LABORATORY OF APPLIED THERMODYNAMICS

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Future automotive efficiency and exhaust emissions challenges - Emphasis on nanoparticle Real Driving Emissions

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For the CO2 Scenarios:

- Dr. Stephan Neugebauer (BMW, ERTRAC Chairman)
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For the DownToTen Project:

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- Dr. Athanasios Mamakos (AVL)
- Prof. Alexander Bergmann (Graz University of Technology)
- Mr. Jon Andersson (Ricardo)
- Prof. Leonidas Ntziachristos (LAT)

Outline

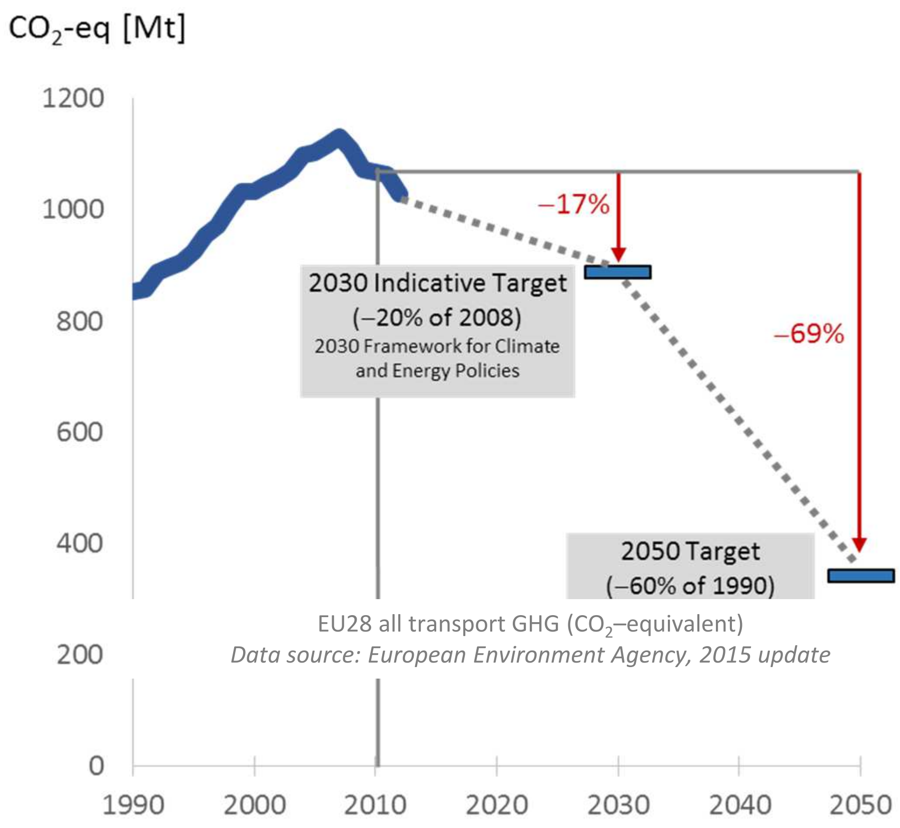
- Environmental Challenges for the Road Transport System
  - CO_2 emissions
  - Pollutant Emissions

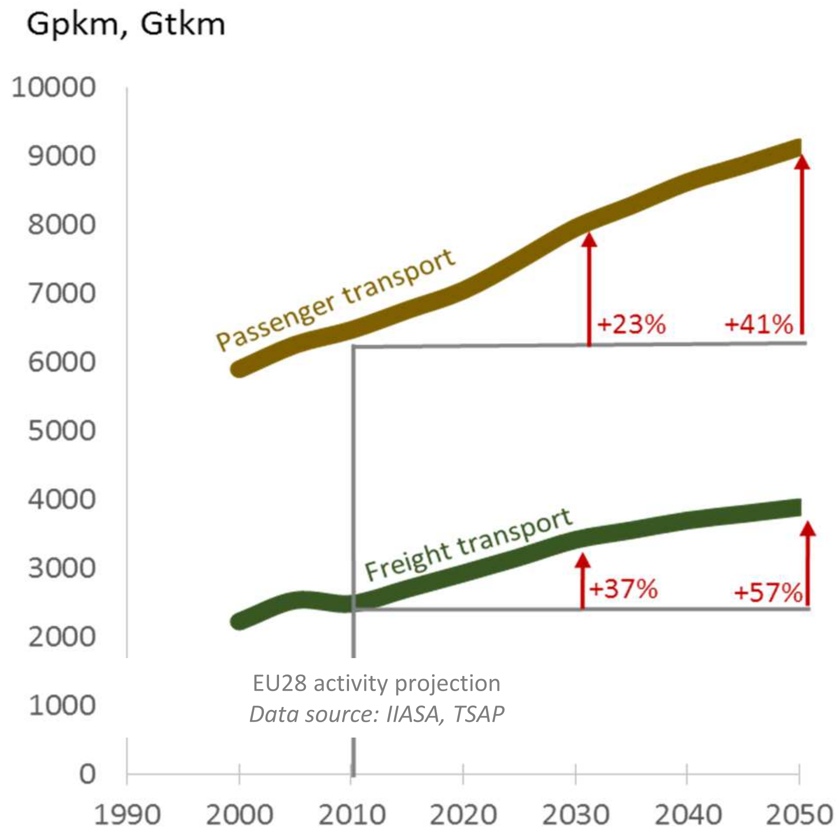
- Focus on Nanoparticles – how small and why?
  - The DownToTen Research Project "Measuring automotive exhaust particles down to 10 nanometers"

