Lowering laboratory and real driving particle emissions of direct injection spark ignition engines with n-butanol and isobutanol blends.

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Veterinary Research Institute, Brno, Czech Republic
Overview of the study

2013 / EURO 6 Ford Focus car with EcoBoost DISI engine

Gasoline, E15, 25% n-butanol, 25% isobutanol

Chassis dynamometer - NEDC, WLTP, Artemis, US06
HC, CO, NO, NO2, PM, PN (PMP), PN (EEPS),
Unregulated: FTIR, PAH, genotoxicity (DNA adducts, ...)

55-km real driving loop - size distribution (onboard EEPS)
Issues addressed in this study

Particle emissions from DISI engines:
- emissions from production / in-use engines
- effects of driving cycle / off-cycle emissions
  - particles smaller than 23 nm
  - volatile nanoparticles

Real driving emissions and their measurement

WLTP vs. NEDC, Artemis, US06, ..., real driving

Effect of renewable alcohol fuels on particle emissions

Butanol as a potential alternative to ethanol
Project BIOTOX – Mechanisms of Toxicity of Particles from Biofuels
PM measurement and sampling using high-volume samplers
Gasoline MPI and direct injection, diesel, Traditional and alternative fuels (ethanol, butanol, biodiesel, NExBTL, blends)

Laboratory and on-road particle emissions of DISI engines fueled with butanol blends.
Vojtisek-Lom, 19th ETH Conference on Combustion Generated Nanoparticles, June 29, 2015
Real driving emissions measurement
Portable on-board monitoring systems (PEMS)

Cars, buses, trucks, tractors, loaders, mowers, small airplanes, mopeds, ferries, locomotives, construction machinery

Laboratory and on-road particle emissions of DISI engines fueled with butanol blends.
Vojtisek-Lom, 19th ETH Conference on Combustion Generated Nanoparticles, June 29, 2015
“Research PEMS”: On-board FTIR (gaseous compounds), EEPS (size distributions), CPC (particle counts)
Student projects: E85, n-butanol, isobutanol in unmodified gasoline engines in Škoda cars

On-board FTIR

~ 30 kg

~ 300-400 W

3 hours on

26 kg of batteries
(Diesel) ICE exhaust particulate matter

- Small particles (units to hundreds of nm) formed by incomplete combustion of fuel and engine lubricating oil and wear metals
- Complex mixture of compounds, many known to be carcinogenic
- More premature deaths (> 400 K per year in EU) than traffic accidents (< 40 K per year)
- One of the most pressing urban environmental problems

Laboratory and on-road particle emissions of DISI engines fueled with butanol blends.

Spořilov – ambient concentrations of 5-100 nm particles (thousands per cm³) – March 26, 2014

Měření 26.3.2014 10:15:13:45
Koncentrace částic
EEPS 5-100 nm
[tisíce částic/cm³]
Roadside & neighborhood ambient PM
Spořilov, February 2014, average of 40 locations, typical concentrations $10^4$-$10^5$ particles/cm$^3$ (max. $10^6$/cm$^3$)

~ 10 nm

~ 30-40 nm

Particle electric mobility diameter [nm]

Mean (error bars - st.dev.)
Geometric mean
Median

Diesel exhaust
Ronkko a kol, EST 2013

Vojtíšek a kol., NanoCon 2014
Is diesel PM becoming more of a question of public policy rather than technology?
Gasoline engine PM: Number vs. Mass limits by driving cycle

WLTP is “not as lame as NEDC”, but does it cover the problem – enrichment at high load (prohibited by EPA)?

US06 and Artemis motorway cycles as a supplement?
Gasoline engine real-driving PM emissions
Gasoline engine on-road PM emissions – steady speed vs. full-power acceleration

Instantaneous fuel consumption

Instantaneous PM emissions

Area of each mark is proportional to the instantaneous PM emissions in mg/s
Laboratory and on-road particle emissions of DISI engines fueled with butanol blends.

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Effects of E85 on real driving emissions in an ordinary car
14 km test route
(SAE 2013-24-0102)

Škoda Felicia passenger car,
Euro 3 1.4-liter MPI SI engine
3 runs on gasoline
3 runs on E85

Cumulative PM length
Laboratory tests

Vehicle:
2013 Ford Focus, Euro 6
EcoBoost 1.0-liter engine
Direct ignition gasoline

Fuels:
Gasoline (no ethanol),
E15 (15% ethanol)
25% n-butanol
25% isobutanol

Cycles:
Fuel change & adaptation,
WLTP preconditioning,
WLTP cold, WLTP hot,
4 x Artemis
Dilution tunnel instrumentation

