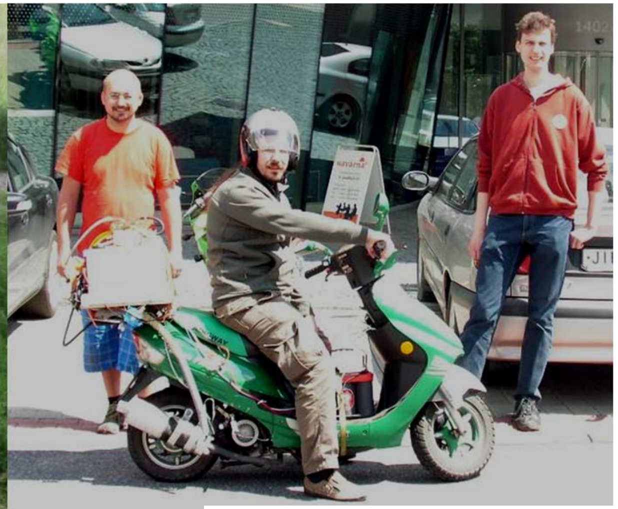
# Measurement of particle emissions from small engines during real-world operation using simple on-board (or off-board) monitoring systems



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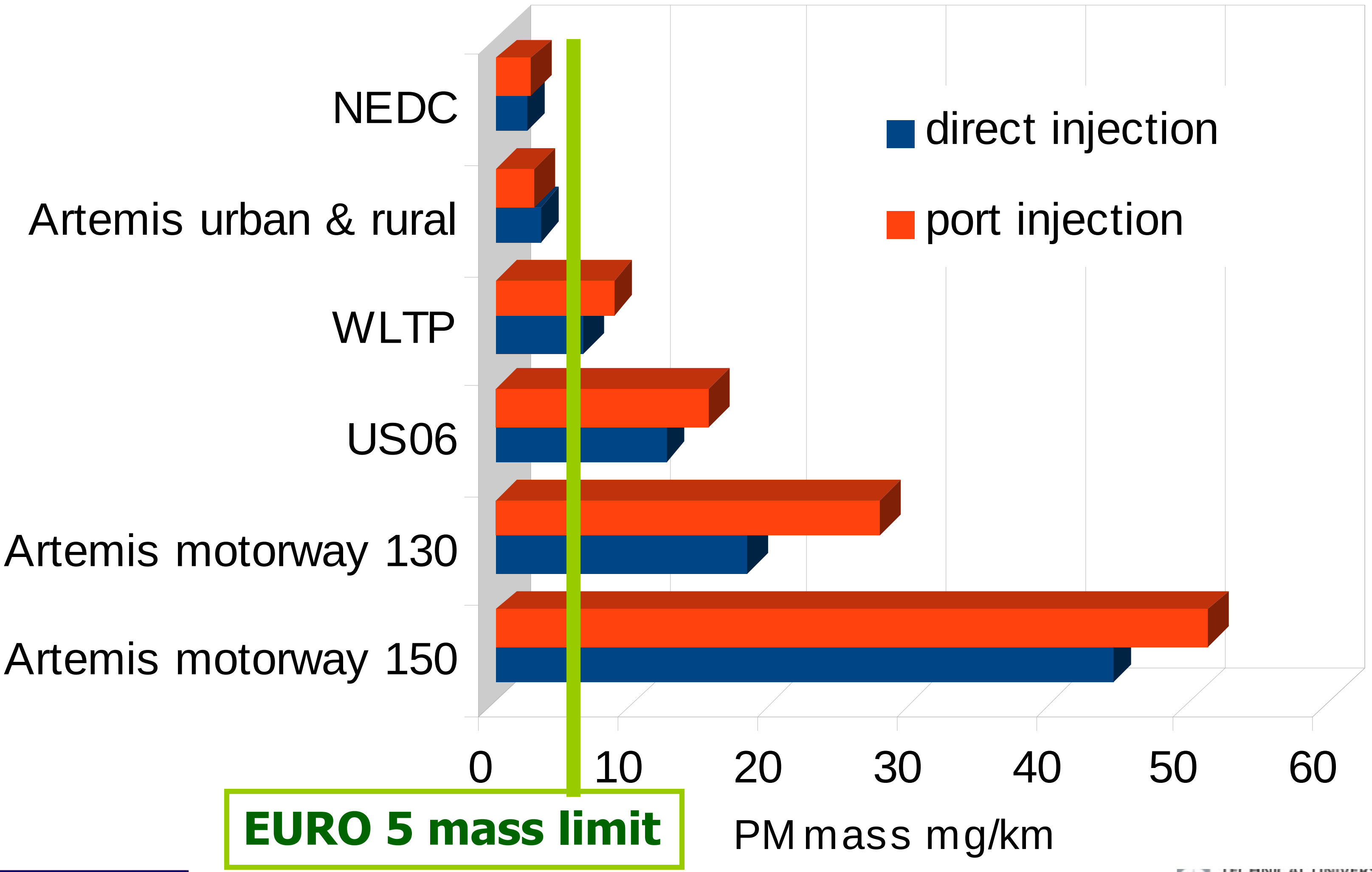
# Is diesel PM becoming more of a question of public policy rather than technology?


# 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)



# Gasoline PM: deterioration vs. enrichment effects

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

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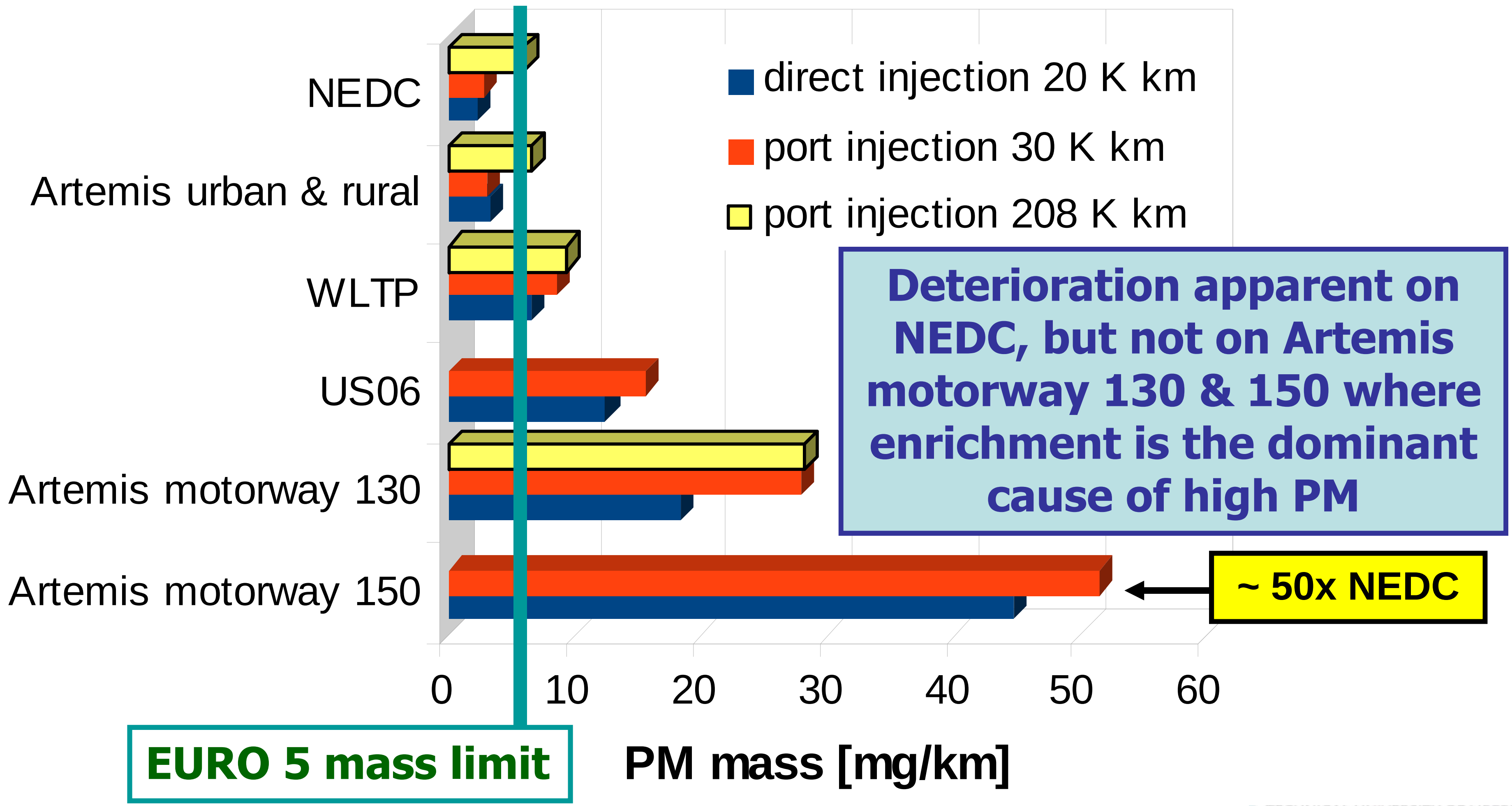
## Port injection: 2 x Škoda Fabia 1.4 MPI (Euro 4)



# Gasoline engine PN emissions

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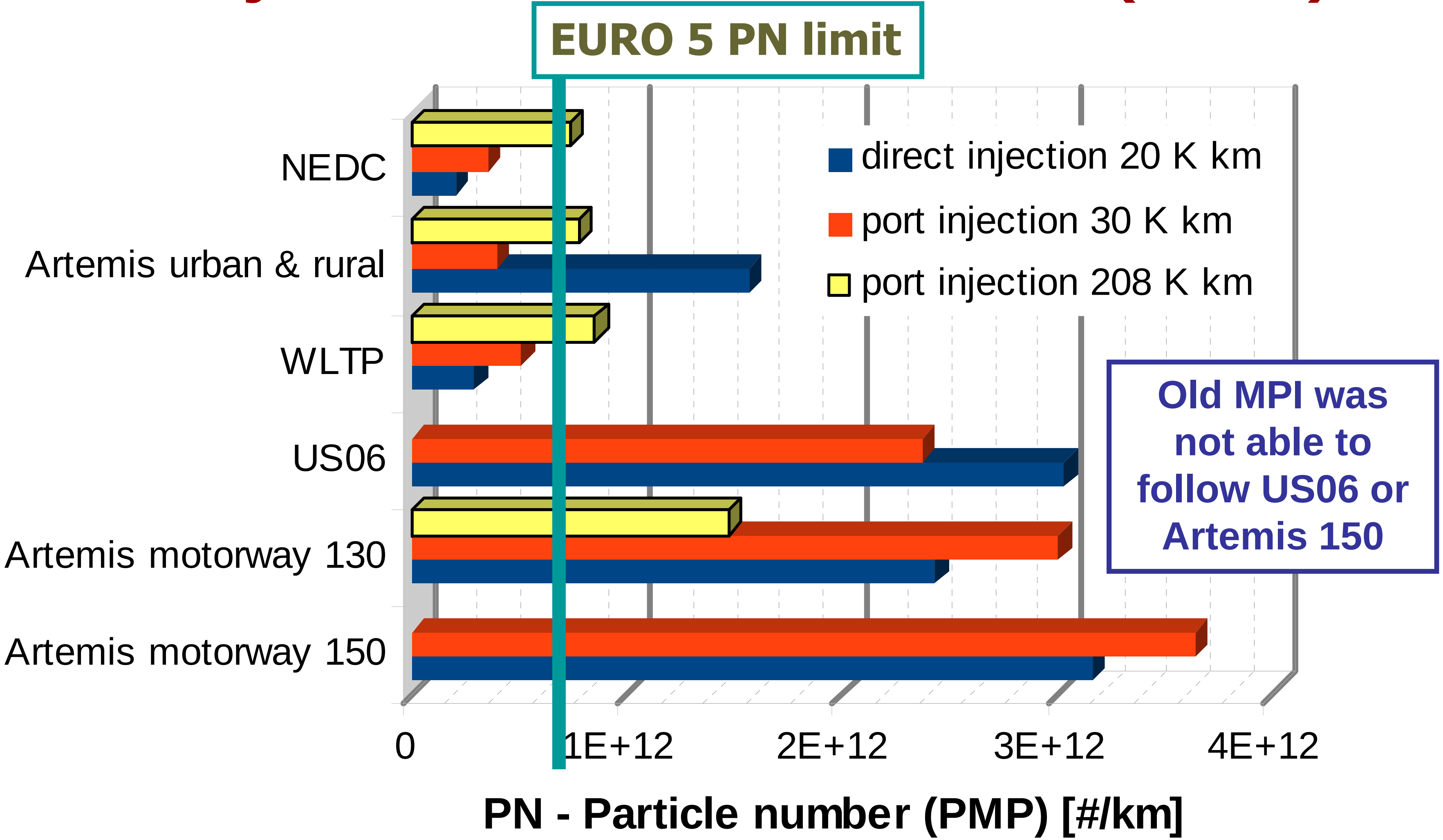
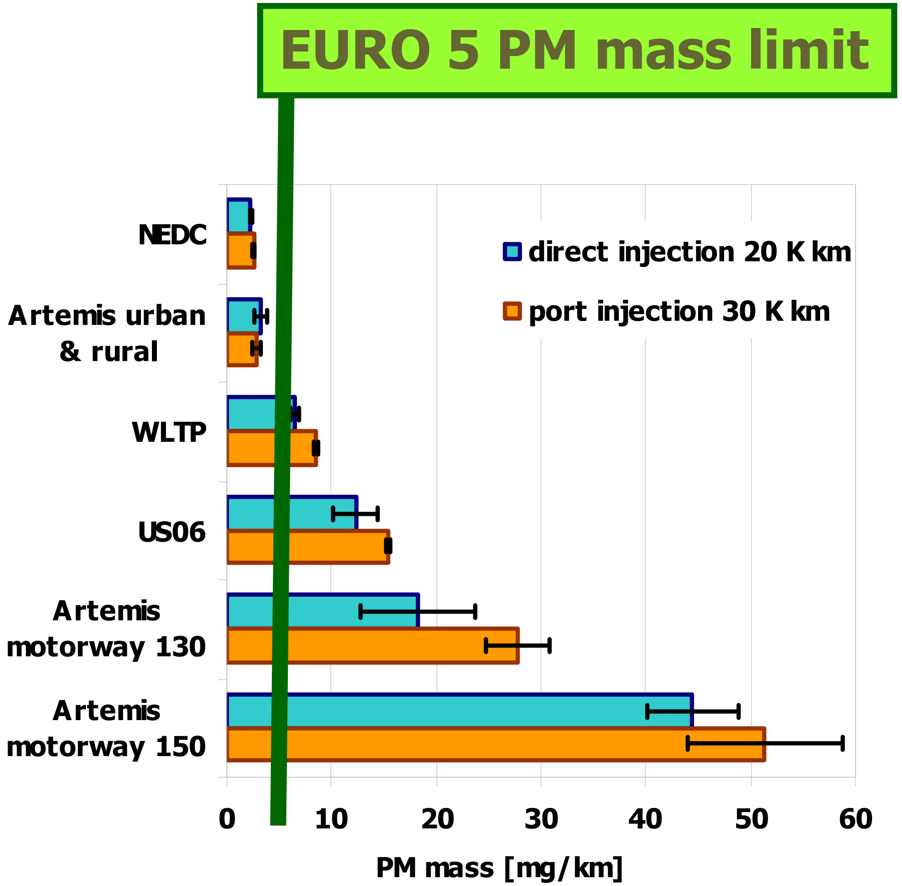
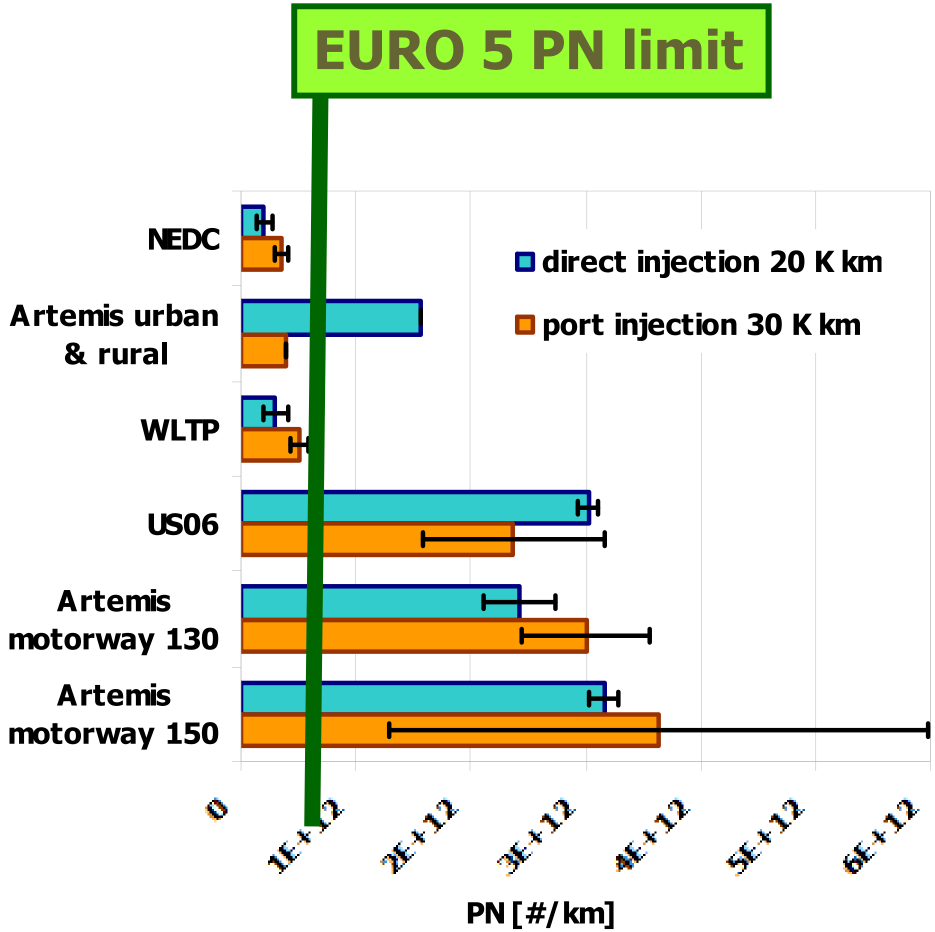


