Performance of Portable Emissions Measurement Systems (PEMS) in Laboratory and On-Road Tests for Improved Quantification of Vehicle Emissions

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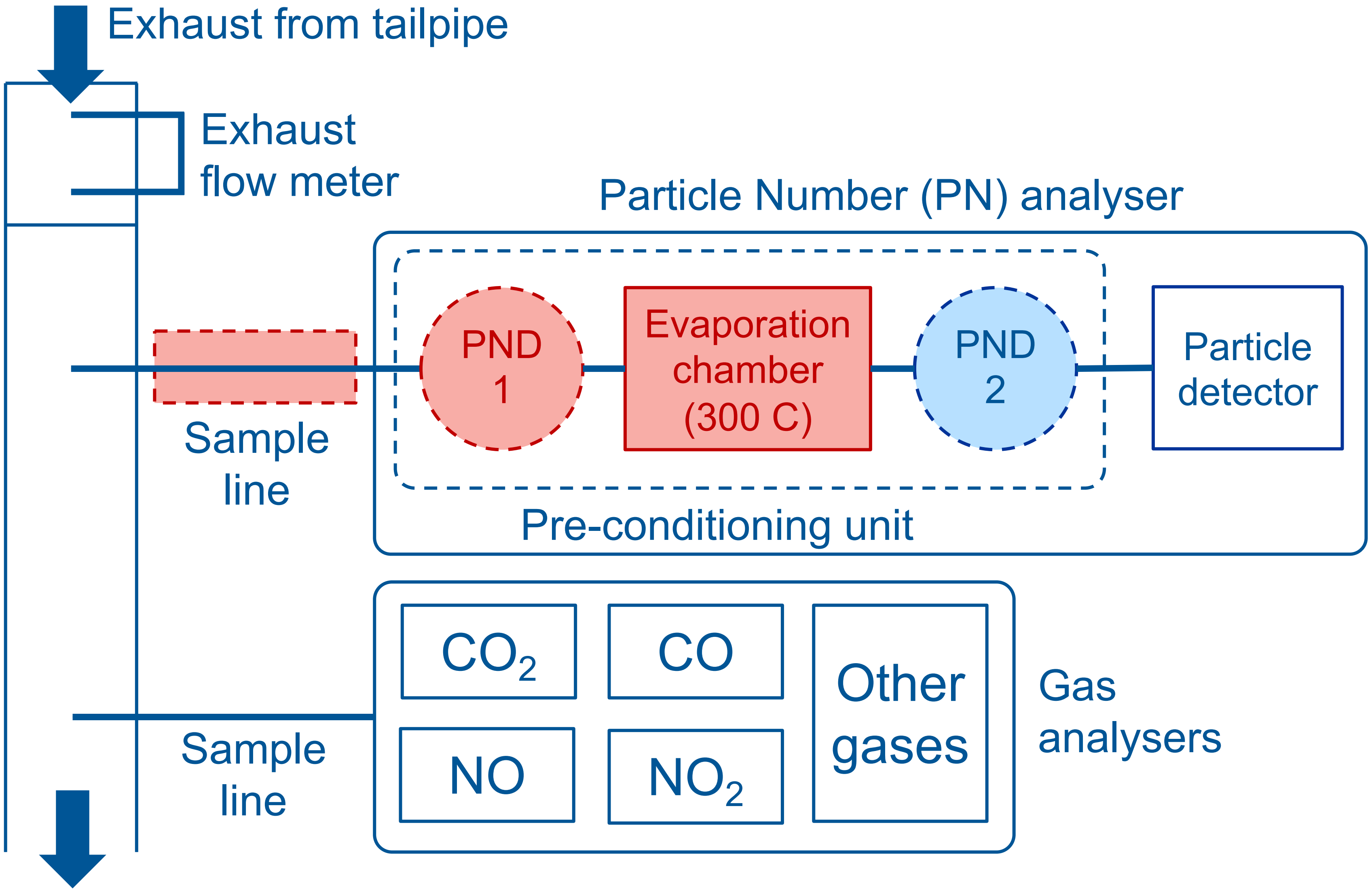
Background

- The Dieselgate scandal in Sept 2015 revealed violation of vehicle emissions measurements under lab testing conditions.
- Since 2016, the EU has introduced real-driving emissions (RDE) testing using portable emissions measurement systems (PEMS) for on-road type approval of vehicles (Regulations 2017/1151 and later 2018/1832).
- Throughout the normal life of a vehicle type, its emissions during RDE test should not be higher than the "not-to-exceed" (*NTE*) values:

$$NTE_{\text{pollutant}} = (\text{Euro 6 emission limit for lab testing}) \times (CF_{\text{pollutant}})$$

- Conformity factor = 1 + "error margin" (measurement uncertainty of PEMS). Conformity factor is reviewed annually as the PEMS technology improves

Portable emissions measurement system (PEMS)



Background

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Conformity factors of PEMS testing by RDE package

RDE procedure	Effective year	NO_x CF	PN CF
2nd RDE package	2017 – 2019	2.10	1.50
3rd RDE package	2020 – 2021	1.50	
4th RDE package	2021 – 2023	1.43	
Euro 6e	2023 –	1.10	1.34

Permissible analyser drift of PEMS over an RDE test

Pollutant	Zero response drift	Span response drift
CO_2	≤ 2000 ppm per test	≤ 2 % reading or 2000 ppm per test, whichever is larger
CO	≤ 75 ppm per test	≤ 2 % reading or 75ppm per test, whichever is larger
NO_2	≤ 5 ppm per test	≤ 2 % reading or 5 ppm per test, whichever is larger
NO/NOx	≤ 5 ppm per test	≤ 2 % reading or 5 ppm per test, whichever is larger
PN	≤ 5000 cm^{-3} per test	N/A (field span calibration developed by MetroPEMS)

Background

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Permissible tolerances for PEMS results in laboratory validation against Constant Volume Sampling (CVS) system

Parameter [Unit]	Permissible tolerances
PN [#/km]	1×10^{11} #/km or 50% of reference lab instrument, whichever is larger*
CO [mg/km]	± 150 mg/km or 15 % of the laboratory reference, whichever is larger**
CO_2 [g/km]	± 10 g/km or 10 % of the laboratory reference, whichever is larger
NOx [mg/km]	± 15 mg/km or 15 % of the laboratory reference, whichever is larger***

