap in 2020, fuels with 0.5% sulfur content should be analyzed. Further, it was agreed that there is a need for more data on Black Carbon emissions from low-speed engines as they are widespread in the global fleet. The revision of the Measurement Reporting Protocol was also agreed by the majority of delegations.

Further, a correspondence group to deal with BC measurements was established to continue discussions about the Measurement Reporting Protocol and the measurement methods between the meetings.

Due to request for further research, the BC data of this measurement campaign were further analyzed by the calculation of emission factors and correlation matrices. The results were submitted to PPR 5 in 2018 under the title „New findings of a multi-instrument Black Carbon measurement campaign“ (PPR5/INF.10), again as a joint submission of Canada and Germany.

The main findings were that the combustion of diesel (0,00063% S) and marine distillate Grade A (0.087% S) resulted in BC emission factors of the same order of magnitude. Whereas the combustion of heavy fuel oil (2.3% S) resulted in ca. 10-fold higher emission factors, depending on the engine load. The correlation of the measured data showed that all instruments behaved fairly linear and that the diesel fuel with the lowest sulfur content gave the highest correlation coefficients. One explanation could be that the sulfur content or a high proportion of organic substances have an impact on the BC measuring instruments by interfering with the measured signal.

The submission further suggests the need for a common calibration method for the different BC measurement methods to minimize the differences in the measured data. It is unclear where the future BC measurements will take place. It is possible to measure BC in the engine test lab during the certification of the engine, or on board of ships while the engines are running. Also, the planned place (positioning of the measurement instrument on board) has an impact on the on the possible choice of the suitable BC measurement method(s).

The three submissions can be found as attachments English. The formatting is conform with the IMO standards.

A. Anhang: IMO-Submissionen zu PPR Agenda item 9: Consideration of the impact on the Arctic of emissions of Black Carbon from international shipping

SUB-COMMITTEE ON POLLUTION
PREVENTION AND RESPONSE
4th session
Agenda item 9

PPR 4/INF.9
11 November 2016
ENGLISH ONLY

CONSIDERATION OF THE IMPACT ON THE ARCTIC OF EMISSIONS OF BLACK CARBON FROM INTERNATIONAL SHIPPING

Technical details of a multi-instrument Black Carbon measurement campaign

Submitted by Canada and Germany

SUMMARY

Executive summary: This document provides technical details of a joint Black Carbon measurement campaign performed by Germany and Canada. The Black Carbon measurements were carried out with a variety of Black Carbon measuring instruments and different fuels on a test engine in the laboratory.

Strategic direction: 7.3

High-level action: 7.3.2

Output: 7.3.2.2

Action to be taken: Paragraph 10

Related documents: MEPC 62/24; MEPC 67/12, MEPC 67/12/4, MEPC 67/12/8, MEPC 67/20, MEPC 67/INF.31; MEPC 68/12/2, MEPC 68/12/5, MEPC 68/12/9, MEPC 68/21; BLG 16/16; BLG 17/18; PPR 1/16; PPR 2/8, PPR 2/21, PPR 2/INF.5; PPR 3/8, PPR 3/8/1, PPR 3/22, PPR 3/INF.6, PPR 3/INF.7 and PPR 4/9/4

Background

1 MEPC 62 agreed to a work plan to consider the impact on the Arctic of Black Carbon emissions from international shipping and instructed the Sub-Committee on Bulk Liquids and Gases (now PPR) to undertake this work by: developing a definition of Black Carbon (BC); identifying the most appropriate measurement method(s) for international shipping; and investigating appropriate control measures. MEPC 68 approved the Bond et al. definition of BC proposed by PPR 2 and noted the need for the development of protocols and further study to collect data in order to identify the most appropriate measurement method(s) of BC emissions from international shipping (MEPC 68/21, paragraphs 3.26 to 3.28).

2 At PPR 3, Germany and EUROMOT (PPR 3/8) proposed a harmonized measurement reporting protocol for voluntary BC measurement campaigns. The Sub-Committee invited interested Member Governments and international organizations to use the protocol and submit data derived from its application to PPR 4 (PPR 3/22).

3 This document provides details on the testing and the measurement approach taken in a German-led research campaign to measure BC emissions from a ship engine in the laboratory. It also includes an example of the modified measurement reporting protocol applied to the measurement campaign.

Black Carbon measurement campaign at the University of Rostock

4 In response to the call at PPR 2 (PPR 2/21) for additional BC measurement studies and the subsequent call at PPR 3 for data on the use of the proposed measurement reporting protocol, the German Federal Ministry for the Environment (BMUB) and the German Federal Environment Agency (UBA) assigned the University of Rostock, assisted by Marena Ltd., CE Delft and the Öko-Institut, to carry out simultaneous BC measurements in the laboratory on a ship engine, allowing for the use of different bunker fuel types, engine ratings and various measurement methods. The measurement campaign was joined by the National Research Council of Canada, with funding provided by Transport Canada, and took place in July 2016.

5 The objectives of the BC measurement campaign were to:

- .1 assess the comparability of six BC measurement instruments applied and to compare with similar campaigns;
- .2 assess the effect of different fuels and engine conditions on BC measurement using various methods; and
- .3 report on the research team's experience using the EUROMOT measurement reporting protocol.

6 Six different BC mass concentration instruments were tested. Three fuels, diesel fuel DIN EN 590, distillate marine grade A (DMA) and intermediate fuel oil (IFO), and nine engine conditions were tested for each fuel (from D2 and E3 cycles). Most instruments functioned as expected throughout the tests, providing for a 96% complete table of BC mass concentrations for all instruments and test points. Due to time constraints, most of the test points were measured only once, while only a few test point measurements were repeated.

7 Supporting instrumentation provided information pertaining to the chemical, physical and optical properties of the particles emitted. This information is particularly useful to help understand the reasons for differences observed in BC mass concentrations across the different measurement methods. At the time of writing this document, the analysis of supporting information has only been partially completed.

EUROMOT measurement reporting protocol

8 The team attempted to use the measurement reporting protocol for Black Carbon determination as proposed by EUROMOT and Germany (PPR 3/8) and found that it is difficult to apply to a campaign with multiple test points and instruments. For additional details on the application of the measurement reporting protocol and a summary of the campaign results please refer to document PPR 4/9/4. An example of the modified measurement reporting protocol is attached to this document in the annex, appendix 1. Suggested modifications, additions and questions directed to EUROMOT are marked in grey.

9 The test plan and approach of the measurement campaign are described in the annex to this document.

Action requested of the Sub-Committee

10 The Sub-Committee is invited to note the information set out in the annex to this document.

ANNEX**TECHNICAL DESCRIPTION OF THE BLACK CARBON MEASUREMENT CAMPAIGN AT THE UNIVERSITY OF ROSTOCK****1 Introduction**

This document describes the engine, fuel types, instruments and the different tests performed during the measurement campaign. It explains how the instrument output was processed for comparison of the different instruments. The test plan and approach of the measurement campaign are described in this annex. The results of the BC measurement campaign are presented in document PPR 4/9/4.

2 Engine

The BC measurements took place in the laboratories of the University of Rostock on a single-cylinder direct-injection diesel engine 1VDS18/15CR, which has a nominal output of 76 kW at 1500 rpm. Because of its heavy fuel oil compatibility this single cylinder engine is countable as a typical medium-speed four-stroke diesel engine with a compression ratio between 13 and 16; a maximum cylinder pressure of 170 bar and a mean effective pressure (BMEP) of 20 bar. The research engine is representative for present four-stroke diesel engines on board ships. The engine is equipped with a common rail system, which is suitable for heavy fuel oil operation. The maximum injection pressure is 1300 bar. For the tests an injection nozzle with 9 holes (0.19 mm bore-diameter) and 155° spray angle was used. A programmable controller allows to set the injection timing and duration as well as the rail pressure individually. The single-cylinder engine is charged by an external mechanical compressor.

3 Fuels

The measurements were carried out with three different fuel types listed in Table 1.

Table 1: Fuels used in the BC measurement campaign

Fuel	Viscosity (at 40°C) [cSt]	Density [kg/m³]	Sulphur content [%]
Diesel fuel DIN EN 590 (Diesel)	2.9	838	$6.3 \cdot 10^{-4}$
Distillate marine grade A (DMA)	4.2	877	0.087
Intermediate fuel oil (IFO)	406	988	2.3

4 Test procedures**Engine ratings**

The measurements were carried out according to test cycles types D2 and E3 as defined in ISO 8178 (DIN EN 28178) and in the NO_x Technical Code 2008 (NTC). However, for each test cycle the order of measurements was from the lowest to the highest load point respectively and each lasted 1 hour. The three different fuel types were tested in the order listed in table 2 for the specified loads and speeds. At the beginning of a measurement day we allowed 120 minutes for the engine to warm up and to be adjusted to the correct load point and to set up and calibrate the measurement instruments. In between each test point, we allowed 30 minutes for the engine to stabilize and to secure the correct load point, followed by 60-minute measurements of BC. After that time the engine was tuned to the next load point. At the end of each measurement day we allowed 30 minutes for purging the pipes, cleaning, etc.

Table 2: Measurement points

Fuel type	Engine load [%]	Speed [rpm]	Filter Acquisition Duration [min]
Test cycle D2			
Diesel	10%	1500	60
Diesel	25%	1500	60
Diesel	50%	1500	60
Diesel	75%	1500	60
Diesel	100%	1500	60
Test cycle E3			
Diesel	25%	945	60
Diesel	50%	1200	60
Diesel	75%	1365	60
Diesel	100%	1500	60
Test cycle D2			
DMA	10%	1500	60
DMA	25%	1500	60
DMA	50%	1500	60
DMA	75%	1500	60
DMA	100%	1500	60
Test cycle E3			
DMA	25%	945	60
DMA	50%	1200	40
DMA	50%	1200	59
DMA	75%	1365	60
DMA	100%	1500	60
Test cycle D2			
IFO	10%	1500	42
IFO	25%	1500	31
IFO	50%	1500	60
IFO	75%	1500	30
			20
IFO	100%	1500	13
			5
			10
Test cycle E3			
IFO	25%	945	17
IFO	50%	1200	60
IFO	75%	1365	40
IFO	100%	1500	9
			13
			13

5 Engine performance measurements

The test engine was adjusted to IMO Tier II NO_x performance with DMA as representative engine set-up. For the other fuel types, the same engine adjustments were used, although Tier II NO_x performance might not be fulfilled. The test bench measurement system recorded various parameters for monitoring and controlling the engine behaviour while using different fuels. This included temperature and pressure measurements at the important positions in the air supply, exhaust and cooling systems of the engine. For the evaluation of the combustion process, a water-cooled piezoelectric quartz sensor, which is installed flush with the combustion chamber surface, measured the cylinder pressure. With a high-speed data logging system, the cylinder pressure was recorded in 0.25 °CA steps. Additionally, the rail pressure and the needle stroke of the injector (current feed) were recorded at the same rate.

6 Experimental set-up

Figure 1 provides a graphical representation of the layout of the BC instruments and supporting instruments. Heated lines (in yellow in figure 1) were used between the exhaust line and the instruments or dilution points. The use of heated lines up to the point of dilution reduces condensation of water or other organic semi- and volatile compounds on the line walls. The temperature of the lines varied from one instrument to another. All instruments' reported concentrations were corrected for thermophoretic losses and reported for STP (T=0°C, P=1 atm).

Some instruments were directly connected to the exhaust line and some others were measuring diluted exhaust. BC mass concentration measurements happened on three different ratios of dilution (table 3).

Table 3: Dilution ratios of the different instruments

Instrument	Dilution ratio	Comments
AVL 415SE	1:1	
Laser-Induced Incandescence-1 (LII-1)	1:1	
Micro Soot Sensor (MSS)	8:1	Dilution apparatus is included in the instrument but can be bypassed if needed
Thermal-Optical Analysis (OCEC)	(8-24:1)	Sampling tunnel
Laser-Induced Incandescence-2 (LII-2)	(8-24:1)	Sampling tunnel
Photoacoustic Extinctionmeter (PAX)	(8-24:1)	Sampling tunnel

Dilution can be used to accommodate the measurement range of an instrument or to prevent condensation in the instruments. The dilution system used for the MSS is based on flow measurement principles and a temperature of 120°C was kept at the dilution point. The dilution system used prior to the sampling tunnel is described in more detail in section 7.1 and used an ejector dilutor in combination with a cyclone. The compressed air used for dilution as well as the dilutor itself were kept at 50°C. The dilution ratio in the sampling tunnel was measured based on CO₂ concentrations before and after the point of dilution. The LII-1 sample line was heated to 100°C and no dilution was applied.

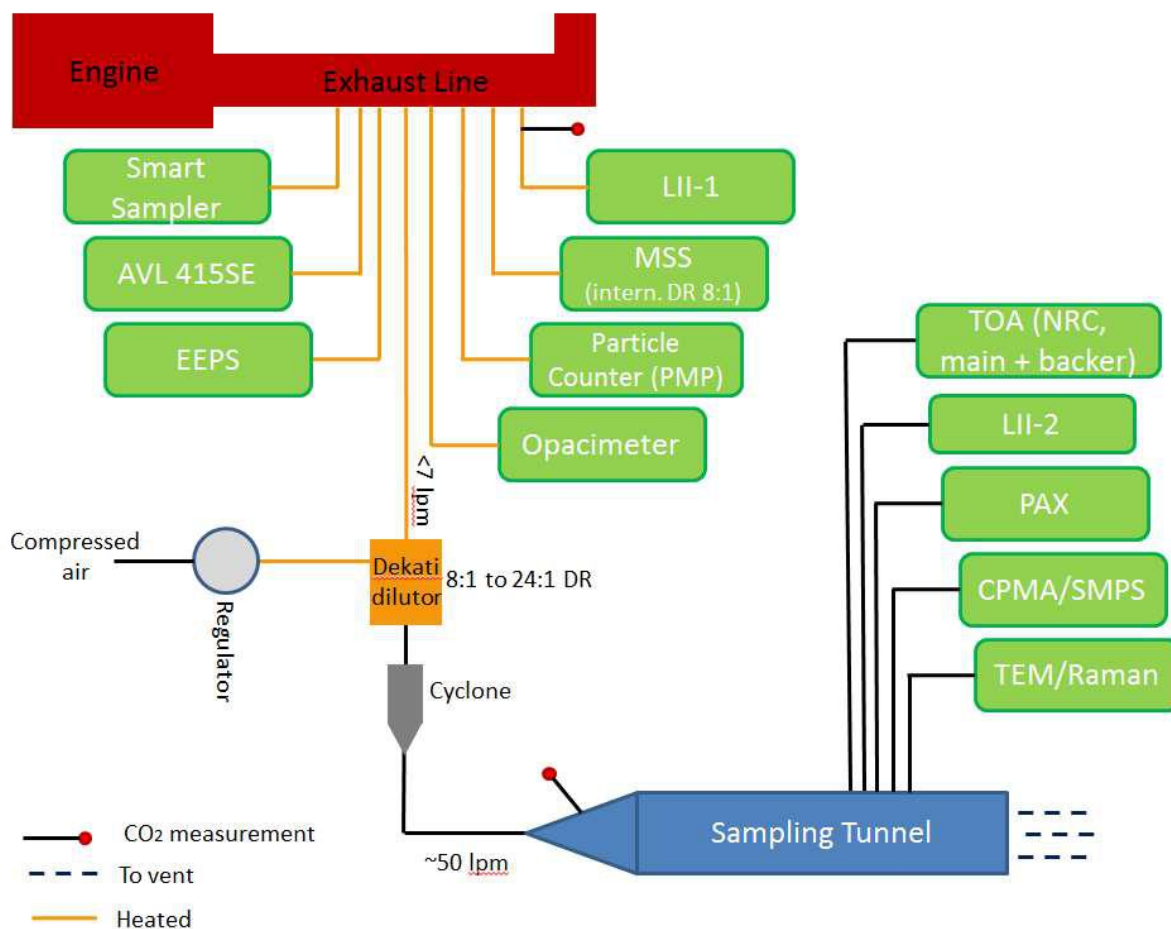


Figure 1: Experimental setup during the Rostock Measurement Campaign

7 Instrumentation

7.1 Sampling tunnel and dilution system (with CO₂ tracking)

A dilution system consisting of a DI-1000 Dekati ejector dilutor followed by a cyclone (1 µm cut-off at 50 litres per minute (lpm)) was used to dilute the sample. The dilution air, the sample line upstream of the dilutor, and the Dekati dilutor were all heated to 50°C, 125°C and 50°C, respectively, to avoid condensation. A sampling tunnel compliant with ISO 8178 was used to distribute the diluted sample to multiple instruments. The CO₂ concentration was measured prior to and after the dilution point and served as a tracer to calculate the dilution ratio. Measuring instrument for CO₂: NDIR Gas Analyzer by California Analytical Instruments, model 603.

7.2 Black Carbon Measurements

In the report of PPR 2 to MEPC (PPR 2/21, paragraph 8.5.3), four different measurement methods were identified to measure BC according to the Bond et al. (2013) definition: Photo Acoustic Spectroscopy (PAS), Multi Angle Absorption Photometry (MAAP), Laser Induced Incandescence (LII) and Filter Smoke Number (FSN). PAS, MAAP and FSN measure equivalent BC (eBC), LII measures refractory BC (rBC) and Thermal-Optical Analysis, an often-used measurement method which was used during this campaign, measures elemental carbon (EC).

