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Research of Emissions with Gas PEMS and PN PEMS

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Abstract

Measuring and controlling of real driving emissions (RDE) of passenger cars with PEMS (portable emission measuring systems) is an actual requirement.

In different projects the Laboratory for Exhaust Emissions Control (AFHB) of the Berne University of Applied Sciences (BFH) performed comparisons on passenger cars with different PEMS's on chassis dynamometer and on road, considering the quality and the correlations of results. A system measuring the particle number (PN PEMS) was also included in the investigations.

This paper presents: the experiences with PN PEMS, the comparisons of Horiba OBS1 with SEMTECH, the correlations of Pitot flowmeter on engine dynamometer and influences of slope on chassis dynamometer.

The most important statements are:

PN PEMS, which is based on DC-classifier (DiSC) indicates higher PN-values, than the stationary CPC, but these results can be validated and adapted by means of WLTC on chassis dynamometer.

The investigated GasPEMS indicate higher values of CO_2, than the stationary installations.

The flowmeters show the biggest dispersion of results in the lowest flow-range, which is typical for idling.

Varying slope has clear influences on emissions and must be considered in the measuring procedures.

The presented works brought further insight in improving the procedures and the quality of results.

Introduction

Measurement of Real Driving Emissions (RDE) becomes since this year (2017) an element of legal homologation procedure for passenger cars WLTP (Worldwide Harmonized Light-Duty Vehicles Test Procedure), [1, 2, 3]. This new procedure will enforce for new cars (introduced to the market since this year), that there will be no discrepancy between the emissions and fuel consumption values obtained in the homologation tests and in real application, [4, 5].

Unlike previous vehicle emission tests, parameters such as engine load and vehicle speed are no longer defined by a fixed pattern, but are largely determined by the traffic situation, driver behaviour and the course of the route during the RDE test. [6, 7, 8].

There is a change of paradigma for all market players:

First of all, the manufacturers have to adapt their R&D processes to meet with the calibration of engines and of exhaust systems the extreme multitude of operating conditions which may occur. There are efforts and possibilities to use dynamic engine- or chassis test benches, equipped with specific software, to fulfil the requirements of new development tasks, [6, 9, 10, 11].

An important requirement is the continuous improvement and development of measuring technics, both: for laboratory and for on-road testing, [12]. Since 2015, the portable particle number measuring systems (PN PEMS) have been tested and introduced in the activities of development and legislation, [13].

The official testing laboratories and organisations perform intense research activities in order to increase the knowledge, the experience and to adapt the testing capacities to the new requirements, [4, 5, 7, 8, 14].

The RDE legislation is divided into four packages:

The first package of RDE legislation requires an on-the-road test of up to 2 h, including urban, rural and motorway journeys with clearly specified conditions, which will allow effective evaluation of the emissions produced. The second package of the legislation determines the NO_X emission limits using a conformity factor (CF). The third RDE package extends this conformity factor to the particle number (PN) emissions limit and outlines the relevant requirements for measuring technology (PN-PEMS). The legislation package as a whole also covers cold starts, particulate filter regeneration and validation of hybrid vehicles. The fourth and final RDE package defines in-service conformity testing as well as surveillance tests carried out by third parties.

The independent surveillance test procedures, called New Periodical Technical Inspection (NPTI) are actually a subject of research and discussions, [15, 16]. These procedures have to be adapted to the actually used exhaust aftertreatment and OBD technologies.

In this interesting dynamic situation of progress AFHB performs several test & research projects, or working packages. Some of the recent results are presented in this paper.

Test installations

Chassis dynamometer

Parts of the tests were performed on the 4WD-chassis dynamometer of AFHB (Laboratory for Exhaust Emission Control of the Bern University of Applied Sciences, Biel, CH).

The stationary system for regulated exhaust gas emissions is considered as reference.

This equipment fulfils the requirements of the Swiss and European exhaust gas legislation.

- regulated gaseous components:
  exhaust gas measuring system Horiba MEXA-7200
  CO, CO_2… infrared analysers (IR)
  HC_{FID}... flame ionization detector for total hydrocarbons
  CH_{4FID}... flame ionization detector with catalyst for only CH4
  NO/NO_x...chemiluminescence analyzer (CLA)

The dilution ratio DF in the CVS-dilution tunnel is variable and can be controlled by means of the CO_2-analysis.

The measurements of summary particle counts in the size range 23-1000nm were performed with the CPC TSI 3790 (according to PMP).

For the exhaust gas sampling and conditioning a ViPR system (ViPR...volatile particle remover) from Matter Aerosol was used. This system contains:

- Primary dilution - MD19 tunable rotating disk diluter (Matter Eng. MD19-2E)
- Secondary dilution – dilution of the primary diluted and thermally conditioned sample gas on the outlet of evaporative tube.
- Thermoconditioner (TC) - sample heating at 300°C.

The overview of used PEMS is given in Table 1.

Table 1. Overview of used measuring systems.

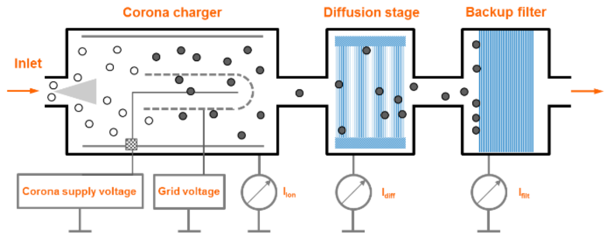
GAS PEMS

	HORIBA MEXA 7200	HORIBA OBS ONE	SEMTECH
	4x4 chassis dyno CVS	PEMS① wet	PEMS② dry
CO	NDIR	heated NDIR	NDIR
CO_2	NDIR	heated NDIR	NDIR
NO_x	CLD	CLD	calculated
NO	CLD	CLD	NDUV
NO_2	calculated	calculated	NDUV
O_2	-	-	
HC	FID	-	electrochemical
PN	not measured	-	-
OBD logger	-	yes	yes
GPS logger	-	yes	yes
ambient (p, T, H)	yes	yes	yes
EFM	-	pitot tube	pitot tube (SEMTECH-EFM)

OBS - one H_2O monitored to compensate the H_2O interference on CO and CO_2 sample cell heated to 60°C

PN PEMS

As PN PEMS for Real Driving Emissions the NanoMet3-PS from Matter Aerosol-TESTO (NM3) was used. The exhaust gas conditioning, as described above for chassis dynamometer, is integrated in this analyzer and it indicates the solid particle number concentration and geometric mean diameter in the size range 10-700 nm. TESTO NanoMet3 presents several advantages like compactness, robustness, fast on-line response and it has been considered in the preparatory activities of on-coming RDE type approval in EU as a “Golden Instrument” (see [1]). This instrument works on the diffusion charging classifier principle (DiSC), which is represented in Fig. 1.