# Gasoline engine PM: Choice of cycles

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

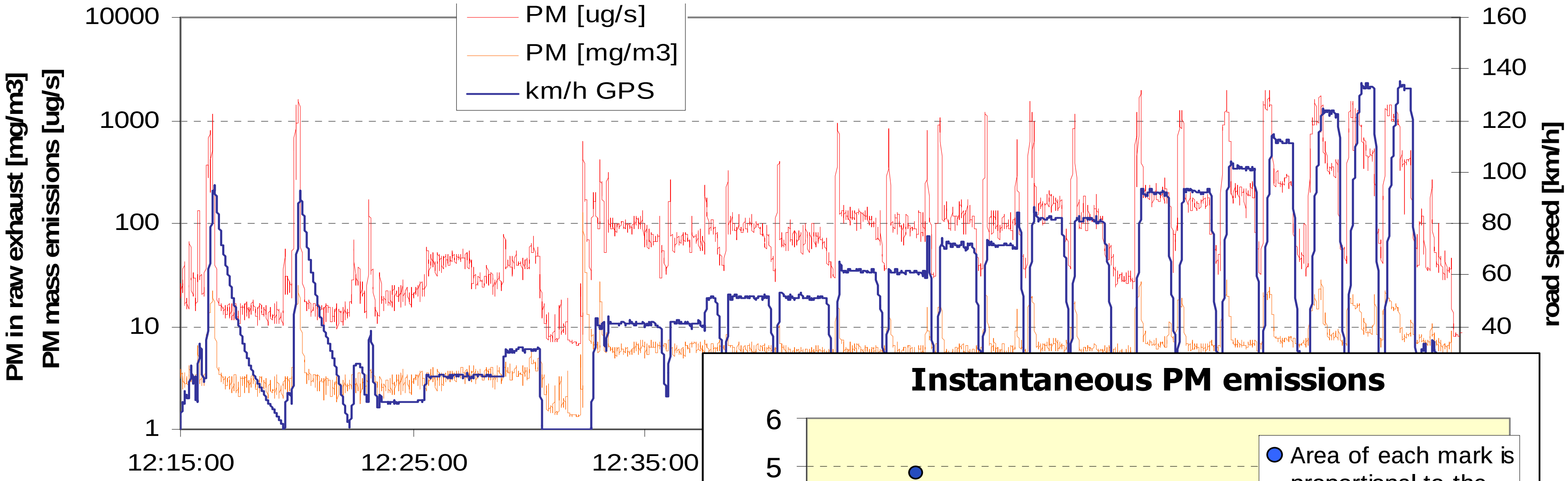
**US06 and Artemis motorway cycles as a supplement?**

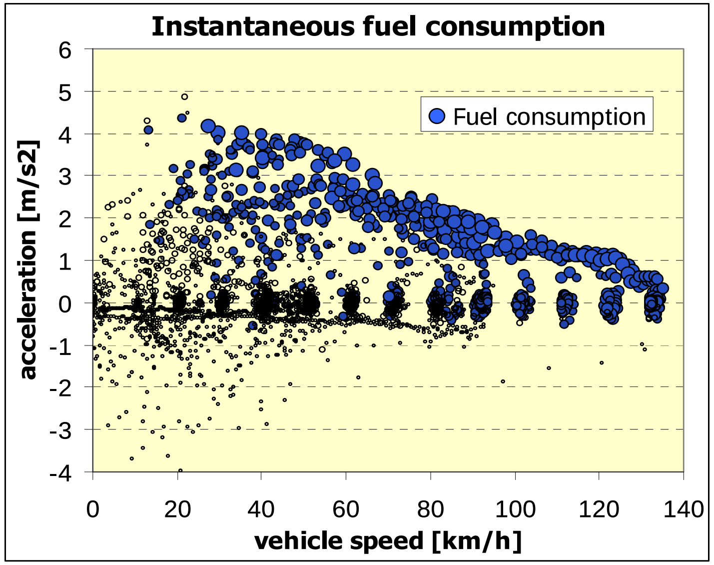


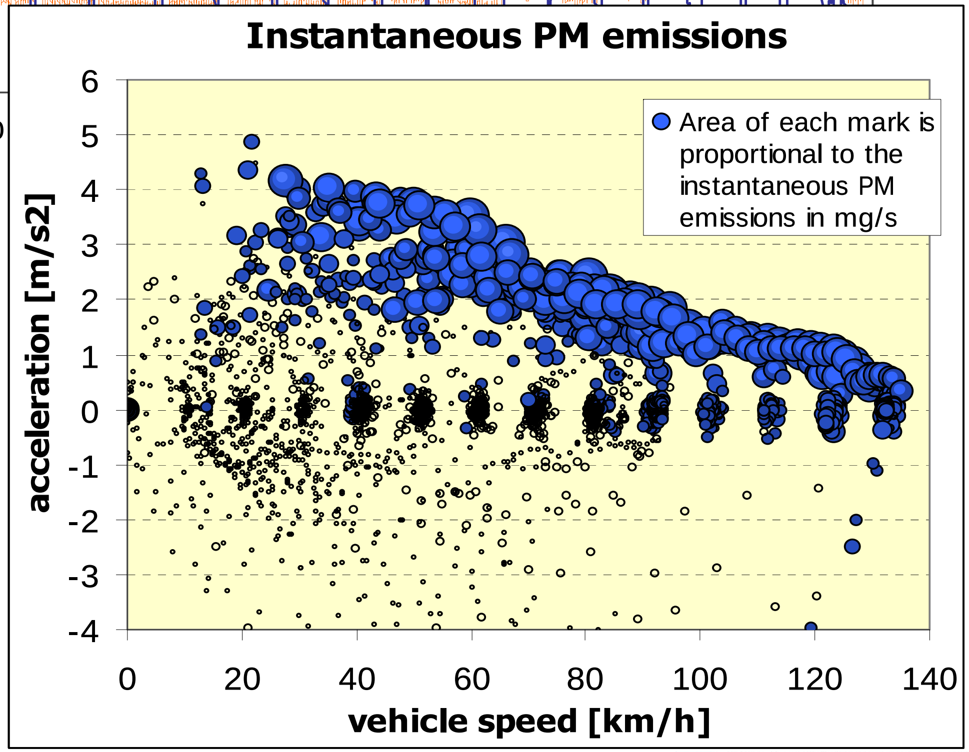



# Gasoline engine real-driving PM emissions


# Gasoline engine on-road PM emissions – steady speed vs. full-power acceleration



# This work: Particle emissions from small engines under real "driving" conditions

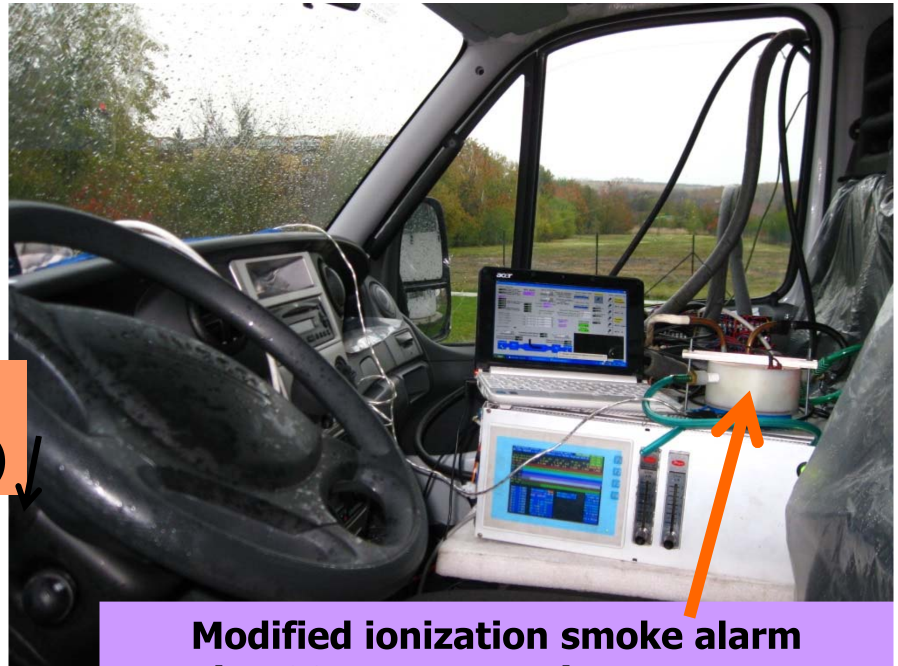
- Cheap simple engines
- No electronic controls
- No aftertreatment
- Immediate proximity of the operator from the tailpipe