7.2.1 AVL Smoke Meter (FSN, eBC)

The smoke meter is a standardized method for measuring "soot" content in the exhaust of diesel engines and conforms with ISO 10054. The smoke meter samples a user-defined volume of exhaust gas and draws it through a clean filter paper. The filtered "soot" causes blackening of the filter paper which is measured by an optical measuring head. The measurement principle implemented in the AVL smoke meter is based on light absorption. It measures the change in optical reflectance of visible light from a loaded filter paper relative to the clean filter paper. The basis of the Filter Smoke Number (FSN) measurement is that light is backscattered by the filter paper and a diffuse (i.e. backscattering) reflector behind the filter paper. The backscattered light is recorded by the detector. The intensity of backscattered light decreases due to absorbing particles filtered by the paper. Conversion of FSN to the eBC concentration is calculated according to Equation 1 as recommended by the instrument manufacturer:

$$C \left[\frac{mg}{m^3} \right] = \frac{1}{0.405} \times 5.32 \times FSN \times e^{FSN * 0.3062} \quad \text{[Equation 1]}$$

The AVL 415SE is equipped with a shop air option, which ensures improved cleaning efficiency and increased robustness against wet exhaust gas due to shop air purging of the sampling line and the sample probe. Measuring instrument: AVL Smoke Meter 415SE.

7.2.2 AVL Micro Soot Sensor (PAS, eBC)

During the photoacoustic measurement, a diluted sample gas with "black", i.e. strongly absorbing, soot particulates, is directed through a measuring chamber where it gets thermally animated by a modulated laser beam with a wavelength of 808 nm. The periodical warming and cooling and the resulting expansion and contraction of the carrier gas produce a periodic pressure pulsation, which is detected by a microphone as an acoustic wave. The signal is amplified in a preamplifier and filtered in a "lock-in" amplifier. The MSS consists of a sensor unit and a conditioning unit for dilution, and provides a continuous real-time measurement of eBC concentration. Measuring instrument: AVL MSSplus.

7.2.3 Photoacoustic Extinctionmeter, PAX (PAS, eBC)

A real-time BC mass-concentration instrument, the Droplet Measurement Technology PAX uses a wavelength of 870 nm and a photoacoustic method to measure light absorption, and a reciprocal nephelometer to measure total light scattering of aerosol particles. From these two measurements, it derives the equivalent BC (eBC) particle mass concentration and the single scattering albedo. Measuring instrument: PAX 870 nm by Droplet Measurement Technologies.

7.2.4 Artium Laser-Induced Incandescence (LII, rBC)

Two Artium LII 300 instruments were used. This instrument is a real-time BC mass-concentration instrument that applies a high-energy pulsed laser to sampled emissions and heats them up to a temperature close to BC's sublimation temperature (~4000 K). The incandescence signal emitted from the BC particles is proportional to the mass of the particles. It is also a function of particle temperature. Particle temperature is determined from two colour pyrometries and combined with incandescent signal strength to determine refractory BC (rBC) particle mass concentration. Measuring instrument: LII 300 by Artium Technologies.

7.2.5 EUSAAR-2 Thermal-Optical Analysis (TOA, EC)

Exhaust emissions are collected on a quartz filter. The total volume of exhaust is characterized by the flow rate across the filter and the sampling time. An extra-situ filter analysis routine is carried out in a laboratory. A punch is taken off the filter and analyzed by Thermal-Optical Analysis (TOA, also known as OCEC analysis). TOA is performed in two phases, following a temperature protocol, each with increasing temperature: the first in a helium atmosphere (during which organic carbon evolves) and the second in a helium + oxygen atmosphere (during which elemental carbon evolves). The evolved carbon is counted using FID (Flame Ionization Detector) and the filter's carbon loading is monitored with a red laser to correct for possible pyrolysis of organic carbon. In the case of this campaign, the EUSAAR-2 temperature protocol was used to analyse the filters. Measuring instrument: Sunset Laboratory Model 5L OCEC analyzer.

7.3 Supporting measurements

7.3.1 Gravimetric determination of particle mass

A partial flow dilution system of 1:10 was used for gravimetric determination of particle mass. The system mixes and dilutes a small sample of the exhaust flow with filtered air and samples the diluted exhaust gas over a filter that collects the particles and is subsequently weighed. Measuring instrument: AVL Smart Sampler 478 ISO 8178-compliant.

7.3.2 Particle number

Particle number was measured with a condensation nucleus counter (butanol condensed onto the particles which are subsequently measured with light scattering). The measuring instrument fulfils all requirements of the PMP Group (Particle Measurement Program) and of the latest version of the UNECE-R49 respectively R83 law (standard for trucks and cars). Measuring Instrument: AVL Particle Counter 489.

7.3.3 Particle size distribution

The instrument charges the particles electrically and separates the particles via electromagnetic deflection according to their size class with a diameter ranging from 5.6 to 560 nm. The particles are counted by selective bursts, when the charged particles reach the wall in the different size-related areas. Measuring instrument: TSI – Model 3090 Engine Exhaust Particle Sizer™ (EEPS) Spectrometer.

7.2.4 Opacity

The opacity measurement principle is based on the decrease of light intensity in a measuring chamber of defined length (430mm) and non-reflecting surface filled with exhaust gas. The loss of light intensity is measured and the opacity [N] of the exhaust gas is calculated based

on the Beer-Lambert law. The AVL Opacimeter is a dynamic partial-flow measuring instrument for the continuous measurement of exhaust gas opacity conforming with ISO 11614. Measuring instrument: AVL Opacimeter 439.

7.3.5 Carbon grids for TEM analysis

Particles are collected on a carbon film-coated copper grid using an ESPNano sampler, and analyzed using Transmission-Electron Microscopy (TEM). TEM images of the particles allow measurement of the primary particle size, aggregate size of BC and further provides information on other types of particles that were found in the emissions. It allows the observation of particle coating (to some extent) and the influence of coating on aggregate shape.

7.3.6 Gold grids for Raman analysis

A bulk of particles is collected on gold-coated grids using an ESPNano sampler, and analysed by Raman spectrometry. Raman spectrometry allows the detection of different carbon bonds within the particles. Based on this analysis, it is possible to determine whether the particles were rather graphitic, amorphous or a combination of both. It also gives information on the particle surface and bulk structure.

7.3.7 Effective density (CPMA/SMPS)

By selecting particle size using a differential mobility analyzer (DMA) and scanning for different masses using a centrifugal particle mass analyzer (CPMA), it is possible to calculate the effective density of particles as a function of mobility size. The effective density is measured with and without a thermodenuder / catalytic stripper to remove the coating. This gives information on the importance of organic coating on BC particles. Measuring instruments: Centrifugal Particle Mass Analyzer (CPMA) by Cambustion and Scanning Mobility Particle Sizer (SMPS) by TSI.

7.3.8 Black Carbon determination from gravimetric analysis filters

The filters used for the gravimetric particle mass determination are also used to determine the BC mass according to Council Directive 1999/96/EC. University of Rostock used pure borosilicate filters made of reinforced glass microfibers with woven glass cloth and bonded with PTFE. The particle mass on the filter is analyzed in 5 consecutive steps to determine BC according to the Bond et al. (2013) definition.

7.3.9 Gaseous exhaust components

The following exhaust gas components were recorded: CO₂, CO, SO₂, O₂, THC, NO, NO₂. The gaseous emissions were measured undiluted in an exhaust gas analyzer by ABB AO2020.

8 Corrections, dilution, uncertainty and data averaging

Particulate deposition is an unavoidable effect in any sampling situation. As the instruments were sampling from different points, different corrections for losses and dilution had to be applied.

For the smoke meter, the compensation for particle deposition is an intrinsic part of the mg/m^3 scale. The reference for the mg/m^3 scale (including the compensation for particle losses) is the concentration at sampling point determined empirically. The correlation curve to mg/m^3 scale, applied in this instrument, does not discriminate between the different factors (e.g. thermophoretic losses, diffusional losses, etc.) contributing to particle deposition.

For all other instruments, BC mass concentration was corrected only for thermophoretic losses using the relation $(\text{Conc}_{\text{in}}/\text{Conc}_{\text{out}}) = (T_{\text{in}}/T_{\text{out}})^{0.38}$ [Kittleson & Johnson, 1991]. In MSS T_{in} and T_{out} is measured and the thermophoretic loss correction is automatically applied by the instrument software. For the other instruments, the correction was applied during post-processing.

Instruments on the diluted groups were corrected to report undiluted concentration using the time-resolved dilution ratio data. In the case of the MSS, the dilution ratio was around 8:1 with an uncertainty of 6%. In the case of instruments sampling from the sampling tunnel, the dilution ratio (measured through CO_2 monitoring) varied between 8:1 and 24:1 throughout the whole campaign. The broad range of dilution ratios observed was an artifact of minor clogging of the sample orifice of the Dekati dilutor. Between sampling points, the dilutor was pack-purged to keep the orifice clear.

The uncertainty of the dilution factor was ~4% below the measurement point and ~18% above the measurement point. The uncertainty is composed of the instrument uncertainty and a component due to the environmental conditions where the CO_2 detector was operating.

The CO_2 concentration detector, a California Analytical NDIR Gas Analyzer, is not designed for significant ambient temperature changes or temperatures above 40°C . As the room temperature was increasing during the day, from about 25°C to very close to 40°C , the instrument's span was drifting. We used a worst-case scenario drift and conservatively applied an extra-uncertainty of ~15% to all the test points, despite this temperature effect being less important for some test points than others. In the worst-case scenario, both the undiluted and diluted CO_2 spans increased as the day went by, but the undiluted channel increased by a higher percentage (21%) than the diluted channel (6%). This resulted in an uncertainty varying between 10 and 14%, depending on the test points. Since this phenomenon only affects the uncertainty above the measurement point, a 15% uncertainty was added across all test points, above the measured dilution ratio.

The BC mass concentration was averaged for each test point. Each test point was defined by the acquisition time of a filter for Thermal-Optical Analysis (see table 2). For some test points where BC concentration was very high, it was possible to acquire multiple filters as indicated in table 2. For instruments sampling from the sampling tunnel, the conversion of the diluted mass concentration to undiluted mass concentration was done on a per-second basis before averaging the concentration. The MSS outputs second by second: the raw exhaust soot concentration, the diluted soot concentration and the dilution ratio. The BC exhaust soot concentration was averaged over the second by second data. In the case of the smoke meter, an instrument which takes regular integrated measurements on a filter, the BC mass concentration was averaged over the values of the integral measurements taken during the test point.

References

ECE R49 Heavy Duty Emission legislation

ISO 10054:1998 "Internal combustion compression-ignition engines -- Measurement apparatus for smoke from engines operating under steady-state conditions -- Filter-type smoke meter"

ISO 8178-1:2006 "Reciprocating internal combustion engines -- Exhaust emission measurement -- Part 1: Test-bed measurement of gaseous and particulate exhaust emissions"

Kittelson, D.B. and J.H. Johnson. 1991. "Variability in Particle Emission Measurements in the Heavy-Duty Transient Test," SAE Paper No. 910738.

Appendix 1:

MEASUREMENT REPORTING PROTOCOL FOR BLACK CARBON DETERMINATION

1. Engine design parameters (to be completed before measurement)

1.1 Engine	Production year:	<u>1993</u>
	Location:	<input checked="" type="checkbox"/> Testbed <input type="checkbox"/> Ship
1.2 Engine freshly manufactured	<input type="checkbox"/> Yes	<input checked="" type="checkbox"/> No
	If no: Documentation of relevant maintenance provided	<input type="checkbox"/> Yes <input checked="" type="checkbox"/> No
1.3 Engine total running hours	_____	[h]
1.4 Regular maintenance interval	_____	[h]
1.5 Hours since last regular maintenance	_____	[h]
1.6 Engine category	<input checked="" type="checkbox"/> 4-stroke <input type="checkbox"/> 2-stroke	
1.7 Engine fuel type	<input checked="" type="checkbox"/> Diesel <input type="checkbox"/> Gas <input type="checkbox"/> Dual fuel	
1.8 Engine max. rated power	_____	76 [kW]
1.9 Mean effective pressure at rated power	_____	20 [bar]
1.10 Engine speed	<input type="checkbox"/> Less than 130 rpm <input checked="" type="checkbox"/> 130 or more but less than 2,000 rpm <input type="checkbox"/> 2,000 rpm or more	
1.11 Method of air aspiration	<input type="checkbox"/> Naturally aspirated <input type="checkbox"/> Pressure-charged single stage <input type="checkbox"/> Pressure-charged multi stage	
1.12 Injection system	<input type="checkbox"/> Conventional <input checked="" type="checkbox"/> Common rail	
1.13 Applicable emission limit	<input type="checkbox"/> IMO Tier I <input checked="" type="checkbox"/> IMO Tier II <input type="checkbox"/> IMO Tier III <input type="checkbox"/> Others: _____	
1.14 Applicable test cycle	<input type="checkbox"/> C1 <input checked="" type="checkbox"/> D2 <input checked="" type="checkbox"/> E2 <input checked="" type="checkbox"/> E3 <input type="checkbox"/> Others:	

1.15.1 Specific lubrication oil consumption		SLOC: _____ [g/kWh]	
		Breaking-in period:	<input type="checkbox"/> Finished <input type="checkbox"/> Not finished <input type="checkbox"/> Not applicable
1.15.2 Cylinder liner lubrication	<input checked="" type="checkbox"/> None <input type="checkbox"/> Yes, active at	<input type="checkbox"/> 100% <input type="checkbox"/> 75% <input type="checkbox"/> 50% <input type="checkbox"/> 25% <input type="checkbox"/> 10%	Feed rate: _____ [g/h] Feed rate: _____ [g/h] Feed rate: _____ [g/h] Feed rate: _____ [g/h] Feed rate: _____ [g/h]
		Breaking-in period:	<input type="checkbox"/> Finished <input type="checkbox"/> Not finished <input type="checkbox"/> Not applicable
1.15.3 Inlet valve seat lubrication	<input checked="" type="checkbox"/> None <input type="checkbox"/> Yes, active at	<input type="checkbox"/> 100% <input type="checkbox"/> 75% <input type="checkbox"/> 50% <input type="checkbox"/> 25% <input type="checkbox"/> 10%	Feed rate: _____ [g/h] Feed rate: _____ [g/h] Feed rate: _____ [g/h] Feed rate: _____ [g/h] Feed rate: _____ [g/h]
1.16 Exhaust gas treatment device	<input checked="" type="checkbox"/> None <input type="checkbox"/> Yes	<input type="checkbox"/> SCR <input type="checkbox"/> Scrubber <input type="checkbox"/> EGR <input type="checkbox"/> Water injection <input type="checkbox"/> Others: _____	

2. Fuel

- 2.1 Fuel in use**
- ULSD DMX X DMA DMZ DMB
 RMA RMB RMD RME RMG RMK
- Other: _____ acc. standard: _____
- Natural Gas
- Other gases acc. IGF: _____
- Liquid to gas fuel ratio as certified at mode point:
- 100% _____
 75% _____
 50% _____
 25% _____
 10% _____

Fuel properties and composition (in use during testing)

2.2 Gas

Please fill in as far as possible most important marked with *)

Property	Unit / Standard	Actual value	Remark
Methane number*)	[-] / DIN EN 16726		
Lower calorific value*)	[MJ/kg] / ISO 6976		
Higher calorific value	[MJ/kg] / ISO 6976		
Wobbe Indices Ws / Wi	[MJ/m ³] / ISO 6976		
Density*)	[kg/m ³] / ISO 6976		
Methane*)	wt.-% [kg/kg] / ISO 6974 or DIN 51894		
Ethane*)	wt.-% [kg/kg] / ISO 6974 or DIN 51894		
Propane*)	wt.-% [kg/kg] / DIN 51894		
Isobutane*)	wt.-% [kg/kg] / DIN 51894		
N-Butane*)	wt.-% [kg/kg] / DIN 51894		
Pentane	wt.-% [kg/kg] / DIN 51894		
Hexane	wt.-% [kg/kg] / DIN 51894		
Heptane	wt.-% [kg/kg] / DIN 51894		
Nitrogen	wt.-% [kg/kg] / ISO 6974		
Sulphur*)	wt.-% [kg/kg] / ISO 6326-5		
Hydrogen sulfide	wt.-% [kg/kg] / ISO 8819		
Carbon dioxide	wt.-% [kg/kg] / ISO 6974		
Hydrogen	wt.-% [kg/kg] / DIN 51894		
Others			

2.3 Liquid fuel Please fill in as far as possible most important marked with *) essential **)	Property	Unit / Standard	Actual value	Remark
	Type of fuel	Grade / ISO 8217	DMA	
	Flash point*)	[°C] / ISO 2719	92	
	Viscosity @ 40/50°C **)	[mm ² /s] / ISO 3104	4.2	
	Density @ 15°C *)	[kg/m ³] / ISO 3675 or 12185	877	
	Net calorific value (Hu) *)	[J/g] / DIN 51900	42318	
	Sulphur content*)	ppm [mg/kg] / ISO 8754 or 14596	800	
	Ash content*)	ppm [mg/kg] / ISO 6245	<0.001	
	Water content*)	ppm [mg/kg] / ISO 3733	98	
	Carbon content*)	wt.-% [kg/kg] / ASTM D5291	85.86	
	Hydrogen content*)	wt.-% [kg/kg] / ASTM D5291	13.14	
	Nitrogen content*)	wt.-% [kg/kg] / DIN 51444	0.02	
	Oxygen content*)	wt.-% [kg/kg] / DIN 51732		
	Cetane index*)	ISO 4264	45	
	CCAI*)			
	FAME content*)	wt.-% [kg/kg] / EN 14078		
	Mono aromatic compounds*)	wt.-% [kg/kg] / EN 12916	27.9	
	Poly aromatic compounds*)	wt.-% [kg/kg] / EN 12916	13.8	
	Di aromatic compounds	wt.-% [kg/kg] / EN 12916	11.8	
	Tri aromatic compounds	wt.-% [kg/kg] / EN 12916	2.1	
Inorganic constituents (V)	ppm [mg/kg] / ISO 14597 or 8691			
Inorganic constituents (Ni)	ICP			
Carbon residues*)	wt.-% [kg/kg] / ASTM D4530	0.06		
Others				