* Has been reduced in Euro 6e to 8×10^{10} #/km or 42 % of the laboratory reference, whichever is larger

** Has been reduced in Euro 6e to ±100 mg/km or 15 % of the laboratory reference, whichever is larger

*** Has been reduced in Euro 6e to ±10 mg/km or 12.5 % of the laboratory reference, whichever is larger

Methodology

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	Performance evaluation of commercial PEMS devices	Set-up and performance evaluation of a ‘Golden’ PEMS system
2021	1st validation of commercial PEMS devices Condition: **Aged**	Initial validation of Golden-PEMS Condition: **Factory calibration**
2022	2nd validation of commercial PEMS devices Condition: **Serviced**	‘Golden’ calibration by NMI partners
2023	3rd validation of commercial PEMS devices Condition: **Aged**	Final validation of Golden-PEMS Condition: **‘Gold’ calibration**

RDE testing in Denmark

RDE testing in Finland

Laboratory testing with CVS & chassis dynamometer

Overview of test principle conducted between 2021 – 2023

Test vehicles and PEMS systems

Make	Model	MY	Emission class	Fuel type	Drivetrain type
Skoda	Octavia	2017	Euro 6 d-TEMP	Gasoline	Manual
Skoda	Octavia	2019	Euro 6 d-TEMP	Diesel	Automatic
Toyota	C-HR	2016	Euro 6	Gasoline	Automatic
Peugeot	308	2020	Euro 6	Diesel	Manual

Component	PEMS type 1	PEMS type 2
CO_2	ND-IR	ND-IR
CO	ND-IR	ND-IR
NO	ND-UV	CLD
NO_2	ND-UV	PAS
Particle number (PN)	DC	CPC
Exhaust flow rate	Pitot tube	Pitot tube

Test matrix

Test #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Timeline	Before service 2021						After service 2021			Before service 2022											Before service 2023							
Test type	WLTC	RDE	WLTC	RDE	RDE	RDE	WLTC	WLTC	WLTC	WLTC	WLTC	WLTC	RDE	WLTC	WLTC	RDE	RDE	RDE	RDE	WLTC	WLTC	WLTC	RDE	RDE	WLTC	WLTC	RDE	RDE

WLTC: Laboratory test on a chassis dyno
RDE: On-road test

Representative test vehicles

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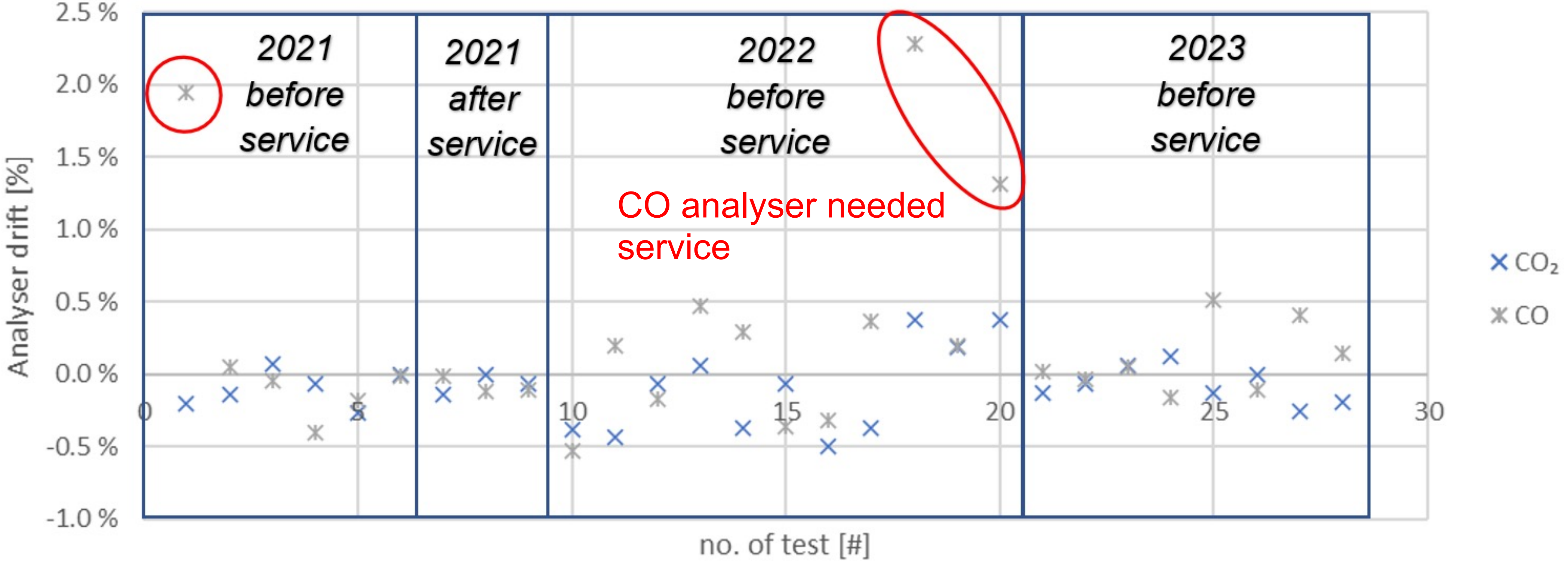
Toyota C-HR gasoline hybrid with two PEMS systems installed on chassis dyno

Skoda Octavia gasoline with two PEMS systems installed before RDE test

Pre- and Post-RDE Drift – CO_2/CO analysers



- The absolute span drift for CO_2 remain within ±0.5 % in all 28 tests regardless of the PEMS status (aged or serviced).
- Zero and span drift data had no systematic trend in all tests. The ND-IR CO_2/CO analysers performed well within the requirements of current regulation.

Pre- and Post-RDE Drift – PN analyser

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- In 2021, DC-based PN analyser suffered from sustained/recurring error messages, preventing PN zero tests → OK after servicing
- In 2022, the problem with PN analyser recurred after ~6 months with high zero drift (~2700 cm^{-3}) → PN sensor was replaced completely
- In 2023, the PN analyser worked well and the zero drift was < 200 cm^{-3}
- Since the permissible PN zero is set at 5000 cm^{-3}, all successfully conducted PN zero tests were within this limit.

