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

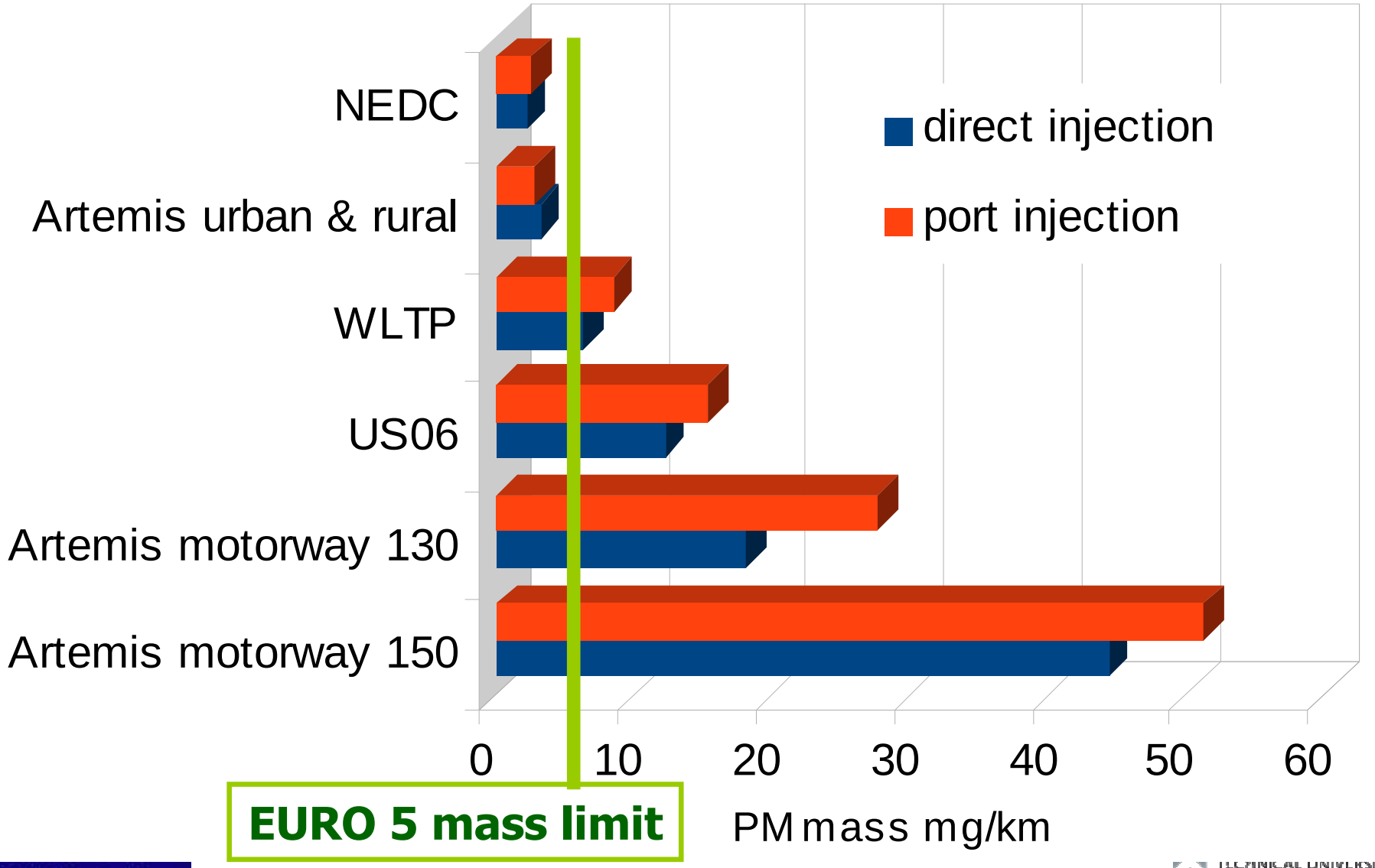
Euro 5 with no DPF
(Prague, CZ)

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)



Gasoline PM: deterioration vs. enrichment effects

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

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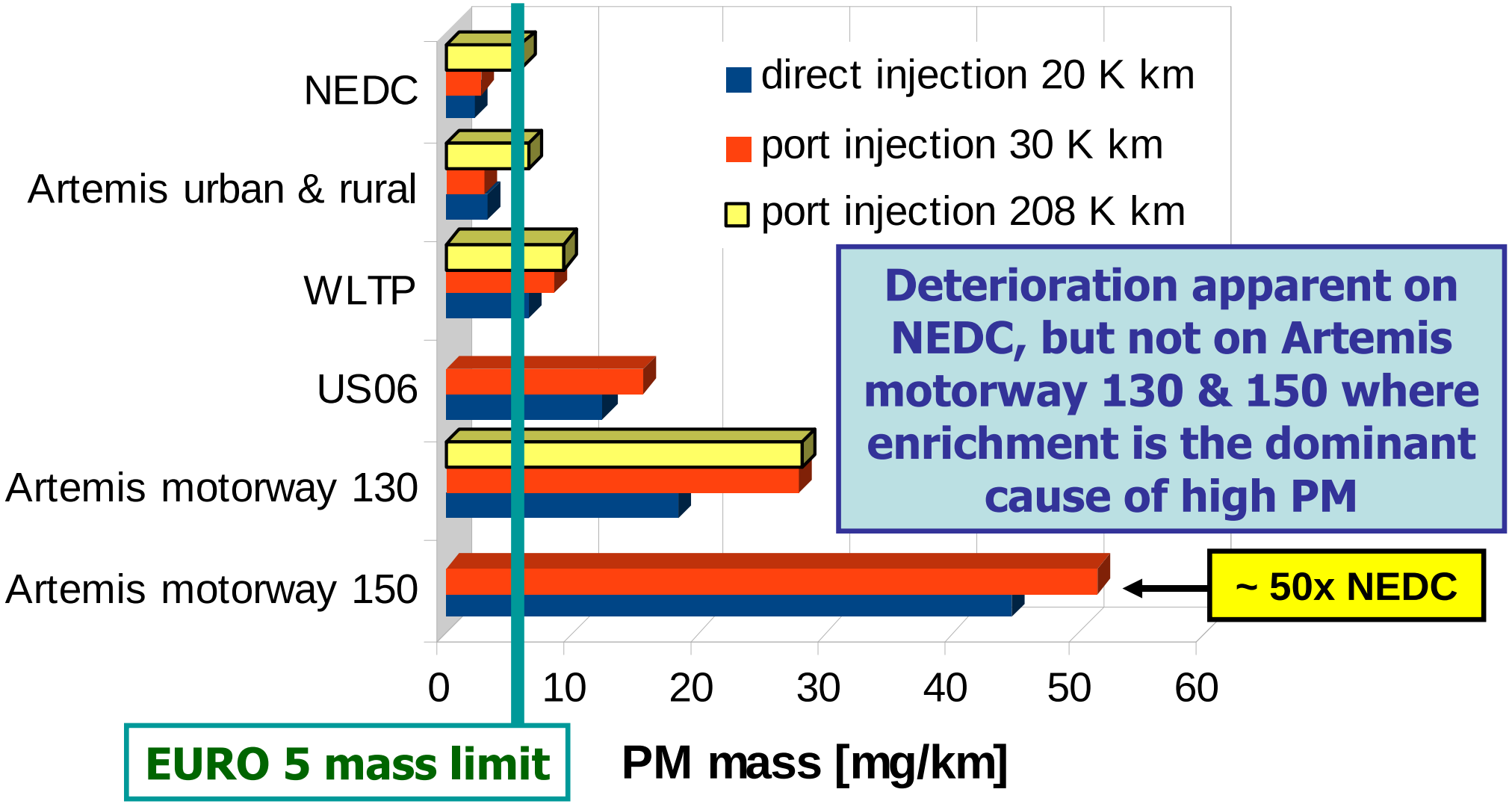

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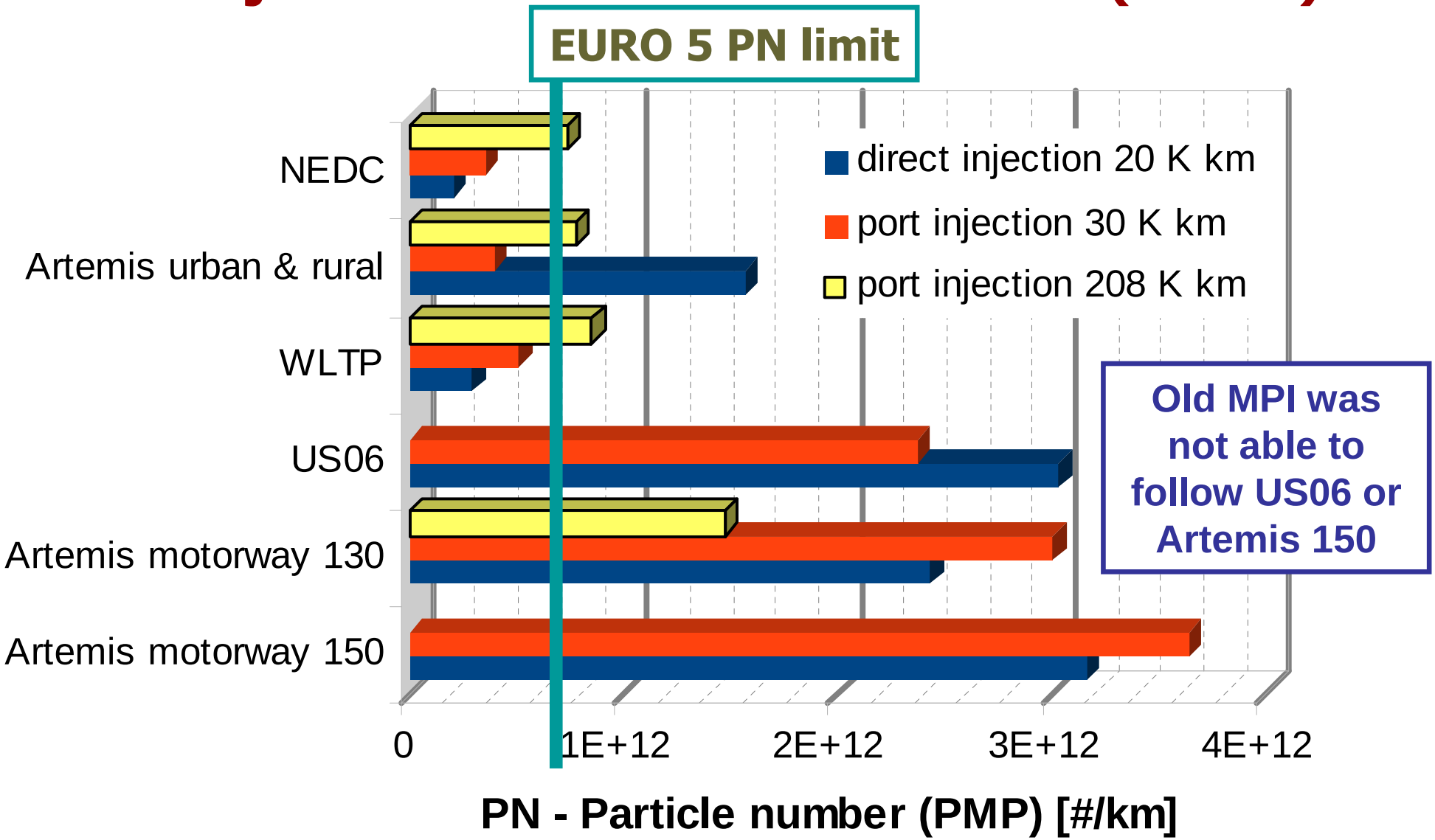
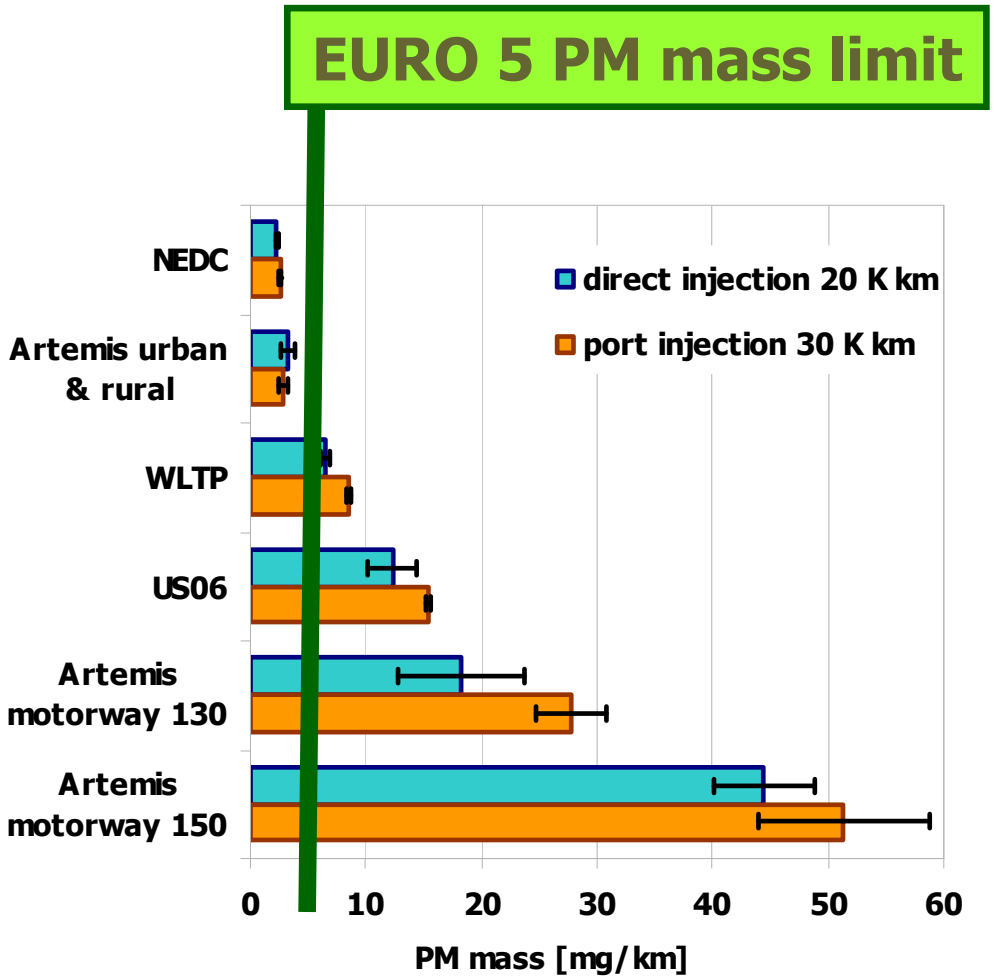
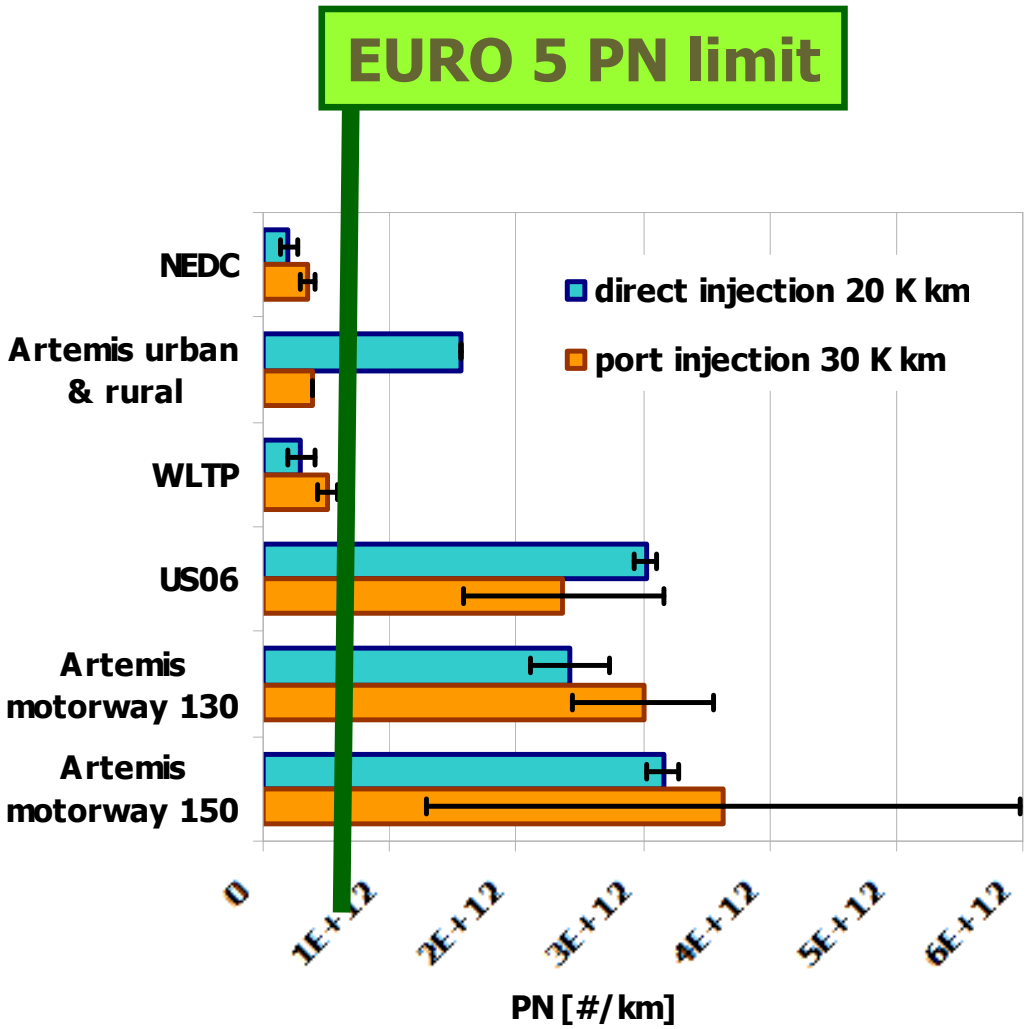


