Marine Black Carbon Emissions Testing
Test Plan and Approach

September 16th, 2015

Presented By:
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² Environment Canada
³ National Research Council - Canada
⁴ University of California, San Diego
⁵ Eastern Research Group
Presentation Outline

- Background
- Objectives
- Research Team
- Research Approach
  - Laboratory bench testing
  - Ocean testing
- Parallel efforts
  - California Air Resources Board
  - Carnival
Background-Policy

- Marine traffic and related port activities contribute to air pollution in many cities, ports and along inland waterways.
- The allowable sulphur level for marine fuels in Canada in some cases can reach 1000 mg/kg*.
- Canada’s 2013 National Pollutant Release Inventory (NPRI) shows that marine transportation contributes 89% of the total mobile SO$_2$ emissions#.

• According to the first Canadian Black Carbon (BC) Inventory released in 2013†, a 65% of the total 45,000 tonnes of BC emitted in Canada was attributed to the transportation sector.
• Marine BC emissions was 1600 tonnes in 2013 compared to the total 29,000 tonnes of BC from all mobile sources.

† http://ec.gc.ca/pollution/default.asp?lang=En&n=3F796B41-1&offset=3&toc=show
Drivers for on-board / real world marine emissions measurements

- Real world measurement and analysis of exhaust emissions from various off-road equipment including marine is done to support:
  - Development of regulations, emissions factors, and inventories
  - Method development for sampling and analysis
  - Evaluation of emissions control technologies and strategies such as cleaner fuels

Emerging issues for Marine Sector

- Emissions control and reduction targets for various competing transportation modes
- Generic emissions factors typically used; not specific to engine age or technology, fuel quality, engine operation parameters, etc.
- Changing emissions profiles resulting from new exhaust emissions control strategies and technologies
Background-Technical

- BC EF quantification practices not well understood with the different fuels, loads, engines, and measurement methods, thus making BC mitigation difficult

- Reported BC EF vary by a factor of 10
PM Also Varies by Sampling Approaches

Source: Moldanova et al ICCT 2014 workshop
Why is BC Characterization Difficult

Light-Absorption Classification

- More light-absorbing
  - Light-absorbing carbon (LAC)
  - Black carbon ($BC_a$)
  - Brown carbon ($BrC$)

- Less light-absorbing

Thermal-Optical Classification

- More refractory
  - Elemental carbon ($EC_a$)
  - Organic carbon ($OC_a$)

- Less refractory

* Measurement technique-specific split point

Source: EPA
Objectives

- Controlled laboratory testing (engine test stand)
  - Evaluate numerous BC instruments
  - Vary engine load and fuel
  - Identify recommended practices

- Evaluate recommended practices on OGV
Engine Laboratory Test Stand

<table>
<thead>
<tr>
<th>Engine Description</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Detroit Diesel 6-71N (naturally aspirated)</td>
<td>4 valves per cylinder</td>
<td>210 hp</td>
<td>High speed (2100 rpm)</td>
</tr>
<tr>
<td>2-stroke design with uniflow scavenging</td>
<td>0.348 lb/bhp-hr</td>
<td>7.0 L Disp.</td>
<td>18.7:1 Compression Ratio mechanically controlled</td>
</tr>
</tbody>
</table>

- The DDC 71 series diesel engine was very popular in marine propulsion
- Valley Power Systems was contracted to operate this engine on HFO for the Navy
- Current status
Engine Test Stand Conditions

<table>
<thead>
<tr>
<th>Fuel ²</th>
<th>Load (ISO E-3)</th>
<th>Repeats</th>
<th>Instruments ¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>MGO &lt;0.1 S</td>
<td>Load: 100, 75, 50, 25, and 10% (VSR)</td>
<td>3</td>
<td>Table 3-2, 3-3, and 3-4</td>
</tr>
<tr>
<td></td>
<td>Speed: 100, 91, 80, 63, and 45% (VSR)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HFO high S</td>
<td>Load: 100, 75, 50, 25, and 10% (VSR)</td>
<td>3</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

¹ Additionally UCR plans to measure the criteria pollutants (CO, NOx, SO2), total hydrocarbons and CO2 following methods outlined in 8178-1/-2. The main purpose of these measurements is to ensure that the engine operation is representative of a well maintained engine. The Team will report any changes in the measured gases.

