Journal of Earth Sciences and Geotechnical Engineering, vol.6, no. 4, 2016, 91-106
ISSN: 1792-9040 (print version), 1792-9660 (online)
Scienpress Ltd, 2016

Experiences and Results with different PEMS

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Abstract

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). 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.
For the real-world testing a road circuit was fixed: approximately 1h 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 (NOx, CO, CO2) and on the test cycles. Repeated test on the same road circuit produce dispersing emission results depending on the traffic situation, dynamics of driving and ambient conditions.

Keywords: PEMS, RDE, HD-vehicles and LD-vehicles

1 Test vehicle

The rented test vehicle was a 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. In the present tests the lube oil was not changed, or analyzed – the same oil was used for all tests.

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Figure 1a: Vehicle used for research on PEMS

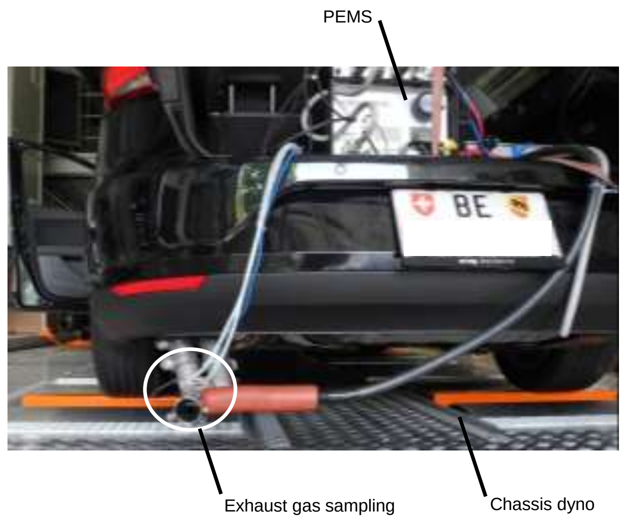


Figure 1b: Test vehicle with installed PEMS on chassis dynamometer

Table 1: Data of tested vehicle

Vehicle	**SEAT Leon 1.4 TSI ST**
Number and arrangement of cylinder	4 / In line
Displacement cm^3	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

2 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
  CH4FID... 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.

The overview of used PEMS is given in the Table 2. 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.

Table 2: 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	PEMS① wet	PEMS② dry	PEMS③ dry
CO	NDIR	heated NDIR	NDIR	NDIR
CO_2	NDIR	heated NDIR	NDIR	NDIR
NO_x	CLD	CLD	NDUV	Zirkonium-dioxid
NO	CLD	CLD	-	Electro-chemical + 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

3 Test procedures

Part of the tests were performed on the 4WD-chassis dynamometer of AFHB

3.1 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.

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.

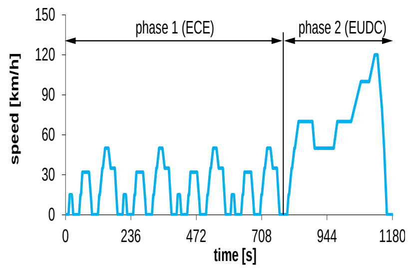


Figure 2: NEDC European driving cycle

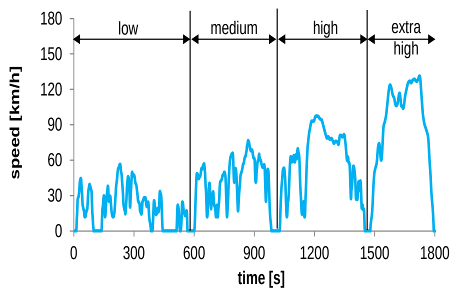


Figure 3: WLTC driving cycle

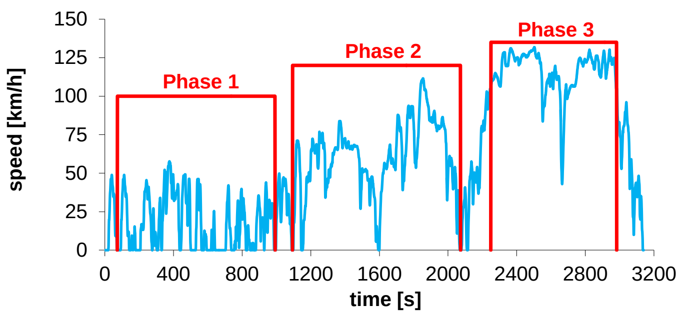


Figure 4: CADC driving cycle

3.2 On-road testing

With each PEMS several road tests were performed. The used road circuit was always the same with approximately 1h duration and parts of urban, rural and highway roads (see Fig. 9).