Gasoline engine PM: Choice of cycles

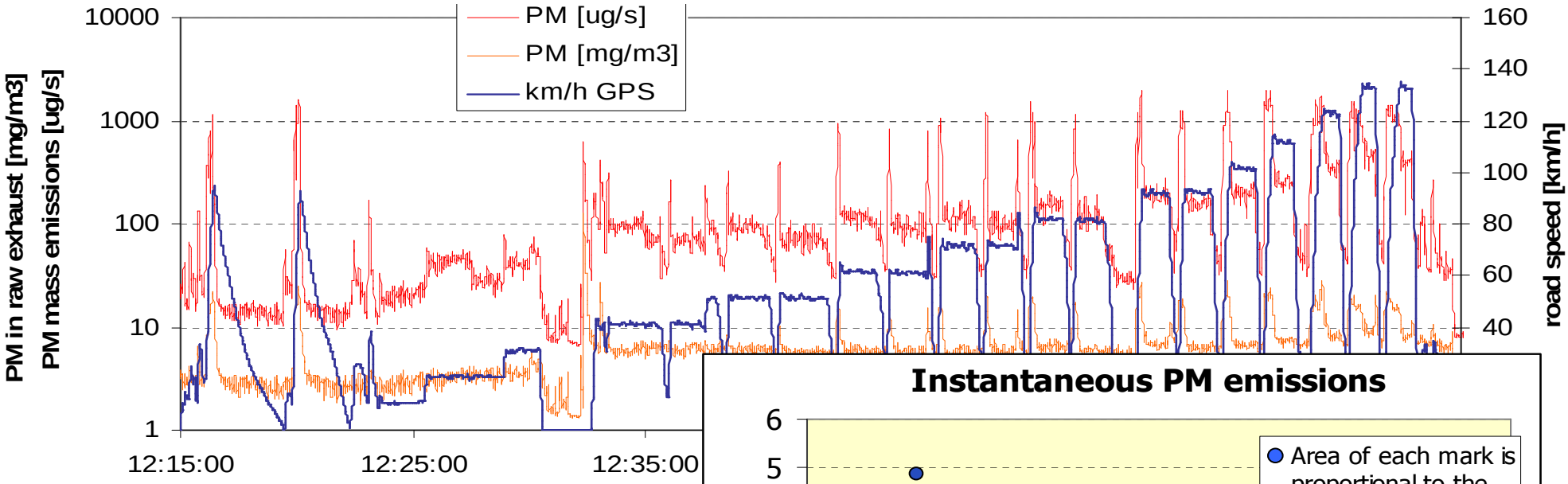
WLTP is "not as lame as NEDC", but does it cover the problem – enrichment at high load (prohibited by EPA)**?**
US06 and Artemis motorway cycles as a supplement?

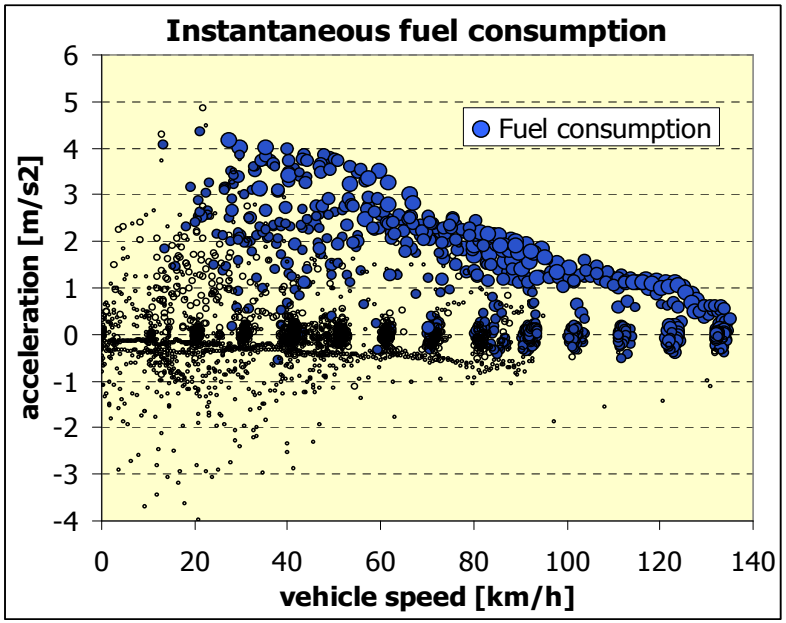


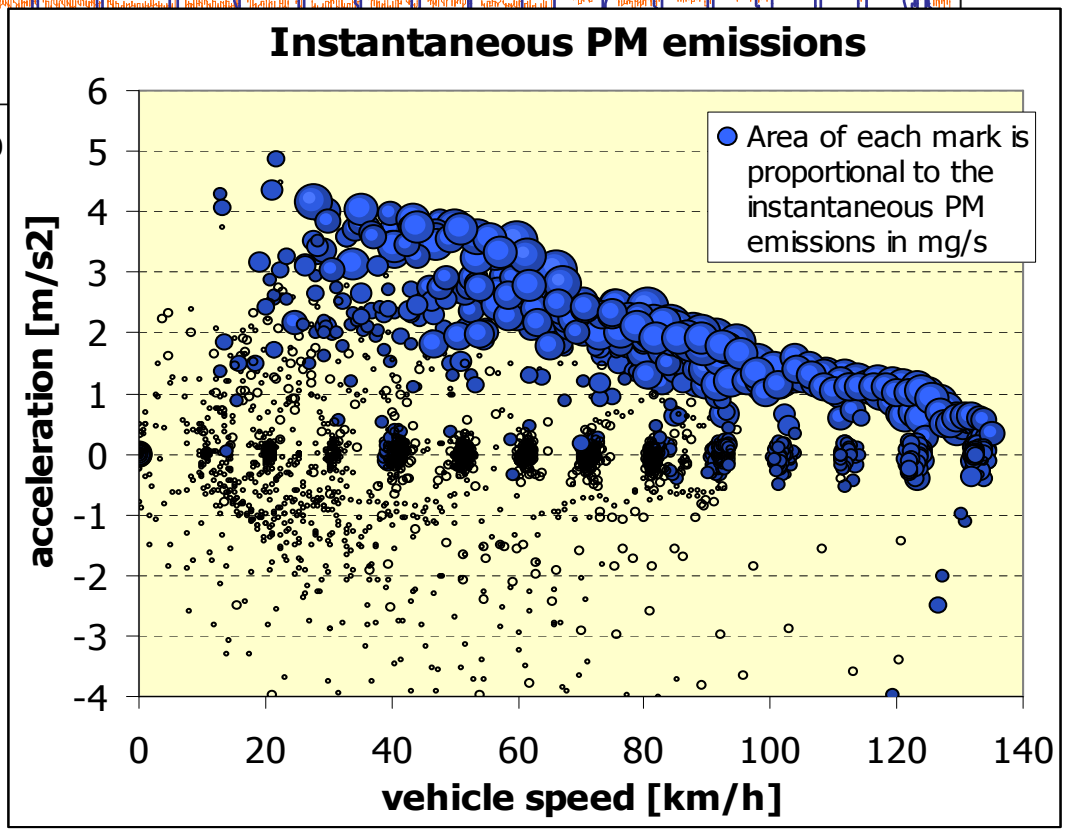


Gasoline engine real-driving PM emissions

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

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?)

Filtered dilution air

10-12 lpm raw exhaust

Before or after DOC, DPF, …

Sample cool & reheat

Condensate and large particle removal

CAT

Charge meter (ionization chamber)

F-FC-P

F-FC-P

F-FC-P

NDIR-HC,CO,CO2

chem.cell NO

F-FC-P

NDIR-HC,CO,CO2

chem.cell NO

F-FC-P

Filter, flow control, pump

Engine

outflow

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"

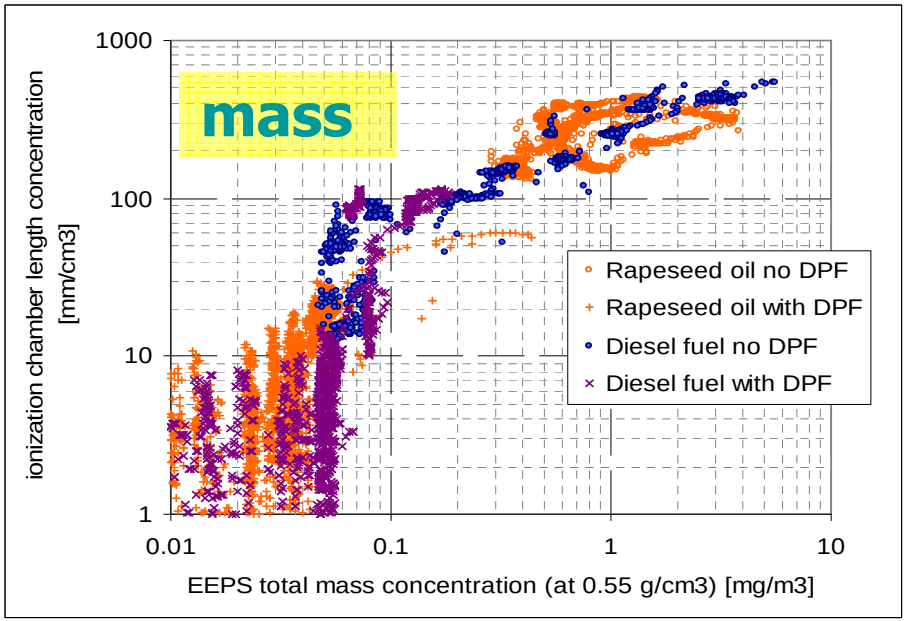
undiluted raw exhaust

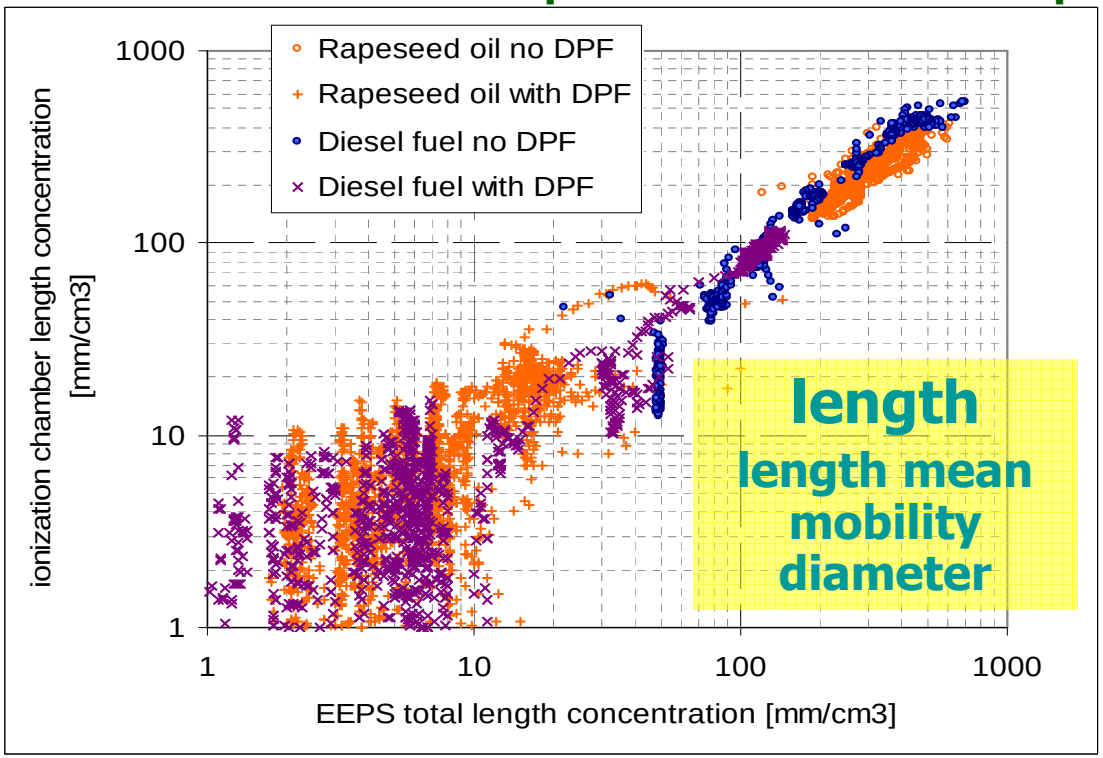
(multiplied by intake air flow for comparison measurements)

