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Testing emissions of passenger cars in laboratory and on-road (PEMS, RDE)

In the present paper, the results and experiences of testing different PEMS on the chassis dynamometer and on-road are presented. In the first part of work the measuring systems were installed on the same vehicle (Seat Leon 1.4 TSI ST) and the results were compared on the chassis dynamometer in the standard test cycles: NEDC, WLTC and CADC. In the second part of work the nanoparticle emissions of three Diesel cars were measured with PN-PEMS. PN-PEMS showed an excellent correlations with CPC in the tests on chassis dynamometer and it indicated very well the efficiency of DPF in eliminating the nanoparticles in real world driving.

Key words: *PEMS, RDE, HD-vehicles and LD-vehicles*

1. Introduction

PEMS – portable emissions measuring systems were introduced in the last stage of exhaust gas legislation for HD-vehicles in order to measure and to limit the real driving emissions (RDE). PEMS were also confirmed by EU to be applied for the LD-vehicles in the next legal steps.

In the present paper, the results and experiences of testing different PEMS on the chassis dynamometer and on-road are presented.

The investigated PEMS were: Horiba OBS ONE, AVL M.O.V.E and OBM Mark IV (TU Wien). In the first part of work the measuring systems were installed on the same vehicle (Seat Leon 1.4 TSI ST) and the results were compared on the chassis dynamometer in the standard test cycles: NEDC, WLTC and CADC. As reference, the results of the stationary laboratory equipment (CVS and Horiba MEXA 7200) were considered. In the second part of work the nanoparticle emissions of three Diesel cars were measured with PN-PEMS.

For the real-world testing a road circuit was fixed: approximately 1 h driving time with urban/rural and highway sections.

Comparisons of results between the PEMS and with stationary reference system show different tendencies, depending on the considered parameter (NO_x, CO, CO_2) and on the test cycles. In this respect all investigated PEMS show similar behavior and regarding over average of all parameters and tests no special preferences or disadvantages can be declared.

Repeated test on the same road circuit produce dispersing emission results depending on the traffic situation, dynamics of driving and ambient conditions. Also the calculated portions of urban, rural and highway modes are varying according to the traffic conditions.

PN-PEMS showed an excellent correlations with CPC in the tests on chassis dynamometer and it indicated very well the efficiency of DPF in eliminating the nanoparticles in real world driving.

2. Tested vehicles

The comparisons of different PEM's in the first part of work were performed on the test vehicle Seat Leon 1.4 TSI (GDI, TWC) in used state (1½ year, 20'800 km). During the tests approximately 2000 km were driven.

The above mentioned vehicle is presented in Fig. 1 and Tab. 1. The gasoline used was from the Swiss market, RON 95, summer quality, according to SN EN228.
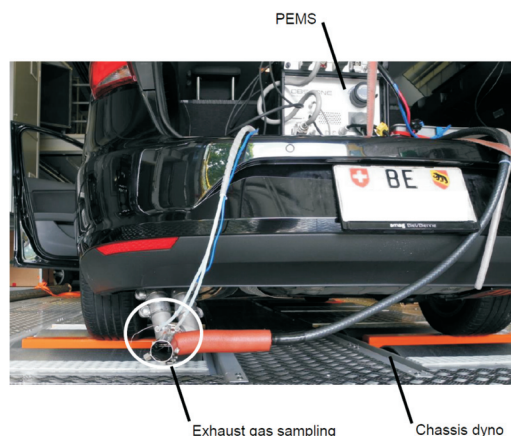

Fig. 1. Test vehicle with installed PEMS on chassis dynamometer

Table 1. Data of tested gasoline (GDI) vehicle

Vehicle	SEAT Leon 1.4 TSI ST
Number and arrangement of cylinder	4 / In line
Displacement cm³	1395
Power kW	103 @ 4500–6000 rpm
Torque Nm	250 @ 1500–3500 rpm
Injection type	Direct Injection (DI)
Curb weight kg	1275
Gross vehicle weight kg	1840
Drive wheel	Front-wheel drive
Gearbox	M 6
First registration	21.01.2014
Exhaust	Euro 5b

In the present tests the lube oil was not changed, or analyzed – the same oil was used for all tests.

