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Assessing Real Driving Emissions in Europe: An Update - Focus on PN Emissions

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7th Conference & Workshop
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Acknowledgments

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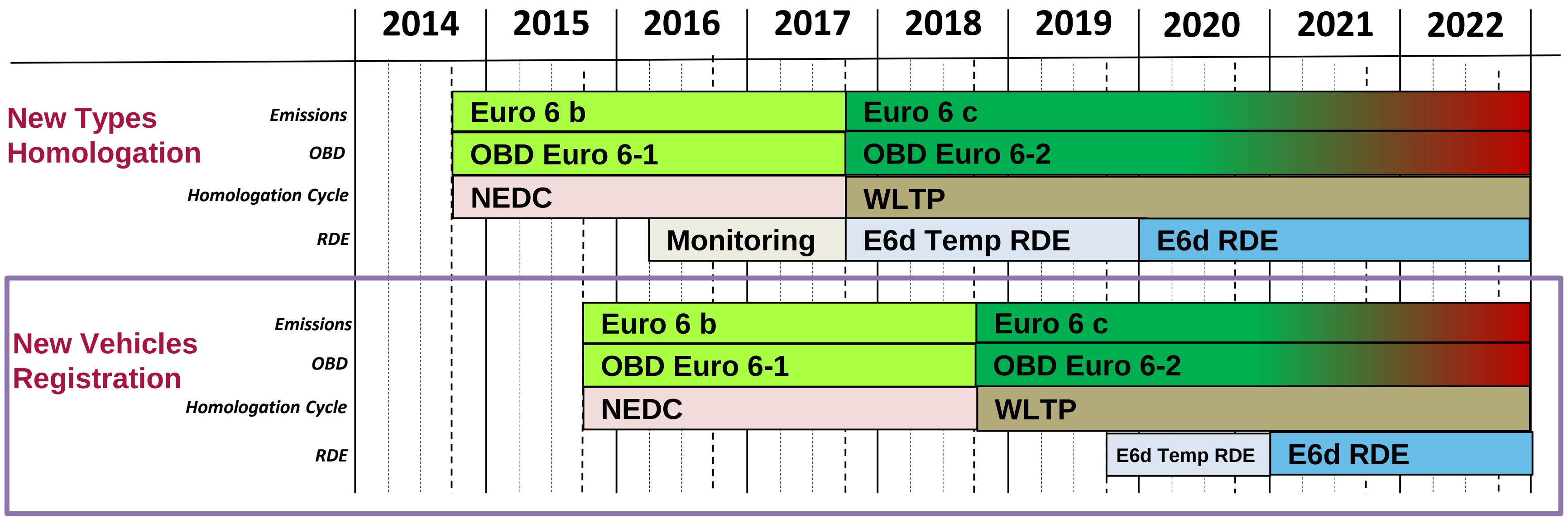
For the DownToTen Project:

- Prof. Jorma Keskinen, Dr. Panu Karjalainen (Tampere University of Technology)
- Prof. Alexander Bergmann (Graz University of Technology)
- Prof. Leonidas Ntziachristos (LAT)

Outline

- Update on the recent Real Driving Emissions Regulations in Europe
  - RDE3
  - RDE4
- The DownToTen Research Project “Measuring automotive exhaust particles down to 10 nanometers”
- Summary and conclusions

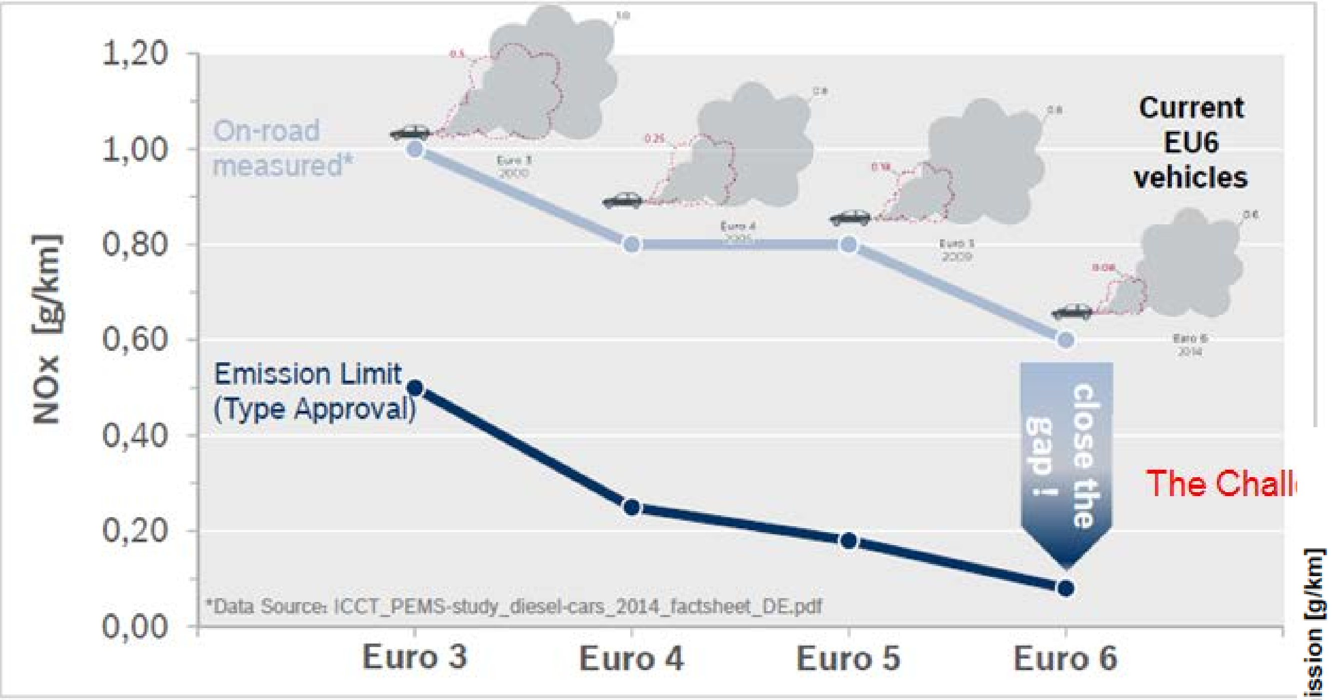
Emissions regulation evolution

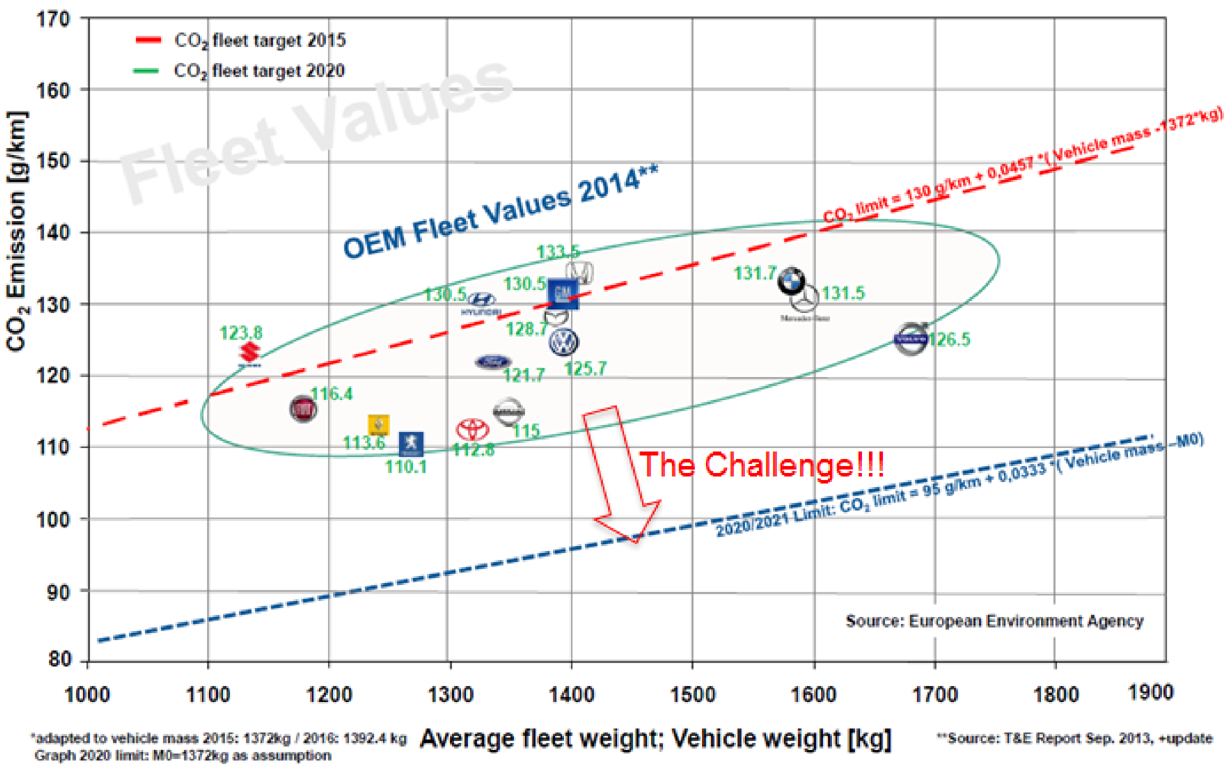


Euro 6c/d compliance requirements:

- ❑ For S.I. GDI engines the **Particulate Number (PN) limit** will be aligned with the diesel one: **$6*10^{11}$ #/km**
- ❑ **OBD** thresholds reduction both for NOx and Particulate Matter (PM).
- ❑ **WLTP** in phase with Euro 6c timing (approved on 14.06.2016)
- ❑ **RDE (Real Driving Emissions)** with Conformity Factors (CF) limits on:
  - **NOx** 2.1 temporary RDE – 1.5 Final RDE
  - **PN** 1.5 recently confirmed

Environmental challenges



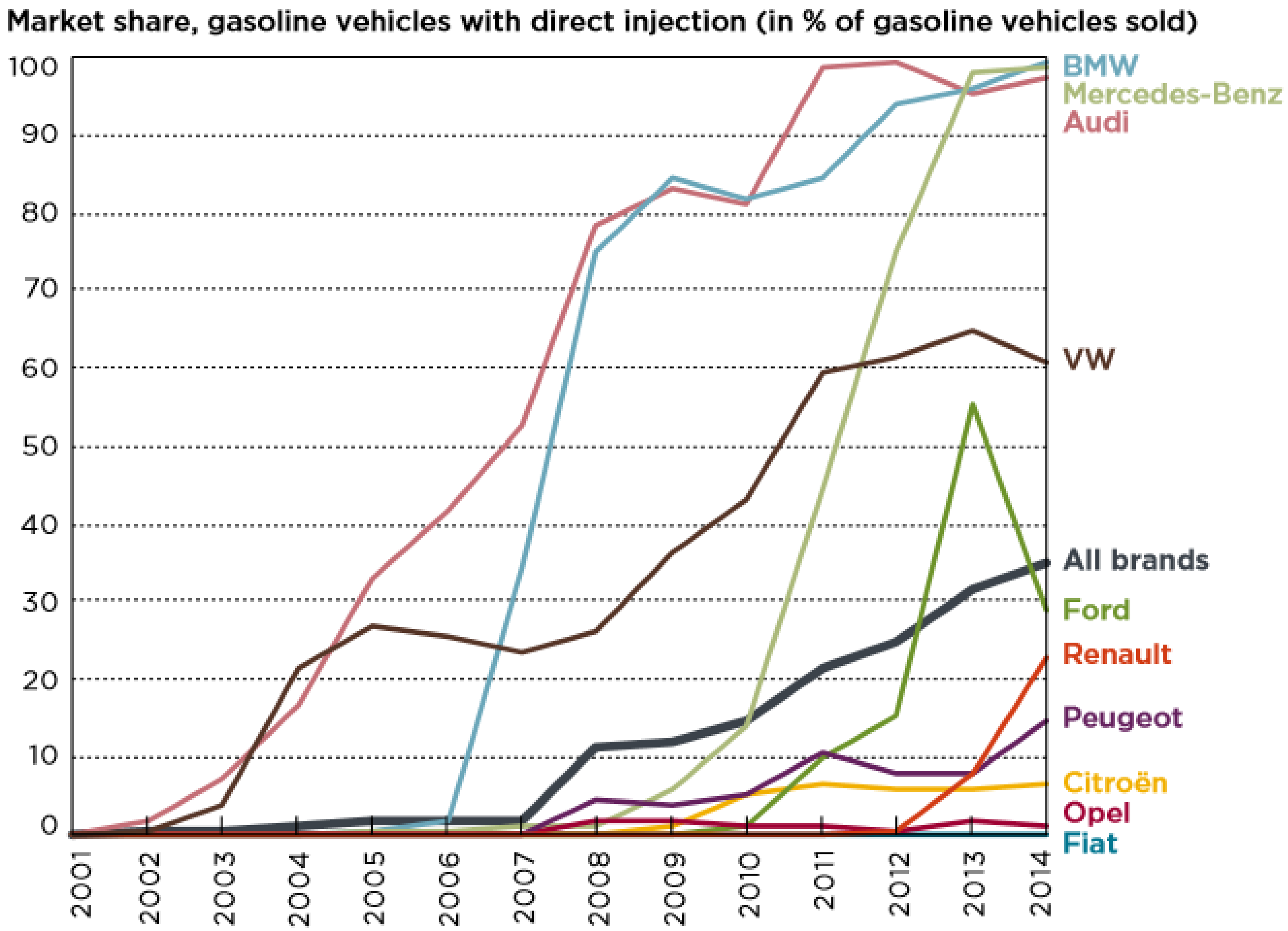


RDE3 Tasks

- PN inclusion
  - ⇨ according to EU regulations only solid particles > 23 nm are regulated so far
- Cold start inclusion
- Provisions for Hybrids
- Regeneration inclusion
- Other issues

Gasoline Direct Injection (GDI) passenger cars in the EU

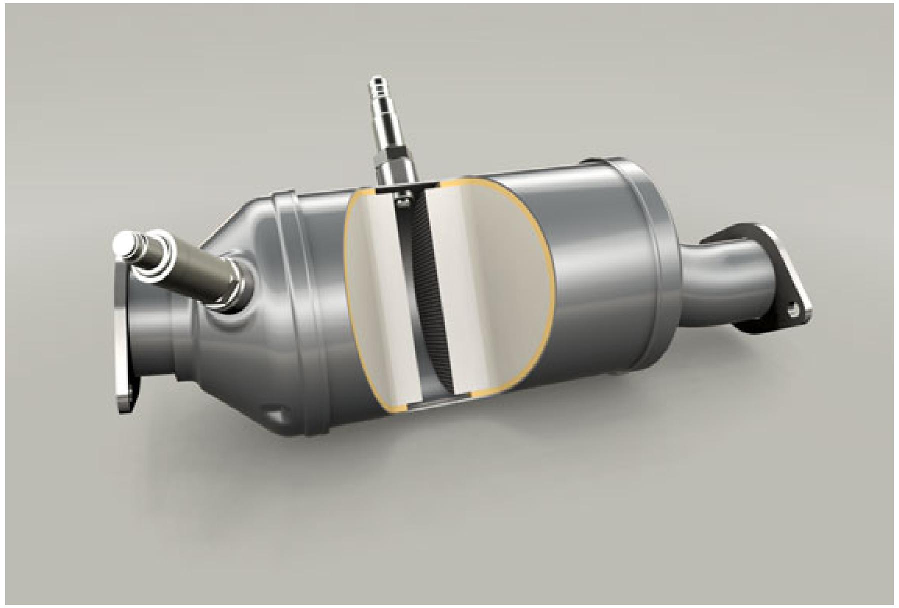
- In 2015 the market share of GDIs represented 40 % of new gasoline car registrations or 2.4 million units, up from 35% or 2 million units in 2014.
- In 2005, GDI appeared on a mere 3%, or 232,000, of cars sold in the EU.
- These vehicles conform to a temporary EURO6 emission limit of $6*10^{12}$