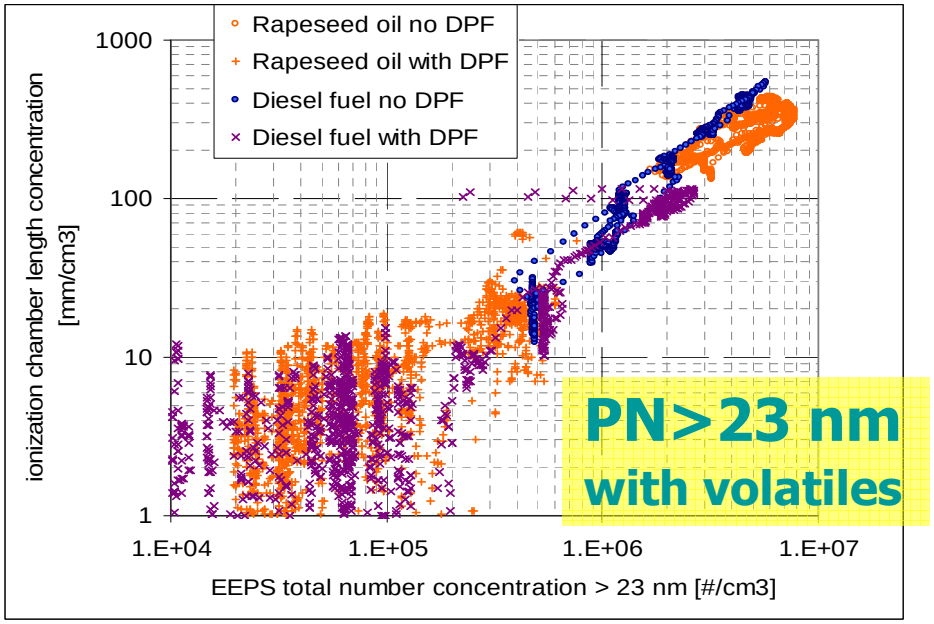
~ 0.1 mg/m3 sensitivity

cheap (100 EUR)

"poor man's PEMS" concept

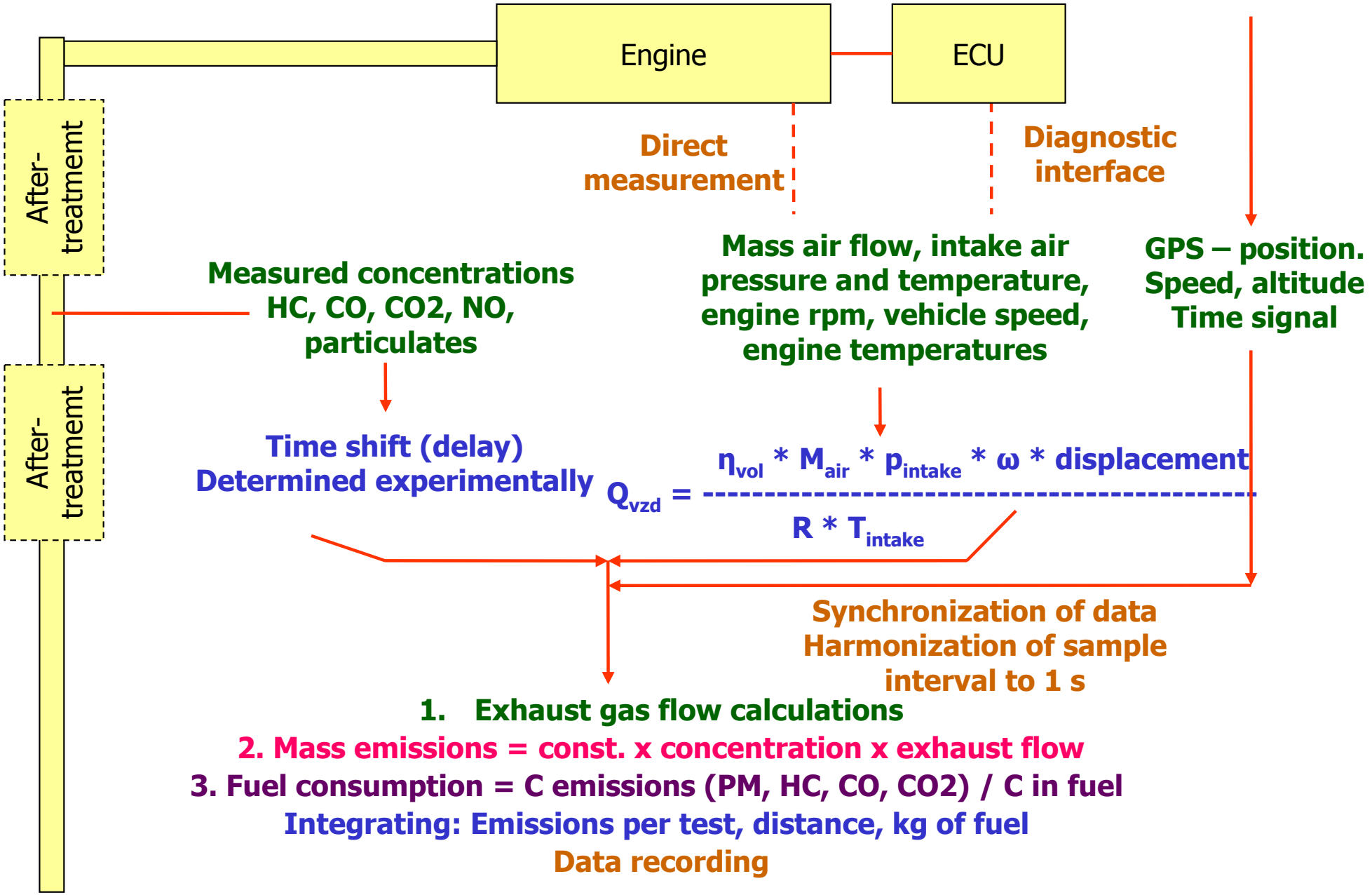




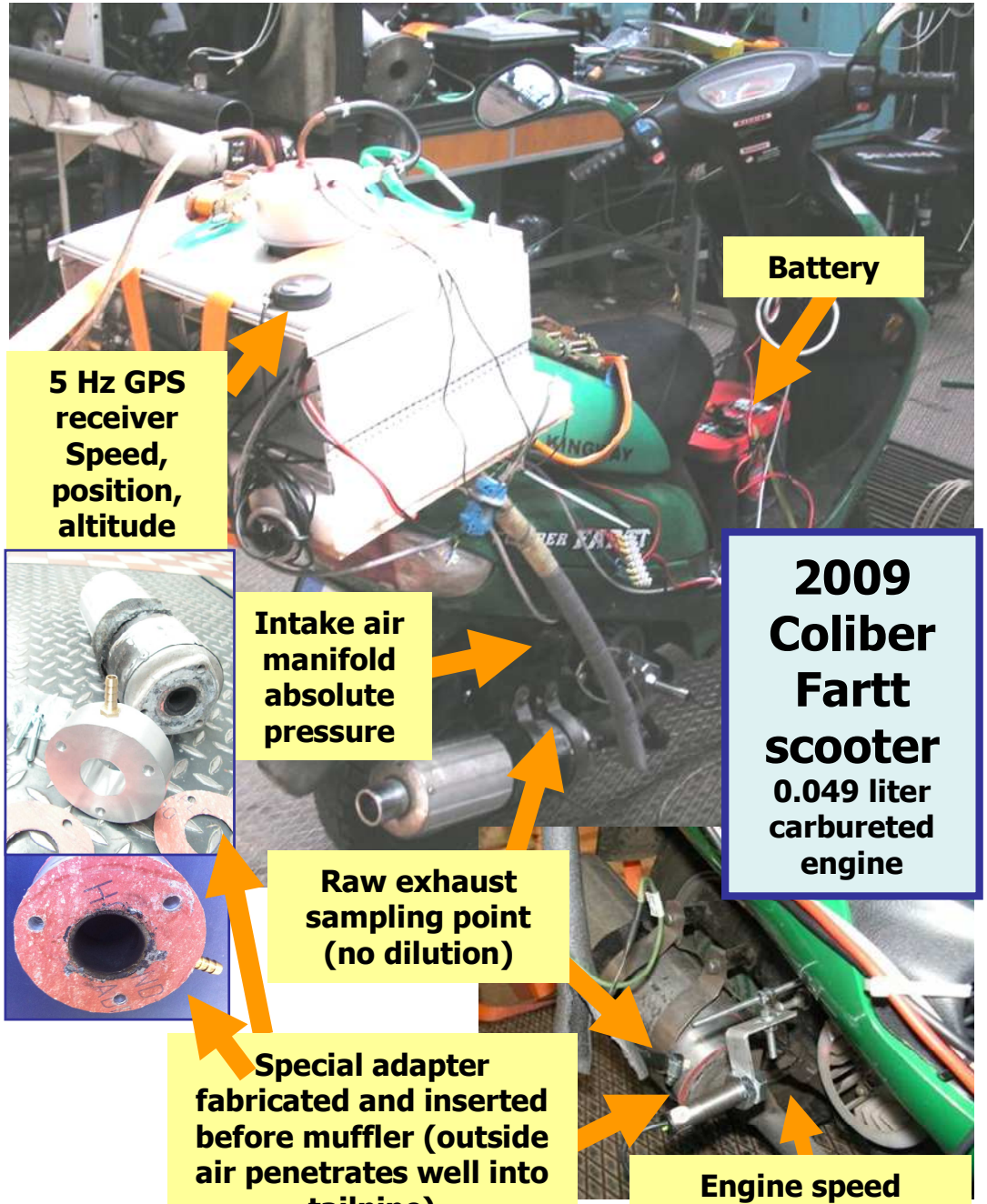


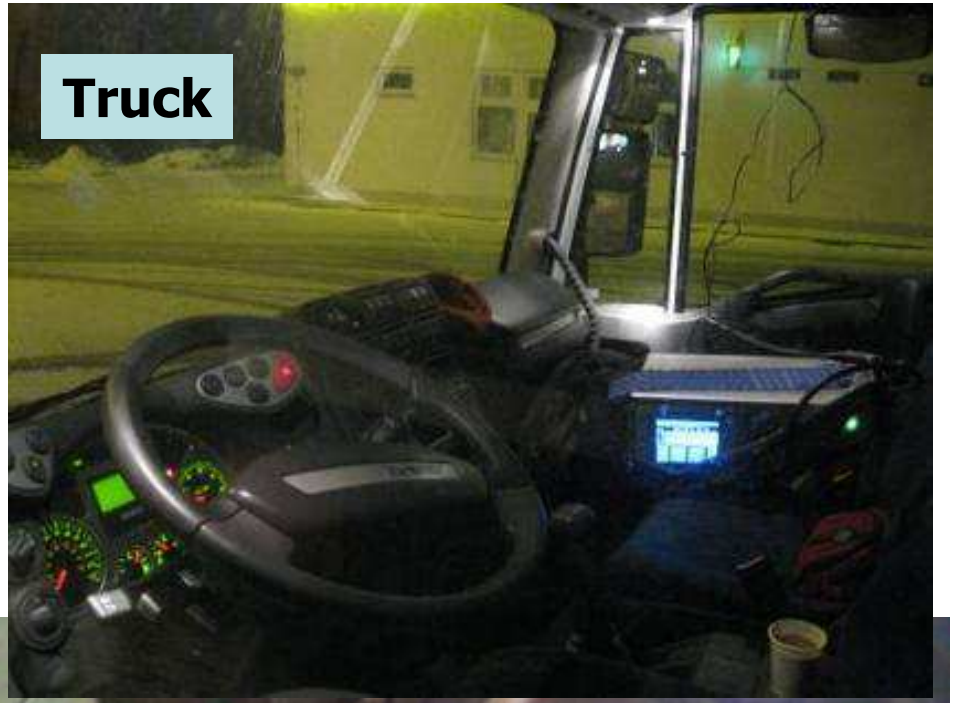
Low-cost on-board system overview

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



On-board system versatility: Motorcycle to locomotive





Portable proportional sampling

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

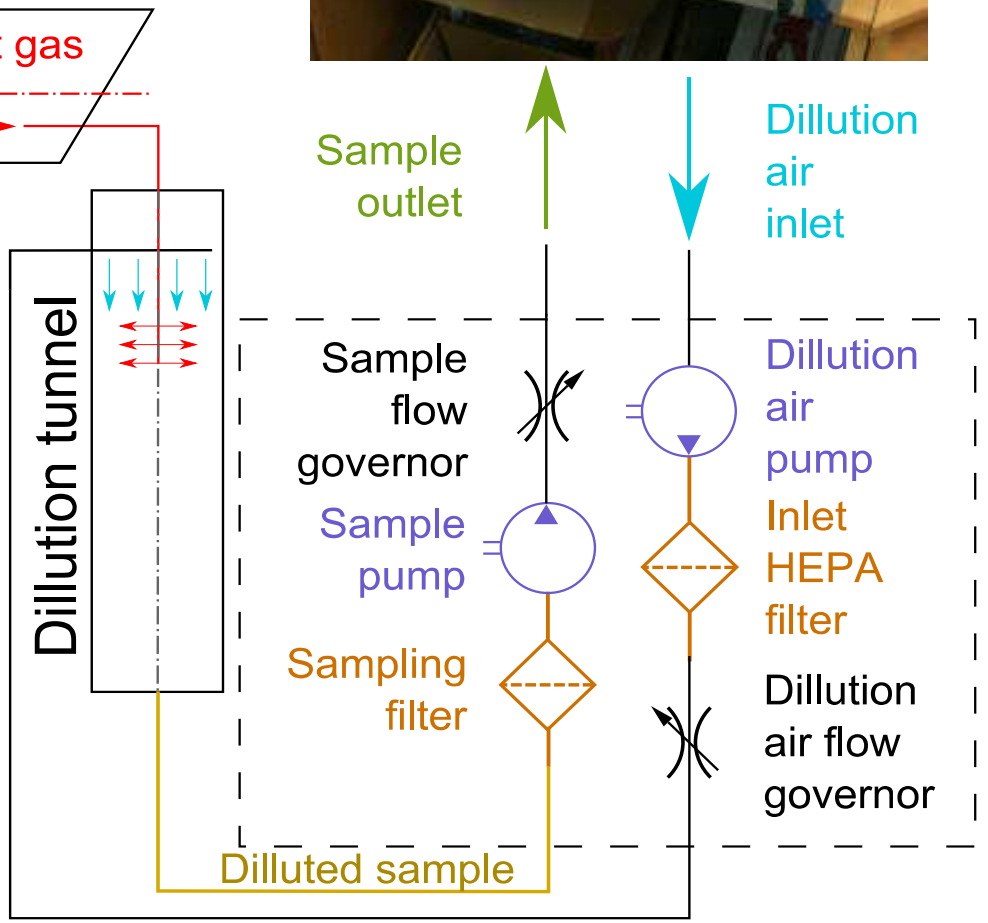
Dilution air flow is regulated so that raw exhaust flow into microdilution tunnel is proportional to the total exhaust flow.