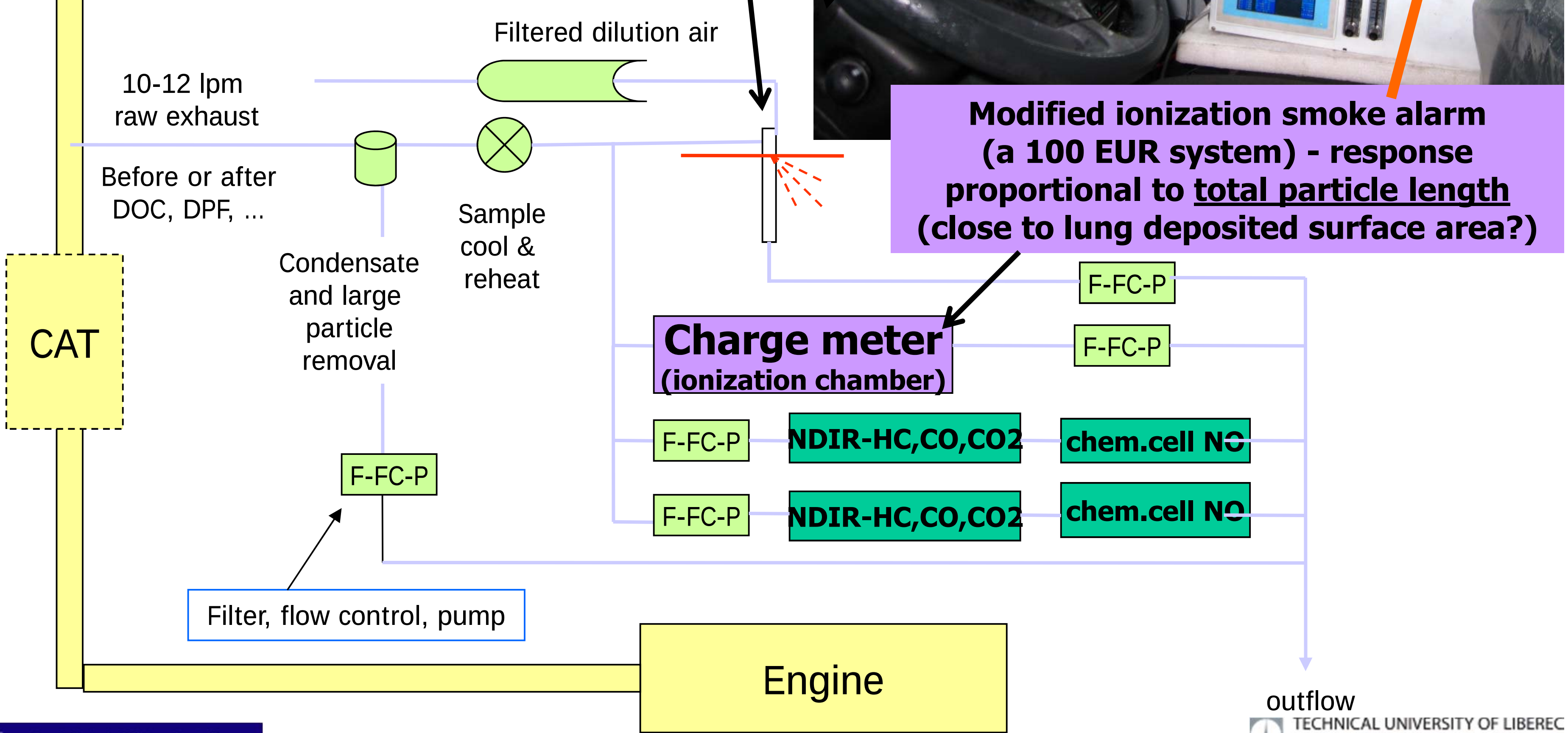
**Approaches:**

- On-board system
- Off-board system on accompanying vehicle
- PM sampling

# This work: Particle emissions from small engines under real “driving” conditions

# Low-cost on-board monitoring system designed & used by the author:
# Analytical hardware





# 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"**

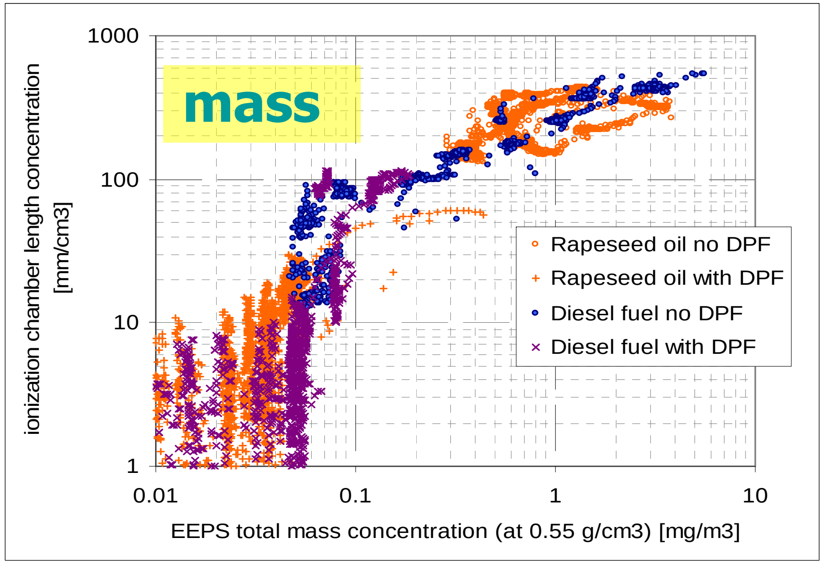
**undiluted raw exhaust**

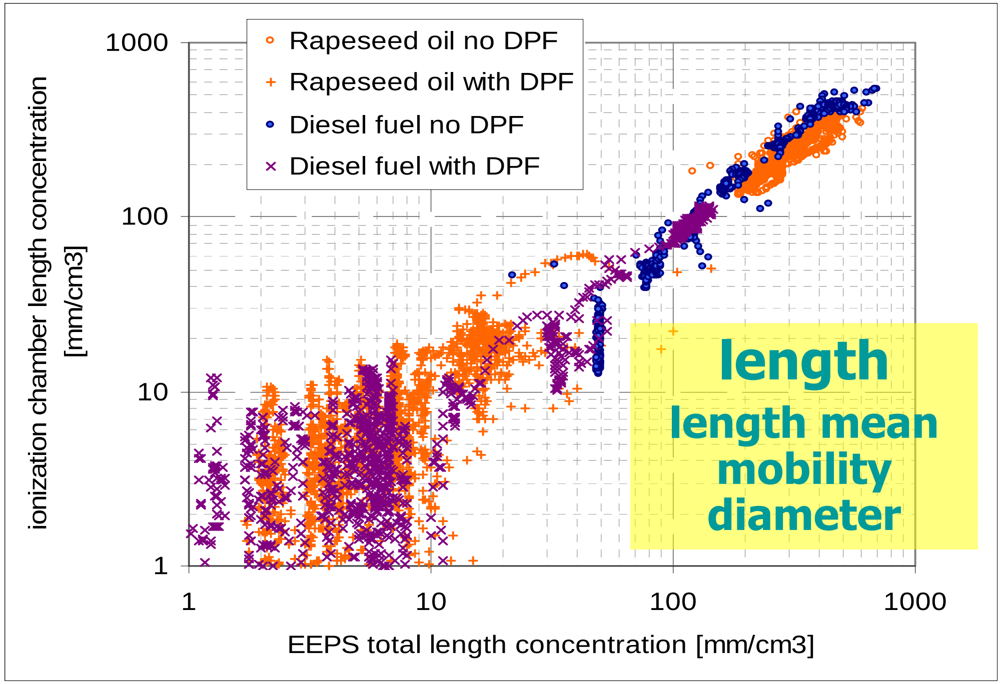
**(multiplied by intake air flow for comparison measurements)**

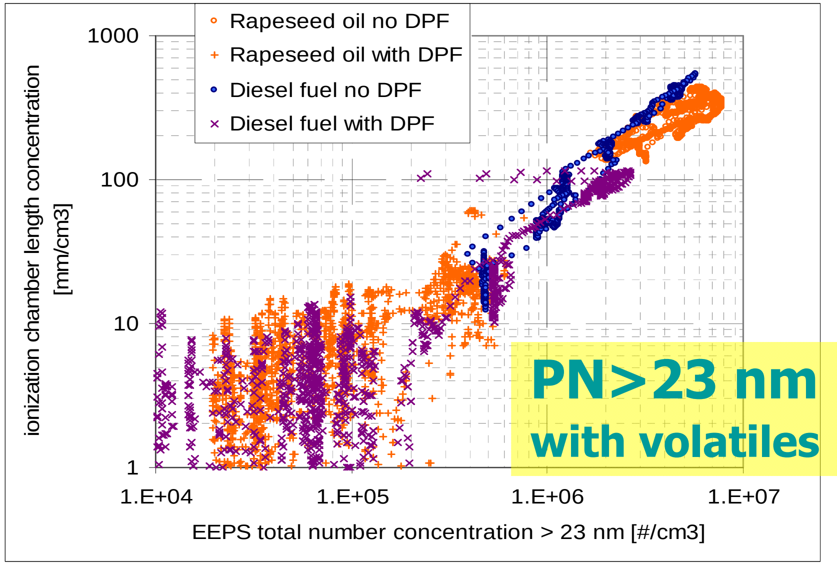
**~ 0.1 mg/m3 sensitivity**

**cheap (100 EUR)**

**"poor man's PEMS"**

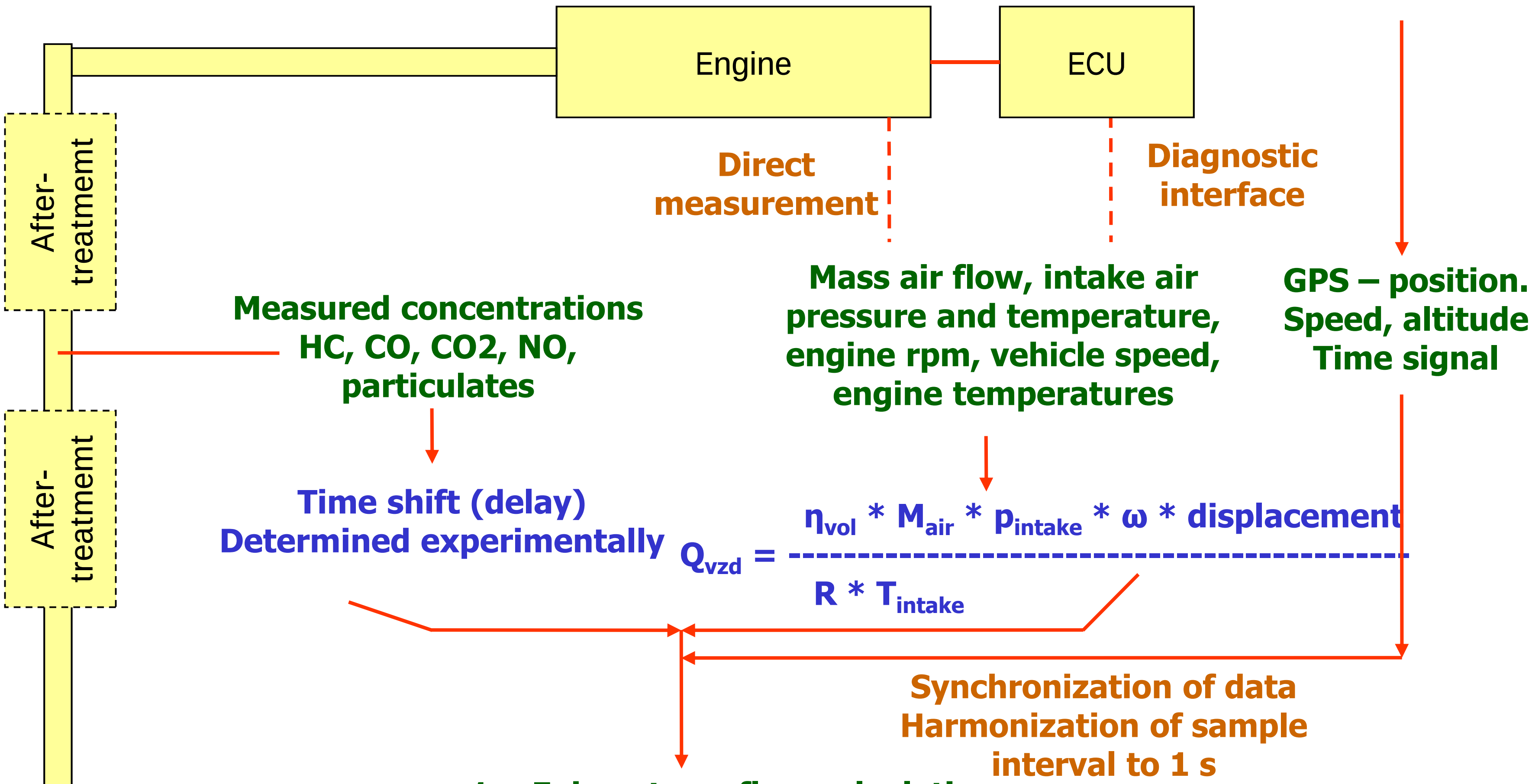


# Low-cost on-board system overview

(Vojtisek-Lom and Cobb, CRC On-road vehicle emissions workshop, 1998)

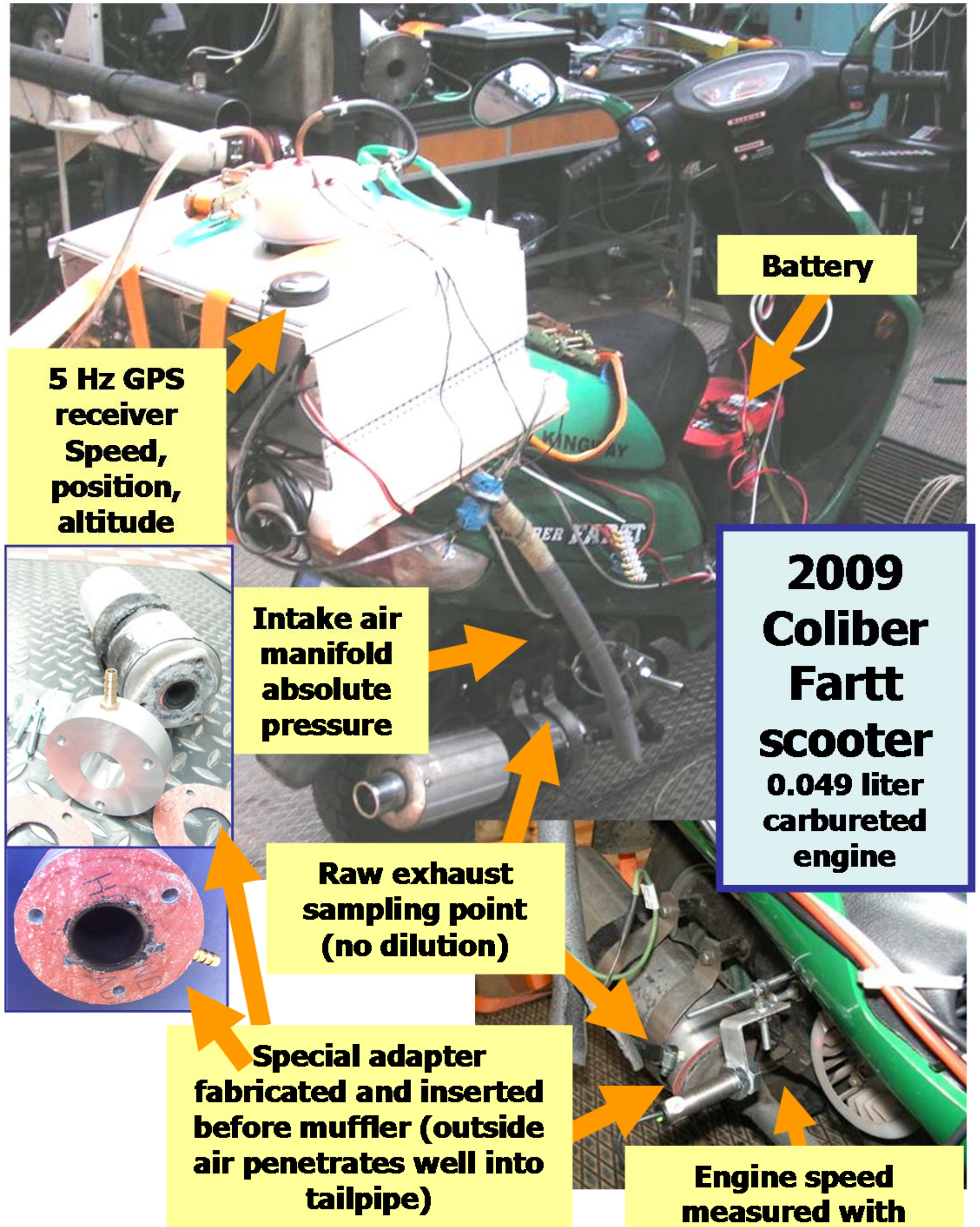



1. Exhaust gas flow calculations
2. Mass emissions = const. x concentration x exhaust flow
3. Fuel consumption = C emissions (PM, HC, CO, CO2) / C in fuel

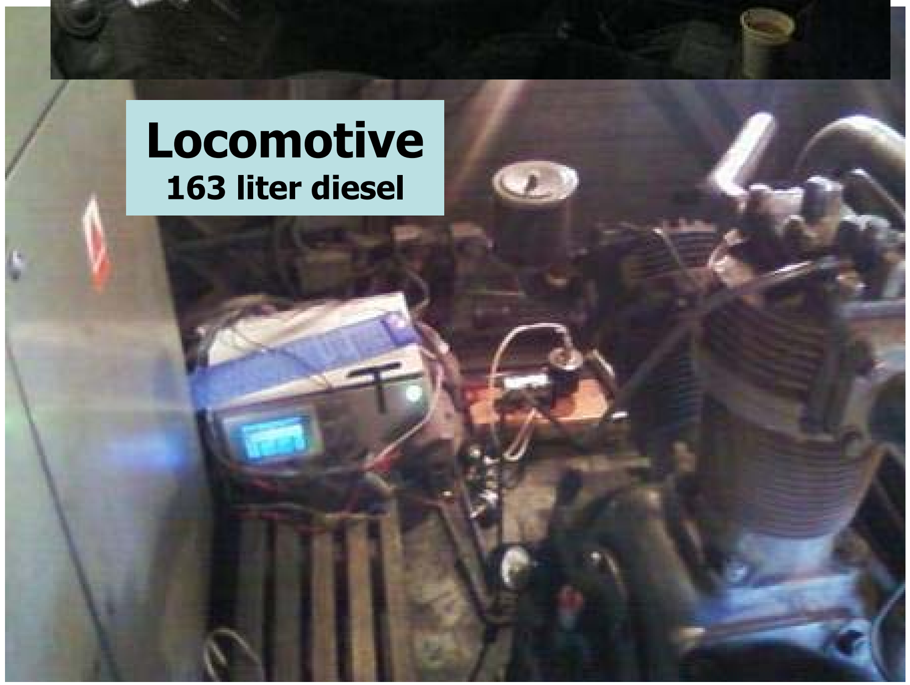
Integrating: Emissions per test, distance, kg of fuel

