



174(3), 2018



**COMBUSTION ENGINES**

# Emissions testing for R&D work and certification at the Euro 6d level (WLTP/RDE)

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## Testing under laboratory conditions on chassis dynamometers in climate controlled test cells

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## Particle number measurements in the European legislation and future JRC activities

*The solid particle number method was introduced in the European Union (EU) light-duty legislation for diesel vehicles to ensure the installation of the best-available technology for particles (i.e., wall-flow diesel particulate filters) without the uncertainties of the volatile nucleation mode and without the need of large investment for purchasing the equipment. Later it was extended to gasoline vehicles with direct injection engines, heavy-duty engines (both compression ignition and positive ignitions) and non-road mobile machinery engines. Real Driving Emissions (RDE) testing on the road with Portable Emissions Measurement Systems (PEMS) for particle number (and NO<sub>x</sub>) during type approval and in-service conformity testing was recently (in 2017) introduced for light-duty vehicles, and is under discussion for heavy-duty vehicles in-service conformity testing.*

*This paper will summarize the existing legislation regarding solid particle number and discuss the on-going activities at EU level. The main focus at the moment is on improving the calibration procedures, and extending the lower detection size below 23 nm with inter-laboratory exercises. In parallel, discussions are on-going to introduce testing at low ambient temperature, regeneration emissions in the light-duty regulation, a particle limit for other technologies such as gasoline port-fuel injection vehicles, and the feasibility of particle measurements to L-category vehicles (mopeds, motorcycles, tricycles and minicars). A short overview of periodical technical inspection investigations and the situation regarding non-exhaust traffic related sources with special focus on brakes and tyres will be described.*

Key words: vehicle emissions regulation, particle measurement programme (PMP), portable emission measurement systems (PEMS), real driving emissions (RDE), periodical technical inspection, particle number, sub-23 nm

### 1. Introduction

Ultrafine particles (smaller than 0.1  $\mu\text{m}$ ) have been associated with adverse health effects and act through mechanisms not shared with larger particles [1]. Road traffic contributes significantly to Particle Number (PN) concentrations and can reach 90% in busy roads [2].

At the beginning of the 90's the Particulate Matter (PM) emissions were regulated for light-duty vehicles in the European Union (EU) by weighing the mass collected on filters before and after a prescribed test cycle (speed profile). However, since early 2000, the gravimetric method was not sensitive enough to accurately determine the PM emissions of vehicles equipped with Diesel Particulate Filter (DPF). The possibility to develop a more sensitive and accurate methodology that would replace or complement the regulated gravimetric procedure, requiring low investment costs, was the objective of the Particle Measurement Program (PMP). The final decided method was based upon counting solid (non-volatile) particles larger than 23 nm [3]. A minimum diameter of 23 nm size was selected in order to include the smallest soot particles and exclude volatile nucleation mode particles. Volatile particles were excluded in order to improve the repeatability and reproducibility of the method to levels acceptable for legislative purposes [4]. The PMP working group had no medical expertise and did not seek to pre-judge the advice from medical experts with respect to the most crucial particle characteristics affecting human health. The new method was introduced to ensure the installation of the best-available technology for particles (i.e., wall-flow DPFs) without the uncertainties of the volatile nucleation mode

and without the need of large investment for purchasing the equipment. Furthermore, the particle counting method did not replace but rather complemented the gravimetric procedure that is still in force.

The PMP group activities stopped at the end of 2011 with the introduction of the Solid Particle Number > 23 nm (SPN23) method in the light-duty and heavy-duty European regulations. In 2013 EU and Switzerland requested further investigation of particle number emissions from spark ignition engines. There were also concerns regarding the existence of sub-23 nm particles. The new Terms of Reference included the following topics [5]:

- Engine dyno raw exhaust SPN measurements for heavy-duty at type approval
- Emissions during regeneration events
- Emissions from Gasoline Direct Injection (GDI) vehicles
- Development of SPN equipment to measure below 23 nm
- Calibration procedures update (and if necessary for lower size)
- Non-exhaust particle emissions

The EU vehicle emissions legislation is the only one that controls SPN23 emissions, with the exception of the recently introduced China 5&6 limits. Since the introduction of the first SPN limit in 2011 (Euro 5b) for diesel vehicles the progress has been very fast. The first review on the SPN23 regulation in 2012 summarized the PMP activities until the introduction of the SPN23 limits in the light-duty and heavy-duty emissions regulations [4]. A later review summarised the European SPN23 legislations [6]. Other reviews summarised the instrumentation typically used for particle measurements [7, 8].