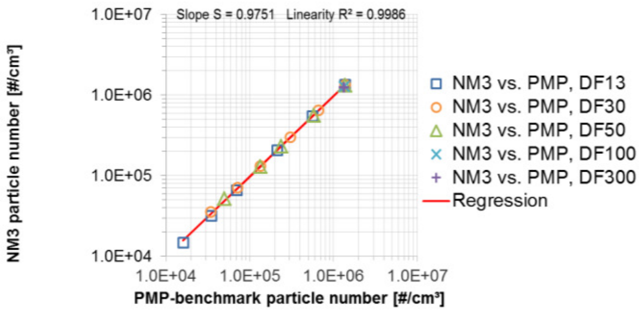


[Source: Testo]

Figure 1. Setup of the particle sensor DiSC

Operating principle of DiSC:

- Particles are labeled with positive charges in a unipolar charger, so that they can later be detected by the current they induce.
- Particles are deposited by diffusion in a "diffusion stage" and detected as an electrical current $D = I_{diff}$; Diffusion stage penetration is size-selective.
- Remaining particles end up in a filter stage and also produce an electrical current $F = I_{filt}$.
- DiSC Sensor measures both currents D and F simultaneously, with 1s time resolution.
- Measured ratio $D/F = I_{diff} / I_{filt}$ → particle diameter.
- Charge per particle is a function of particle diameter → once the particle diameter is known, DiSC computes the particle number from the total current $I_{diff} + I_{filt}$ and the flow rate.
- Diffusion charger DC signal correlates well with lung-deposited (alveolar or tracheobronchial) surface area.



[Source: Testo, PMP]

Figure 2. Correlation NanoMet 3 vs. PMP (GDM 70 nm; CAST soot generator)

The correlation of readings with a PMP-benchmark is very good. Example of a correlation at geometric mean diameter (70nm) is given in Fig. 2.

Engine test bench

The test engine used for comparisons of the flowmeters was an Iveco F1C engine with following data:

Manufacturer:	Iveco, Torino Italy
Type:	F1C Euro 3 / Euro 4
Displacement:	3.00 Liters
RPM:	max. 4200 rpm
Rated power:	100 kW @ 3500 rpm
Model:	4 cylinder in-line
Combustion process:	direct injection
Injection system	Bosch Common Rail 1600 bar
Supercharging:	Turbocharger with intercooling
Emission control:	none
Development period:	until 2000 (Euro 3/Euro 4)

The test bench is equipped with:

- Dynamic test dynamometer Kristl & Seibt
- Tornado Software Kristl & Seibt
- Fuel flow measurement AIC 2022
- Air mass meter ABB Sensiflow P
- Pressure transducers Keller KAA-2/8235, PD-4/8236
- Thermo-couples Type K.

There is also extensive equipment for measurement of legislated and non-legislated exhaust emission components, which was not used and will not be more specified for this part of work. Since this engine test stand is accredited according to ISO 17025, the used flowmeters, as well as all used measuring chains are subject of a continuous calibration and quality control.

Test Procedures

Driving cycles on chassis dynamometer

The vehicles were tested on a chassis dynamometer in the dynamic driving cycles:
WLTC, Fig. 3, NEDC Fig. 4 and CADC, Fig. 5.
The first WLTC of each test series was performed with cold start (20-25°C) and further cycles followed with warm engine. Between the cycles, always 3 minutes of constant speed of 80 km/h, in 4th gear, were performed as conditioning.

The braking resistances were set according to legal prescriptions; they were not increased i.e. responded to the horizontal road.

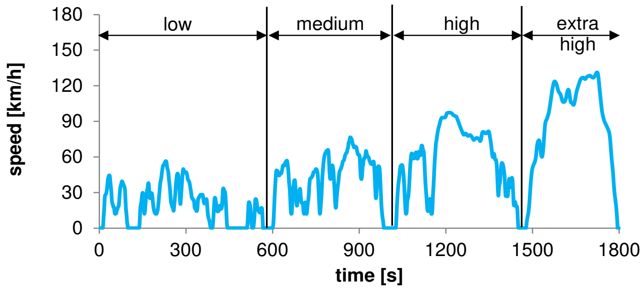


Figure 3. WLTC driving cycle

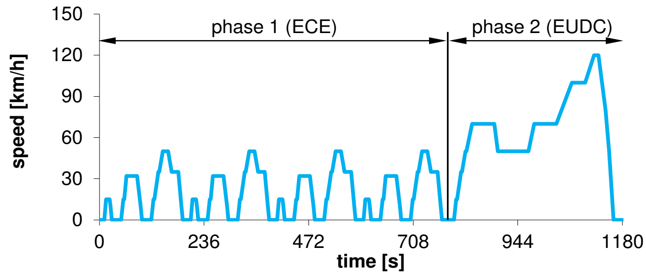


Figure 4. NEDC European driving cycle

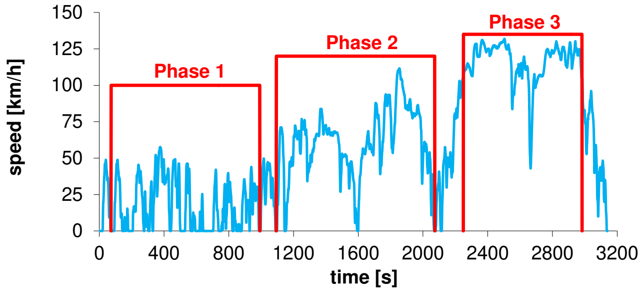


Figure 5. CADC driving cycle

On road testing

In order to reach the validity according to the actual requirements several road tests were performed. Finally, the used valid road circuit was always the same with approximately 1.5h duration and parts of urban, rural and highway roads. Fig. 6 represents an example of a road trip from the PN PEMS test program.