2. Fuel																																																																																																			
2.1 Fuel in use	<input checked="" type="checkbox"/> ULSD <input type="checkbox"/> DMX <input type="checkbox"/> DMA <input type="checkbox"/> DMZ <input type="checkbox"/> DMB <input type="checkbox"/> RMA <input type="checkbox"/> RMB <input type="checkbox"/> RMD <input type="checkbox"/> RME <input type="checkbox"/> RMG <input type="checkbox"/> RMK <input type="checkbox"/> Other: _____ acc. standard: _____	<input type="checkbox"/> Natural Gas <input type="checkbox"/> Other gases acc. IGF: _____ <input type="checkbox"/> Liquid to gas fuel ratio as certified at mode point: 100% _____ 75% _____ 50% _____ 25% _____ 10% _____																																																																																																	
2.3 Liquid fuel Please fill in as far as possible most important marked with *) essential **)	<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="width: 40%;">Property</th> <th style="width: 20%;">Unit / Standard</th> <th style="width: 20%;">Actual value</th> <th style="width: 20%;">Remark</th> </tr> </thead> <tbody> <tr> <td>Type of fuel</td> <td>Grade / ISO 8217</td> <td>Diesel DIN EN 590 2014-04</td> <td></td> </tr> <tr> <td>Flash point*)</td> <td>[°C] / ISO 2719</td> <td></td> <td></td> </tr> <tr> <td>Viscosity @ 40/50°C **)</td> <td>[mm²/s] / ISO 3104</td> <td>2.893</td> <td></td> </tr> <tr> <td>Density @ 15°C *)</td> <td>[kg/m³] / ISO 3675 or 12185</td> <td>838.05</td> <td></td> </tr> <tr> <td>Net calorific value (Hu) *)</td> <td>[J/g] / DIN 51900</td> <td>42543</td> <td></td> </tr> <tr> <td>Sulphur content*)</td> <td>ppm [mg/kg] / ISO 8754 or 14596</td> <td>6.3</td> <td></td> </tr> <tr> <td>Ash content*)</td> <td>ppm [mg/kg] / ISO 6245</td> <td></td> <td></td> </tr> <tr> <td>Water content*)</td> <td>ppm [mg/kg] / ISO 3733</td> <td>110</td> <td></td> </tr> <tr> <td>Carbon content*)</td> <td>wt.-% [kg/kg] / ASTM D5291</td> <td>85.6</td> <td></td> </tr> <tr> <td>Hydrogen content*)</td> <td>wt.-% [kg/kg] / ASTM D5291</td> <td>13.6</td> <td></td> </tr> <tr> <td>Nitrogen content*)</td> <td>wt.-% [kg/kg] / DIN 51444</td> <td><0.5</td> <td></td> </tr> <tr> <td>Oxygen content*)</td> <td>wt.-% [kg/kg] / DIN 51732</td> <td></td> <td></td> </tr> <tr> <td>Cetane index*)</td> <td>ISO 4264</td> <td>53.5</td> <td></td> </tr> <tr> <td>CCAI*)</td> <td></td> <td></td> <td></td> </tr> <tr> <td>FAME content*)</td> <td>wt.-% [kg/kg] / EN 14078</td> <td>6.0</td> <td></td> </tr> <tr> <td>Mono aromatic compounds*)</td> <td>wt.-% [kg/kg] / EN 12916</td> <td>20.7</td> <td></td> </tr> <tr> <td>Poly aromatic compounds*)</td> <td>wt.-% [kg/kg] / EN 12916</td> <td>3.1</td> <td></td> </tr> <tr> <td>Di aromatic compounds</td> <td>wt.-% [kg/kg] / EN 12916</td> <td>2.8</td> <td></td> </tr> <tr> <td>Tri aromatic compounds</td> <td>wt.-% [kg/kg] / EN 12916</td> <td>0.3</td> <td></td> </tr> <tr> <td>Inorganic constituents (V)</td> <td>ppm [mg/kg] / ISO 14597 or 8691</td> <td><0.1</td> <td></td> </tr> <tr> <td>Inorganic constituents (Ni)</td> <td>ICP</td> <td><0.1</td> <td></td> </tr> <tr> <td>Carbon residues*)</td> <td>wt.-% [kg/kg] / ASTM D4530</td> <td>0.07</td> <td></td> </tr> <tr> <td>Others</td> <td></td> <td></td> <td></td> </tr> </tbody> </table>			Property	Unit / Standard	Actual value	Remark	Type of fuel	Grade / ISO 8217	Diesel DIN EN 590 2014-04		Flash point*)	[°C] / ISO 2719			Viscosity @ 40/50°C **)	[mm ² /s] / ISO 3104	2.893		Density @ 15°C *)	[kg/m ³] / ISO 3675 or 12185	838.05		Net calorific value (Hu) *)	[J/g] / DIN 51900	42543		Sulphur content*)	ppm [mg/kg] / ISO 8754 or 14596	6.3		Ash content*)	ppm [mg/kg] / ISO 6245			Water content*)	ppm [mg/kg] / ISO 3733	110		Carbon content*)	wt.-% [kg/kg] / ASTM D5291	85.6		Hydrogen content*)	wt.-% [kg/kg] / ASTM D5291	13.6		Nitrogen content*)	wt.-% [kg/kg] / DIN 51444	<0.5		Oxygen content*)	wt.-% [kg/kg] / DIN 51732			Cetane index*)	ISO 4264	53.5		CCAI*)				FAME content*)	wt.-% [kg/kg] / EN 14078	6.0		Mono aromatic compounds*)	wt.-% [kg/kg] / EN 12916	20.7		Poly aromatic compounds*)	wt.-% [kg/kg] / EN 12916	3.1		Di aromatic compounds	wt.-% [kg/kg] / EN 12916	2.8		Tri aromatic compounds	wt.-% [kg/kg] / EN 12916	0.3		Inorganic constituents (V)	ppm [mg/kg] / ISO 14597 or 8691	<0.1		Inorganic constituents (Ni)	ICP	<0.1		Carbon residues*)	wt.-% [kg/kg] / ASTM D4530	0.07		Others			
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Others																																																																																																			

2. Fuel

- 2.1 Fuel in use**
- ULSD DMX DMA DMZ DMB
 RMA RMB RMD RME RMG RMK
- Other: _____ acc. standard: _____
- Natural Gas
- Other gases acc. IGF: _____
- Liquid to gas fuel ratio as certified at mode point:
- 100% _____
 75% _____
 50% _____
 25% _____
 10% _____

2.3 Liquid fuel
Please fill in as far as possible most important marked with *) essential **)

Property	Unit / Standard	Actual value	Remark
Type of fuel	Grade / ISO 8217	RMG-500	
Flash point*)	[°C] / ISO 2719	140	
Viscosity @ 40/50°C **)	[mm ² /s] / ISO 3104	441.5/405.9	
Density @ 15°C *)	[kg/m ³] / ISO 3675 or 12185	988.2	
Net calorific value (Hu) *)	[J/g] / DIN 51900	40291	
Sulphur content*)	ppm [mg/kg] / ISO 8754 or 14596	2.3	
Ash content*)	ppm [mg/kg] / ISO 6245	0.055	
Water content*)	ppm [mg/kg] / ISO 3733	3800	
Carbon content*)	wt.-% [kg/kg] / ASTM D5291	85.8	
Hydrogen content*)	wt.-% [kg/kg] / ASTM D5291	10.4	
Nitrogen content*)	wt.-% [kg/kg] / DIN 51444	0.41	
Oxygen content*)	wt.-% [kg/kg] / DIN 51732		
Cetane index*)	ISO 4264		
CCAI*)		848	
FAME content*)	wt.-% [kg/kg] / EN 14078		
Mono aromatic compounds*)	wt.-% [kg/kg] / EN 12916	12.6	
Poly aromatic compounds*)	wt.-% [kg/kg] / EN 12916	14.9	
Di aromatic compounds	wt.-% [kg/kg] / EN 12916	11.1	
Tri aromatic compounds	wt.-% [kg/kg] / EN 12916	3.8	
Inorganic constituents (V)	ppm [mg/kg] / ISO 14597 or 8691		
Inorganic constituents (Ni)	ICP		
Carbon residues*)	wt.-% [kg/kg] / ASTM D4530	15.6	
Others			

3. Lube oil properties and composition (in use during testing; Producers specification can be used)				
3.1 Circulation lubrication oil Please fill in as far as possible	Property	Unit / Standard	Actual value	Remark
	Lube oil	Brand / Type Gulfmar Select Plus	430	
	Grade	Multi / Mono	Mono	
	BN	mg KOH/g / ISO 3771	30	
	Ash content	wt.-% [kg/kg] / ISO 6245		
	Viscosity	[mm ² /s] / ASTM D7042	15.3	SAE40
	Sulphur content	wt.-% [kg/kg] / ISO 20884		
3.2 Cylinder oil Please fill in as far as possible Please fill in if applicable	Property	Unit / Standard	Actual value	Remark
	Lube oil	Brand / Type		
	Grade	Multi / Mono		
	BN	mg KOH/g / ISO 3771		
	Ash content	wt.-% [kg/kg] / ISO 6245		
	Viscosity	[mm ² /s] / ASTM D7042		
	Sulphur content	wt.-% [kg/kg] / ISO 20884		
3.3 Valve seat lubrication oil Please fill in as far as possible Please fill in if applicable	Property	Unit / Standard	Actual value	Remark
	Lube oil	Brand / Type		
	Grade	multi / mono		
	BN	mg KOH/g / ISO 3771		
	Ash content	wt.-% [kg/kg] / ISO 6245		
	Viscosity	[mm ² /s] / ASTM D7042		
	Sulphur content	wt.-% [kg/kg] / ISO 20884		

4. Measurement equipment information (to be completed before measurement) and parameters

Measurement instrument

4.1 BC measurement instrument information	Make:	AVL	Model:	415SE
4.2 Measurement principle	<input type="checkbox"/> LII	<input checked="" type="checkbox"/> FSN	<input type="checkbox"/> PAS	<input type="checkbox"/> MAAP
	<input type="checkbox"/> Others:	_____		
4.3 Values reported as	<input type="checkbox"/> EC (thermal)	Protocol acc.: _____		
	<input type="checkbox"/> rBC			
	<input checked="" type="checkbox"/> eBC			
	<input checked="" type="checkbox"/> FSN			
	<input type="checkbox"/> Others:	_____		
4.4 Values reported in unit	<input checked="" type="checkbox"/> mg/m_n^3	(wet basis; act. O ₂ -concentration)	H ₂ O-conc.:	_____ [Vol.-%] (wet)
	<input type="checkbox"/> mg/m_n^3	(dry basis; act. O ₂ -concentration)		
	<input type="checkbox"/> mg/m_n^3	(dry basis; Ref. O ₂ -concentration)	O ₂ -conc.:	_____ [Vol.-%] (dry)
	<input type="checkbox"/> mg/kWh	refer to 5.		
	<input checked="" type="checkbox"/> FSN			
	<input type="checkbox"/> $\text{mg}/\text{kg fuel}$	refer to 5.		
	<input type="checkbox"/> Others:	_____		
4.5 Reference conditions	Norm temperature:	25 [°C]		
(only if 4.4 is referred to Norm-cubic meters [m_n^3])	Norm pressure:	1000 [mbar]		
4.6 Sampling time / -number	Sampling time of each measurement:	variable (depending on the soot concentration)	[s]	
	If mean values are reported: Number of consecutive measurements at each mode point:	~ 40 for 1 hour measurement	[-]	
	Acc. manufacturer specification:	<input checked="" type="checkbox"/> Yes	<input type="checkbox"/> No	
4.7 BC instrument parameter	Temperature inside measuring cell:	heated to 70 [°C]		
	Pressure inside measuring cell:	pressure of exhaust gas + pressure drop of sampling line	[mbar]	

	Wavelength(s) used:	420-680 (highest intensity at 550) [nm]								
	Mass absorption cross section(s) used:	- [m ² /g]								
	Conversion equation(s) used:	(5.32*FSN*EXP(FSN*0.3062))/0.405								
	Repeatability of the instrument used:	in FSN 1σ ≤ ±(0.05/seconds sampling time + 3% of measured value)								
	Reproducibility of the instrument used:	in FSN 1σ ≤ ±(0.05/seconds sampling time + 6% of measured value)								
	Acc. manufacturer specification:	<input checked="" type="checkbox"/> Yes <input type="checkbox"/> No								
	Other parameters which could influence the measured values:									
	<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="width: 80%;">Parameter / Correction</th> <th style="width: 20%;">Unit</th> </tr> </thead> <tbody> <tr><td> </td><td> </td></tr> <tr><td> </td><td> </td></tr> <tr><td> </td><td> </td></tr> </tbody> </table>		Parameter / Correction	Unit						
Parameter / Correction	Unit									
4.8 BC Instrument Calibration	Date of last calibration:	17.06.2015 Also, measuring head calibration with the reflectance standards was performed before the measuring campaign.								
	Calibration procedure according manufacturer specification:	<input checked="" type="checkbox"/> Yes <input type="checkbox"/> No <input type="checkbox"/> Others: _____								
	Calibration including zero point:	<input checked="" type="checkbox"/> Yes <input type="checkbox"/> No								
	Used medium for zero point calibration:	a) white value reflectance standard b) before every measurement an adjustment is performed using the white filter paper + white plate								
	Used calibration standard:	<input type="checkbox"/> Synthetic flame soot <input type="checkbox"/> Printex-U <input type="checkbox"/> Graphite spark aerosol generator GfG soot <input type="checkbox"/> Soot with inorganic coatings <input type="checkbox"/> Soot without inorganic coatings <input checked="" type="checkbox"/> Reflectance standards <input checked="" type="checkbox"/> Others: glass cylinder (standard) for calibration of the suction volume								
	Remark:	_____								
	Leakage test performed before or after calibration: <input checked="" type="checkbox"/> Yes <input type="checkbox"/> No <input type="checkbox"/> Not applicable									
4.9 Sample gas pre-treatment Please fill in if applicable	Exhaust gas dilution:	<input type="checkbox"/> Yes <input checked="" type="checkbox"/> No								
	If yes, dilution ratio (1:x)	at mode point: _____ [%] _____ _____ _____ _____								

Dilution medium:		<input type="checkbox"/> Ambient air	<input type="checkbox"/> Exhaust gas
		<input type="checkbox"/> Others: _____	
Filtration of the dilution medium before dilution:		_____ <input type="checkbox"/> Yes	x No
Temperature of the dilution medium:		_____ [°C]	
Temperature of the diluted exhaust gas:		_____ [°C]	
Evaporation tube	<input type="checkbox"/> Yes	x No	
Temperature	_____ [°C] acc. manufacturer spec.	<input type="checkbox"/> Yes	x No
Catalytic stripper	<input type="checkbox"/> Yes	x No	
Temperature	_____ [°C] acc. manufacturer spec.	<input type="checkbox"/> Yes	x No
Thermo-denuder	<input type="checkbox"/> Yes	x No	
Temperature	_____ [°C] acc. manufacturer spec.	<input type="checkbox"/> Yes	<input type="checkbox"/> No
Others:		_____	
4.10 Sample flow rate/volume	Acc. manufacturer specification:	x Yes	<input type="checkbox"/> No
	Sample flow rate of the raw exhaust gas:	_____ 10	[l/min]
	Sample flow rate of the diluted exhaust gas:	_____	[l/min]
	Sample volume of the raw exhaust gas:	_____	[l]
	Sample volume of the diluted exhaust gas:	_____	[l]
	<input type="checkbox"/> Subkinetic	<input type="checkbox"/> Isokinetic	<input type="checkbox"/> Superkinetic
		<input type="checkbox"/> Not applicable	
Sample line and probe			
4.11 Sample/transfer line	Use of a sample line:	x Yes	<input type="checkbox"/> No (in situ,...)
Please fill in if applicable	Acc. manufacturer specification:	x Yes	<input type="checkbox"/> No
	Length of the sample line:	_____ 3	[m]
	Heated sample line:	x Yes	Temperature: _____ 70 [°C]
		<input type="checkbox"/> No	
	Sample line material:	_____ Viton	
	Inner diameter of the sample line:	_____ 4.0 [mm]	
	Insulated or heated connections between sample line, measurement instrument and probe:	x Yes - between sampling line and instrument	x No - between the outside part of the probe to the sampling line

	Electrical conductive (sample line material):	<input type="checkbox"/> Yes	<input checked="" type="checkbox"/> No Antistatic Viton
	Grounded:	<input checked="" type="checkbox"/> Yes	<input type="checkbox"/> No
	Grounding method:	_____	
	Backflushing sample line between measurements:	<input type="checkbox"/> Yes	<input checked="" type="checkbox"/> No it was stopped with the ready command
4.12 Sample probe Please fill in if applicable	Use of sample probe:	<input checked="" type="checkbox"/> Yes	<input type="checkbox"/> No (in situ,...)
	Acc. manufacturer specification:	<input checked="" type="checkbox"/> Yes	<input type="checkbox"/> No
	Material:	<input checked="" type="checkbox"/> Stainless steel	<input type="checkbox"/> Others: _____
	Type/design:	<input type="checkbox"/> Probe with single hole at the end (pipe) <input checked="" type="checkbox"/> Probe with single hole at the end (45° beveled) <input type="checkbox"/> Multi-hole <input type="checkbox"/> L-shaped pipe with single hole, opening shielded with preclassifier (e.g. hat) <input type="checkbox"/> Others: _____	
	Direction of the probe opening relative to the exhaust gas flow:	<input checked="" type="checkbox"/> With flow <input type="checkbox"/> Against flow (the probe opening was facing the flow) <input type="checkbox"/> Others: _____	
	Effective cross section of sample hole opening(s)	_____ 12.6 [mm ²]	
	Backflushing sample probe between measurements:	<input type="checkbox"/> Yes	<input checked="" type="checkbox"/> No