- High-volume samplers
- Rotating disc Microdiluter & EEPS
- PMP-compliant particle counter
- Full-flow Dilution tunnel
- Laboratory FTIR
- Portable FTIR

Laboratory and on-road particle emissions of DISI engines fueled with butanol blends.
Vojtisek-Lom, 19th ETH Conference on Combustion Generated Nanoparticles, June 29, 2015
Effect of cycle & effect of “PN” definition:
PN (PMP), PN (EEPS 5-560 nm), PN (EEPS 23-560 nm)
Gasoline, PM is gravimetric on TX40HI20-WW Emfab filters

<table>
<thead>
<tr>
<th>Cycle</th>
<th>PM mass [mg/km]</th>
<th>PN (PMP) [#/km x 10^12]</th>
<th>PN EEPS 24-560 nm</th>
<th>PN EEPS 5-560 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>WLTP cold</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WLTP hot</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NEDC hot</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Art urb</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Art rur</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Art 130</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>US06</td>
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</tr>
</tbody>
</table>
Fuel effect on HC, CO, NOx, CO2: 4 runs of Artemis cycle

SAE 2015-24-2513 in review
Laboratory and on-road particle emissions of DISI engines fueled with butanol blends.

Vojtisek-Lom, 19th ETH Conference on Combustion Generated Nanoparticles, June 29, 2015

**Fuel effect on PM, PN (PMP), PN (EEPS, 24-560 and 5-560 nm)**

### PM - gravimetric

<table>
<thead>
<tr>
<th>mg/km</th>
<th>PM</th>
<th>Gas E0</th>
<th>E15</th>
<th>nBu25</th>
<th>iBu25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Art urb</td>
<td>3.5</td>
<td>3.0</td>
<td>2.5</td>
<td>2.0</td>
<td>1.5</td>
</tr>
<tr>
<td>Art rur</td>
<td>3.0</td>
<td>2.5</td>
<td>2.0</td>
<td>1.5</td>
<td>1.0</td>
</tr>
<tr>
<td>Art 130</td>
<td>2.5</td>
<td>2.0</td>
<td>1.5</td>
<td>1.0</td>
<td>0.5</td>
</tr>
</tbody>
</table>

### PN - EEPS 24-560 nm

<table>
<thead>
<tr>
<th>#/km</th>
<th>PN-EEPS &gt; 23 nm</th>
<th>Gas E0</th>
<th>E15</th>
<th>nBu25</th>
<th>iBu25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Art urb</td>
<td>6.0E+12</td>
<td>5.0E+12</td>
<td>4.0E+12</td>
<td>3.0E+12</td>
<td>2.0E+12</td>
</tr>
<tr>
<td>Art rur</td>
<td>5.0E+12</td>
<td>4.0E+12</td>
<td>3.0E+12</td>
<td>2.0E+12</td>
<td>1.0E+12</td>
</tr>
<tr>
<td>Art 130</td>
<td>4.0E+12</td>
<td>3.0E+12</td>
<td>2.0E+12</td>
<td>1.0E+12</td>
<td>6.0E+12</td>
</tr>
</tbody>
</table>

### PN - PMP

<table>
<thead>
<tr>
<th>#/km</th>
<th>PN (PMP)</th>
<th>Gas E0</th>
<th>E15</th>
<th>nBu25</th>
<th>iBu25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Art urb</td>
<td>2.5E+12</td>
<td>2.0E+12</td>
<td>1.5E+12</td>
<td>1.0E+12</td>
<td>6.0E+12</td>
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<tr>
<td>Art rur</td>
<td>2.0E+12</td>
<td>1.5E+12</td>
<td>1.0E+12</td>
<td>6.0E+12</td>
<td></td>
</tr>
<tr>
<td>Art 130</td>
<td>1.5E+12</td>
<td>1.0E+12</td>
<td>6.0E+12</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### PN - EEPS 5-560 nm

<table>
<thead>
<tr>
<th>#/km</th>
<th>PN-EEPS 5-560 nm</th>
<th>Gas E0</th>
<th>E15</th>
<th>nBu25</th>
<th>iBu25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Art urb</td>
<td>4.5E+13</td>
<td>4.0E+13</td>
<td>3.5E+13</td>
<td>3.0E+13</td>
<td>2.5E+13</td>
</tr>
<tr>
<td>Art rur</td>
<td>4.0E+13</td>
<td>3.5E+13</td>
<td>3.0E+13</td>
<td>2.5E+13</td>
<td>2.0E+13</td>
</tr>
<tr>
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<td>3.5E+13</td>
<td>3.0E+13</td>
<td>2.5E+13</td>
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</table>

**SAE 2015-24-2513 in review**
Fuel effect on PM mass – gravimetric and EC
Artemis cycle (4 runs on each fuel)

Gravimetric:
TX40HI20-WW Filters

EC:
Quartz fiber filter
EC/OC split: EUSAAR 2 protocol
"Non-volatile" component of PM and PN
Artemis cycle (4 runs on each fuel)

Are solid particles mostly larger, and volatiles smaller ???
Or artefact ???