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

Raw exhaust flow =

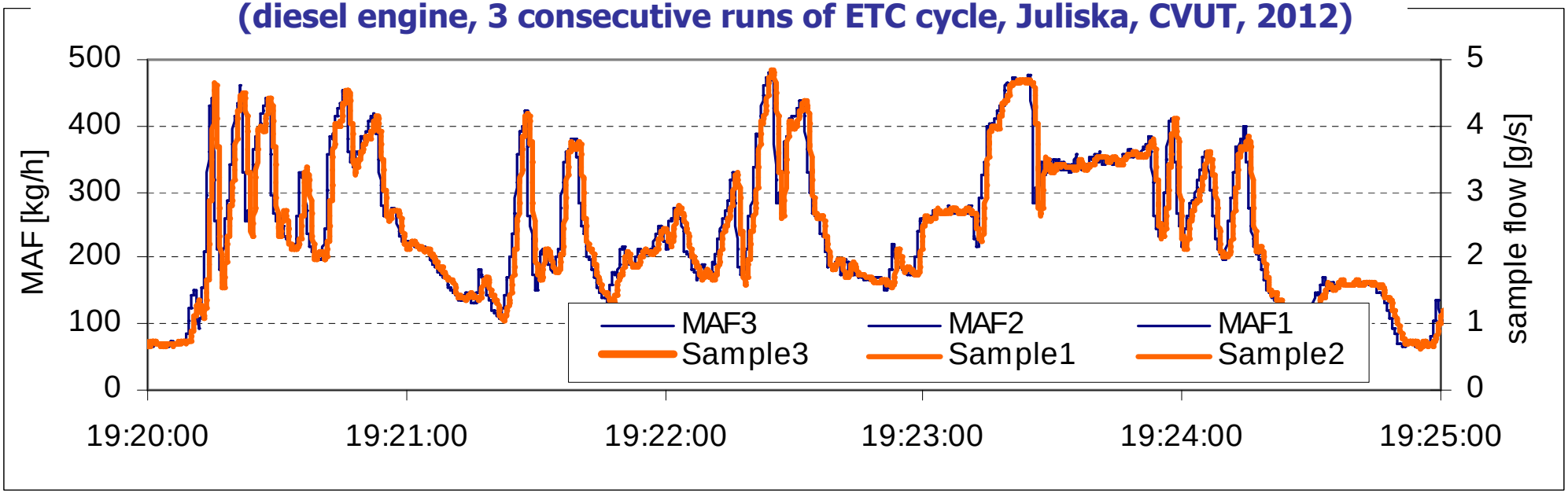
= total sample flow – dilution air flow

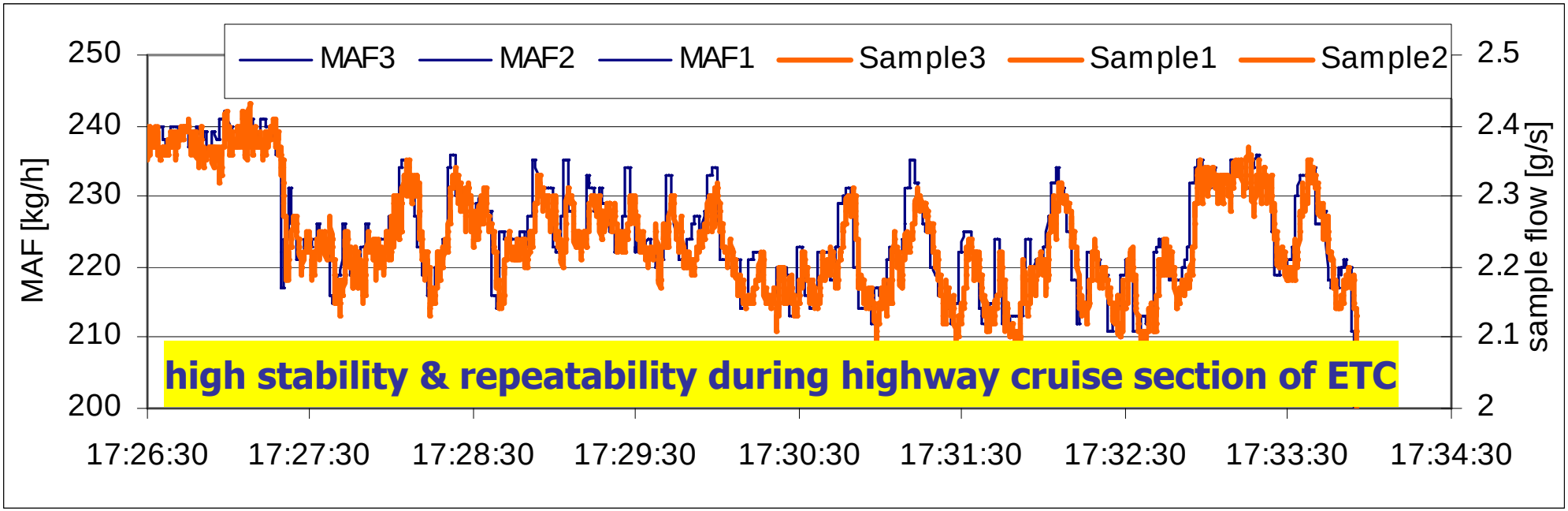
Exhaust flow ~ measured intake air flow



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

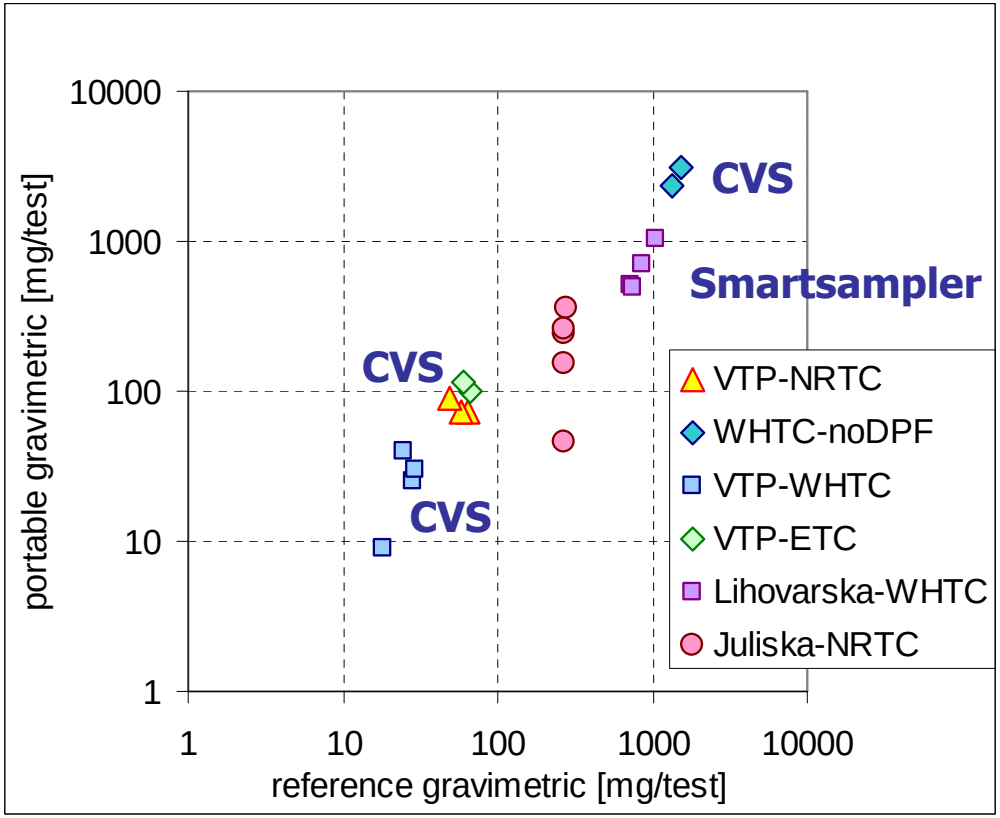
In-use diesel engines, various manufacturers, ~ 1-50 mg/kWh PM

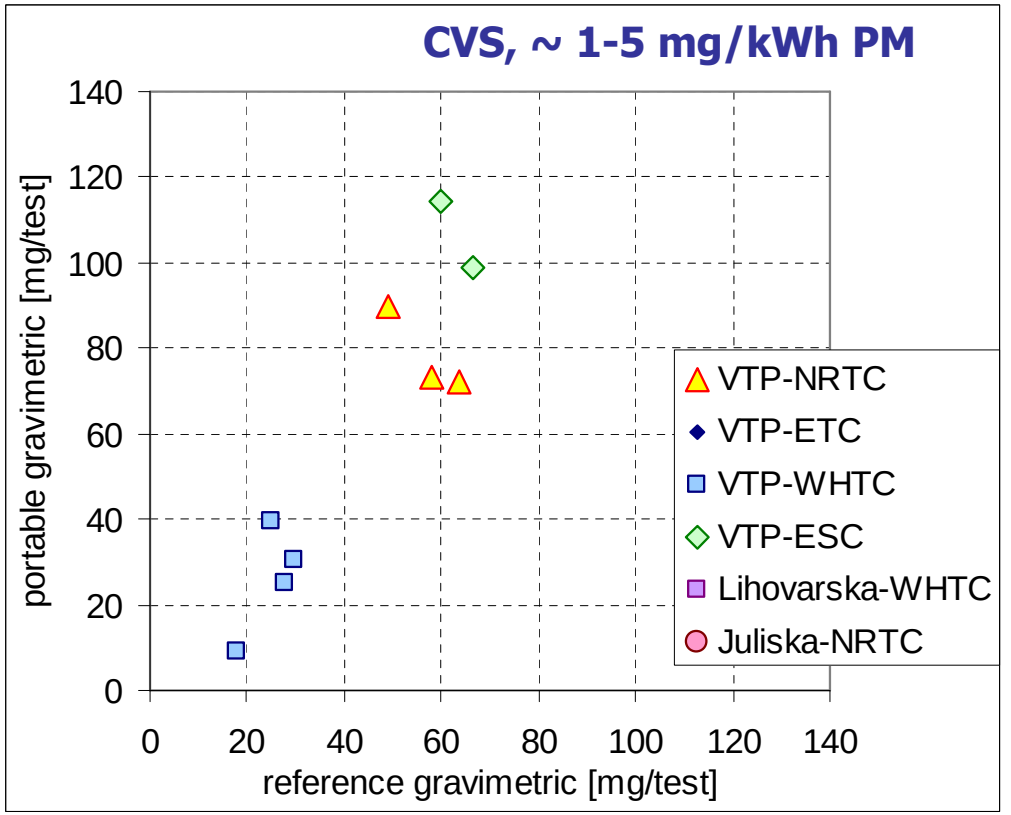
Transient operation on engine dynamometer (NRTC, WHTC, ETC)

CVUT - Juliska: DC dynamometer, reference AVL SmartSampler

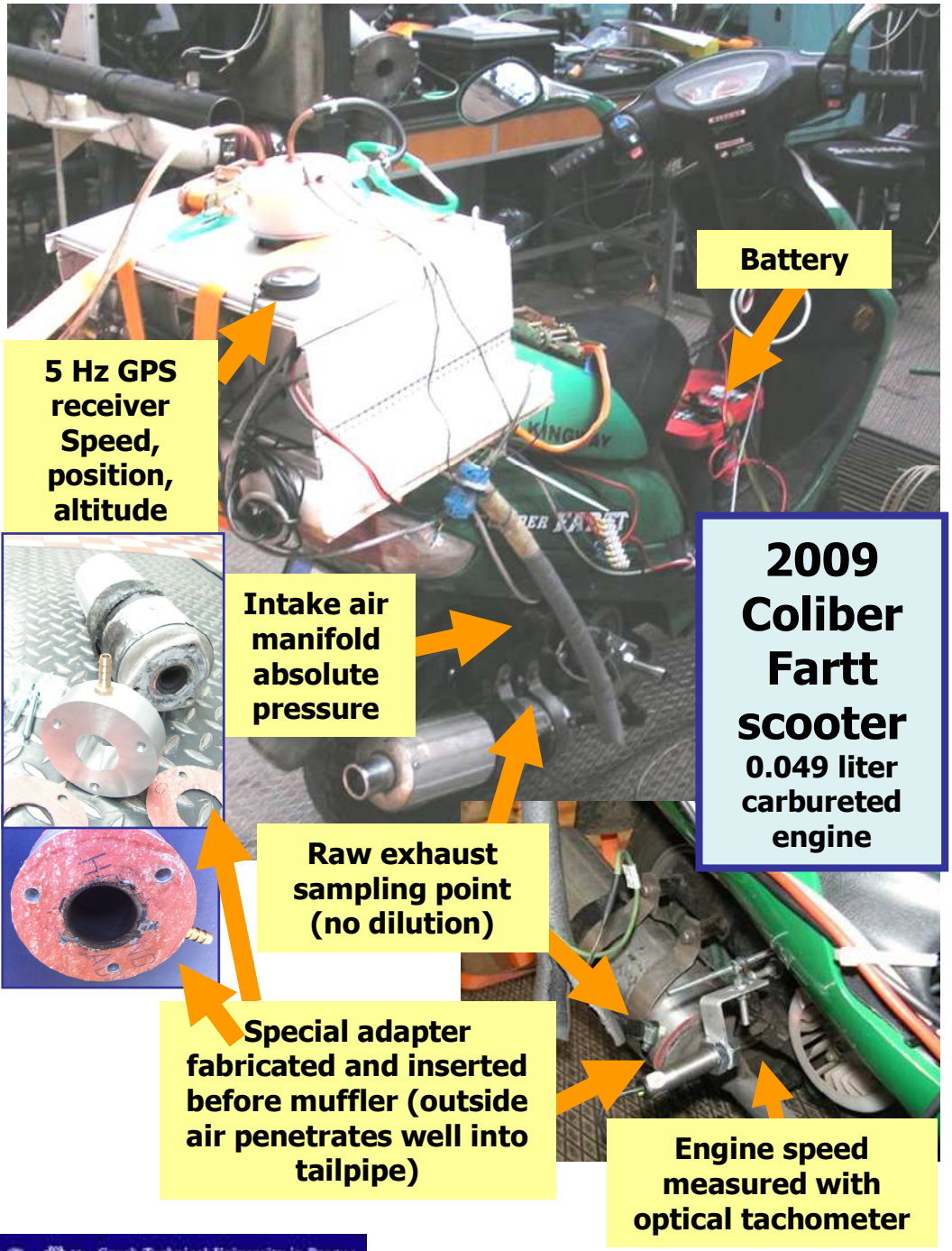
TUV - Lihovarska: AC dynamometer, reference AVL SmartSampler

