Black Carbon Particle Emissions from GDI Vehicles Operating on Different Fuels

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Workshop on Effects of Fuel Composition on PM
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Studies exploring fuel effects on PM

- **Ambient air study**
  - Study conducted during a local diesel bus strike event
  - Compare physical and chemical properties of ambient particles collected before, during, and after the strike

- **Laboratory based emissions study**
  - Particle emission characteristics from GDI and PFI vehicles
  - GDI PFI particle morphology
  - Ambient temperature effect on particle and black carbon emissions
  - Fuel composition on particle and black carbon emissions
Ambient particle measurements

Ambient air sampling

Air flow

~ 4 m

Photo by T. Chan
Ambient particle composition

Mass concentration (ng/m³)

- NAP = Naphthalene
- ACY = Acenaphthylene
- ACE = Acenaphthene
- FLU = Fluorene
- PHEN = Phenanthrene
- ANTH = Anthracene
- FLT = Fluoranthene
- PYR = Pyrene
- BaA = Benzo[a]anthracene
- BaP = Benzo[a]pyrene
- CHR = Chrysene
- BbF = Benzo[b]-fluoranthene
- BkF = Benzo[k]fluoranthene
- IcdP = Indeno[1,2,3-cd]pyrene
- DBahA = Dibenz[a,h]anthracene
- BghiP = Benzo[ghi]perylene

Page 4 – December-12-16

Ding et al. (2009) Atmos. Environ. 43, 4894-4902.
Lab based particle sampling system

**Key Equipment & Measurements**

- **DMM**: Dekati mass monitor
- **LII**: Laser induced incandescence
- **Micro aeth.**: micro-aethalometer
- **EEPS**: Engine exhaust particle sizer
- **EECPC**: Engine exhaust condensation particle counter
- **UCPC**: Ultrafine condensation particle counter
- **ESP**: Electrostatic precipitator
- **PND**: Particle number dilution

**(Near-)Real-time particle info:**

- Particle mass
- Black carbon mass
- Particle number/distribution
- Particle morphology

**Graph:**

- **FTP-75**: FTP-75 phase 1 phase 2
- **FTP-75 phase 3**: US06 US06

**Flowchart Description:**

- **Dilution air**
- **Exhaust flowmeter**
- **Dekati thermodenuder**
- **2.5 micron cyclone**
- **Volatile Particle Remover**
- **ET**
- **PND1**
- **PND2**
- **EEPC**
- **UCPC**

**Flowchart Notes:**

- **Filter packs**
- **VOC bags**
- **DNPH cartridges**
- **Blower**

**Graph Notes:**

- **Graph X-axis:** Time (s)
- **Graph Y-axis:** Speed (km/h)

**Environment and Climate Change Canada**

Environment et Changement climatique Canada
PFI engine particle morphology

MY2009 2.4L PFI engine operated on Tier 2 certification gasoline

TEM photos are shown in various resolutions for clarification
GDI engine particle morphology

MY2012 2.0L GDI vehicle operated on Tier 2 certification gasoline

TEM photos are shown in various resolutions for clarification
GDI engine particle morphology

- GDI soot morphology is independent of the driving condition.
- GDI soot morphology is comparable to diesel soot morphology.
- Area-equivalent particle diameter is consistent with particle size distribution measurements.

<table>
<thead>
<tr>
<th>Cycle</th>
<th>DF</th>
<th>D (nm)</th>
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<tbody>
<tr>
<td>FTP-75 cold-start</td>
<td>1.8</td>
<td>88</td>
</tr>
<tr>
<td>FTP-75 urban</td>
<td>1.8</td>
<td>80</td>
</tr>
<tr>
<td>FTP-75 hot-start</td>
<td>1.7</td>
<td>85</td>
</tr>
<tr>
<td>US06</td>
<td>1.8</td>
<td>78</td>
</tr>
</tbody>
</table>
Fuel composition and properties

- Alcohol is not the only compound in fuel that can influence particle emissions. Various hydrocarbons have different soot formation tendencies.
- Hydrocarbon soot formation tendency: Paraffins < isoparaffins < mono-olefins < naphthenes < alkynes < aromatics