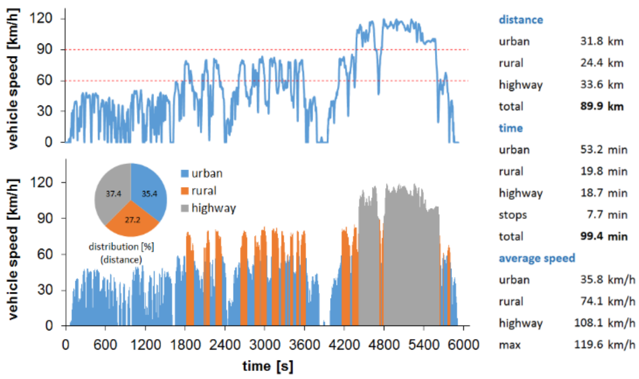


Figure 6. AFHB, road trip for RDE; vehicle 1, PEMS 2 & PN PEMS

Engine testing

The correlation tests of gas flow measuring devices were performed at 35 steady state operating points (OP) of the engine.

Tested cars

Fig. 7 shows the tested vehicles and the data of them are represented in the Table 2. Each vehicle was used for different working task:

- Vehicle 1 was a “golden vehicle” (GDI) of the inter-laboratory comparison tests with JRC,
- vehicle 2 (Diesel) was used for a comparisons of PN PEMS- and CPC-results,
- vehicle 3, GDI flex fuel vehicle (FFV) was used for correlations of PEMS with E10,
- vehicle 4 (Diesel) served for demonstration of impact of slope on the chassis dynamometer.

All vehicles were operated with the Swiss market fuels and with the lubricating oil, which was actually present in each vehicle.

Results and discussions

RDE & PN PEMS

Including the particle number (PN) measuring device in the portable emission measuring systems (PEMS) is an important objective of the EU legislation.

Table 2. Data of tested vehicles

Vehicle	① **VW Golf TSI 1.2l gasoline**	② **Opel Astra 16V Diesel**	③ **Audi A4 2.0 TFSI FFV gasoline**	④ **Mercedes VITO Diesel**
Number and arrangement of cylinder	4 in line	R 4	4 in line	4 in line
Displacement cm^3	1197	1994	1984	2143
Power kW	63 @ 4800rpm	60@ 4300 rpm	132@ 4000rpm	100 @ 3800rpm
Torque Nm	160 @ 1500-3500rpm	185@ 1800-2500rpm	320@ 1500rpm	310 @ 1400-2400rpm
Injection type	gasoline direct injection	Distributor pump / DI	Direct Injection (DI)	Direct Injection (DI)
Curb weight kg	1129	1390	1570	2180
Gross vehicle weight kg	1229	1845	2065	3050
Drive wheel	2WD	2WD	2WD	Rear-wheel drive
Gearbox	m5	m5	m6	AT 5
First registration	10.03.15	1998	2010	16.11.10
Exhaust	Euro 5	Euro 2	Euro 5	Euro 5a

Vehicle ① VW Golf TSI 1.2l

Vehicle ② Opel Astra 16V in the laboratory

Vehicle ③ Audi A4

Vehicle ④ Mercedes VITO

Figure 7. The tested cars

The Swiss developments at ETHZ, FHNW and Matter Aerosol, which were supported by the Swiss Federal Office of Environment (BAFU) gave a strong contribution to the progress of portable PN-measurements.

2015/2016 inter-laboratory comparison test series (ILCE … Inter-Laboratory-Comparison-Exercise) with PN-PEMS were organized and performed by the VELA (Vehicle Emissions Laboratory) of the EC-JRC, Ispra. For the tests a “golden vehicle” with a “golden PN-analyzer” (TESTO NanoMet3) have been circulated among different laboratories.

The comparison test series were also performed in Switzerland in the frame of collaboration between EC-JRC and BAFU.

A modern GDI car (vehicle 1) equipped with PEMS SEMTECH, both “golden” systems (Gas & PN) from the ILCE, were tested in standard test cycles (NEDC and WLTC) on the chassis dynamometer and on-road (RDE).

For the real-world testing a road circuit was fixed: approximately 1.5h driving time with urban/rural and highway sections. This circuit fulfils the actual RDE-requirements. A portable system for measurements of nanoparticles (TESTO NanoMet3) was included in the tests and the results were compared with CPC (PMP) on the chassis dynamometer.

Fig. 8 compares the emission results obtained on chassis dynamometer and in the road circuit with PEMS.

The average emission values, which are found with PEMS in on-road (warm) operation (RDE) are well responding to the average values in WLTC warm (measured with PEMS), which confirms that WLTC represents well the real driving behaviour.

The emissions measured with PEMS in repeated road driving circuit are generally well repetitive. Exceptions can happen due to extreme driving behaviour, special traffic situations or activities of vehicle electronic control (here especially NO_x).

Fig. 9 shows the comparisons of results obtained in WLTC warm in the present tests with the min/max/average values obtained during the JRC-ILCE.
Regarding the results from stationary installation (CVS) – CO_2 (not represented here) and PN on the lowest side of the ILCE-dispersion range – it is assumed that the driving resistances of the chassis dyno were too low.
Regarding the PEMS-results; nevertheless, this sup-position does not seem to be right. The average values of NO_x and PN measured with PEMS in WLTC warm correlate very well with the average PEMS-values from ILCE.

Analysis of data from two RDE trips was performed by means of the JRC EMROAD program using the verification method of trip dynamics with moving averaging windows (MAW), [1,13].