Test #	Timeline	Test type	PN ADC PN zero pre [p/cm^3]	PN ADC PN zero post [p/cm^3]	PN ADC PN zero drift [p/cm^3]	PN ADC PN zero drift %
1	Before service 2021	WLTC	n/a	n/a	n/a	n/a
2		RDE	1428	n/a	n/a	n/a
3		WLTC	n/a	n/a	n/a	n/a
4		RDE	n/a	n/a	n/a	n/a
5		RDE	n/a	n/a	n/a	n/a
6		RDE	n/a	n/a	n/a	n/a
7	After service 2021	WLTC	2543	2336	-207	-8 %
8		WLTC	1701	1669	-32	-2 %
9		WLTC	1693	2509	816	48 %
10	Before service 2022	WLTC	927	n/a	n/a	n/a
11		WLTC	1773	n/a	n/a	n/a
12		WLTC	1182	1564	382	32 %
13		RDE	4375	1618	-2757	-63 %
14		WLTC	1331	1494	163	12 %
15		WLTC	n/a	2025	n/a	n/a
16		RDE	1499	1272	-226	-15 %
17		RDE	n/a	1018	n/a	n/a
18		RDE	1532	4323	2791	182 %
19		RDE	1643	n/a	n/a	n/a
20		WLTC	n/a	1495	n/a	n/a
21	Before service 2023	WLTC	670	647	-23	-3 %
22		WLTC	781	810	29	4 %
23		RDE	707	617	-90	-13 %
24		RDE	699	927	228	33 %
25		WLTC	762	775	14	2 %
26		WLTC	587	1183	596	101 %
27		RDE	763	842	79	10 %
28		RDE	646	657	11	2 %

Validation of PEMS against laboratory reference

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- Performed using a chassis dyno equipped with a CVS based emission sampling system.
- Test results were compared against the limits defined the most recent regulations, RDE4 package and Euro 6e.

Test information for CVS validations						
Year	Fuel type	Test type	PEMS type and status		PEMS type and status	
2021	Diesel	WLTC	Type 1	Aged	Type 2	
2021	Gasoline	WLTC	Type 1	Aged	Type 2	
2021	Diesel	WLTC	Type 1	Freshly calibrated	Type 2	Used but serviced
2021	Gasoline	WLTC	Type 1	Freshly calibrated	Type 2	Used but serviced
2021	Gasoline	WLTC	Type 1	Freshly calibrated	Type 2	Used but serviced
2022	Diesel	WLTC	Type 1	Aged	Type 2	Used but serviced
2023	Diesel	WLTC	Type 1	Aged	Type 2	goldenPEMS
2023	Gasoline	WLTC	Type 1	Aged	Type 2	goldenPEMS
2023	Gasoline	WLTC	Type 1	Aged	Type 2	goldenPEMS

Validation of PEMS Type 1 against CVS

Test information				PEMS Deviation compared to CVS [abs]				
	Test type	PEMS status	Year	ND-IR CO_2 (g/km)	ND-IR CO (mg/km)	ND-UV NOx (mg/km)	ADC PN (10^11#/km)	Distance (m)
Diesel	WLTC	Aged	2021	5	167	4	0.00	200
Diesel	WLTC	Freshly calibrated	2021	2	4	5	0.01	278
Diesel	WLTC	Aged	2022	10	10	5	0.33	20
Diesel	WLTC	Aged	2023	6	5	8	0.00	155
Gasoline	WLTC	Aged	2021	6	10	2	2.27	17
Gasoline	WLTC	Freshly calibrated	2021	8	8	2	1.07	5
Gasoline	WLTC	Freshly calibrated	2021	7	10	3	0.87	111
Gasoline	WLTC	Aged	2023	5	4	5	1.52	26
Gasoline	WLTC	Aged	2023	5	3	4	1.34	30

Passed
Exeed Euro 6E limits
Exceed RDE 4 limits

Validation of PEMS Type 2 against CVS

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Test information				PEMS Deviation compared to CVS [abs]				
l type	Test type	PEMS status	Year	ND-IR CO_2 (g/km)	ND-IR CO (mg/km)	CLD + PAS NOx (mg/km)	CPC PN (10^11#/km)	Distance (m)
Diesel	WLTC Cold	Used but serviced	2021	14	7	7	0.0	273
Diesel	WLTC Cold	Used but serviced	2022	14	1	12	0.3	232
Diesel	WLTC Cold	goldenPEMS	2023	3	2	3	0.0	154
Gasoline	WLTC Cold	Used but serviced	2021	27	19	8	2.1	116
Gasoline	WLTC Cold	Used but serviced	2021	28	13	0	1.9	106
Gasoline	WLTC Cold	goldenPEMS	2023	5	11	0	0.2	21
Gasoline	WLTC Cold	goldenPEMS	2023	4	12	0	0.2	33