4 Results

4.1 Comparisons of PEMS on chassis dynamometer

All three PEMS were tested on chassis dynamometer in the driving cycles $NEDC_{cold}$, $NEDC_{warm}$, $WLTC_w$ and $CADC_w$ and the results were compared with

the stationary CVS-installation (with Horiba MEXA 7100), which is shortly called here "CVS".
Fig. 5 gives an example of correlations of NO_x, CO and CO_2 measured with PEMS and with "CVS" in $NEDC_{cold}$ (which is still the legal test procedure of today). The emission components are given in [mg/km] or [g/km].

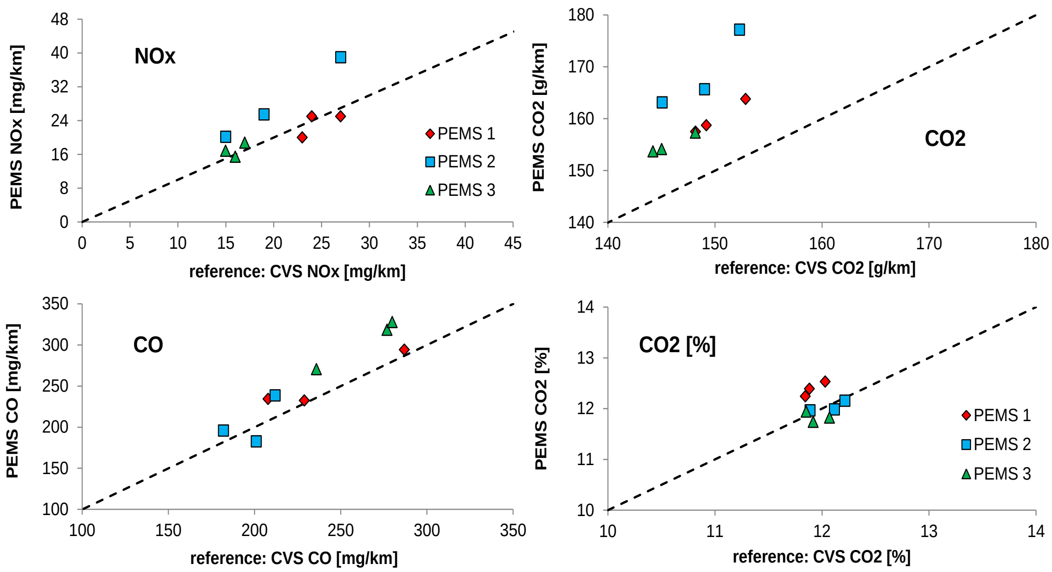


Figure 5: Correlations of emissions measured with PEMS and with stationary CVS-installation in NEDC cold.

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:

$$\dot{m}_x = \dot{V}_{exh} \cdot k_x \cdot \varrho_x$$
$$[\frac{kg_x}{s} = \frac{m^3{}_{exh}}{s} \cdot \frac{m^3{}_x}{m^3{}_{exh}} \cdot \frac{kg_x}{m^3{}_x}]$$

where:
$\dot{V}_{exh}$ … volumetric flow of exhaust gas
kx … 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 linearisations.

In order to exclude the influence of volumetric flow (V_{exh}) and density (ϱx) 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. 5 as CO_2 in [%].

The comparison of concentrations indicates much better correlations.

About the magnitude of values obtained in $NEDC_{cold}$ it can be remarked:

- NO_x results are lower than the Euro 6 limit (60 mg/km)
- CO results are lower than the Euro 6 limit (1000 mg/km)
- CO_2 results are greater than 119 g/km (manufacturer specifications)
  - ⇨ average of all CVS results: 148 g/km [average of all road measurements (different PEMS): 134g/km]

The correlations of emissions measured with all three PEMS and with “CVS” in all driving cycles are represented in Fig. 6. The tendencies of the too high indications with PEMS’a are confirmed: too high NO_x-values with PEMS2, high CO_2-values with all PEMS’s.

