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Comparison of exhaust emission results obtained from Portable Emissions Measurement System (PEMS) and a laboratory system

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Exhaust emissions testing of vehicles under real driving conditions (real driving emissions, RDE) using portable exhaust emissions measurement systems (PEMS) was introduced a few years ago by the European Commission as a mandatory test during type approval and later also for in-service conformity. This paper compares results from mobile systems for measuring exhaust gas emissions (PEMS) with a stationary laboratory (BOSMAL's Exhaust Emissions Testing Laboratory). The tests were carried out using a passenger car equipped with a spark ignition engine, which was tested on a chassis dynamometer over the WLTC cycle. The results showed that the differences between PEMS analysers and stationary analysers range from a few percent to a dozen or so percent, depending on the component and the measurement method.

Key words: *Portable Emissions Measurement System; Worldwide harmonized Light vehicles Test Cycle; Real Driving Emissions; Conformity Factor*

1. Introduction

Environmental protection and improvement of air quality have become a major goal set by many governments around the world and by the European Commission. In many areas, the largest contributor (or one of the largest contributors) to the deterioration of air quality and greenhouse gas emissions is the road transport sector. In Europe, the road transport contributed 39% of total anthropogenic NO_x emissions and 23% of carbon dioxide emissions in 2015, reducing to 37% of total anthropogenic NO_x emissions and 18% of carbon dioxide emissions in Europe in 2020 [1, 3, 17]. In order to reduce the emission of harmful substances and greenhouse gases, exhaust emissions standards and fuel efficiency requirements for road vehicles are being tightened around the world. Over the years 2018/2019, the driving cycle in force in the EU for laboratory testing of light duty vehicles was changed from the NEDC to the WLTC, which reflected more natural/realistic driving, and Euro 6d-temp emission limits were introduced [18]. Despite the change in the driving cycle (as well as some other aspects of the test procedure), there were concerns that exhaust emissions under laboratory conditions still did not correspond to exhaust emissions under real driving conditions. For that reason, since September 2019 the regulations for measuring exhaust emissions in real-world conditions (on public roads) for all newly type-approved vehicles in accordance with EC Regulation (EU) 2017/1151 have been in force in Europe. Measurements of the emission of harmful exhaust compounds under real-world conditions (RDE) forced the manufacturers of exhaust gas analysers to develop portable exhaust emission systems (PEMS), which were initially intended for testing heavy-duty vehicles [22]. The Euro 6 standard defines the permissible emission limits for passenger cars (M1) and light commercial vehicles (N1), which include such components as CO, THC, NO_x, as well as particulate matter by mass (PM) and by number (PN) [3, 9. 11, 13, 22].

Exhaust emission tests under real-world (RDE) driving conditions are carried out on public roads in accordance with the applicable requirements within Regulation (EC) No 715/2007, with all applicable amendments. These regulations specify what devices and mobile analysers must be fitted to the vehicle during the RDE test. The PEMS system consists of portable exhaust gas analysers, an exhaust gas mass flow meter (EFM), a weather station, and a positioning monitoring system (GPS). These devices must be integrated and the control system logging their data must operate at an acquisition frequency of at least 1 Hz [22]. The regulations specify not only the devices that must be used during the RDE test, but also the route conditions such as minimum and maximum test duration, distance travelled, speed ranges and ambient conditions such as minimum and maximum altitude above sea level, as well as temperature [2, 10, 13]. For cold start testing, the regulations also specify the maximum temperature difference of the vehicle (coolant and engine oil) in relation to the ambient temperature at the start of the test. Each test route for vehicles of category M1 must include three ranges: the urban part, the extra-urban part, and the motorway part; the relative (percentage) shares of which are specified in the regulation.

Currently, Europe mandates Euro 6 emission limits, whose values for M1 vehicles are given in Tables 1–2.