Data recording

# On-board system versatility: Motorcycle to locomotive







# Portable proportional sampling

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

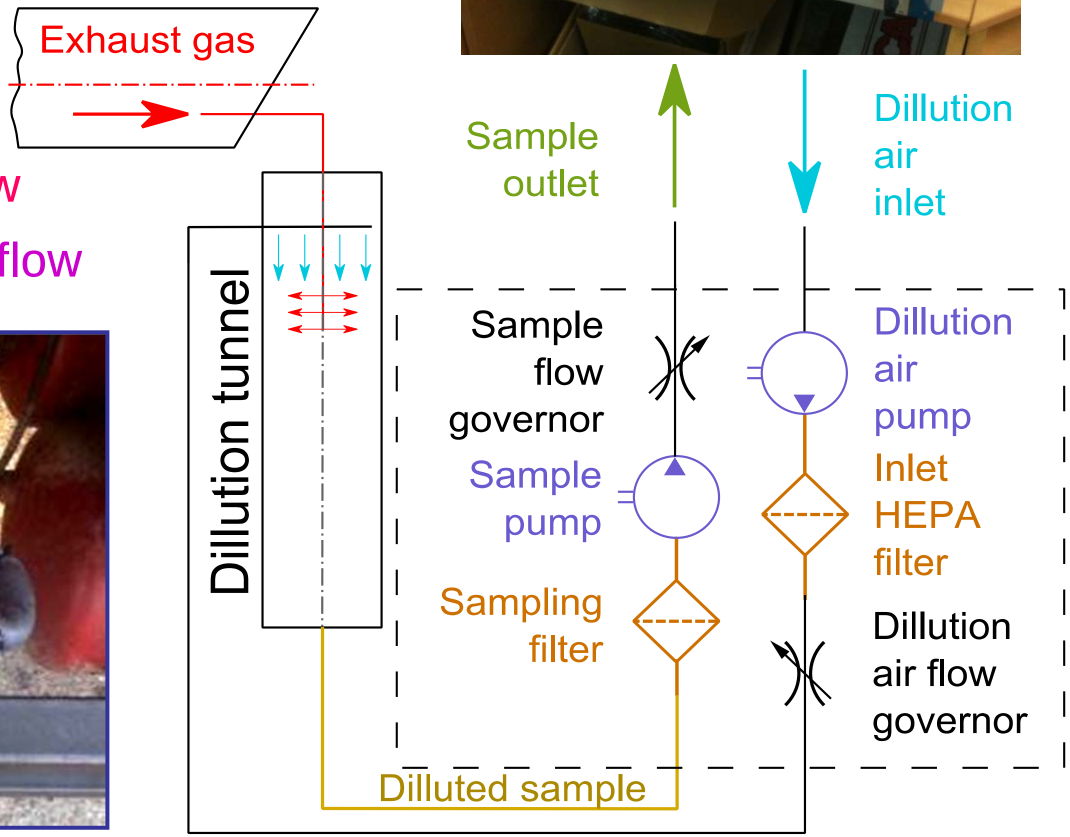
Dilution air flow is regulated so that raw exhaust flow into microdilution tunnel is proportional to the total exhaust flow.

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

Raw exhaust flow =

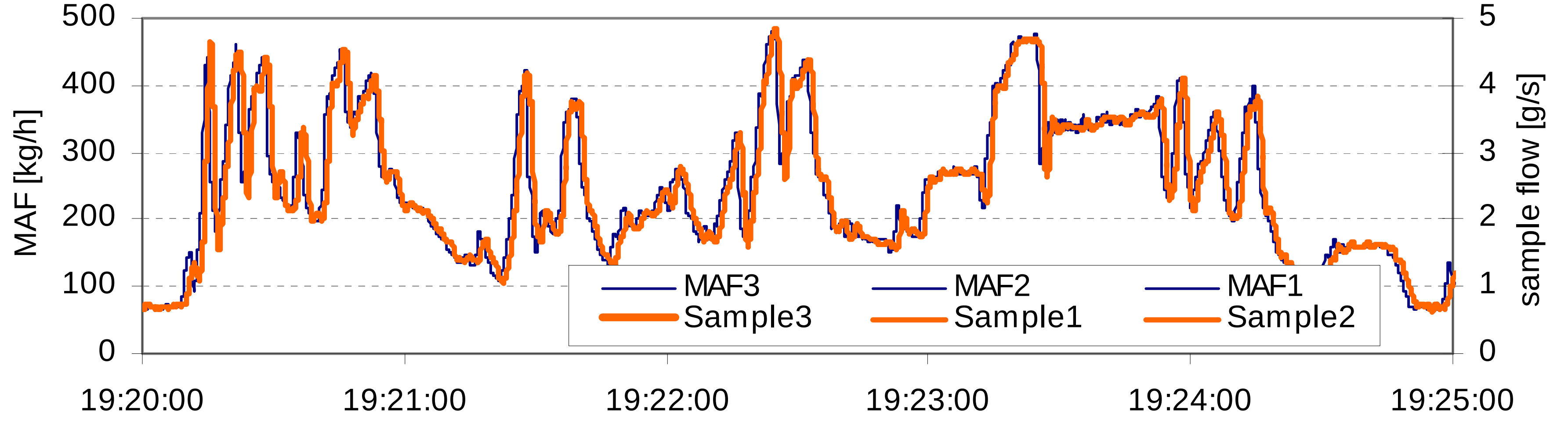
= total sample flow – dilution air flow

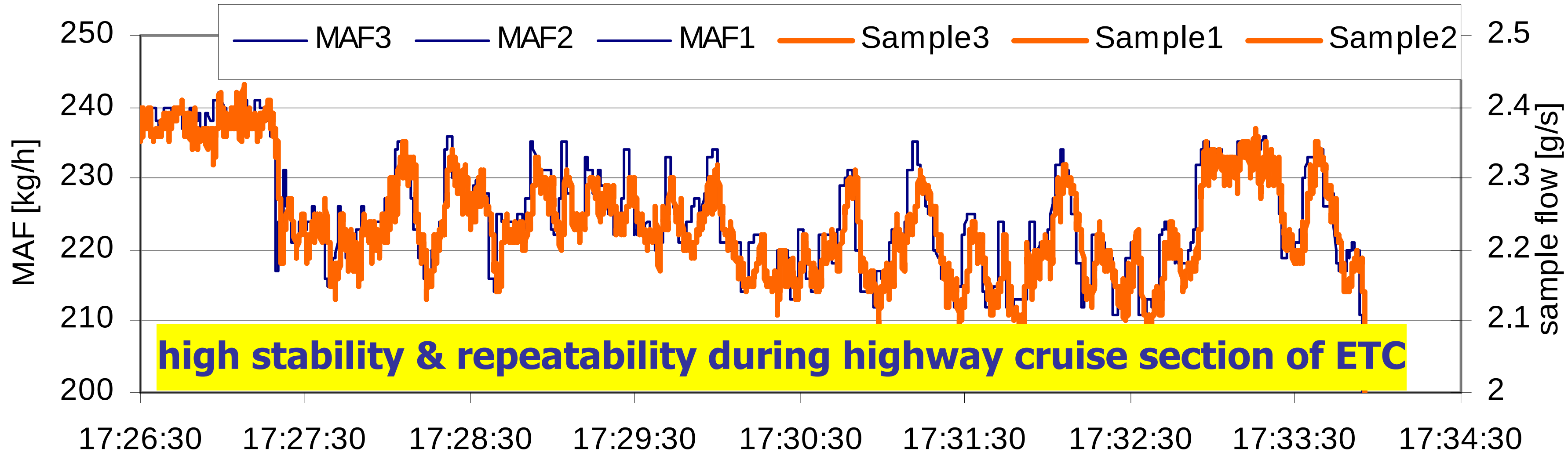
Exhaust flow ~ measured intake air flow



# Enhanced gain algorithm: Fast response vs. stability and repeatability

**(diesel engine, 3 consecutive runs of ETC cycle, Juliska, CVUT, 2012)**



# Portable proportional sampling vs. traditional system: PM mass per transient test cycle

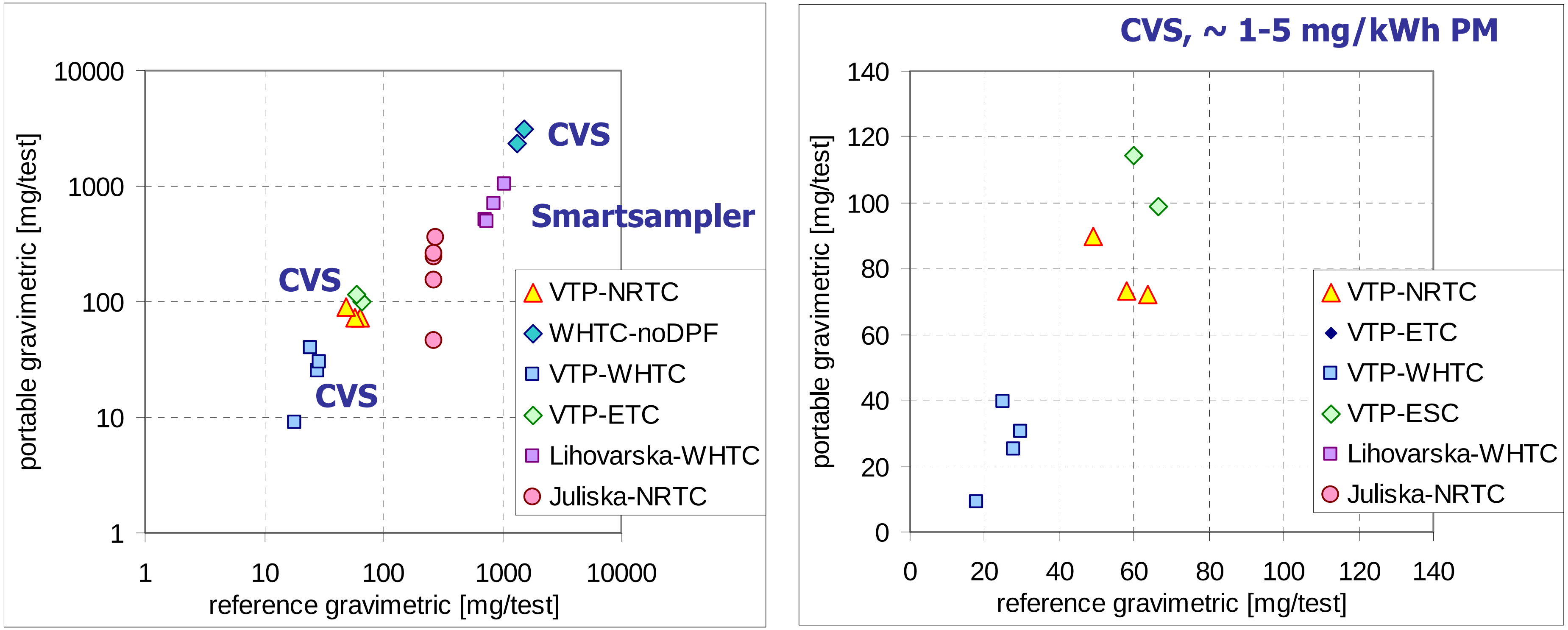
## In-use diesel engines, various manufacturers, ~ 1-50 mg/kWh PM

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

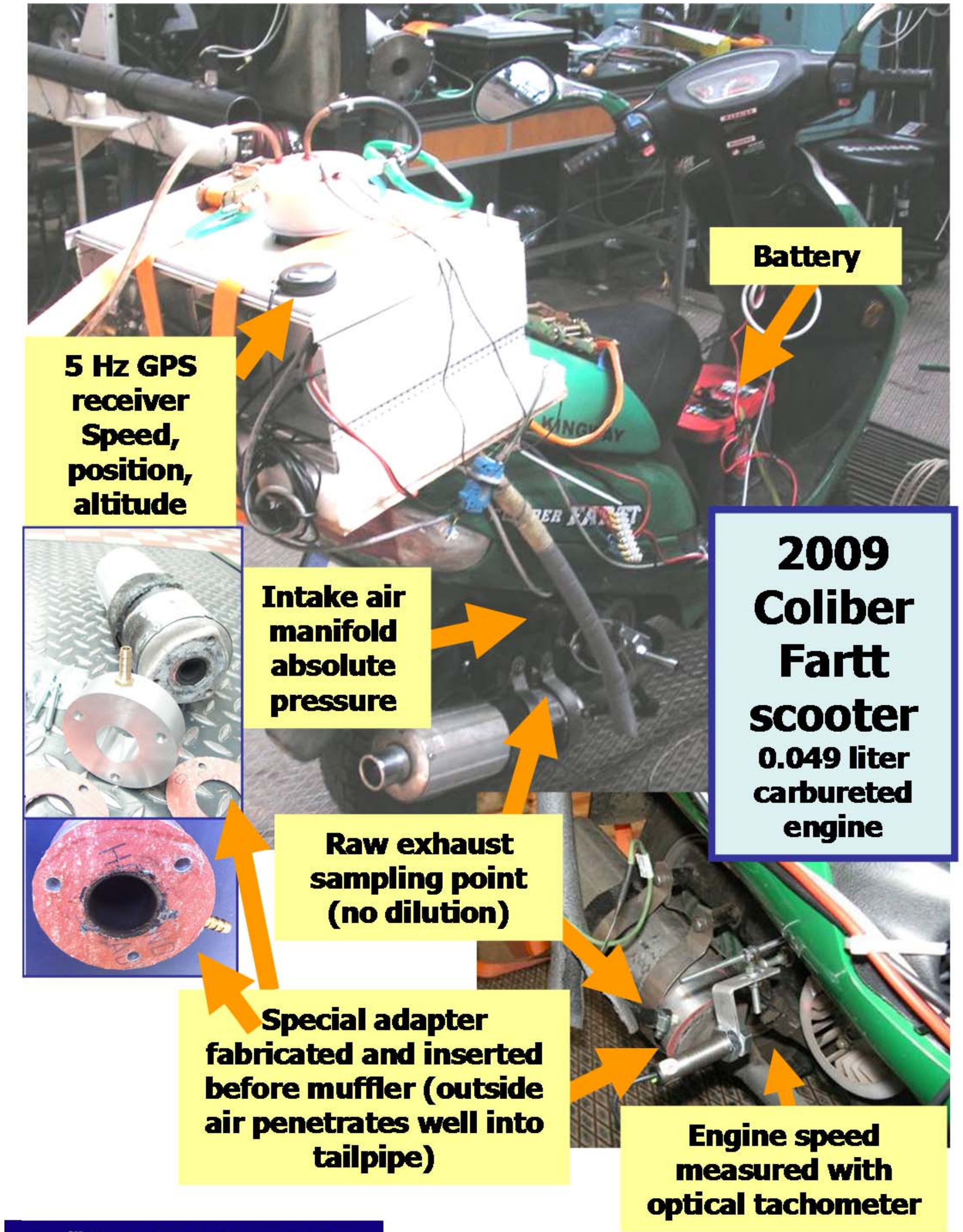
CVUT - Juliska: DC dynamometer, reference AVL SmartSampler