The measurements with PN-PEMS in the second part of work were performed on different Diesel passenger cars. The most important data from three vehicles are presented in Table 2.

Table 2. Data of tested Diesel vehicles

	Vehicle 1	Vehicle 2	Vehicle 3
Engine	R4	R4	R4
Displacement cc	1560	2143	1994
Gear box	m6	a5	m5
First registration	2015	2010	1998
Exhaust	Euro 6b	Euro 5a	Euro 2
Aftertreatement	DPF	DPF	–

3. Test equipment

Part 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)

HCFID... flame ionisation detector for total hydrocarbons

CH_4 FID... flame ionisation detector with catalyst for only CH_4

NO/NO_x... chemoluminescence analyser (CLA)

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

4. Nanoparticle analysis

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

For the dilution and sample preparation an ASET system from Matter Aerosol was used (ASET … aerosol sampling and evaporation tube). This system contains:
– Primary dilution air – MD19 tunable minidiluter (Matter Eng. MD19-2E).
– Secondary dilution air – dilution of the primary diluted and thermally conditioned measuring gas on the outlet of evaporative tube.
– Thermoconditioner (TC) – sample heating at 300°C.

As a portable system for on-road application the NanoMet 3-PS from Matter Aerosol-TESTO (NM3) was used. The sample preparation, as described above, is integrated in this analyzer and it indicates the nanoparticles in the size spectrum 10-700 nm.

The overview of used PEMS is given in the Table 3. Let us remark that the OBM Mark IV system does not use any flowmeter for exhaust flow measurement. It calculates the necessary parameters from the on-board data. Thanks to that this apparatus can be much simpler and quicker adapted on the vehicle.

5. Test procedures

Driving cycles on chassis dynamometer

The vehicle was tested on a chassis dynamometer in the dynamic driving cycles: NEDC, Fig. 2, WLTC, Fig. 3 and CADC, Fig. 4.

Table 3. Overview of used measuring systems

	HORIBA MEXA 7100	HORIBA OBS ONE	AVL M.O.V.E	TU Wien OBM Mark IV
	4x4 chassis dyno CVS	PEMS (1) wet	PEMS (2) dry	PEMS (3) dry
CO	NDIR	heated NDIR	NDIR	NDIR
CO2	NDIR	heated NDIR	NDIR	NDIR
NO_x	CLD	CLD	NDUV	Zirkonium-dioxid
NO	CLD	CLD	–	Electrochemical + NDIR
NO_2	calculated	calculated	NDUV	–
O_2	–	–	electro-chemical	electro-chemical
HC	FID	–	IR	IR
PN	not measured	–	–	–
OBD logger	–	yes	yes	yes (Bluetooth dongle)
GPS logger	–	yes	yes (Garmin GPS16)	yes (GPS – Bluetooth receiver)
ambient (p, T, H)	yes	yes	yes	no
EFM	–	pitot tube	pitot tube (SEMTECH-EFM HS)	no