Table 1. Euro 6 emission limits for M1 cars with SI engine (* GDI engine)

Parameter	Unit	Value
CO	mg/km	1000
THC	mg/km	100
NMHC	mg/kg	68
NO_x	mg/km	60
PM*	mg/km	4.5
PN*	#/km	$6 \cdot 10^{11}$

Table 2. Euro 6 emission limits for M1 vehicles with CI engine

Parameter	Unit	Value
CO	mg/km	500
NO_x	mg/km	80
THC + NO_x	mg/km	170
PM	mg/km	4.5
PN	#/km	$6 \cdot 10^{11}$

These limits apply to laboratory testing in the WLTP test. For RDE tests, emissions of two components are currently limited: NO_x and PN. These limits are closely related to (in fact, derived from) the respective Euro 6 limits. Due to methodological differences in measurement rules, Euro 6/VI introduces so-called conformity factors for LD and HD vehicles. These conformity factors reflect the additional uncertainty of the PEMS measurement compared to laboratory measurements [21]. The current conformity factors (CFs) are 1.43 for NO_x and 1.5 for PN, respectively. From September 2023 (Euro 6e) they will be 1.1 for NO_x and 1.34 for PN [8].

In order to verify the correct installation and operation of the PEMS system, it is necessary to perform a validation test for LD vehicles in accordance with Annexes XXI and IIIA of Regulation (EU) No. 2017/1151, as amended by Regulation (EU) No. 2018/1832. The validation test is the measurement of exhaust emissions from a vehicle during a laboratory test on a chassis dynamometer with the PEMS system installed on this vehicle. Emissions are measured by both systems, then the measurement results are compared with each other. The emission results from the PEMS system are compared with the results from the stationary system, while the measurement of exhaust gas emissions from the PEMS system is carried out on the basis of modal measurement of undiluted exhaust gas using fast analysers and flow meters (EFM), and the measurement from the stationary system on the basis of measurement from measuring bags diluted exhaust gases [19]. Table 3 shows the acceptable differences between the results of laboratory tests and the results of PEMS in accordance with Regulation EU 2020/49 of 21.01.2020 and new acceptable differences in accordance with Regulation EU 2023/443 of 08.02.2023 [8, 20].

Table 3. Limits for validation test limits between laboratory results

		Limit abs. 2020/49	Limit abs. 2023/443	Limit rel. 2020/49	Limit rel. 2023/443
		[±]		[%]	
Distance	km	0.250			
NO_x	mg/km	15	10	15	12.5
CO	mg/km	150	100	15	15
CO_2	g/km	10	10	10	7.5
NMHC	mg/km	20	20	20	20
CH_4	mg/km	15	15	15	15
THC	mg/km	15	15	15	15
PN	#/km	$1 \cdot 10^{11}$	$8 \cdot 10^{10}$	50	42

2. Characteristics of the emissions laboratories

BOSMAL's emissions testing laboratory is an advanced, climate-controlled facility for performing emissions, fuel consumption and performance tests over a range of driving cycles and a broad range of ambient conditions. Exhaust emissions testing is carried out with the aid of sampling bags (legislative tests), diluted and raw modal analysis (development tests) for use with CI, SI, and hybrid vehicles. These facilities permit the execution of a wide range of legislative and development emissions tests, including:

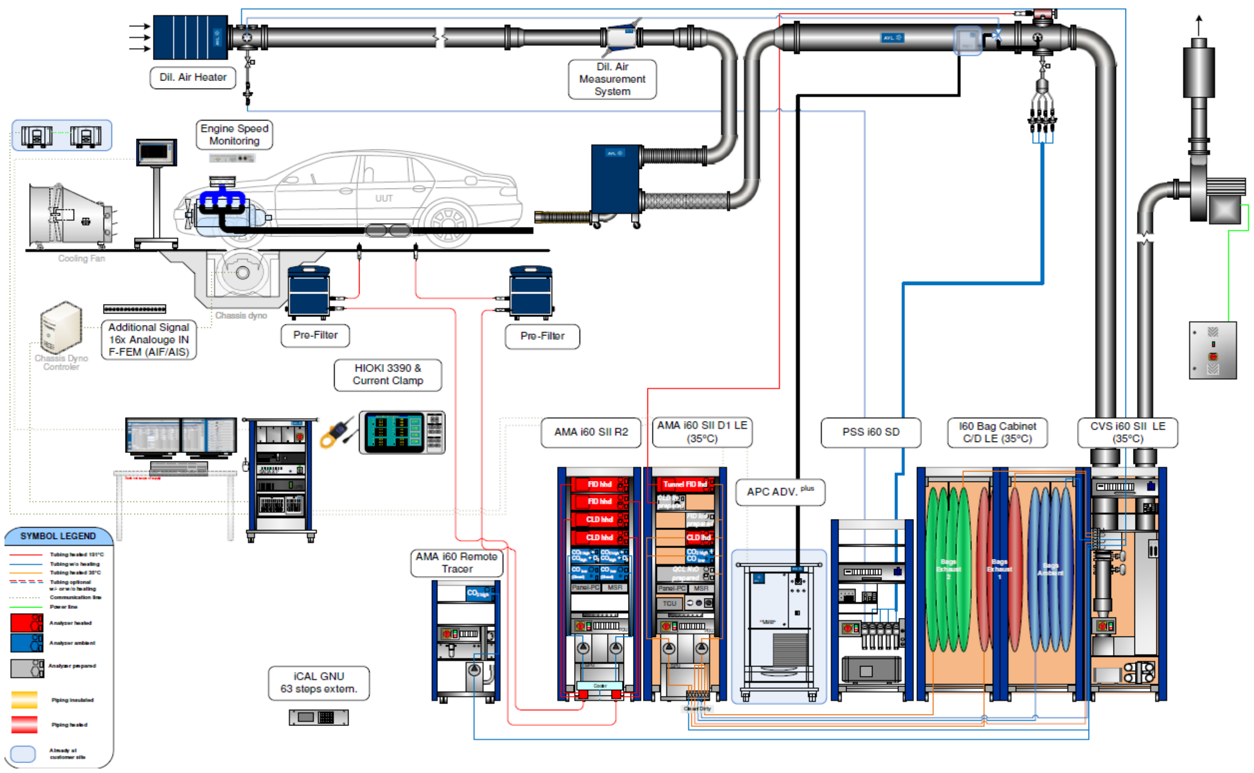

Fig. 1. Schematic laboratory

- CVS bag diluted emissions testing to international standards [6, 7]
- CO_2 emissions and fuel consumption measurement according to EU standards [20]
- gravimetric and numerical quantification of particulate matter emission according to [12, 15]
- measurement of soot and particulate matter from raw exhaust gases using additional devices.

A schematic of the Laboratory is shown in Fig. 1.

3. Emissions testing system

The emissions system in Laboratory consists of a sampling system, together with a dilution tunnel (Fig. 2), a set of exhaust analysers and a management/automation system (Fig. 3).

Fig. 2. View of the emission laboratory

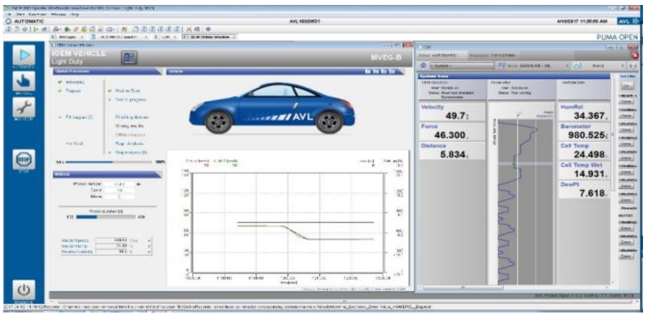

Fig. 3. View of test management/automation system in the laboratory

The emissions system's bags for the sampling of diluted exhaust gas ambient and ambient air are housed in a heated, insulated unit maintained at 35°C to prevent condensation. The software (automation system) controls the analysers and their various activities during testing and analysis of bag emissions, such as calibration, purging, etc. The system automates the signals sent to the driver's aid, and include options for testing over all the test cycles previously mentioned, as well as any other cycle added to the system via the implementation of new programs. Additionally, the software monitors the laboratory's environmental parameters (temperature, pressure, humidity) as well as ambient concentrations of THC, CH_4, CO, and CO_2 within the laboratory to ensure that each test is safe, reliable, repeatable, and thoroughly documented [3]. Table 4 gives the measurement principles and analysers' ranges for stationary laboratory equipment.