¹ If additional fuels are available for testing and additional dollars are allocated the testing matrix can easily be expanded to consider these other fuels.
Engine Dynamometer Test Stand

UC Riverside's Engine Dynamometer (15 years of experience)

1) Up to 600 hp
2) Repeatability ~ 1% (torque/ Hp)
3) Transient and steady state
4) Fuel control (temperature and pressure)
5) Intake air control (humidity and temperature)
6) Cooling water control
7) Room ventilation control
Engine Test Stand Proposed Layout

Source: NRC
Sampling Approach

- Dilution: three main sample branches
  - No dilution (raw sampling)
  - Traditional IMO type stack sampling ~ 10:1
  - High dilution (simulated plume sampling) > 100:1

- Sample conditioning
  - Best recommended practices

- Calibration (CAST)
Selecting the Correct Dilution is Important

Source: Moldanova et al ICCT 2014 workshop
## Expected Test Stand PM Concentrations
(HFO 3% Sulfur Fuel)

<table>
<thead>
<tr>
<th>PM (ug/m³)</th>
<th>Species</th>
<th>1 : 1</th>
<th>10 : 1</th>
<th>300 : 1</th>
<th>1000 : 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>total PM</td>
<td></td>
<td>5,656</td>
<td>12,000</td>
<td>480.0</td>
<td>144.0</td>
</tr>
<tr>
<td>organics</td>
<td></td>
<td>656</td>
<td>4,800</td>
<td>192.0</td>
<td>57.6</td>
</tr>
<tr>
<td>sulfate</td>
<td></td>
<td>0</td>
<td>6,600</td>
<td>264.0</td>
<td>79.2</td>
</tr>
<tr>
<td>elemental</td>
<td></td>
<td>5,000</td>
<td>500</td>
<td>16.7</td>
<td>5.0</td>
</tr>
<tr>
<td>ash other</td>
<td></td>
<td>100</td>
<td>10</td>
<td>0.3</td>
<td>0.1</td>
</tr>
</tbody>
</table>
## Engine Test Stand Measurements

**Raw dilution samplers (1:1)**

<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVL 415SE Smoke Meter from the raw exhaust</td>
<td>Filter-type smoke meter (ISO 10054) from raw exhaust in-kind contribution AVL see Attachment E for letter.</td>
</tr>
<tr>
<td>(Optional) Laser Induced Incandescence (LII)</td>
<td>(Optional) PM mass collected on Teflon filter.</td>
</tr>
<tr>
<td>(Optional) Elemental &amp; organic carbon on quartz filter analyzed by NIOSH &amp; IMPROVE methods (Sunset instrument)</td>
<td>(Optional) GC by GC Mass Spectroscopy</td>
</tr>
</tbody>
</table>
## Engine Test Stand Measurements

### ISO dilution samplers (~10:1)

<table>
<thead>
<tr>
<th>Instrument/Method</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVL Micro soot sensor (MSS) 870 nm wavelength</td>
<td>Elemental &amp; organic carbon on quartz filter analyzed by NIOSH &amp; IMPROVE methods (Sunset instrument)</td>
</tr>
<tr>
<td>Laser Induced Incandescence (LII)</td>
<td>PM mass collected on Teflon filter.</td>
</tr>
<tr>
<td><strong>Optional</strong> AVL 415SE Smoke Meter from the raw exhaust</td>
<td><strong>Optional</strong> GC by GC Mass Spectroscopy</td>
</tr>
<tr>
<td>Droplet Measurement Technologies (PAX) PA system, in-kind contribution DMT, see Attachment E for letter.</td>
<td>DMT PAX PA system 375 nm wavelength</td>
</tr>
</tbody>
</table>
Engine Test Stand Measurements

High dilution samplers (~300:1 up to 1000:1)

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aethalometer AE33</td>
<td>Multi-angle absorption photometer (MAAP)</td>
</tr>
<tr>
<td>Condensation particle counter (CPC)</td>
<td>Single Particle Soot Photometer (SP2)</td>
</tr>
<tr>
<td>Particle size distribution with (SMPS)</td>
<td>Transmission Electron Microscopy (TEM)</td>
</tr>
<tr>
<td>(Optional) GC by GC Mass Spectroscopy</td>
<td>Aerosol Mass Spectrometer (AMS)</td>
</tr>
<tr>
<td>CPC-Catalytic Stripper (CPC-CS)</td>
<td>Aerosol Particle Mass Analyzer APM-SMPS</td>
</tr>
</tbody>
</table>
Proposed Engine Test Stand Arrangement

1:1

- 3-way splitter
- manifold
- 3m heated carbon-impregnated Teflon?
- Pagsor
- OBD PM
- Meth 5 Quartz
- Meth 5 Teflon

10:1

- 10:1 dilutor (output 50 lpm)
- manifold
- common length carbon-impregnated silicon? or copper?