PN	– Particles Number
OBD	– On Board Diagnostics
EFM	– Exhaust Flow Meter

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

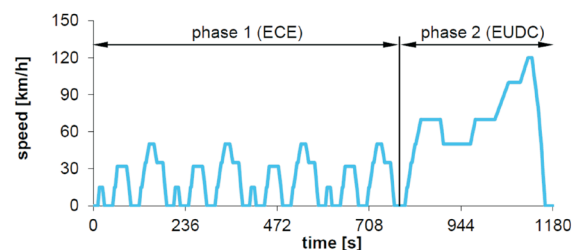AVL Move – dry to wet correction applied

Fig. 2. NEDC European driving cycle

The first NEDC of each test series was performed with cold start (20-25°C) and further cycles followed with warm engine. Between the cycle always 3 minutes of constant speed 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.
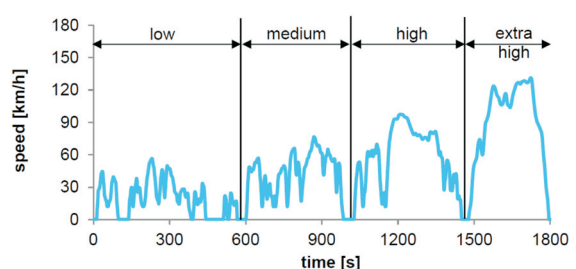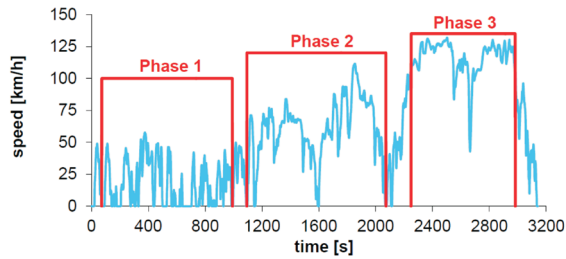

Fig. 3. WLTC driving cycle

Fig. 4. CADC driving cycle

On-road testing

With each PEMS several road tests were performed. The used road circuit was always the same with approximately 1 h duration and parts of urban, rural and highway roads (see Fig. 8).

5. Results

Comparisons of PEMS on chassis dynamometer

The correlations of emissions measured with all three PEMS and with "CVS" in all driving cycles are represented in Fig. 5.

The correlations for NO_x and CO are in an overall view quite good, but there is tendency of too high NO_x-values with PEMS2 and too high CO-values with PEMS1 and PEMS3. For CO_2, which is naturally presented in much higher concentrations, than NO_x & CO, the deviations – too high values obtained with all PEMS – are clearly pronounced.

What can be the reasons of these deviations?

The mass flow $(\dot{m}_x)$ of an emissions component "x" is calculated as:

$$\dot{m}_x = \dot{V}_{exh} \cdot k_x \cdot \rho_x$$

$$\left[\frac{kg_x}{s} = \frac{m^3_{exh}}{s} \cdot \frac{m^3_x}{m^3_{exh}} \cdot \frac{kg_x}{m^3_x} \right]$$

where: $\dot{V}_{exh}$ – volumetric flow of exhaust gas, k_x – volumetric concentration of component "x" in the exhaust gas, ρ_x – density of the component "x"

For dynamic measurements with PEMS in the real-world transient operation there is a challenge to well synchronize the signals of all three parameters, which are continuously changing with the operating conditions. (The instantaneous density varies with the pressure and temperature of exhaust gas).

All PEMS try to perform this synchronization as to the best, but the authors presume that this is the major reason for the indicated differences. Of course the measuring accuracy of the parameters also contributes to the results. In measurements of concentrations there are for the different PEMS's different: measuring principles, wet-dry-corrections and linearization.

In order to exclude the influence of volumetric flow $(\dot{V}_{exh})$ and density (ρ_x) the concentrations of CO_2 were correlated: integral averages measured with PEMS against the bag-concentrations (diluted) recalculated to the non-diluted

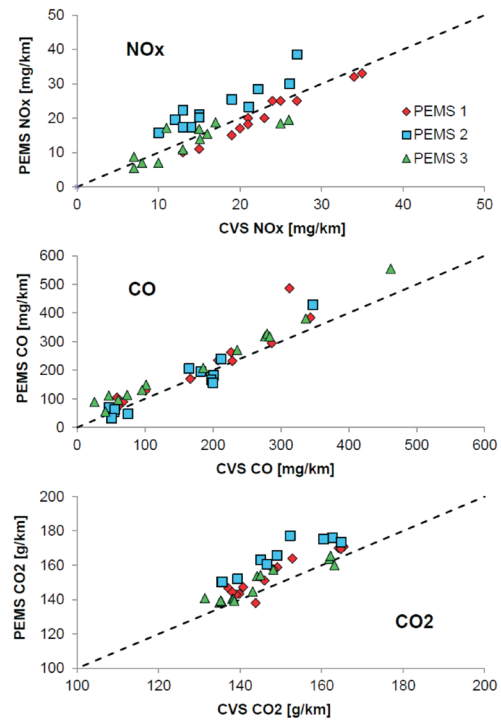concentrations at tailpipe. This is represented at the bottom of Fig. 6 as CO_2 in [%].