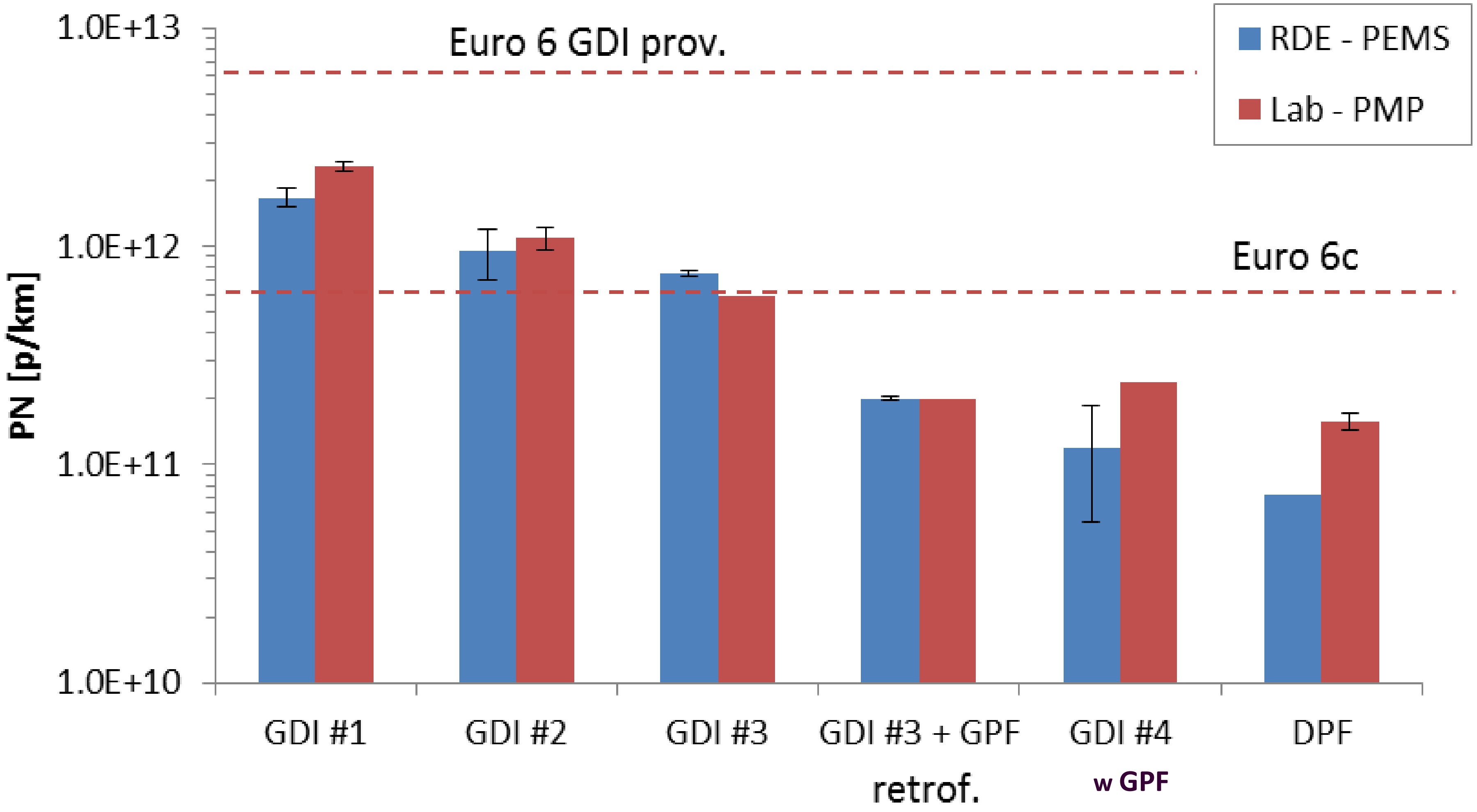
Source: ICCT. 2016

Gasoline Particle Filters (GPF)

- Gasoline Particle Filters are a cheap *(less than 50 Euro)* and clear solution for the issue of particles from GDIs
- The temporary emission limit was granted in order to allow time for manufacturers to implement properly GPFs in their vehicles, but….
- Currently only one model is equipped with GPF: Mercedes S 500
- Mercedes, VW and PSA group announced in 2016 full introduction of GPF in their vehicles *(combined covering around 50% of GDI sales in Europe)*



PN emissions with in lab (PMP) and on the road (PEMS)

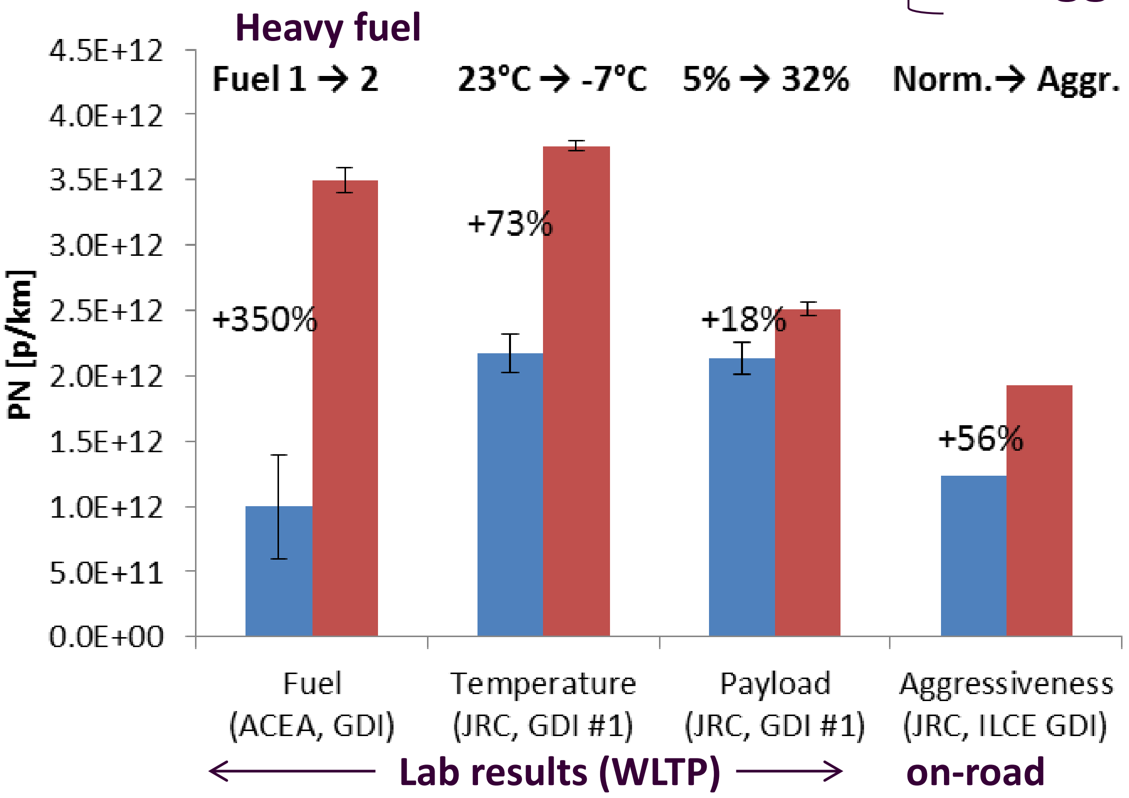


GDI1,2, DPF : Giechaskiel et al. 2015, Frontiers in Env. Sci. Air Pollution
GDI3: Demuynck (AECC) 2016, Bonn, ICPC 4
GDI4: Bosteels (AECC) 2016, ICPC 3rd

Real world influence on particle generation

- The previous was just a snapshot
- Many other influences:

Fuel
Ambient temperature
Payload
Aggressive Driving

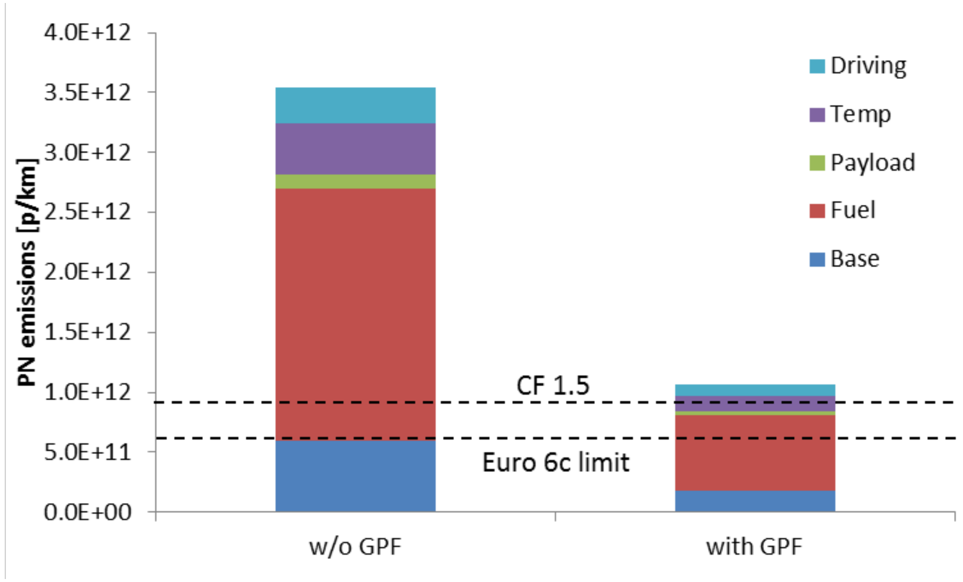


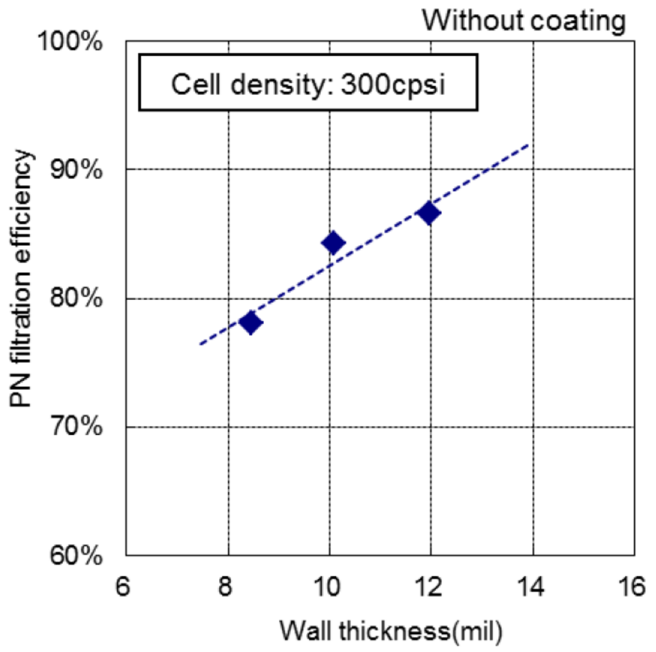
- Giechaskiel et al. 2015, Frontiers in Env. Sci. Air Pollution
- Riccobono et al. 2016
- ACEA/JAMA presentation

How low can PN from GDIs go in real life?

- Even with a Gasoline Particle Filter (GPF) these influences can amount to a significant contribution
- Care needs to be taken to have efficient GPFs
- Current practice suggests 60% efficiency, but can go up to 80% or even higher

Theoretical scenario





Summary of results from LDV PN-PEMS investigations

- **Equipment improved a lot and is improving continuously.**
- **Issues: Condensation at electrometers, dilution ratio uncertainty, failure of heated line, noise at low temperatures**

PN-PEMS	Phase I (LDV)	Phase II (LDV)	ILCE (LDV)
	End of 2013	Sep – Dec 2014	Sep – Dec 2015
AVL (DC)	-40% to +80%	-49% to +48%	-
Horiba (DC) ^ $	-100% to +100%	+11% to +150%	-
Horiba (CPC)	-	-21% to +49%	-41% to 54%
Testo (DC)	-6% to +114%	-48% to +55%	-39% to 42%
Pegasor (DC) ^	-50% to +120%	-58% to +199%	-
Sensors (DC) $	-50% to +200%	-85% to +309%	-
Sensors (CPC)	-	Technical issues	-
Maha (CPC)	-	-45% to +49%	-
Shimadzu (DC) ^	-	-35% to +97%	-

^ Not compliant with latest technical specs
$ Concept prototype. Discontinued

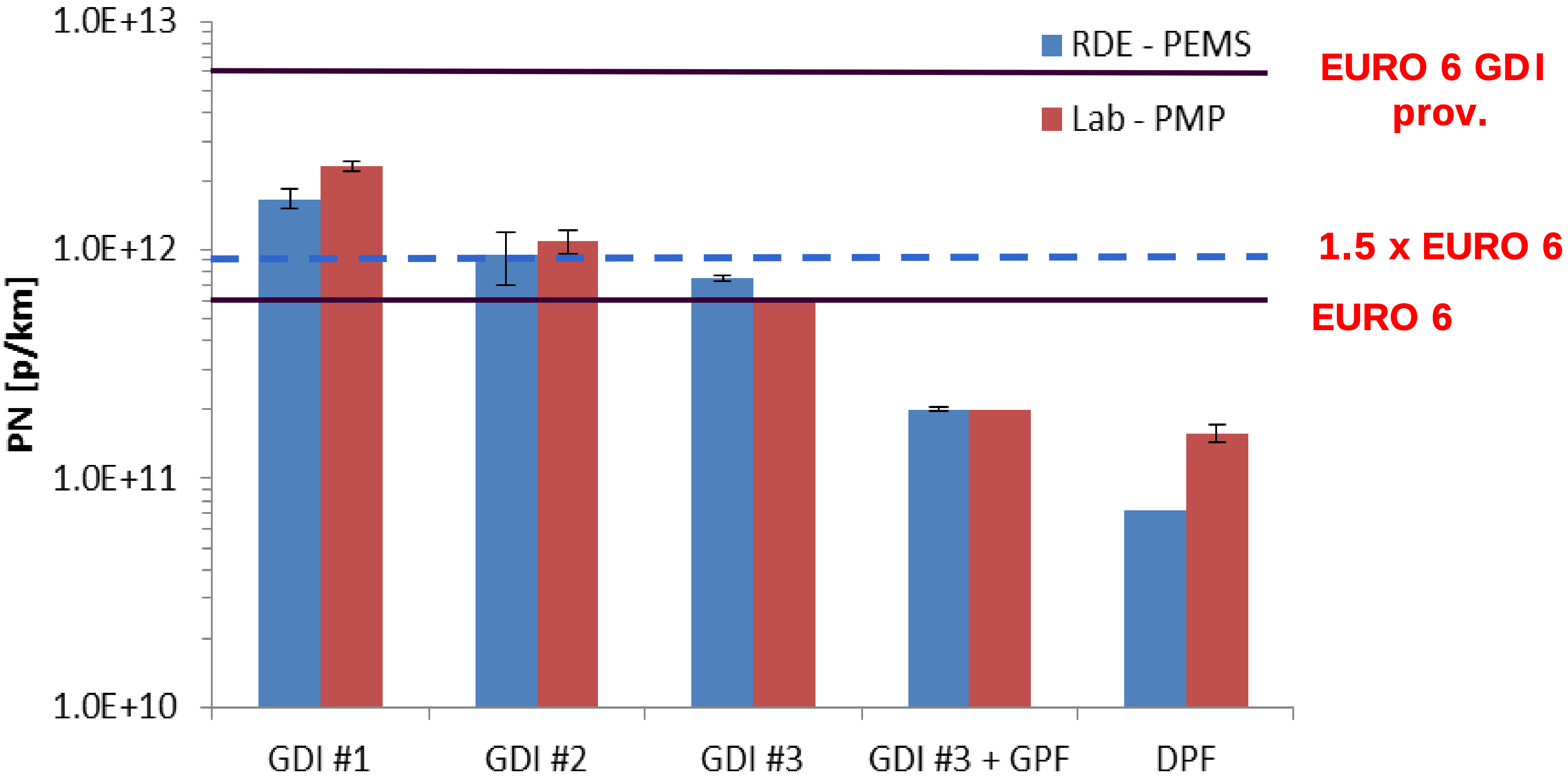
PN-PEMS Measurement uncertainty

Translation of the EURO-6 limit (measured by PMP at CVS) into the equivalent measured with PN-PEMS