Sampling point and probe location

4.13 Sample point and probe location

- Engine Outlet
- Downstream heat exchanger
- Downstream exhaust gas treatment device
- Treatment device active during measurement: Yes No
- Others: _____
- Distance between engine outlet and sampling point: _____ [m]
- Diameter of the exhaust gas pipe: _____ [m]
- Type of exhaust gas pipe where the sample probe is located:
- Straight part of the exhaust gas pipe
- Bent part of the exhaust gas pipe
- Immersion depth of the sample probe: _____ in the centre of the exhaust duct [m]
- Orientation of the exhaust gas pipe where the sample probe is located:
- Horizontal Vertical Others:
- Length of straight part of the exhaust gas pipe, if sample probe is located at straight part of the exhaust gas pipe:
- Upstream sample probe: _____ [m]
- Downstream sample probe: _____ [m]
- Exhaust gas pulsation at the sampling point during measurement:
- No Yes [mbar]

4. Measurement equipment information (to be completed before measurement) and parameters

Measurement instrument

4.1 BC measurement instrument information

Make: AVL Model: MSSplus AVL Micro Soot Sensor

4.2 Measurement principle

- LII FSN PAS MAAP
- Others: _____

4.3 Values reported as

- EC (thermal) Protocol acc.: _____
- rBC

	<input checked="" type="checkbox"/> eBC <input type="checkbox"/> FSN <input type="checkbox"/> Others: _____								
4.4 Values reported in unit	<input type="checkbox"/> mg/mn3	(wet basis; act. O2-concentration)	H2O-conc.: _____ [Vol.-%] (wet)						
	<input type="checkbox"/> mg/mn3	(dry basis; act. O2-concentration)							
	<input checked="" type="checkbox"/> mg/mn3	(dry basis; Ref. O2-concentration)	O2-conc.: _____ [Vol.-%] (dry)						
	<input type="checkbox"/> mg/kWh	refer to 5.							
	<input type="checkbox"/> FSN								
	<input type="checkbox"/> mg/kg fuel	refer to 5.							
	<input type="checkbox"/> Others: _____								
4.5 Reference conditions	Norm temperature:	0 [°C]							
(only if 4.4 is referred to Norm-cubic meters [m ³])	Norm pressure:	1013 [mbar]							

4.6 Sampling time / -number	Sampling time of each measurement:	continuous on-line measurement	[second by second]						
	If mean values are reported: Number of consecutive measurements at each mode point:	_____	[-]						
	Acc. manufacturer specification:	<input checked="" type="checkbox"/> Yes	<input type="checkbox"/> No						
4.7 BC instrument parameter	Temperature inside measuring cell:	52	[°C]						
	Pressure inside measuring cell:	ambient ± 20	[mbar]						
	Wavelength(s) used:	808	[nm]						
	Mass absorption cross section(s) used:		[m ² /g]						
	Conversion equation(s) used:								
	Repeatability of the instrument used:	± 3.5%							
	Reproducibility of the instrument used:	± 6%							
	Acc. manufacturer specification:	<input checked="" type="checkbox"/> Yes	<input type="checkbox"/> No						
	Other parameters which could influence the measured values:								
	<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="width: 70%;">Parameter / Correction</th> <th style="width: 30%;">Unit</th> </tr> </thead> <tbody> <tr> <td> </td> <td> </td> </tr> <tr> <td> </td> <td> </td> </tr> </tbody> </table>			Parameter / Correction	Unit				
Parameter / Correction	Unit								
4.8 BC Instrument Calibration	Date of last calibration:	calibration performed by the manufacturer before the measuring campaign							
	Calibration procedure according manufacturer specification:								
	<input checked="" type="checkbox"/> Yes	<input type="checkbox"/> No	<input type="checkbox"/> Others: _____						
	Calibration including zero point:	<input type="checkbox"/> Yes	<input checked="" type="checkbox"/> No						

	Used medium for zero point calibration: _____			
	Used calibration standard:	<input checked="" type="checkbox"/> Synthetic flame soot		
		<input type="checkbox"/> Printex-U		
		<input type="checkbox"/> Graphite spark aerosol generator GfG soot		
		<input type="checkbox"/> Soot with inorganic coatings		
		<input type="checkbox"/> Soot without inorganic coatings		
		<input type="checkbox"/> Reflectance standards		
		<input type="checkbox"/> Others: _____		
	Remark: _____			
	Leakage test performed before or after calibration:	<input checked="" type="checkbox"/> Yes	<input type="checkbox"/> No <input type="checkbox"/> Not applicable	
4.9 Sample gas pre-treatment Please fill in if applicable	Exhaust gas dilution:	<input checked="" type="checkbox"/> Yes	<input type="checkbox"/> No	
	If yes, dilution ratio (1:x)	01:06	at mode point: 4-5,14, [Test point No.]	
		01:08	1-3, 6-13, 15-18, 21-22, 24-27	
		01:10	20, 23	
		01:12	19	
		_____	_____	
		_____	_____	
		_____	_____	
		Dilution medium:	<input checked="" type="checkbox"/> Ambient air	<input type="checkbox"/> Exhaust gas
			<input type="checkbox"/> Others: _____	
	Filtration of the dilution medium before dilution:	<input checked="" type="checkbox"/> Yes	<input type="checkbox"/> No	
	Temperature of the dilution medium:	_____ [°C]		
	Temperature of the diluted exhaust gas:	52 [°C]		
	Evaporation tube Temperature _____ [°C] acc. manufacturer spec.	<input type="checkbox"/> Yes	<input checked="" type="checkbox"/> No	
		<input type="checkbox"/> Yes	<input checked="" type="checkbox"/> No	
	Catalytic stripper Temperature _____ [°C] acc. manufacturer spec.	<input type="checkbox"/> Yes	<input checked="" type="checkbox"/> No	
		<input type="checkbox"/> Yes	<input checked="" type="checkbox"/> No	
	Thermo-denuder	<input type="checkbox"/> Yes	<input checked="" type="checkbox"/> No	
	Temperature _____ [°C] acc. manufacturer spec.	<input type="checkbox"/> Yes	<input checked="" type="checkbox"/> No	
	Others: _____			
4.10 Sample flow rate/volume	Acc. manufacturer specification:	<input checked="" type="checkbox"/> Yes	<input type="checkbox"/> No	
	Sample flow rate of the raw exhaust gas:	1.9	[l/min]	
	Sample flow rate of the diluted exhaust gas:	1.9	[l/min]	
	Sample volume of the raw exhaust gas:	_____	[l]	
	Sample volume of the diluted exhaust gas:	_____	[l]	
	<input type="checkbox"/> Subkinetic <input type="checkbox"/> Isokinetic <input type="checkbox"/> Superkinetic		<input checked="" type="checkbox"/> Not applicable	

Sample line and probe

4.11	Use of a sample line:	<input checked="" type="checkbox"/> Yes	<input type="checkbox"/> No (in situ,...)
Sample/transfer line			
Please fill in if applicable			
	Acc. manufacturer specification:	<input checked="" type="checkbox"/> Yes	<input type="checkbox"/> No
	Length of the sample line:	<u>2</u> [m]	
	Heated sample line:	<input checked="" type="checkbox"/> Yes <input type="checkbox"/> No	Temperature: <u>52</u> [°C]
	Sample line material:	<u>carbon impregnated Teflon</u>	
	Inner diameter of the sample line:	4.8 [mm]	
	insulated or heated connections between sample line, measurement instrument and probe:	<input checked="" type="checkbox"/> Yes - between sampling line and instrument	<input checked="" type="checkbox"/> No - between the outside part of the probe to the sampling line
	Electrical conductive (sample line material):	<input checked="" type="checkbox"/> Yes	<input type="checkbox"/> No
	Grounded:	<input checked="" type="checkbox"/> Yes	<input type="checkbox"/> No
	Grounding method:	_____	
	Backflushing sample line between measurements:	<input type="checkbox"/> Yes	<input checked="" type="checkbox"/> No
4.12	Use of sample probe:	<input checked="" type="checkbox"/> Yes	<input type="checkbox"/> No (in situ,...)
Sample probe			
Please fill in if applicable			
	Acc. manufacturer specification:	<input checked="" type="checkbox"/> Yes	<input type="checkbox"/> No
	Material:	<input checked="" type="checkbox"/> Stainless steel	<input type="checkbox"/> Others: _____
Type/design:			
<input type="checkbox"/> Probe with single hole at the end (pipe)			
<input checked="" type="checkbox"/> Probe with single hole at the end (45° beveled)			
<input type="checkbox"/> Multi-hole			
<input type="checkbox"/> L-shaped pipe with single hole, opening shielded with preclassifier (e.g. hat)			
<input type="checkbox"/> Others: _____			
Direction of the probe opening relative to the exhaust gas flow:			
<input checked="" type="checkbox"/> With flow <input type="checkbox"/> Against flow			
(the probe opening was facing the flow)			
<input type="checkbox"/> Others: _____			
	Effective cross section of sample hole opening(s)	<u>12.5</u> [mm ²]	

Backflushing sample probe between measurements:	<input type="checkbox"/> Yes <input checked="" type="checkbox"/> No
Sampling point and probe location	
4.13 Sample point and probe location	<input type="checkbox"/> Engine Outlet <input type="checkbox"/> Downstream heat exchanger <input type="checkbox"/> Downstream exhaust gas treatment device Treatment device active during measurement: <input type="checkbox"/> Yes <input type="checkbox"/> No <input type="checkbox"/> Others: _____
Distance between engine outlet and sampling point:	_____ [m]
Diameter of the exhaust gas pipe:	_____ [m]
Type of exhaust gas pipe where the sample probe is located:	
<input checked="" type="checkbox"/> Straight part of the exhaust gas pipe	
<input type="checkbox"/> Bent part of the exhaust gas pipe	
Immersion depth of the sample probe:	_____ in the centre of the exhaust duct [m]
Orientation of the exhaust gas pipe where the sample probe is located:	
<input checked="" type="checkbox"/> Horizontal <input type="checkbox"/> Vertical <input type="checkbox"/> Others: _____	
Length of straight part of the exhaust gas pipe, if sample probe is located at straight part of the exhaust gas pipe:	
Upstream sample probe:	_____ [m]
Downstream sample probe:	_____ [m]
Exhaust gas pulsation at the sampling point during measurement:	
<input checked="" type="checkbox"/> No <input type="checkbox"/> Yes _____ [mbar]	

4. Measurement equipment information (to be completed before measurement) and parameters			
Measurement instrument			
4.1 BC measurement instrument information	Make:	Artium	Model: LII300
	s/n:	0574	_____
4.2 Measurement principle	<input checked="" type="checkbox"/> LII	<input type="checkbox"/> FSN	<input type="checkbox"/> PAS <input type="checkbox"/> MAAP
	<input type="checkbox"/> Others: _____		

4.3 Values reported as	<input type="checkbox"/> EC (thermal) <input checked="" type="checkbox"/> rBC <input type="checkbox"/> eBC <input type="checkbox"/> FSN <input type="checkbox"/> Others: _____	Protocol acc.: _____
4.4 Values reported in unit	<input checked="" type="checkbox"/> mg/m _n ³ (wet basis; act. O ₂ -concentration) <input type="checkbox"/> mg/m _n ³ (dry basis; act. O ₂ -concentration) <input type="checkbox"/> mg/m _n ³ (dry basis; Ref. O ₂ -concentration) <input type="checkbox"/> mg/kWh refer to 5. <input type="checkbox"/> FSN <input type="checkbox"/> mg/kg fuel refer to 5. <input type="checkbox"/> Others: _____	H ₂ O- n/a [Vol.-%] conc.: _____ (wet) O ₂ -conc.: n/a [Vol.-%] _____ (dry)
4.5 Reference conditions	Norm temperature:	0 [°C]
(only if 4.4 is referred to Norm-cubic meters [m _n ³])	Norm pressure:	1013 [mbar]
4.6 Sampling time / -number	Sampling time of each measurement:	0.05 [s]
	If mean values are reported: Number of consecutive measurements at each mode point:	6000-72000 [-]
	Acc. manufacturer specification:	<input checked="" type="checkbox"/> Yes <input type="checkbox"/> No
4.7 BC instrument parameter	Temperature inside measuring cell:	heated to 100 [°C]
	Pressure inside measuring cell:	999 [mbar]
	Wavelength(s) used:	442 and 716 [nm]

	Mass absorption cross section(s) used:	9.0 and 5.5	[m ² /g]
	Conversion equation(s) used:	Snelling Applied Optics 2005, v44(31)	
	Repeatability of the instrument used:	2%	
	Reproducibility of the instrument used:	not reported	
	Acc. manufacturer specification:	<input checked="" type="checkbox"/> Yes <input type="checkbox"/> No	
	Other parameters which could influence the measured values:		
	Parameter / Correction		Unit
	calibration correlation factor = 0.68		unitless
	(see calibration note next page)		
4.8 BC Instrument Calibration	Date of last calibration:	02.09.2016	(dd.mm.yyyy)
	Calibration procedure according manufacturer specification:		
	<input type="checkbox"/> Yes	<input type="checkbox"/> No	<input checked="" type="checkbox"/> Others: SAE E-31 AIR6241
	Calibration including zero point:		
			<input type="checkbox"/> Yes <input checked="" type="checkbox"/> No
	Used medium for zero point calibration:		
	Used calibration standard:		
			<input checked="" type="checkbox"/> Synthetic flame soot
		<input type="checkbox"/> Printex-U	
		<input type="checkbox"/> Graphite spark aerosol generator GfG soot	
		<input type="checkbox"/> Soot with inorganic coatings	
		<input type="checkbox"/> Soot without inorganic coatings	
		<input type="checkbox"/> Reflectance standards	
		<input type="checkbox"/> Others: _____	
Remark:		miniCAST 5201C C3H8 = 53 mL/min, air = 1.6 lpm, N2 = 0 mL/min, quench 7 lpm, dilution air 20 lpm	
Leakage test performed before or after calibration: <input type="checkbox"/> yes <input type="checkbox"/> no <input checked="" type="checkbox"/> not applicable			
4.9 Sample gas pre-treatment Please fill in if applicable	Exhaust gas dilution:	<input type="checkbox"/> Yes	<input checked="" type="checkbox"/> No
	If yes, dilution ratio (1:x)	at mode point: _____ [%]	
		_____	_____
		_____	_____
		_____	_____
		_____	_____
		_____	_____
		_____	_____
Dilution medium:	<input type="checkbox"/> Ambient air	<input type="checkbox"/> Exhaust gas	
	<input type="checkbox"/> Others: _____		
Filtration of the dilution medium before dilution:			<input type="checkbox"/> Yes <input checked="" type="checkbox"/> No

	Temperature of the dilution medium:	_____	[°C]
	Temperature of the diluted exhaust gas:	_____	[°C]
	Evaporation tube Temperature	_____	<input type="checkbox"/> Yes <input checked="" type="checkbox"/> No [°C] acc. manufacturer spec.
	Catalytic stripper Temperature	_____	<input type="checkbox"/> Yes <input checked="" type="checkbox"/> No [°C] acc. manufacturer spec.
	Thermo-denuder Temperature	_____	<input type="checkbox"/> Yes <input checked="" type="checkbox"/> No [°C] acc. manufacturer spec.
	Others:	_____	
4.10 Sample flow rate/volume	Acc. manufacturer specification:		<input checked="" type="checkbox"/> Yes <input type="checkbox"/> No
	Sample flow rate of the raw exhaust gas:	_____	5 [l/min]
	Sample flow rate of the diluted exhaust gas:	_____	n/a [l/min]
	Sample volume of the raw exhaust gas:	_____	n/a [l]
	Sample volume of the diluted exhaust gas:	_____	n/a [l]
	<input type="checkbox"/> Subkinetic <input type="checkbox"/> Isokinetic <input type="checkbox"/> Superkinetic		<input checked="" type="checkbox"/> Not applicable
Sample line and probe			
4.11 Sample/transfer line Please fill in if applicable	Use of a sample line:		<input checked="" type="checkbox"/> Yes <input type="checkbox"/> No (in situ,...)
	Acc. manufacturer specification:		<input checked="" type="checkbox"/> Yes <input type="checkbox"/> No
	Length of the sample line:	_____ 3 _____	[m]
	Heated sample line:	<input checked="" type="checkbox"/> Yes <input type="checkbox"/> No	Temp.: _____ 100 _____ [°C]
	Sample line material:	_____ Carbon impregnated teflon _____	
	Inner diameter of the sample line:	_____ 8.00 _____	[mm]

	Insulated Isolated or heated connections between sample line, measurement instrument and probe	<input checked="" type="checkbox"/> Yes	<input type="checkbox"/> no	
		line and instrument		
	Electrical conductive (sample line material):	<input checked="" type="checkbox"/> yes	<input type="checkbox"/> no	
	Grounded:	<input checked="" type="checkbox"/> yes	<input type="checkbox"/> no	
	Grounding method:	Metal fittings at both ends connect to exhaust tube & instrument chassis		
	Backflushing sample line between measurements:	<input type="checkbox"/> Yes	<input checked="" type="checkbox"/> No	
4.12 Sample probe	Use of sample probe:	<input checked="" type="checkbox"/> Yes	<input type="checkbox"/> No (in situ,...)	
	Please fill in if applicable			
	Acc. manufacturer specification:	<input type="checkbox"/> Yes	<input type="checkbox"/> No	<input checked="" type="checkbox"/> n/a
	Material:	<input checked="" type="checkbox"/> Stainless steel	<input type="checkbox"/> Others:	_____
	Type/design:			
	<input type="checkbox"/> Probe with single hole at the end (pipe)			
	<input checked="" type="checkbox"/> Probe with single hole at the end (45° beveled)			
	<input type="checkbox"/> Multi-hole			
	<input type="checkbox"/> L-shaped pipe with single hole, opening shielded with preclassifier (e.g. hat)			
	<input type="checkbox"/> Others:	_____		
	Direction of the probe opening relative to the exhaust gas flow:			
	<input type="checkbox"/> With flow	<input type="checkbox"/> Against flow		
	<input checked="" type="checkbox"/> Others:	90° to flow with bevel opening facing flow		
	Effective cross section of sample hole opening(s)		50.3	[mm ²]
	Are effective cross sections meant to be the cross section the flow sees or the surface area of the hole in the plane of the cut?			
This is a repeat of row 117	Backflushing sample probe between measurements:	<input type="checkbox"/> yes	<input type="checkbox"/> no	

Sampling point and probe location

4.13 Sample point and probe location

Engine Outlet

Downstream heat exchanger

Downstream exhaust gas treatment device

Treatment device active during measurement:

Yes No

Others: _____

Distance between engine outlet and sampling point: _____

3 [m]

Diameter of the exhaust gas pipe: _____

0.1 [m]

Type of exhaust gas pipe where the sample probe is located:

Straight part of the exhaust gas pipe

Bent part of the exhaust gas pipe

Immersion depth of the sample probe: _____

in the centre of the exhaust duct [m]

Orientation of the exhaust gas pipe where the sample probe is located:

Horizontal

Vertical

Others: _____

Length of straight part of the exhaust gas pipe,

if sample probe is located at straight part of the exhaust gas pipe:

Does this mean the length of straight pipe upstream/downstream of sampling point?