Table 4. Parameters of the stationary emissions measurement system

Measuring ranges of gas analyzers of stationary systems			
Measured component (measurement method)	Bag measurement/ continuous dilution measurement		Measuring accuracy
Range	Low	High	
CO low (NDIR)	0–50 ppm	0–5000 ppm	±2% at the measuring point ±1% of scale
CO_2 (NDIR)	0–1%	0–20%	
NO_x (CLD)	0–5 ppm	0–1000 ppm	
NO (CLD)	0–5 ppm	0–1000 ppm	
THC (FID)	0–17 ppm	0–3000 ppm	
CH_4 (NMHC cutter)	0–10 ppm	0–400 ppm	
PN (condensing)	0–50000 #/cm^3		±10%

4. Research aim and research object

The aim of the research was to measure and analyse the exhaust emissions results of a passenger car (and to compare the fuel consumption) with measurements carried out over WLTC test on stationary laboratory with simultaneous measurement from a PEMS system. The test object was a PEMS system, data for which are shown in Table 5.

Table 5. Parameters of the mobile emissions measurement system

Measuring ranges of gas analyzers of mobile system		
Measured component (measurement method)	Continuous measurement of diluted exhaust gas	Measuring accuracy
CO (NDIR)	0–5%	±2% or ≤ 30 ppm
CO_2 (NDIR)	0–20%	±2% or ≤ 0.06%
NO2 (NDUV)	0–2500 ppm	±2% or ≤ 5 ppm
NO (NDUV)	0–5000 ppm	±2% or ≤ 10 ppm
THC (FID)	0–30 000 ppm C1	±2% or ≤ 5 ppm
PN (electrostatic)	0–2×10^7 #/cm^3	±10%

A brand new passenger car equipped with gasoline direct injection and fulfilling the Euro 6 norm was used for the measurements. Table 6 shows the data of the vehicle.

Table 6. Data of the test vehicle

Parameter	Value
Fuel type	Gasoline
Fuel delivery strategy	GDI
Vehicle mass [kg]	1008
Swept volume [cm^3]	1000
Power [kW]	51
Gearbox	Manual (5-speed)
Mileage [km]	170
Emission standard	Euro 6d

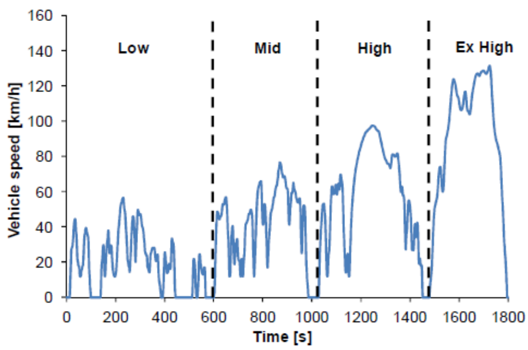

Fig. 4. The speed trace for the WLTC class 3b test cycle

The speed profile of the WLTC test, consisting of four phases: low, middle, high, and extra-high, is the legislative test for EU type approval testing of vehicles with a total weight not exceeding 3.5 t, introduced in September 2018 for all newly manufactured vehicles (Fig. 4; detailed data on test characteristics are presented in Table 7).

Table 7. WLTC test data

Parameter	Unit	Value
Distance	km	23.266
Duration	s	1800
Number of pull-away events	–	8
Pull-away events per km	km^{-1}	0.34
Length of initial idling (before first pull-away event)	s	11
Total idling time	s	234
Idling time (proportion)	%	13
Maximum speed	km/h	131.3
Mean speed (all phases, including idling)	km/h	46.50
Time at which the mean speed is first exceeded	s	217
Maximum acceleration	m/s^2	1.67
Maximum value of v·a	m^2/s^3, W/kg	20.57
Proportion of time for which speed > 100 km/h	%	10.11
Engine temperature before test start	°C	23 ±3