300:1 to 1000:1

- rotary dilutor (output 1.4 lpm)
- evaporator tube (350°C)
- educator dilutor (output 14 lpm)

Source: NRC

- Semi-continuous OC/EC (2)
- MSS
- LII300
- PAX 534 and PAX 375
- Dustrak
- 415SE Smoke Meter (for some tests or get a second one)
- Filters (Teflon and Quartz)
- Aethalometer
- CPC 1
- SMPS
- MAAP
- SP2
- TEM
- CPC 2?
Possible Duplicate Measurements Between Dilution Probes

- All (1:1, 10:1, and 300:1)
  - GC by GC MS
  - LLI
- 1:1 and 10:1
  - Smoke meter?
  - Teflon PM mass
  - EC/OC

- 10:1 and 300:1
  - PA 820 nm
  - PAX 375 nm
  - PAX 534 nm?
## Comprehensive Team

<table>
<thead>
<tr>
<th>Team Member</th>
<th>Expertise</th>
</tr>
</thead>
</table>
| **From UCR: Drs. Johnson & Miller plus Professors Cocker, Jung, and Bahreini;** | • Measurement and analysis of marine air emissions  
• Familiarity with BC instrumentation approaches and sampling  
• Experience with bench testing of emissions from marine engines  
• Experience with on-board vessel emissions testing |
| **From Environment Canada:**  
Scientific members from Dr. Tak Chan group | • Measurement and analysis of marine air emissions  
• Familiarity with BC instrumentation approaches and sampling  
• Experience with bench testing of emissions from marine engines  
• Experience with on-board vessel emissions testing |
| Dr. John Koupal of Eastern Research Group (ERG) | Familiarity with marine inventory development, including emission factor analysis, vessel population, and activity patterns. |
| Dr. Miller of UCR | Has proven relationships within the industry and demonstrated ability to access vessels for testing. |
| Professor Lynn Russell of UC San Diego | • Familiarity with BC instrumentation approaches and sampling  
• Expert on marine aerosol and SP2 method |
| **From National Resource Canada (NRC), Dr. Kevin Thomson** | • Measurement and analysis of marine air emissions  
• Familiarity with BC instrumentation approaches and sampling  
• Experience with bench testing of emissions from marine engines  
• Experience with on-board vessel emissions testing |
| AVL/Sun Set Laboratories | Familiarity with BC instrumentation approaches, sampling and access to new instruments |
Ocean Going Vessel Testing

- Recommend a BC EF:
  - Measurement method
  - Sampling conditioning method

- Evaluate recommendations on various in-use vessels
  - Fuel switching
  - Controls (Scrubbers and Flow through filters)
  - Various loads (as permitted)
### Ocean Going Vessels Proposed

<table>
<thead>
<tr>
<th>Vessel Name</th>
<th>Vessel Type</th>
<th>Engine</th>
<th>PM Control</th>
<th>Contract</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tarago</td>
<td>RORO</td>
<td>Maine: MAN B&amp;W 21 Mw</td>
<td>Pre/Post Scrubber</td>
<td>ICCT</td>
</tr>
<tr>
<td>Tarago</td>
<td>RORO</td>
<td>AE: MAN B&amp;W 1MW</td>
<td>Pre/Post Scrubber</td>
<td>ICCT</td>
</tr>
<tr>
<td>tbd</td>
<td>tbd</td>
<td>tbd</td>
<td>tbd</td>
<td>ICCT?</td>
</tr>
<tr>
<td>tbd</td>
<td>tbd</td>
<td>tbd</td>
<td>tbd</td>
<td>ARB (up to 3)</td>
</tr>
<tr>
<td>Carnival</td>
<td>Cruise Line</td>
<td>Wartsila and MAK 8-12 Mw (multiple)</td>
<td>Pre/Post PM Scrubber and Filter</td>
<td>Carnival (up to 7)</td>
</tr>
</tbody>
</table>