Passed
Exeed Euro 6E limits
Exceed RDE 4 limits

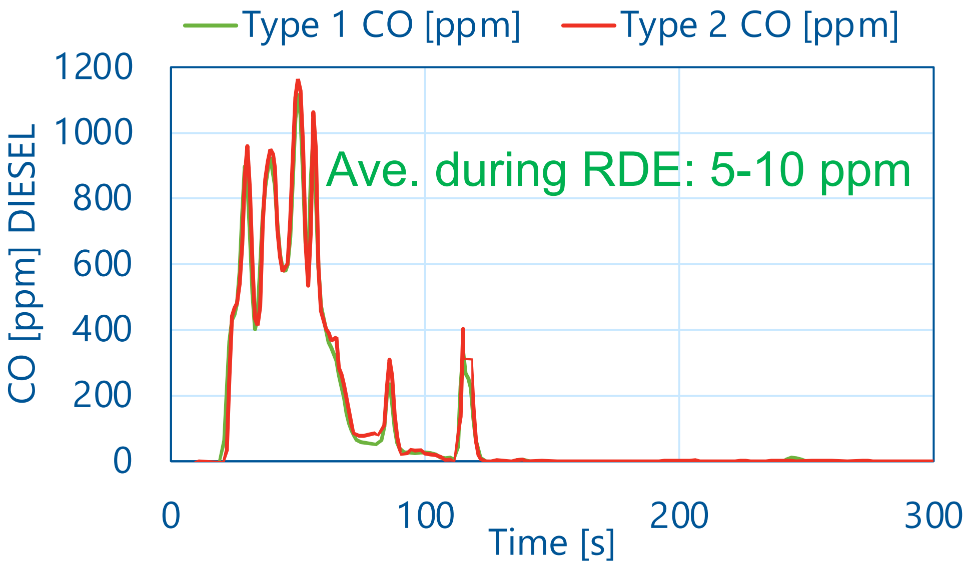
Performance of two PEMS in RDE tests

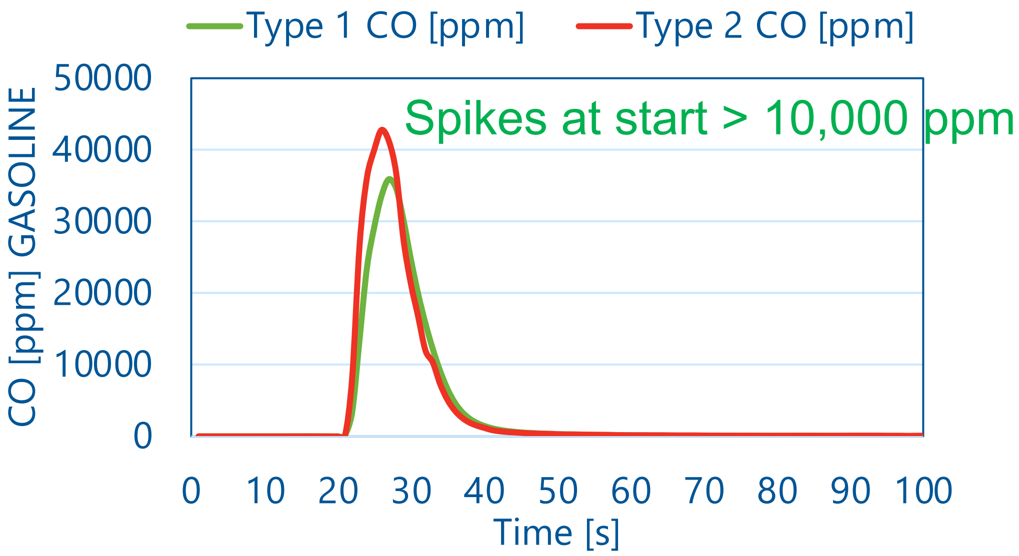
- PEMS Type 1 and PEMS Type 2 were installed in series during RDE tests to allow direct comparison.
- 24 RDE trips were made in total with all four vehicles. The same route and same driver were used for RDE test of each vehicle on repeated days.

Overview of RDE tests done with Type 1 and 2 PEMS devices

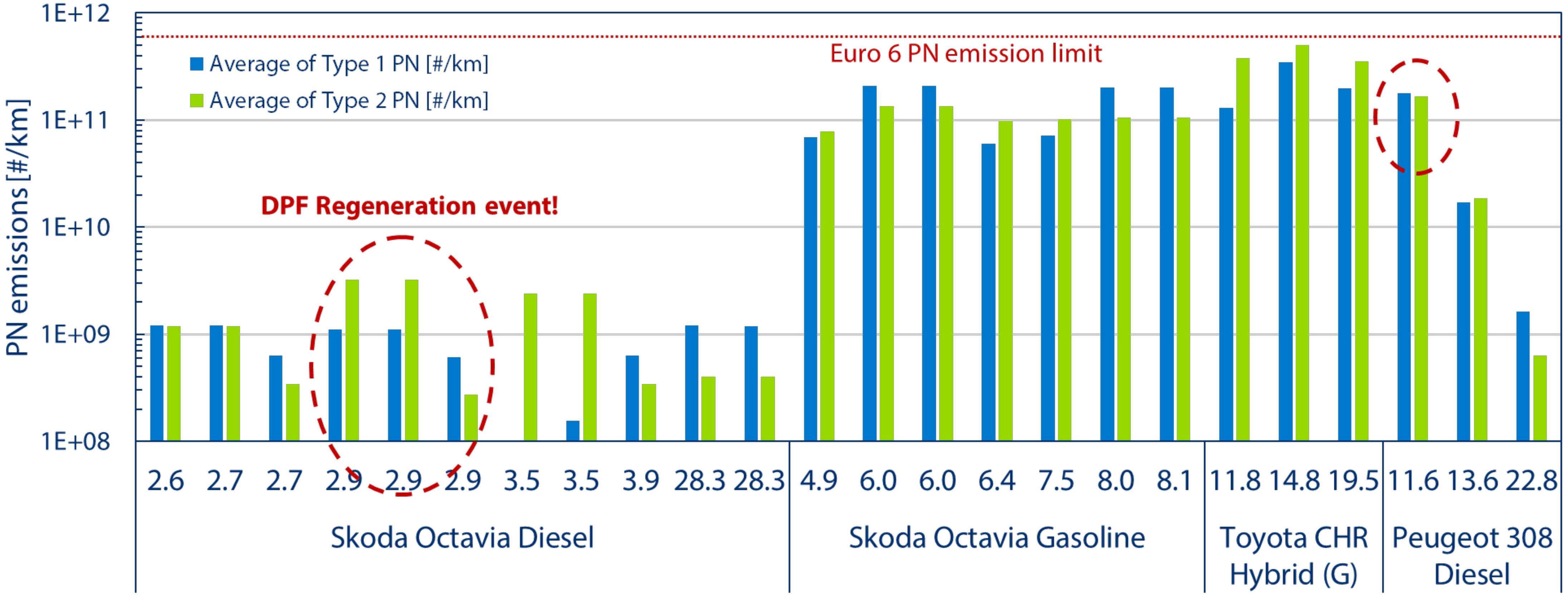
Car model	Tests withType 1 device	Tests with Type 2 device
Skoda Octavia Diesel	11	11
Skoda Octavia Gasoline	7	7
Toyota CHR Hybrid (G)	3	3
Peugeot 308 Diesel	3	3
Grand Total	24	24