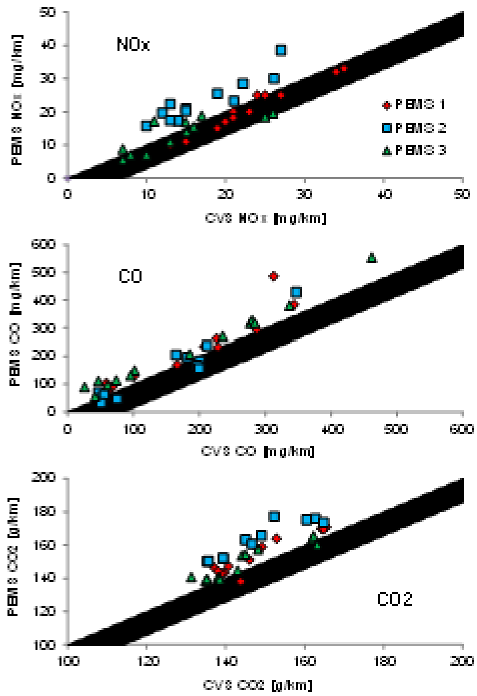


Figure 6: Correlations of emissions measured with PEMS and with stationary CVS-installation in all investigated driving cycles: NEDC cold, NEDC, WLTC, CADC.

As already demonstrated in Fig. 5, the major reason for the higher CO_2 mass-emissions with PEMS's is the insufficient synchronization and accuracy of transient parameters. The average CO_2 concentrations are in a much better accordance.

A general comparison of average results: CVS versus all PEMS's is represented in Fig. 7 for $NEDC_{cold}$ 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. 8 summarizes the average deviations between the PEMS- and CVS – values considering all cycles, including $NEDC_{cold.}$. Considering the maximum deviations: for NO_x at 37% and for CO at 67%, it seems too much, but on the other hand taking in view the very low absolute values of NO_x and CO these deviations become more comprehensible.

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.

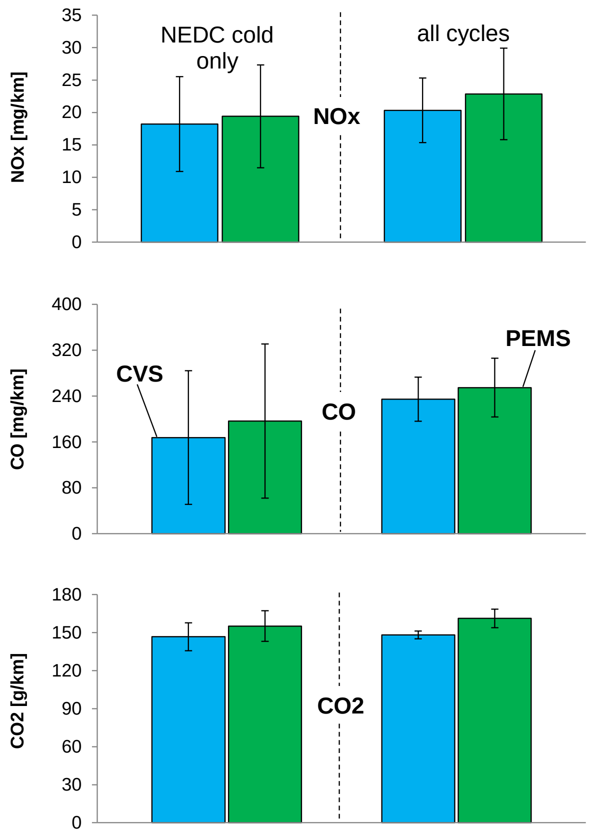


Figure 7: Comparisons of average results: CVS versus all PEMS's.

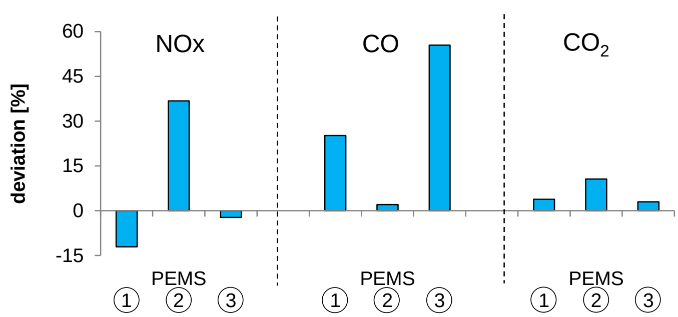
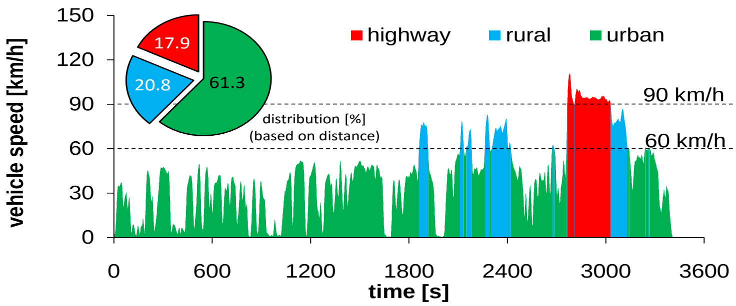


Figure 8: Average deviations between PEMS and CVS values; all cycles.