- Summary and outlook

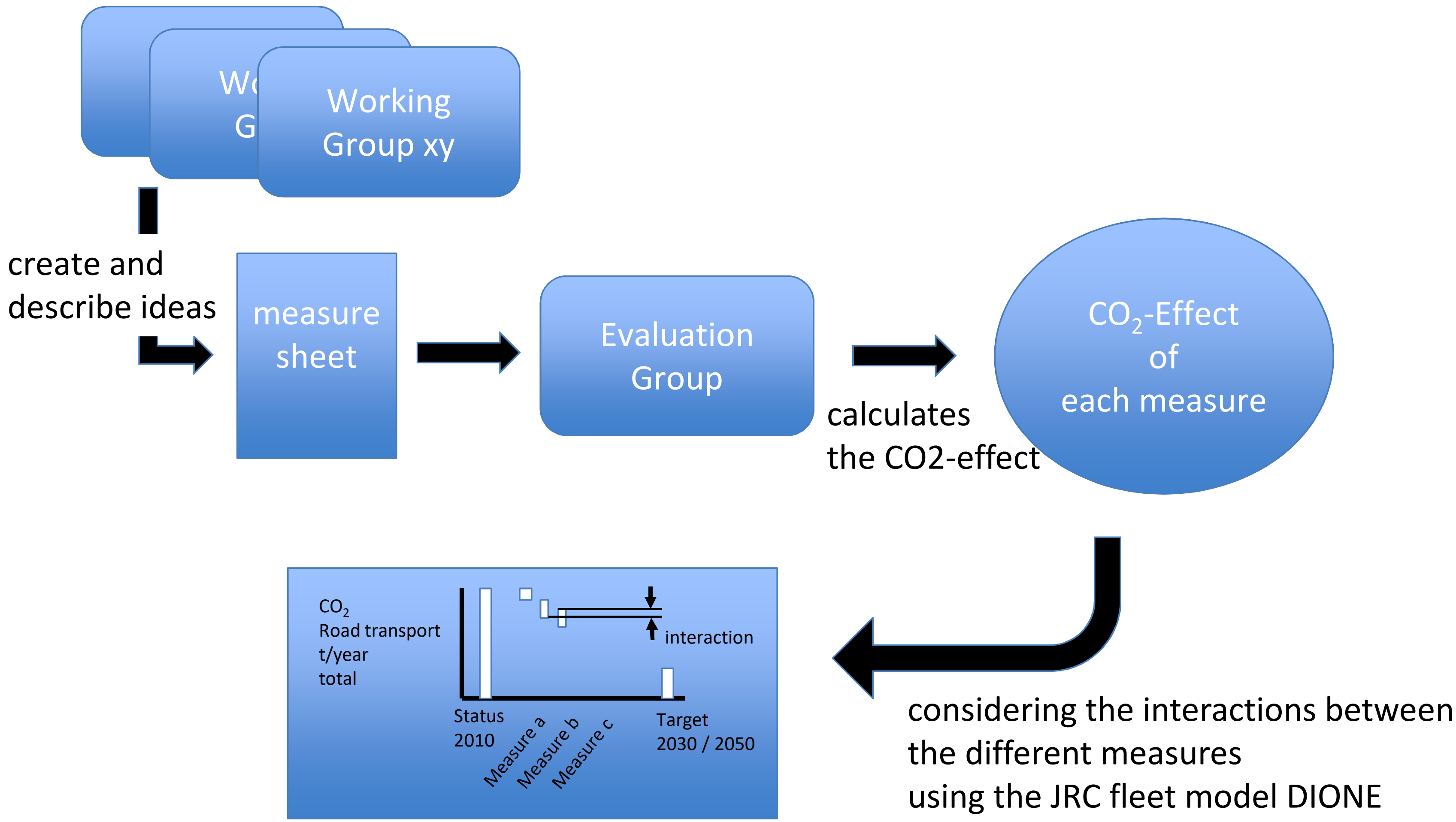
European CO2 objectives for Transport

Demanding CO_2 objectives……………..despite projected strong activity growth

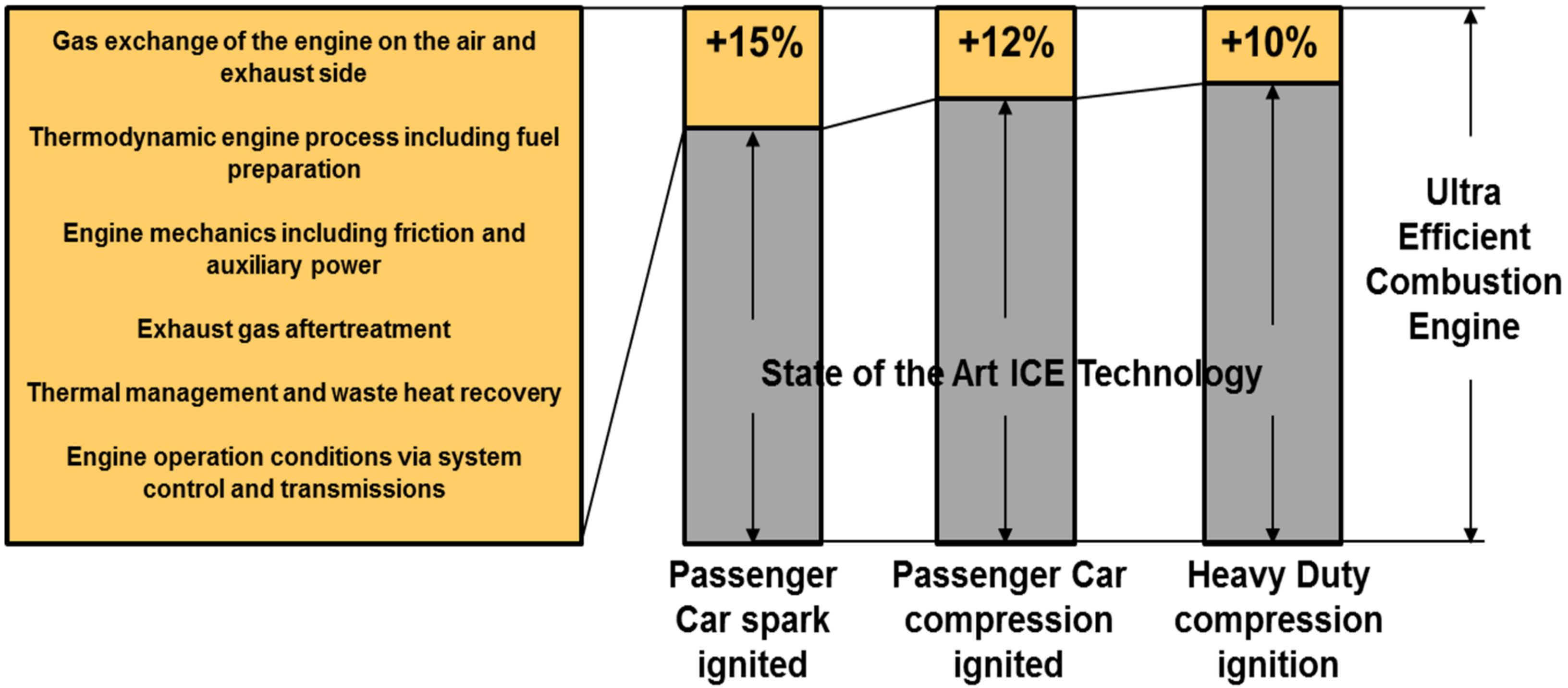




The ERTRAC CO2 Emission Scenarios
(European Road Transport Research Advisory Council)



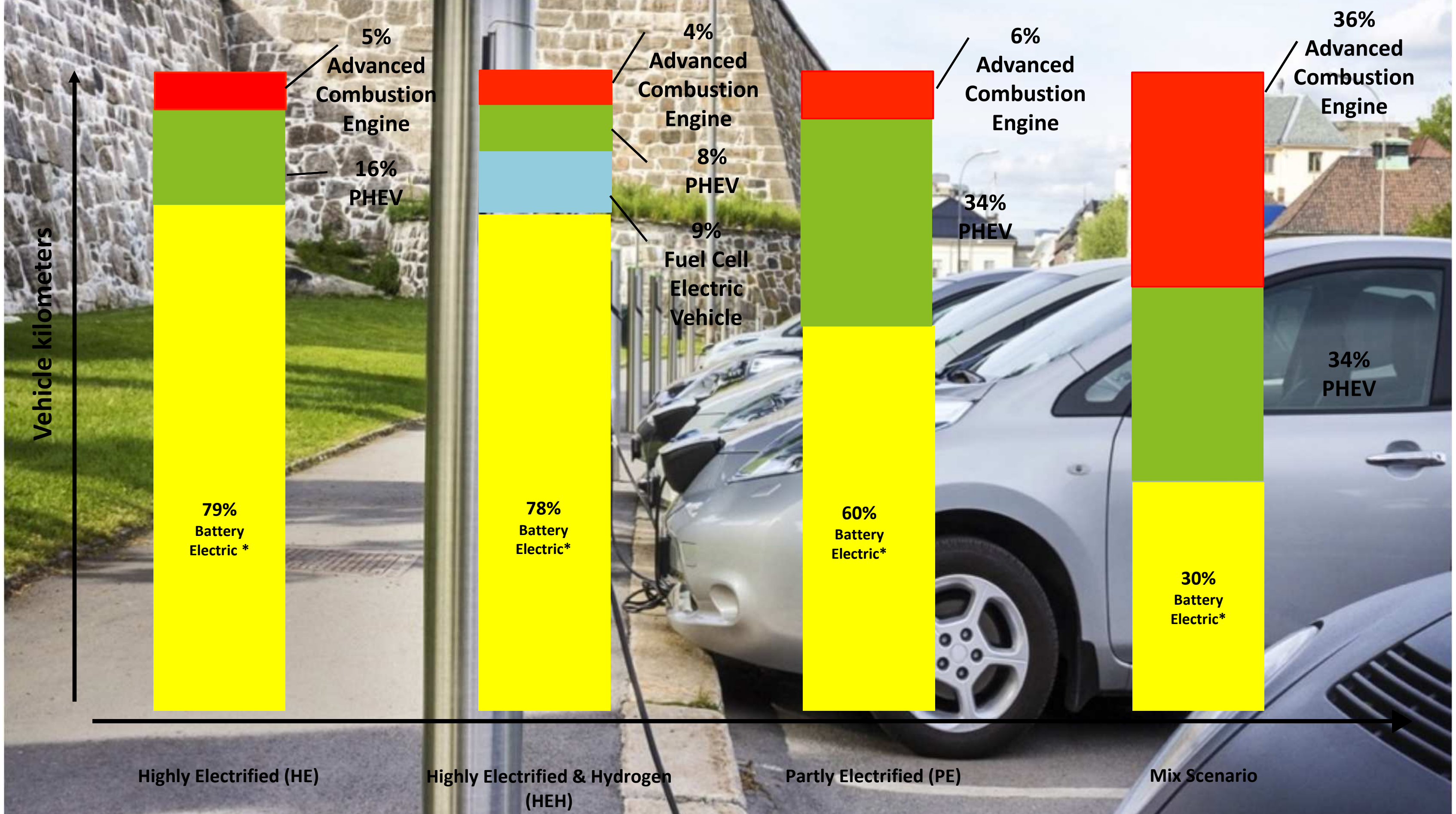
ERTRAC targets for spark- and compression ignition engines to reach 50%/55% efficiency



The above were translated in terms of cycle fuel consumption

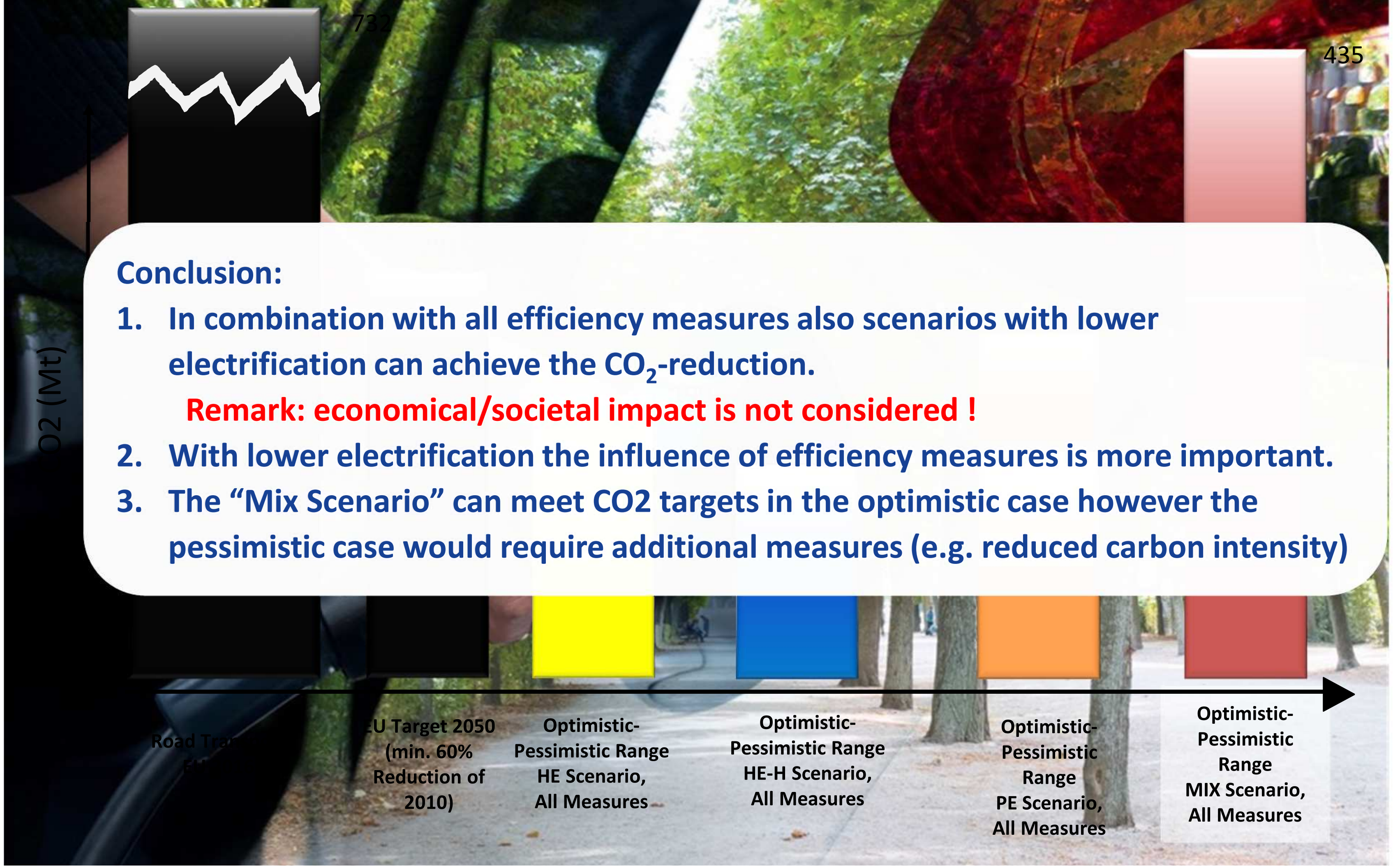
⇨ **Closure of the gap between real world and cycle fuel consumption**