PN-PEMS vs	Theory	1 lab – many cars	1 car – many labs
PMP_TP	<25%	<35%	<40%
PMP_CVS	<50%*	<55%	<54%
TP vs CVS (PMP)	<30%	<40%	<35%

* Assuming 25% effect of sampling location (losses + exhaust flow uncertainties)

Margin added only to account for the uncertainty of the measurement equipment



Proposal for PEMS-PN

- Inclusion of PN for RDE is technically feasible
- Equipment fulfills the technical specifications and have shown good behaviour during extensive testing
- Since technology exists (GPF) that allows even GDIs to be significantly lower than the EURO 6 limits, only the measurement uncertainty may be recognised
- Theory and the most extensive set of data available (JRC interlab and own tests) show that the uncertainty of measuring at the EURO 6 limit is at maximum 50%
- **NTE_{PN}: 1+ Margin PN (with Margin PN=0.5)**
- **With annual review clause**
- **In 2017 for new types, in 2018 for new vehicles**

Cold Start

- Approach 0:Cold-start as part of RDE urban evaluation

- Approach 1: $M_{urban}\left[\frac{mg}{km}\right] = \frac{m_{cold}[mg]+m_{hot}[mg]}{d_{urban}[km]} = \frac{m_{cold}[mg]}{d_{urban}[km]} + \frac{m_{hot}[mg]}{d_{urban}[km]}$

$$M_{urban}\left[\frac{mg}{km}\right] \approx \frac{m_{cold}[mg]}{d_{urban}[km]} + RDE_{hot,urban}\left[\frac{mg}{km}\right]$$

- Approach 2a: $M_{urban}\left[\frac{mg}{km}\right] = w \cdot M_{cold}\left[\frac{mg}{km}\right] + (1-w) \cdot RDE_{hot,urban}\left[\frac{mg}{km}\right]$

$$\text{with } w = \frac{d_{cold}[km]}{d_{urban}[km]}$$

- Approach 2b: $M_{urban}\left[\frac{mg}{km}\right] = w \cdot M_{cold}\left[\frac{mg}{km}\right] + (1-w) \cdot RDE_{hot,urban}\left[\frac{mg}{km}\right]$

$$\text{with } w = \frac{d_{cold} = 2km}{d_{urban}[km]}$$

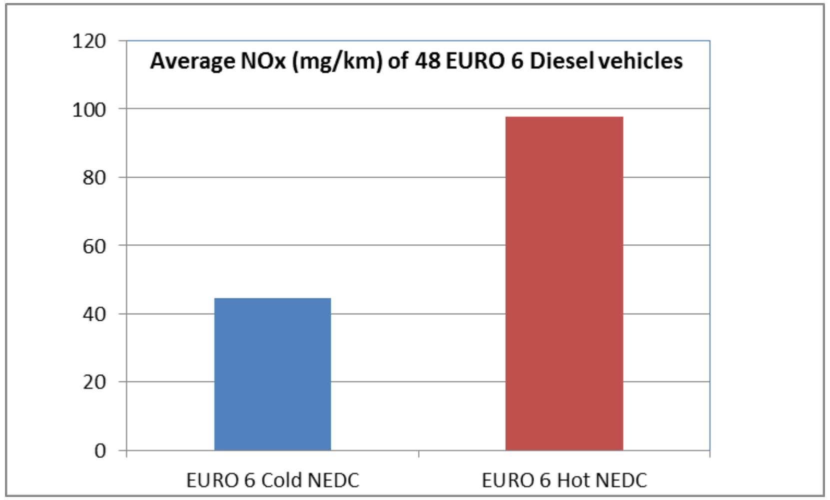
Cold Start Inclusion

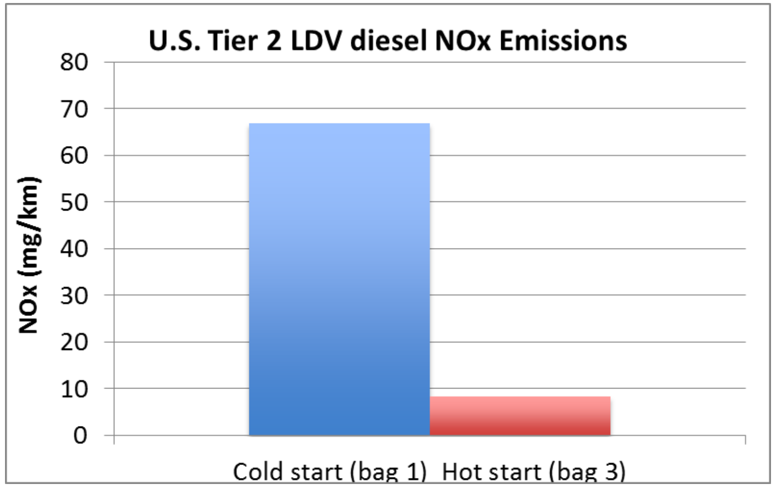
- New Preconditioning and Boundary Conditions included
- Approach 0: straight forward, need to check the application with the two tools
- Approach 2A: Technically correct, but care needs to be taken to select the appropriate d_{urban}
  - *Trip data show substantial variability*
- Dates for inclusion into RDE with 1st step
- Contribution of first 5 min contributes in the 16 km of urban driving (approx. to 30 min) because of NTE_{urban}

- Introduction of a hot start RDE trip

Hot Start Inclusion

- Recent revelations of national investigations confirm that currently most vehicles emit higher in the hot cycle than in the cold one
- Engineering/physical principles cannot explain this
- In the USA hot start cycle emits 12% of the cold one!





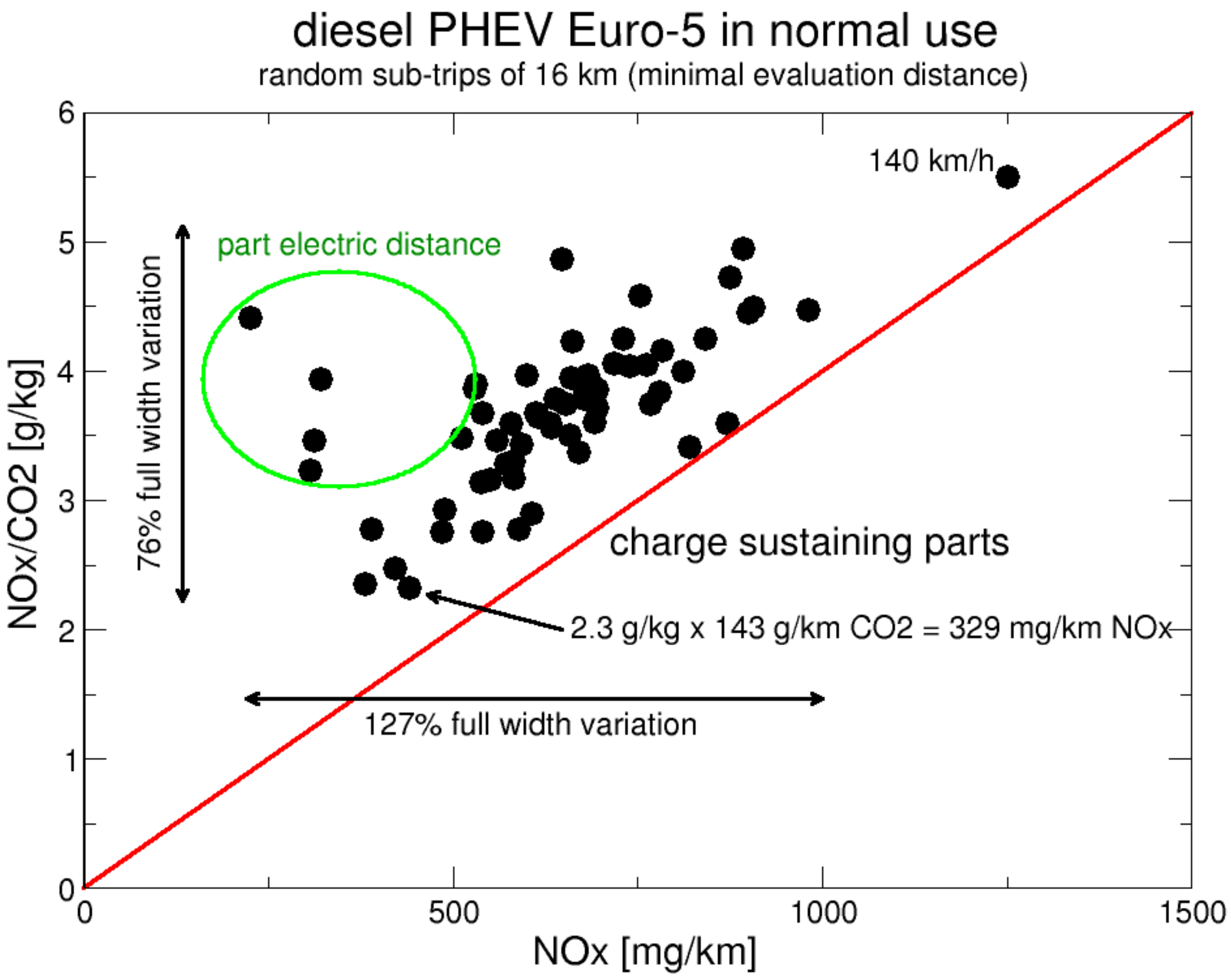
- Prescribe in RDE that at least 1 vehicle per PEMS family shall be tested with hot engine to avoid tuning for cold testing only

Hybrids

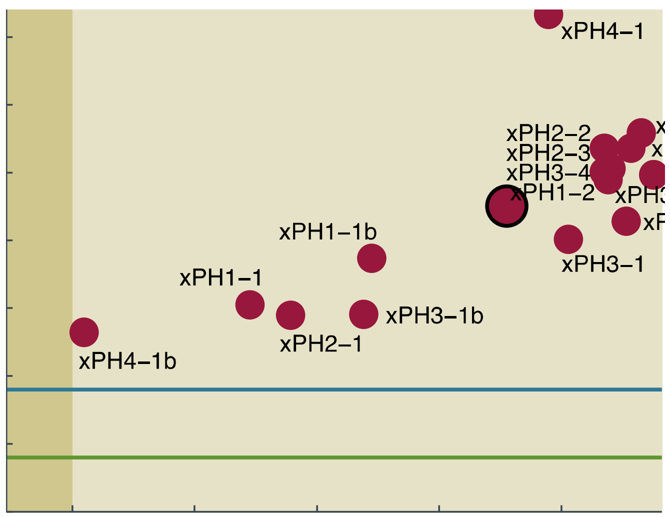
- Only for OVC-HEVs:
- Use normalised NOx/CO2
- Smaller variation than NOx
- **RDE NOx[mg]/CO_2[g] < limit[mg/km]*CF/CO_2ref[g/km]**

- Use for the following CO_2reference [g/km] in charge sustain mode:
  - For full RDE trip: WLTP total CO_2 [g/km]
  - For urban RDE trip: low + medium phase WLTP CO_2 [g/km]
  - *For the moment NOVC-HEVs only with EMROAD/CLEAR (tbc)*

- ***Review necessary in order to introduce a more complete/appropriate methodology that captures all benefits of PHEVs***
- **Urban driving mostly in Charge Depleting mode may not be reflected adequately**



Diesel Hybrids: Average on-road NO_X and CO_2 emission results by vehicle and trip for 3 diesel PHEVs



Peugeot 3008
(Euro 5, 99 g/km CO_2)

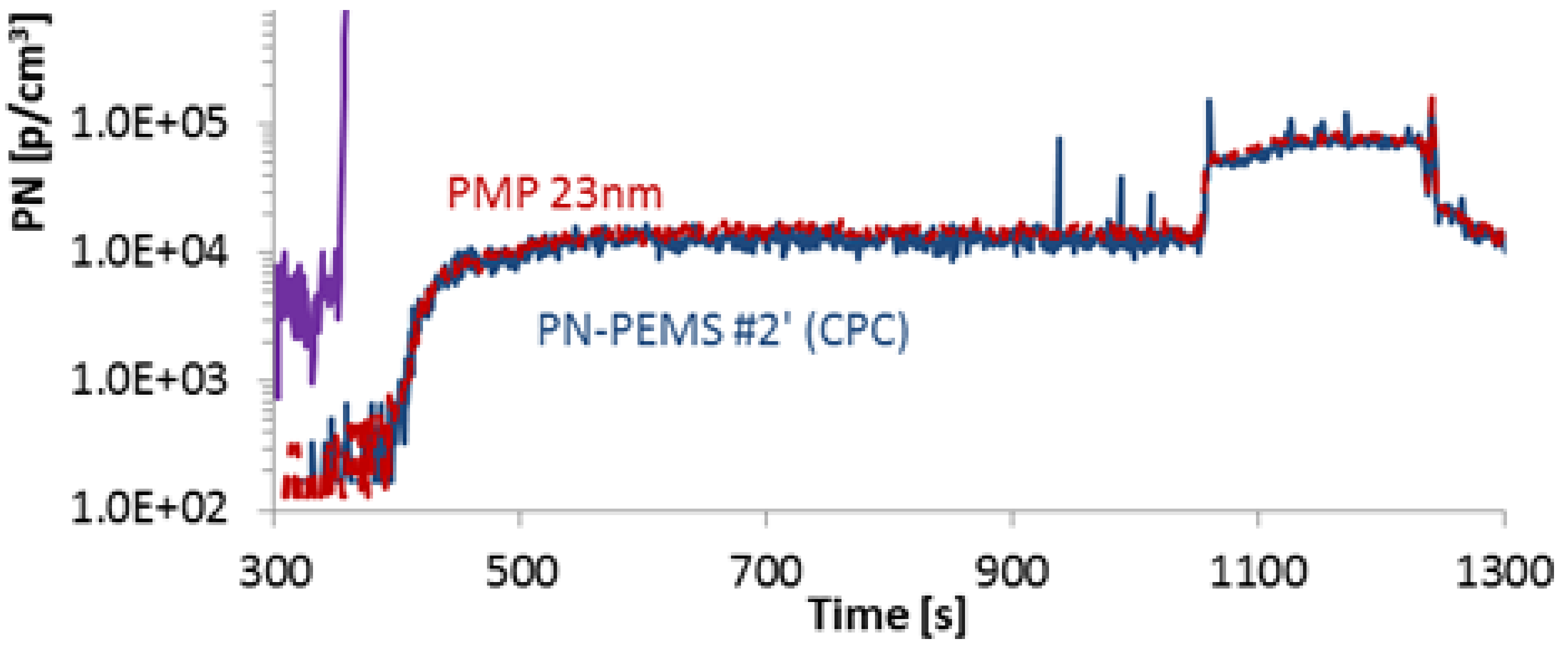
Franco et al, ES&T, 2016

/km CO_2)

/

Regeneration

- Multiply results of PEMS with K_i-factors
- If vehicle is below the limit PASS
- If vehicle is above the limit, then check if regeneration occured
- If yes, then take away K_i-factors and check if results are below the limit: then PASS
- If yes, but results above the limit, finish regeneration and retest.