TUV - Lihovarska: AC dynamometer, reference AVL SmartSampler

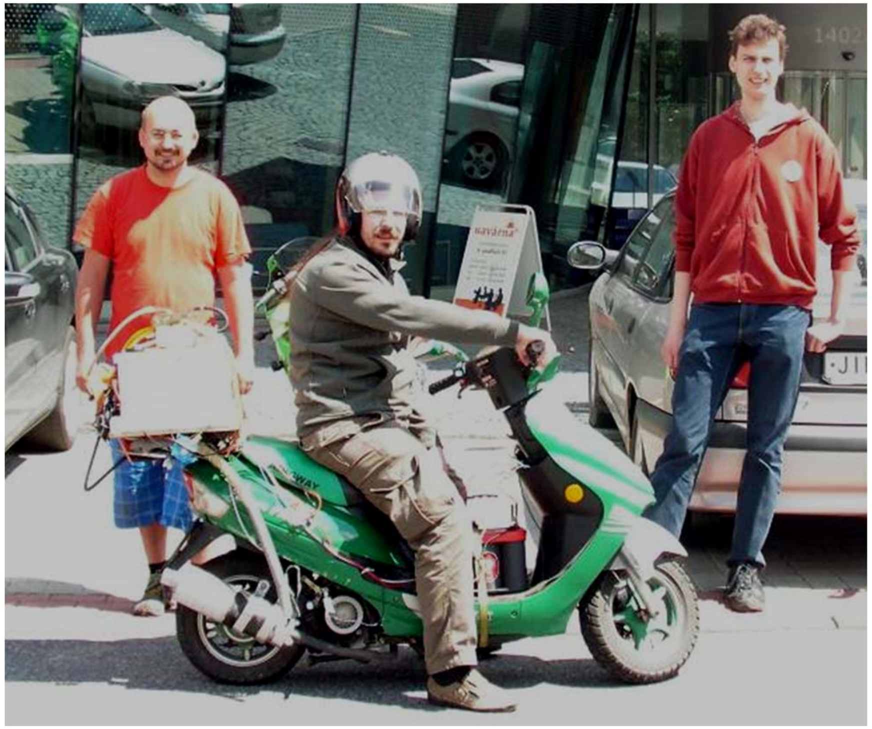
CVUT - VTP: AC dynamometer, reference full-flow dilution tunnel



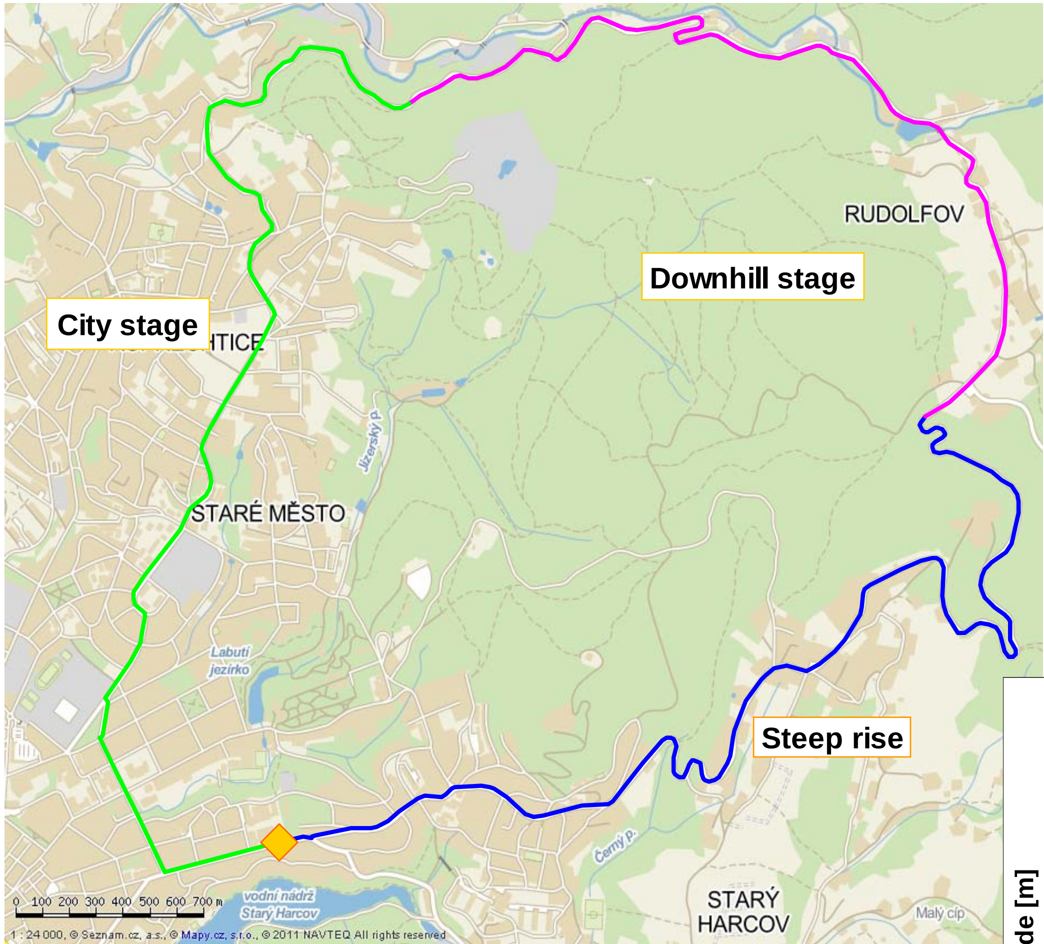
# Experimental – Motorcycle (scooter)



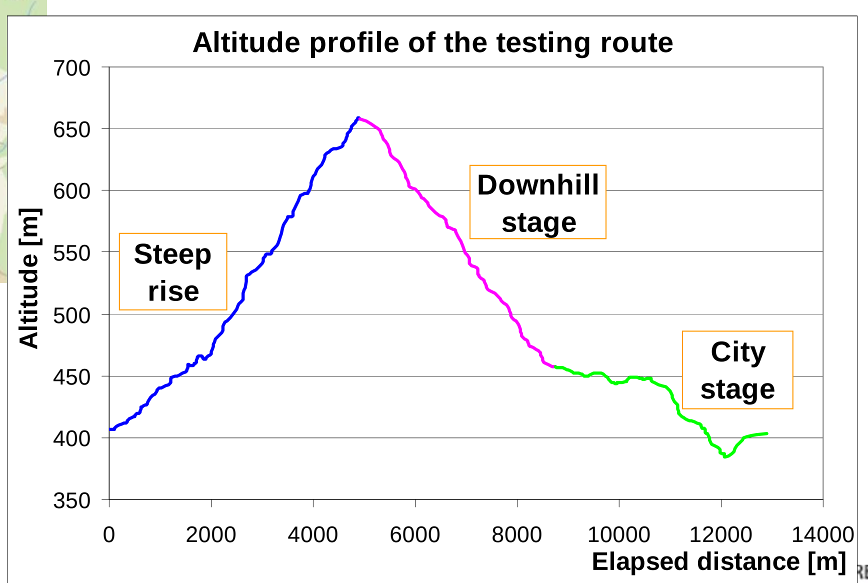

- **4-cycle 50-cc SI engine**
- **13 kg PEMS on luggage rack**
- **Battery-powered system**
- **SAE J-2711: Pre-run & at least 3 runs along the route**



# Experimental – Test route

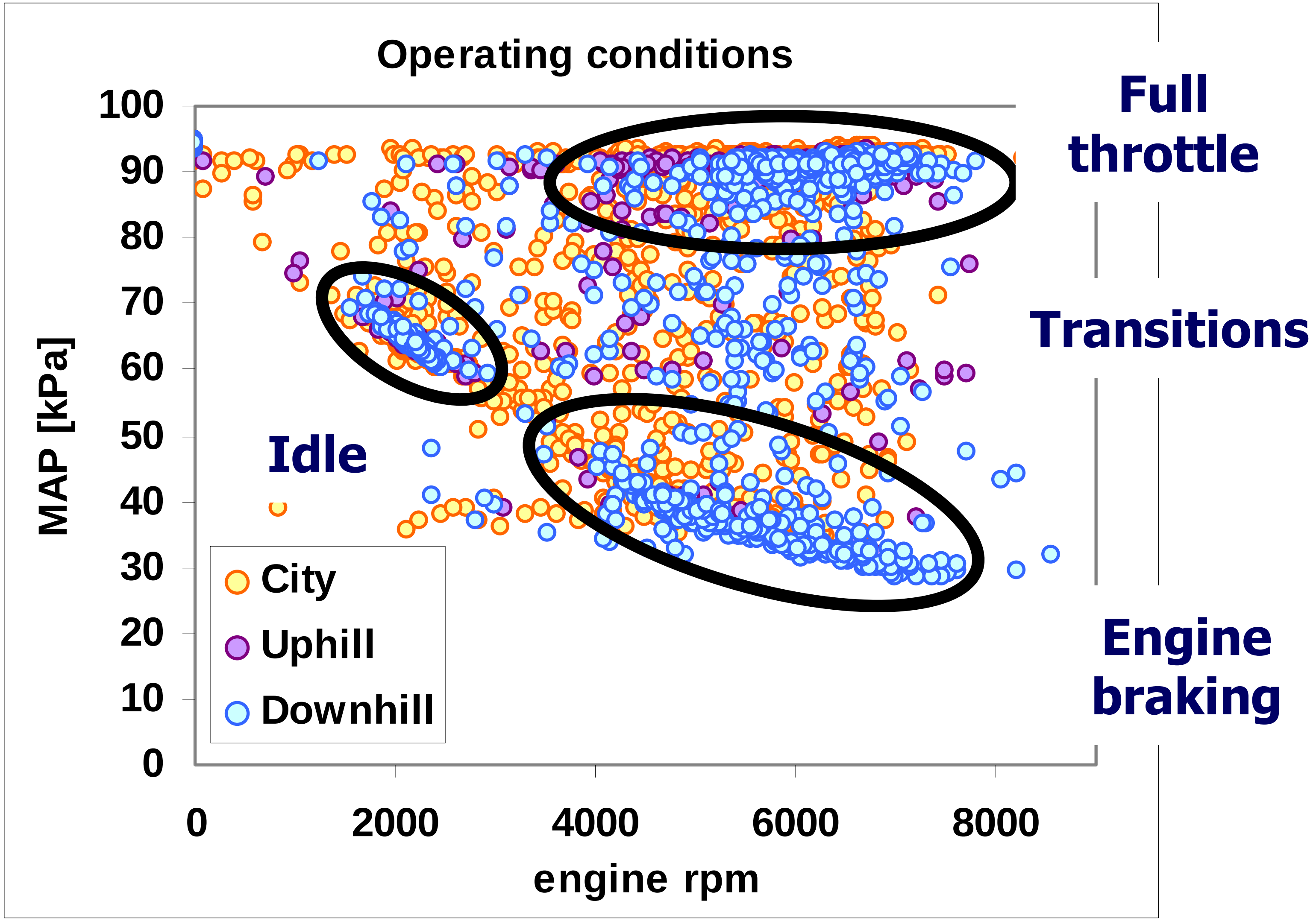



- Route length: approx. 13 km
- Start point altitude: 410 m
- Peak altitude: 660 m
- Lowest point altitude: 380 m



# How a scooter is driven

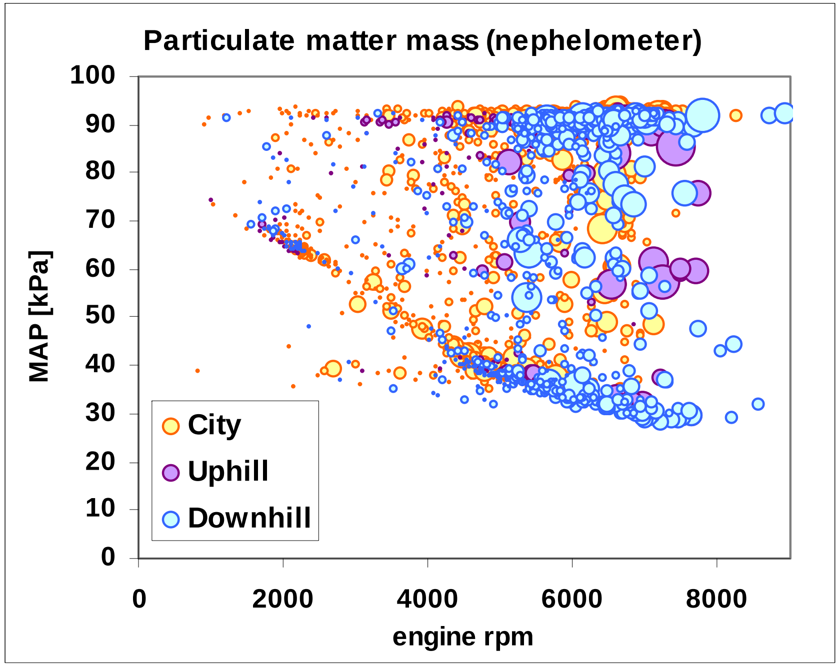
## Mostly "full power or nothing", pulse-width modulation
## Example: Liberec region, each point = 1 second of operation
## Distinct regions: idle, full-power, engine braking, transitions