Upstream sample probe: _____

3 [m]

Downstream sample probe: _____

4 [m]

Exhaust gas pulsation at the sampling point during measurement:

No

Yes

unknown [mbar]

4. Measurement equipment information (to be completed before measurement) and parameters

Measurement instrument

4.1 BC measurement instrument

Make: Artium Model: LII300
s/n: 0331

4.2 Measurement principle

LII
 FSN PAS MAAP
 Others: _____

4.3 Values reported as

EC (thermal) Protocol acc.: _____
 rBC
 eBC
 FSN
 Others: _____

4.4 Values reported in unit

mg/m^3 (wet basis; act. O_2 -concentration) H_2O -conc.: _____ [Vol.-%] (wet)
 mg/m^3 (dry basis; act. O_2 -concentration)
 mg/m^3 (dry basis; Ref. O_2 -concentration) O_2 -conc.: n/a [Vol.-%] (dry)
 mg/kWh refer to 5.
 FSN
 mg/kg fuel refer to 5.
 Others: _____

4.5 Reference conditions

Norm temperature: 0 [°C]

(only if 4.4 is referred to Norm-cubic meters [m^3])

Norm pressure: 1013 [mbar]

4.6 Sampling time / -number

Sampling time of each measurement: 0.05 [s]
If mean values are reported: Number of consecutive measurements at each mode point: 6000-72000 [-]
Acc. manufacturer specification: Yes No

4.7 BC instrument parameter

Temperature inside measuring cell: 24-46 [°C]
Pressure inside measuring cell: 1013.5 [mbar]
Wavelength(s) used: 442 and 716 [nm]

	Mass absorption cross section(s) used: <u>9.0 and 5.5</u> [m ² /g]						
	Conversion equation(s) used: <u>Snelling Applied Optics 2005, v44(31)</u>						
	Repeatability of the instrument used: <u>2%</u>						
	Reproducibility of the instrument used: <u>not reported</u>						
	Acc. manufacturer specification: <input checked="" type="checkbox"/> Yes <input type="checkbox"/> No						
	Other parameters which could influence the measured values:						
	<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="width: 80%;">Parameter / Correction</th> <th style="width: 20%;">Unit</th> </tr> </thead> <tbody> <tr> <td>calibration correlation factor = 0.79</td> <td>unitless</td> </tr> <tr> <td>(see calibration note next page)</td> <td></td> </tr> </tbody> </table>	Parameter / Correction	Unit	calibration correlation factor = 0.79	unitless	(see calibration note next page)	
Parameter / Correction	Unit						
calibration correlation factor = 0.79	unitless						
(see calibration note next page)							
4.8 BC Instrument Calibration	Date of last calibration: <u>02.09.2016</u> (dd.mm.yyyy)						
	Calibration procedure according manufacturer specification:						
	<input type="checkbox"/> Yes <input type="checkbox"/> No <input checked="" type="checkbox"/> Others: <u>SAE E-31 AIR6241</u>						
	Calibration including zero point: <input type="checkbox"/> Yes <input checked="" type="checkbox"/> No						
	Used medium for zero point calibration: _____						
	Used calibration standard: <input checked="" type="checkbox"/> Synthetic flame soot						
	<input type="checkbox"/> Printex-U						
	<input type="checkbox"/> Graphite spark aerosol generator GfG soot						
	<input type="checkbox"/> Soot with inorganic coatings						
	<input type="checkbox"/> Soot without inorganic coatings						
<input type="checkbox"/> Reflectance standards							
<input type="checkbox"/> Others: _____							
Remark: <u>miniCAST 5201C C3H8=53 mL/min, air=1.6 lpm, N2=0 mL/min</u>							
Leakage test performed before or after calibration: <input type="checkbox"/> yes <input type="checkbox"/> no <input checked="" type="checkbox"/> not applicable							
4.9 Sample gas pre-treatment Please fill in if applicable	Exhaust gas dilution: <input checked="" type="checkbox"/> Yes <input type="checkbox"/> No						
	If yes, dilution ratio (1:x) <u>1:8-1:24</u> at mode point: _____ [%]						
	<u>(varies)</u> _____						

	Dilution medium: <input type="checkbox"/> Ambient air <input type="checkbox"/> Exhaust gas						
	<input checked="" type="checkbox"/> Others: <u>Synthetic air</u>						
	Filtration of the dilution medium before dilution: <input type="checkbox"/> Yes <input checked="" type="checkbox"/> No						

	Temperature of the dilution medium:	50	[°C]
	Temperature of the diluted exhaust gas:	25-46	[°C]
	Evaporation tube Temperature	<input type="checkbox"/> Yes <input checked="" type="checkbox"/> No	[°C] acc. manufacturer spec. <input type="checkbox"/> Yes <input checked="" type="checkbox"/> No
	Catalytic stripper Temperature	<input type="checkbox"/> Yes <input checked="" type="checkbox"/> No	[°C] acc. manufacturer spec. <input type="checkbox"/> Yes <input checked="" type="checkbox"/> No
	Thermo-denuder Temperature	<input type="checkbox"/> Yes <input checked="" type="checkbox"/> No	[°C] acc. manufacturer spec. <input type="checkbox"/> Yes <input type="checkbox"/> No
	Others:		
4.10 Sample flow rate/volume	Acc. manufacturer specification:	<input checked="" type="checkbox"/> Yes	<input type="checkbox"/> No
	Sample flow rate of the raw exhaust gas:	n/a	[l/min]
	Sample flow rate of the diluted exhaust gas:	5	[l/min]
	Sample volume of the raw exhaust gas:	n/a	[l]
	Sample volume of the diluted exhaust gas:	n/a	[l]
	<input type="checkbox"/> Subkinetic <input type="checkbox"/> Isokinetic <input type="checkbox"/> Superkinetic	<input checked="" type="checkbox"/> Not applicable	
Sample line and probe			
4.11 Sample/transfer line	Use of a sample line:	<input checked="" type="checkbox"/> Yes	<input type="checkbox"/> No (in situ,...)
Please fill in if applicable	Acc. manufacturer specification:	<input checked="" type="checkbox"/> Yes	<input type="checkbox"/> No
With a dilution tunnel there is a heated line upstream of the dilution stage, the details of the tunnel, and a sampling line from the tunnel. The form only allows one sampling line to be documented.	Length of the sample line:	3	[m]
	Heated sample line:	<input type="checkbox"/> Yes <input checked="" type="checkbox"/> No	Temperature: _____ [°C]
	Sample line material:	Carbon impregnated silicone	
	Inner diameter of the sample line:	7.9	[mm]

	Insulated Isolated or heated connections between sample line, measurement instrument and probe	<input type="checkbox"/> Yes	<input checked="" type="checkbox"/> no
	Electrical conductive (sample line material):	<input checked="" type="checkbox"/> yes	<input type="checkbox"/> no
	Grounded:	<input checked="" type="checkbox"/> yes	<input type="checkbox"/> no
	Grounding method:	Connected to dilution tunnel & instrument	
	Backflushing sample line between measurements:	<input type="checkbox"/> Yes	<input checked="" type="checkbox"/> No
4.12 Sample probe	Use of sample probe:	<input checked="" type="checkbox"/> Yes	<input type="checkbox"/> No (in situ,...)
Please fill in if applicable	Acc. manufacturer specification:	<input type="checkbox"/> Yes	<input type="checkbox"/> No <input checked="" type="checkbox"/> n/a
	Material:	<input checked="" type="checkbox"/> Stainless steel	<input type="checkbox"/> Others: _____
There are two sampling probes; one in engine exhaust and one in sampling tunnel. The form does not allow for both to be documented. The sample probe from the tunnel is documented.	Type/design:	<input checked="" type="checkbox"/> Probe with single hole at the end (pipe) <input type="checkbox"/> Probe with single hole at the end (45° beveled) <input type="checkbox"/> Multi-hole <input type="checkbox"/> L-shaped pipe with single hole, opening shielded with preclassifier (e.g. hat)	
	<input type="checkbox"/> Others:	_____	
	Direction of the probe opening relative to the exhaust gas flow:	<input type="checkbox"/> With flow <input type="checkbox"/> Against flow <input checked="" type="checkbox"/> Others: 90° to flow	
Are effective cross sections meant to be the cross section the flow sees or the surface area of the hole in the plane of the cut?	Effective cross section of sample hole opening(s)	50.3	[mm ²]
This is a repeat of row 117	Backflushing sample probe between measurements:	<input type="checkbox"/> yes	<input type="checkbox"/> no

Sampling point and probe location

4.13 Sample point and probe location

Engine Outlet

Downstream heat exchanger

Downstream exhaust gas treatment device

Treatment device active during measurement:

Yes

No

Others: _____

Distance between engine outlet and sampling point: _____

3 [m]

Diameter of the exhaust gas pipe: _____

0.1 [m]

Type of exhaust gas pipe where the sample probe is located:

Straight part of the exhaust gas pipe

Bent part of the exhaust gas pipe

Immersion depth of the sample probe: _____

in the centre of the exhaust duct

[m]

Orientation of the exhaust gas pipe where the sample probe is located:

Horizontal

Vertical

Others: _____

Length of straight part of the exhaust gas pipe, if sample probe is located at straight part of the exhaust gas pipe:

Upstream sample probe: _____

3 [m]

Downstream sample probe: _____

4 [m]

Exhaust gas pulsation at the sampling point during measurement:

No

Yes

unknown

[mbar]

4. Measurement equipment information (to be completed before measurement) and parameters			
Measurement instrument			
4.1 BC measurement instrument	Make:	Droplet Meas. Tech.	Model: PAX 870
	s/n	PAX-870-P-1502-072	
4.2 Measurement principle	<input type="checkbox"/> LII	<input type="checkbox"/> FSN	<input checked="" type="checkbox"/> PAS <input type="checkbox"/> MAAP
	<input type="checkbox"/> Others:	_____	
4.3 Values reported as	<input type="checkbox"/> EC (thermal)	Protocol acc.: _____	
	<input type="checkbox"/> rBC		
	<input checked="" type="checkbox"/> eBC		
	<input type="checkbox"/> FSN		
	<input type="checkbox"/> Others:	_____	
4.4 Values reported in unit	<input checked="" type="checkbox"/> mg/m_n^3	(wet basis; act. O_2 -concentration)	H_2O -conc.: _____ [Vol.-%] (wet)
	<input type="checkbox"/> mg/m_n^3	(dry basis; act. O_2 -concentration)	
	<input type="checkbox"/> mg/m_n^3	(dry basis; Ref. O_2 -concentration)	O_2 -conc.: n/a [Vol.-%] (dry)
	<input type="checkbox"/> mg/kWh	refer to 5.	
	<input type="checkbox"/> FSN		
	<input type="checkbox"/> mg/kg fuel	refer to 5.	
	<input type="checkbox"/> Others:	_____	
4.5 Reference conditions	Norm temperature:	0 [°C]	
(only if 4.4 is referred to Norm-cubic meters [m_n^3])	Norm pressure:	1013 [mbar]	
4.6 Sampling time / -number	Sampling time of each measurement:	1	[s]
	If mean values are reported: Number of consecutive measurements at each mode point:	300-3600	[-]
	Acc. manufacturer specification:	<input checked="" type="checkbox"/> Yes	<input type="checkbox"/> No
4.7 BC instrument parameter	Temperature inside measuring cell:	25-46	[°C]
	Pressure inside measuring cell:	971-1005	[mbar]
	Wavelength(s) used:	870	[nm]

	Mass absorption cross section(s) used:	4.74 [m ² /g]
	Conversion equation(s) used:	Mass = abs coeff/ MAC
	Repeatability of the instrument used:	not reported
	Reproducibility of the instrument used:	not reported
	Acc. manufacturer specification:	<input checked="" type="checkbox"/> Yes <input type="checkbox"/> No
Other parameters which could influence the measured values:		
Parameter / Correction		Unit
calibration factor absorption: 3.6, cal factor scattering: 46273		unitless
(see calibration note next page)		
4.8 BC Instrument Calibration	Date of last calibration:	24.02.2016
		_____ (dd.mm.yyyy)
	Calibration procedure according manufacturer specification:	
	<input checked="" type="checkbox"/> Yes <input type="checkbox"/> No <input type="checkbox"/> Others:	_____
	Calibration including zero point:	<input checked="" type="checkbox"/> Yes <input type="checkbox"/> No
	Used medium for zero point calibration:	HEPA filtered air
Used calibration standard:	<input type="checkbox"/> Synthetic flame soot <input type="checkbox"/> Printex-U <input type="checkbox"/> Graphite spark aerosol generator GfG soot <input type="checkbox"/> Soot with inorganic coatings <input type="checkbox"/> Soot without inorganic coatings <input type="checkbox"/> Reflectance standards <input checked="" type="checkbox"/> Others: ammonium sulphate and inverted burner soot	
Remark:	_____	
	Leakage test performed before or after calibration:	<input type="checkbox"/> yes <input checked="" type="checkbox"/> no <input type="checkbox"/> not applicable
4.9 Sample gas pre-treatment Please fill in if applicable	Exhaust gas dilution:	<input checked="" type="checkbox"/> Yes <input type="checkbox"/> No
	If yes, dilution ratio (1:x)	1:8-1:24 at mode
		_____ point: _____ [%]
		(varies) _____

Dilution medium:	<input type="checkbox"/> Ambient air <input type="checkbox"/> Exhaust gas <input checked="" type="checkbox"/> Others: Synthetic air	
Filtration of the dilution medium before dilution:	<input type="checkbox"/> Yes <input checked="" type="checkbox"/> No	

	Temperature of the dilution medium:		50	[°C]
	Temperature of the diluted exhaust gas:		25-46	[°C]
	Evaporation tube Temperature	<input type="checkbox"/> Yes [°C] acc. manufacturer spec.	<input checked="" type="checkbox"/> No	<input type="checkbox"/> Yes <input checked="" type="checkbox"/> No
	Catalytic stripper Temperature	<input type="checkbox"/> Yes [°C] acc. manufacturer spec.	<input checked="" type="checkbox"/> No	<input type="checkbox"/> Yes <input checked="" type="checkbox"/> No
	Thermo-denuder Temperature	<input type="checkbox"/> Yes [°C] acc. manufacturer spec.	<input checked="" type="checkbox"/> No	<input type="checkbox"/> Yes <input type="checkbox"/> No
	Others:			
4.10 Sample flow rate/volume	Acc. manufacturer specification:		<input checked="" type="checkbox"/> Yes	<input type="checkbox"/> No
	Sample flow rate of the raw exhaust gas:		n/a	[l/min]
	Sample flow rate of the diluted exhaust gas:		1	[l/min]
	Sample volume of the raw exhaust gas:		n/a	[l]
	Sample volume of the diluted exhaust gas:		n/a	[l]
	<input type="checkbox"/> Subkinetic	<input type="checkbox"/> Isokinetic	<input type="checkbox"/>	<input checked="" type="checkbox"/> Not applicable
				Superkinetic
Sample line and probe				
4.11 Sample/transfer line	Use of a sample line:		<input checked="" type="checkbox"/> Yes	<input type="checkbox"/> No (in situ,...)
Please fill in if applicable	Acc. manufacturer specification:		<input checked="" type="checkbox"/> Yes	<input type="checkbox"/> No
With a dilution tunnel there is a heated line upstream of the dilution stage, the details of the tunnel, and a sampling line from the tunnel. The form only allows one.	Length of the sample line:	4.4	[m]	
	Heated sample line:	<input type="checkbox"/> Yes	Temperature	[°C]
		<input checked="" type="checkbox"/> No	:	
	Sample line material:	Carbon impregnated silicone		
	Inner diameter of the sample line:	7.874	[mm]	

	Insulation or heated connections between sample line, measurement instrument and probe:	<input type="checkbox"/> Yes	<input checked="" type="checkbox"/> no	
	Electrical conductive (sample line material):			<input checked="" type="checkbox"/> yes <input type="checkbox"/> no
	Grounded:	<input checked="" type="checkbox"/> yes	<input type="checkbox"/> no	
	Grounding method:	Connected to dilution tunnel and instrument		
	Backflushing sample line between measurements:	<input type="checkbox"/> Yes	<input checked="" type="checkbox"/> No	
4.12 Sample probe Please fill in if applicable	Use of sample probe:	<input checked="" type="checkbox"/> Yes	<input type="checkbox"/> No (in situ,...)	
	Acc. manufacturer specification:	<input type="checkbox"/> Yes	<input type="checkbox"/> No	<input checked="" type="checkbox"/> n/a
	Material:	<input checked="" type="checkbox"/> Stainless steel	<input type="checkbox"/> Others: _____	
	Type/design:	<input checked="" type="checkbox"/> Probe with single hole at the end (pipe) <input type="checkbox"/> Probe with single hole at the end (45° beveled) <input type="checkbox"/> Multi-hole <input type="checkbox"/> L-shaped pipe with single hole, opening shielded with preclassifier (e.g. hat) <input type="checkbox"/> Others: _____		
	Direction of the probe opening relative to the exhaust gas flow:	<input type="checkbox"/> With flow <input type="checkbox"/> Against flow <input checked="" type="checkbox"/> Others: 90° to flow _____		
	Effective cross section of sample hole opening(s)	50.3	[mm ²]	
	Backflushing sample probe between measurements:	<input type="checkbox"/> yes	<input type="checkbox"/> no	