RDE 4 issues

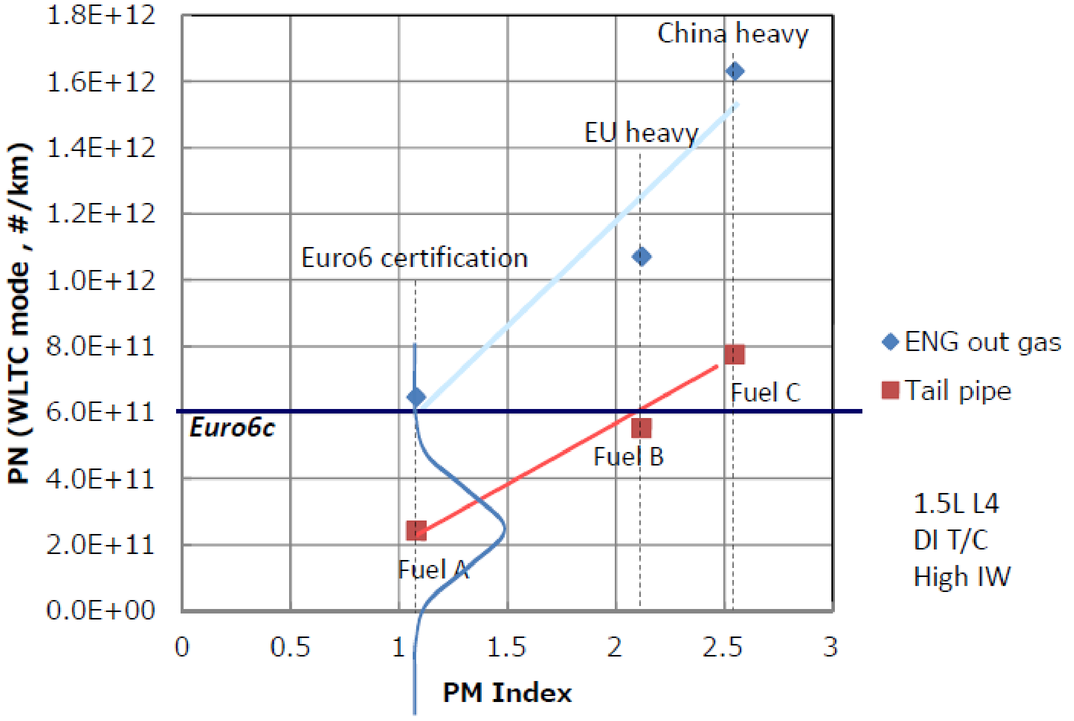
- RDE testing during ISC, introducing however the possibility to take into account independent testing by third parties
- Dealing with issues related to LCVs, multistage and special purpose vehicles
- Other pending issues like transfer functions and the fuel issue

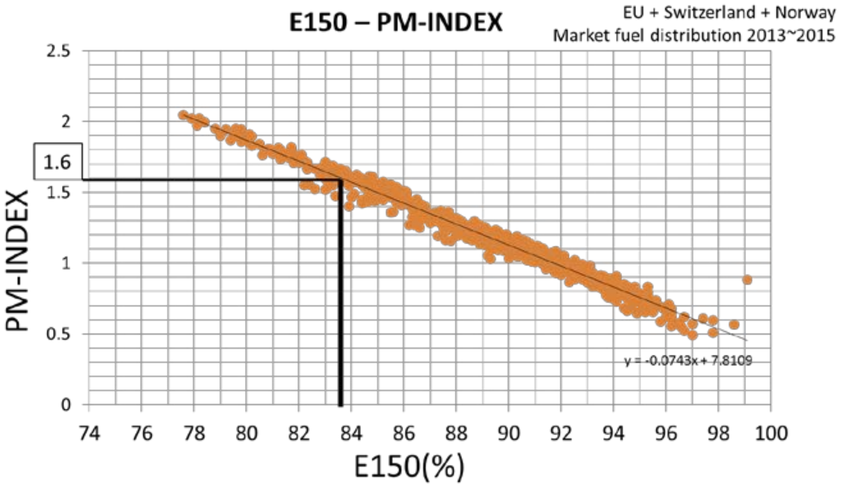
Reviews:

- New, more representative method for testing hybrid vehicles
- Review of uncertainty margins for both NOx and PN
- Review of ki factors
- Possible review of the cold start analysis
- Review of evaluation methods to develop a single one

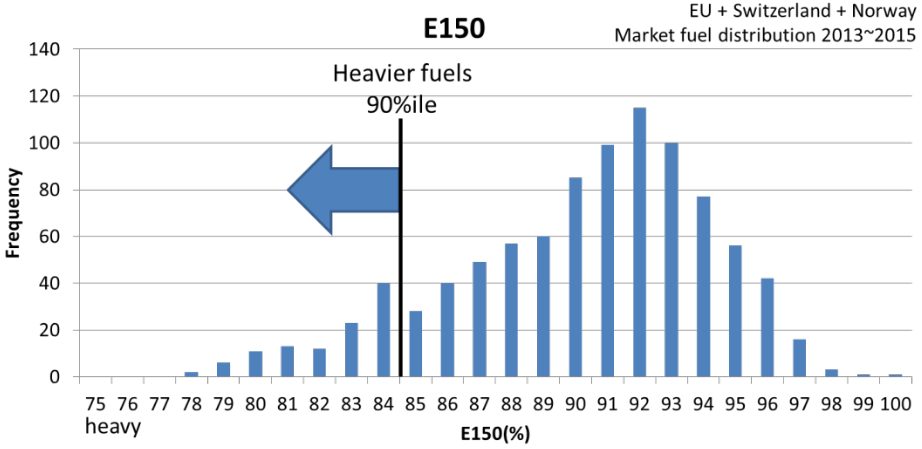
Fuel Quality issue

➢ Heavy fuel with high aromatic content lead to high production of particles.





	E150	PM INDEX value
90%ile	83.7	1.60



Evaluation methods (not Normalisation methods**)**

- The tools should be evaluated by independent consultant against the following criteria:
  - Efficiency and accuracy of the method
  - Normalisation against CO_2
  - Practicality, ease of use, ease of correcting it
  - Transparency, ease of understanding
  - Robustness against Defeat Device practices
  - Robustness against intentional misuse
  - Applicability for all technologies

HORIZON 2020

Call: H2020-GV-2016-2017

Technologies for low emission light duty powertrains

Action:

"Measuring automotive exhaust particles down to 10 nanometres – DownToTen"

Project Overview

Project Partners

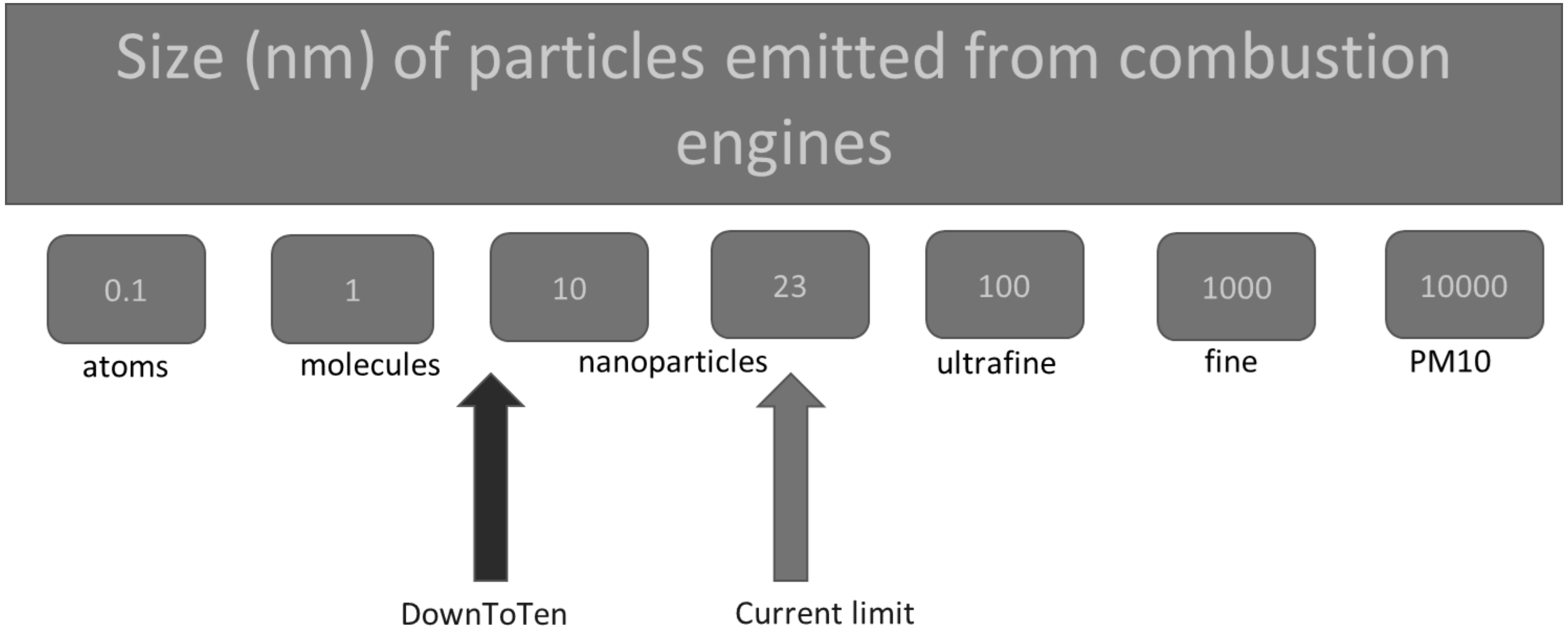
In collaboration with:

The University of California at Riverside,

National Traffic Safety and Environmental Lab (Japan)
and
National Metrology Institute (Japan)

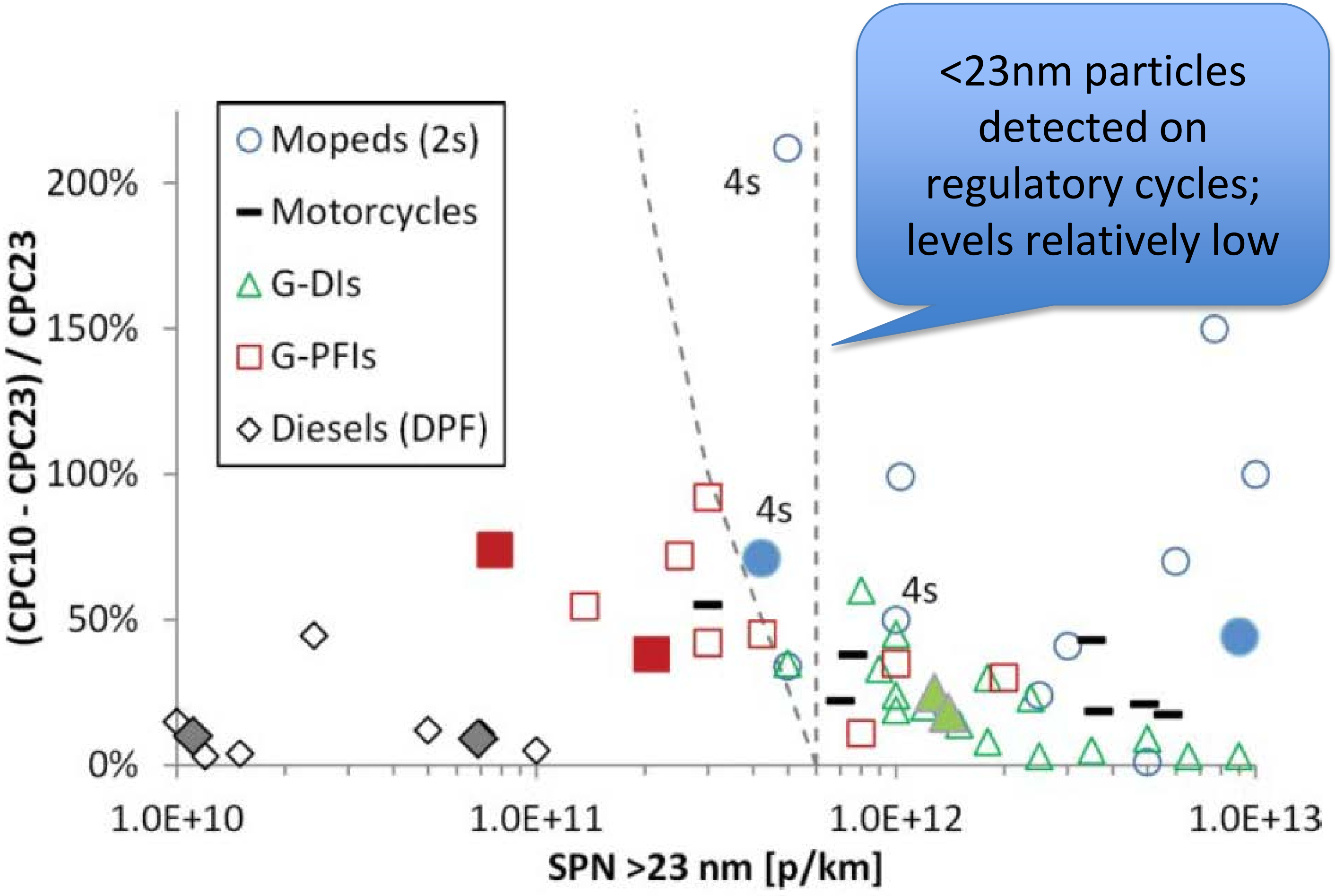
Aim of the project

To propose a robust approach for the measurement of particles from about 10 nm both for PMP and RDE, complementing and building upon regulation development activities and addressing topics not tackled so far



The objective is a PN-Portable Emission Measurement System (PEMS) demonstrator with high efficiency in determining PN emissions of current and future engine technologies in the real worldc