2050 Fleet Activity by Powertrain



* Remark PHEV: First 50 km of driving-cycle always in electric mode

2050 Total CO2 Emissions Road Transport EU Fleet Mix scenarios + all efficiency measures



Conclusion:

1. **In combination with all efficiency measures also scenarios with lower electrification can achieve the CO_2-reduction.**
   Remark: economical/societal impact is not considered !
2. **With lower electrification the influence of efficiency measures is more important.**
3. **The "Mix Scenario" can meet CO2 targets in the optimistic case however the pessimistic case would require additional measures (e.g. reduced carbon intensity)**

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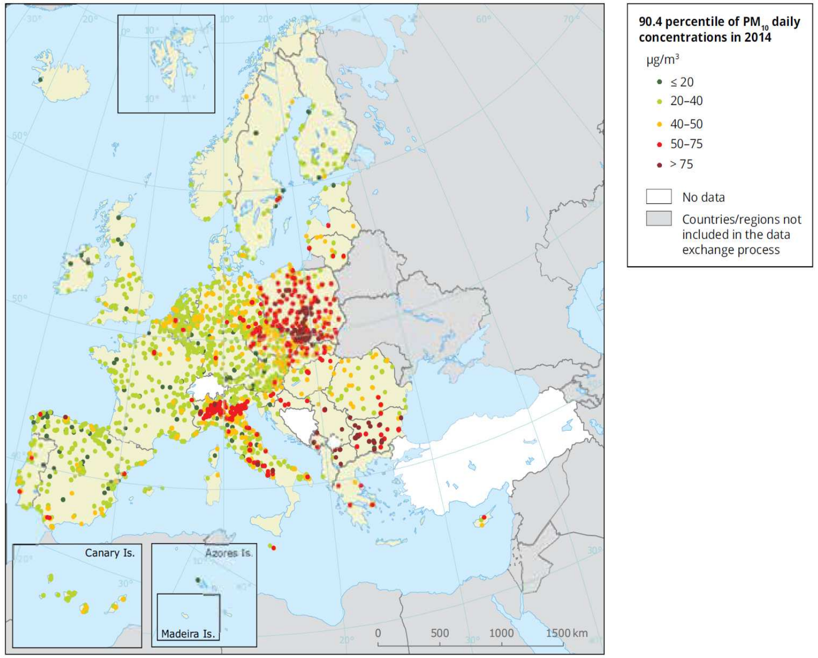
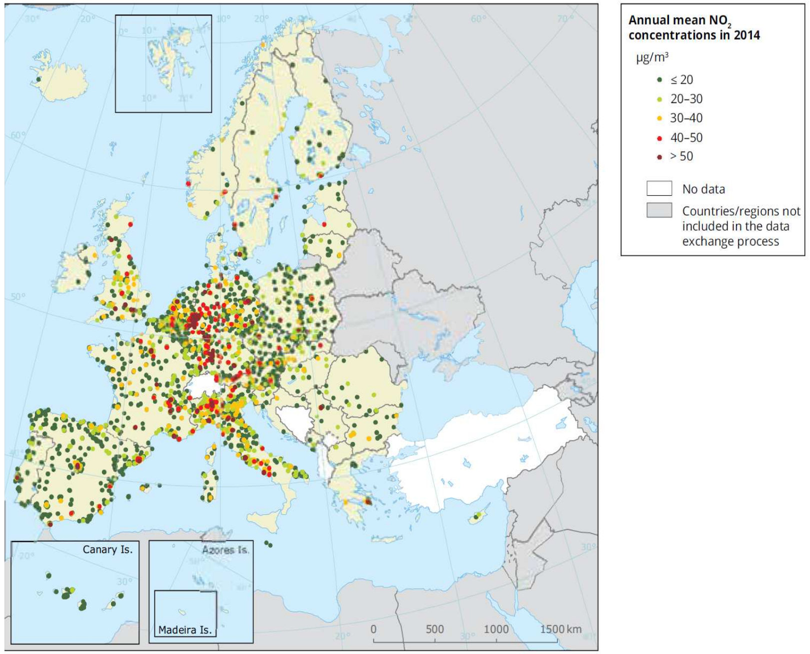
Annual Mean Air Quality in the EU (PM and NO2)

PM10 conc. ● > 40 µg/m3



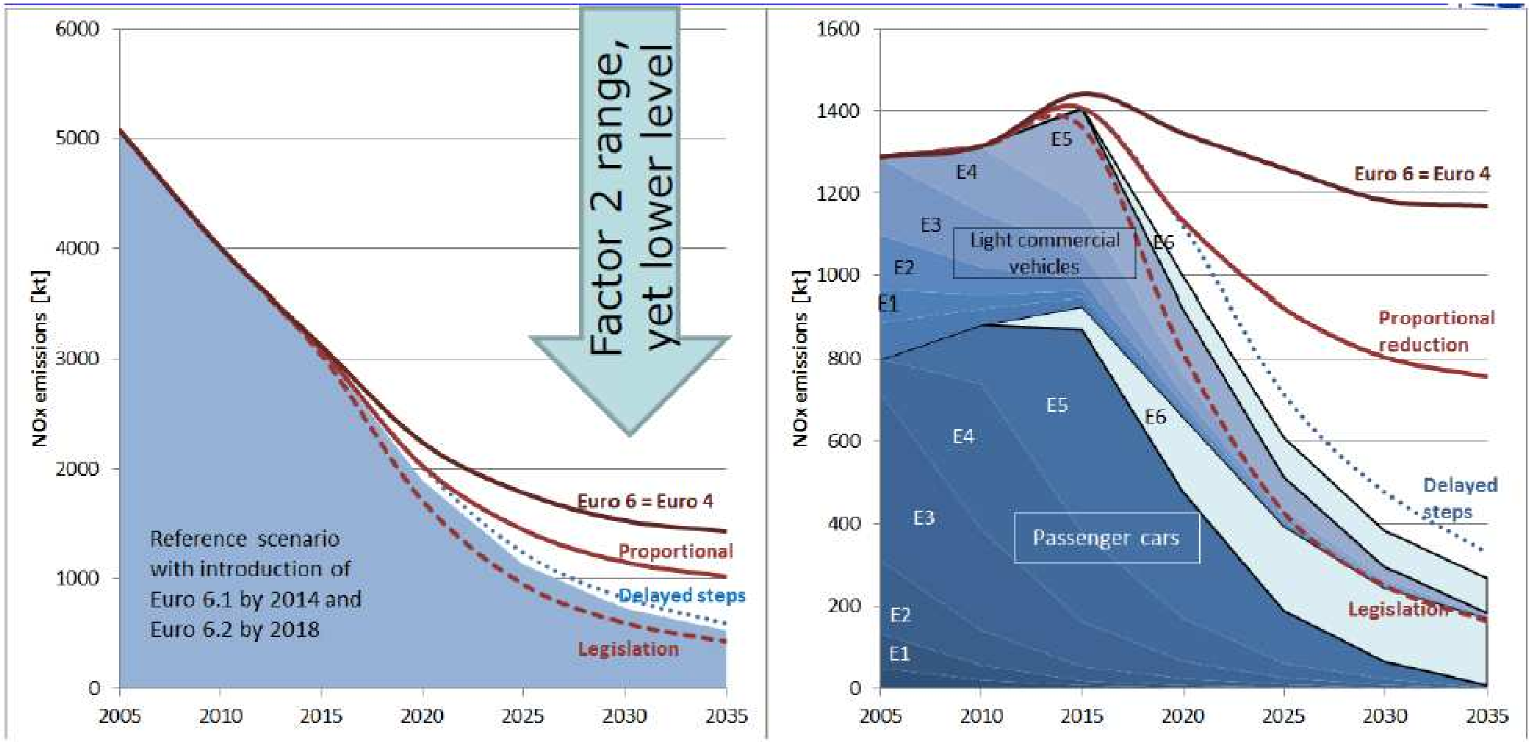
NO2 conc. ● > 40 µg/m3



Some European areas show high PM and NO_2 concentrations.
The average contribution of local traffic to urban PM10, PM2.5 and NO_2 is estimated at 15%, 35% and 46%, respectively.