Fig. 5. Correlations of emissions measured with PEMS and with stationary CVS-installation in all investigated driving cycles: NEDC cold, NEDC, WLTC, CADC
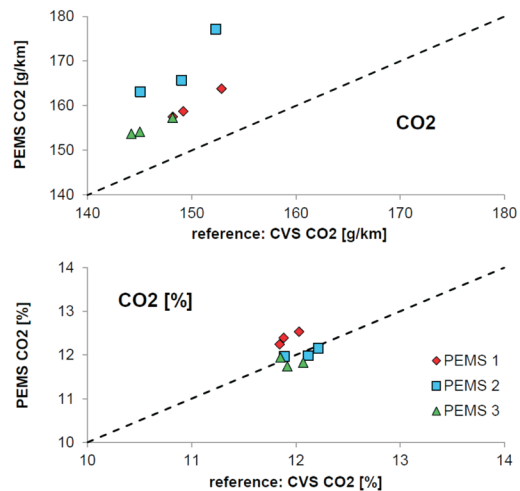

Fig. 6. Correlations of emissions measured with PEMS and with stationary CVS-installation in NEDC cold

The comparison of concentrations indicates much better correlations.

A general comparison of average results: CVS versus all PEMS's is represented in Fig. 7 for NEDCcold only and for all performed driving cycles. The higher readings with PEMS's are confirmed. CO and NO_x have very low concentrations, so they have generally higher standard deviations, than CO_2. For "all cycles" the standard deviations of CO are higher, because of considering the cold start cycle.
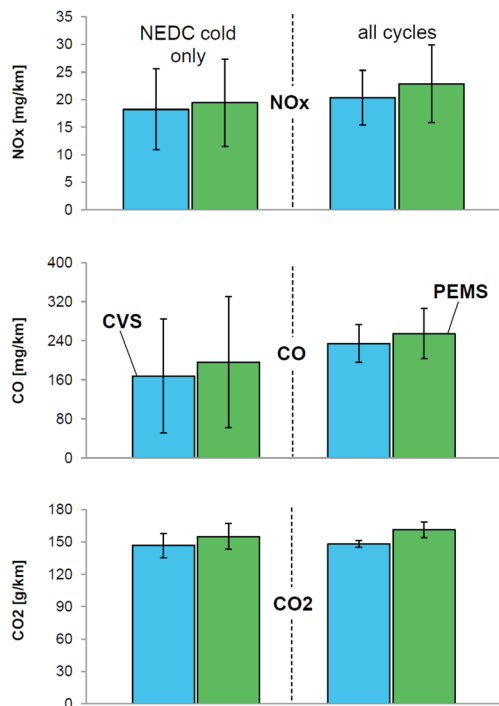
Fig. 7. Comparisons of average results: CVS versus all PEMS's

Each of the tested systems has some little and some big deviations. This conducts us to the statement that in the average view there is no best or worst system. All of them represent a similar balance of advantages and disadvantages and their measuring quality can be regarded as similar. There are of course still big potentials for improvements.

Road tests and comparisons with chassis dynamometer GDI car

The road test route used for the tests is described in Fig. 8.

The time and the average speed in each type of (urban, rural, highway) may vary according to the traffic situation. Testing in peak traffic hours was avoided.