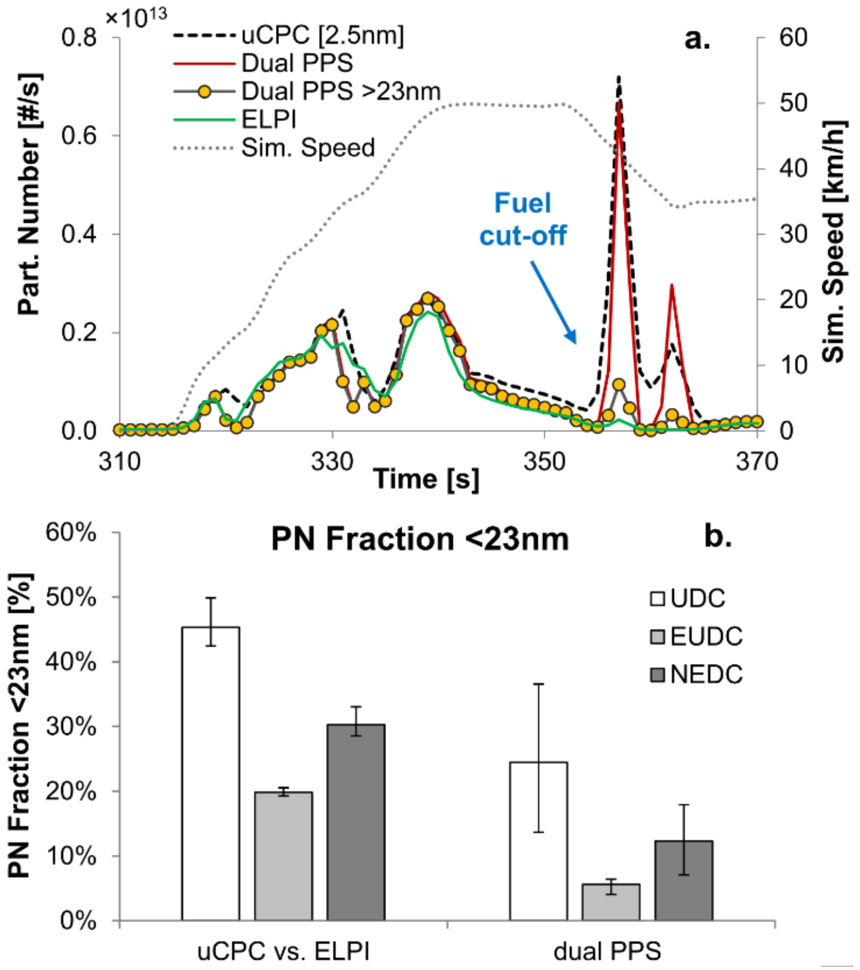
Why measure sub-23nm Particle Number?



- Sub-23 nm fraction of solid particles
  - estimated by differences between 10 nm & 23 nm CPCs
  - Loss corrected (between x1.7 and x2)
- Vertical dashed line
  - $6\text{x}10^{11}$ p/km limit for particles >23 nm
  - Other line indicates $6\text{x}10^{11}$ p/km limit for particles >10 nm
- All mopeds were 2-stroke unless otherwise specified in the figure

B. Giechaskiel, J. Vanhanen, M. Väkevä & G. Martini (2017): Investigation of vehicle exhaust sub-23 nm particle emissions, Aerosol Science and Technology

Some interesting results: <23nm non-volatile PN from diesel fuel cuts and >23nm particles derived from urea-SCR



Light-duty (1.4L, 66kW) turbocharged diesel
Amanatidis et al. (2017) J Aerosol Sci

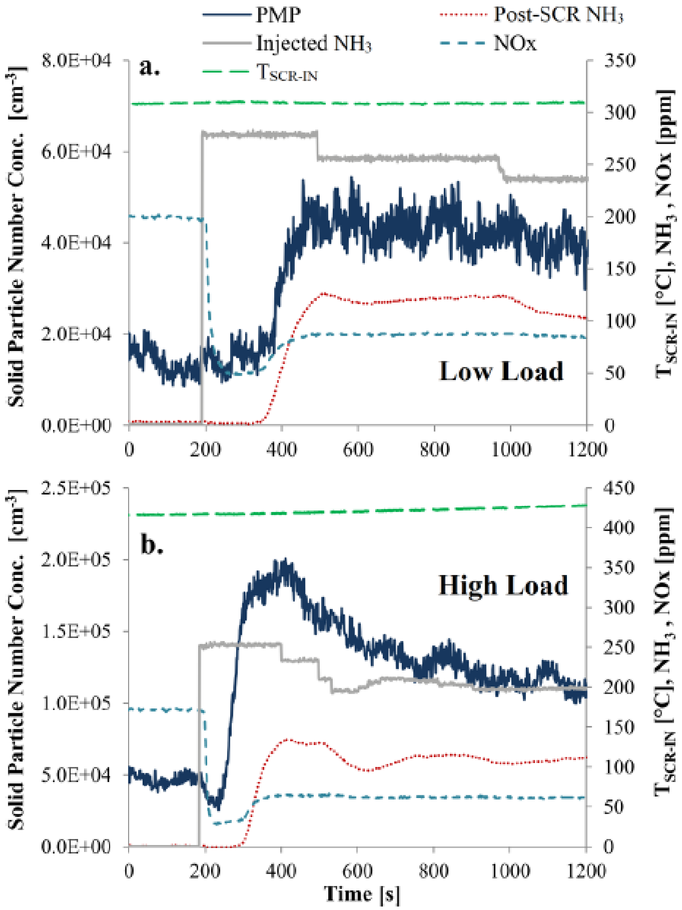
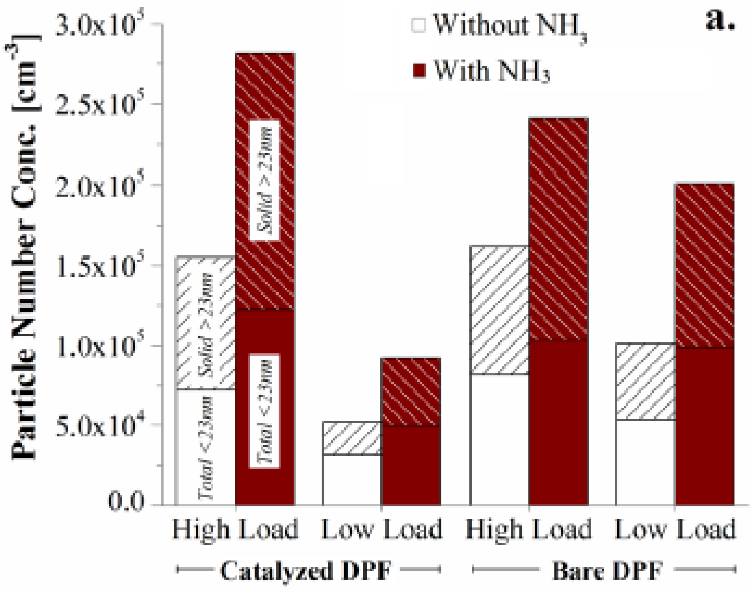


Figure 2. Solid (>23 nm) particle number concentration measured at tailpipe conditions prior to and after NH_3 injection at (a) low load, and (b) high load engine operation, with a catalyzed DPF upstream of the SCR.

Driving events and ECT do produce <23nm particles: further investigation required



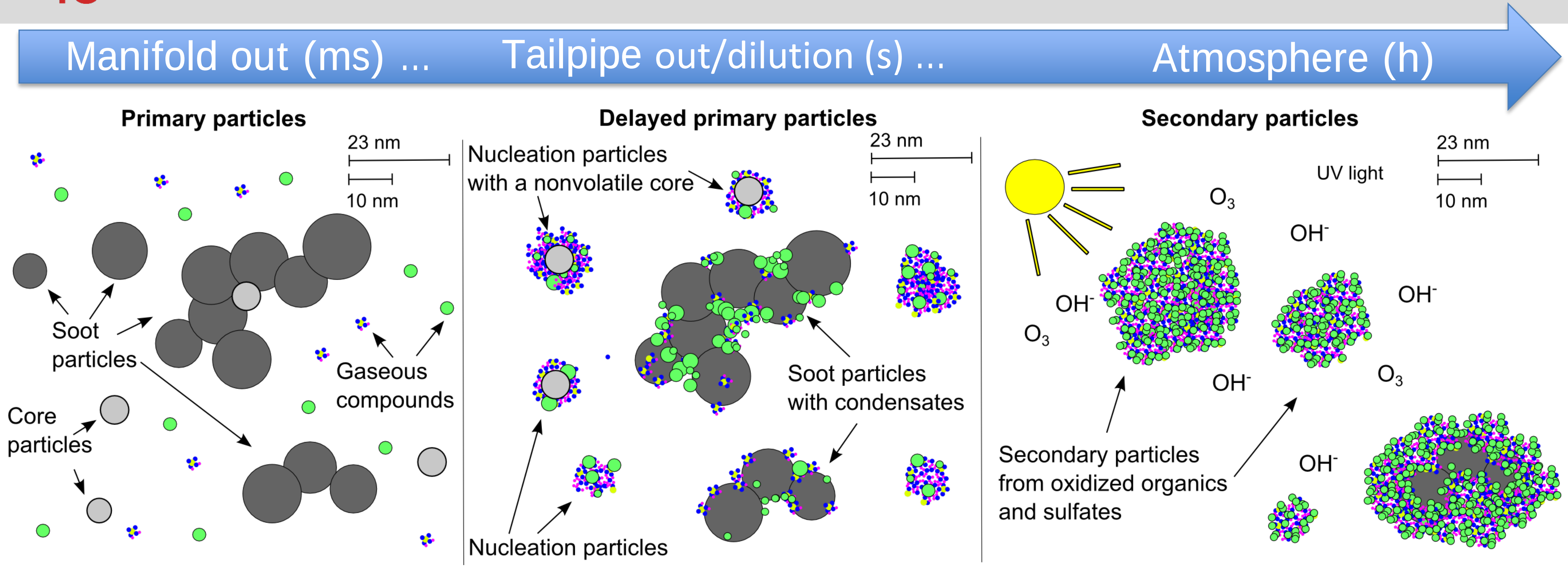
Amanatidis et al. (2014) ES&T

Questions to be answered within the new size range

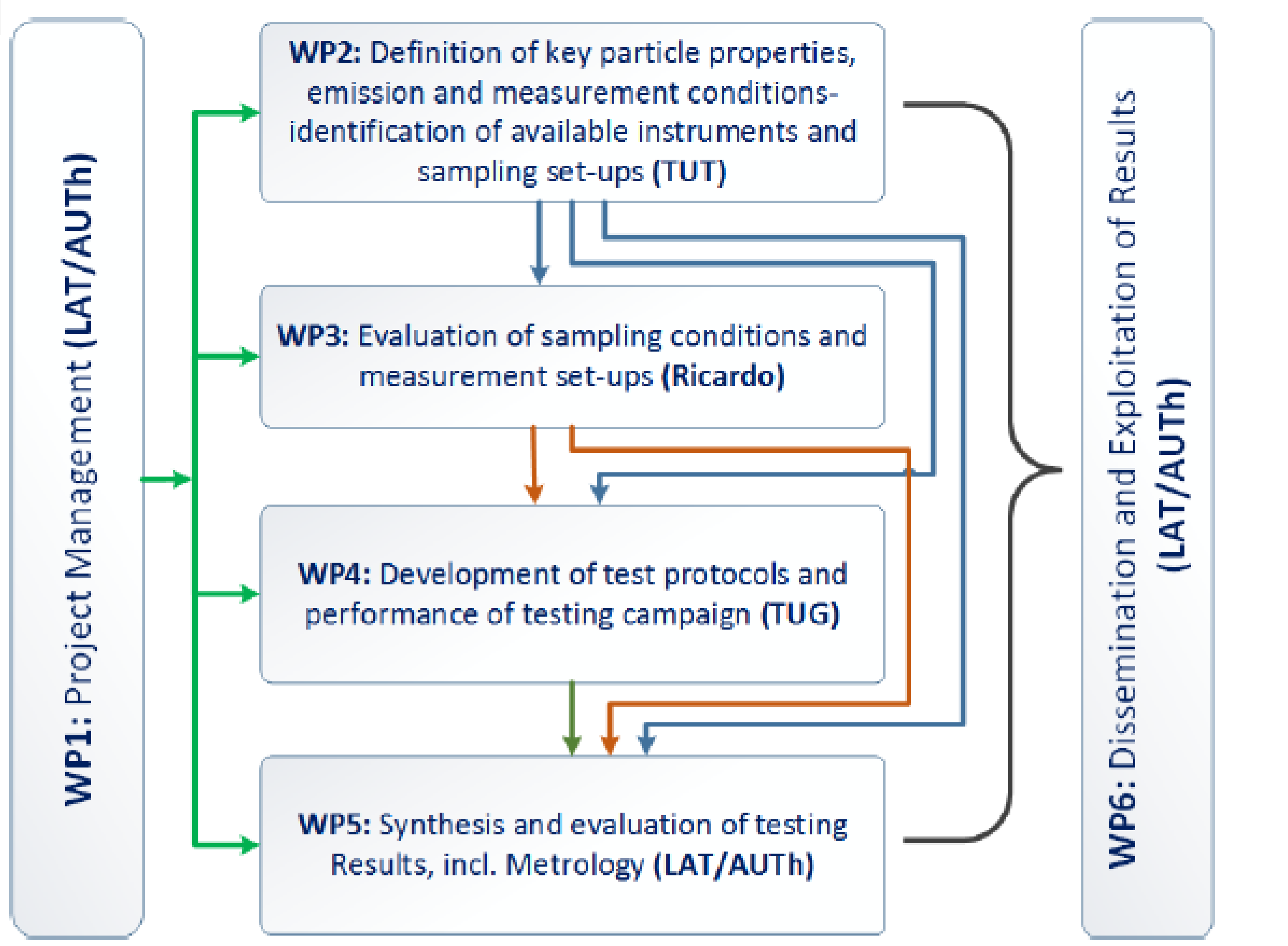
1. What is the number fraction of exhaust particles below 23 nm?
2. What is the specific chemistry of the particles?
3. How to define the particle species: accumulation – nucleation mode, volatile – non-volatile, solid –liquid, Black Carbon – Elemental Carbon (BC-EC)
4. What fraction of exhaust particles corresponds to which species?
5. Which is the appropriate exhaust particle cut size?
6. How potentially un-regulated particles are linked to secondary aerosol formation
7. How to robustly correlate raw exhaust sampling suitable for both RDE engine development with dilution methods and sampling approaches employed during engine and vehicle type approval?