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



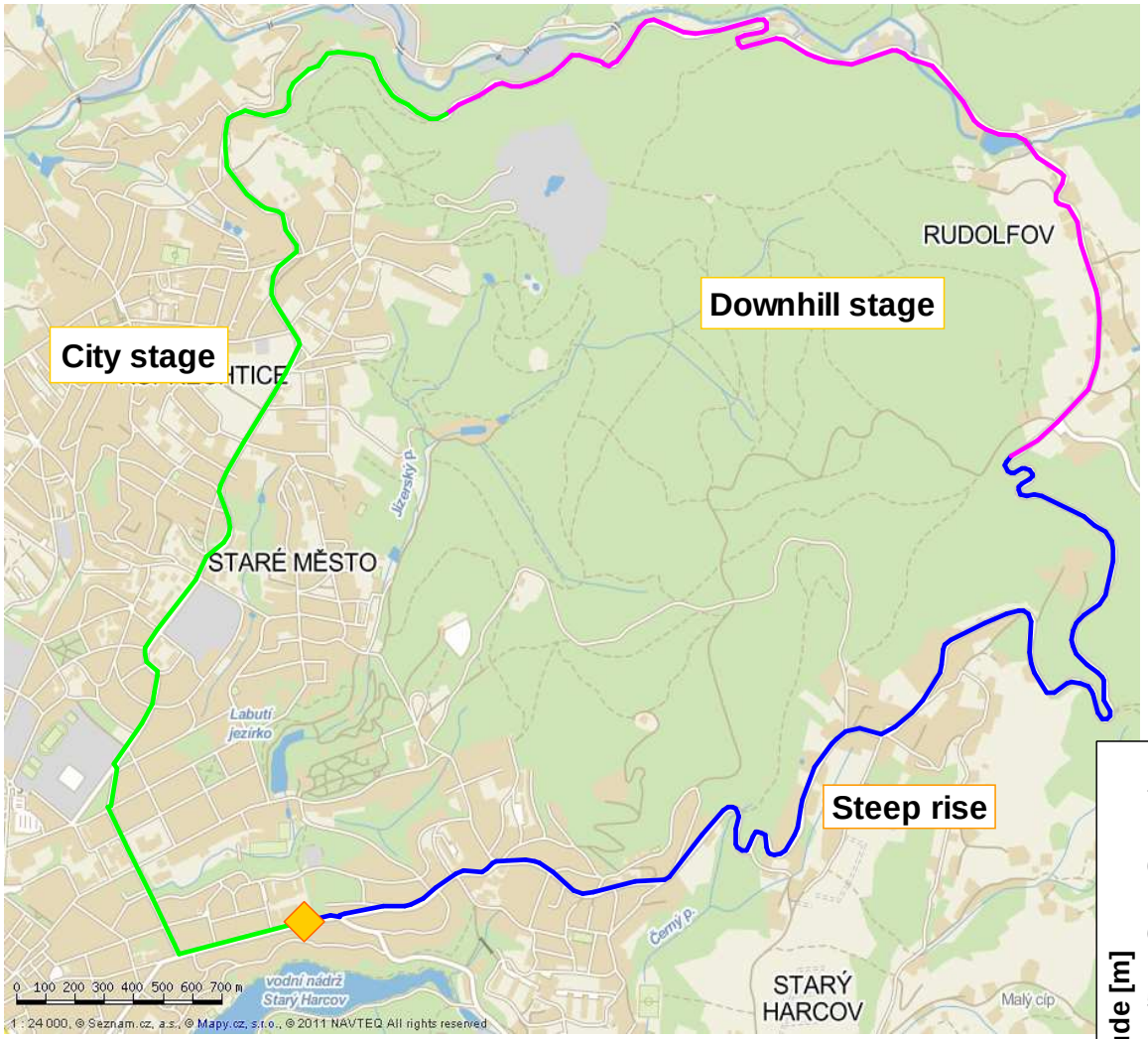


Experimental – Motorcycle (scooter)

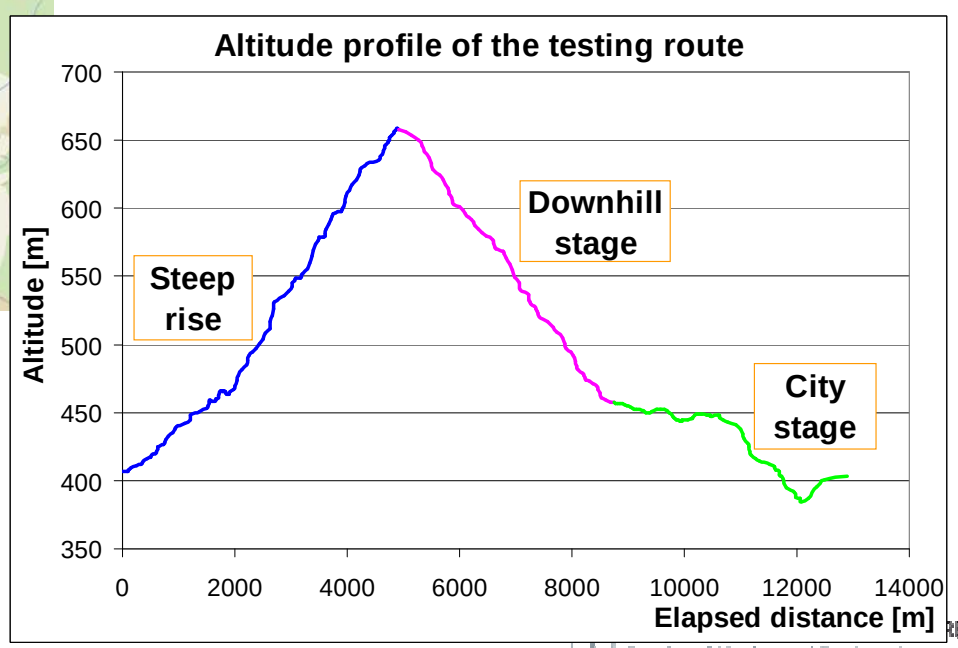


- 4-cycle 50-cc SI engine
- 13 kg PEMS on luggage rack
- Battery-powered system
- SAE J-2711: Pre-run & at least 3 runs along the route

Experimental – Test route

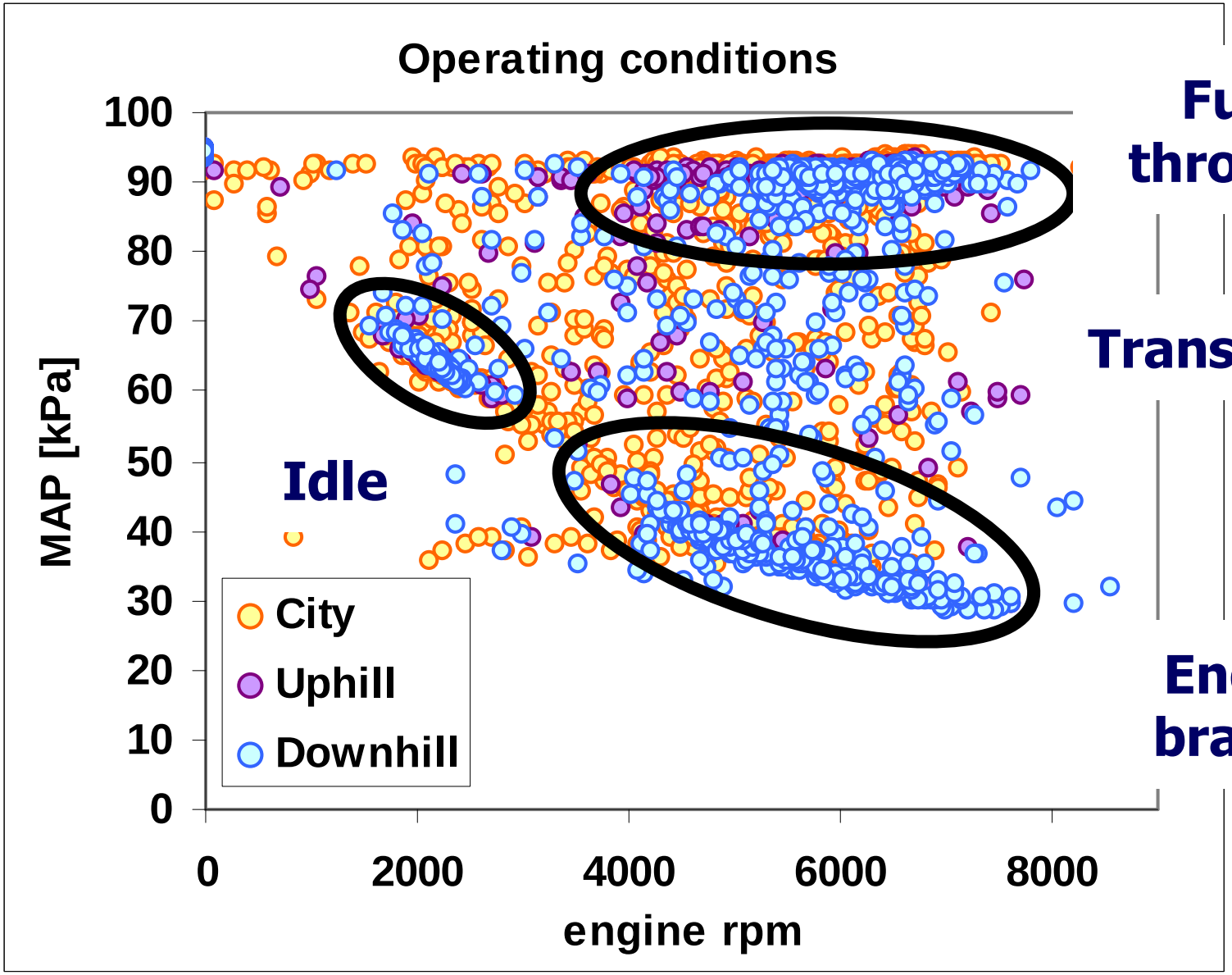


- Route length: approx. 13 km
- Start point altitude: 410 m
- Peak altitude: 660 m
- Lowest point altitude: 380 m



How a scooter is driven

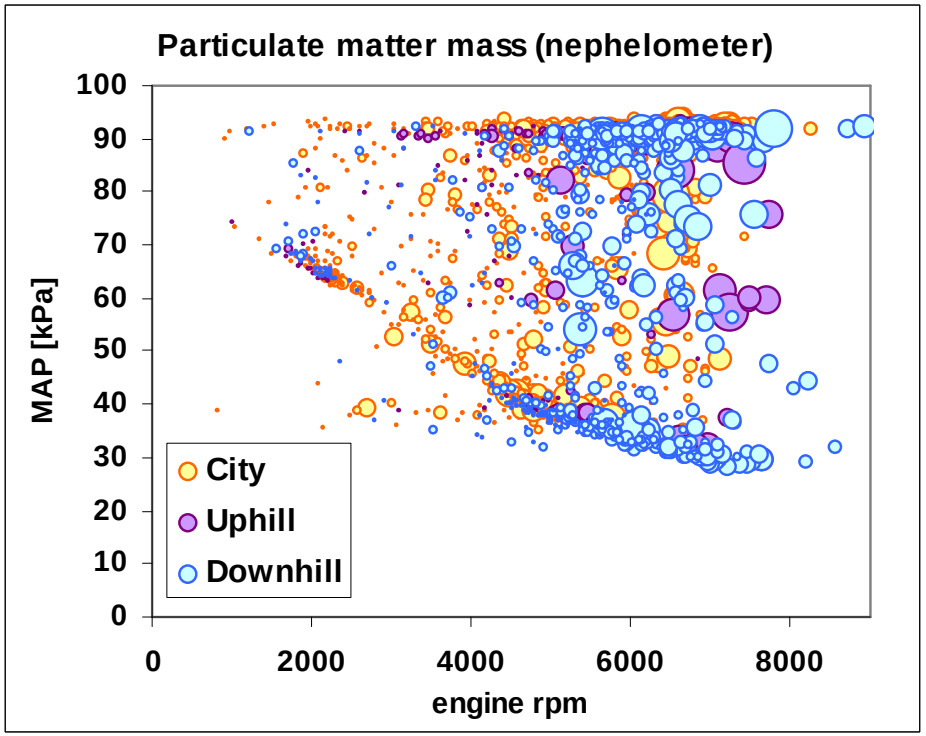
Mostly "full power or nothing", pulse-width modulation
Example: Liberec region, each point = 1 second of operation
Distinct regions: idle, full-power, engine braking, transitions