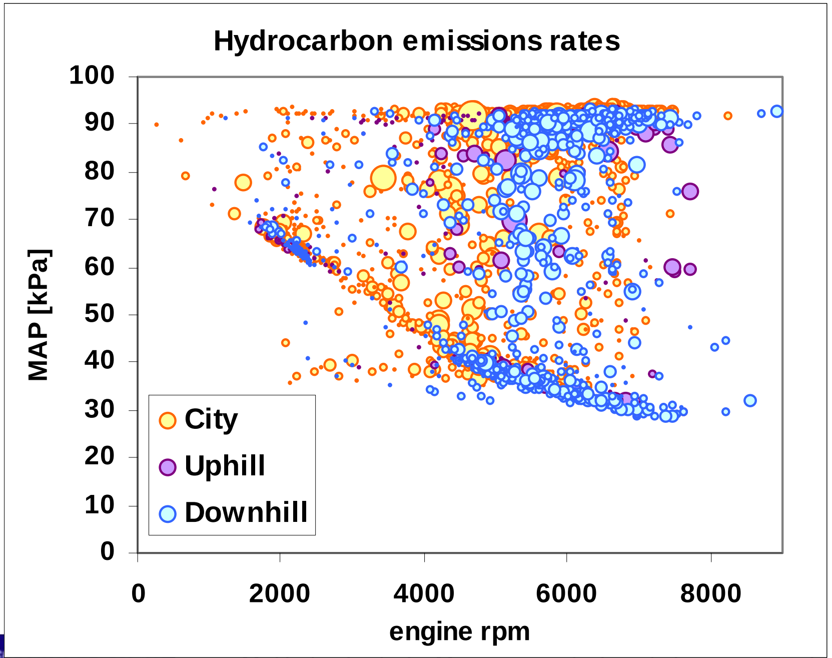


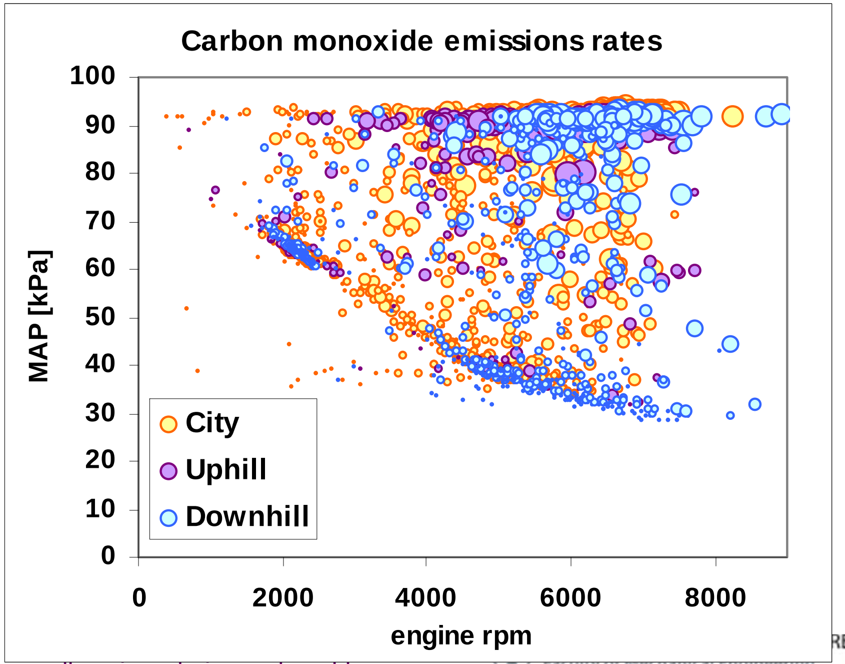
# Emissions patterns

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

**CO high during transitions and at full power**



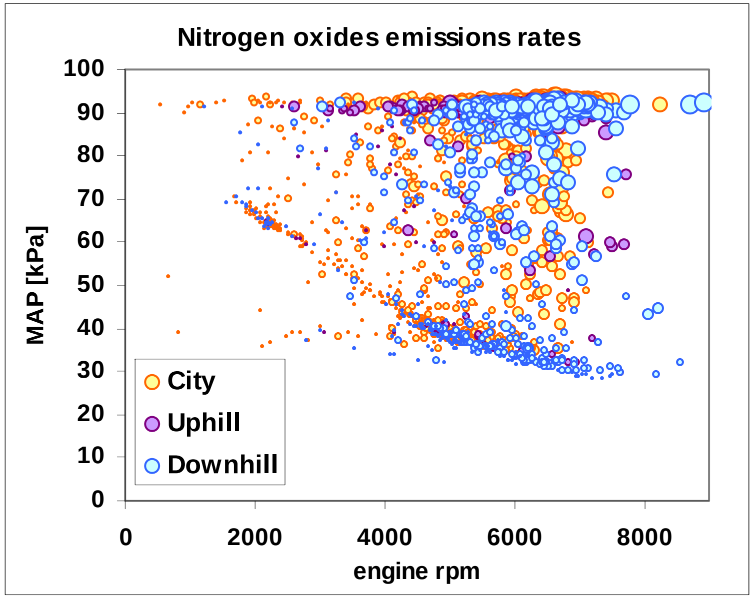



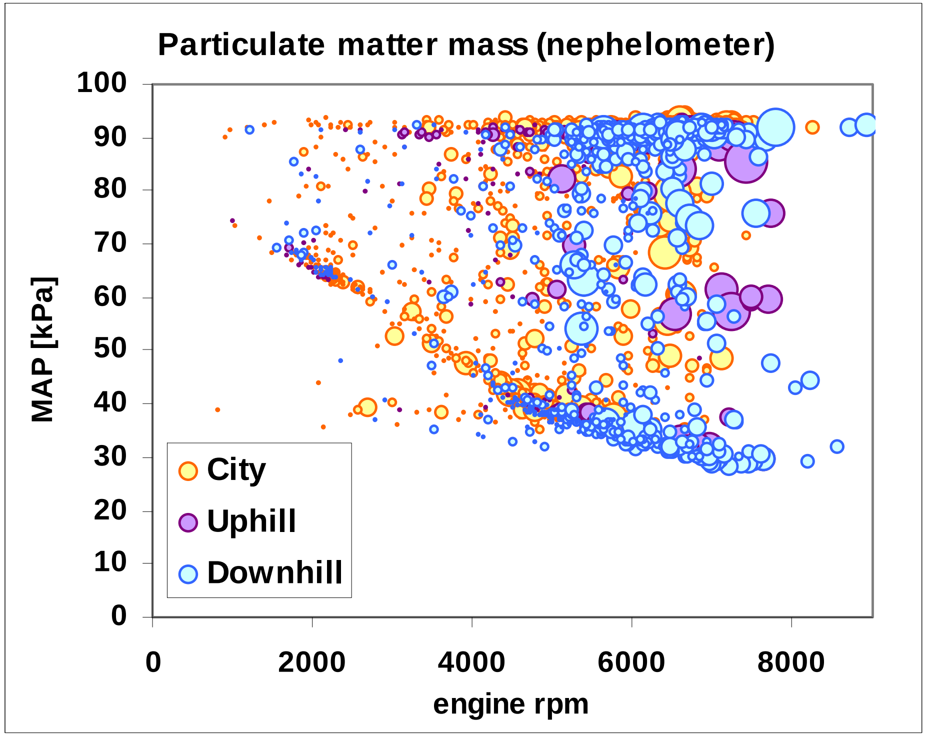
# Emissions patterns

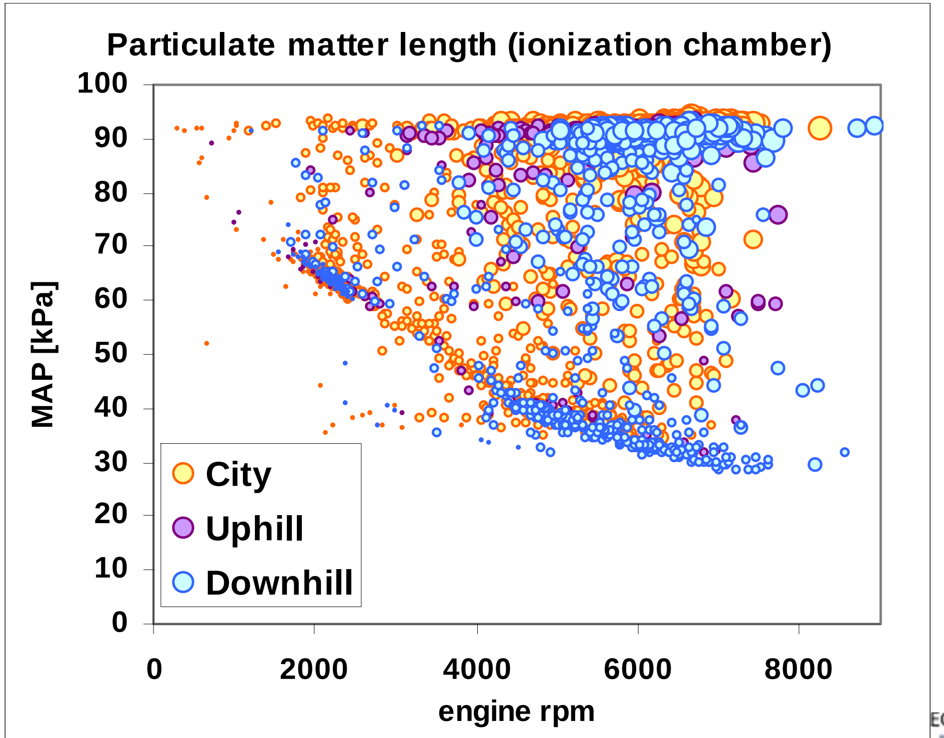
**Larger particles (detected by light scattering) and hydrocarbons dominated by transitions**

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

**NOx highest at full power**



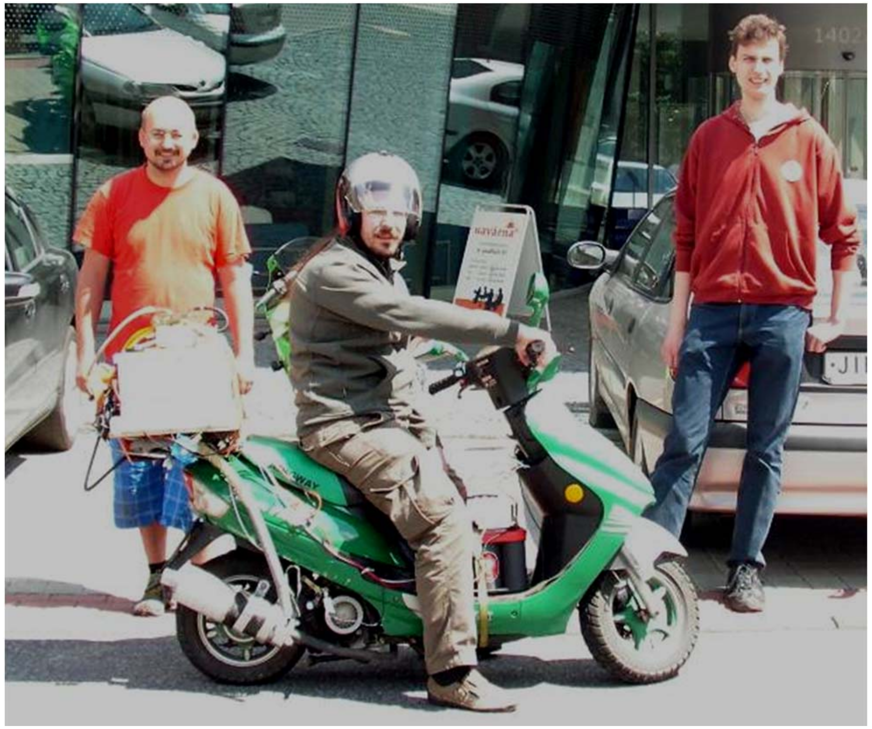



# Motorcycle (scooter) – test summary per km

| Emissions per km | HC [g] | CO [g] | $NO_x$ [g] | PM laser [mg] | PM ion1 [km] | PM ion2 [km] | $CO_2$ [g] |
|---|---|---|---|---|---|---|---|
| Urban | 2.72 | 11.2 | 0.50 | 3.3 | 406 | 386 | 53 |
| Rural | 1.30 | 8.4 | 0.41 | 2.7 | 320 | 255 | 39 |

- Route length: approx. 13 km
- Start point altitude: 410 m
- Peak altitude: 660 m
- Lowest point altitude: 380 m

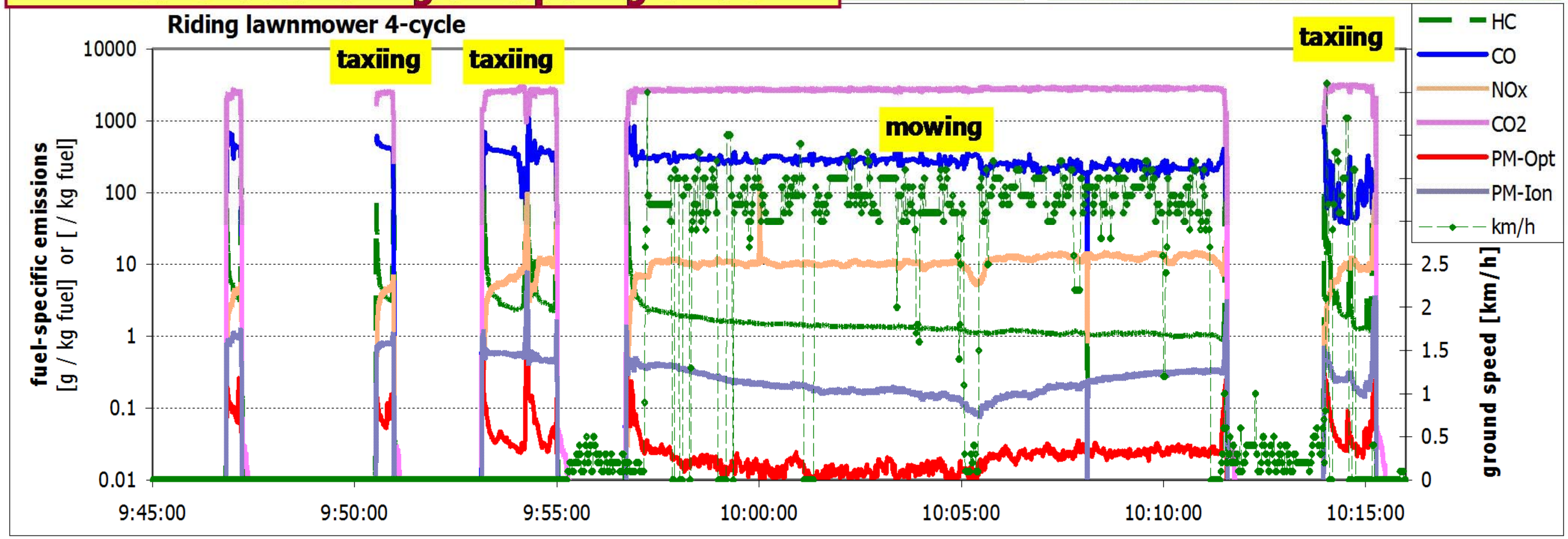


# On-board measurement – riding mower

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

**Mowing family house lawn**

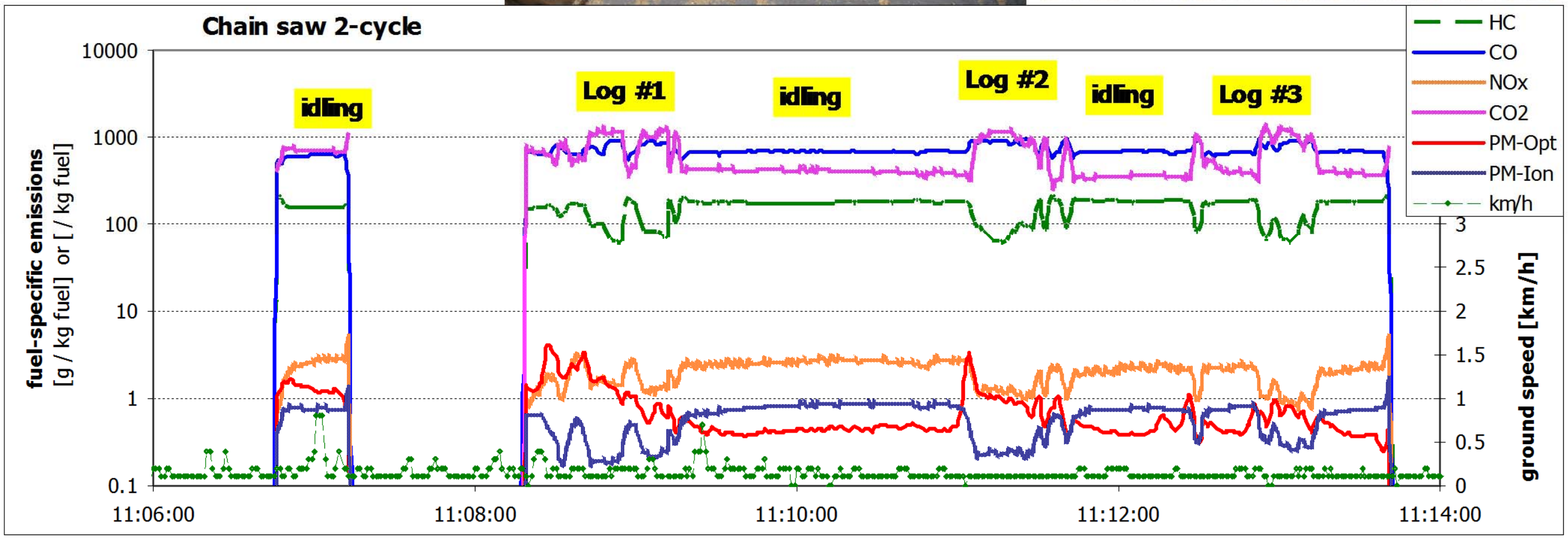
**PM length is relative units per kg of fuel**
**All other data is in grams per kg of fuel**



# 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**

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Faculty of Mechanical Engineering
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# Off-board measurement – chain saw