Performance of two PEMS under RDE tests – CO analyser



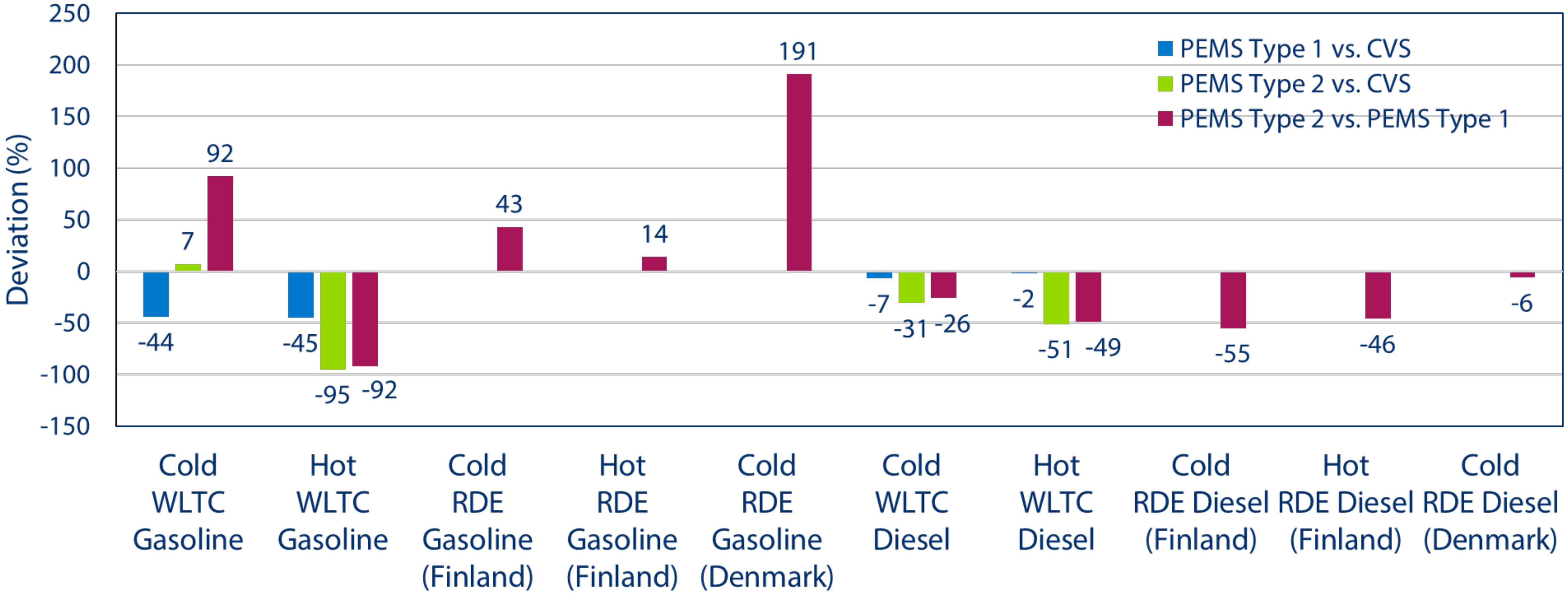


Performance of two PEMS under RDE tests – PN analyser



- Good agreement at higher PN concentrations (gasoline vehicles).
- Some day-to-day variance in diesel vehicles (mainly during DPF regeneration).
- Values < 10^9 #/km (which is only < 0.2% of the legal limit) are uncertain.

Correlation of PEMS response between lab & RDE testing



The deviations for PN emissions seemed to vary significantly depending on test type (WLTC vs. RDE) and test vehicle (make, fuel).

Correlation of PEMS response between lab & RDE testing

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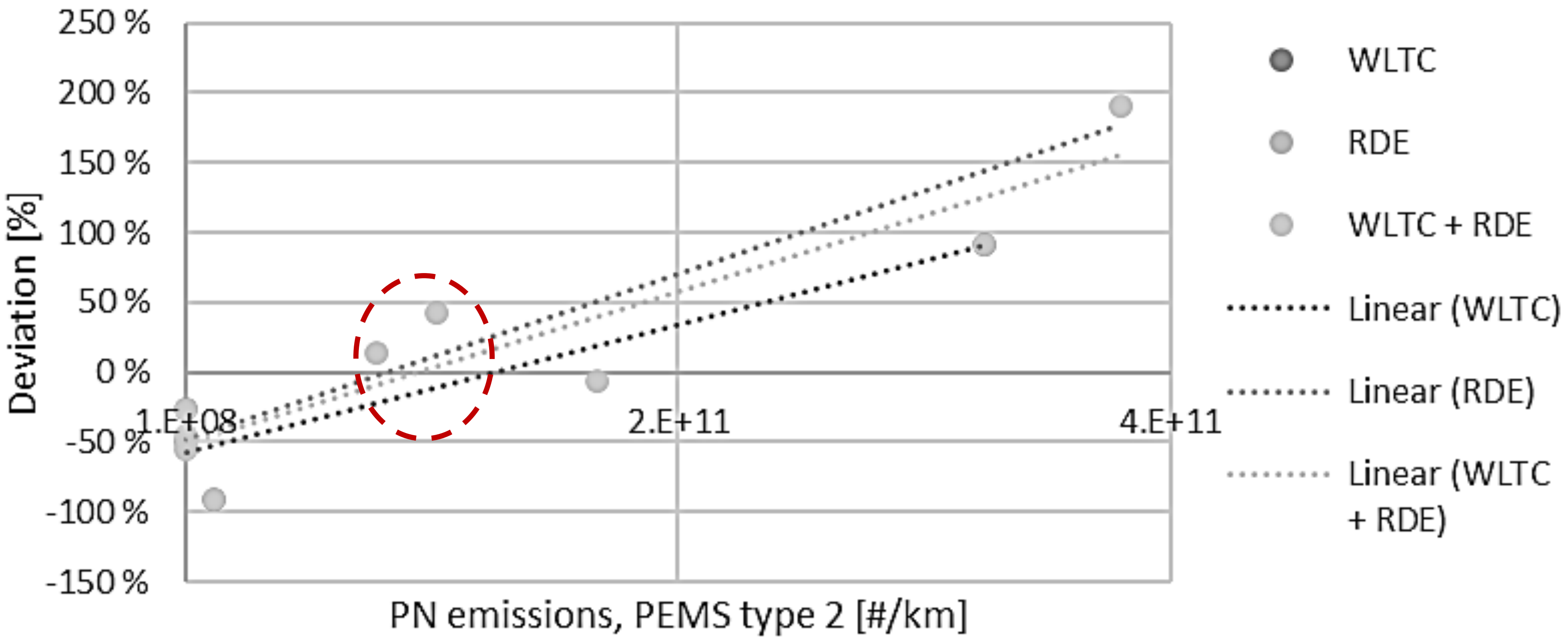

The trendlines show that PEMS type 2 with respect to PEMS type 1:

- underestimates PN emissions below ~1x10^{11} #/km; and
- overestimates the PN emissions above ~1*10^{11} #/km.