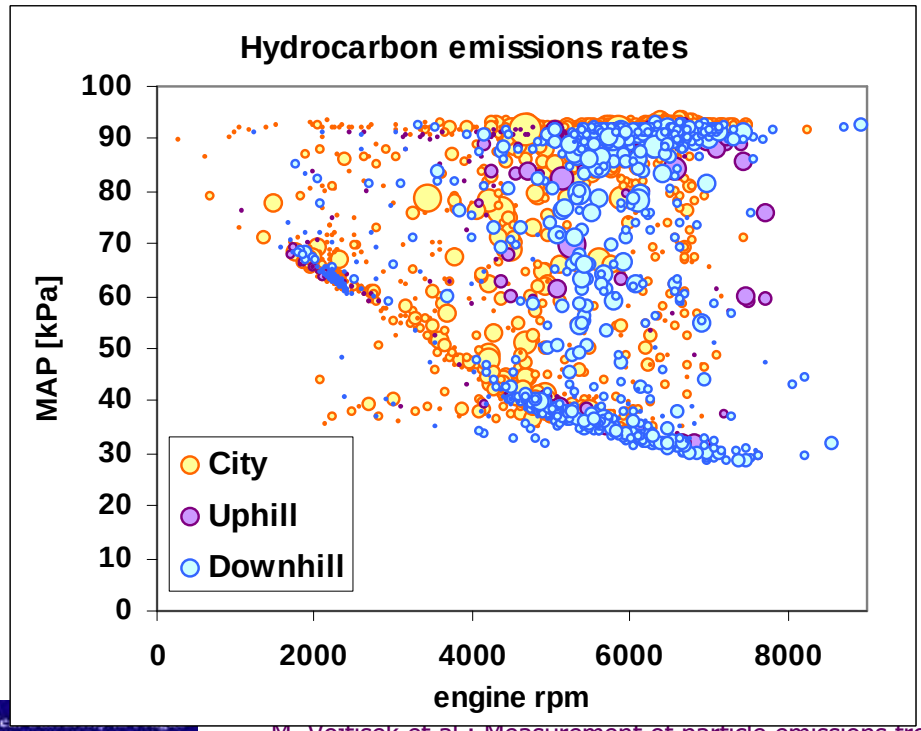


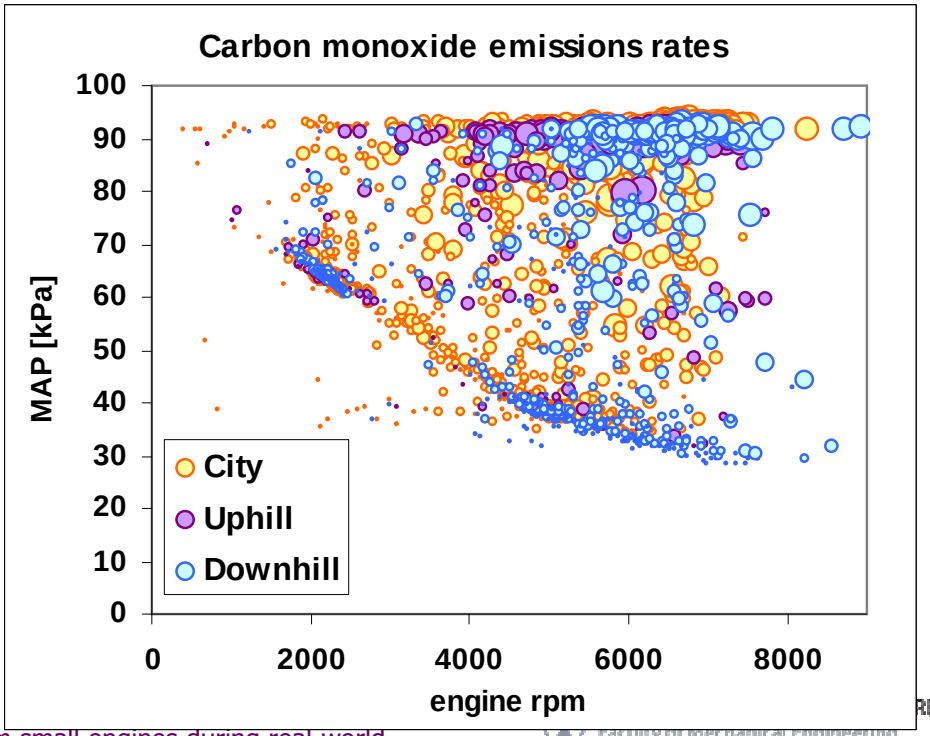
Emissions patterns

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

CO high during transitions and at full power





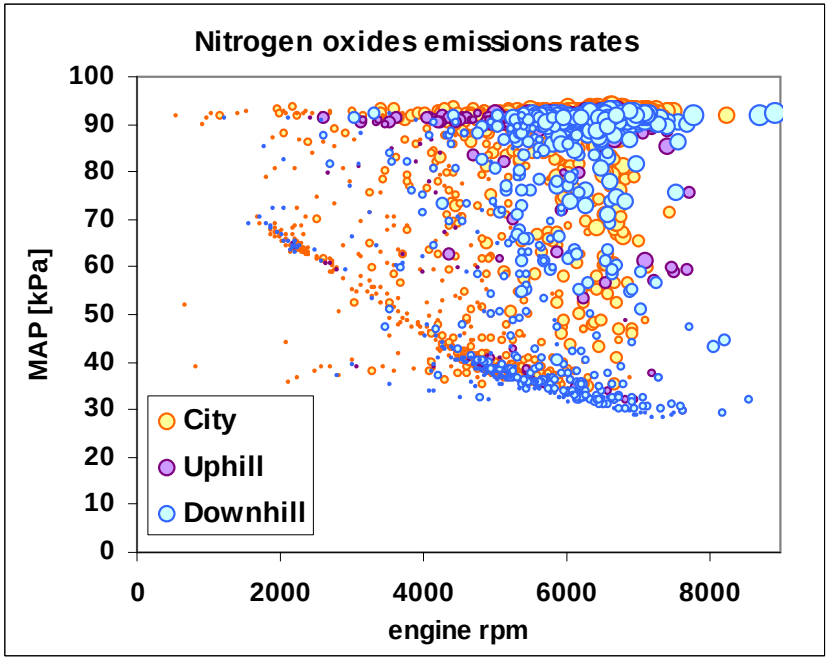


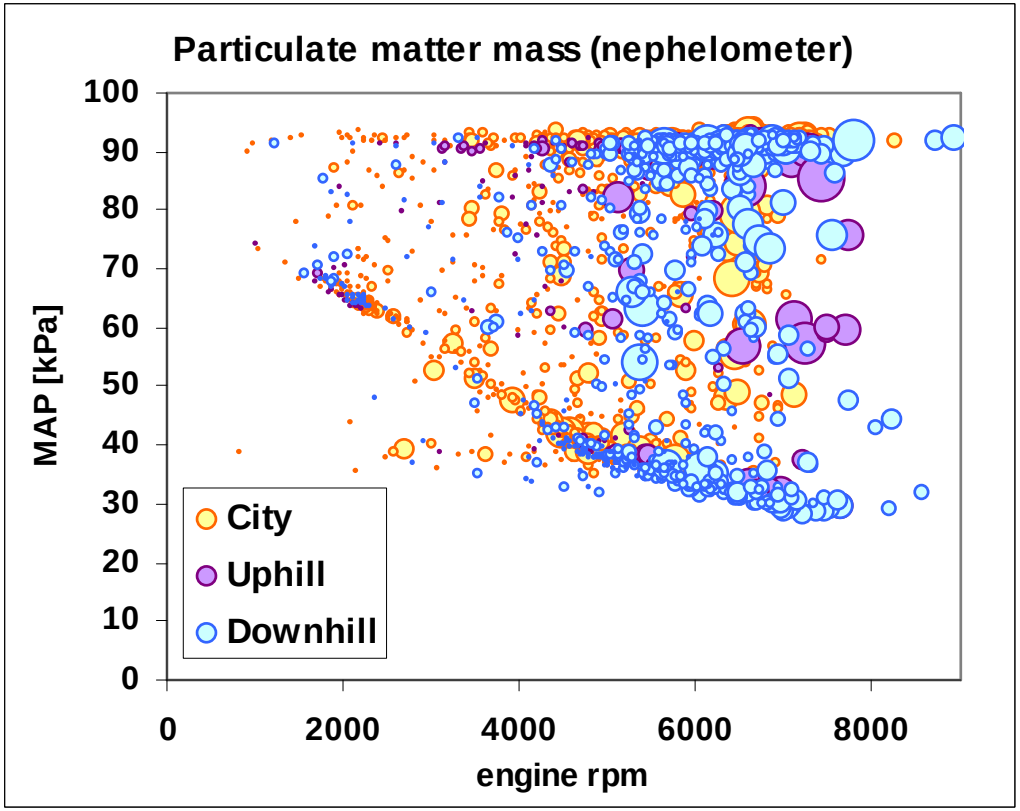
Emissions patterns

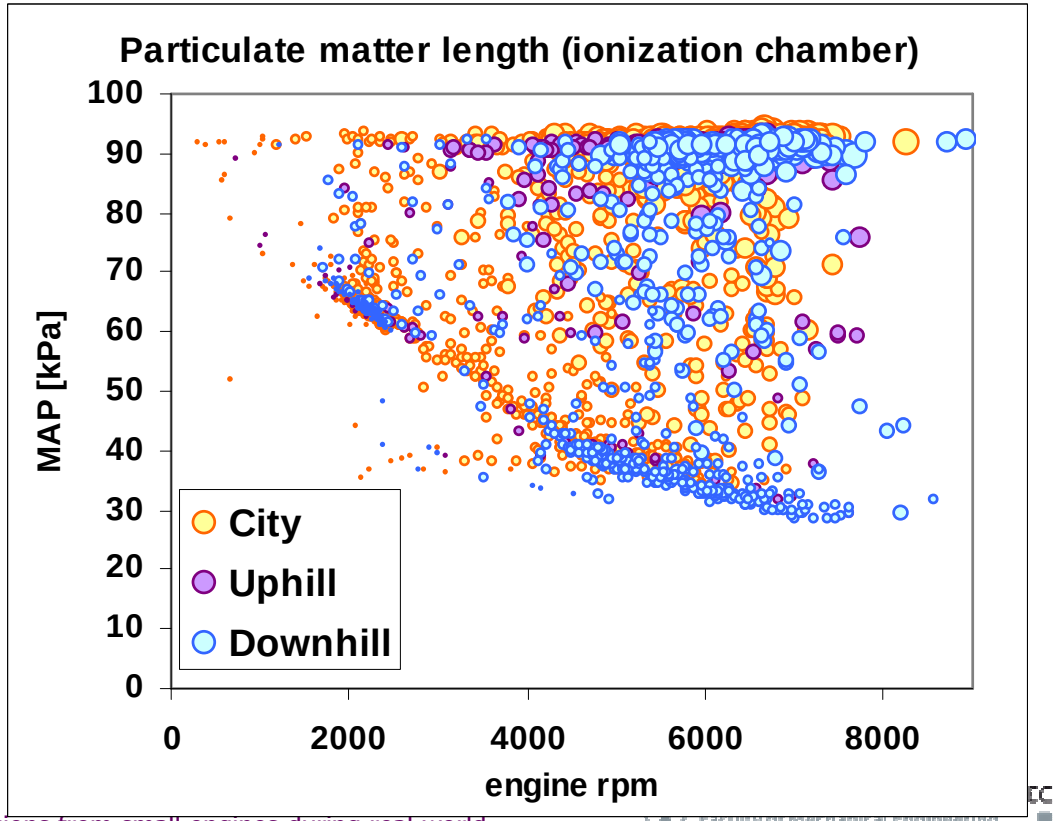
Larger particles (detected by light scattering) and hydrocarbons dominated by transitions

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

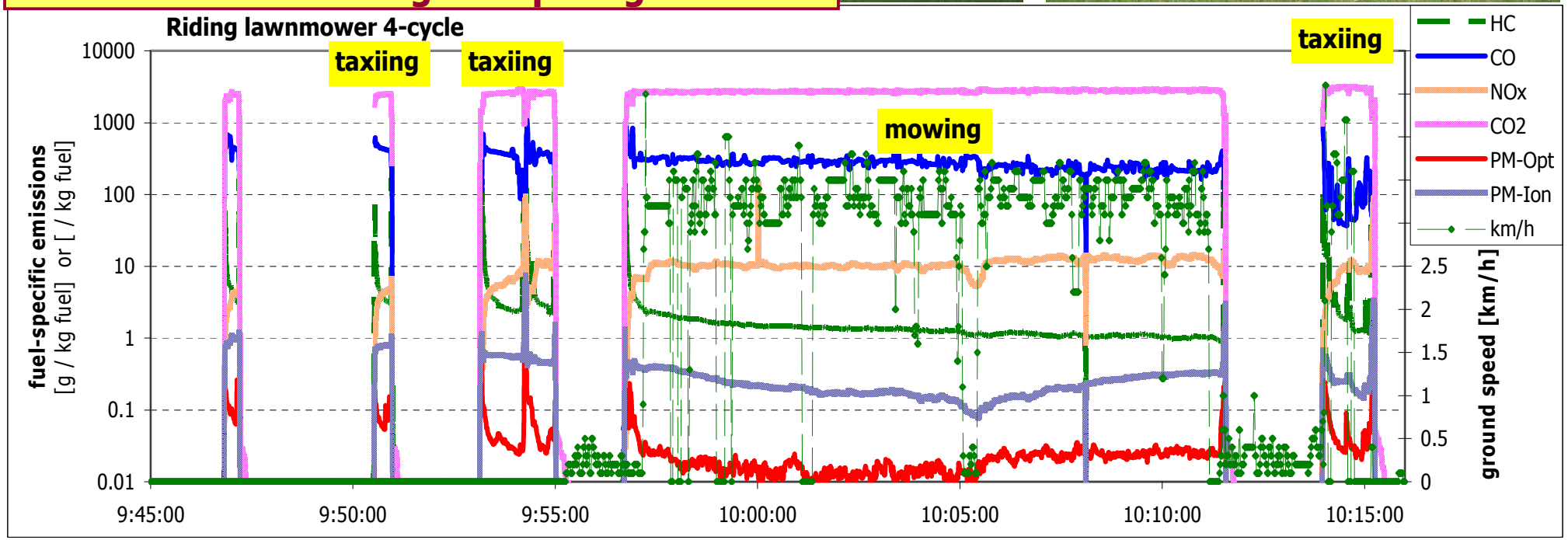
- Route length: approx. 13 km
- Start point altitude: 410 m
- Peak altitude: 660 m
- Lowest point altitude: 380 m

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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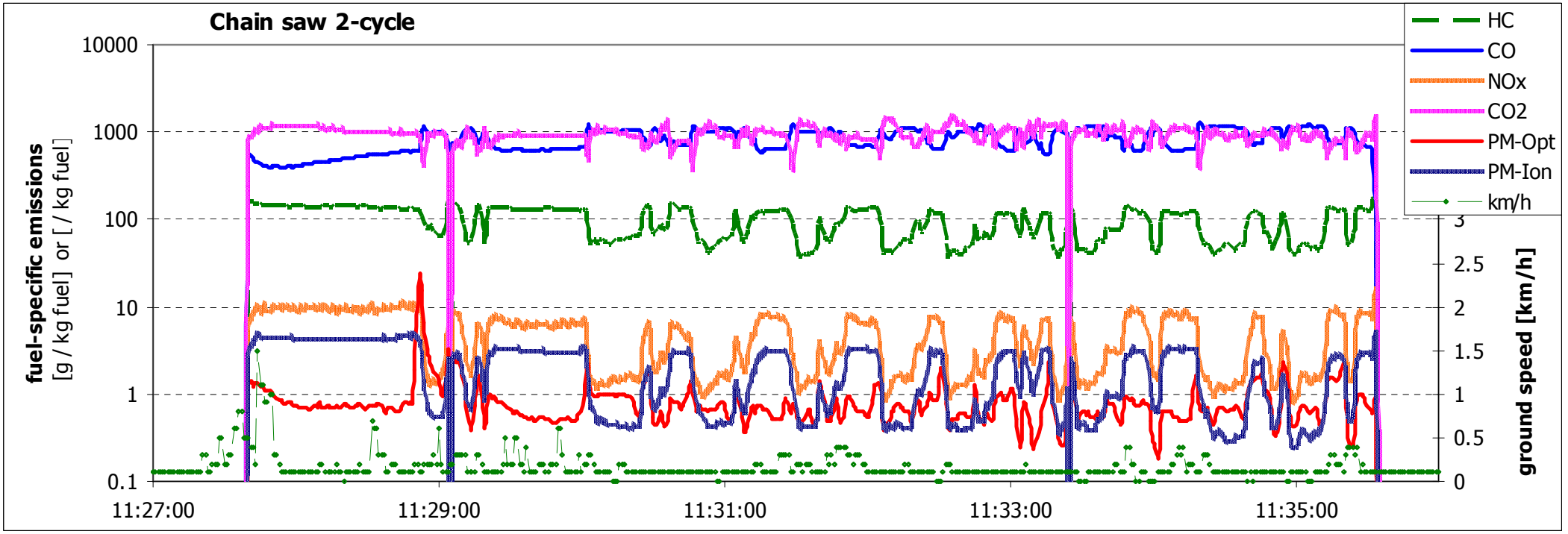
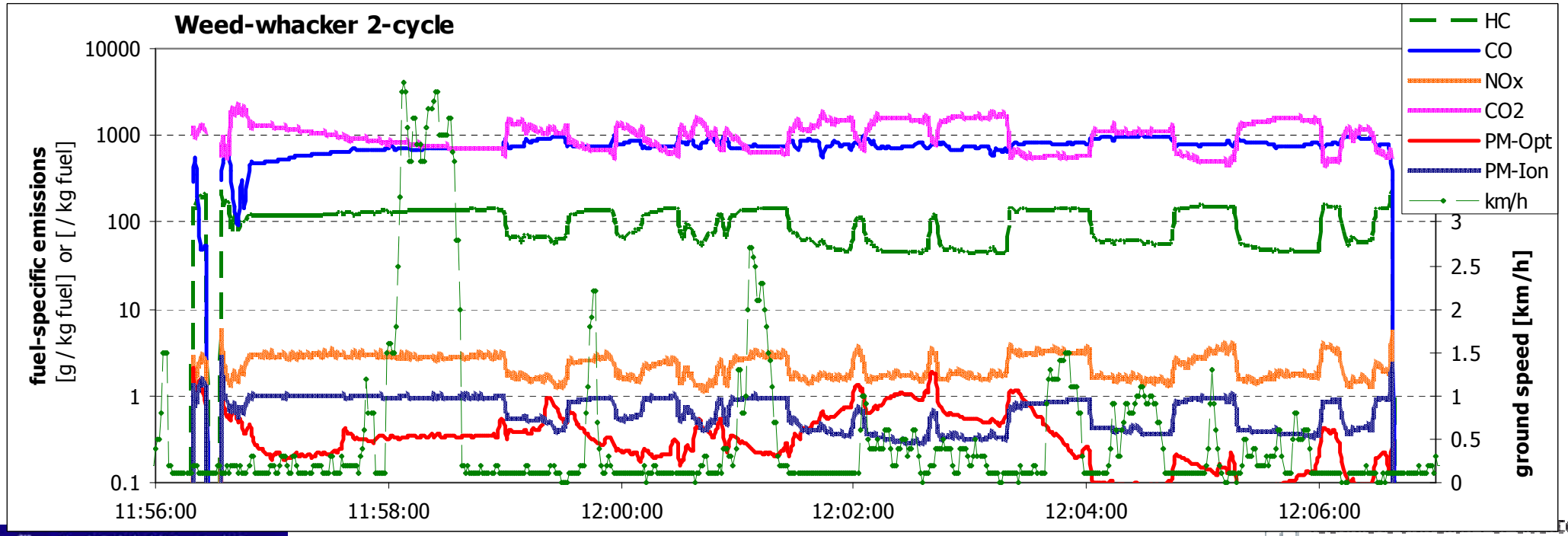


