Measurement of particle emissions from small engines during real-world operation using simple on-board (or off-board) monitoring systems

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Is diesel PM becoming more of a question of public policy rather than technology?

With DPF

Euro 5 with no DPF
(Prague, CZ)
Gasoline engine PM emissions – DISI vs. MPI
Chassis dynamometer tests by authors (warm - no cold start)
Direct injection (DISI): Škoda Octavia 1.4 TSI (Euro 5)
Port injection (MPI): Škoda Fabia 1.4 MPI (Euro 4)

PM mass mg/km

NEDC
Artemis urban & rural
WLTP
US06
Artemis motorway 130
Artemis motorway 150

EURO 5 mass limit

direct injection
port injection

0 10 20 30 40 50 60 PM mass mg/km
Gasoline PM: deterioration vs. enrichment effects

Chassis dynamometer tests by authors (warm - no cold start)

Direct injection: Škoda Octavia 1.4 TSI (Euro 5)
Port injection: 2 x Škoda Fabia 1.4 MPI (Euro 4)

Deterioration apparent on NEDC, but not on Artemis motorway 130 & 150 where enrichment is the dominant cause of high PM

~ 50x NEDC
Gasoline engine PN emissions

Chassis dynamometer tests by authors (warm - no cold start)
Direct injection: Škoda Octavia 1.4 TSI (Euro 5)
Port injection: 2 x Škoda Fabia 1.4 MPI (Euro 4)

EURO 5 PN limit

Old MPI was not able to follow US06 or Artemis 150
Gasoline engine PM: Choice of cycles

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?

**EURO 5 PM mass limit**

**EURO 5 PN limit**

- NEDC
- Artemis urban & rural
- WLTP
- US06
- Artemis motorway 130
- Artemis motorway 150

PM mass [mg/km]

- direct injection 20 K km
- port injection 30 K km

PM mass [mg/km]

- direct injection 20 K km
- port injection 30 K km

PM [#/km]
Gasoline engine real-driving PM emissions
Gasoline engine on-road PM emissions – steady speed vs. full-power acceleration

### Instantaneous fuel consumption

- **PM [ug/s]**
- **PM [mg/m^3]**
- **km/h GPS**

**Road speed [km/h]**

**PM [ug/s]**

**PM [mg/m^3]**

**Area of each mark is proportional to the instantaneous PM emissions in mg/s**
This work: Particle emissions from small engines under real “driving” conditions

- Cheap simple engines
- No electronic controls
- No aftertreatment
- Immediate proximity of the operator from the tailpipe

Approaches:
- On-board system
- Off-board system on accompanying vehicle
- PM sampling
This work: Particle emissions from small engines under real "driving" conditions

Only direct exhaust emissions considered here. Non-engine & secondary emissions not considered.
Low-cost on-board monitoring system designed & used by the author:

Analytical hardware

Response approximately proportional to PM mass concentrations for a given engine

Nephelometer (laser scattering)

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

0.1 g/kWh PM engine, various fuels and modes, EC 1%-79%
reference: EEPS sampling from dilution tunnel

heated ionization
“smoke detector”
undiluted raw exhaust
(multiplied by intake air flow for comparison measurements)

~ 0.1 mg/m³
sensitivity
cheap (100 EUR)
“poor man’s PEMS”

EEPS total number concentration > 23 nm [#/cm³]
ionization chamber length concentration [mm/cm³]

Rapeseed oil no DPF
Rapeseed oil with DPF
Diesel fuel no DPF
Diesel fuel with DPF

EEPS total mass concentration (at 0.55 g/cm³) [mg/m³]
ionization chamber length concentration [mm/cm³]

Rapeseed oil no DPF
Rapeseed oil with DPF
Diesel fuel no DPF
Diesel fuel with DPF

PN > 23 nm with volatiles

EEPS total length concentration [mm/cm³]
ionization chamber length concentration [mm/cm³]

Rapeseed oil no DPF
Rapeseed oil with DPF
Diesel fuel no DPF
Diesel fuel with DPF