Source: EEA 2016

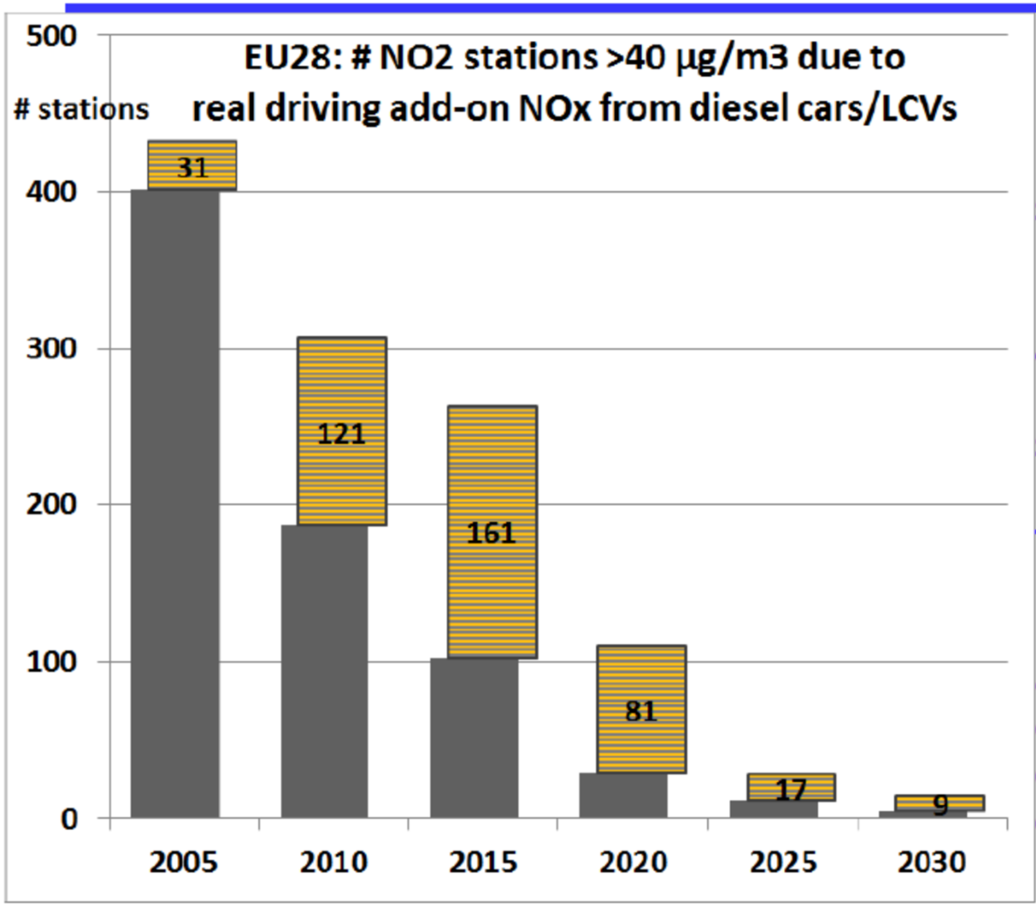
NOx projections



"Legislation": Euro 6 = 80 mg/km from 2015. **"Delayed steps"**: As Reference, but Euro 6.2 only from 2020 onwards. "**Proportional reduction"**: Euro 6 = 380 mg/km from 2015.
"Euro 6 = Euro 4": Euro 6 = 730 mg/km from 2015

Source: Kleefeld and Ntziachristos (2012) TSAP Review

Impact of failing NOx on air quality exceedances



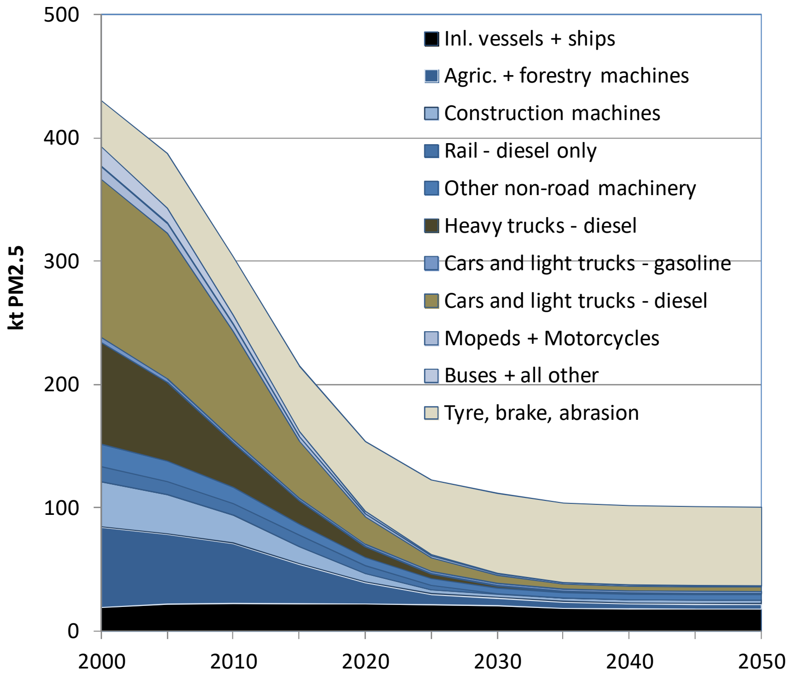
2010:
300 instead of 190 stations
⇔ **one third of total**…

and 2015:
260 instead of 100 stations
⇔ **two thirds of total**…

…exceed the NO_2 ambient limit value due to "add-on" NO_x emissions from diesel cars (and LCVs)

Source: Borken-Kleefeld (IIASA)

$PM_{2.5}$ projections



Baseline:

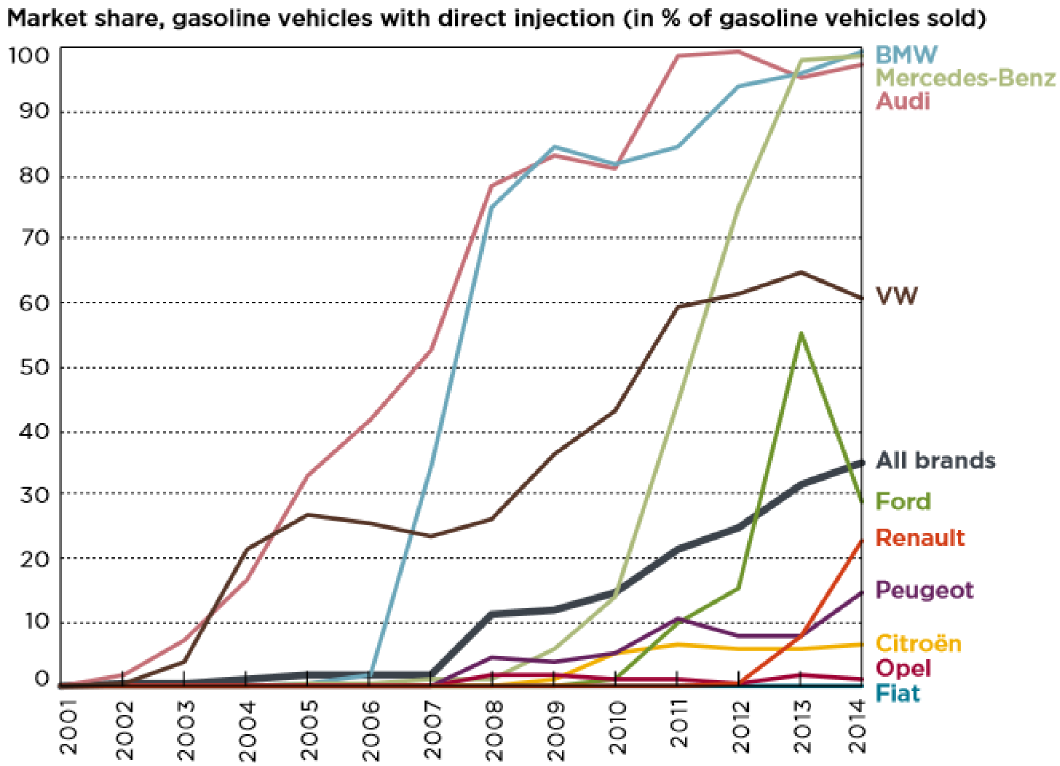
- Reductions until 2030 vs. 2005
  >90%: diesel HDV&LDV, locos, NRMM
  ~70% other mobile machines

- **Road abrasion**, tyre, clutch and brake wear increase with traffic volume, >80% of emissions from road vehicles in 2030

Source: Kleefeld and Ntziachristos (2012) TSAP Review

Nanoparticles: how small? (1)

- The fraction of the GDI vehicles in the vehicle fleet is forecast to grow significantly during the next years
- GDI vehicles offer lower fuel consumption and NOx emission but the knowledge related to exhaust particles is not at the same level as the knowledge of diesel exhaust particles
- Evidence that solid nucleation mode of particles <23 nm can be emitted and sometimes in high concentrations



Nanoparticles: how small? (2)

- As a result of these concerns and criticism for the direct application of the PMP protocol to gasoline vehicles, there is on-going research and discussion on the extension of the PMP to control particles in the sub-23nm range
- 3 Horizon 2020 projects (SUREAL-23, PEMs4Nano and DownToTen) have been launched in this area. In all these projects, the size of approximately 10nm is selected to ensure that sub 23nm particles are regulated while avoiding measurement artefacts that may arise in the <10nm range

DOWN TO 10

HORIZON 2020

Call: H2020-GV-2016-2017

Technologies for low emission light duty powertrains

Action:

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

HORIZON 2020

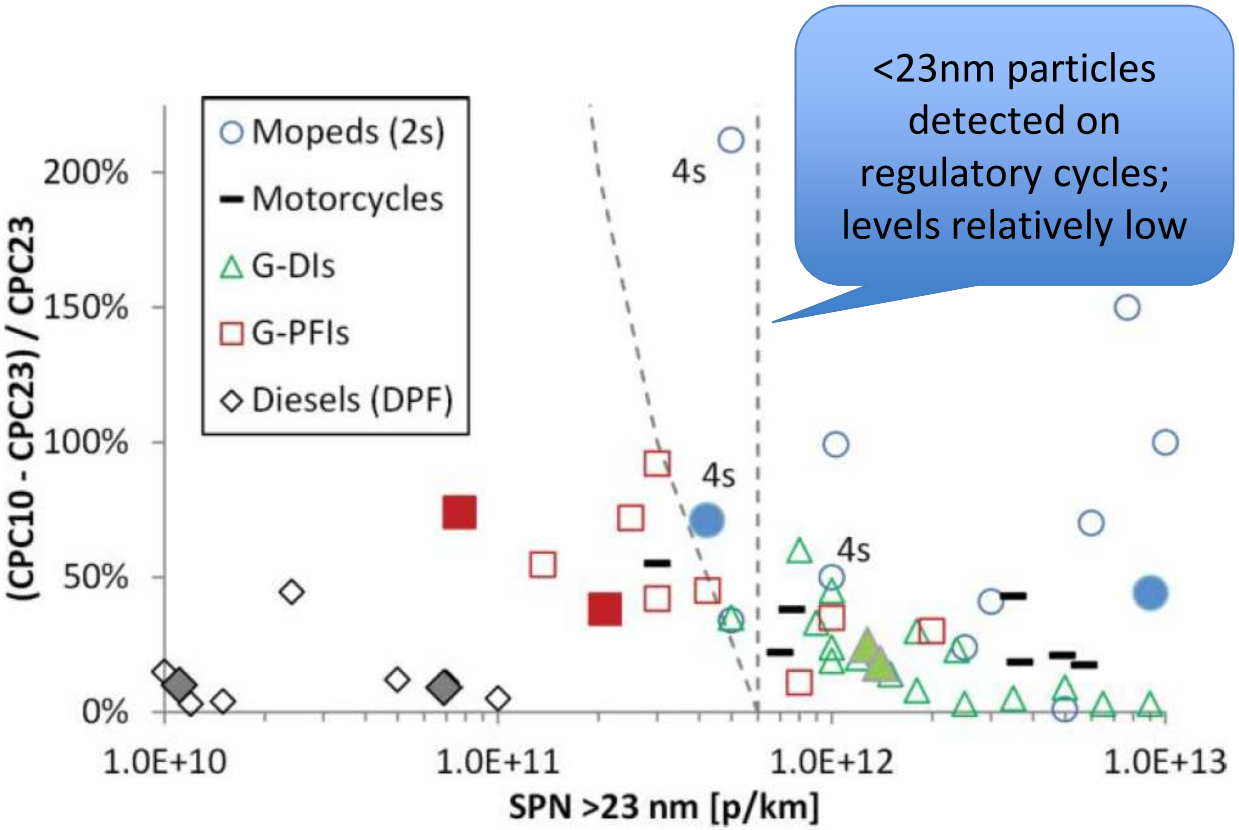
Project Partners

In collaboration with:

The University of California at Riverside,

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

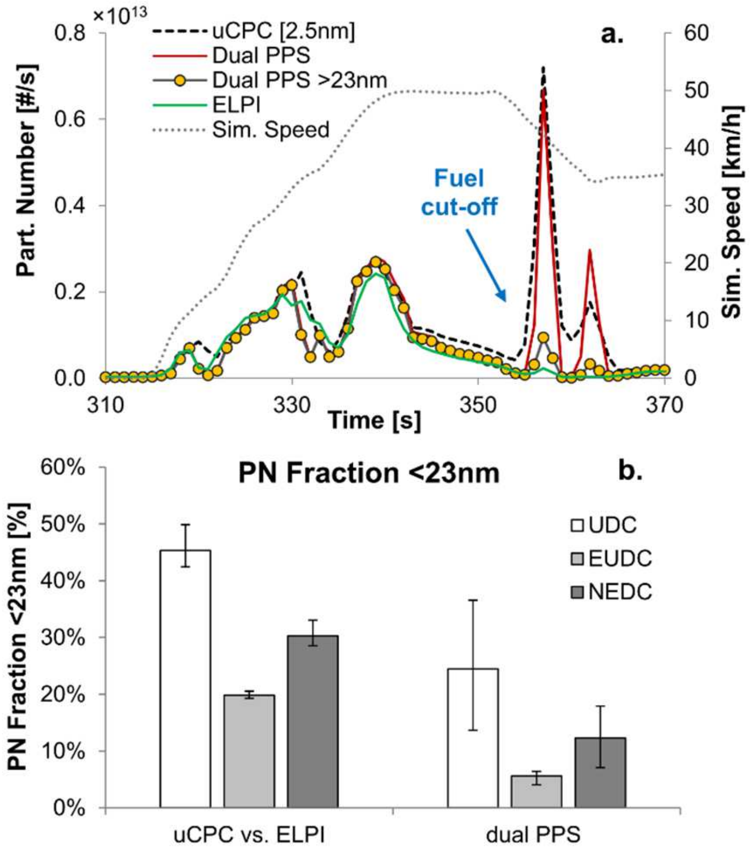
Why measure sub-23nm Particle Number?



- 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
  - $6x10^{11}$ p/km limit for particles >23 nm
  - Other line indicates $6x10^{11}$ 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 engine
Amanatidis et al. (2017) J Aerosol Sci

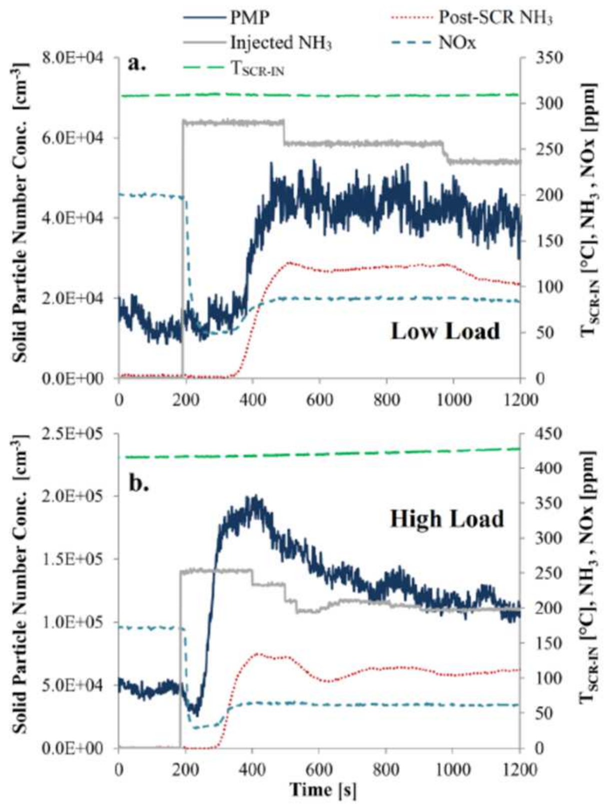
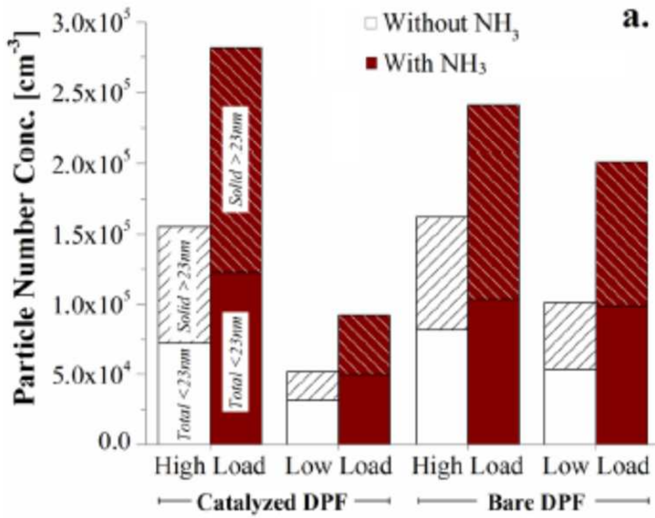


Figure 2. Solid (>23 nm) particle number concentration measured at tailpipe conditions prior to and after NH_3 injection at (a) low load, and (b) high load engine operation, with a catalyzed DPF upstream of the SCR.

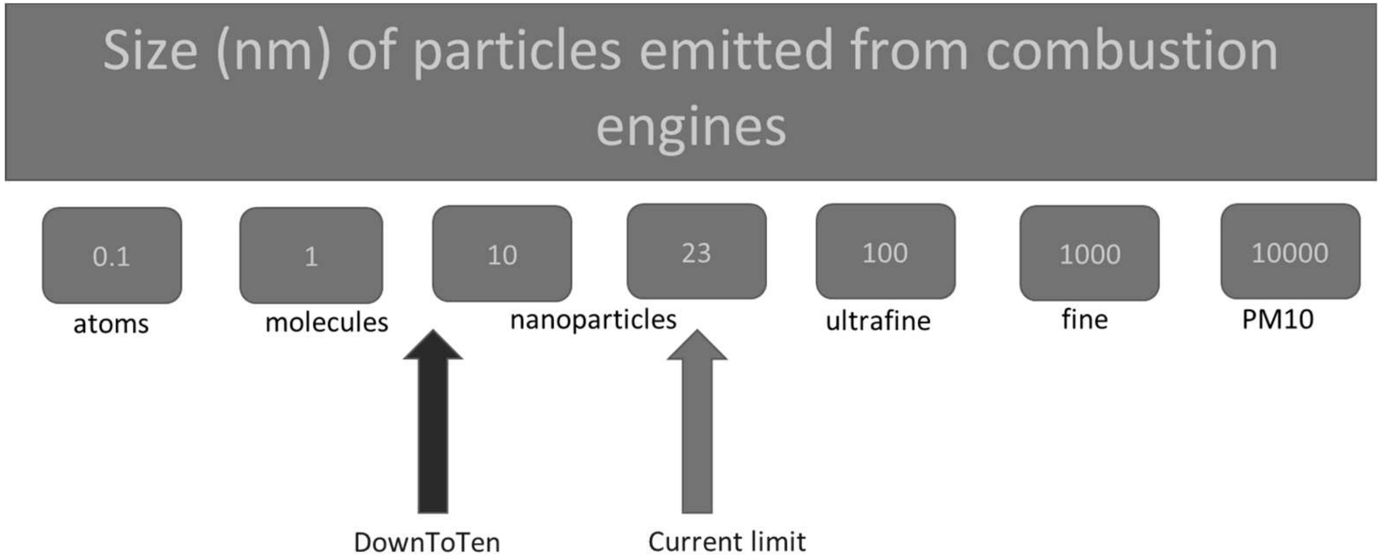
Driving events and ECT do produce <23nm particles: further investigation required