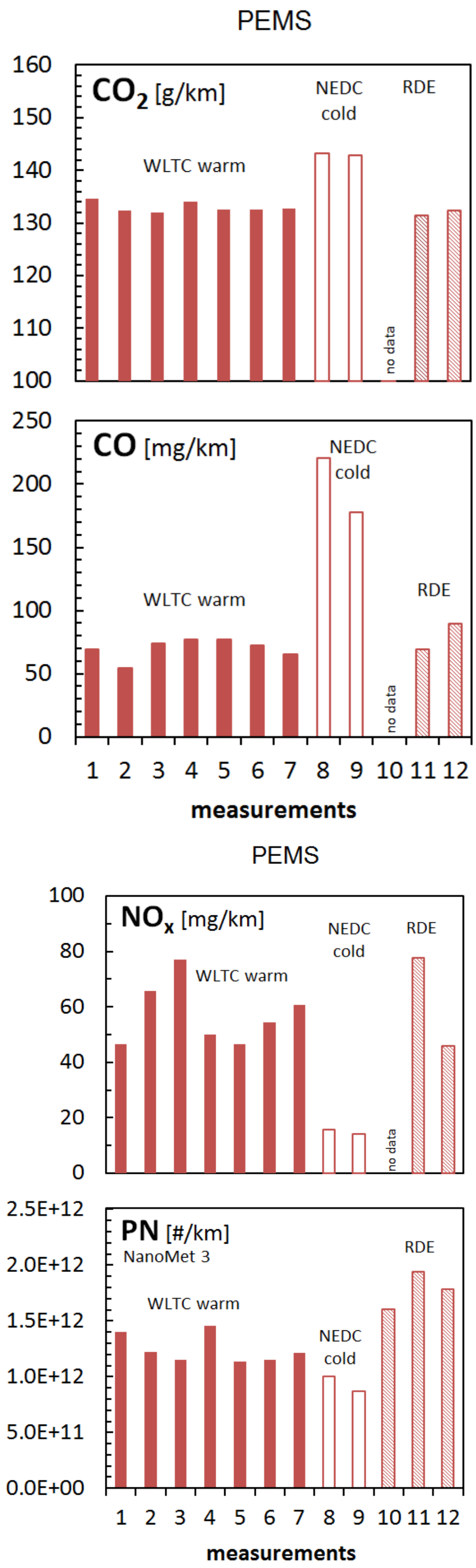


Figure 8. Comparison of emissions in WLTC- NEDC on chassis dynamometer and RDE on road measurements, vehicle 1, PEMS 2

Some explanations from [1] are:

The Moving Averaging Window method provides an insight on the real-driving emissions (RDE) occurring during the test at a given scale of speed. The test is divided in sub-sections (windows) and the subsequent statistical treatment aims at identifying which windows are suitable to assess the vehicle RDE performance.

The “normality” of the windows is concluded by comparing their CO_2 distance-specific emissions with a reference curve. The test is complete when the test includes a sufficient number of normal windows, covering different speed areas (urban, rural, motorway).

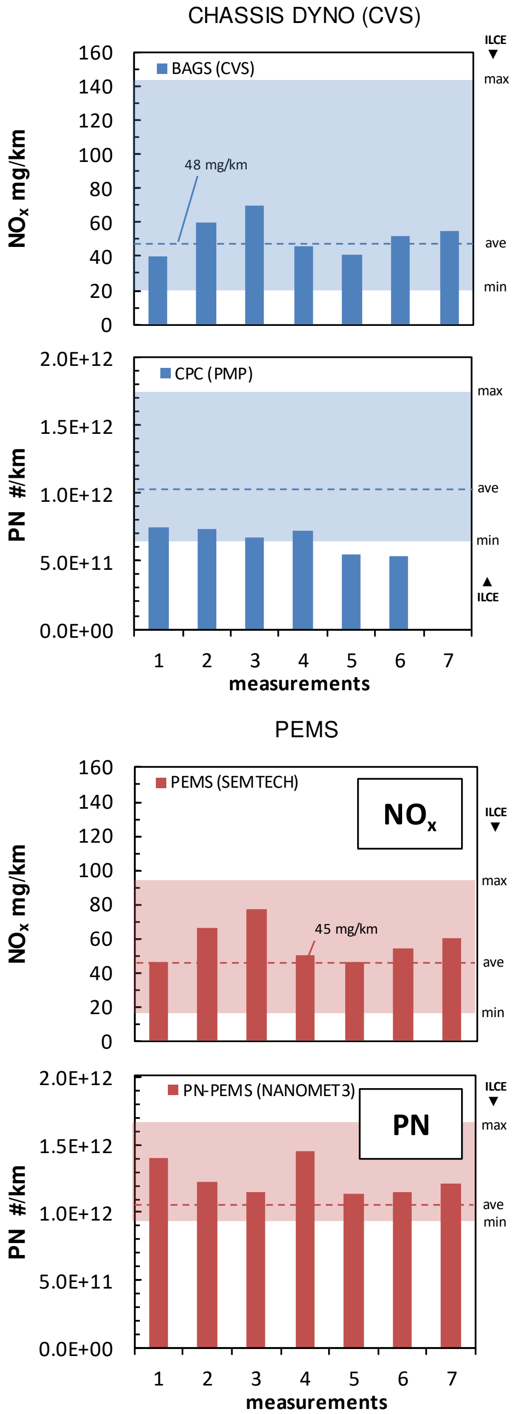


Figure 9. Comparison of Emissions in WLTC warm Chassis Dynamometer, vehicle 1, PEMS 2

During the evaluation the following steps are performed:

Step 1 Segmentation of the data and exclusion of cold start emissions.

Step 2 Calculation of emissions by sub-sets or “windows”.

Step 3 Identification of normal windows.

Step 4 Verification of test completeness and normality.

Step 5 Calculation of emissions using the normal windows and weighted windows.

The following data are not considered for the calculation of the CO_2 mass, the emissions and the distance of the averaging windows:

- the periodic verification of the instruments and/or after the zero drift verifications
- the cold start emissions
- vehicle ground speed < 1 km/h
- any sections of the test during which the combustion engine is switched off.

The reference dynamic conditions of the test vehicle are set out from the vehicle CO_2 emissions versus average speed measured at type approval and referred to as “vehicle CO_2 characteristic curve”.

In Fig. 10 such CO_2 characteristic curves are represented for one of the evaluated trips. The trip and its dynamic conditions are normal, since the characteristic curves are in the primary tolerance of +/- 25% (of the average WLTC-CO_2-values).

The emissions resulting from EMROAD-evaluation are generally considerably lower, than the values of integral averages (without any exclusion). The differences are caused mainly by excluding the cold start emissions from the EMROAD-evaluation, Fig. 11.

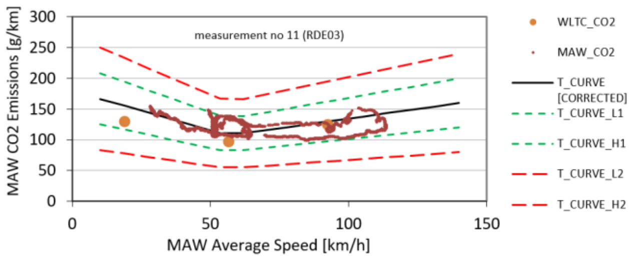


Figure 10. JRC / EMROAD test, normality verification (CO_2 vs speed, MAW… moving average windows)

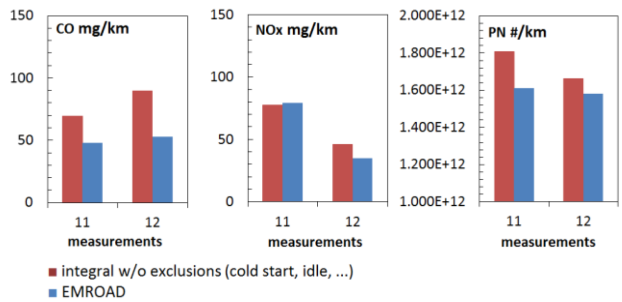


Figure 11. Comparison of results in RDE EMROAD vs integral calculation (SEMTECH & NanoMet 3)

Comparison NM3 – CPC

The PN-results obtained with NanoMet3 (NM3) were compared with the PN-results of a CPC on vehicle 2.