EEPS total number concentration > 23 nm [#/cm³]
Low-cost on-board system overview
(Vojtisek-Lom and Cobb, CRC On-road vehicle emissions workshop, 1998)

1. Exhaust gas flow calculations
2. Mass emissions = const. x concentration x exhaust flow
3. Fuel consumption = C emissions (PM, HC, CO, CO2) / C in fuel

Integrating: Emissions per test, distance, kg of fuel

Data recording

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Engine

ECU

Direct measurement

Diagnostic interface

Mass air flow, intake air pressure and temperature, engine rpm, vehicle speed, engine temperatures

GPS – position.
Speed, altitude
Time signal

Measured concentrations
HC, CO, CO2, NO, particulates

Time shift (delay)
Determined experimentally

\[ Q_{vzd} = \frac{\eta_{vol} \cdot M_{air} \cdot P_{intake} \cdot \omega \cdot \text{displacement}}{R \cdot T_{intake}} \]

Synchronization of data
Harmonization of sample interval to 1 s
On-board system versatility: Motorcycle to locomotive

5 Hz GPS receiver
Speed, position, altitude

Intake air manifold absolute pressure

Raw exhaust sampling point (no dilution)

Special adapter fabricated and inserted before muffler (outside air penetrates well into tailpipe)

Engine speed measured with optical tachometer

2009 Coliber Fartt scooter
0.049 liter carbureted engine

Locomotive
163 liter diesel

Truck
Portable proportional sampling

Diluted sample flow through filter is constant (20-50 dm³/min).

Dilution air flow is regulated so that raw exhaust flow into microdilution tunnel is proportional to the total exhaust flow.

HEPA filtered air is metered into microdilution tunnel near sampling point.

Raw exhaust flow =
= total sample flow - dilution air flow

Exhaust flow ~ measured intake air flow
Enhanced gain algorithm:
Fast response vs. stability and repeatability
(diesel engine, 3 consecutive runs of ETC cycle, Juliska, CVUT, 2012)

high stability & repeatability during highway cruise section of ETC
Portable proportional sampling vs. traditional system: PM mass per transient test cycle

In-use diesel engines, various manufacturers, \( \sim 1-50 \text{ mg/kWh PM} \)

Transient operation on engine dynamometer (NRTC, WHTC, ETC)

CVUT - Juliska: DC dynamometer, reference AVL SmartSampler

TUV - Lihovarska: AC dynamometer, reference AVL SmartSampler

CVUT - VTP: AC dynamometer, reference full-flow dilution tunnel

![Graph showing comparison between portable proportional sampling and traditional system.](image-url)
Experimental – Motorcycle (scooter)

- 4-cycle 50-cc SI engine
- 13 kg PEMS on luggage rack
- Battery-powered system
- SAE J-2711: Pre-run & at least 3 runs along the route

- 5 Hz GPS receiver
  - Speed, position, altitude
- Intake air manifold
  - Absolute pressure
- Raw exhaust sampling point
  - (no dilution)
- Special adapter
  - Fabricated and inserted before muffler (outside air penetrates well into tailpipe)
- Engine speed
  - Measured with optical tachometer

2009 Coliber Fartt scooter
- 0.049 liter carbureted engine
Experimental – Test route

- Route length: approx. 13 km
- Start point altitude: 410 m
- Peak altitude: 660 m
- Lowest point altitude: 380 m
How a scooter is driven

- Mostly “full power or nothing”, pulse-width modulation
- Example: Liberec region, each point = 1 second of operation
- Distinct regions: idle, full-power, engine braking, transitions

![Graph showing operating conditions with regions marked: Full throttle, Transitions, Engine braking, Idle]
Emissions patterns

Larger particles (detected by light scattering) and hydrocarbons dominated by transitions

CO high during transitions and at full power
Emissions patterns

Larger particles (detected by light scattering) and hydrocarbons dominated by transitions