Table 1. Overview of European regulations regarding PM and SPN23 for light-duty, heavy-duty, NRMM and L-category vehicles. Status 2018

	Regulation	Cycle	PM [mg/km or mg/kWh]	SPN23 [p/km or p/kWh]
<b>Light-duty (Euro 6)</b>				
Type approval	2017/1151 2017/1154	WLTC On-road (RDE)	4.5	$6 \times 10^{11}$ CF = 1.5
ISC	To be adopted end 2018	WLTC On-road (RDE)	–	$6 \times 10^{11}$ CF = 1.5
<b>Heavy-duty (Euro VI)</b>				
Type approval	582/2011	WHTC WHSC	10 10	$6 \times 10^{11}$ $8 \times 10^{11}$
ISC		On-road	–	CF = 1.63 (tbc)
<b>NRMM (Stage V)</b>				
Type approval	2017/654 2016/1628	NRTC NRSC	15	$1 \times 10^{12}$
ISC (monitoring)			–	–
<b>L-category (Euro 5 from 2020)</b>				
Type approval	2013/168	WMTC	4.5 (diesel/GDI)	–

However, since these reviews, and especially in 2017, many changes took place. The objective of this paper is to briefly update on the current status and near future activities regarding the SPN regulation. The focus is the EU legislation and in particular activities of the Joint Research Centre (JRC) of the European Commission.

## 2. SPN23 legislation in EU

An overview of current regulations regarding SPN23 emissions is given below and presented in Table 1.

### 2.1. EU and UNECE

In the framework of the United Nations' Economic Commission for Europe (UNECE) in Geneva, WP.29 (World Forum for Harmonization of Vehicle Regulations) and its subsidiary bodies are developing the Regulations under the 1958 Agreement in cooperation with all Contracting Parties to the Agreement and non-governmental organizations (NGOs). United Nations (UN) Regulations are not applicable on a mandatory basis, but if a Contracting Party decides to apply a UN Regulation, the adoption becomes a binding act.

The WP.29 and the European Commission are currently working on the harmonization between UN Regulations and EU Directives or Regulations. Currently, some of the EU Directives or Regulations are technically equivalent to UN Regulations or only refer to the requirements of the corresponding UN Regulation.

The UN Global Technical Regulations (GTRs) are the technical regulations being established under the 1998 Agreement and do not refer to a type approval or certification procedure as mentioned in the EU Directives or UN Regulations. The main reason is that the process of self-certification used in the United States is incompatible with the type approval. The UN Regulations are considered candidates for the elaboration of UN GTRs.

### 2.2. Light-duty vehicles

The EU emissions regulation requires, in addition to PM mass, the measurement of Solid Particle Number > 23 nm (SPN23) for type approval of diesel light-duty vehicles since 2011 (Euro 5b) (Regulation 692/2008) (limit  $6 \times 10^{11}$  p/km), and for Gasoline Direct Injection (GDI) light-duty vehicles since 2014 (Euro 6) (Regulation 459/2012) (limit  $6 \times 10^{12}$  p/km and  $6 \times 10^{11}$  p/km after 2017). Regulation 2017/1151 repealed Regulation 692/2008 and introduced

a new test cycle (WLTC). In addition, Real Driving Emissions (RDE) testing on the road with Portable Emissions Measurement Systems (PEMS) for SPN23 and NO<sub>x</sub> during type approval (Regulation 2016/427) and in-service conformity testing (RDE 4th package) were introduced in 2017, where: from 2017 (Euro 6d Temp) a CF of 1.5 for SPN23 (Regulation 2017/1154) and 2.1 (Regulation 2016/646) for NO<sub>x</sub> applies and from 2020 the CF of NO<sub>x</sub> will be reduced to 1.5 (Euro 6d). The CFs are under annual revision. The first 2017 revision decreased the NO<sub>x</sub> CF to 1.43 [9]. The test procedure and the test cycle are described in 2017/1151, of which Annex XXI is basically UNECE GTR No. 15.