<table>
<thead>
<tr>
<th>Abbrev.</th>
<th>Description</th>
<th>Drive cycle tested</th>
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<tbody>
<tr>
<td>Tier 2</td>
<td>EPA Tier 2 certification gasoline</td>
<td>FTP-75, US06</td>
</tr>
<tr>
<td>Tier 2/E10</td>
<td>Splash blended 10%vol ethanol with Tier 2</td>
<td>FTP-75, US06</td>
</tr>
<tr>
<td>Tier 2/iB16</td>
<td>Splash blended 16%vol isobutanol with Tier 2</td>
<td>FTP-75, US06</td>
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<tr>
<td>Tier 2/E15</td>
<td>Splash blended 15%vol ethanol with Tier 2</td>
<td>FTP-75, US06</td>
</tr>
<tr>
<td>Tier 2/E20</td>
<td>Splash blended 20%vol ethanol with Tier 2</td>
<td>FTP-75, US06</td>
</tr>
<tr>
<td>Tier 3</td>
<td>EPA Tier 3 certification gasoline</td>
<td>FTP-75, US06</td>
</tr>
</tbody>
</table>

EPA Tier 2 certification gasoline

- I-Paraffins: 47%
- Mono-Aromatics: 42%
- Naphthenes: 0%
- Naphtheno/Olefin: 0%
- Iso-Olefin: 0%
- n-Olefin: 0%
- Oxygenates: 0%

EPA Tier 3 certification gasoline

- I-Paraffins: 26%
- Mono-Aromatics: 28%
- Naphthenes: 1%
- Naphtheno/Olefin: 2%
- Iso-Olefin: 7%
- n-Olefin: 8%
- Paraffin: 17%
- Oxygenates: 10%
Fuels and solid particle emissions

- GDI vehicles have very different particle emissions characteristics compared to PFI vehicles.
- For GDI vehicles, particle number emission characteristics could vary from one vehicle to another.
- Effect of alcohol on particle number emissions from GDI and PFI vehicles is minor but varies greatly from one vehicle to the next.
Fuels and black carbon emissions

- Black carbon emissions from GDI vehicles is much different compared to PFI vehicles.
- Variability in black carbon emissions from different GDI vehicles could be larger than from different PFI vehicles.
- Different splash blended alcohol containing fuels have minor influences on GDI than for PFI on black carbon emissions.
Ambient temperature has a large impact on particle and black carbon emissions from both GDI and PFI vehicles. Impact is further enhanced during cold-start emissions.

PFI vehicles could potentially have comparable black carbon emissions as GDI vehicles during cold temperature.
Particle number size distributions generally look similar from vehicle GDI#2 but operating on Tier 2 produced slightly more particles. During aggressive driving condition significant number of ultrafine particles were emitted when operating on Tier 2. Slightly higher sulfur content from Tier 2 (37 ppm) vs. Tier 3 (8.4 ppm) could be one contributing factor.
For the GDI#2 test vehicle, operating on Tier 3 generally led to lower solid particle (>23 nm) emissions by 20-50%.

Operating GDI#2 test vehicle on Tier 3 also led to lower black carbon emissions by 40-60%.
Conclusions

• Compositions of the combustion generated particles are influenced by engine types, vehicle fleet mix, gasoline composition.
• Black carbon particles from GDI vehicles appear to be different than that from traditional PFI vehicles.
• Ethanol and isobutanol could have mixed effects on particle number and black carbon emissions from GDI and PFI vehicles.
• Aromatic hydrocarbons in gasoline could play a role in black carbon formation from gasoline engines.
• Gasoline composition could have different effects on black carbon emissions from different vehicles.
• Vehicle operating condition could add another degree of complexity on black carbon emissions from a passenger car or light-duty truck (current work).
Research gap

• Origin of the variability of the emissions from different vehicles:
  – With respect to GDI: Wall guided vs. spray guided
  – Advanced technologies on emissions: Engine start/stop, cylinder deactivation, hybrids, turbochargers
  – Octane level in gasoline on engine efficiency and particle formation
  – Real-world emissions
  – Non-road engines and equipment

• Understand the fuel composition effect:
  – Presence of various hydrocarbons in gasoline in relation to black carbon formation and emissions from vehicles
  – Vehicular emitted particle composition and fuel composition relationship

• Health effect:
  – Potential health effects of different exhaust emission particles