Small particles (detected by ionization chamber) emitted throughout the operating range

NOx highest at full power
Motorcycle (scooter) – test summary per km

<table>
<thead>
<tr>
<th>Emissions per km</th>
<th>HC [g]</th>
<th>CO [g]</th>
<th>NOx [g]</th>
<th>PM laser [mg]</th>
<th>PM ion1 [km]</th>
<th>PM ion2 [km]</th>
<th>CO2 [g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban</td>
<td>2.72</td>
<td>11.2</td>
<td>0.50</td>
<td>3.3</td>
<td>406</td>
<td>386</td>
<td>53</td>
</tr>
<tr>
<td>Rural</td>
<td>1.30</td>
<td>8.4</td>
<td>0.41</td>
<td>2.7</td>
<td>320</td>
<td>255</td>
<td>39</td>
</tr>
</tbody>
</table>

- Route length: approx. 13 km
- Start point altitude: 410 m
- Peak altitude: 660 m
- Lowest point altitude: 380 m
On-board measurement – riding mower

Riding lawnmower
TCP 102, Castelgarden, Italy, mfg. in 2001, 4-cycle gasoline

Mowing family house lawn

PM length is relative units per kg of fuel
All other data is in grams per kg of fuel
Off-board measurement – chain saw

Chainsaws
Stihl 029 (top)
Stihl MS361 (bottom)
2-cycle gasoline

Cutting firewood (logs)
On-board system mounted on accompanying tractor
Off-board measurement – chain saw

Chainsaws
Stihl 029 (top)
Stihl MS361 (bottom)
2-cycle gasoline

Cutting firewood (logs)
On-board system mounted on accompanying tractor

Fuel-specific emissions
[g / kg fuel] or [g / kg fuel]

Ground speed [km/h]

Chain saw 2-cycle

M. Vojtisek et al.: Measurement of particle emissions from small engines during real-world operation using simple on-board (or off-board) monitoring systems
18th ETH Conference on Combustion Generated Nanoparticles, Zurich, CH, June 22-25, 2014
Off-board measurement – weed-eater
PEMS mounted on accompanying tractor

Weed-whacker
Oleo-Mac 746T
2-cycle gasoline

Cutting /clearing an overgrown ditch
On-board system mounted on accompanying tractor

![Image of a weed-whacker and tractor]

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**Figure:**
The figure shows a graph labeled "Weed-whacker 2-cycle." It plots fuel-specific emissions (g/kg fuel) on the y-axis against time on the x-axis. The emissions are categorized by different pollutants: HC, CO, NOx, CO2, PM-Opt, and PM-Ion. The graph also includes a separate y-axis for speed in km/h. The data is collected during the operation of a weed-whacker, and the graph shows variations in emissions over time with corresponding speed changes.
Off-board full-flow dilution tunnel

- Mass flow meter
- Sample filter 142-150 mm
- 50 EUR retired baby stroller (a designer 5000 EUR PEMS cart available)
- An industrial vacuum cleaner can be used in lieu of the blower
- PEMS
- Blower
- rpm sensor
- Highly insulated transfer line
- Intake manifold pressure sensor

Not a true CVS: As all exhaust passes through the filter, constant flow does not have to be maintained.
Off-board full-flow dilution tunnel

Entrance of raw exhaust

Dilution air inlet & filter

Transfer line

Power options:
• lithium battery & 1000 W inverter
• extension cord to generator or power outlet
Choice of raw / diluted measurement

Sampling ("CVS") mode:
• PEMS measuring diluted exhaust
• Diluted mass exhaust flow measured directly
• All diluted exhaust sampled through the filter (no need for absolutely constant flow)

Raw & PEMS only mode:
• Intake air flow computed from engine rpm, manifold pressure and temperature
• PEMS measuring raw exhaust
• CVS not needed
• air/fuel ratio monitoring
High-volume sampling for advanced analysis

30-60 m³/min sampling on 142/150 mm filters for analyses (i.e. PAH) and toxicological assays