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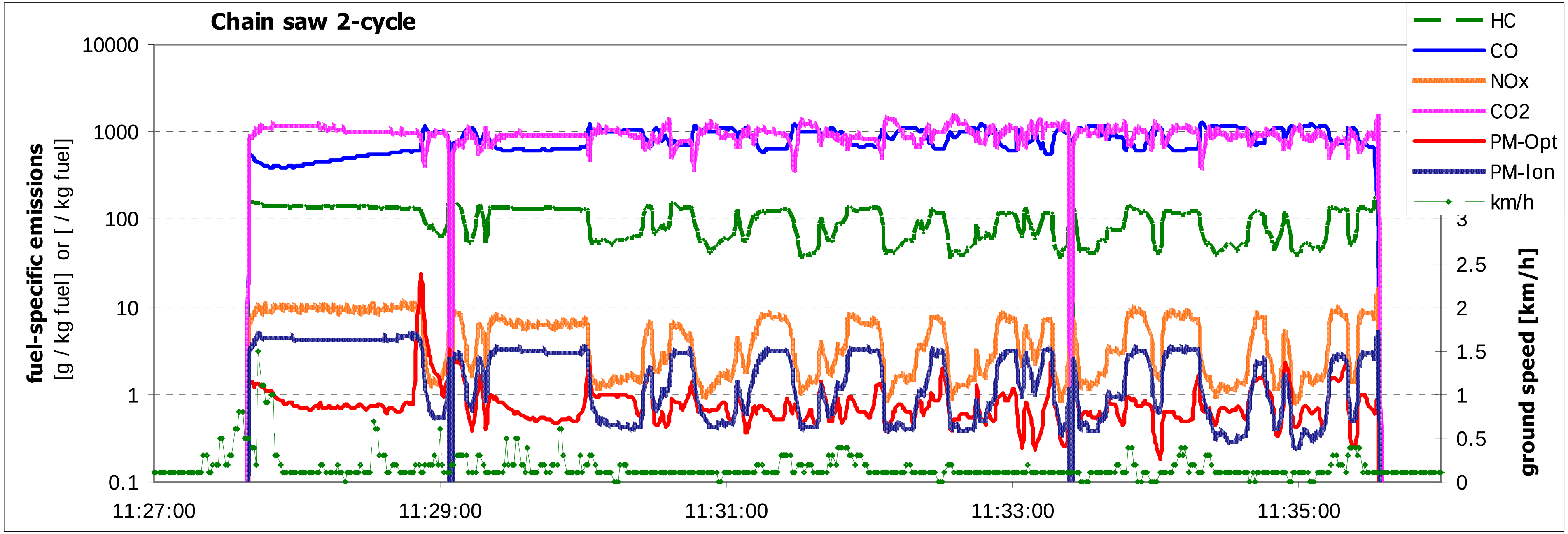
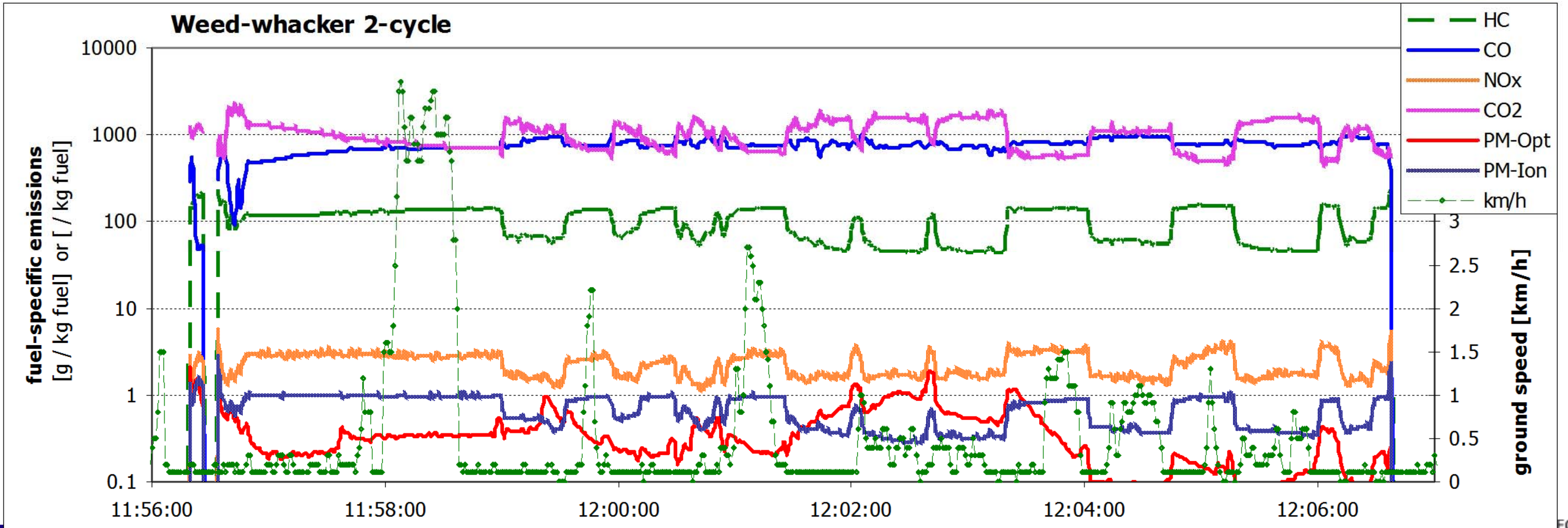


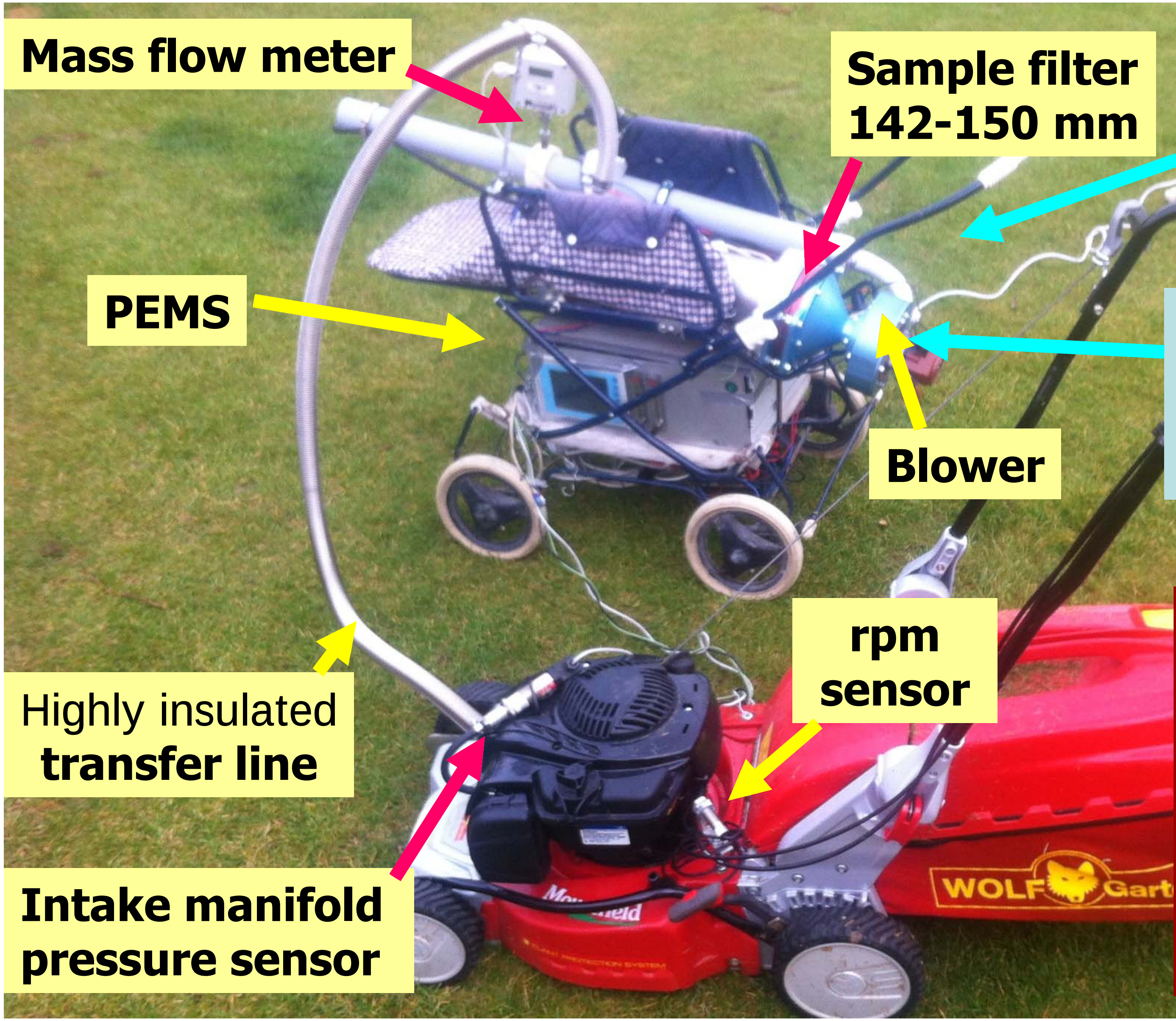
# Off-board measurement – weed-eater
# PEMS mounted on accompanying tractor

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

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

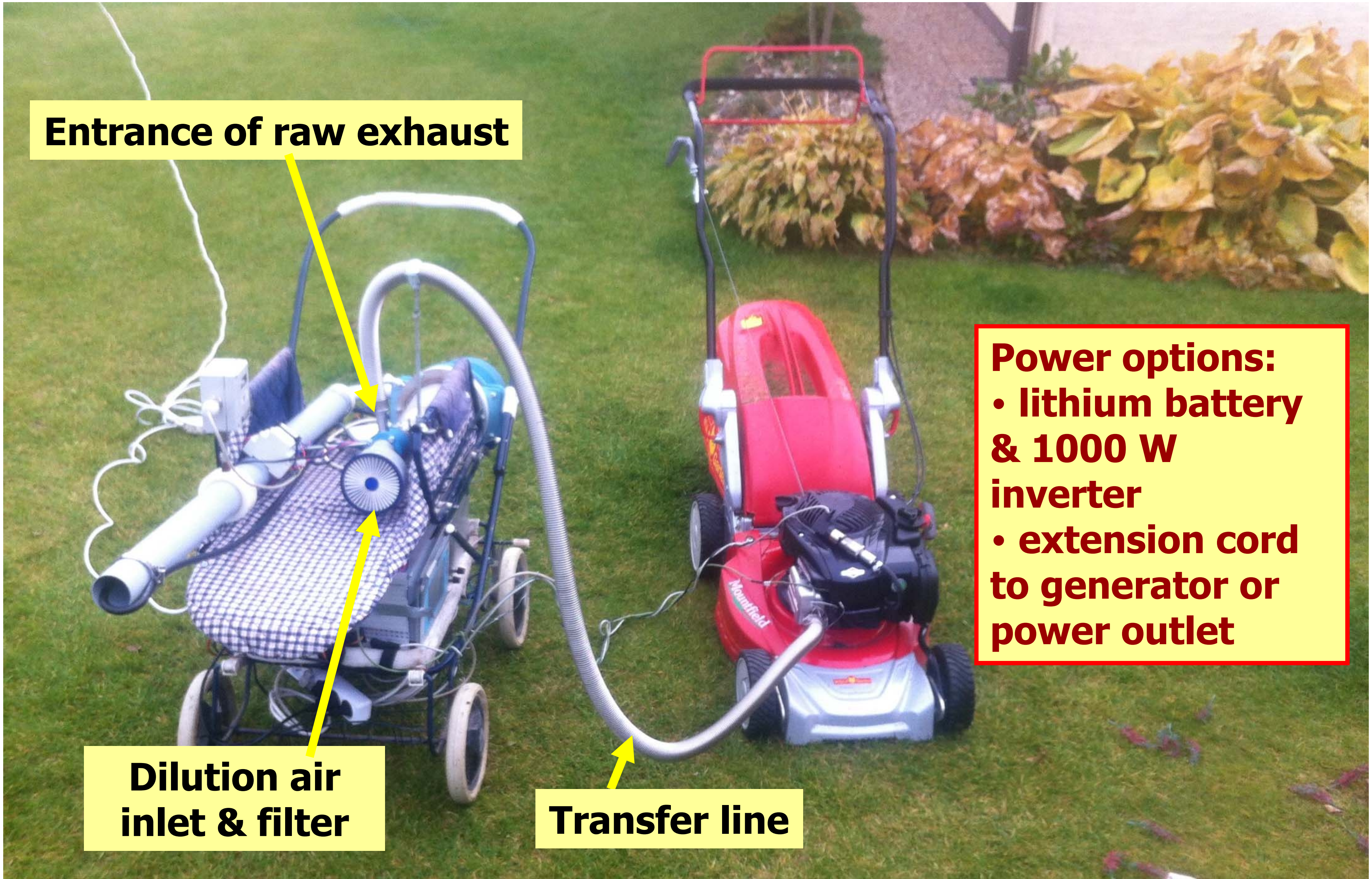



# Off-board full-flow dilution tunnel




**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



# 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

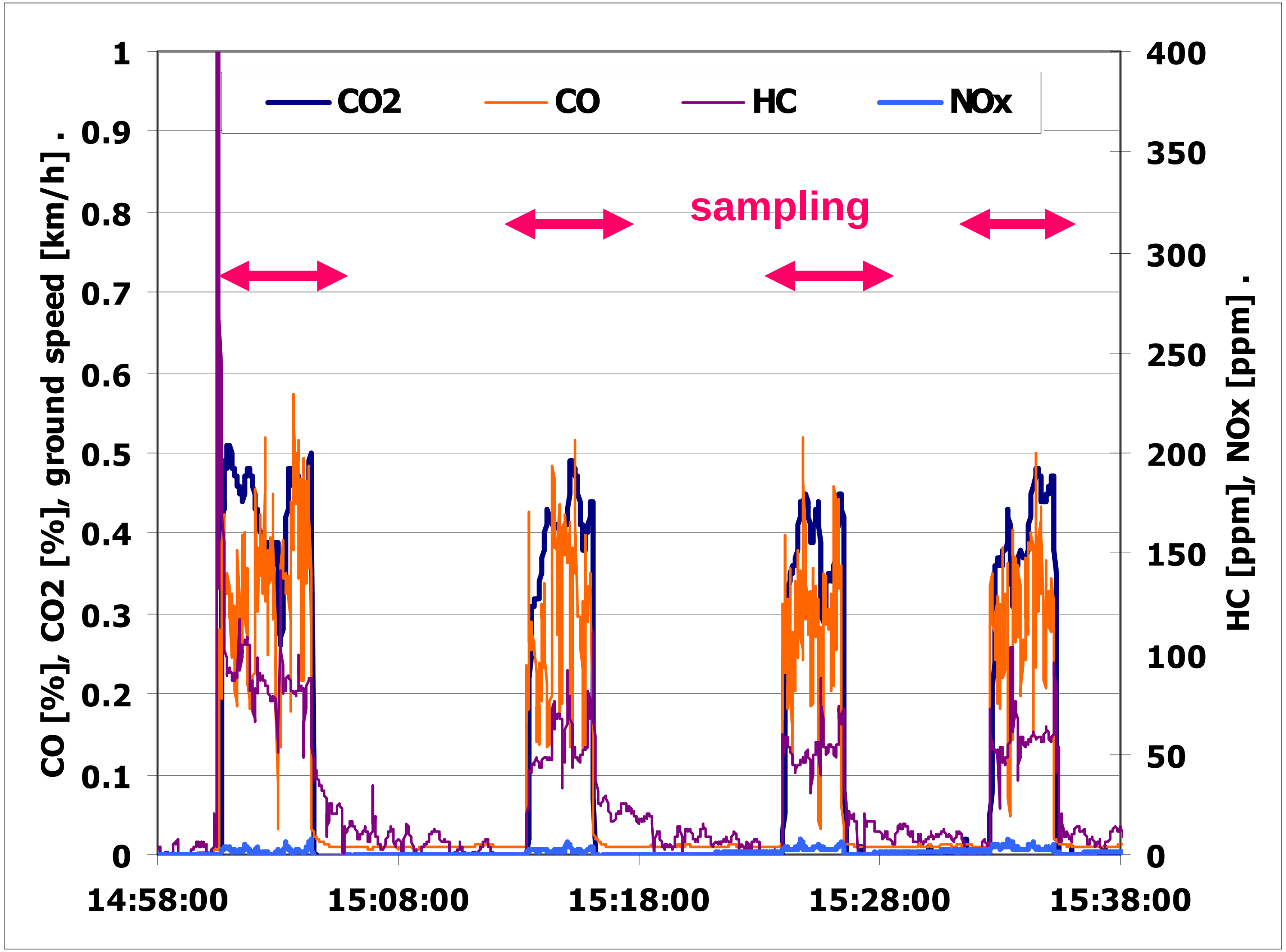
**30-60 m³/min sampling on 142/150 mm filters for analyses (i.e. PAH) and toxicological assays**