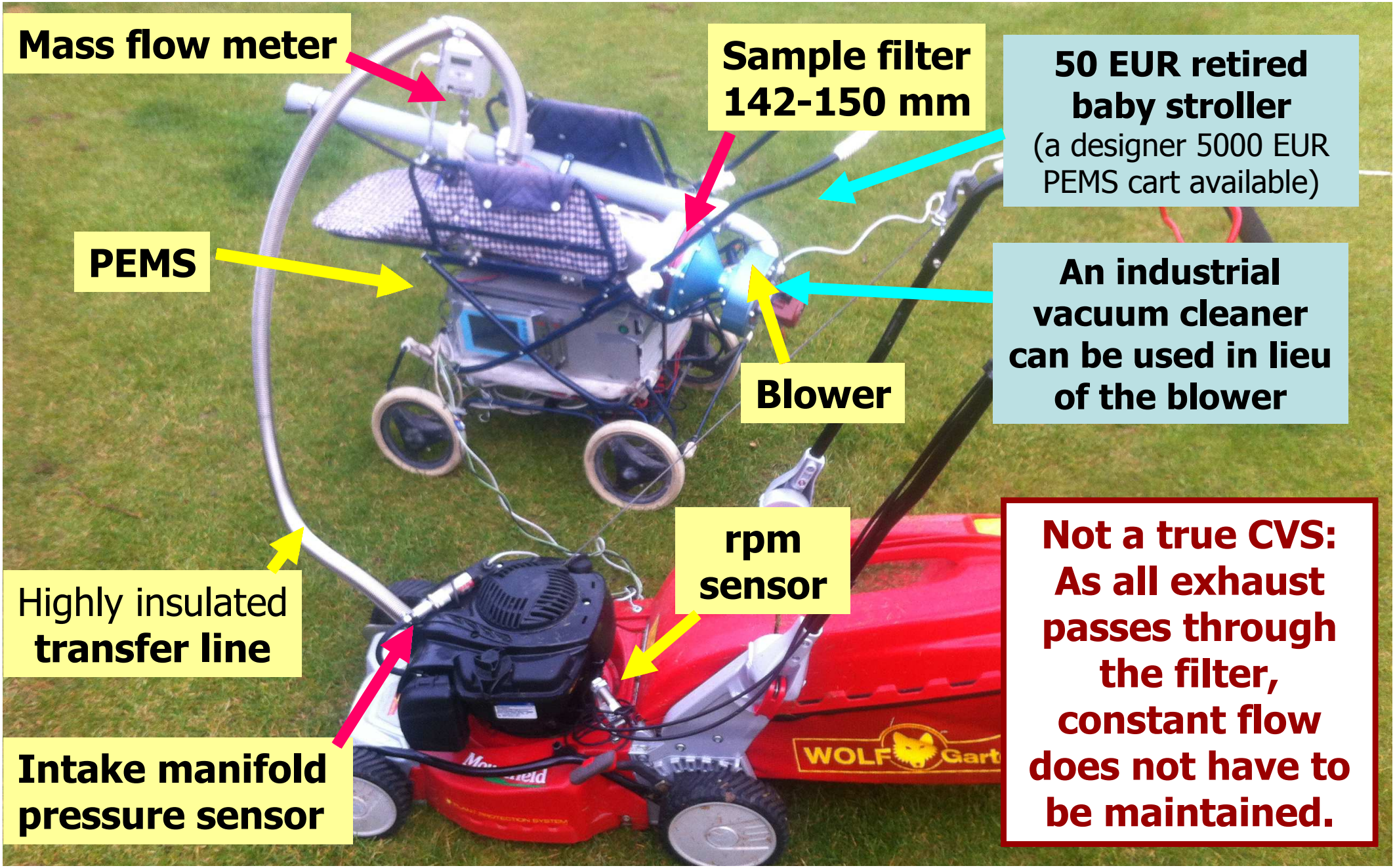
Off-board measurement – weed-eater
PEMS mounted on accompanying tractor

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

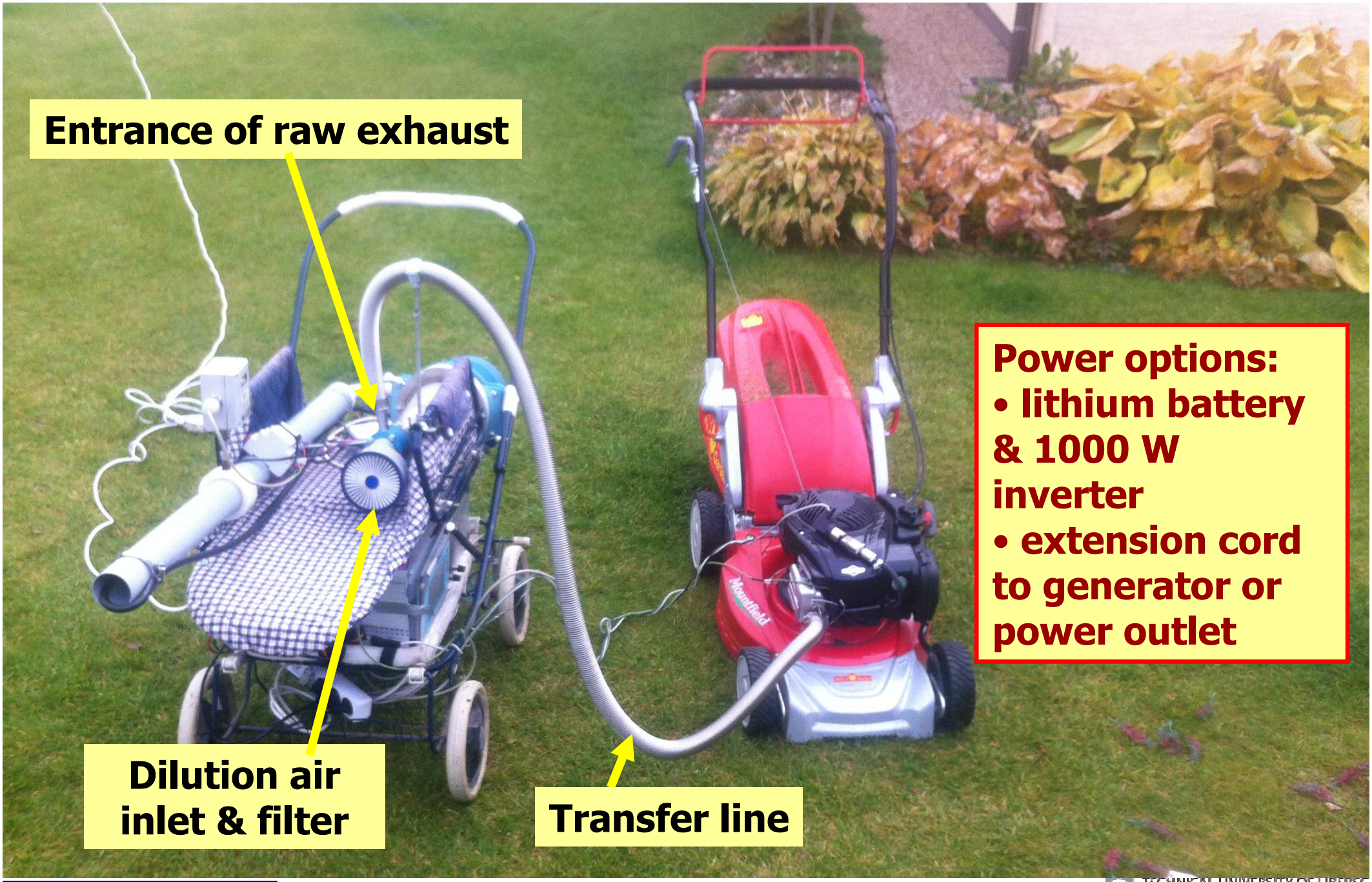
Cutting /clearing an overgrown ditch
On-board system mounted on accompanying tractor



Off-board full-flow dilution tunnel



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

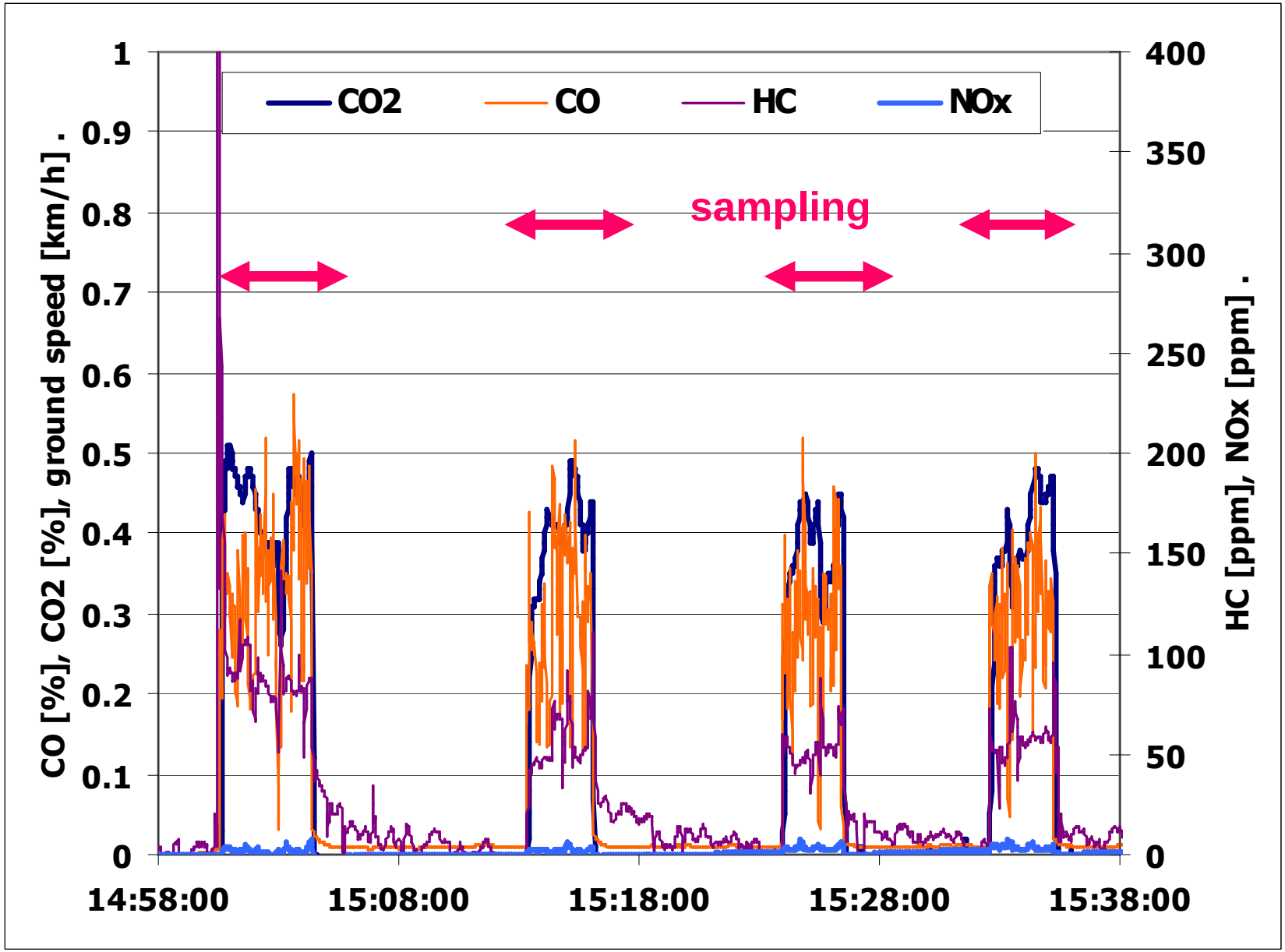
30-60 m³/min sampling on 142/150 mm filters for analyses (i.e. PAH) and toxicological assays