Sampling point and probe location

4.13 Sample point and probe location

Engine Outlet

Downstream heat exchanger

Downstream exhaust gas treatment device

Treatment device active during measurement:

Yes

No

Others: _____

Distance between engine outlet and sampling point: _____

3 [m]

Diameter of the exhaust gas pipe: _____

0.1 [m]

Type of exhaust gas pipe where the sample probe is located:

Straight part of the exhaust gas pipe

Bent part of the exhaust gas pipe

Immersion depth of the sample probe: _____

in the centre of the exhaust duct

[m]

Orientation of the exhaust gas pipe where the sample probe is located:

Horizontal

Vertical

Others: _____

Length of straight part of the exhaust gas pipe, if sample probe is located at straight part of the exhaust gas pipe:

Upstream sample probe: _____

3 [m]

Downstream sample probe: _____

4 [m]

Exhaust gas pulsation at the sampling point during measurement:

No

Yes

unknown

[mbar]

4. Measurement equipment information (to be completed before measurement) and parameters			
Measurement instrument			
4.1 BC measurement instrument information	Make: <u>Sunset Laboratory</u>	Model: <u>5L</u>	
	s/n: <u>350-142</u>		
4.2 Measurement principle	<input type="checkbox"/> LII	<input type="checkbox"/> FSN	<input type="checkbox"/> PAS
	<input type="checkbox"/> MAAP		
	x Others: <u>Thermal-Optical Analysis</u>		
4.3 Values reported as	x EC (thermal)	Protocol acc.: <u>EUSAAR-2</u>	
	<input type="checkbox"/> rBC		
	<input type="checkbox"/> eBC		
	<input type="checkbox"/> FSN		
	<input type="checkbox"/> Others: _____		
4.4 Values reported in unit	X mg/m_n^3	(wet basis; act. O ₂ -concentration)	H ₂ O-conc.: _____ [Vol.-%] (wet)
	<input type="checkbox"/> mg/m_n^3	(dry basis; act. O ₂ -concentration)	
	<input type="checkbox"/> mg/m_n^3	(dry basis; Ref. O ₂ -concentration)	O ₂ -conc.: <u>n/a</u> [Vol.-%] (dry)
	<input type="checkbox"/> mg/kWh	refer to 5.	
	<input type="checkbox"/> FSN		
	<input type="checkbox"/> mg/kg fuel	refer to 5.	
	<input type="checkbox"/> Others: _____		
4.5 Reference conditions	Norm temperature:	0	[°C]
(only if 4.4 is referred to Norm-cubic meters [m_n^3])	Norm pressure:	1013	[mbar]
4.6 Sampling time / -number	Sampling time of each measurement:	<u>6000-72000</u>	[s]
	If mean values are reported: Number of consecutive measurements at each mode point:	<u>6000-72000</u>	[-]
	Acc. manufacturer specification:	x Yes	<input type="checkbox"/> No
4.7 BC instrument parameter	Temperature inside measuring cell:	<u>n/a</u>	[°C]
	Pressure inside measuring cell:	<u>n/a</u>	[mbar]
	Wavelength(s) used:	<u>n/a</u>	[nm]

	Mass absorption cross section(s) used:	<u>n/a</u>	[m ² /g]						
	Conversion equation(s) used:	<u>n/a</u>							
	Repeatability of the instrument used:	<u>5%+0.2</u>							
		<u>ug/cm2</u>							
	Reproducibility of the instrument used:	<u>not reported</u>							
	Acc. manufacturer specification:	<input checked="" type="checkbox"/> Yes	<input type="checkbox"/> No						
	Other parameters which could influence the measured values:								
	<table border="1"> <thead> <tr> <th>Parameter / Correction</th> <th>Unit</th> </tr> </thead> <tbody> <tr> <td>calibration factor = 20.07</td> <td>unitless</td> </tr> <tr> <td>(see calibration note next page)</td> <td></td> </tr> </tbody> </table>		Parameter / Correction	Unit	calibration factor = 20.07	unitless	(see calibration note next page)		
Parameter / Correction	Unit								
calibration factor = 20.07	unitless								
(see calibration note next page)									
4.8 BC Instrument Calibration	Date of last calibration:	<u>12.10.2016</u>	(dd.mm.yyyy)						
	Calibration procedure according manufacturer specification:								
	<input checked="" type="checkbox"/> Yes	<input type="checkbox"/> No	<input type="checkbox"/> Others: _____						
	Calibration including zero point:								
		<input type="checkbox"/> Yes	<input checked="" type="checkbox"/> No						
	Used medium for zero point calibration:								
		<u>blank filter</u>							
	Used calibration standard:								
		<input type="checkbox"/> Synthetic flame soot <input type="checkbox"/> Printex-U <input type="checkbox"/> Graphite spark aerosol generator GfG soot <input type="checkbox"/> Soot with inorganic coatings <input type="checkbox"/> Soot without inorganic coatings <input type="checkbox"/> Reflectance standards <input checked="" type="checkbox"/> Others: <u>sucrose</u>							
	Remark: _____								
Leakage test performed before or after calibration: <input type="checkbox"/> yes <input type="checkbox"/> no <input checked="" type="checkbox"/> not applicable									
4.9 Sample gas pre-treatment Please fill in if applicable	Exhaust gas dilution:	<input checked="" type="checkbox"/> Yes	<input type="checkbox"/> No						
	If yes, dilution ratio (1:x)	<u>1:8-1:24</u>	at mode point: _____ [%]						
		<u>(varies)</u>	_____						
		_____	_____						
		_____	_____						
		_____	_____						
	Dilution medium:								
		<input type="checkbox"/> Ambient air	<input type="checkbox"/> Exhaust gas						
		<input checked="" type="checkbox"/> Others:	<u>Synthetic air</u>						
	Filtration of the dilution medium before dilution: <input type="checkbox"/> Yes <input checked="" type="checkbox"/> No								

	Temperature of the dilution medium:		<u>50</u>	[°C]	
	Temperature of the diluted exhaust gas:		<u>25-46</u>	[°C]	
	Evaporation tube Temperature	<input type="checkbox"/> Yes [°C] acc. manufacturer spec.	<input checked="" type="checkbox"/> No	<input type="checkbox"/> Yes <input checked="" type="checkbox"/> No	
	Catalytic stripper Temperature	<input type="checkbox"/> Yes [°C] acc. manufacturer spec.	<input checked="" type="checkbox"/> No	<input type="checkbox"/> Yes <input checked="" type="checkbox"/> No	
	Thermo-denuder Temperature	<input type="checkbox"/> Yes [°C] acc. manufacturer spec.	<input checked="" type="checkbox"/> No	<input type="checkbox"/> Yes <input type="checkbox"/> No	
	Others:	<hr/>			
4.10 Sample flow rate/volume	Acc. manufacturer specification:		<input checked="" type="checkbox"/> Yes	<input type="checkbox"/> No	
	Sample flow rate of the raw exhaust gas:		<u>n/a</u>	[l/min]	
	Sample flow rate of the diluted exhaust gas:		<u>4.4,</u> <u>11.0</u>	[l/min]	
	Sample volume of the raw exhaust gas:		<u>n/a</u>	[l]	
	Sample volume of the diluted exhaust gas:		<u>n/a</u>	[l]	
	<input type="checkbox"/> Subkinetic	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/> Not applicable	
		Isokinetic	Superkinetic		
Sample line and probe					
4.11 Sample/transfer line Please fill in if applicable	Use of a sample line:		<input checked="" type="checkbox"/> Yes	<input type="checkbox"/> No (in situ,...)	
	Acc. manufacturer specification:		<input checked="" type="checkbox"/> Yes	<input type="checkbox"/> No	
	Length of the sample line:	<u>1.2</u>	[m]		
	Heated sample line:	<input type="checkbox"/> Yes	Temperature	[°C]	
		<input checked="" type="checkbox"/> No	:	<u> </u>	
	Sample line material:	<u>Carbon impregnated silicone</u>			
	Inner diameter of the sample line:	<u>7.9</u>	[mm]		

	Insulated or heated connections between sample line, measurement instrument and probe:	<input type="checkbox"/> Yes	<input checked="" type="checkbox"/> no
	Electrical conductive (sample line material):	<input checked="" type="checkbox"/> yes	<input type="checkbox"/> no
	Grounded:	<input checked="" type="checkbox"/> yes	<input type="checkbox"/> no
	Grounding method:	Connected to dilution tunnel and instrument	
	Backflushing sample line between measurements:	<input type="checkbox"/> Yes	<input checked="" type="checkbox"/> No
4.12 Sample probe Please fill in if applicable	Use of sample probe:	<input checked="" type="checkbox"/> Yes	<input type="checkbox"/> No (in situ,...)
	Acc. manufacturer specification:	<input type="checkbox"/> Yes	<input type="checkbox"/> No <input checked="" type="checkbox"/> n/a
	Material:	<input checked="" type="checkbox"/> Stainless steel	<input type="checkbox"/> Others: _____
	Type/design:	<input checked="" type="checkbox"/> Probe with single hole at the end (pipe) <input type="checkbox"/> Probe with single hole at the end (45° beveled) <input type="checkbox"/> Multi-hole <input type="checkbox"/> L-shaped pipe with single hole, opening shielded with preclassifier (e.g. hat) <input type="checkbox"/> Others: _____	
	Direction of the probe opening relative to the exhaust gas flow:	<input type="checkbox"/> With flow <input type="checkbox"/> Against flow <input checked="" type="checkbox"/> Others: 90° to flow	
	Effective cross section of sample hole opening(s)	50.3	[mm ²]
	Backflushing sample probe between measurements:	<input type="checkbox"/> yes	<input type="checkbox"/> no

Sampling point and probe location

4.13 Sample point and probe location

Engine Outlet

Downstream heat exchanger

Downstream exhaust gas treatment device

Treatment device active during measurement:

Yes

No

Others: _____

Distance between engine outlet and sampling point: _____

3 [m]

Diameter of the exhaust gas pipe: _____

0.1 [m]

Type of exhaust gas pipe where the sample probe is located:

Straight part of the exhaust gas pipe

Bent part of the exhaust gas pipe

Immersion depth of the sample probe: _____

centre duct [m]

Orientation of the exhaust gas pipe where the sample probe is located:

Horizontal

Vertical

Others: _____

Length of straight part of the exhaust gas pipe,

if sample probe is located at straight part of the exhaust gas pipe:

Upstream sample probe: _____

3 [m]

Downstream sample probe: _____

4 [m]

Exhaust gas pulsation at the sampling point during measurement:

No

Yes

unknown [mbar]

5. Determination of engine load, exhaust gas flow, exhaust water content, fuel mass flow, O₂ and CO₂

(if applicable)

5.1 Determination of values, instrument performance and calibration shall be in accordance with the requirements of NOx Technical Code 2008 (NTC 2008) and its applicable appendices

5.2.1 Method of load determination Multiplication of speed and moment

5.2.2 Estimated accuracy of engine load determination +/- _____ [%] of reading

5.3.1 Method of exhaust gas flow determination Addition of fuel and air

5.3.2 Estimated accuracy of exhaust gas flow determination +/- _____ [%] of reading

5.4.1 Method of exhaust water content determination Calculated over fuel analysis

5.4.2 Estimated accuracy of exhaust water content determination +/- _____ [%] of reading

5.5.1 Method of fuel mass flow determination Coriolis mass flow meter

5.5.2 Estimated accuracy of fuel mass flow determination +/- _____ [%] of reading

5.6.1 Method of O₂ and CO₂ determination Paramagnetism and non dispersive infrared

5.6.2 Estimated accuracy of O₂ and CO₂ determination +/- _____ [%] of reading

6. Measured values for BC determination (to be completed during measurement; measured values)

Test Point	6	7	10	11	21	
Date of measurement	18.07.2016	18.07.2016	19.07.2016	19.07.2016	21.07.2016	[dd.mm.yyyy]
Time of measurement	15:17	13:36	16:10	14:36	13:12	[hh:mm]
Time on Setpoint	60	60	60	60	60	[min]

Engine parameters

these cells replaced by the nominal speed and load cells below.

Measurement at mode points:						[%]
	↓	↓	↓	↓	↓	

6.1 Stabilized mode point

Target Speed	1500	1365	1500	1500	1500	[rpm]
Actual Speed	1500	1365	1500	1500	1500	[rpm]
Speed variation during measuring						+/- [%]

Target Load	100	75	100	75	50	%
Actual Load	76	57	76	57	38	[kW]
Load variation during measuring						+/- [%]

6.2 Charge air temperature	45	35	45	40	35	[°C]
-----------------------------------	----	----	----	----	----	------

6.3 Charge air pressure	3060	2600	3060	2415	1908	[mbar]
--------------------------------	------	------	------	------	------	--------

6.4 Exhaust gas temp. at engine outlet	502	473	503	488	390	[°C]
---	-----	-----	-----	-----	-----	------

6.5 Exh. gas temp. at sampling point	490	435	492	449	466	[°C]
---	-----	-----	-----	-----	-----	------

(only if there is a significant difference to the exhaust gas temperature at the engine outlet)

6.6 Exhaust gas back pressure	2480	2160	2470	2070	1676	[mbar]
--------------------------------------	------	------	------	------	------	--------

6.7 Exhaust gas mass flow	568	433	570	447	366	[kg/h]
----------------------------------	-----	-----	-----	-----	-----	--------

Ambient conditions

6.8 Ambient temp. at engine inlet						[°C]
--	--	--	--	--	--	------

6.9 Ambient pressure at engine inlet						[mbar]
---	--	--	--	--	--	--------

6.10 Absolute humidity of ambient air						[g/kg]
--	--	--	--	--	--	--------

7. Black Carbon						
Test Point	6		Sample Acquisition Time (min)			60
Instrument	415SE	MSS	LII300-1	LII300-2	PAX	TOA EC
Reported as (see 4.3)	eBC	eBC	rBC	rBC	eBC	EC
Units (see 4.4)	mg/m ³	mg/m ³	mg/m ³	mg/m ³	mg/m ³	mg/m ³
7.1 Estimated accuracy of measured value	n/a	n/a	n/a	n/a	n/a	n/a
7.2 Black Carbon emission	13.5	12.0	13.7	7.0	11.7	8.5
Remarks:	Uncertainty of BC readings is not known for this engine/fuels. Uncertainty of dilution for MSS is 6% and for LII-2, PAX, TOA EC is +18%/-5%.					
8. Measurement repeatability Indicators						
8.1 95% confidence interval (+/- unit measured)	n/a	n/a	n/a	n/a	n/a	n/a
8.2 Variance	n/a	n/a	n/a	n/a	n/a	n/a
8.3 Sample size (number of measurements taken)	1	1	1	1	1	1
7. Black Carbon						
Test Point	7		Sample Acquisition Time (min)			60
Instrument	415SE	MSS	LII300-1	LII300-2	PAX	TOA EC
Reported as (see 4.3)	mg/m ³	mg/m ³	mg/m ³	mg/m ³	mg/m ³	mg/m ³
Units (see 4.4)						
7.1 Estimated accuracy of measured value	n/a	n/a	n/a	n/a	n/a	n/a
7.2 Black Carbon emission	6.2	6.3	5.8	3.0	5.3	3.8
Remarks:	Uncertainty of BC readings is not known for this engine/fuels. Uncertainty of dilution for MSS is 6% and for LII-2, PAX, TOA EC is +18%/-5%.					
8. Measurement repeatability Indicators						
8.1 95% confidence interval (+/- unit measured)	n/a	n/a	n/a	n/a	n/a	n/a
8.2 Variance	n/a	n/a	n/a	n/a	n/a	n/a
8.3 Sample size (number of measurements taken)	1	1	1	1	1	1

7. Black Carbon						
Test Point	10	Sample Acquisition Time (min)				60
Instrument	415SE	MSS	LII300-1	LII300-2	PAX	TOA EC
Reported as (see 4.3)	eBC	eBC	rBC	rBC	eBC	EC
Units (see 4.4)	mg/m ³	mg/m ³	mg/m ³	mg/m ³	mg/m ³	mg/m ³
7.1 Estimated accuracy of measured value	n/a	n/a	n/a	n/a	n/a	n/a
7.2 Black Carbon emission	6.4	6.8	8.5	3.1	6.0	3.8
Remarks:	Uncertainty of BC readings is not known for this engine/fuels. Uncertainty of dilution for MSS is 6% and for LII-2, PAX, TOA EC is +18%/-5%.					
8. Measurement repeatability Indicators						
8.1 95% confidence interval (+/- unit measured)	n/a	n/a	n/a	n/a	n/a	n/a
8.2 Variance	n/a	n/a	n/a	n/a	n/a	n/a
8.3 Sample size (number of measurements taken)	1	1	1	1	1	1
7. Black Carbon						
Test Point	11	Sample Acquisition Time (min)				60
Instrument	415SE	MSS	LII300-1	LII300-2	PAX	TOA EC
Reported as (see 4.3)	eBC	eBC	rBC	rBC	eBC	EC
Units (see 4.4)	mg/m ³	mg/m ³	mg/m ³	mg/m ³	mg/m ³	mg/m ³
7.1 Estimated accuracy of measured value	n/a	n/a	n/a	n/a	n/a	n/a
7.2 Black Carbon emission	6.1	7.0	7.3	2.9	5.8	3.6
Remarks:	Uncertainty of BC readings is not known for this engine/fuels. Uncertainty of dilution for MSS is 6% and for LII-2, PAX, TOA EC is +18%/-5%.					
8. Measurement repeatability Indicators						
8.1 95% confidence interval (+/- unit measured)	n/a	n/a	n/a	n/a	n/a	n/a
8.2 Variance	n/a	n/a	n/a	n/a	n/a	n/a
8.3 Sample size (number of measurements taken)	1	1	1	1	1	1

7. Black Carbon						
Test Point	21		Sample Acquisition Time (min)			60
Instrument	415SE	MSS	LII300-1	LII300-2	PAX	TOA EC
Reported as (see 4.3)	eBC	eBC	rBC	rBC	eBC	EC
Units (see 4.4)	mg/m _n ³	mg/m _n ³	mg/m _n ³	mg/m _n ³	mg/m _n ³	mg/m _n ³
7.1 Estimated accuracy of measured value	n/a	n/a	n/a	n/a	n/a	n/a
7.2 Black Carbon emission	7.3	4.6	2.3	1.5	3.8	2.9
Remarks:	Uncertainty of BC readings is not known for this engine/fuels. Uncertainty of dilution for MSS is 6% and for LII-2, PAX, TOA EC is +18%/-5%.					
8. Measurement repeatability Indicators						
8.1 95% confidence interval (+/- unit measured)	n/a	n/a	n/a	n/a	n/a	n/a
8.2 Variance	n/a	n/a	n/a	n/a	n/a	n/a
8.3 Sample size (number of measurements taken)	1	1	1	1	1	1

SUB-COMMITTEE ON POLLUTION
PREVENTION AND RESPONSE
4th session
Agenda item 9

PPR 4/9/4
11 November 2016
Original: ENGLISH

CONSIDERATION OF THE IMPACT ON THE ARCTIC OF EMISSIONS OF BLACK CARBON FROM INTERNATIONAL SHIPPING

Results of a multi-instrument Black Carbon measurement campaign

Submitted by Canada and Germany

SUMMARY

Executive summary: This document summarizes the preliminary results of a joint Black Carbon measurement campaign jointly performed by Germany and Canada. The Black Carbon measurements were carried out with a variety of Black Carbon measuring instruments and different fuel types on a test engine in the laboratory.