4.2 Road tests and comparisons with chassis dynamometer

The road test route used for the tests is described in Fig. 9.

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.
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.



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**		

Figure 9: AFHB Road-Test Route. PEMS 2, Seat Leon 1.4 TSI Euro 5b

Fig. 10 shows a comparison of accumulated results from five road trips with PEMS1.

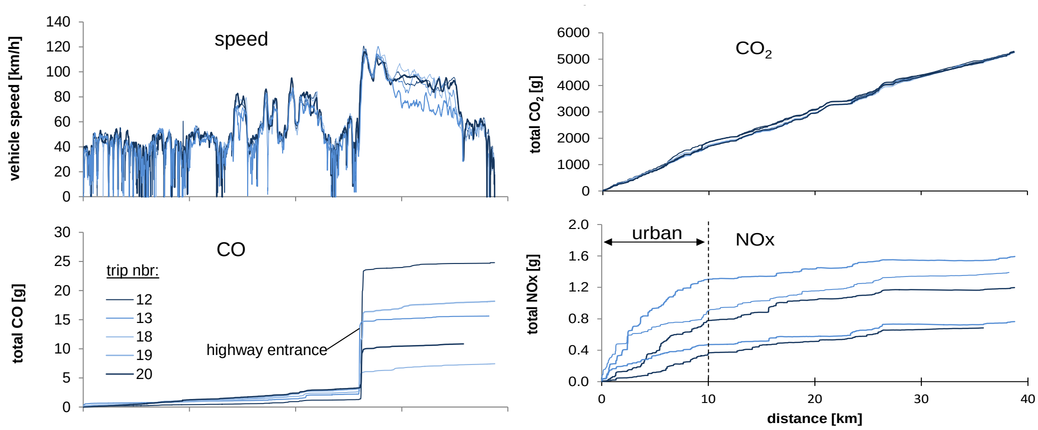


Figure 10: Comparison of accumulated results from five road trips

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 10km 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.

Fig. 11 summarizes the results from several road tests with all three PEMS. Following can be remarked:

- 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 300mg/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 <50ppm; CO average <300ppm).
- The results from the PEMS3, which has no EFM (Exhaust mass Flow Meter), are similar to the results of other measuring systems.