Fig. 12 illustrates an example of correlation of results obtained with CPC (according to PMP) and with NM3 in NEDC. A very good correlation of both measuring systems is demonstrated. The ability of NM3 to show higher peaks during the transients and also higher average values in the driving cycles is to explain with the fact, that NM3 is more sensitive in the lowest size range below 23nm, while CPC has a cut-off below 23nm.

Similar relationships of results NM3/CPC were confirmed with other vehicles (also GDI) at different operating conditions.

Fig 13 shows on-line PN-courses with NM3 and CPC obtained at tailpipe (TP) and at the end of the CVS-tunnel during a constant operation of 80 km/h. The non-corrected values on the left side of the figure indicate that the diffusion losses between TP and CVS are higher for the CPC-measured aerosol. Consequently, there are higher PN-values measured with NM3 in CVS.

It is possible to find a constant correction factor for NM3, which evens out the differences of both results. This factor, see on the right side of this figure is different for TP and for CVS.

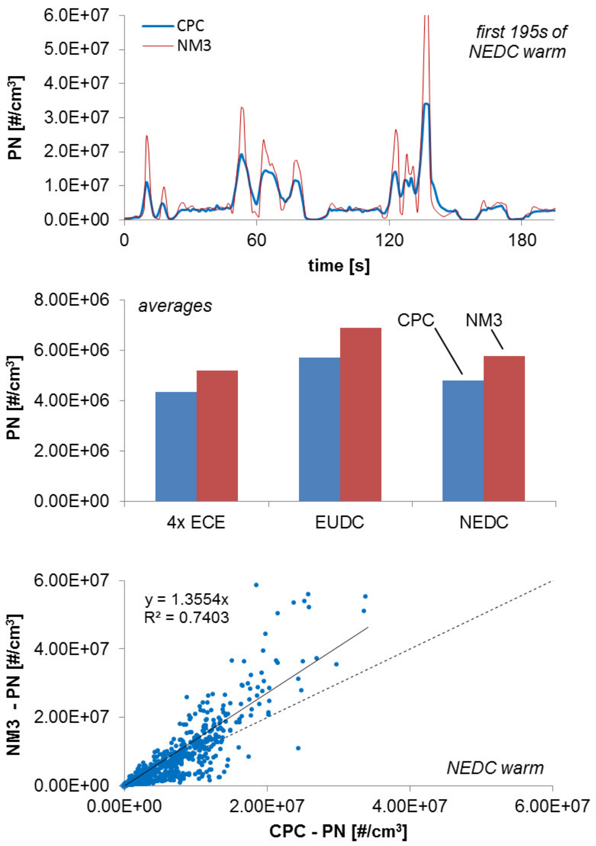


Figure 12. Particle counts concentrations measured simultaneously at tailpipe with NanoMet 3 (NM3) and with CPC.

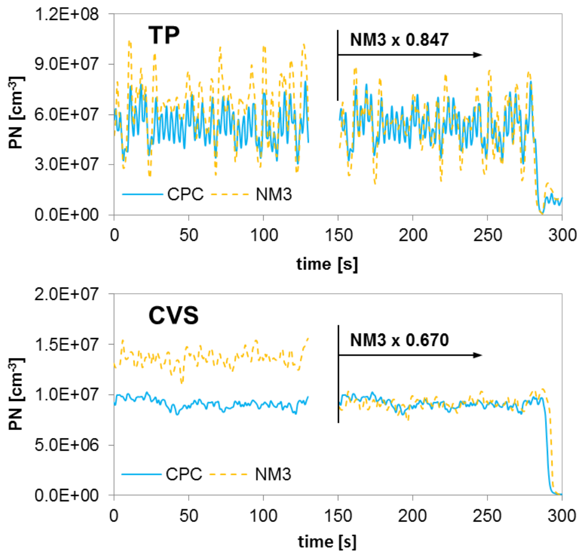


Figure 13. PN at tailpipe (TP) and in CVS tunnel by constant speed 80 km/h.

Similar exercise was performed for the transient operation (WLTC) and similar factors were found. They are: 0.662 for CVS and 0.885 for TP. Fig. 14 illustrates the effects of corrections in different phases of the WLTC.

As a lesson learned from these considerations, it can be said that it is possible to verify the PN PEMS results with CPC (PMP) on chassis dynamometer by repeating some $WLTC_{warm}$ cycles, which were previously remarked to be also an excellent tool to corroborate the Gas PEMS, [8].

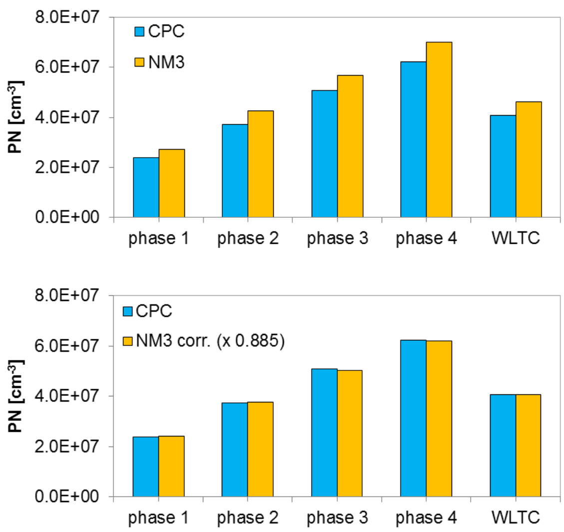


Figure 14. PN at tailpipe (TP) in WLTC.