DOWN TO 10

Exhaust emission related particle types

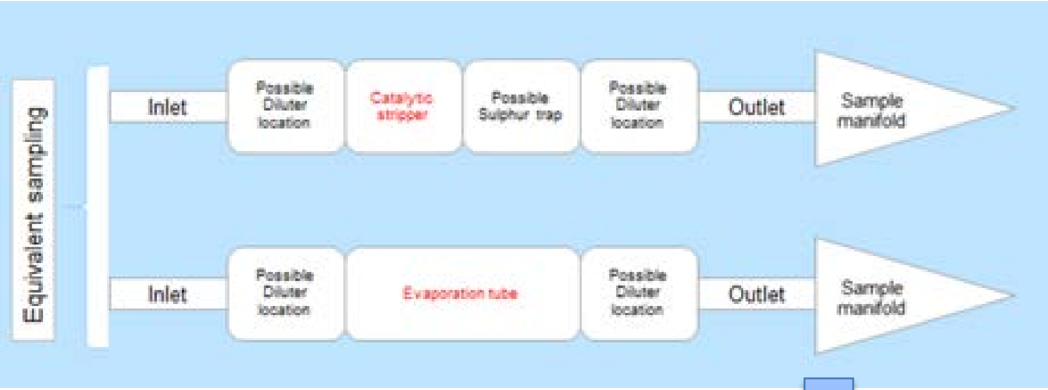


DownToTen structure and WP interaction

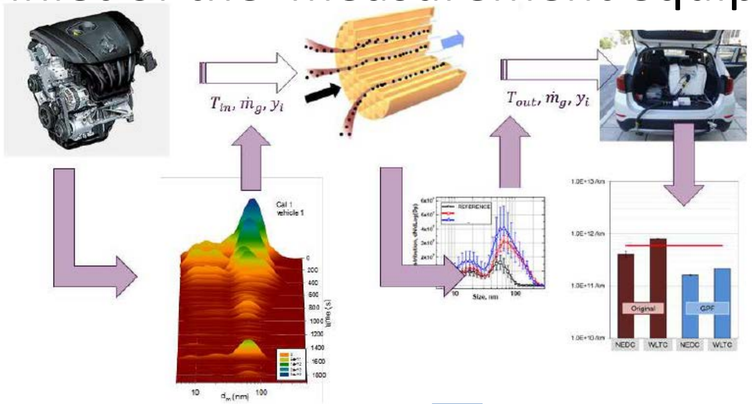


Concepts and approach

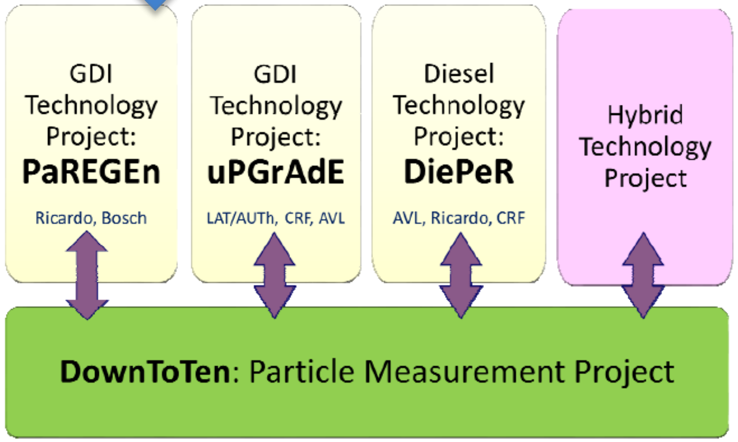
Equipment and sampling set-up (WP2 & WP3)



Modelling particle transformation (tailpipe-out to the inlet of the measurement equipment) (WP3)



Testing (emphasis on technologies that are being developed in the parallel projects (WP4)



Synthesis and evaluation of testing results, incl. metrology (WP5)

Vehicle class	Engines	Exhaust aftertreatment	Fuels	Cycles	Source of the test vehicles
Passenger cars	GDI & PFI	3WC with and without GPF	Reference Petrol and biofuel admixtures	NEDC, WLTC, 3 RDE cycles; real PEMS trips	uPGrAdE, PaREGEn
	SI-Hybrid	3WC with and without GPF			A hybrid from GV-2-2016
	Diesel	SCR and/ or NSC with DPF	Reference diesel and biofuel admixtures		DiePeR
	CI-Hybrid	SCR/NSC with DPF			A hybrid from GV-2-2016
	CNG	3WC with and without GPF	Different qualities		GasON
HDV	Diesel	SCR and DPF	Reference diesel and biofuel admixtures	WHVC, standard CO2-vehicle test cycles; PEMS trips	To be decided
	CNG	Not decided yet	Different qualities		To be decided
2-wheelers	≥500ccm	3WC	Reference Petrol and biofuel admixtures	WMTC, RDE cycles, PEMS test for >500ccm	Suggestions from the German programme
	50ccm	3WC			

Overview of key project results

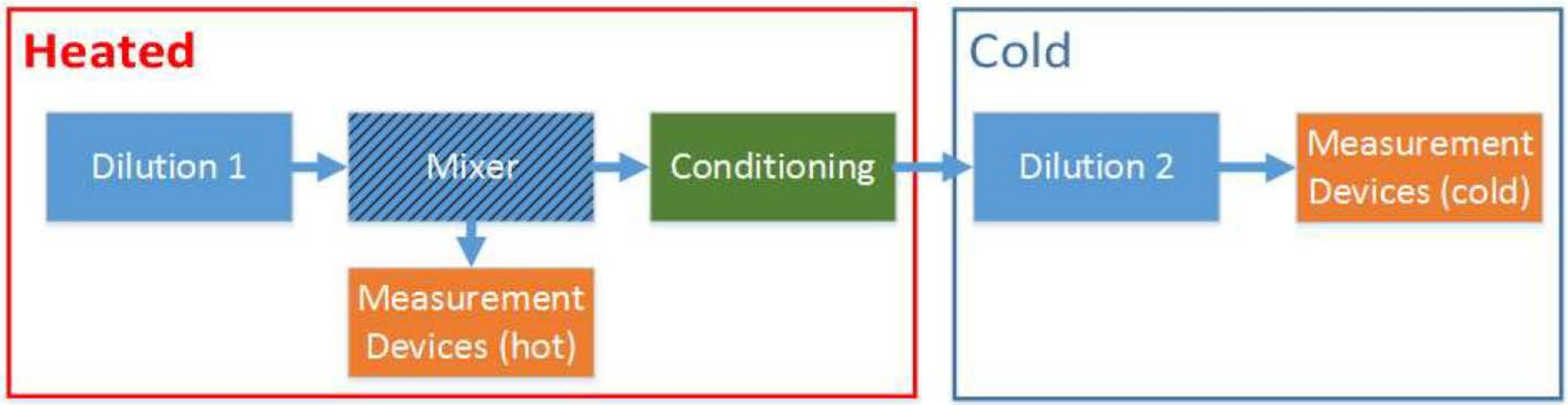
WP	Exploitable knowledge	Exploitable product(s) or measure(s)	Sector(s) of application	Timetable for commercial use	Owner & other partners involved
WP2	Proposal for system to generate laboratory-grade exhaust-type of aerosol	Device and method to generate aerosol (demonstrator in month 14)	Calibration institutes, users of aerosol instruments	2020	TUT, TUM
WP2	Instrument benchmarking below 23 nm	Knowledge on instrument performance	Exhaust aerosol measurement labs	Not relevant	TUT, AVL, LAT/AUTh, RICARDO
WP3	Understanding formation, properties and characteristics of PN <23 nm	PN <23 nm definition for regulatory purposes	Standardization and regulatory bodies	2018	Entire consortium
WP3	PN <23 nm sampling configuration for laboratory testing and PEMS	Demonstrator (in month 17)	Exhaust aerosol measurement labs	2020	TUT, AVL, LAT/AUTh, RICARDO
WP3	PN <23 nm measurement configuration	Instrumentation to be proposed	Exhaust aerosol measurement labs	Not relevant	Entire consortium
WP4	DownToTen PN PEMS demonstrator unit	Device and Test protocol (demonstrator in month 22)	Exhaust aerosol measurement labs, regulatory authorities	2020	TUG, AVL, LAT/AUTh, RICARDO, TUT
WP4	Evaluation procedures for RDE particle number	Software code and method (demonstrator in month 32)	Exhaust aerosol measurement labs, regulatory authorities	2019	TUG, AVL, LAT/AUTh, RICARDO, JRC
WP5	Emission performance of late and forthcoming vehicle types	Emission factors to be used in models and estimates	Air quality research, policy making	2019	LAT/AUTH, TUG, TUT, TUM
WP5	Calibration procedures for measuring PN<23 nm	Calibration test protocols	Standardization and regulatory bodies	2020	TUT, TUG, TUM, JRC
WP5	Modelling of exhaust particle processes from emission to dilution	Simulation model	Researchers, manufacturers	2021	LAT/AUTH, TUT

Currently at Month 5

Progress in the first 5 months of the project

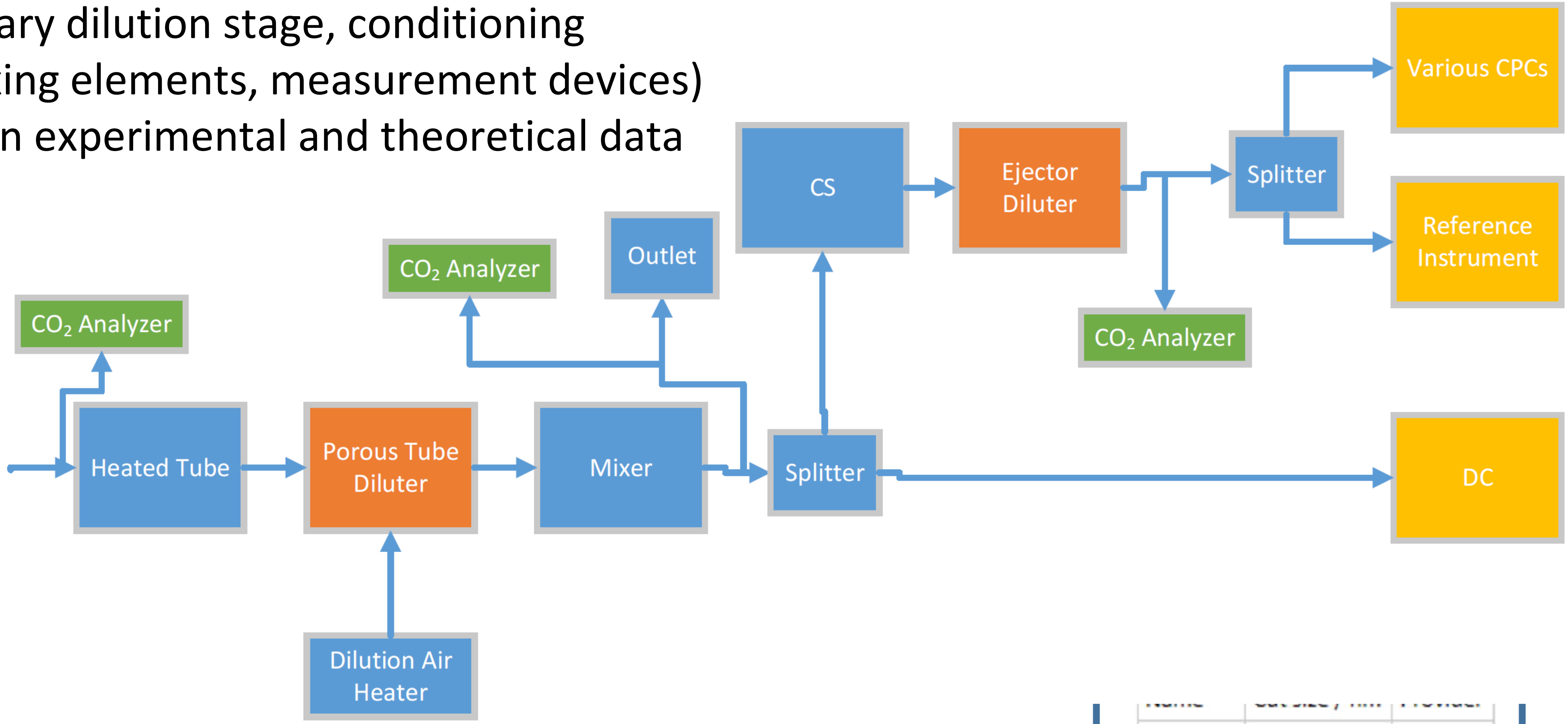
Sampling setup for testing in the synthetic aerosol laboratory

- A setup was designed to maximize the penetration of non-volatile particles below 23 nm, while avoiding the creation of gaseous artefacts
- Important factors like robustness against artefacts (re-nucleation, growth of sub-cut particles), losses of (solid) particles, storage/release effects of gas phase compounds are being assessed in detail



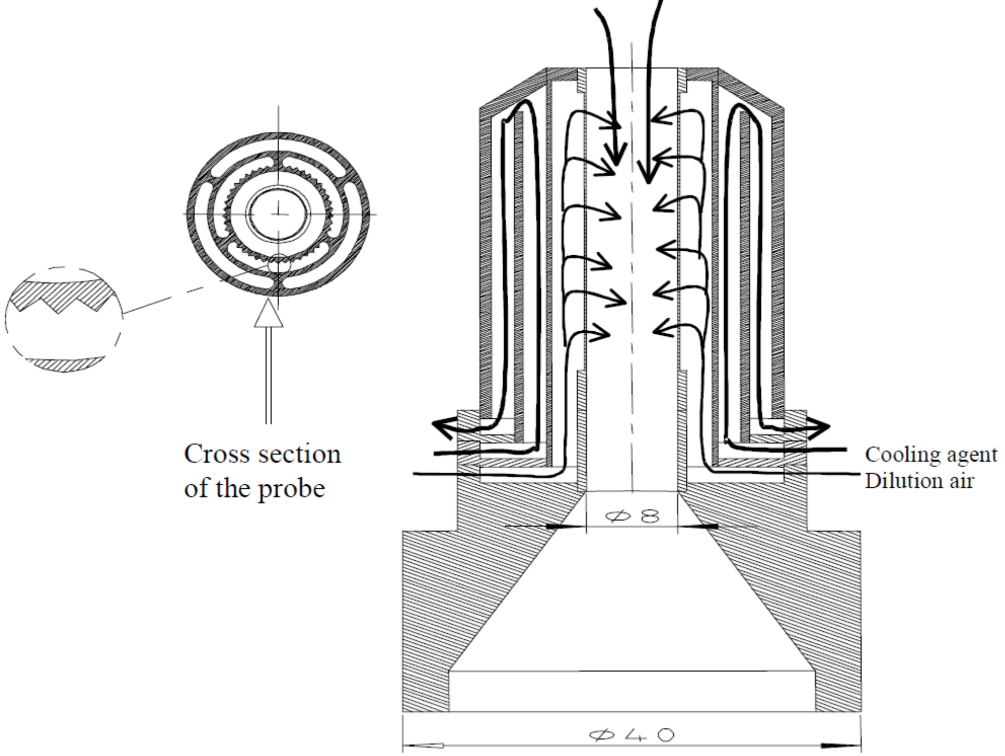
Sampling setup for testing in the synthetic aerosol laboratory

The selection of the setup's components (primary and secondary dilution stage, conditioning system, mixing elements, measurement devices) are based on experimental and theoretical data