5. Results

Currently, in order to allow a new vehicle type to be sold for use on public roads, it is necessary to thoroughly check the exhaust emissions. For this purpose, exhaust gas analysers – both stationary and mobile – are used. The results presented below show the difference between the results from the stationary and mobile analysers. Each of the WLTC tests was performed by the same experienced driver, to minimise driver-dependent variables (and their influence on the results) as directly as possible. In addition, the test vehicle performed each test in the same selectable driving mode with the same chassis dynamometer settings. In order to eliminate additional measurement irregularities, prior to each test the vehicle was stored in a climatic chamber under constant atmospheric conditions. After each test, the vehicle was conditioned for at least 12 hours so that the temperature of operating fluids stabilized in the range of 22–24°C. The results of the three exhaust emissions and fuel consumption were averaged and then analysed and presented in the graphs below. Tests were conducted with the Start&Stop system turned off, and the results were presented without RCB and S&D corrections. In addition, the graphs showing the final exhaust emissions show the current Euro 6 exhaust gas limits as well as RDE limits and validation test limits in accordance with Regulation EU 2020/49 from 21.01.2020.

Figure 5 shows the average results of hydrocarbon emissions from the WLTC test carried out in the stationary laboratory. The results are within the Euro 6 limits and meet the validation condition. The absolute difference between the results from the stationary system and the mobile system is at a level of a few milligrams per km. Additionally, the maximum value of THC emissions is shown in purple; the minimum THC emission value is shown in yellow.

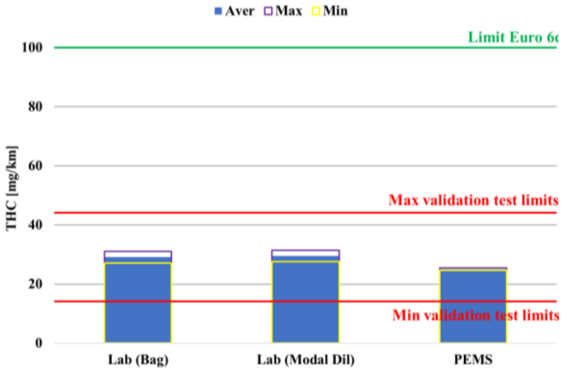

Fig. 5. THC emissions over the WLTC cycle measured by laboratory system (Bag and Modal Dil) and by PEMS

Figure 6 shows the percentage difference in the THC results from the mobile system in relation to the measurements from the stationary system, both with measuring bags (Bag) and with continuous measurement of diluted exhaust gas (Modal Dil). These differences amount to 14% in comparison with the results from the measuring bags and more than 15% compared to the results from Modal Dil.

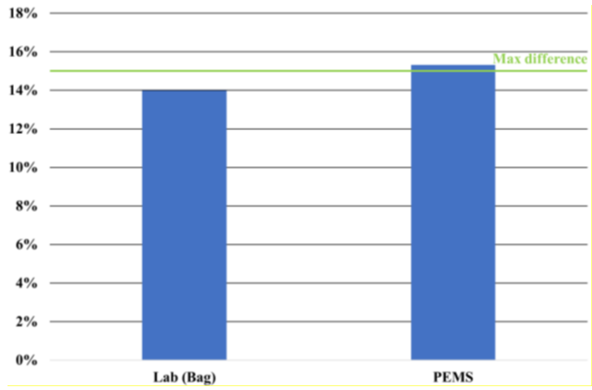

Fig. 6. Percentage differences between PEMS and results THC from Bag

Table 8. Validation test results

Inertia: 1162 kg	WLTC emissions							Remarks
Loading coefficients F0/F1/F2	km	mg/km			#/km	g/km	$dm^3/100km$	
	Distance	THC	CO	NO_x	PN	CO_2	FC	
18/-0,28/0.0316	23.28	29	210	14	4.18E+11	118.9	5.11	Laboratory (BAG results)
	23.28	30	211	14		119.6	5.14	Laboratory (DIL results)
	23.12	25	218	19	3.17E+11	122.9	5.26	PEMS
Difference Lab to PEMS	0.16	4	8	5	1.01E+11	4	0.15	
Maximum permissible tolerance	0.25	15	150	15	1.00E+11	11.9		

Figure 7 shows the CO_2 emissions results from the stationary system and the results from the mobile system. The validation conditions are met and the emission difference is 4 grams per km compared to the results from the measuring bags of the stationary system. The maximum CO_2 emission value is shown in purple; the minimum CO_2 emission value is shown in yellow.