Amanatidis et al. (2014) ES&T

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



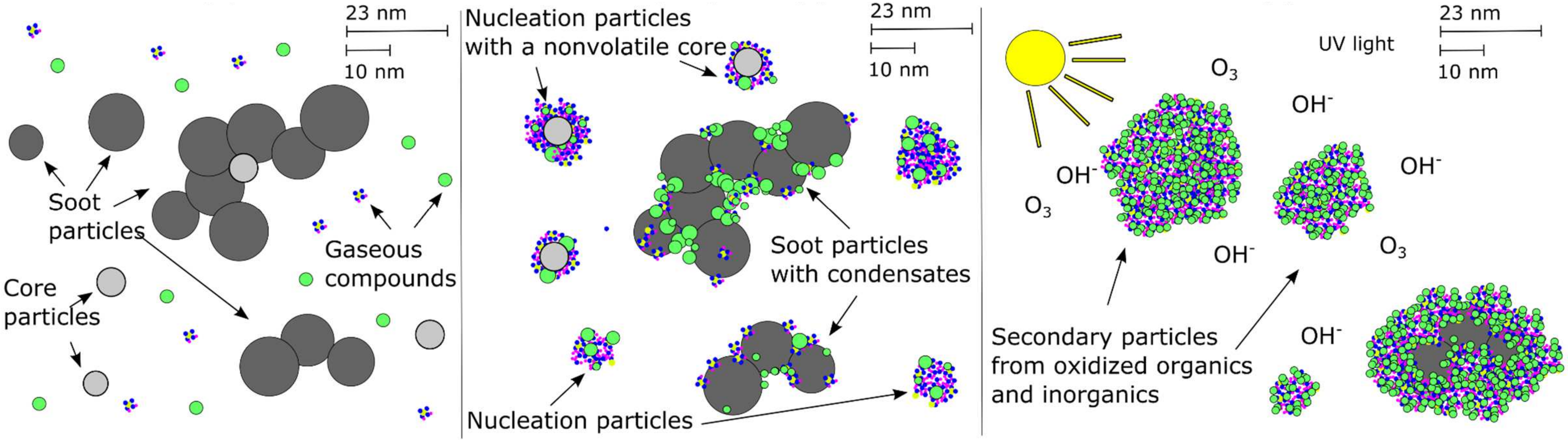
The objective is a PN-Portable Emission Measurement System (PEMS) demonstrator with high efficiency in determining PN emissions of current and future engine technologies in the real worldc

Exhaust emission related particle types

<u>Exhaust pipe</u> aerosol contains primary particles

<u>Fresh</u> (emitted) exhaust aerosol includes delayed primary aerosol

<u>Aged</u> aerosol includes also secondary aerosol



Time scale

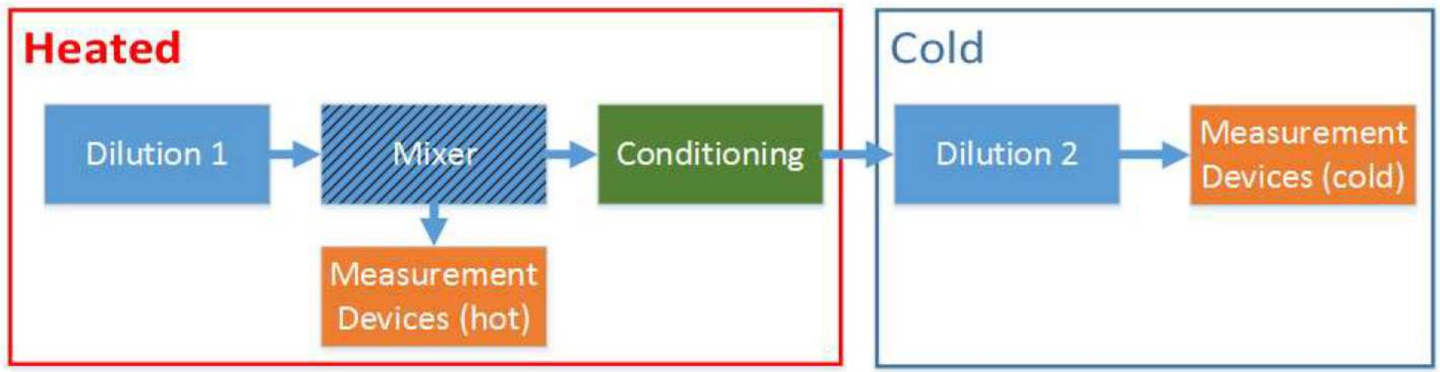
Seconds → **Seconds to minutes** → **Hours to days**

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?

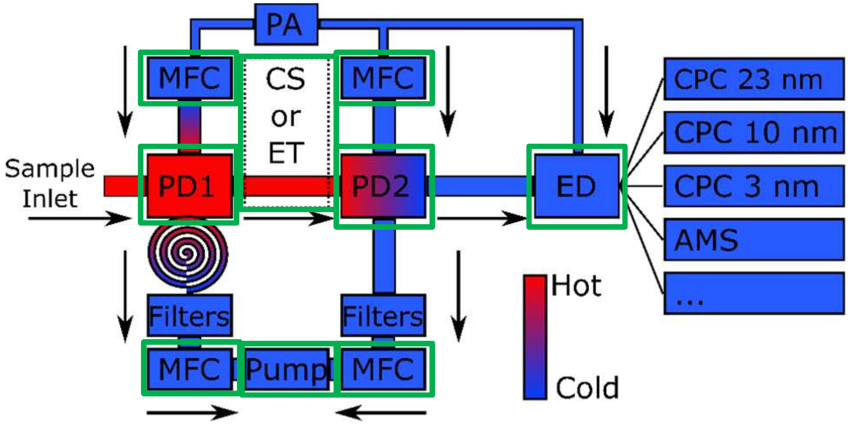
Sampling setup specifications

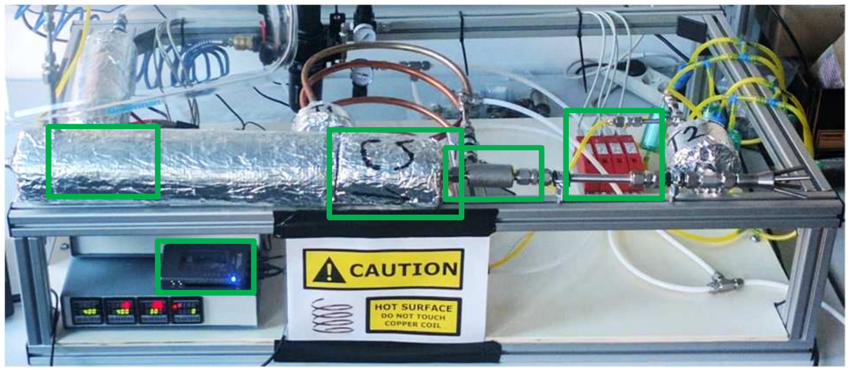
- A setup was designed to maximize the penetration of non-volatile particles below 23 nm, while avoiding the creation of gaseous artefacts
- Important factors like robustness against artefacts (re-nucleation, growth of sub-cut particles), losses of (solid) particles, storage/release effects of gas phase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



Sampling Setup to measure (primary) particles

Overview





- 2-3 Dilution stages:

1. Stage (hot or cold)	Porous Tube (PD1)	30 lpm
2. Stage (cold)	Porous Tube (PD2)	30 lpm
3. Stage (cold)	Ejector (ED)	1:10

- 2x MFC 60 lpm against ambient pressure
- 2x MFC >150 lpm against vacuum

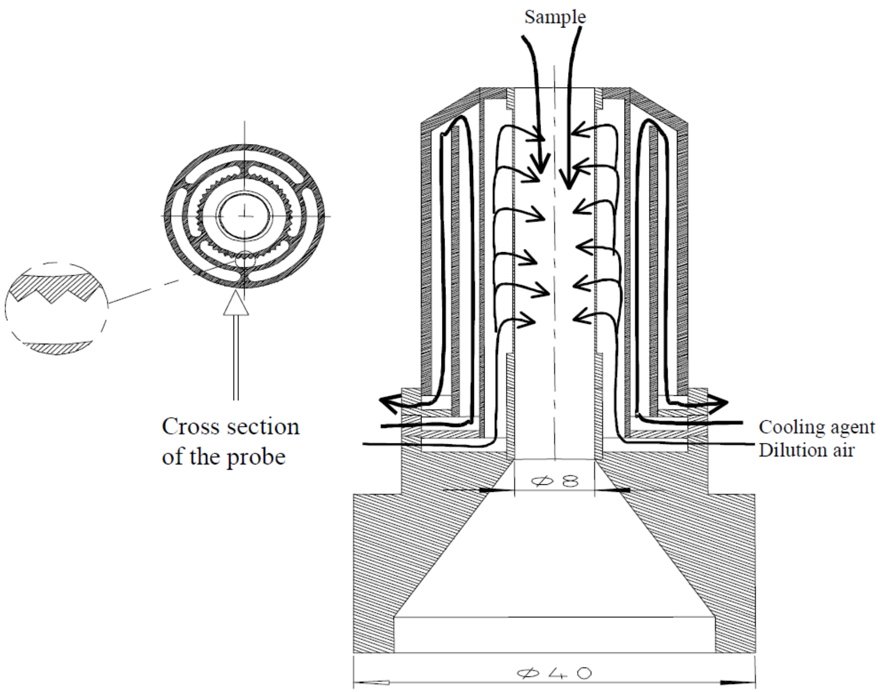
- Exchangable volatile particle remover:
  Catalytic stripper or evaporation tube