Correlation of PEMS

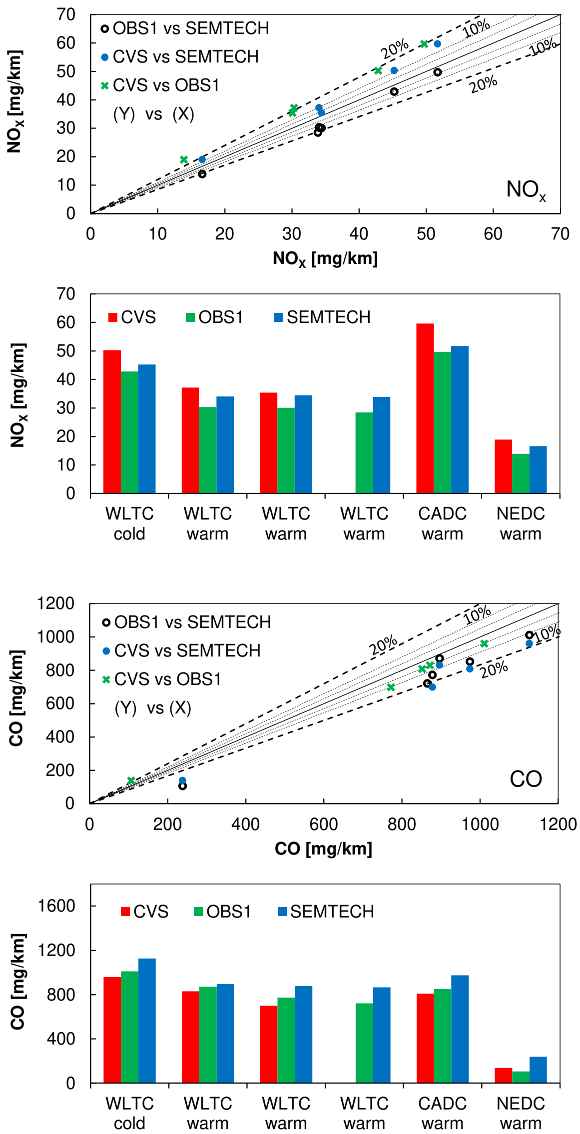
In this part of work comparison tests with two PEMS's – Horiba OBS1 and SEMTECH – were performed on chassis dynamometer in different driving cycles with vehicle 3. The results were correlated with the stationary installation with bag-sampling (called here as "CVS").

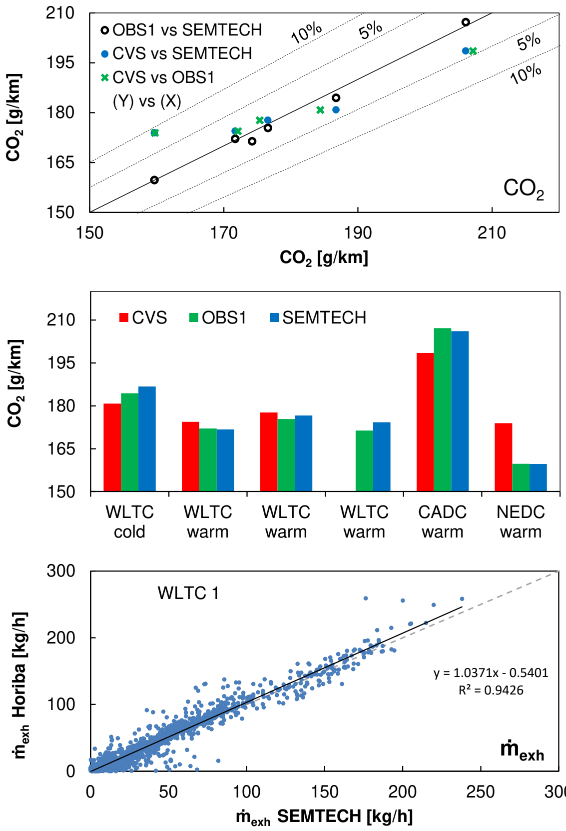
Fig. 15 shows correlations of NO_x, CO & CO_2 with the three systems measuring simultaneously in different driving cycles – $WLTC_{cold}$, 3x $WLTC_{warm}$, $CADC_w$ and $NEDC_w$.

The visible tendencies are:

- both PEMS indicate slightly lower NO_x-values and higher CO-values, than CVS; for CO_2 there is no uniform trend,
- comparing the PEMS's between each other mostly higher readings result with SEMTECH, than with Horiba,
- for NO_x & CO most correlation values are in the dispersion range of 20%, for CO_2 in the range of 10%.

A comparison of exhaust gas mass flows measured with both PEMS's shows an excellent correlation. At the lowest flows there is the biggest dispersion of results.





Exhaust gas	*Horiba OBS1* kg/test	*Semtech* kg/test	*dev.* %
WLTC 1	20.0	19.6	-1.9
WLTC 2	19.9	20.0	0.6
WLTC 3	20.2	20.2	-0.1
CADC	51.2	50.9	-0.6
NEDC	8.6	8.6	0.0

Figure 15. Comparison of emissions & exhaust flow measured with Horiba OBS1 and with SEMTECH in different driving cycles on chassis dynamometer.

Correlations on engine dynamometer

Correlation tests of Horiba OBS1 and engine test bench equipment were performed on the IVECO F1C engine at 35 stationary OP's. A major interest was about the accuracy of different Pitot Tube flowmeters.

Fig. 16 gives an example of correlation of $\dot{m}_{exh}$-results obtained with Pitot flowmeter (PF) and with the stationary installation. At idling, in the lowest range of flow-values there are the strongest deviations of PF-indications. This is a repetitive tendency in all tests. It can be explained with the difficulty to reach a repetiveness of measuring very low pressure increments, which in addition are influenced by the pulsation of flow.

Fig. 17 indicates that also during these comparison tests there were higher readings of some gaseous components (NO_x, NO_2, CO_2) with PEMS than with the stationary instruments.