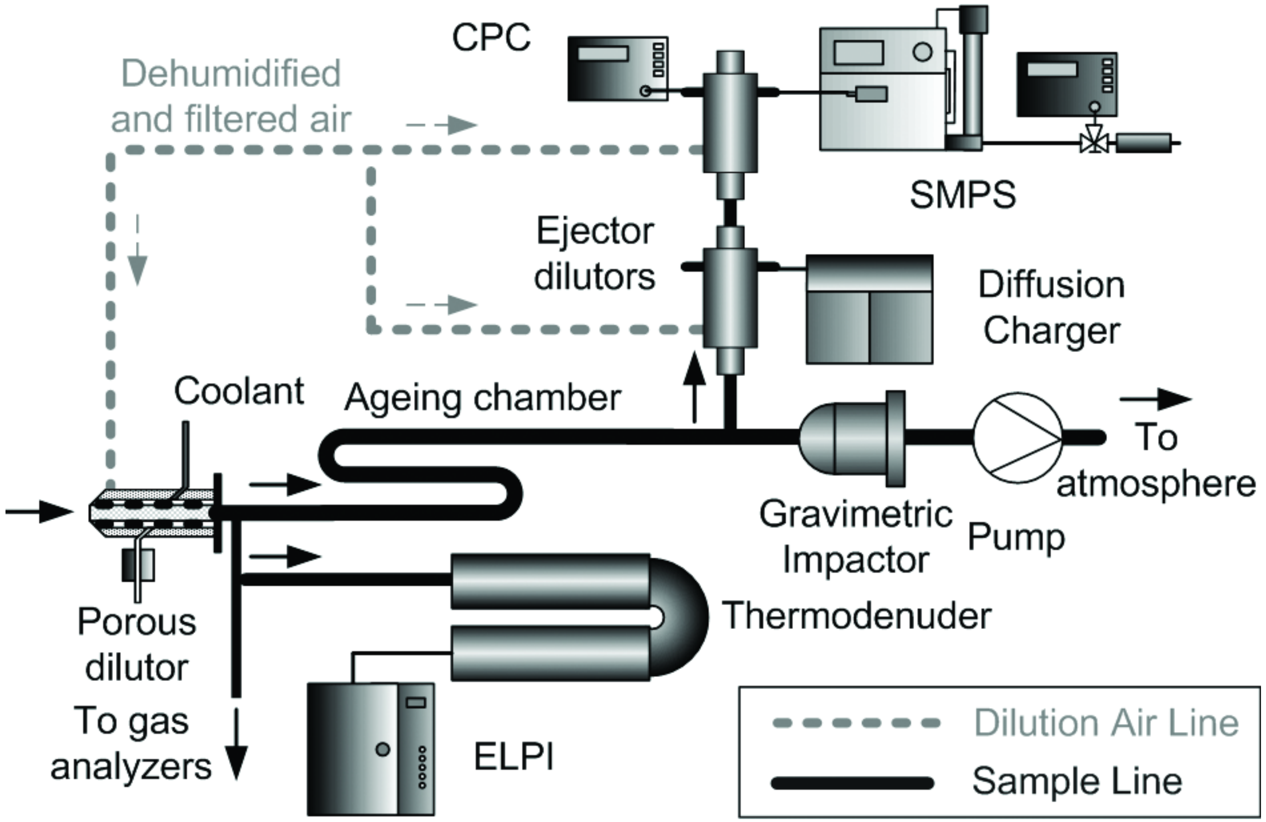


3790	23	TUG

Porous tube dilutor as primary dilutor

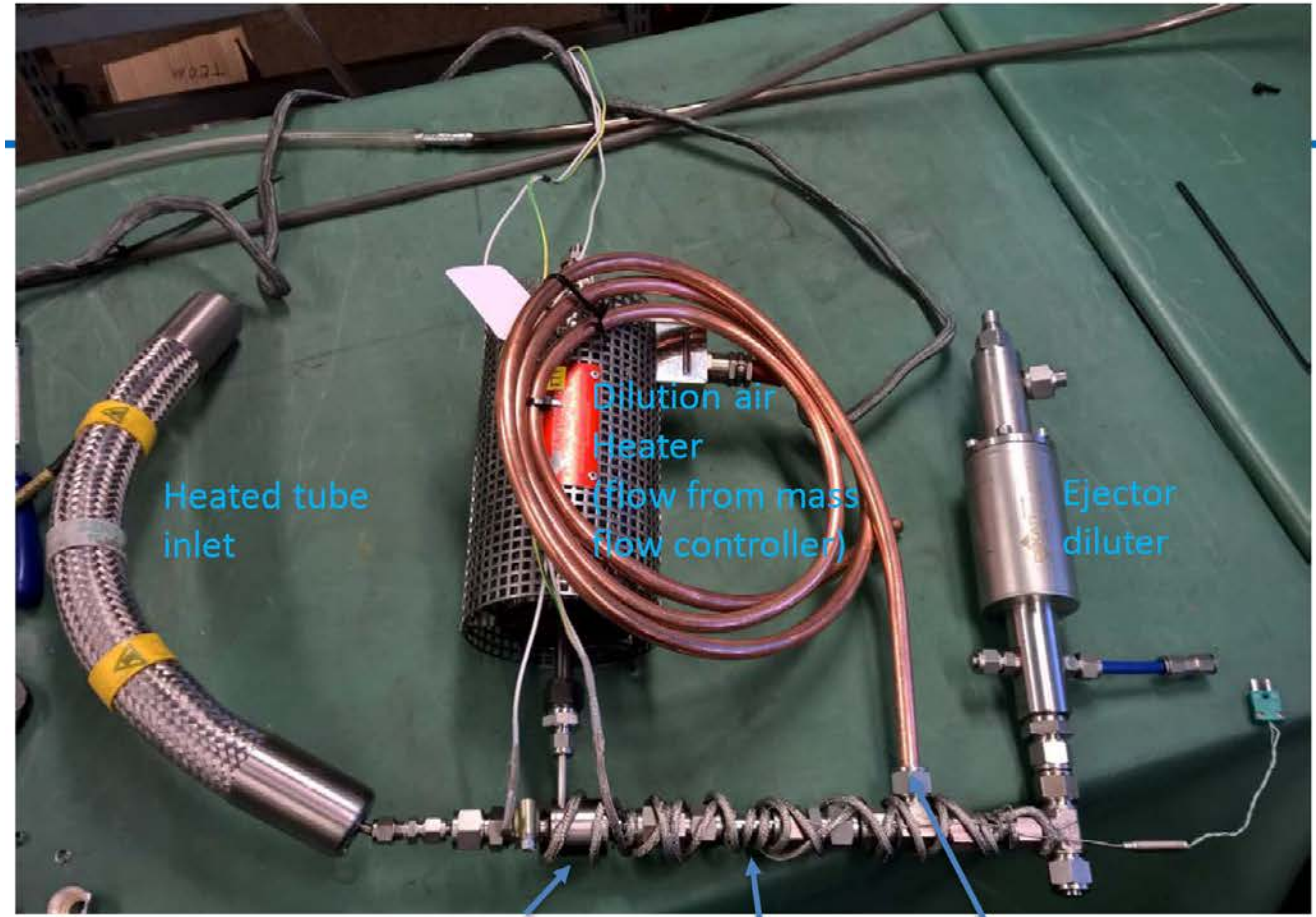


Mikkanen et. al., SAE Paper 2001-01-0219

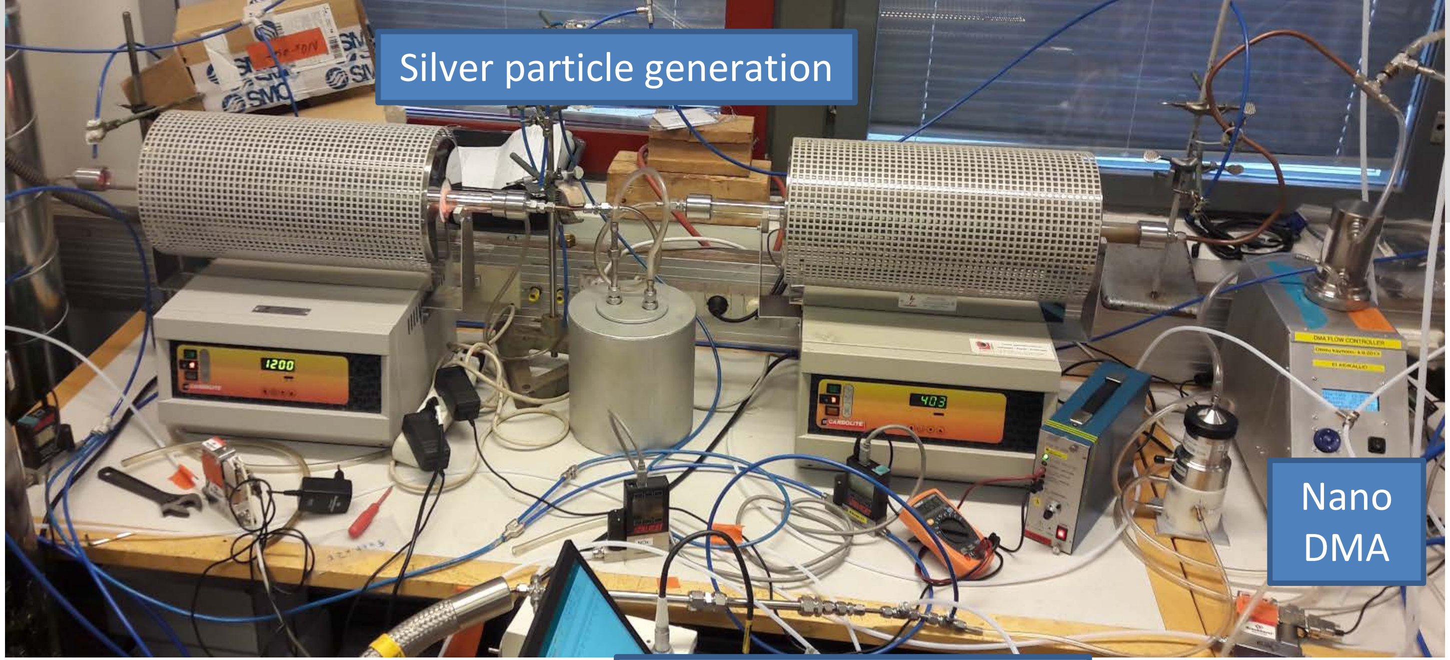


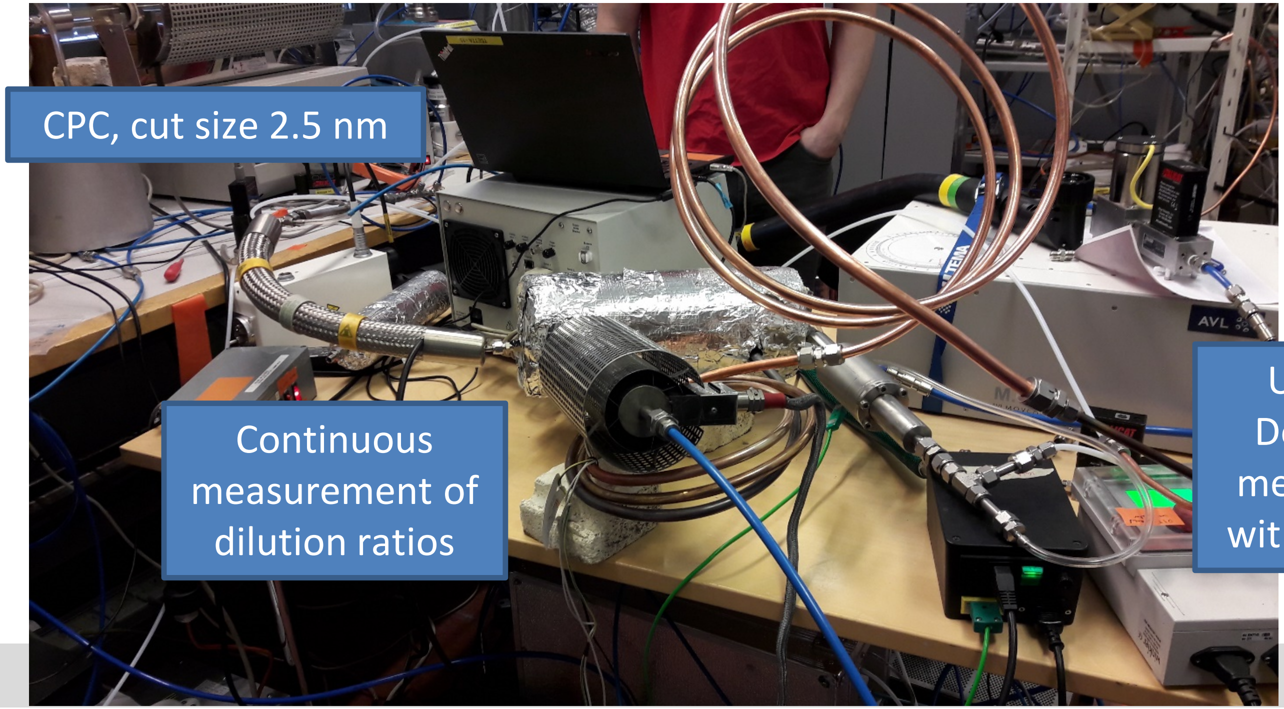
Ntziachristos and Samaras. JAWMA 2009

Preliminary sampling setup for testing in the synthetic aerosol laboratory



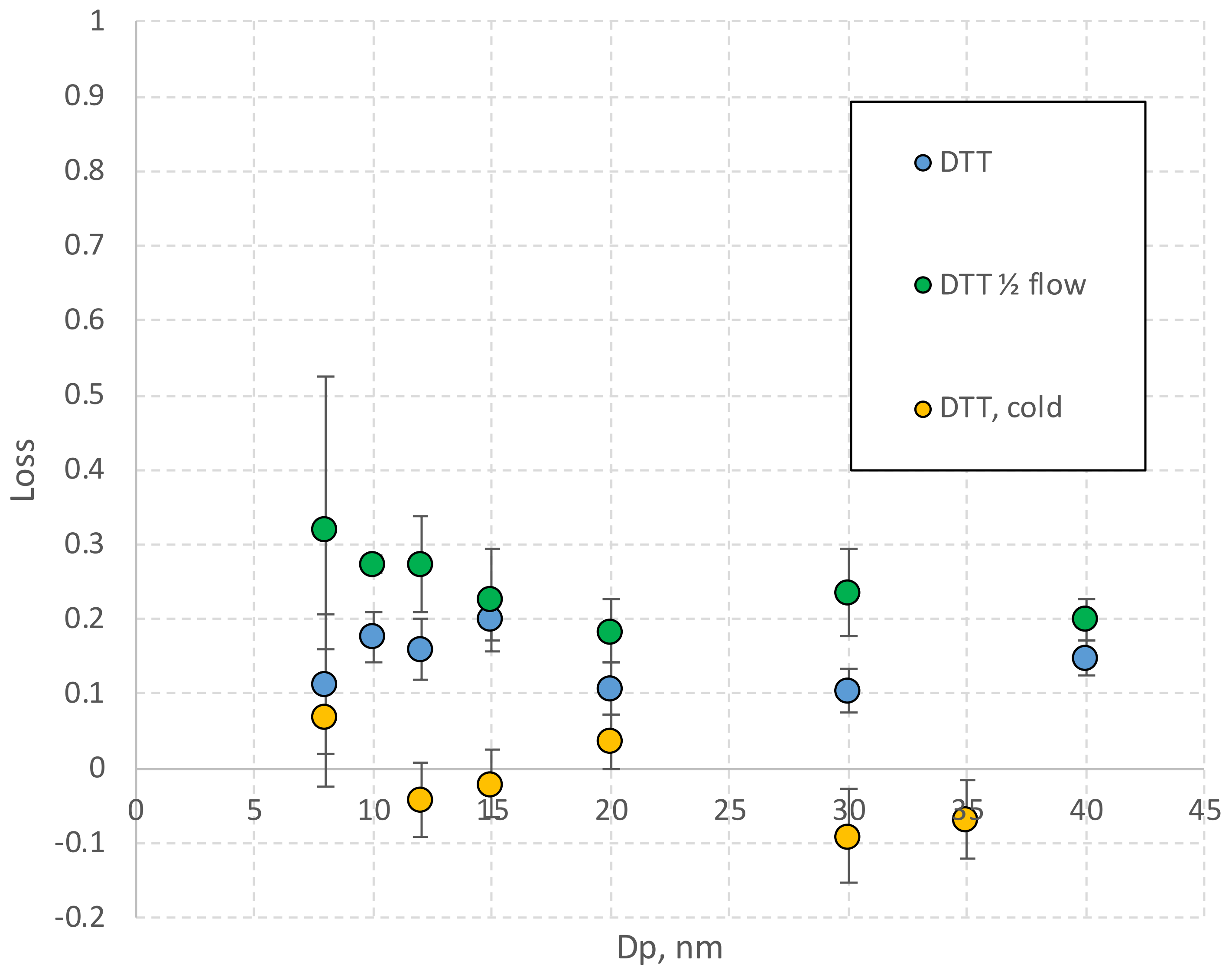
Testing in the synthetic aerosol laboratory