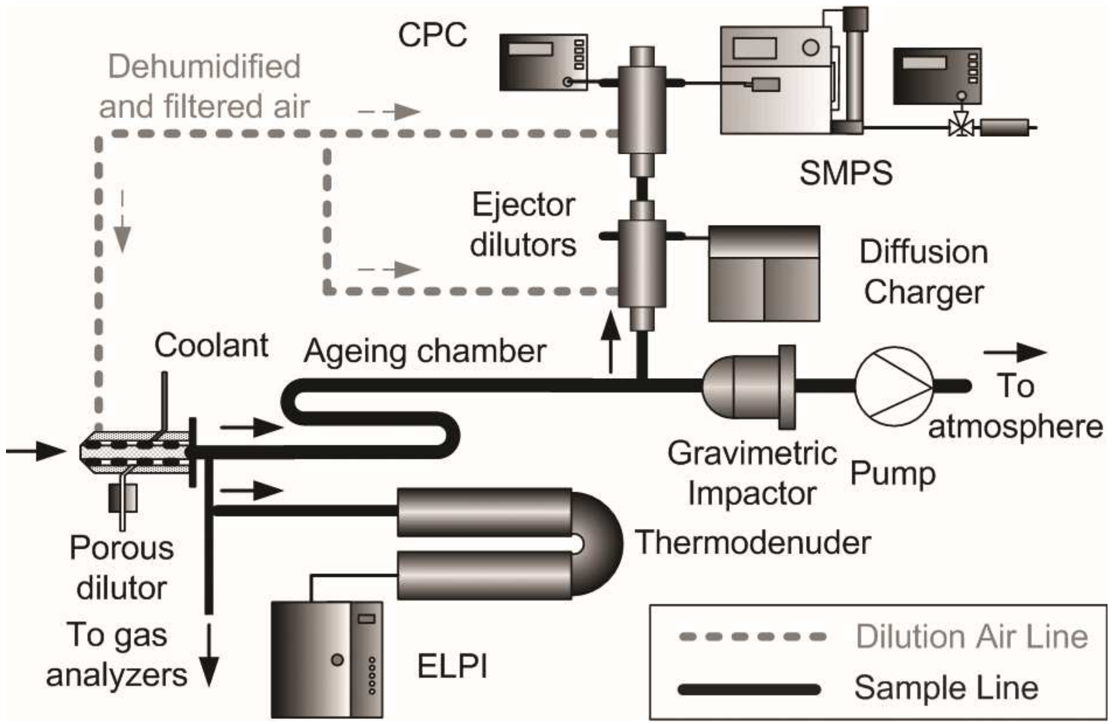
- Vacuum pump 100 lpm

- NI myRIO + LabVIEW virtual instrument

- **Online chemical analysis with MS with ionization source** **Mostly appropriate for volatile and semi-volatile species**
- **Offline chemical analyses of sub-23 nm particles**

Porous tube dilutor as primary dilutor

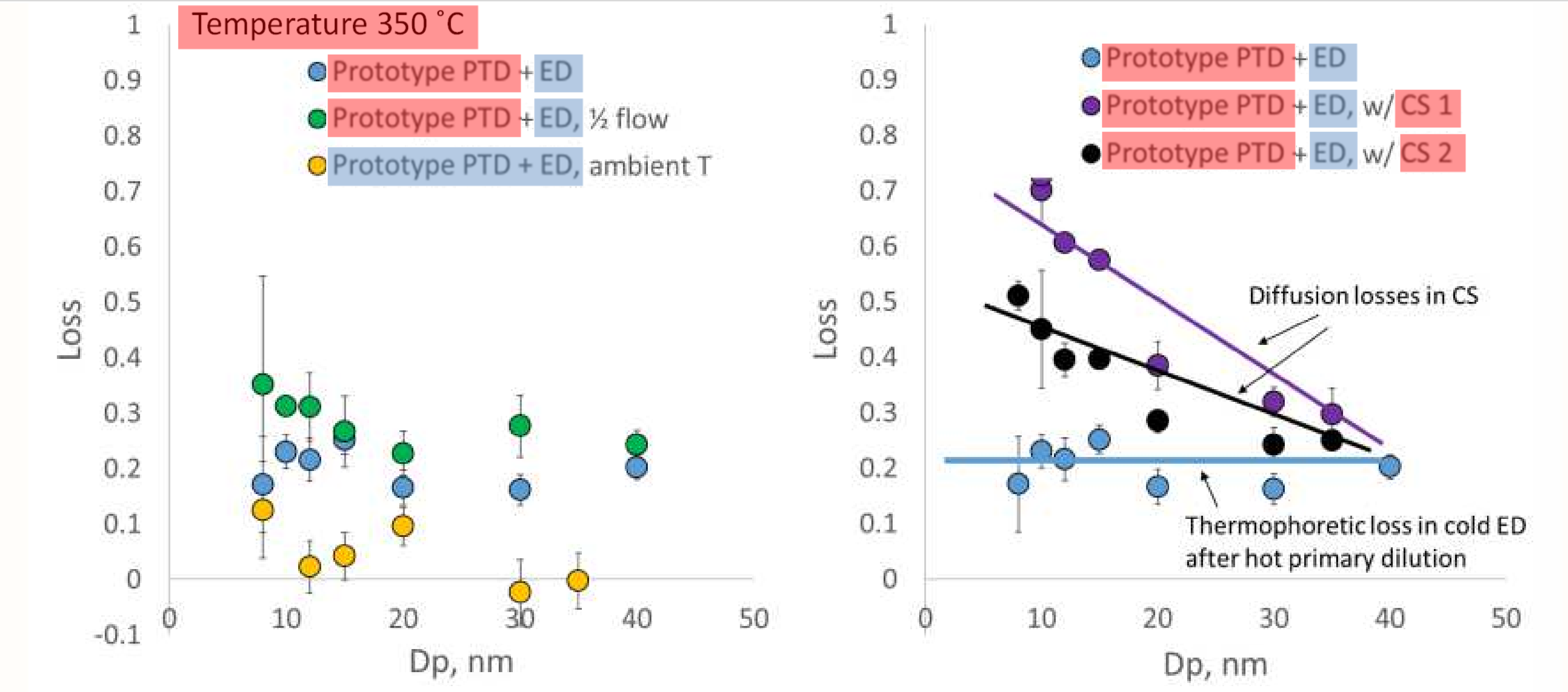




Mikkanen et. al., SAE Paper 2001-01-0219

Ntziachristos and Samaras. JAWMA 2009

Identified losses with the DTT system (silver particle tests at TUT)



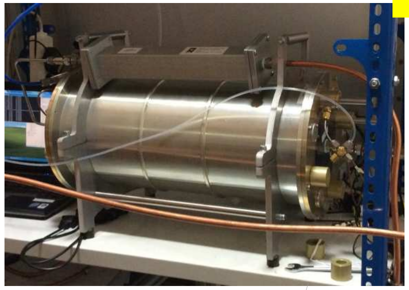
Particle Losses

- **Thermophoretic** losses are mainly caused by cooling down the sample with an ejector diluter (ED). Using a porous tube diluter (PTD) to cool down the diluted exhaust expected to reduce thermophoretic losses.
- The catalytic stripper (CS) is the dominating source of **diffusional** losses. They are reduced by downsizing the CS.

Different techniques to measure secondary particles and the one selected in our project

Equiv. atmospheric age	days	hours	hours- days
Experimental throughput-time	hours -days	hours	<2min residence time

Selected in our project



Concept of Potential Aerosol Mass: Kang et al. 2007

Continuous flow oxidation reactors enable vehicle technology development to reduce SA?

Chassis dyno testing

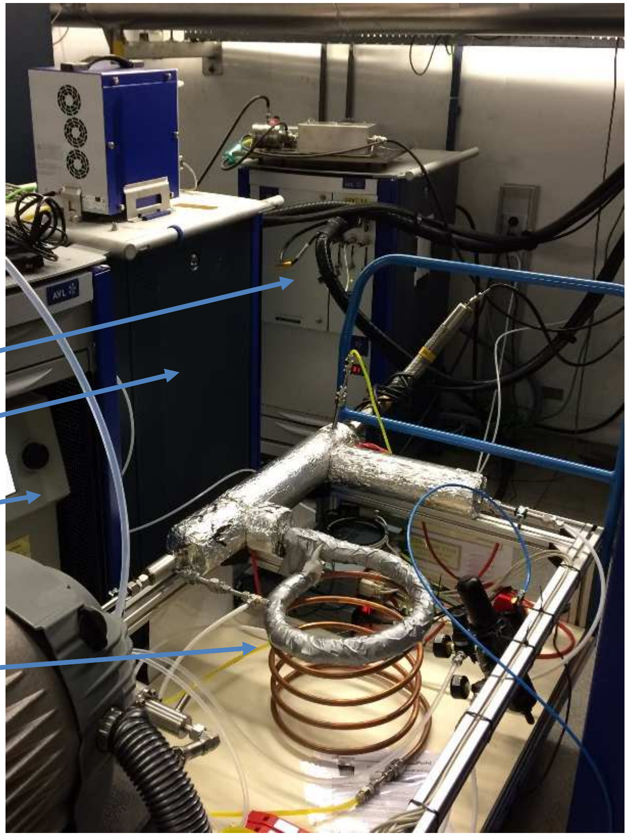
Setup

Instrumentation

Engine out:
- AVL MSS
- AVL APC (23 nm)
- AVL APC + CS (10 nm)

Tailpipe:
- AVL APC + CS (10 nm + 23 nm)
- AVL PN-PEMS

CVS:
- AVL APC (23 nm) reference
- AVL APC + CS@350 (10 nm + 23 nm)
- 10:1 cold dilution + CS@350 + EEPS
- DTT (PD + CS@350 + PD + Ejector + 10 nm + 23 nm)
- AVL MSS