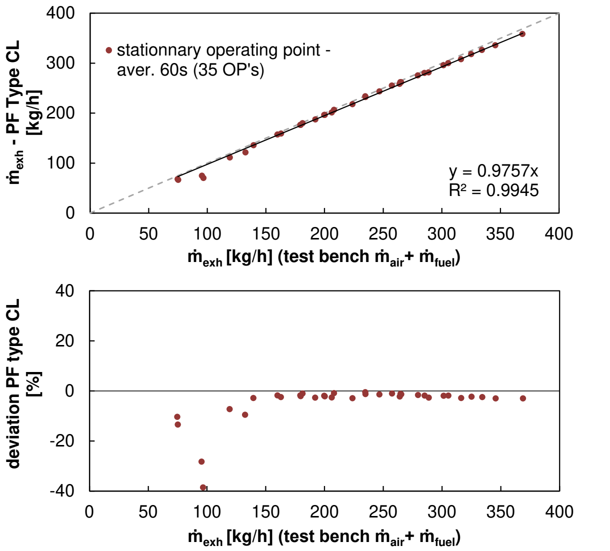


Fig. 16: Correlation of ṁexh – results measured with Pitot Tube Flowmeter (PF) and with engine test bench equipment at 35 OP's. OBS1, IVECO F1C, ulsd

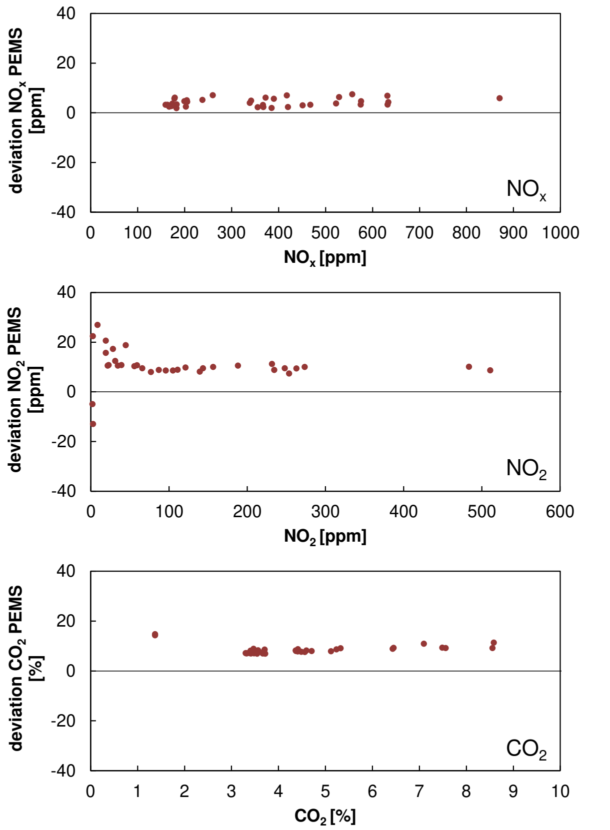
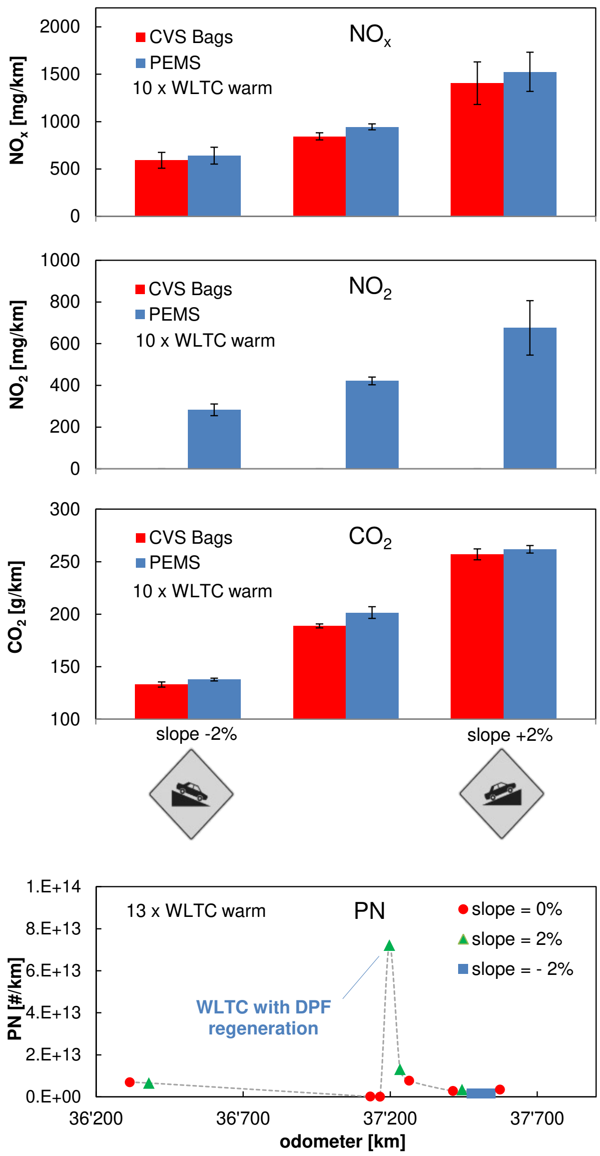


Fig 17: Deviations of gaseous emissions with PEMS and with test bench equipment at 35 OP's. OBS1, IVECO F1C, ulsd

Influences of slope on emissions

The driving resistance of chassis dynamometer was changed in order to simulate the slope +/- 2%. 10 x $WLTC_{warm}$ was performed with vehicle 4 with different slope. The slope nevertheless was kept constant during the cycle.



Chassis dyno, OBS1, MB Vito 113 CD, ulsd

Figure 18. Influence of slope on emissions in WLTC warm

Fig. 18 confirms that the emissions of NO_x, NO_2 and CO_2 principally rise with the increased slope. The most observed tendency that PEMS indicates higher gas-values than CVS is confirmed for NO_x & CO_2. Nanoparticle emissions are principally independent on slope. In one of the cycles the regeneration of DPF took place and this provoked a visible increase of PN in this one cycle.

It can be concluded, that the slope has an important impact on emissions and it should be considered during the reproduction of RDE driving cycles on the chassis dynamometer.

Conclusions

Following conclusions can be mentioned:

- the emissions CO, CO_2, NO_x measured with PEMS are generally higher than the same emissions simultaneously measured in the same driving cycle on the chassis dynamometer with the stationary measuring system (CVS),

- the average values of NO_x and PN measured with PEMS in WLTC warm (chassis dynamometer) correlate very well with the average PEMS-values from ILCE (on road),
- the PN-measuring device – TESTO NanoMet3 – is confirmed as a useful device for PEMS-application,
- the evaluation EMROAD with the moving averaging windows method showed that:
  - the trips were normal from the point of view of CO_2 vs. speed,
  - the driving circuit is valid,
  - the emission results from EMROAD are lower than the results of integration due to neglecting the cold start, near to zero speeds, engine stop periods and devaluation of "unnormal" windows.
- PN PEMS (TESTO NanoMet3) indicates higher peak values during cold start, or dynamic events and it depicts more sensitive the variations of speed of the driving cycle, than CPC (PMP),
- PN PEMS average values at transient operation were higher, than the average values measured with CPC,
- it is possible to verify the PN PEMS results with CPC (PMP) on chassis dynamometer by repeating some $WLTC_{warm}$ cycles,
- the investigated GasPEMS correlate well to each other and they indicate higher CO_2-values, than the stationary installation,
- The flowmeters show the biggest dispersion of results in the lowest flow-range, which is typical for idling,
- Varying slope has clear influences on emissions and must be considered in the measuring procedures.