Strategic direction: 7.3

High-level action: 7.3.2

Output: 7.3.2.2

Action to be taken: Paragraph 28

Related documents: MEPC 62/24; MEPC 67/12, MEPC 67/12/4, MEPC 67/12/8, MEPC 67/20, MEPC 67/INF.31; MEPC 68/12/2, MEPC 68/12/5, MEPC 68/12/9, MEPC 68/21; BLG 16/16; BLG 17/18; PPR 1/16; PPR 2/8, PPR 2/21, PPR 2/INF.5; PPR 3/8, PPR 3/8/1, PPR 3/22, PPR 3/INF.6, PPR 3/INF.7; and PPR 4/INF.9

Background

1 MEPC 62 agreed to a work plan to consider the impact on the Arctic of Black Carbon emissions from international shipping and instructed the Sub-Committee on Bulk Liquids and Gases (now PPR) to undertake this work by: developing a definition of Black Carbon (BC); identifying the most appropriate measurement method(s) for international shipping; and investigating appropriate control measures. MEPC 68 approved the Bond et al. definition of BC proposed by PPR 2 and noted the need for the development of protocols and further study to collect data in order to identify the most appropriate measurement method(s) of BC emissions from international shipping (MEPC 68/21, paragraphs 3.26 to 3.28).

2 At PPR 3, Germany and EUROMOT (PPR 3/8) proposed a harmonized measurement reporting protocol for voluntary BC measurement campaigns. The Sub-Committee invited interested Member Governments and international organizations to use the protocol and submit data derived from its application to PPR 4 (PPR 3/22).

3 This document describes the results of a German-led research campaign to measure BC emissions from a ship engine in the laboratory. The description of engine, fuel types, instruments and the different tests performed during the measurement campaign is presented in a second submission (PPR 4/INF.9).

Introduction

4 This BC measurement campaign responds to the call at PPR 2 (PPR 2/21) for additional BC measurement studies and the subsequent call at PPR 3 for data on the use of the proposed measurement reporting protocol (PPR 3/22). The document presents the results of a joint Germany and Canada BC measurement campaign performed in July 2016 at the University of Rostock, Germany. The measurement campaign was funded by the German Federal Ministry for the Environment (BMUB), the German Federal Environment Agency (UBA) and Transport Canada. The measurement campaign was performed by the University of Rostock (Germany) and the National Research Council (Canada) and was assisted by Marena Ltd., CE Delft and the Öko-Institut.

5 The goal of the project was to carry out simultaneous Black Carbon measurements on a ship engine, allowing for different bunker fuel types, engine ratings and different measurement methods. The specific objectives of the BC measurement campaign were to:

- .1 assess the comparability of six BC measurement instruments applied and to compare with similar campaigns;
- .2 assess the effect of different fuels and engine conditions on BC measurement using various methods; and
- .3 report on the research team's experience using the EUROMOT measurement reporting protocol.

Description of the Black Carbon measurement campaign

6 In the report of PPR 2 to MEPC (PPR 2/21, paragraph 8.5.3), four different measurement methods were identified as example methods to measure BC: Photo Acoustic Spectroscopy (PAS), Multi Angle Absorption Photometry (MAAP), Laser Induced Incandescence (LII) and Filter Smoke Number (FSN). PAS, MAAP and FSN measure equivalent BC (eBC), while LII measures refractory BC (rBC). In this campaign, FSN, LII, PAS and also Thermal-Optical Analysis (TOA) and will report elemental carbon (EC) were used.

Results and discussion

Comparability of the different instruments

7 In order to compare the different BC instruments and measurement methods in a marine context, all test points, regardless of the engine condition, were used. The BC mass concentration (i.e. eBC, rBC and EC) as a function of the EC mass concentration measure with TOA for each marine fuel used is presented in figure 1. This figure shows that all of the BC measurement instruments behaved fairly linearly when plotted as a function of TOA EC with a fairly significant noise in the results. In this campaign, the instruments were calibrated according to the manufacturer's recommended calibration method. The linearity suggests that a common calibration could lead to a better agreement between the different methods.

8 A linear least-squares regression fit was applied to the data for each instrument for each fuel type. These results are presented in table 1. The spreads in the regression fit slopes varied between $\pm 30\%$ and $\pm 41\%$. The spreads are $(\text{max slope} - \text{min slope}) / (\text{max slope} + \text{min slope})$, in percent, and represent the half-width of the triangles formed in the subfigures in figure 1. These spreads are similar to the spreads observed at the campaign that took place at the University of California Riverside (UCR), funded by the International Council on Clean Transportation (ICCT).

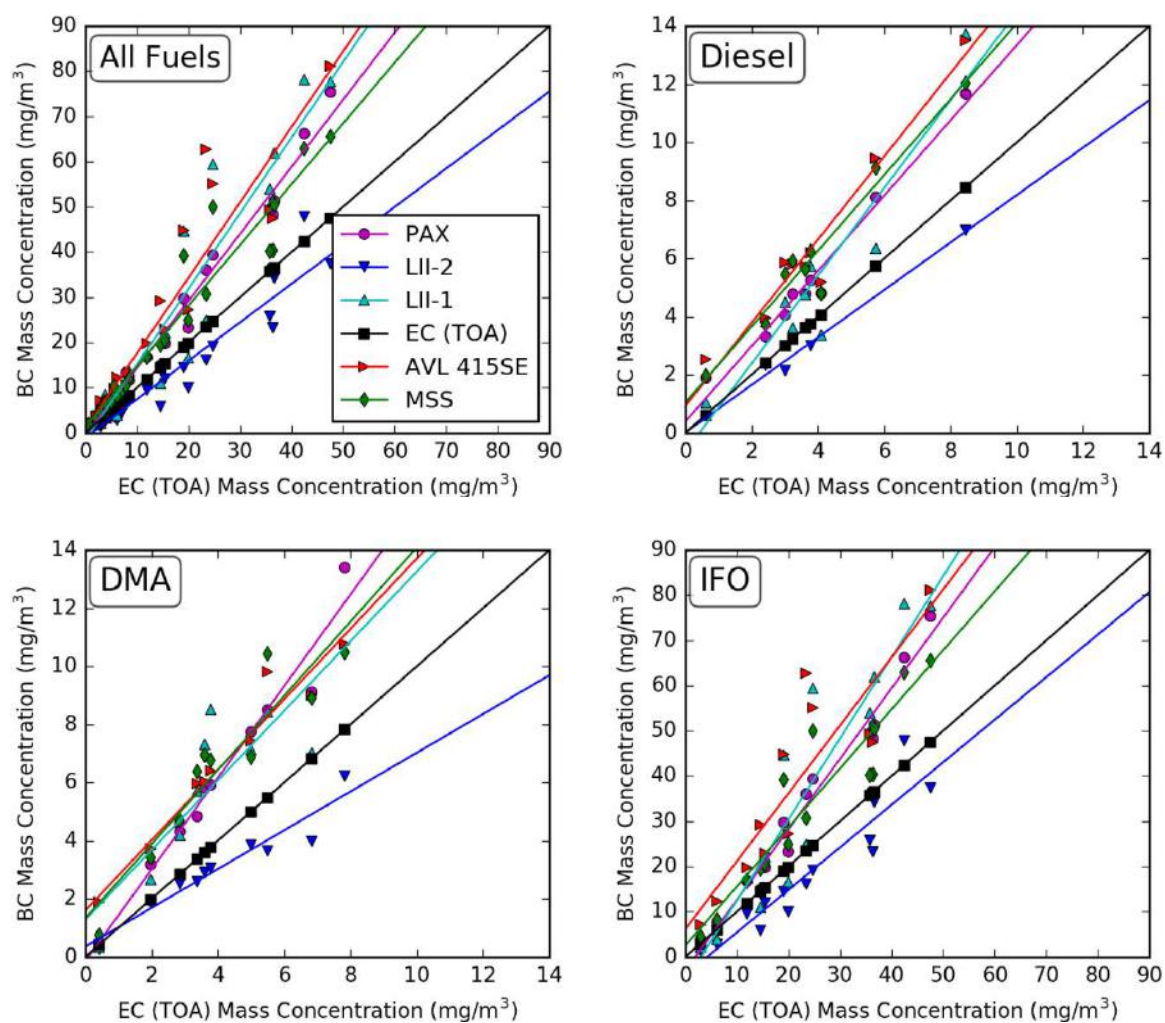


Figure 1: Comparison of BC mass concentration measured with different instruments as a function of EC mass concentration for the tested fuel types (see fuel information in upper left corner box)

Table 1: Slopes, intercepts and spread of instruments for each fuel

	All fuel types		Diesel		DMA		IFO	
	slope	intercept	slope	intercept	slope	intercept	slope	intercept
PAX	1.48	-0.53	1.30	0.39	1.58	-0.15	1.56	-3.03
LII-2	0.85	-1.09	0.82	0.01	0.67	0.35	0.94	-4.02
LII-1	1.67	-1.63	1.51	-0.64	1.20	1.28	1.79	-5.49
TOA	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00
AVL								
415SE	1.67	0.88	1.43	0.92	1.21	1.59	1.50	6.09
MSS	1.34	1.23	1.31	1.04	1.28	1.32	1.31	2.48
Spread (±)	32%		30%		41%		31%	
Spread (±) excl. LII-2	25%		20%		22%		28%	

9 Noticeably, the LII-2 and the TOA results stand apart from the others. The co-sponsors do not have an explanation as to why the LII-2 has much smaller slopes than the other instruments and, in particular, such a different slope from the other LII. This behaviour is still under investigation at the time of writing this document.

10 In the UCR campaign, where the NIOSH5040 thermal protocol was used with the Sunset Lab Model 5 analyser, TOA EC values were also consistently lower than the other instruments (PPR 3/INF.6). In a campaign conducted in Japan, where the IMPROVE thermal protocol was used with the Sunset Lab Model 5 analyser, TOA seemed to agree well with PAS but, due to the limited information included in document PPR 3/INF.5, the co-sponsors cannot quantify this. In a campaign conducted at VTT Technical Research Centre of Finland (PPR 4/9/2), where the EUSAAR-2 thermal protocol and a Sunset Lab Model 4L was used, TOA concentration was only smaller for test points with a 25% engine load. This does not correspond to the situation observed in this campaign where the same thermal protocol and a Sunset Lab Model 5L analyser were used. In comparing these three campaigns, the co-sponsors noticed that Rostock and UCR both used a rather small engine at 76 kW/1 cylinder and 187 kW/6 cylinders, respectively, while VTT was using a 1.6 MW/4 cylinders engine. The Rostock engine was the only of the three that was equipped with common rail technology. Japan used a variety of engines. It is possible that the tendency of TOA EC results to be lower than eBC and rBC may be a consequence of the properties of particles produced from different engine technologies. Given this very small sample size, more data from various engine technologies would be needed to validate this hypothesis.

11 When removing the LII-2 and the TOA from the spreads, the different instruments agree remarkably well with spreads of $\pm 7\%$ for diesel, $\pm 14\%$ for DMA and $\pm 15\%$ for IFO. The apparent scatter of points around their fit line is reduced when plotted with an instrument other than TOA on the x-axis. This suggests the scatter in the TOA results is more important than in other instruments. This campaign also included supporting instrumentation that may help tease out which method(s) was(were) affected and how, but this analysis has not been performed at the time of writing this document.

Effect of the different fuel types and engine loads

12 It is interesting to note that the order of the slopes for each instrument changes depending on fuel composition except for the tendency of TOA and the LII-2 to be lower than the rest.

13 Using effective density measurements, it was observed that the organic coating on the particles was more important at low engine loads than at high loads. Confirmation of this observation using the organic carbon (OC) fraction of TOA analysis will become available in the near future but was not available at the time of submitting this document.

14 Using Transmission-Electron Microscopy (TEM) imaging, it was possible to see that particles from all three fuel types appeared to be decorated with ash (confirmation analysis not yet performed). The ash content of the fuels was below 0.01% for diesel, below 0.001% for DMA, and 0.055% for IFO. This indicates that the ash on the particles was probably coming from the lubricant oil rather than the fuels themselves (except perhaps for the IFO).

15 After analysing the quartz filters using TOA, the filter on which IFO particles had been deposited remained coloured with a light orange. This was not observed for diesel or DMA, for which the fully analysed filters came out white, as expected. The remaining IFO filters will be analysed for metal content in the future.

16 Data from supporting instruments will be analysed in the near future and will become available to help interpreting the results presented here.

Using the EUROMOT measurement reporting protocol

17 During the measurement campaign, the EUROMOT measurement reporting protocol was used. It is observed that the protocol requests many useful details related to the exact methods by which the samples are acquired and conditions of the measurements.

18 However, it was noted that the protocol is difficult to apply to a measurement campaign involving multiple fuel types, measurement instruments, and engine loads and speeds. For the present test involving 6 instruments, 3 fuel types and 9 engine conditions, it would have been very difficult to complete the protocol in the final version adopted at PPR 3 (PPR 3/22) as it would have generated hundreds of pages of information. Such a document would also be very difficult to digest by potential reviewers.

19 In order to reduce repetition in the report, make completion more feasible, and to make the report easier to review, the co-sponsors propose a few modifications. An example of this modified protocol, applied to the measurement campaign at the University of Rostock, is included as an appendix in the annex to document PPR 4/INF.9. Suggested modifications, additions and questions directed to EUROMOT are marked in grey.

- .1 section 4 is completed only once per instrument. In some cases, the cells to be completed could change from test point to test point. In these cases, the range of measured values or a typical value are indicated. As an example, the pressure in the measurement cell which is reported in section 4 can potentially vary as engine conditions and atmospheric pressure changes. In section 4 it would be sufficient to list the range of pressures in the cell rather than repeating the section for each instrument and each test point in order to capture the variations of the pressure (and other such properties, which can vary between test points);
- .2 section 6 is completed only once per test point. In order to clarify the related conditions for each test point, some additional rows have been added to the section, which include information such as the test point name, fuel type and target engine conditions; and

- .3 sections 7 and 8 have been separated from section 6 and reformatted so that data is reported for all instruments at each test point.

20 With these changes, the length of the report has been significantly reduced, repetition has been minimized, and the data is more clearly presented.

21 Further improvement to the document, in terms of reducing the length, ease of completion and ease of review, could be achieved with refinement to the document formatting, including drop-down lists, radio buttons, and regions which can be hidden if not applicable to the measurement being reported.

Conclusions

22 Six different instruments (PAX, LII-1, LII-2, TOA, AVL 415SE and MSS) covering 4 measurement methods (PAS, LII, TOA and FSN) were compared. The PAX, the LII-1, the MSS and the AVL415SE agreed remarkably well with spreads of $\pm 7\%$ for diesel, $\pm 14\%$ for DMA and $\pm 15\%$ for IFO. The LII-2 agreed better with TOA and did not agree well with the other LII. The reasons for this behaviour are unknown at this moment. TOA reported BC mass concentrations lower than the rest of the instruments. This could be due to particle properties for particles emitted with a rather small engine; however, more testing with different engine technologies is required to understand how different methods perceive the BC mass concentration. Information from supporting instrumentation was presented and more will be added in the near future to support the analysis of fuel and engine load effects. Finally, a suggestion is presented for improving the EUROMOT protocol user experience.

Next steps

23 The co-sponsors will continue to analyse the results, especially taking into account the fuel and load effects using the supporting instrumentation described in document PPR 4/INF.9.

24 EUROMOT is invited to consider the campaign experience with the EUROMOT measurement reporting protocol for the continued refinement of the protocol.

25 Observations from this campaign and previous campaigns demonstrate that more testing is required to understand how different measurement methods react to particles with different physical, chemical and optical properties. In addition to varying fuel types and engine conditions, further testing on different engine technologies would be beneficial. The co-sponsors encourage and invite further study in this area.

26 The co-sponsors encourage improved coordination between campaigns with proposed sampling protocols, including sample conditioning. This would improve the comparability between the few measurement campaigns that are organized.

27 The four methods used in this campaign to measure BC, including FSN, LII, PAS and TOA merit continued consideration in future measurement campaigns.