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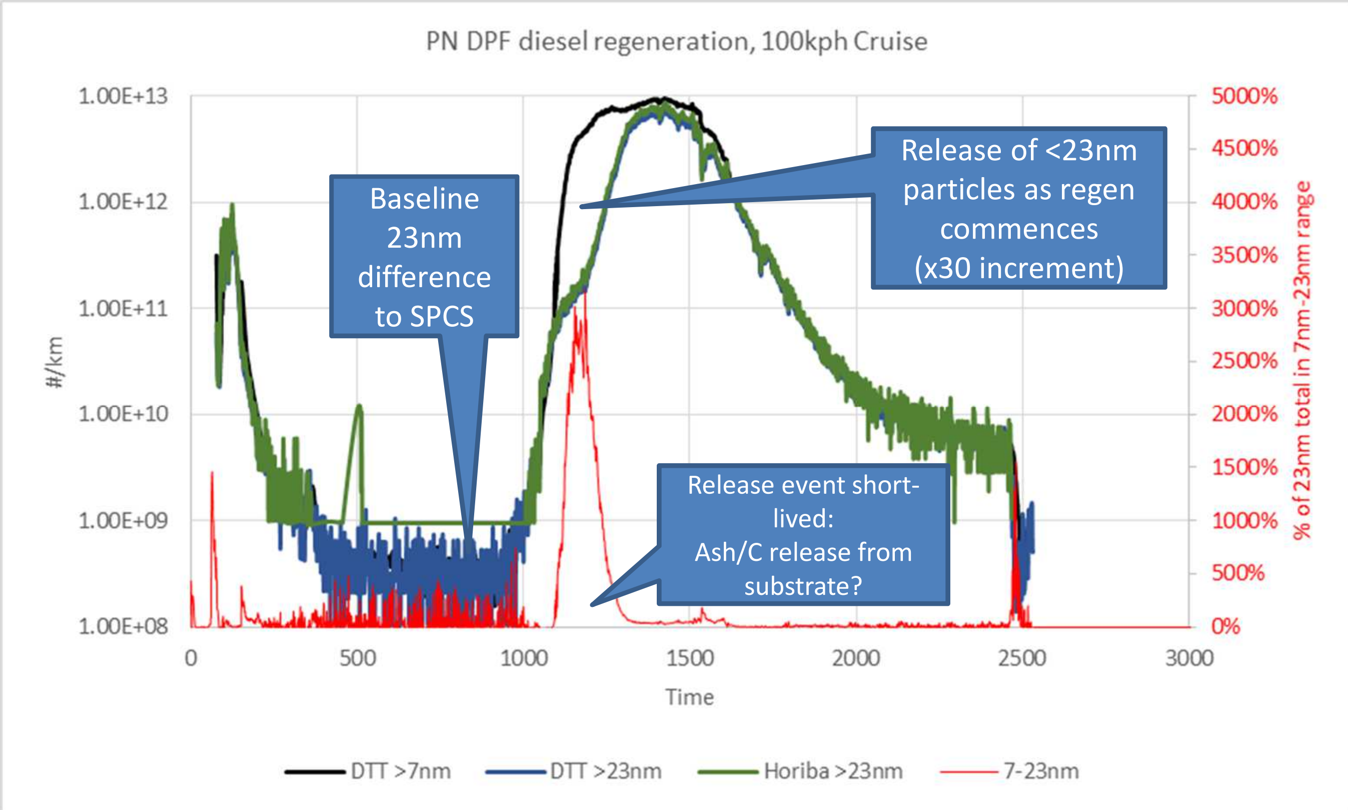
Interesting result: Elective testing of active DPF regeneration
Real-time data at 100kph



- Real-time traces of PN production indicate specific <23nm production at regeneration outset
- Short-lived event, but ~35x increase in >7nm relative to >23nm range
  - Ash / carbon release from substrate?
  - Calculations show this event is not sufficient to take the weighted vehicle emissions above $6x10^{11}$#/km on WLTC (Ki factor)

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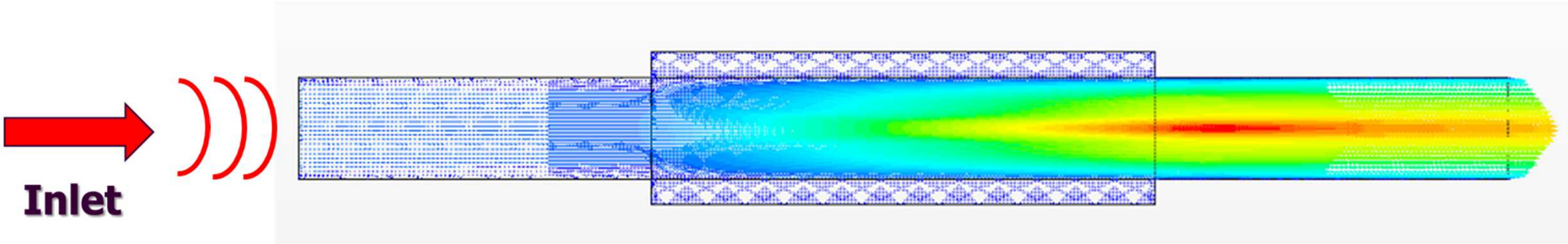
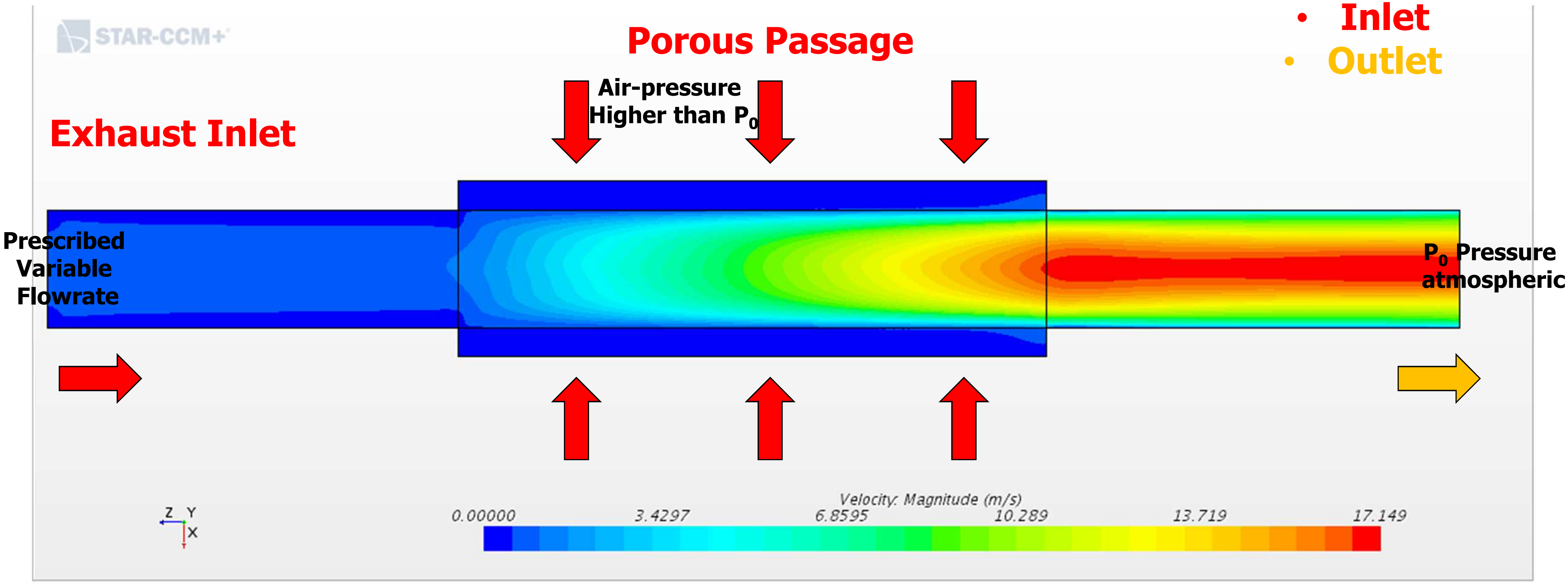
Vehicle class	Engines	Exhaust aftertreatment	Fuels	Cycles	Source of the test vehicles
Passenger cars	GDI & PFI	3WC with and without GPF	Reference Petrol and biofuel admixtures	NEDC, WLTC, 3 RDE cycles; real PEMS trips	uPGrAdE, PaREGEn
	SI-Hybrid	3WC with and without GPF			A hybrid from GV-2-2016
	Diesel	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 CO_2-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			

Raw vs Diluted 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 (Star-CCM+), based on previously published work (Olin et al. 2015)



CFD porous diluter cross section

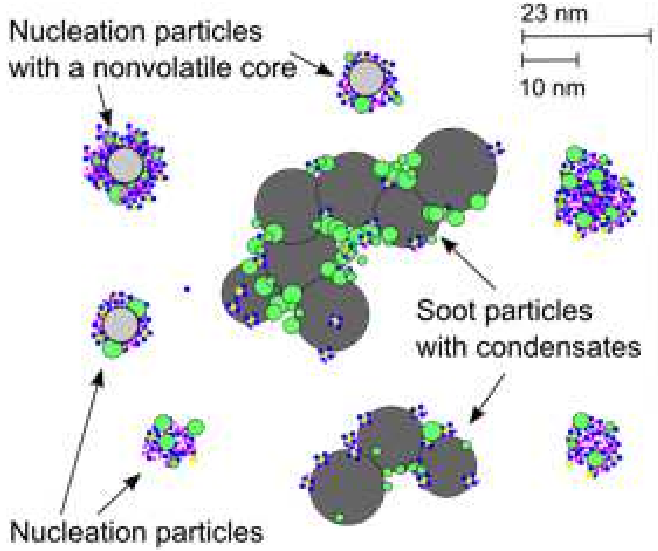


Summary and Outlook

- CO2 control will continue to be in the forefront of EU policy and related technological advances
  - Variable degrees of hybridization, Shift to low carbon intensity fuels, Technology and infrastructure based efficiency improvements
- ICEs will continue to be the powertrains of option for the foreseeable future.
- ICEs have to be virtually emissions free under all driving conditions
- In this context 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.

DOWN TO 10

Any questions ?



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