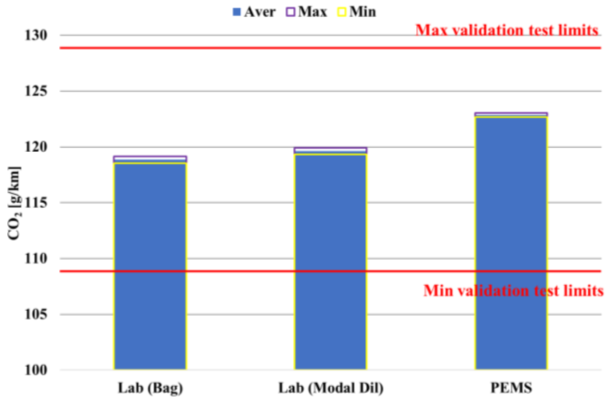

Fig. 7. CO_2 emissions over the WLTC cycle measured by the laboratory system (Bag and Modal Dil) and by the PEMS

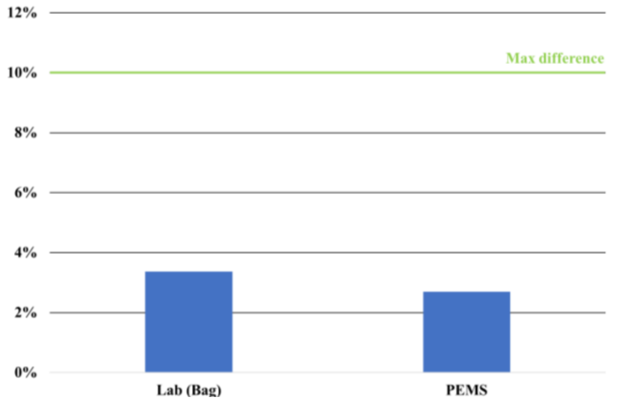

Fig. 8. Percentage differences for CO_2 results between the PEMS and Bag

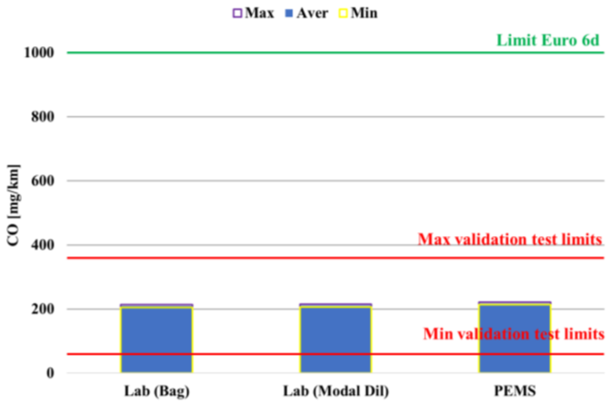

Fig. 9. CO emissions over the WLTC cycle measured by the laboratory system (Bag and Modal Dil) and by the PEMS

Figure 8 shows the percentage difference in the results of carbon dioxide from the Mobile system in relation to the measurements from the stationary system, both with measuring bags (Bag) and with continuous measurement of diluted exhaust gases (Modal Dil). These differences are about 3–4% compared to the results from the measuring bags and the results of Modal Dil.

The figure below shows the results of carbon monoxide emissions. The maximum CO emission value is shown in purple; the minimum CO emission value is shown in yellow; the average emission from emission tests is marked in blue. The vehicle met the emission limits of the Euro 6 standard and the results from the mobile system met the validation condition, and the difference in CO emissions is at a level of 8 mg per km.

The figure below shows the percentage difference in the results of monoxide carbon from the Mobile system in relation to the measurements from the stationary system, both with measuring bags (Bag) and with continuous measurement of diluted exhaust gas (Modal Dil). These differences amount to 4.5% for comparison with the results from measuring bags and less than 3.5% compared to the results of Modal Dil.