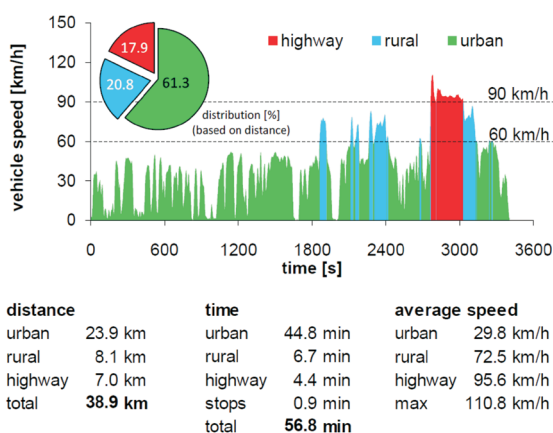| distance		time		average speed	
urban	23.9 km	urban	44.8 min	urban	29.8 km/h
rural	8.1 km	rural	6.7 min	rural	72.5 km/h
highway	7.0 km	highway	4.4 min	highway	95.6 km/h
total	**38.9 km**	stops	0.9 min	max	110.8 km/h
		total	**56.8 min**		

Fig. 8. AFHB Road-Test Route. PEMS 2, Seat Leon 1.4 TSI Euro 5b

The distinction between the driving modes: urban, rural, highway is performed by the evaluating program according

to the RDE requirements (see next section). All cycle parts below 60 km/h are considered as "urban" all intervals with [60 km/h < 90 km/h] are rural and all driving with vehicle speeds v > 90 km/h is highway.

This means, that the distinction is only performed according to the driving speed and not (as usually supposed) according to the type of road.

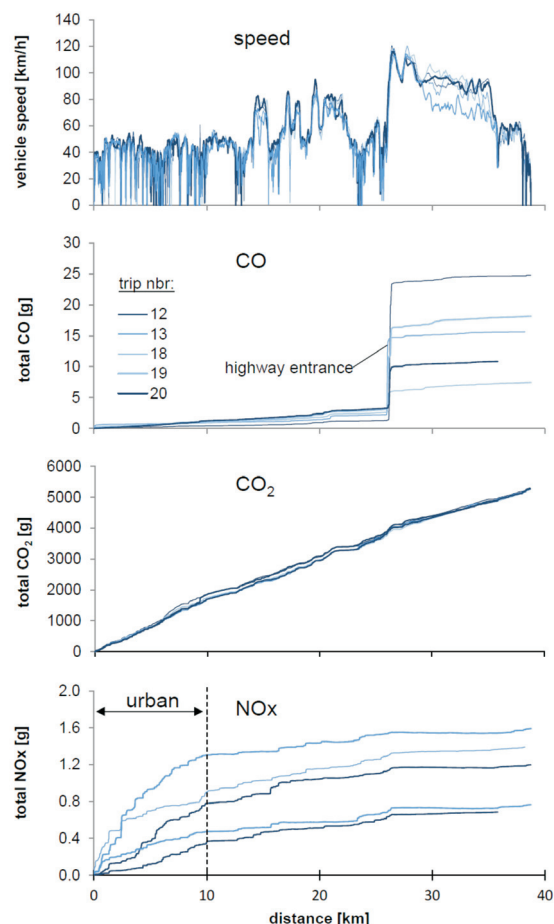Figure 9 shows a comparison of accumulated results from five road trips with PEMS1.

Fig. 9. Comparison of accumulated results from five road trips

From all performed trips can be followed that:
– CO_2 emissions are well repetitive,
– there is a lot of dispersion in the measured NO_x; differences happen mainly during the first 10 km in the urban part of the circuit; the dynamics of driving (traffic) influences strongly the accumulated NO_x,
– a CO peak occurs at the beginning of the highway part; this suddenly increasing CO-amount during entering highway attains different levels depending on acceleration and on the initial state of engine exhaust system; this peak influences massively the accumulated end result,
– The trip composition (operation mode urban, rural, highway) is relatively constant. If there is some congestion or dense traffic on the highway parts, this can influence significantly the share between rural and highway operation.
– CO_2 measurements are repetitive.

– CO results show more dispersion – the level of CO emissions for the whole road trip is below 300 mg/km, a sudden acceleration during the measurement can influence greatly the final results.

– The vehicle has not constant NO_x emissions. This tendency is confirmed by the comparison of the results in different cycles with different instruments.

– CO and NO_x measured levels are relatively low (concentrations not represented here: NO_x average < 50 ppm; CO average < 300 ppm).