Summary

- **Pre- and post-RDE drift:**
  - ➢ Time-consuming compared to the actual RDE test → Simplify drift tests
  - ➢ Our data suggest that permissible analyser drifts over the RDE tests could be further decreased (ND-IR devices ~±0.5%; ND-UV devices ~±0.2%)
  - ➢ Device malfunction or deterioration may be identified in advance
- **Factors affecting PEMS performance:**
  - ➢ Significant day-to-day variance even on the same vehicle on the same route with the same driver.
  - ➢ Day-to-day variations are mostly larger than device-to-device variation.

Summary

- DPF regeneration affects CO, PN, and NO_x emissions; however, these are still within the legal limit.
- Measured PN emissions vary > ±50% depending on device type. Difference between vehicles is much greater, up to several orders of magnitude.

- **Correlation between lab validations and RDE testing:**
  - The deviations between PEMS devices depended on vehicle/fuel type and emissions characteristics.
  - DC-based PN device correlated better with CVS results for lower PN emissions. CPC-based PN device performed better for higher PN emissions.
  - The two types of PN devices may have be tuned for different emission matrixes.

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Thank you for your attention!

Any Questions?

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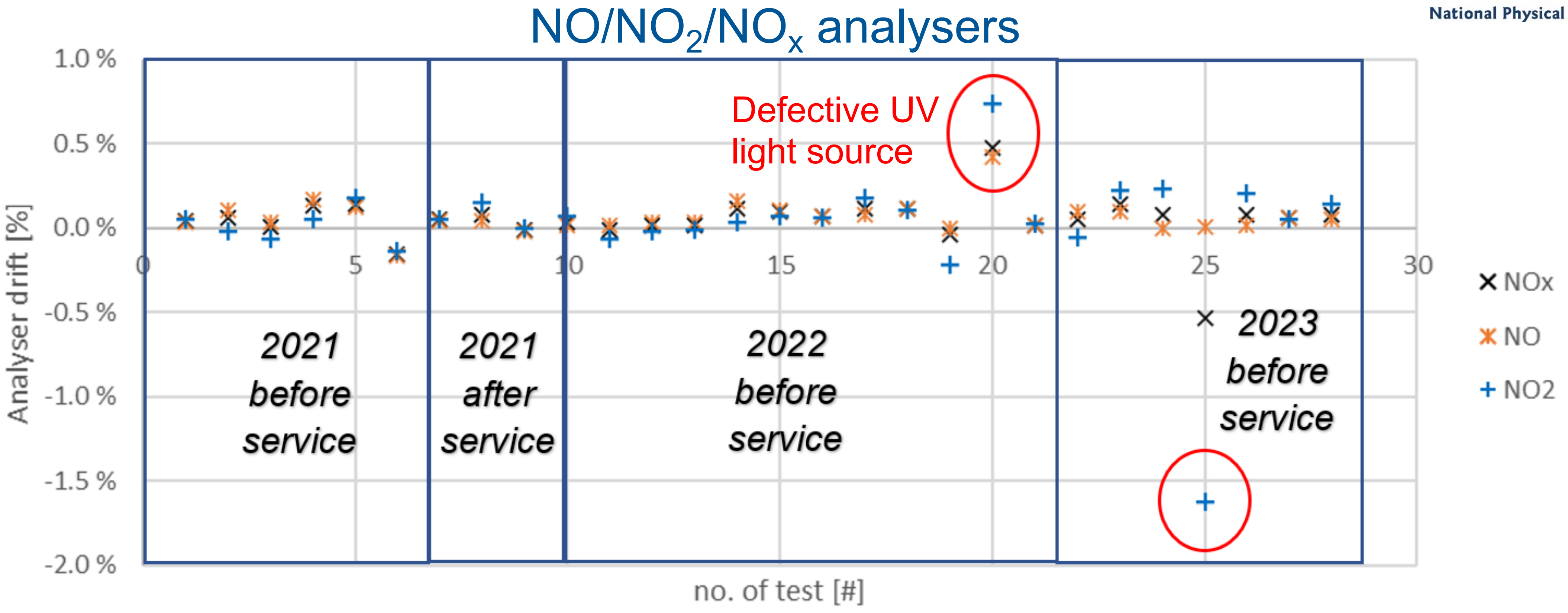
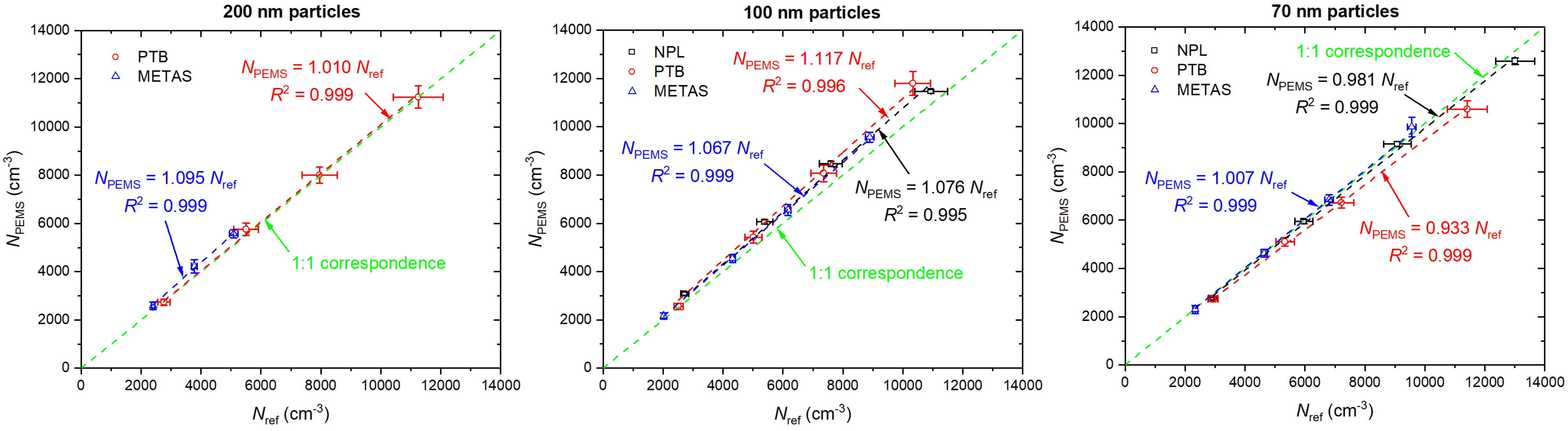
Pre- and Post-RDE Drift