**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**

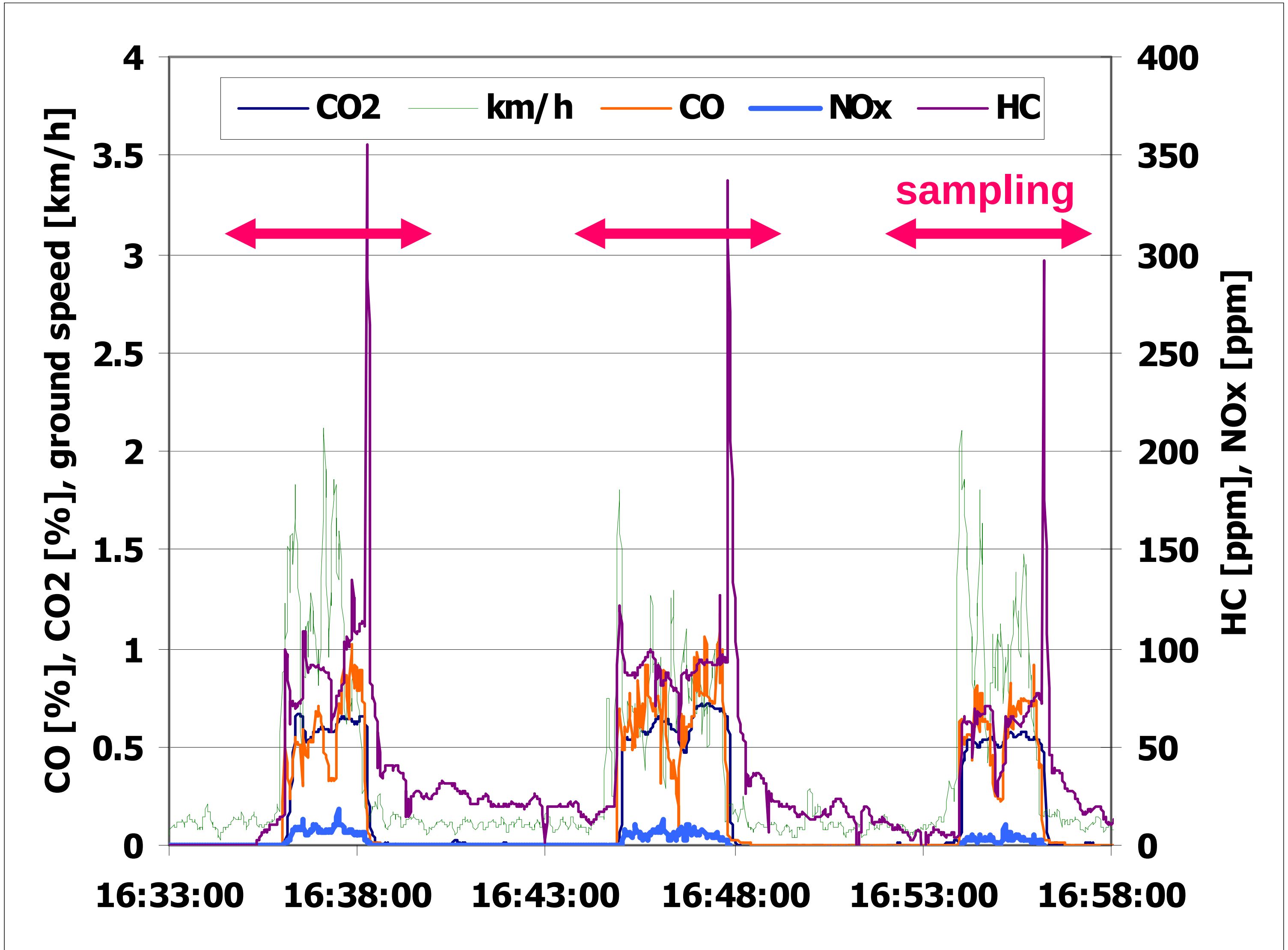
**Large HC spike at (ignition) shutdown**



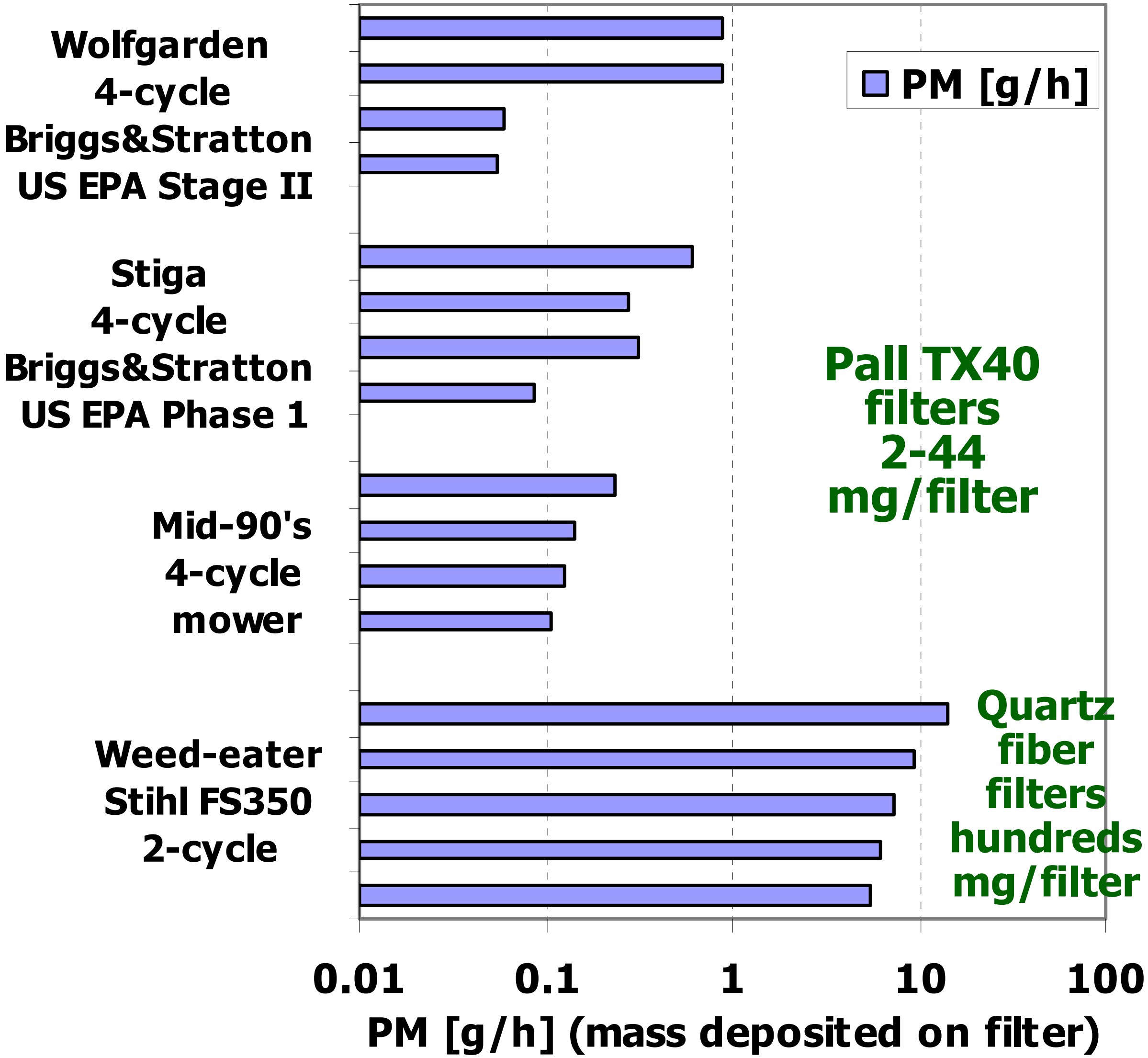
# Base weedeater sequence: CVS on, Engine start, mowing until CVS filter is full, engine off, CVS off

**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)



# CARB Stage II Lawnmower – effect of alcohol fuels 30% iso-butanol, 30% n-butanol in gasoline

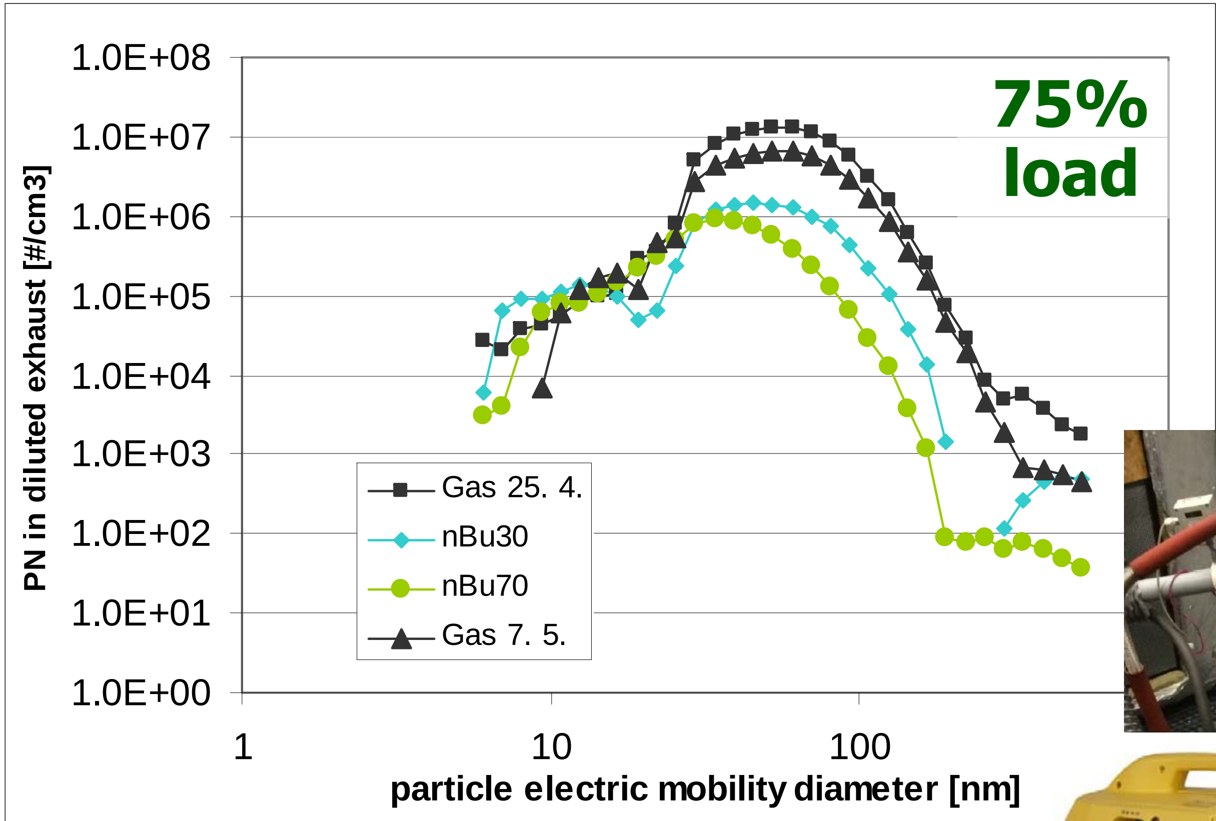
## (SAE 2014, submitted)

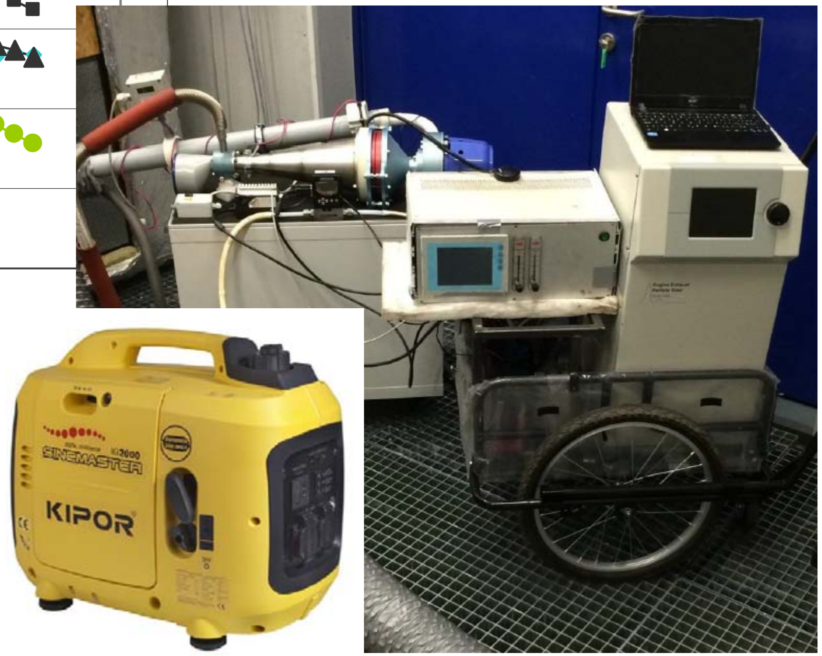
| | HC [g/kg] | CO [g/kg] | NOx [g/kg] | Fuel [g/h] |
|---|---|---|---|---|
| Gasoline cold | 19 | 256 | 3,1 | 433 |
| Gasoline | 19±5 | 293±46 | 6,1±1,6 | 387±82 |
| 30% Isobutanol | 13±4 | 279±52 | 7,7±1,9 | 368±28 |
| 30% n-butanol | 12±1 | 233±20 | 8,3±0,3 | 387±72 |

| | PAH [ug/kg] | cPAH [ug/kg] | BaP [ug/kg] |
|---|---|---|---|
| Gasoline cold | 763 | 80.2 | 16.8 |
| Gasoline warm | 24 | 4.6 | 0.3 |
| 30% Isobutanol | 83 | 8.8 | 1.5 |
| 30% n-butanol | 21 | 2.3 | 0.2 |

# CARB Stage II 2 kW genset – alcohol fuels 10%, 30%, 50%, 70%, 100% n-butanol

## (Diploma thesis Jan Vodrazka, TU Liberec, 2014)



# 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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MEDETOX

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