– The results from the PEMS3, which has no EFM (Exhaust mass Flow Meter), are similar to the results of other measuring systems.

Figure 10 compares the average values from measurements performed on chassis dynamometer and in the road trips. There is a strong dispersion of CO & NO_x in the road trips. This is especially caused by the quite dynamic driving style in the first part of road tests.

It can be said for CO and NO_x that the WLTC depicts the best the average road driving in this circuit.

CO_2-emissions measured on road are lower, than on chassis dynamometer.

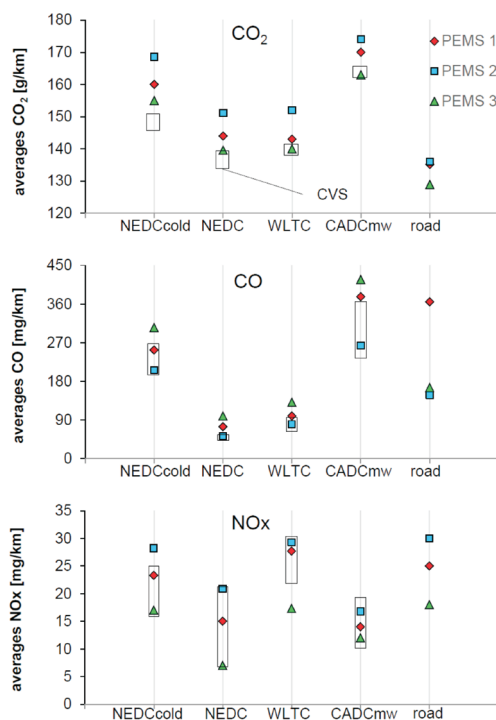

Fig. 10. Comparisons of average values between road trips and cycles on chassis dynamometer. PEMS 1, 2, 3; Seat Leon 1.4 TSI Euro 5b

Testing of Diesel cars with PN-PEMS

For these tests the PEMS (2) completed with NanoMet 3 (NM3) were used. NM3 is working on DC (diffusion charging) principle, it measures transient the particle counts emissions and is used in the EC JRC PN-PEMS Program as a "golden apparatus".

Figure 11 illustrates an example of correlation of results obtained with CPC (according to PMP) and with NM3. A very good correlation of both measuring systems is dem-

onstrated. 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 23 nm.

In Figure 12 emissions of CO, CO_2 and PN of a modern Diesel passenger car, measured in different test cycles on chassis dynamometer (CD) and in road circuit (RDE) are given. The driving cycle of RDE was stored and fed into the driving conductor system of the chassis dynamometer and finally performed on the chassis dynamometer with simultaneous measurements with PEMS (2) and with the stationary system (CVS). This is designated in this figure as RDE-CD.

For CO there are clearly higher values in the "cold" cycle. The repetition of the RDE-cycle on chassis dynamometer results in lower CO-values, which nevertheless was not a repetitive tendency in other repeated tests.
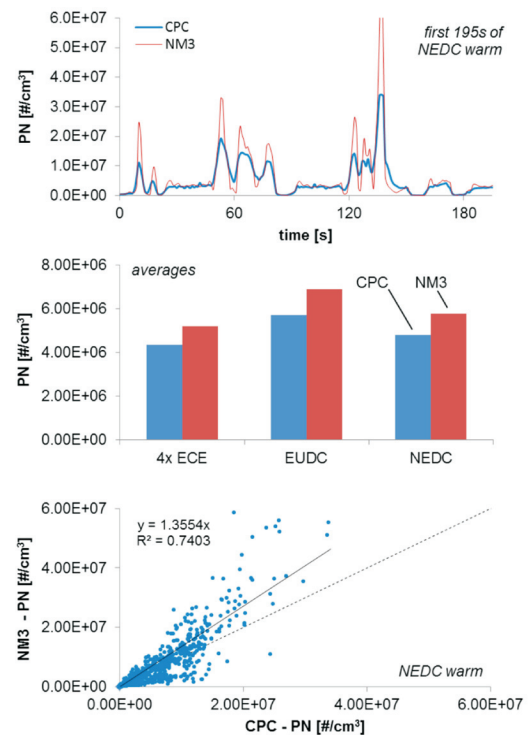

Fig. 11. Particle counts concentrations measured simultaneously at tail-pipe with NanoMet 3 (NM3) and with CPC

For both components CO and CO_2, PEMS indicates clearly higher readings (10% to 20%) than the stationary installation with bags (CVS). This confirms the previous observations (see explanations to Fig. 5&6).