- The ND-UV analyser for NO performed well within the requirements of current regulation (within a ±0.2 % margin), regardless of the PEMS status (aged or serviced).
- The ND-UV analyser for NO_2 failed 5 tests acc. to Euro 6e (< 3 ppm) and 1 test acc. to RDE4 regulation (> 5 ppm).

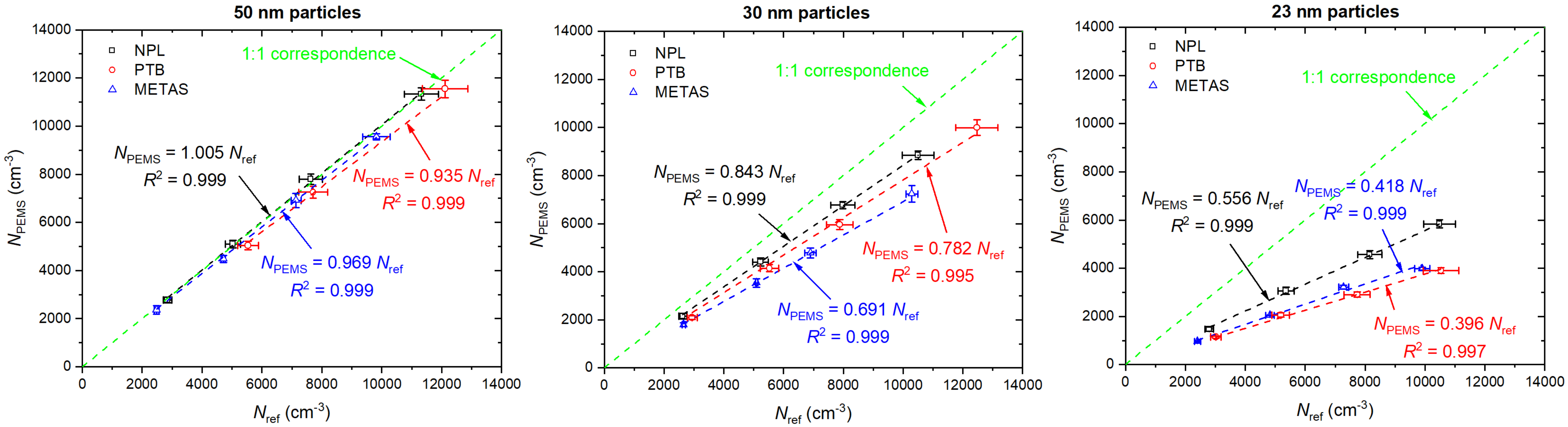
Linearity of PN-PEMS (monodisperse particles)

Monodisperse 200 nm, 100 nm, and 70 nm soot particles with nominal concentrations of 2 500, 5 000, 7 500, and 10 000 cm^{-3}



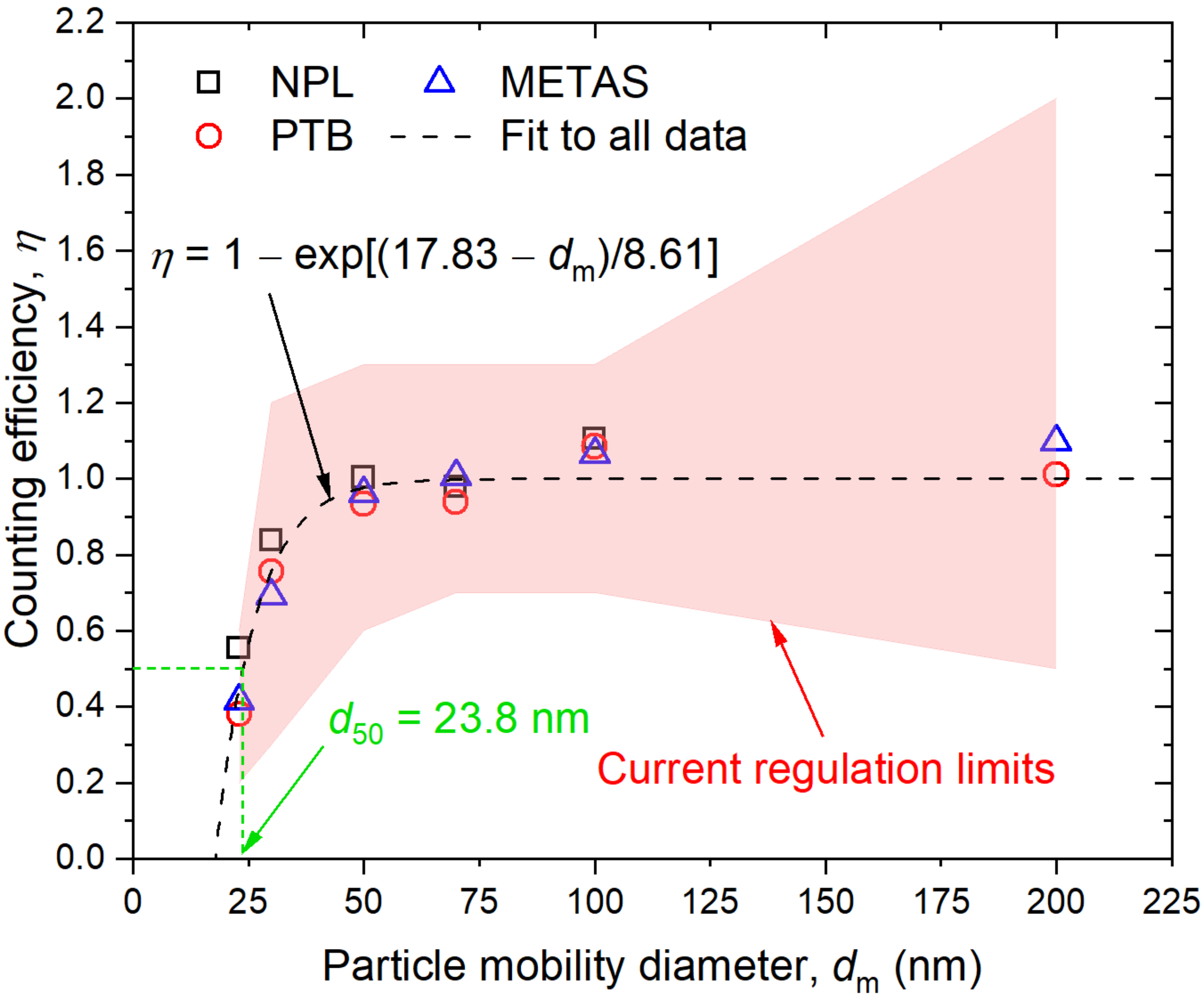
Linearity of PN-PEMS (monodisperse particles)