"Solid PM" fraction: EC (from EC/OC)
-----------------------------
total PM mass

"Solid PN" fraction: PN-PMP
-----------------------------
EEPS 24-560 nm
no volatile removal
Effects of fuel on *normalized* size distribution

Normalized size distributions mostly similar among fuels
Effects of fuel on polyaromatic hydrocarbons (PAH) 
Artemis cycle, all parts, all runs

![Bar Chart]

- Extractable organic matter (ug/km)
- Sum of PAHs (ng/km)
- Sum of 16 US EPA PAHs (ng/km)
- Sum 7 cPAH (ng/km)
Effects of fuel on polyaromatic hydrocarbons (PAH)

Artemis cycle, all parts, all runs

Emissions of 7 carcinogenic PAH [ng/km]

- Benz[a]anthracene
- Chrysene
- Benzo[b]fluoranthene
- Benzo[k]fluoranthene
- Benzo[a]pyrene
- Indeno[1,2,3-cd]pyrene
- Benzo[ghi]perylene

Gasoline, E15, nBu25, iBu25
Toxicity assays: Ongoing, will report later
On-board instrumentation – EEPS, mini-PEMS, batteries

Rotating disc microdiluter, (150 C, DR 300:1) sampling from the tailpipe -> EEPS (5-560 nm, 1 Hz)
On-board monitoring system “Mini-PEMS” (13 kg)

Response approximately proportional to PM mass concentrations for a given engine

Nephelometer (laser scattering)

Sample cool & reheat

Filtered dilution air

10-12 lpm raw exhaust

Before or after DOC, DPF, ...

Condensate and large particle removal

Modified ionization smoke alarm (a 100 EUR system) - response proportional to total particle length (close to lung deposited surface area?)

Filter, flow control, pump

Charge meter

F-FC-P

NDIR-HC,CO,CO2

chem.cell NO

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NDIR-HC,CO,CO2

chem.cell NO

Engine

outflow

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chem.cell NO

F-FC-P

NDIR-HC,CO,CO2

chem.cell NO

Engine

outflow
Test route

55 km, 1-hour
2 times on each fuel

Preconditioning:
(Artemis or 1 run) + 6 km
Instantaneous PN emissions along the test route
Laboratory and on-road particle emissions of DISI engines fueled with butanol blends.

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Laboratory and on-road particle emissions of DISI engines fueled with butanol blends. 

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PN as a function of engine power

Mass air flow used as a surrogate of fuel flow (stoichiometric operation), fuel flow as a surrogate of engine power

EEPS-based particle mass
concentration [mg/m³]

engine mass air flow [g/s]

Gas-2
Gas-3
E15-1
E15-2
nBu-1
nBu-2
iBu-1
iBu-2
PN as a function of road speed and engine power

PN emissions are dominated by full-power accelerations – notably for gasoline, less for E15, and much less for both butanols.
Summary

Particle emissions from DISI engines
- emissions from production / in-use engines -- MEASURED
- effects of driving cycle / off-cycle emissions – investigated & found
- particles smaller than 23 nm – found, about half of 5-560 nm total count
- volatile nanoparticles – found, large part of total PN
- non-regulated compounds – PAH measured, toxicity tests ongoing

Real driving emissions and their measurement
– onboard mini-PEMS and EEPS (onboard FTIR to be done later)
  – PM and PN emissions dominated by high power operation

Effect of butanol on particle emissions
While E15 did not produce consistent PN or PM reduction, both 25% n-butanol and 25% isobutanol reduced elemental carbon (EC), particle number emissions per PMP, and 7 US EPA priority carcinogenic polyaromatic hydrocarbons by roughly one half, with no increase in NOx or other demonstrated problem.
Warning: This engine may produce nanoparticles that are harmful when inhaled.

Laboratory and on-road particle emissions of DISI engines fueled with butanol blends.

Vojtisek-Lom, 19th ETH Conference on Combustion Generated Nanoparticles, June 29, 2015

Czech Science Foundation project BIOTOX (13-0148S): Mechanisms of toxicity of particles from biofuels

EU LIFE+ program, project MEDETOX - Innovative Methods of Monitoring of Diesel Engine Exhaust Toxicity in Real Urban Traffic (LIFE10 ENV/CZ/651)

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Thank you!