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

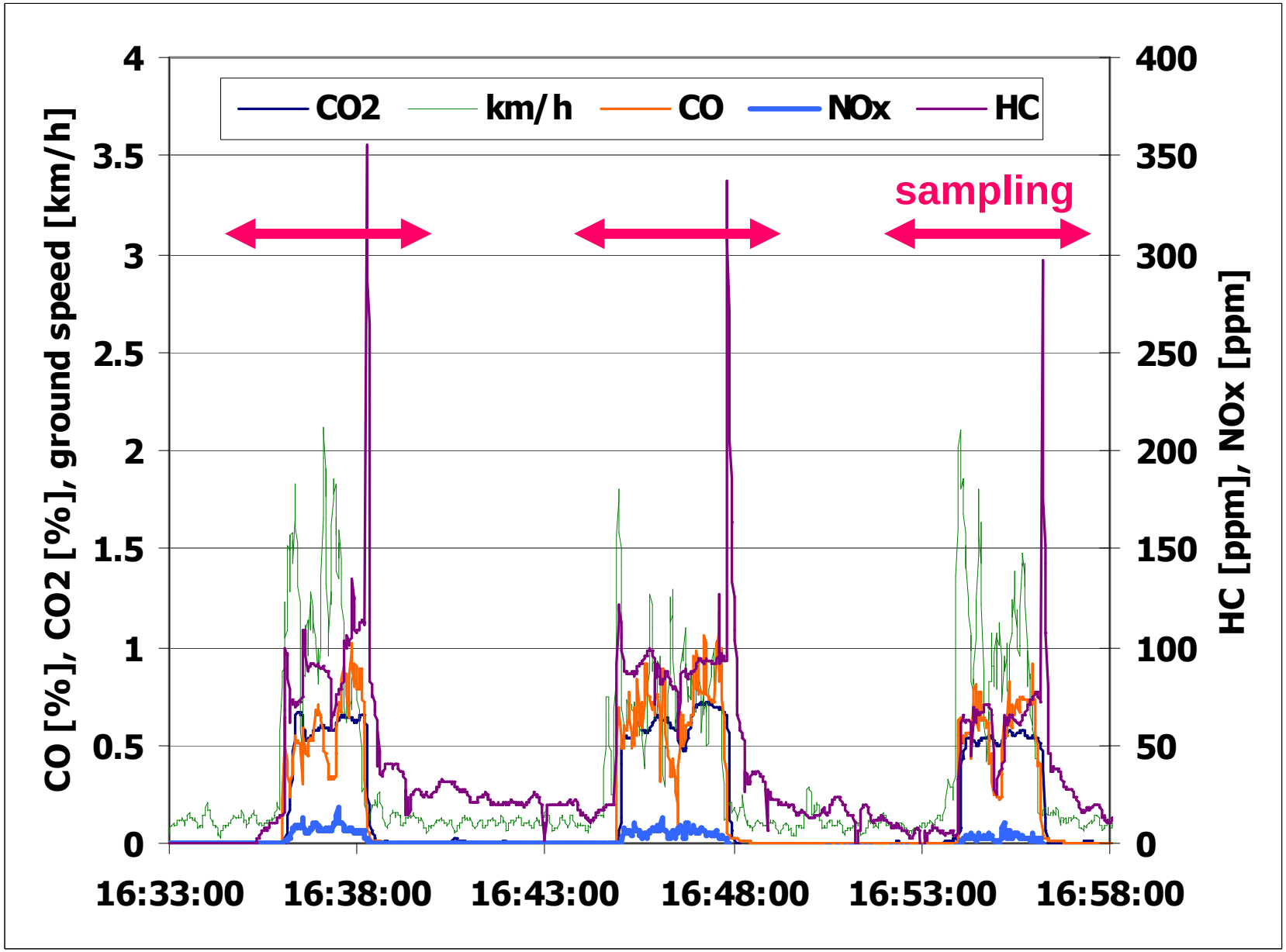
Large HC spike at (ignition) shutdown



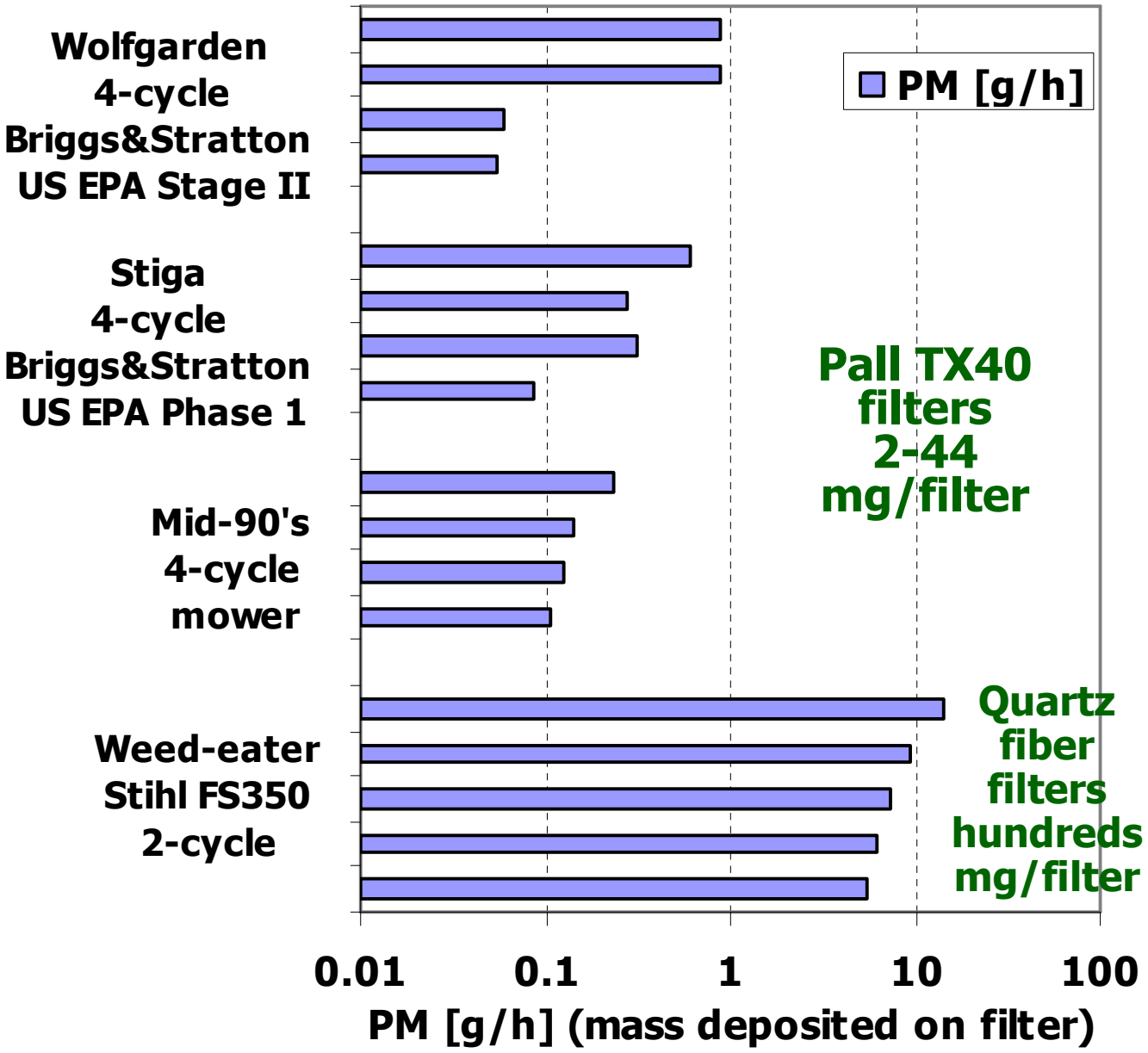
Base weedeater sequence: CVS on, Engine start, mowing until CVS filter is full, engine off, CVS off

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)



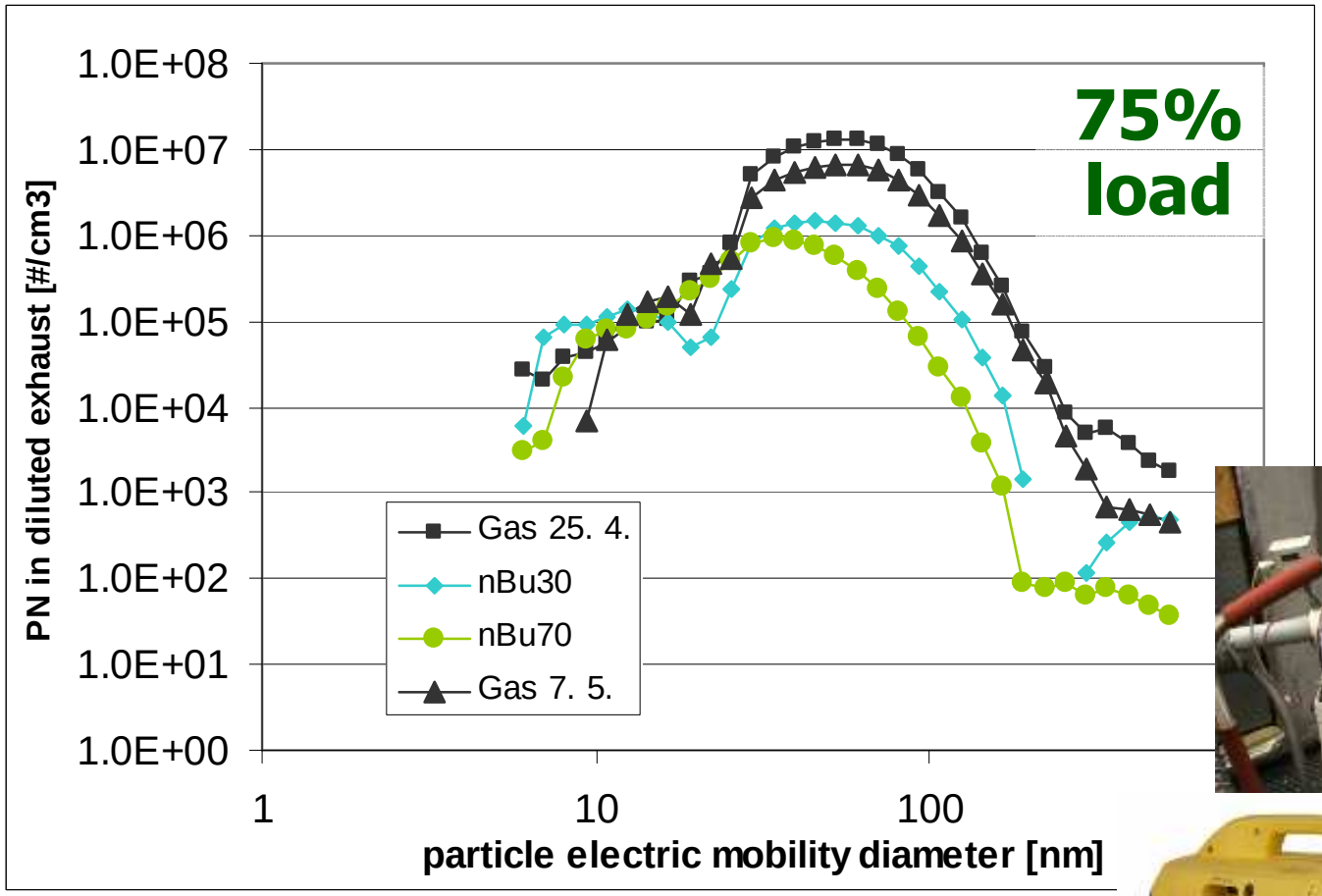
CARB Stage II Lawnmower – effect of alcohol fuels 30% iso-butanol, 30% n-butanol in gasoline
(SAE 2014, submitted)

	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

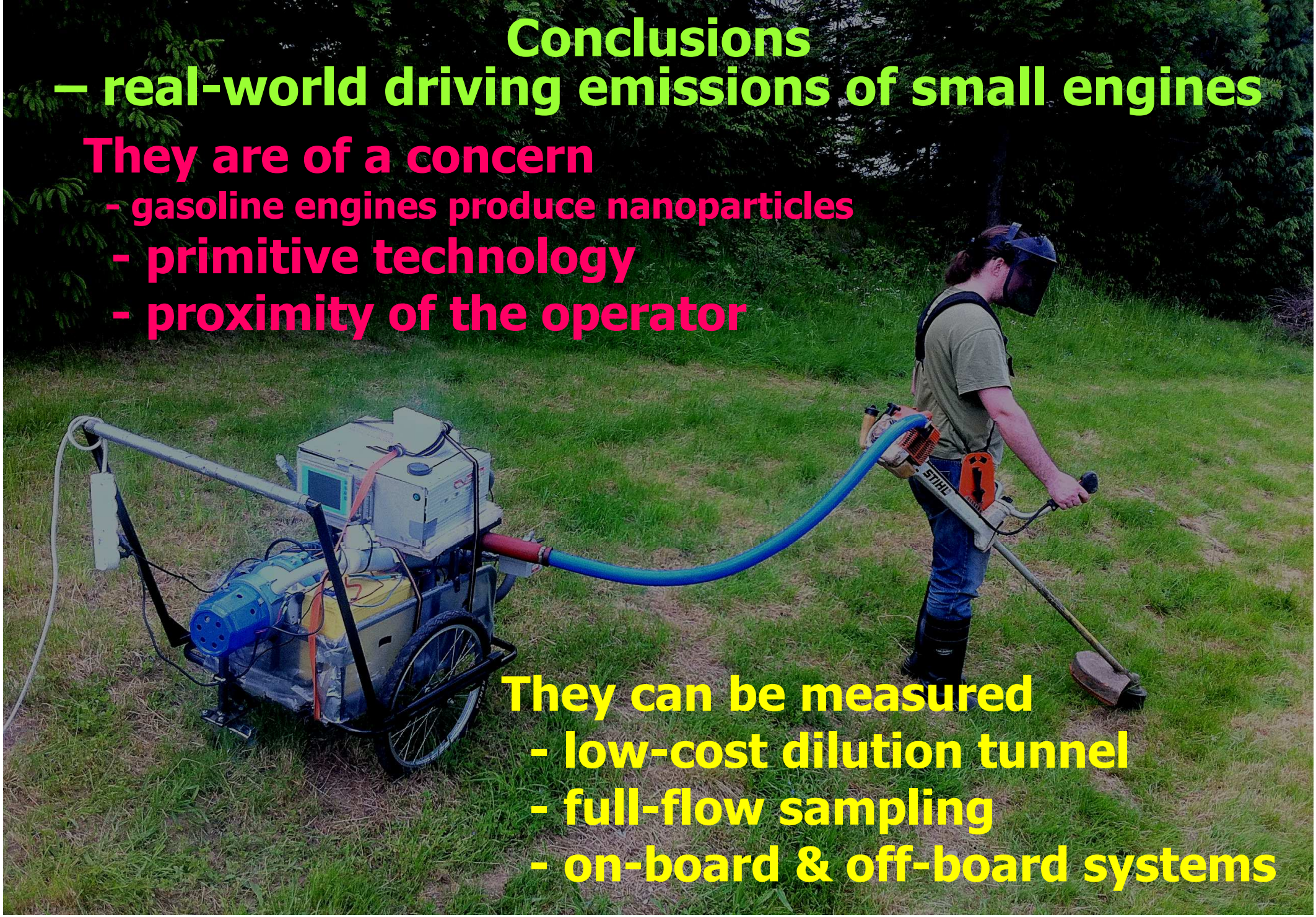
(Diploma thesis Jan Vodrazka, TU Liberec, 2014)



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

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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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