The PN-values of this vehicle with DPF are very low (approximately 30 to 120 times lower than the actual limit value of 6.0×10^{11} #/km), they are at or up to 10 times below the PN background level. This impressively demonstrates the high efficiency of the DPF-technology in eliminating the nanoparticles.

Figure 13 shows in WLTC another example of DPF efficiency: vehicle 1 with a high quality DPF represents the average particle counts reduction rate (PCRR) relatively to

the highest emitting vehicle 3 of 99.998%. The damaged DPF is visible with PCRR = 48.786%.
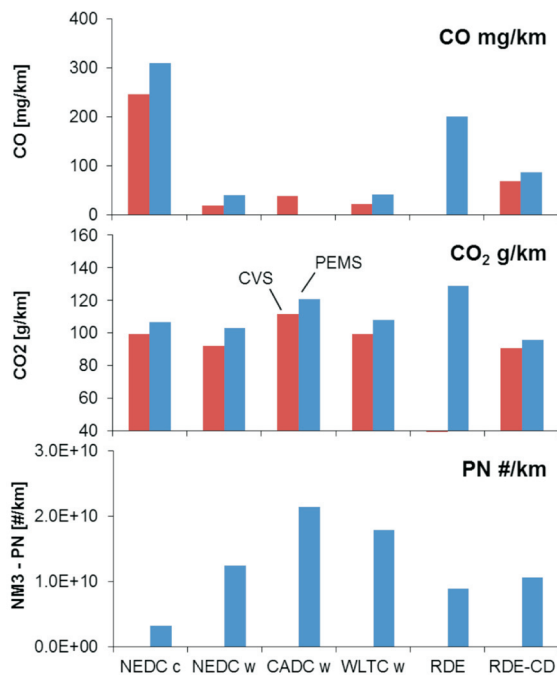

Fig. 12. Emissions of a modern diesel passenger car (Euro 6b) in different driving cycles and in real driving

Fig. 13. Effects of DPF on Diesel Passenger Cars in WLTC (hot) Succes of DPF Technology

RDE requirements for road testing

The requirements concerning: vehicle, test circuit, test equipment, boundary conditions, emission trip validation and evaluation are given in the preliminary version of the Euro 6c Norm, [1, 3]. Useful information and explanations can be found in literature, [2, 4–6].

The objective of this section is to give a possible short summary of the requirements of this testing method.

An extract of the requirements regarding trip validation is:
– DAQ at least at 1 Hz
– percentage of total trip distance (34%–33%–33%)
– urban → rural → highway (continuously run)
– urban: < 60 km/h; rural: 60-90 Km/h; highway: > 90 km/h (≠ 50–80–120 km/h)
– max velocity 145 km/h
– average speed in urban including stops = 15–30 km/h
– stops = vehicle speed < 1 km/h
– urban stops = at least 10% of the time duration of urban operation
– urban shall contain several stop periods of 10 s or longer
– highway speed at least 110 km/h
– highway at least 5 minutes above 100 km/h
– trip duration: 90-120 minutes
– start and end point elevation difference < 100 m
– minimum distance of each mode (urban, rural highway) > 16 km
– measured vehicle speed (GPS or ECU) have to be checked
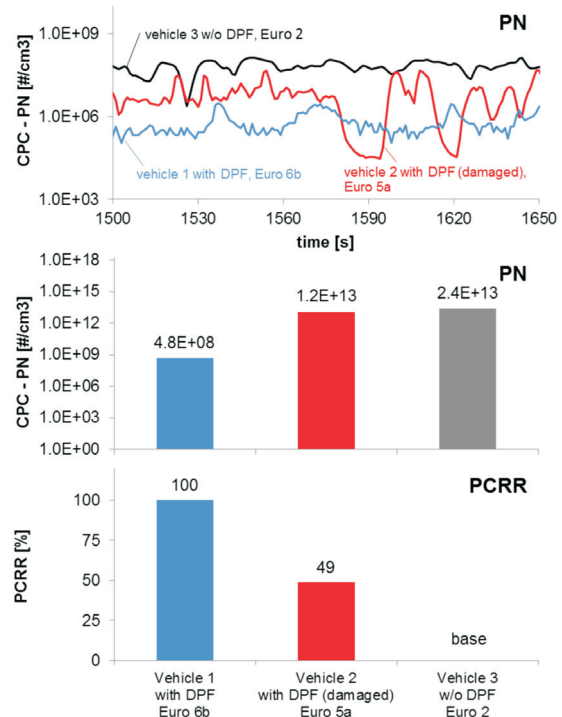– shall be conducted on working day
– off road operation is not permitted