Tampere Technical University, March 2017

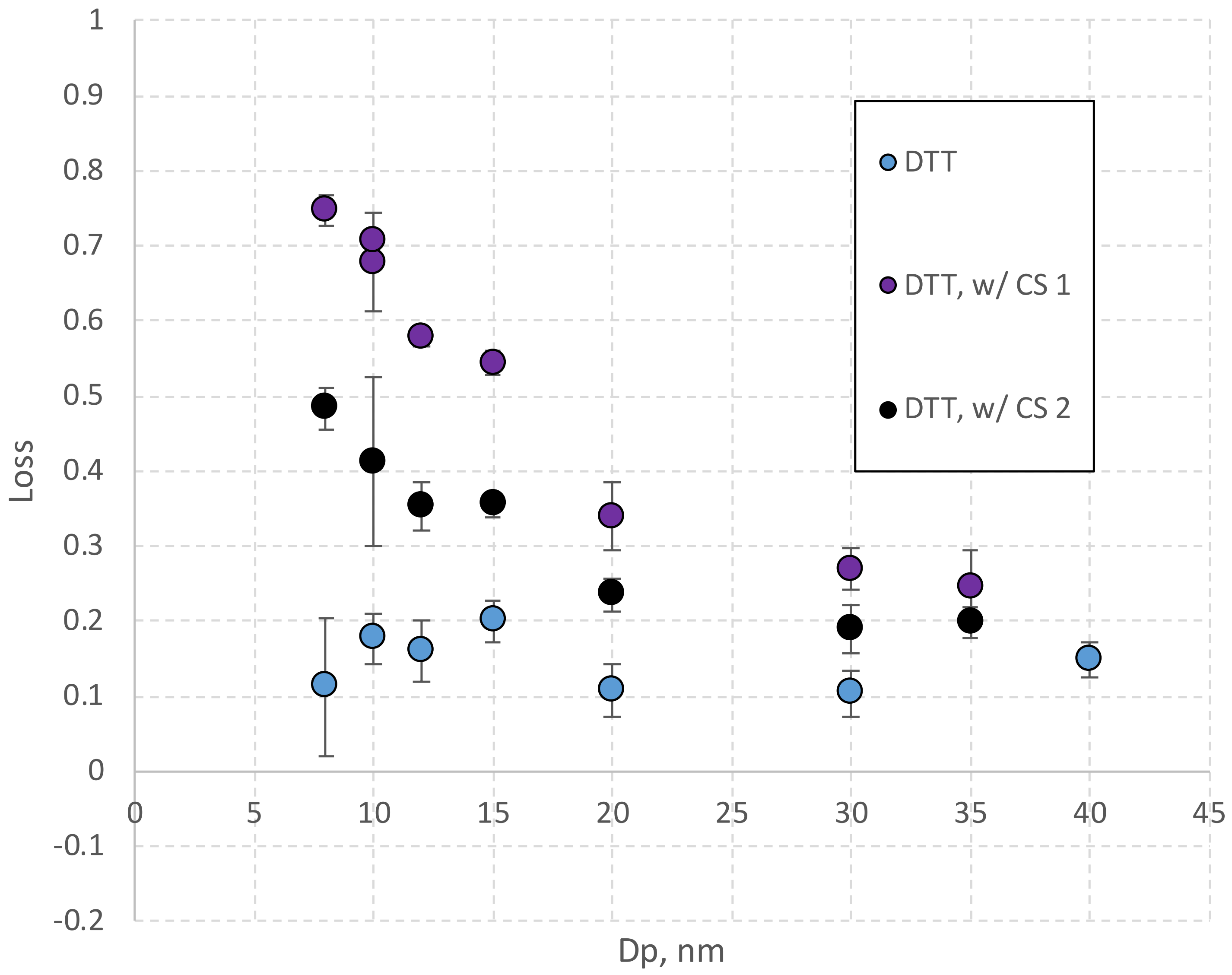
Particle loss measurements, preliminary results



DTT means:
Temperature 350 °C
Porous tube flow ~40 lpm
Excess flow ~40 lpm
Primary DR ~10
Secondary DR ~10
Total DR ~100

DTT cold: Temperature in the DTT system 25 C

Particle loss measurements, preliminary results



DTT means:
Temperature 350 ˚C
Porous tube flow ~40 lpm
Excess flow ~40 lpm
Primary DR ~10
Secondary DR ~10
Total DR ~100

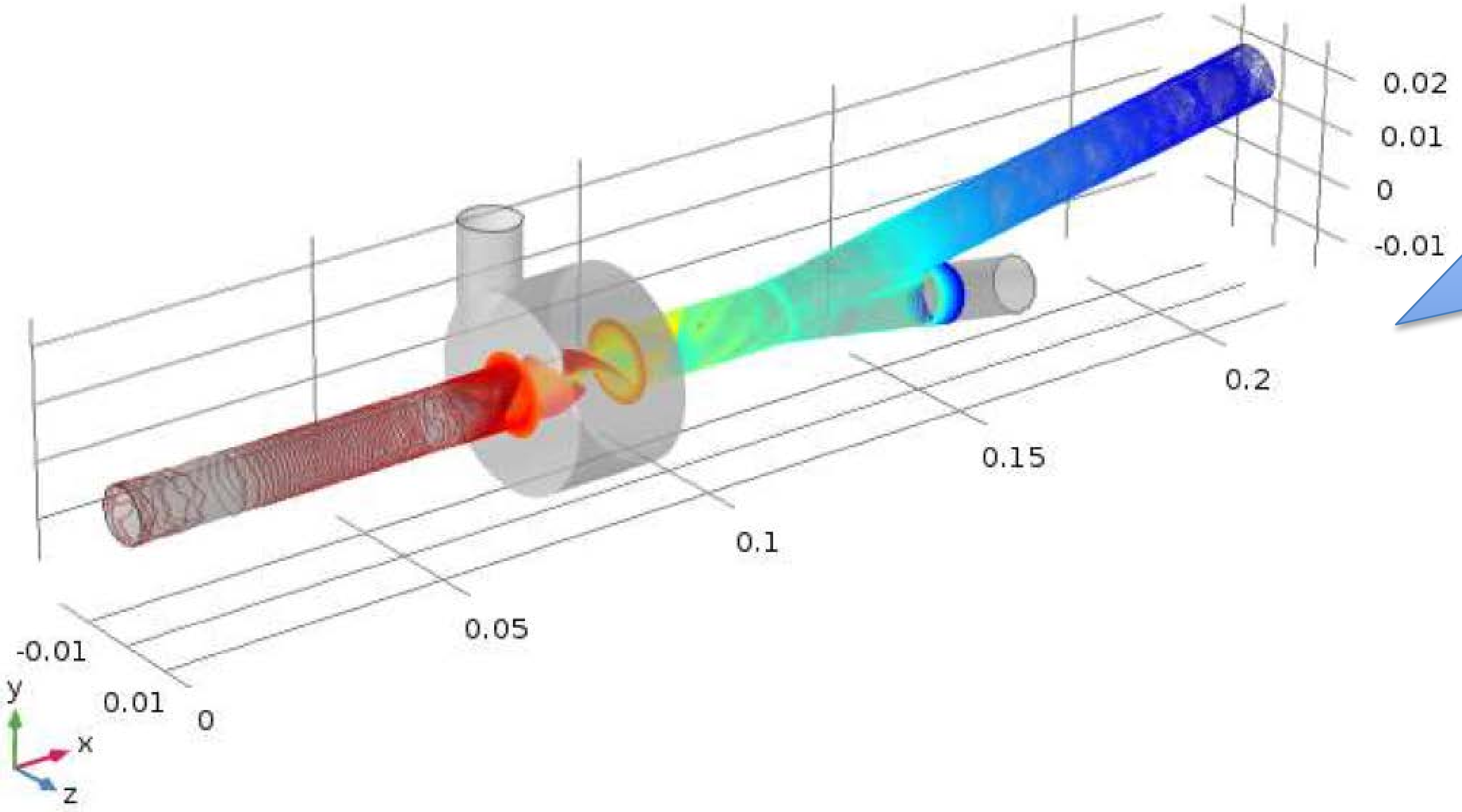
CS 1 = larger one from LAT
CS 2 = smaller one from AVL
flows in CSs were ~4 lpm
temperatures in CSs were 350 ˚C

Raw vs Dilute Particle Sampling Modelling

- **AIM: To understand the relationship between the raw-sampled and dilute sampled "regulated particles"**
  - **Critical for fundamental understanding and determining influence of measurement approach on conformity factors**
- **Modal aerosol dynamics modeling** is being coupled with a CFD commercial code (e.g. ANSYS/FLUENT), similar to partner TUT work (Olin et al. 2015)
- Components to simulate with CFD:
  - Basic CFD simulations , i.e. flow, mixing and heat transfer, is being performed in most components to study effective mixing; some can be simulated in series;
  - In parallel Full Particle Dynamics (PD) simulations will be performed
- Detailed PD simulations will be performed for the Porous Tube Diluter (PTD) & Aging/ Mixing Chamber. Inflow Boundary Conditions (IBC) via 2D simulations and 3D simulations

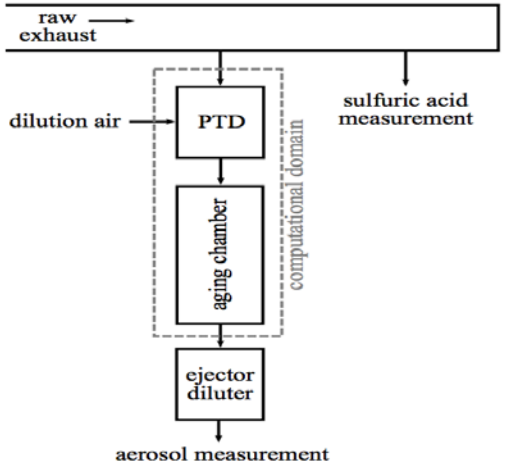
Basic CFD analysis of Porous Tube Dilutor

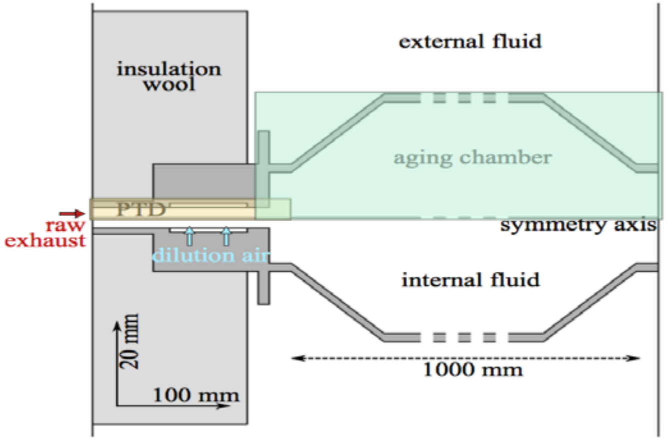
- Critical components will be identified, in which to perform CFD. For example, *flow* and *mixing* unsteady 3D CFD simulations are performed for the PTD and mixer shown below by TU Graz.



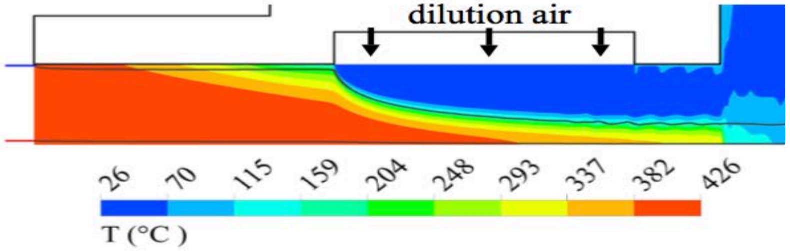
Evaluate pressure fluctuation effects on dilution – no particle impacts assessed yet; work on-going

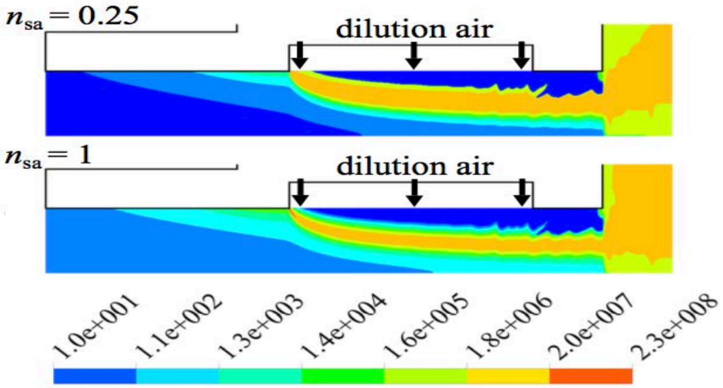
Modeling delayed primary: aerosol formation in the exhaust (CFD model)





Modelling of particle formation rates in exhaust requires determining the spatial profiles of temperature, humidity, vapours and particles.





In work by TUT, an in-house model CFD-TUTEAM, was developed and applied to a PTD dilution system with FLUENT.

Olin, M., T. Rönkkö and M. Dal Maso. (2015). CFD modeling of a vehicle exhaust laboratory sampling system: sulfur-driven nucleation and growth in diluting diesel exhaust. *Atmos. Chem. Phys.*, **15**, 5305.

Summary and Conclusions

- Testing with PEMS is a key element of EU emissions regulations.
  The RDE legislation in the EU is being finalised
- Recent developments expanded and consolidated the RDE regulation:
  - Cold start and DPF regenerations are considered part of normal driving.
  - PN measurements are now included. Still only solid particles >23 nm are addressed.
  - Hybrids and in particular PHEVs are better captured
- Research work is undertaken to expand PN measurement to particle sizes < 23 nm and to expand to total particles under real driving conditions. Special focus on GDI.
- Assessing methods to normalize data without jeopardizing the effectiveness in detecting RDE performance is the next challenge

- As a last step Gasoline PFI vehicles have also to be accounted for

Any questions ?