References

[1] Official Journal of the European Union: Commission regulation (EU) 2016/427 of 10 March 2016, amending regulation (EC) No 692/2008.

[2] COMMISSION REGULATION (EC) no 692/2008 of 18 July 2008 implementing and amending Regulation (EC) No 715/2007 of the European Parliament and of the Council on type-approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair and maintenance information *Available at:* *http://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX:32008R0692*

[3] Darft of the Annex IIIa: *Verifying Real Driving Emissions amending Regulation (EC) No 692/2008 as regards emissions from light passenger and commercial vehicles (Euro 6).*

[4] Hofacker, A. *Abgasnorm und Wirklichkeit Eine Annäherung*. Springer: MTZ-Motortechnische Zeitschrift, January 2015, Vol. 76, Issue **2**, pp 8-13.

[5] Vlachos, T. G., Bonnel, P. und Weiss, M. *Die Bewertung des Abgasverhaltens von Fahrzeugen im realen Fahrbetrieb – Eine Herausforderung für die europäische Emissionsgesetzgebung*. 36. Internationales Wiener Motorensymposium, 2015.

[6] Gerstenberg, J., Schyr, Ch., Sterzing-Oppel, S. and Trenkle, D. *(2017) RDE Engineering via Engine-in-the-loop Test-bench.* MTZ worldwide 78(2017), Nr. **6**, p. 16-23.

[7] Czerwinski, J., Zimmerli, Y., Comte, P. and Bütler, Th. *Experiences and Results with different PEMS*. Laboratory for IC-Engines and Exhaust Emission Control of the University of Applied Sciences, Biel-Bienne. TAP Paper, International Transport and Air Pollution Conference, May 24th-26th, 2016, Lyon, France.

[8] Czerwinski, J., Zimmerli, Y., Comte, P., Cachon, L. and Riccobono, F. *Potentials of the portable emission measuring systems (PN PEMS) to control real driving emissions (RDE).* 38. International Vienna Motor Symposium, 27-28 April 2017, VDI Fortschritt-Bericht Reihe 12, Nr. 802, Vol. 2.

[9] Maschmeyer, H. und Beidl, C. *RDE Homologation – Herausforderungen, Lösungen und Chancen.* MTZ 77 (2016), Nr. **10**, S. 84-91

[10] Zellbeck, H., Walter, R., Stiegler, M. und Roß, T. *RDE – Der reale Fahrbetrieb auf dem hochdynamischen Motorenprüfstand.* MTZ 76 (2015), Nr. **2**, S. 42-47

[11] Röttger, D., Pérez-Guzmàn, E., Vigild, Ch. and De Smet, F. *Feature Function Development for RDE in Diesel Engines.* MTZ 78(2017), Nr. **3**, S. 46-51

[12] Schröder, M., Baltes, N. and Danzer, J. *Impact of RDE Legislation on Test-bed Measurements.* MTZ worldwide 78(2017), Nr. **6**, p. 28-35.

[13] Giechaskiel B., Riccobono, F., Bonnel, P. *Feasibility study on the extension of the Real Driving Emissions (RDE) procedure to Particle Number (PN).* European Commission, Joint Research Centre, ISBN: 978-92-79-51003-8 , ISSN: 1831-9424 , DOI: 10.2790/74218

[14] Anderson, J., May, J., Favre, C., Bosteels, D. et al. *On-Road and Chassis Dynamometer Evaluations of Emissions from Two Euro 6 Diesel Vehicles*. SAE Paper 2014-01-2826. SAE Detroit, April 2014.

[15] Kadijk, G., Elstgeest, M., Ligterink, N.E. and van der Mark, P.J. *Investigation into a Periodic Technical Inspection (PTI) test method to check for presence and proper function of Diesel Particulate Filters in light-duty diesel vehicles.* TNO report TNO(2017)R10530|1.0

[16] Spreen, J.S., Kadijk, G. and van der Mark, P.J. *Diesel Particulate Filters for Light-Duty Vehicles: Operation, Maintenance, Repair, and Inspection.* TNO report TNO(2016)R10958

Abbreviation

AFHB	Abgasprüfstelle FH Biel, CH
ASTRA	Amt für Strassen (CH)
BAFU	Bundesamt für Umwelt, (Swiss EPA)
BC	board computer
CADC	Common Artemis Driving Cycle
CAST	Combustion Aerosol Standard
CD	chassis dynamometer
CLA	chemiluminescence analyser
CLD	chemiluminescence detector
CPC	condensation particle counter
CVS	constant volume sampling
DAQ	data acquisition
DC	diffusion charging
DF	dilution factor
DI	Direct Injection
DiSC	diffusion charge size classifier
EC	European Commission
ECE	Economic Commission Europe
ECU	electronic control unit
EFM	exhaust flowmeter
EMPA	Eidgenössische Material Prüf- und Forschungsanstalt
ETC	European Transient Cycle
ETHZ	Eidgenösische Technische Hochschule Zürich
EUDC	Extra Urban Driving Cycle
FHNW	Fachhochschule Nord West Schweiz
GDI	gasoline direct injection
GMD	geometric mean diameter
HC	unburned hydrocarbons
ILCE	Inter- Laboratory-Comparison-Exercise
JRC	Joint Research Centre (EC)
LFE	laminar flow element
MAW	moving averaging windows
MFS	mass flow sensor
NEDC	New European Driving Cycle (ECE+EUDC)
NM3	NanoMet3
NO	nitrogen monoxide
NO_2	nitrogen dioxide
N_2O	nitrous oxide
NO_x	nitric oxides
OBD	on-board diagnostics
OP	operating point
PCRR	Particulate Counts Reduction Rate
PEMS	portable emission measuring systems
PMP	EC Particle Measuring Program
PN	particle number
PN-PEMS	PEMS with PN measuring device
RDE	real driving emissions
TFZ	Technologie- und Förderzentrum für Nachwachsende Rohstoffe, Straubing, D
TP	tailpipe
TWC	three way catalyst
ViPR	nanoparticle sample preparation with volatile particles remover
WLTC	worldwide harmonized light duty test cycle
WLTP	worldwide harmonized light duty test procedure
3WC	three way catalyst