– it shall not be permitted to combine data of different trips of to modify or remove data from a trip
– cold start shall be recorded but excluded from the emissions evaluation → but included in trip validation

6. Conclusions

Following conclusions can be mentioned:
- Comparisons of PEMS's with a stationary measuring system (CVS) on a chassis dynamometer show similar behavior for all investigated instruments – different dispersion of results, depending on the considered parameter and driving cycle.
- All PEMS's indicated more CO_2 than the "CVS". The reason is most probably the insufficient synchronization of the transient parameters: exhaust gas mass flow, concentration and density of the measured parameter. Further clarifications will be undertaken.
- From the road testing, it can be stated:
  – CO_2 emissions are repetitive,
  – there is a lot of dispersion in the measured NO_x; differences happen mainly during the first 10 km in the urban part,
  – a CO peak occurs at the beginning of the highway part; this peak influences massively the accumulated end result,
  – the results from the OBM system (TU-Wien), which has no EFM (Exhaust mass Flow Meter), are well correlating with the results of other measuring systems.
- The PN-measuring device – NanoMet3 – is confirmed as a useful device for PEMS-application, it impressively demonstrated the efficiency of the DPF-technology in eliminating the nanoparticles.

- There are quite numerous requirements for a trip validation of the RDE-procedures. The road traffic influences some of the validation parameters. It is recommended to select a "flexible" road circuit, which can be adapted to the actual traffic situation.

    Summarizing: the PEMS and RDE testing is a new challenging task for the test laboratories.

Abbreviations

AFHB	Abgasprüfstelle FH Biel, CH
ASTRA	Amt für Strassen (CH)
BAFU	Bundesamt für Umwelt, (Swiss EPA)
BC	board computer
CADC	Common Artemis Driving Cycle
CD	chassis dynamometer
CLA	chemiluminescent analyzer
CLD	chemiluminescent detector
CPC	condensation particle counter
CVS	constant volume sampling
DAQ	data acquisition
DF	dilution factor
DI	Direct Injection
EC	European Commission
ECE	Economic Commission Europe
ECU	electronic control unit
EFM	exhaust flow meter
EMPA	Eidgenössische Material Prüf- und Forschungsanstalt
EUDC	Extra Urban Driving Cycle
ρ_x	density of the component "x"
HC	unburned hydrocarbons
JRC	Joint Research Center
k_x	volumetric concentration of component "x" in the exhaust gas
$\dot{m}_x$	mass flow of emission component "x"
MFS	mass flow sensor
NEDC	New European Driving Cycle (ECE+EUDC)
NM3	NanoMet 3
NO	nitrogen monoxide
NO_2	nitrogen dioxide
N_2O	nitrous oxide
NO_x	nitric oxides
OBD	on-board diagnostics
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
TWC	three way catalyst
V_{exh}	volumetric flow of exhaust gas
WLTC	worldwide harmonized light duty test cycle
WLTP	worldwide harmonized light duty test procedure
3WC	three way catalyst

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