Isokinetic or constant flow sampling is not necessary as 100% of exhaust is sampled
Base mower test sequence: CVS on, Engine start, mowing until clipping bag is full, engine off, CVS off

Variations due to uneven lawn density & qualities
Large HC spike at (ignition) shutdown

![Graph showing CO, CO2, ground speed, HC, NOx concentrations over time]

- CO [%], CO2 [%], ground speed [km/h]
- CO2, CO, HC, NOx
- Sampling indicated
- 14:58:00 to 15:38:00

M. Vojtisek et al.: Measurement of particle emissions from small engines during real-world operation using simple on-board (or off-board) monitoring systems
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Base weed eater sequence: CVS on, Engine start, mowing until CVS filter is full, engine off, CVS off

Variations due to uneven lawn density & qualities

Large HC spike at (ignition) shutdown
Lawnmower and weed-eater – test summary
(PAH analysis and toxicology assays to follow)

<table>
<thead>
<tr>
<th>Equipment</th>
<th>PM [g/h] (mass deposited on filter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wolfgarden 4-cycle Briggs&amp;Stratton US EPA Stage II</td>
<td>0.01 0.1 1 10 100</td>
</tr>
<tr>
<td>Stiga 4-cycle Briggs&amp;Stratton US EPA Phase 1</td>
<td>0.1 1 10 100</td>
</tr>
<tr>
<td>Mid-90's 4-cycle mower</td>
<td>0.1 1 10 100</td>
</tr>
<tr>
<td>Weed-eater Stihl FS350 2-cycle</td>
<td>0.1 1 10 100</td>
</tr>
</tbody>
</table>

Pall TX40 filters 2-44 mg/filter
Quartz fiber filters hundreds mg/filter
## CARB Stage II Lawnmower – effect of alcohol fuels
### 30% iso-butanol, 30% n-butanol in gasoline

*(SAE 2014, submitted)*

<table>
<thead>
<tr>
<th>Fuel</th>
<th>HC  [g/kg]</th>
<th>CO [g/kg]</th>
<th>NOx [g/kg]</th>
<th>Fuel [g/h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline cold</td>
<td>19</td>
<td>256</td>
<td>3.1</td>
<td>433</td>
</tr>
<tr>
<td>Gasoline</td>
<td>19±5</td>
<td>293±46</td>
<td>6.1±1.6</td>
<td>387±82</td>
</tr>
<tr>
<td>30% Isobutanol</td>
<td>13±4</td>
<td>279±52</td>
<td>7.7±1.9</td>
<td>368±28</td>
</tr>
<tr>
<td>30% n-butanol</td>
<td>12±1</td>
<td>233±20</td>
<td>8.3±0.3</td>
<td>387±72</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>PAH [ug/kg]</th>
<th>cPAH [ug/kg]</th>
<th>BaP [ug/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline cold</td>
<td>763</td>
<td>80.2</td>
<td>16.8</td>
</tr>
<tr>
<td>Gasoline warm</td>
<td>24</td>
<td>4.6</td>
<td>0.3</td>
</tr>
<tr>
<td>30% Isobutanol</td>
<td>83</td>
<td>8.8</td>
<td>1.5</td>
</tr>
<tr>
<td>30% n-butanol</td>
<td>21</td>
<td>2.3</td>
<td>0.2</td>
</tr>
</tbody>
</table>
CARB Stage II 2 kW genset – alcohol fuels 10%, 30%, 50%, 70%, 100% n-butanol
(Diploma thesis Jan Vodrazka, TU Liberec, 2014)

PN in diluted exhaust [#/cm³]

- Gas 25.4
- nBu30
- nBu70
- Gas 7.5

75% load

particle electric mobility diameter [nm]
Conclusions
– real-world driving emissions of small engines

They are of a concern
- gasoline engines produce nanoparticles
- primitive technology
- proximity of the operator

They can be measured
- low-cost dilution tunnel
- full-flow sampling
- on-board & off-board systems
Acknowledgements

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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