Action requested of the Sub-Committee

28 The Sub-Committee is invited to note the information in this document.

REFERENCES

UCR Study: IMO PPR 3/INF.6 (2015): Evaluation of Black Carbon measurement methods on a laboratory bench-tested marine diesel engine: a research plan.

VTT Study. Aakko-Saksa, P. et al (2016): Black carbon measurements using different marine fuels. CIMAC Congress, Helsinki, 6.-10. June 2016 and document PPR 4/9/2.

SUB-COMMITTEE ON POLLUTION
PREVENTION AND RESPONSE
5th session
Agenda item 7

PPR 5/INF.10
1 December 2017
ENGLISH ONLY

**CONSIDERATION OF THE IMPACT ON THE ARCTIC OF EMISSIONS OF
BLACK CARBON FROM INTERNATIONAL SHIPPING**

New findings of a multi-instrument Black Carbon measurement campaign

Submitted by Canada and Germany

SUMMARY

Executive summary: This document presents new analysis of data related to a joint Black Carbon measurement campaign performed by Canada and Germany, and originally presented in document PPR 4/9/4. The Black Carbon measurements were carried out with a variety of Black Carbon measuring instruments and different fuel types on a test engine in the lab.

Strategic direction: Number to be assigned after A 30

High-level action: Number to be assigned after A 30

Output: Number to be assigned after A 30

Action to be taken: Paragraph 13

Related documents: MEPC 62/24, MEPC 67/12, MEPC 67/12/4, MEPC 67/12/8, MEPC 67/INF.31, MEPC 67/20, MEPC 68/12/2, MEPC 68/12/5, MEPC 68/12/9, MEPC 68/21, BLG 16/16, BLG 17/18, PPR 1/16, PPR 2/8, PPR 2/21, PPR 2/INF.5, PPR 3/8, PPR 3/8/1, PPR 3/INF.6, PPR 3/INF.7, PPR 3/22, PPR 4/9/4 and PPR 4/INF.9

Background

1 MEPC 62 agreed to a work plan to consider the impact on the Arctic of Black Carbon emissions from international shipping and instructed the Sub-Committee on Bulk Liquids and Gases (now PPR) to undertake this work by developing a definition of Black Carbon (BC); identifying the most appropriate measurement method(s) for international shipping; and investigating appropriate control measures. MEPC 68 approved the Bond et al. definition of BC proposed by PPR 2 and noted the need for the development of protocols and further study to collect data in order to identify the most appropriate measurement method(s) of BC emissions from international shipping (MEPC 68/21, paragraphs 3.26 to 3.28).

2 At PPR 4, Canada and Germany submitted the preliminary results of a multi-instrument BC measurement campaign held at the University of Rostock (PPR 4/9/4). This document describes a number of new findings related to the same German-led research campaign to measure BC emissions from a single-cylinder direct-injection research engine 1VDS18/15CR with a nominal output of 76 kW at 1,500 rpm in the laboratory. The description of engine, fuel types, instruments and the different tests performed during the measurement campaign were presented in document PPR 4/INF.9.

3 The measurement campaign was conducted by the University of Rostock (Germany), National Research Council (Canada), Helmholtz Centre Munich and AVL, assisted by Marena Ltd., CE Delft and the Öko-Institut¹.

4 The goal of the project was to carry out simultaneous BC measurements on a ship engine, allowing for different bunker fuel types, engine ratings and different measurement methods. The purpose of this document is to help the discussion on the most appropriate BC measurement method(s) at PPR 5. Its specific objectives are to:

- .1 assess the effect of different fuels and engine loads on BC measurement, using various methods; and
- .2 assess the comparability of seven BC measurement instruments and compare the results with similar campaigns.

Description of the Black Carbon measurement campaign

5 In the report of PPR 2 to MEPC 68 (PPR 2/21, paragraph 8.5.3), four different measurement methods were identified as example methods to measure BC: Photo Acoustic Spectroscopy (PAS), Multi Angle Absorption Photometry (MAAP), Laser Induced Incandescence (LII) and Filter Smoke Number (FSN). The BC measurement methods applied in this measurement campaign are listed in table 1. Further details of the BC measurement campaign were described in document PPR 4/INF.9.

Table 1: BC measurement methods applied in the measurement campaign

Method	Instrument name	Manufacturer	Reported BC
PAS	MSS and PAX	AVL MSS+ and DMT PAX	eBC
FSN (Filter-based optical)	SM	AVL smoke meter 415SE	eBC
Filter-based optical	Aethalometer	Magee Scientific	eBC
LII	LII	Artium LII 300; LII 1 on raw and LII 2 on diluted exhaust gas	rBC
TOA	TOA	Sunset Laboratory Thermal-optical analyzer	EC

¹ The measurement campaign was funded by the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) and Transport Canada.

Results and discussion

Comparison of the different fuels at different engine loads

6 Three different fuels were used in this measurement campaign: diesel fuel (Diesel, 0.00063% S), Distillate Marine Grade A (DMA, 0.087% S) and intermediate fuel oil (IFO, 2.3% S). Figure 1 shows the BC emission factors measured by each instrument for the different fuels at different engine loads and constant engine ratings (1,500 rpm). The LII 2 was not available for Diesel test cycle D2 measurements but is presented for all other measurements. Figure 1c, which shows results for IFO, has more test points because the absolute BC concentration was higher for this fuel, allowing for the acquisition of multiple TOA filters during the 75% and 100% load test points.

7 The BC emissions are significantly higher for the IFO than for diesel and DMA (notice the scale) on this engine. The trend for IFO is a decrease in BC-emissions from 10 to 50% load, followed by an increase from 50 to 100% load. The absolute mass concentration followed the same trend. This finding is not directly comparable with other studies, as the research engine has a number of different features from engines used in other studies (e.g. number of cylinders, charging, max rated power, etc.). Other studies also typically use HFO (e.g. RMG 380) instead of an intermediate fuel (IFO 380, which is a blend of HFO with Marine Diesel). However, in the Finnish study (PPR 4/9/2), IFO (0.5% S) was used, but only two load points were investigated, making it impossible to see if the same trend would apply. Load trends have been shown to differ from one engine to another (ICCT 2016; see Reference section). A trend such as the one observed here is consistent with the fuel efficiency profile of the engine used in that the engine is optimized for medium loads and reduction of the load leads to lower combustion temperature, a delayed injection time and hence suboptimal combustion efficiency associated with higher BC emissions. The increase in BC emissions with increasing load from 50 to 100% may be related to a reduction in the air/fuel ratio, leading to an incomplete combustion of the fuel.

8 The absolute BC emissions for diesel and DMA increase with increasing load, i.e. when the BC concentrations are calculated as mass concentration in the exhaust gas volume [mg/m^3]. In Figure 1, the BC emission factors, which represent the concentration of BC emitted per unit of energy provided by the engine, do not show any clear trend with engine load.

9 Comparison of the different instruments shows that both filter-based optical methods (FSN and Aethalometer) measure the highest concentrations, especially for 10% engine load with IFO and DMA. The particles emitted at low engine loads, especially for fuels with a higher sulfur content, like DMA and IFO, contained a large amount of organic carbon material (not BC). This organic material is known to cause absorption enhancements with light absorption-based instruments (lensing effect), and a further enhancement artifact in filter-based optical instruments (filter artifact). Due to the complex nature of the interaction of light with particles loaded on a filter, different strategies are used when interpreting measurements. In Aethalometer methods, corrections are applied to the measured filter transmissivity to account for these effects. In the SM, a non-linear empirical relationship has been developed to relate the measured Filter Smoke Number and the filter loading in terms of Black Carbon mass. This relationship accounts for these effects. This enhancement effect should also be observed, to a lesser extent, in PAS instruments (lensing but no filter artifact). Laser Induced Incandescence (LII) might lead to an underestimation of the concentration when the particles contain a high fraction of organic material (part of the heat is absorbed by the organic material and is not delivered to the BC), but to a smaller magnitude than is observed for PAS instruments and filter-based optical instruments. Finally, organics should not impact the accuracy of total carbon readings from TOA analysis but may add uncertainty to the determination of the split point between OC and EC, because of the magnitude of the charring correction, and thus lead to higher or lower EC readings. These effects are consistent with the order observed at 10% engine load for both DMA and IFO.

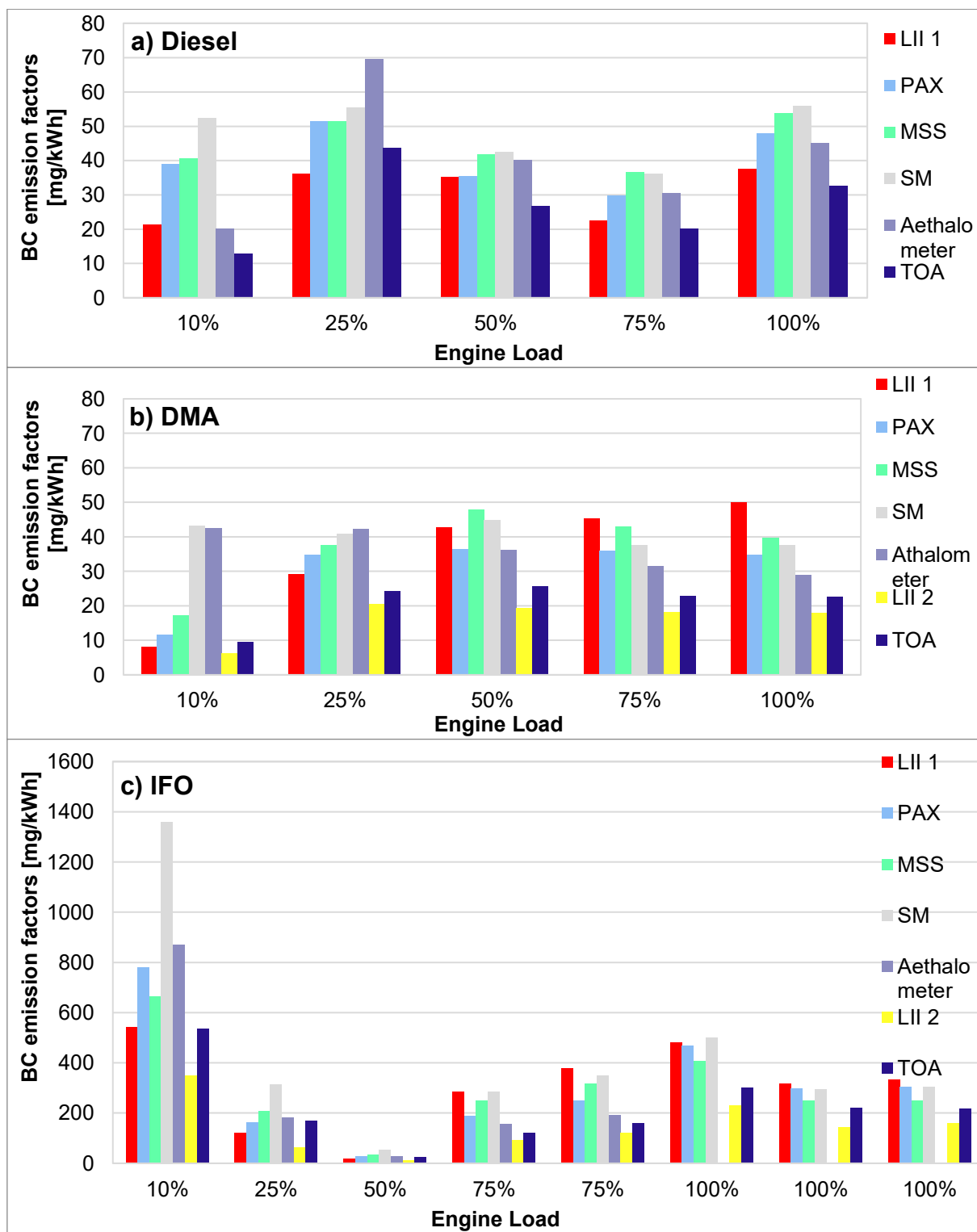


Figure 1: BC emission factors in mass concentration per power [mg/kWh], as measured by different BC instruments for a) diesel, b) DMA and c) IFO at different engine loads (note that the scale on the y-axes is different)

Comparability of the different BC measurement instruments

10 Table 2 shows the correlation coefficient matrices of all BC measurement instruments for the three different fuels separately (diesel, DMA and IFO). Note that the instruments sampled two groups² and the correlation coefficients across groups may not be representative of the true agreement between methods. To account for this, the correlation coefficients across sampling groups were greyed out and not included in the calculation of the average correlation coefficient per fuel. The average correlation coefficient values for different fuels give an indication of the effect of fuels on instrument-relative linearity³. On the undiluted exhaust group, SM, LII1 and MSS are directly comparable; on the diluted exhaust group, PAX, LII2, TOA and Aethalometer are directly comparable.

Table 2: Correlation matrix of all instruments for the different fuels

a) Diesel								
<i>R</i>_{average}=0.97	PAX	LII 2	LII 1	TOA	SM	MSS	Aethalom.	
PAX		0.99	0.95	0.98	0.99	0.99	0.93	R ≥ 0.99
LII 2	0.99		1.00	0.99	0.98	0.97	0.97	R ≥ 0.98
LII 1	0.95	1.00		0.94	0.96	0.94	0.87	R ≥ 0.97
TOA	0.98	0.99	0.94		0.97	0.97	0.98	R ≤ 0.90
SM	0.99	0.98	0.96	0.97		0.99	0.92	Different groups ¹
MSS	0.99	0.97	0.94	0.97	0.99		0.93	
Aethalom.	0.93	0.97	0.87	0.98	0.92	0.93		

b) DMA								
<i>R</i>_{average}=0.95	PAX	LII 2	LII 1	TOA	SM	MSS	Aethalom.	
PAX		0.99	0.88	0.98	0.96	0.93	0.95	
LII 2	0.99		0.90	0.95	0.93	0.90	0.91	
LII 1	0.88	0.90		0.81	0.88	0.92	0.72	
TOA	0.98	0.95	0.81		0.98	0.94	0.97	
SM	0.96	0.93	0.88	0.98		0.98	0.96	
MSS	0.93	0.90	0.92	0.94	0.98		0.90	
Aethalom.	0.95	0.91	0.72	0.97	0.96	0.90		

c) IFO								
<i>R</i>_{average}=0.94	PAX	LII 2	LII 1	TOA	SM	MSS	Aethalom.	
PAX		0.95	0.95	0.99	0.93	0.96	0.96	
LII 2	0.95		0.94	0.93	0.90	0.93	0.89	
LII 1	0.95	0.94		0.92	0.87	0.98	0.85	
TOA	0.99	0.93	0.92		0.90	0.94	0.96	
SM	0.93	0.90	0.87	0.90		0.93	0.97	
MSS	0.96	0.93	0.98	0.94	0.93		0.91	
Aethalom.	0.96	0.89	0.85	0.96	0.97	0.91		

11 For diesel, five sets of instruments (PAX/LII2, PAX/SM, PAX/MSS, LII2/TOA and SM/MSS) showed a very high correlation coefficient with $R \geq 0.99$. For the DMA and IFO, only one set of instruments had a correlation coefficient with $R \geq 0.99$, respectively (DMA: PAX/LII2 and IFO: PAX/TOA). Overall, diesel fuel saw the best relative linearity between the instruments

² Instruments on the undiluted exhaust group: LII1, SM & MSS; instruments on the diluted exhaust group: PAX, LII2, TOA & Aethalometer. Note that the Aethalometer had an additional stage of dilution for most of the test points but is considered as part of the diluted group in this analysis.

³ The relative linearity between instruments, represented by the correlation coefficients, indicates that the two instruments respond proportionally to the same change in BC concentration. Two instruments with a high correlation coefficient have the potential to agree well, given the appropriate calibration factor is applied.

as compared with the other two fuel types, with an average correlation coefficient of 0.97 compared to 0.95 and 0.94 for DMA and IFO, respectively. This is consistent with the fact that instruments are designed, calibrated and tested for particles with less organic content. The ash content and sulfur content specific to marine fuels can also influence the instruments' response in a way that would decrease their correlation coefficient. Overall, every instrument behaved linearly with reasonably good correlations to others, indicating that all these measurement methods are adequate to assess BC concentration. This also indicates that the development of a common calibration method, which would take into account the specificity of marine emissions, would likely improve the agreement between different measurement instruments.

Conclusions

- 12 The joint Black Carbon measurement campaign leads to the following conclusions:
- .1 BC emission factors of the research engine are much higher for IFO as compared to DMA and diesel;
 - .2 different instruments react differently to organic content in the particles. Organic content increases the disagreement between the different instruments. In the presence of high organic fractions, the SM and the Aethalometer would be subject to an enhancement in the reported BC concentration, followed by the PAX and MSS. The LII, on the other hand, could be subject to a reduction in reported BC concentration. It is not clear what happens to the BC reported by TOA, but it certainly increases the magnitude of the split point correction due to charring;
 - .3 the BC concentrations of all instruments behaved linearly with fairly good correlations between each other, indicating that all these measurement methods are valid to assess marine BC concentrations. A common calibration method, specific for marine BC emissions, would likely improve the agreement between different measurement instruments; and
 - .4 consequently, as the response of the different BC measurement instruments is linear, and their agreement depends on an appropriate calibration to a reference material, other factors will play an important role in the assessment of a specific instrument and set-up to measure marine BC emissions for shipping. These factors, such as where and how often the measurement takes place (in the lab during engine certification or on board), will influence which methods are best suited. As such, it is very important to assess the appropriateness of BC measurement methods in consideration of the type of measurement to be performed. In the absence of more detail on the application of these methods, however, each of the BC measurement methods assessed in this study is appropriate for measuring BC from international shipping.

Action requested of the Sub-Committee

- 13 The Sub-Committee is invited to note the information contained in this document.

Reference

ICCT Report 2016: Black Carbon Measurement Methods and Emission Factors from Ships.
http://www.theicct.org/sites/default/files/publications/Marine-BC-Testing_ICCT-UCR_Consultant-Report_16012017_vF.pdf