The Tarago is a vessel that has both main and AE engines for a range of conditions in one setup. Possible fuel changes also.
**Proposed Carnival BC Testing**

**Main Components Exhaust Gas Cleaning System**

1: Engine  
2: Flow-Through Filter  
3: Economizer  
4: Exhaust Gas Scrubber

**Possible Sample Locations**

- **Post Scrubber Sampling**
- **Pre Scrubber Sampling**
- **Post Flow-Through Filter Sampling**
- **Pre Flow-Through Filter Sampling**
Project Expectations

- Comprehensive characterization of laboratory PM from marine engines on marine fuels
- Evaluation and quantification of BC EF measurement methods
  - Instruments
  - Sample conditioning
  - Calibration
- On-vessel demonstration of these methods for validation
Questions
Backup

<table>
<thead>
<tr>
<th>Vessel Type</th>
<th>Engine</th>
<th>Test Count</th>
<th>Motivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Container Class (10), Tankers (1), and Roll On Roll Off (1)</td>
<td>Main/Aux</td>
<td>12</td>
<td>Fuel switching, NO\textsubscript{x} control (SCR aux), PM control (scrubber aux), fuel switching, reduced speed.</td>
</tr>
<tr>
<td>Ferry, Shuttles, Tugs, Dredgers, Hybrid Tug</td>
<td>Main/Aux</td>
<td>10</td>
<td>Fuels (bio), NOx control (SCR), Clean tech’s, hybrids.</td>
</tr>
</tbody>
</table>
Measurement Methods and Instrumentation

### PM Instruments

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVL MSS 483</td>
<td>AVL’s micro soot sensor (photo acoustic abs. 808 nm)</td>
</tr>
<tr>
<td>DMX</td>
<td>Dekati’s mass monitor (aerodynamic size separation)</td>
</tr>
<tr>
<td>EEPS</td>
<td>Engine Exhaust Particle Sizer Spectrometer</td>
</tr>
<tr>
<td>PAX</td>
<td>Photoacoustic Extintiometer (photo acoustic abs. 870 nm)</td>
</tr>
<tr>
<td>AE33</td>
<td>Aethalometer – filter paper transmission</td>
</tr>
<tr>
<td>MAPP</td>
<td>Multi-angle absorption photometer (absorption 670nm)</td>
</tr>
<tr>
<td>fSMPS</td>
<td>In-house fast scanning mobility particle sizer 7 to 2000 nm</td>
</tr>
<tr>
<td>nSMSP</td>
<td>In-house nano scanning mobility particle sizer 3 to 60 nm</td>
</tr>
<tr>
<td>3776 CPC</td>
<td>TSI condensing particle sizer 2.5 nm cut</td>
</tr>
<tr>
<td>3022A CPC</td>
<td>TSI condensing particle sizer 7 nm cut</td>
</tr>
<tr>
<td>3771 CPC</td>
<td>TSI condensing particle sizer 11 nm cut</td>
</tr>
<tr>
<td>3025A CPC</td>
<td>TSI condensing particle sizer 3 nm cut</td>
</tr>
<tr>
<td>Sulfate IC</td>
<td>Sulfate ion chromatography</td>
</tr>
<tr>
<td>EC/OC</td>
<td>Sunset laboratories elemental organic PM analyzer</td>
</tr>
</tbody>
</table>

### Ambient aerosol related instruments

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDL</td>
<td>Tunable diode laser spectroscopy ammonia measurement</td>
</tr>
<tr>
<td>HPLC</td>
<td>High performance liquid chromatograph carbonyls analysis</td>
</tr>
<tr>
<td>GC</td>
<td>Gas chromatographs for speciated hydrocarbon analysis</td>
</tr>
<tr>
<td>AMS</td>
<td>Aerodyne aerosol mass spectrometer chemical characterizations</td>
</tr>
<tr>
<td>APM</td>
<td>Kanomax aerosol particle mass analyzer for density</td>
</tr>
<tr>
<td>TDMA</td>
<td>Tandem differential mobility analyzer</td>
</tr>
<tr>
<td>LC-TOFMS</td>
<td>Liquid chromatograph time-of-flight mass spectrometer</td>
</tr>
</tbody>
</table>