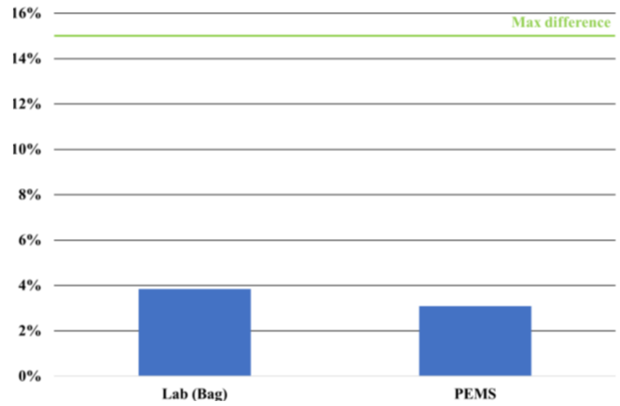

Fig. 10. Percentage differences for CO results between the PEMS and Bag

Figure 11 shows the results of nitrogen oxide emissions. The validation conditions have been met and the Euro 6 limits have not been exceeded. The difference between the results from the measuring bags and the results from the mobile system is at a level of 5 mg per km. The NO_x limit for the RDE result (with CF) is shown in blue in the graph, which for SI Euro 6d vehicles is 60×1.43 mg/km. The maximum value of NO_x emissions is shown in purple and the minimum NO_x emission value is shown in yellow.

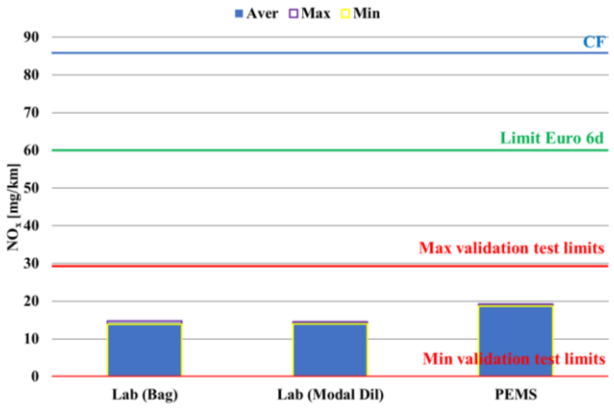

Fig. 11. NO_x emissions over the WLTC cycle measured by the laboratory system (Bag and Modal Dil) and by the PEMS

Figure 12 shows the percentage difference in the results of nitrogen oxides from the Mobile system in relation to the measurements from the stationary system, both with measuring bags (Bag) and with continuous measurement of diluted exhaust gases (Modal Dil). The difference between the mobile system and the results from the stationary system in both methods (Bag and Modal Dil) amounts to 32%.

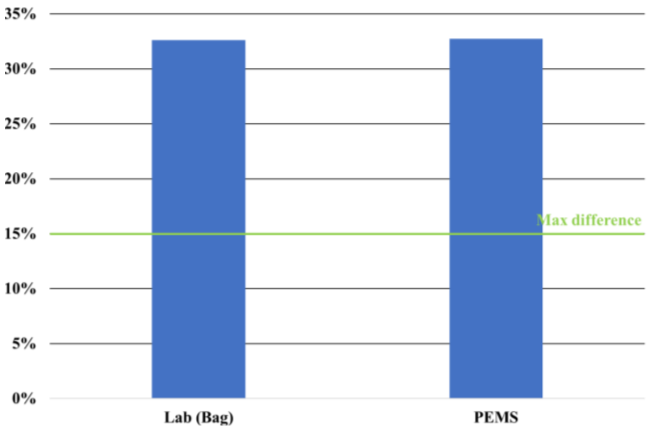

Fig. 12. Percentage differences for NO_x results between the PEMS and Bag

Figure 13 shows the particle number emission results. The validation limits of the particle number measurement are shown in red. Additionally, the maximum value of PN emissions is shown in purple; the minimum PN emission value is shown in yellow.

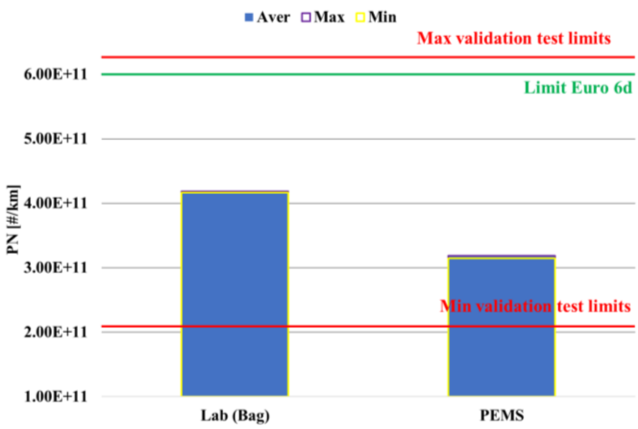

Fig. 13. PN emissions over the WLTC cycle measured by the laboratory system and by the mobile system (PEMS)

The percentage difference in the number of particles from the mobile system in relation to the measurements from the stationary system is 25%. While this relative difference is larger than for some other species measured (especially CO_2), it should be noted that differences of this magnitude may be observed for systems of the same type [4, 14].