Monodisperse 50 nm, 30 nm, and 23 nm soot particles with nominal concentrations of 2 500, 5 000, 7 500, and 10 000 cm^{-3}



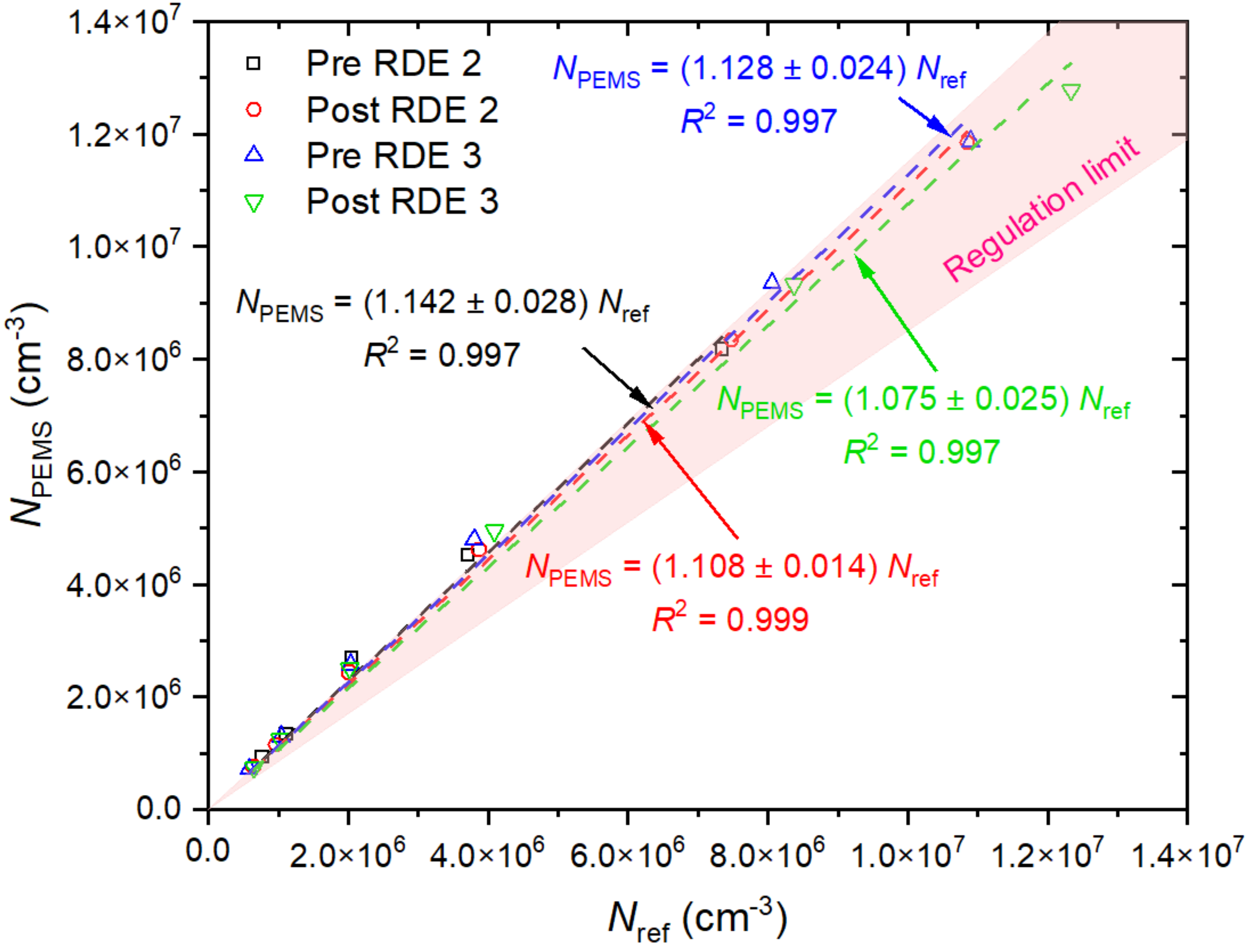
- Fairly good agreement (up to ±8%) between NMIs for particles > 50 nm.
- The smaller the particles, the larger the spread between NMIs results.

Counting efficiency (monodisperse particles)



- Average of counting efficiency at concentrations of 2 500, 5 000, 7 500, 10 000 cm^{-3} using monodisperse particles.
- Cut-off size agrees very well with regulation requirement.
- For CPC-based PEMS technologies, the current regulation limit for counting efficiency is an overkill. But necessary for diffusion charging PEMS.

Linearity results with polydisperse particles



- Polydisperse particles with GMD = 70 nm and GSD ~1.7, with concentrations up to 12×10^6 cm^{-3}
- Aerosol diluter was characterized using two CPCs simultaneously.
- The regression slopes are within regulation limit, but some data points are not.
- Slight drift in PEMS response (due to aging/usage?) can be seen.