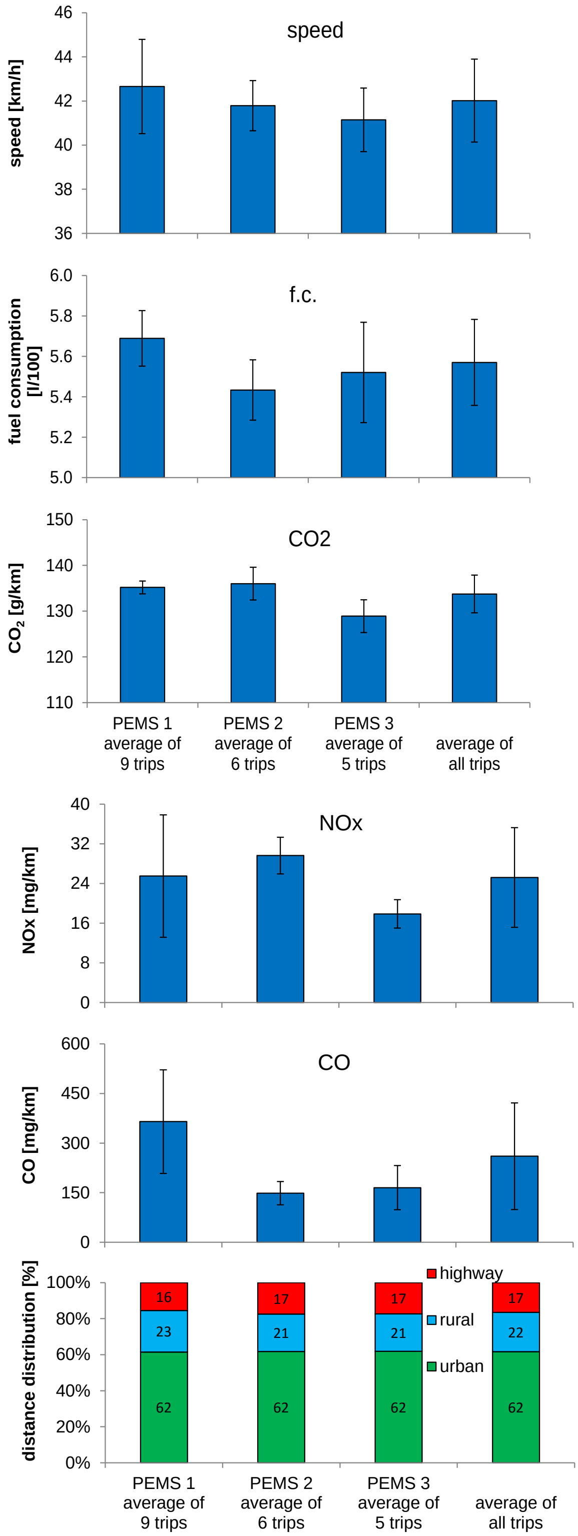


Figure 11: Results from road trips (38km) with different PEMSs. PEMS 1, 2, 3; Seat Leon 1.4 TSI Euro 5b.

Fig. 12 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.

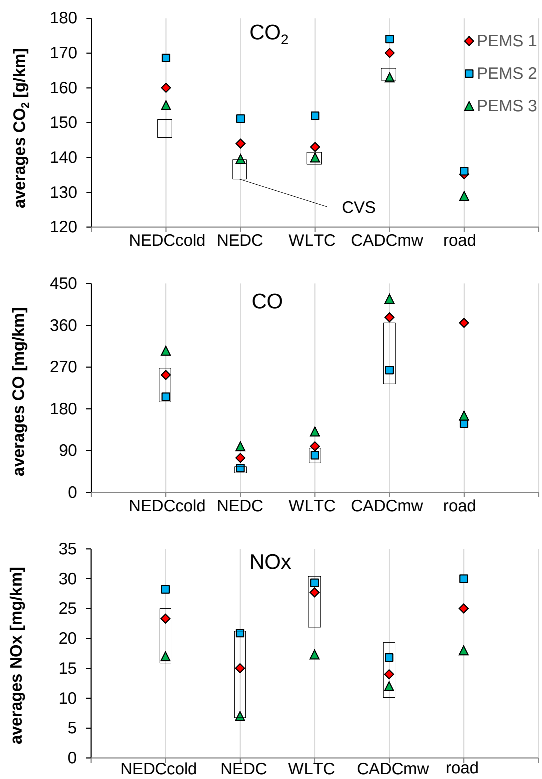


Figure 12. Comparisons of average values between road trips and cycles on chassis dynamometer. PEMS 1, 2, 3; Seat Leon 1.4 TSI Euro 5b.

4.3 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, 5, 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 1Hz
- 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 < 1km/h
- urban stops = at least 10% of the time duration of urban operation
- urban shall contain several stop periods of 10s or longer
- highway speed at least 110km/h
- highway at least 5 minutes above 100 km/h
- trip duration: 90-120 minutes
- start and end point elevation difference < 100m
- 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

5 Conclusion

Following conclusions can be mentioned:

- Comparisons of PEMS's with a stationary measuring system (CVS) on a chassis dynamometer show similar behaviour 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 of the present vehicle 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.

• 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.

ACKNOWLEDGEMENTS. The authors express their thanks to the Swiss Federal Office of Environment BAFU, Dr. M. Schiess and Mr. G. D'Urbano for the financial support and inspiration of the project.

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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
CLA	chemiluminescent analyzer
CLD	chemiluminescent detector
CVS	constant volume sampling
DAQ	data aquisition
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
ϱx	density of the component "x"
HC	unburned hydrocarbons
kx	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)
NO	nitrogen monoxide
NO_2	nitrogen dioxide
N_2O	nitrous oxide
NO_x	nitric oxides
OBD	on-board diagnostics
PEMS	portable emission measuring systems
PN	particle number
RDE	real driving emissions
TWC	three way catalyst
$\dot{V}_{exh}$	volumetric flow of exhaust gas
WLTC	worldwide harmonized light duty test cycle
WLTP	worldwide harmonized light duty test procedure
3WC	three way catalyst