Figure 14 shows the results of fuel consumption. The difference between the results from the measuring bags and the results from the mobile system is 0.14 dm^3/100 km.

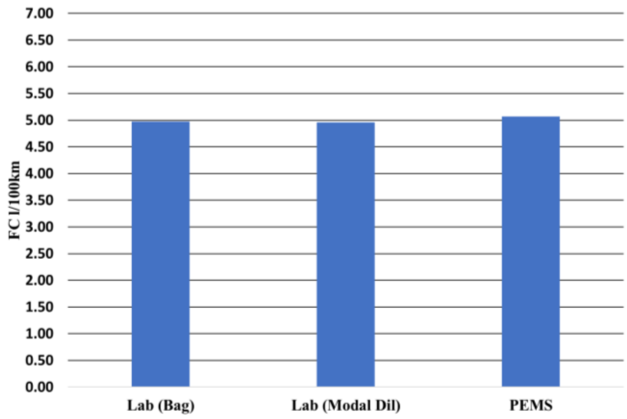

Fig. 14. FC results over the WLTC cycle by the laboratory system (Bag and Modal Dil) and by the PEMS

6. Conclusions

Based on the testing conducted, it was found that the absolute difference of a few milligrams per km for the measurement of hydrocarbons between the mobile system and the stationary system (for both measurement methods) is 14% for the measurement via bag and 15% for the continuous measurement of diluted exhaust gas. The difference at the level of 4 g per km for the measurement of carbon dioxide gives a relative value not exceeding 4% for the measurement from the bags, while for continuous measurement of diluted exhaust gas it is about 3%. In the case of carbon monoxide, the difference in relative measurements is at a level of 3–4%, which in fact gives a difference of about 8 mg per km. The results for NO_x show the largest relative difference, which is 33%, which in fact translates into a relative difference of 4.5 mg per km. The absolute difference in the concentration of particles for the mobile system is 1.01E+11 #/cm^3, which translates to a relative difference of approx. 25% compared to the PN measurement from the stationary emission system.

The research reported in this article allows it to be concluded that the absolute differences in the results of exhaust emissions between the mobile system and the measurements from the stationary system are small – and often amount to a few milligrams (or grams in the case of CO_2) per unit distance. The difference in the distance measured from the stationary and mobile system is 160 m, which may be due to the measurement of the distance traveled using the dyno for the stationary system and by speed signals from the OBD using the mobile system, but the value is within the limit of 250 m. However, the relative differences amount to several dozen percent. It can be seen that the greatest relative differences for the measurement of NO_x and the measurement of PN. These differences may result from different measurement methods for both nitrogen oxides (stationary: CLD/mobile: NDUV) and measurement of the number of particles (stationary: condensing/mobile: electrostatic). Taking into account the values measured by the mobile system (excluding measurement errors), it can be concluded that both systems are reliable and the absolute differences in the emission results do not differ significantly from the results from the stationary laboratory equipment (although the relative differences may be large for low absolute values).

Nomenclature

CF	conformity factor
CH_4	methane
CI	compression ignition
CO	carbon monoxide
CO_2	carbon dioxide
CVS	constant volume sampler
EFM	exhaust gas mass flow meter
FC	fuel consumption
GDI	gasoline direct injection
GPS	global positioning system
HD	heavy duty
LD	light duty
NEDC	New European Driving Cycle
NO_x	nitrogen oxides
PEMS	Portable Emissions Measurement Systems
PM	particle mass
PN	particle number
RDE	Real Driving Emissions
SI	spark ignition
THC	total hydrocarbons
WLTC	Worldwide harmonized Light-duty vehicles Test Cycles

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