### 2.3. Heavy-duty engines/vehicles

The type approval of an engine is conducted on an engine dynamometer with a cold start and a hot start transient cycle and a steady cycle. The SPN23 limit for heavy-duty engines was introduced in 2013 (Euro VI) for compression ignition (diesel) engines (Regulation 582/2011) and in 2014 for positive ignition engines (Regulation 133/2014). The limit is  $6 \times 10^{11}$  p/kWh for the transient cycle (weighing 14% the cold start cycle and 86% the hot start cycle) and  $8 \times 10^{11}$  p/kWh for the steady cycle. The SPN23 measurement procedure (Regulation 64/2012, UNECE Regulation 49) is almost identical to the light-duty vehicles procedure. The relevant GTR is UNECE GTR No. 4.

Since Euro VI the in-service conformity (ISC) testing of a heavy-duty engine is conducted on the road over normal driving patterns, conditions and payloads using PEMS (Regulation 582/2011). The testing is conducted over a mix of urban (50 km/h), rural, and motorway (highway) (> 75 km/h) conditions, with exact percentages of these conditions depending on vehicle category (Regulation 2016/1718). The first in-use test should be conducted at the time of type approval testing and the result should be lower than the Euro VI limit corrected with a conformity factor (1.5 for gaseous pollutants) that takes into account the PEMS measurement uncertainty and the test-to-test variability. The PEMS testing is currently applicable only to gaseous pollutants. After a long evaluation of the PM mass method with PEMS [10], in 2015 it was decided to evaluate the SPN23 method. The evaluations at JRC [11] and OEMs [12] were promising and the ISC SPN23 PEMS method will be introduced in the next years.

## 2.4. Non-Road Mobile Machinery (NRMM)

Regulation 2016/1628 repealed Directive 97/68/EC in 2016 and introduced SPN23 limits to non-road engines (19–560 kW), inland waterway vessels (> 300 kW), and rail traction engines in 2017. The procedures and test cycles (NRSC and NRTC) are described in Regulation 2017/654. The 05 series of amendments updates UNECE Regulation No. 96, based on the European regulation. The relevant GTR is GTR No. 11.

In service monitoring (no conformity factor) is applicable to 56–560 kW engines (Regulation 2017/655) with PEMS, but only for gaseous pollutants. A near future amendment will include 19–56 kW engines and above 560 kW, while < 19 kW engines are currently under a feasibility study by JRC.

In addition to the type approval SPN23 limits, Swiss Regulation SR 941.242 (published in 2015) mandates the in-use compliance testing of all construction machinery DPFs, bi-annually starting from 2017 (SPN23 limit 250 000 p/cm<sup>3</sup> at high idle).

## 2.5. L-category vehicles

Regulation (EU) 168/2013 provides the details of a revised vehicle classification together with the provisions for approval and market surveillance of L-category vehicles at Euro 4 (from 2016) and Euro 5 levels (from 2020). PM measurements were introduced at Euro 4 level with a lenient limit of 80 mg/km required for compression ignition (diesel) and gasoline direct injection (GDI) engines mounted on motorcycles, tricycles and minicars. A more stringent limit value of 4.5 mg/km is set at Euro 5 level for all sub-categories with GDI and compression ignition engines. No provisions on SPN23 were introduced. UNECE Regulation No. 40 (motorcycles) and UNECE Regulation No. 47 (mopeds) are outdated. The current GTR No. 2 does not contain SPN23 provisions either, but only PM and it is under revision by the relevant group within the UNECE (GRPE).

Article 23 of the Regulation 168/2013, mandated an environmental effect study to provide additional underpinning of the Euro 5 step through modelling, technical feasibility, and cost effectiveness analysis. JRC performed a Preparatory work phase [13] and Phase 1 [14] of this environmental effect study with the objectives to take stock of fleet and structure of the L-category vehicle sector, perform relevant data-mining, and to prepare the technical approach. The preparatory work showed that L-category vehicles can have high SPN emissions with a high percentage of them not counted by the current SPN23 protocol. However, it was argued that decreasing the lower detectable size could result in artefacts and more research was therefore considered necessary [15].

The final environmental study [16] concluded that introducing specific SPN23 limits for any L-category vehicles would first require better understanding of the emissions performance of such vehicles, as new emission control technologies at Euro 5 step become available. SPN emissions from L-category vehicles are mostly linked to lube oil consumption and upcoming stringent hydrocarbons limits at Euro 5 may be proven effective to control SPN emissions from such vehicles as well, without the need of mandating a separate SPN standard [16].

## 2.6. Other

Periodic Technical Inspection (PTI): Directive 2014/45/EU repealed Directive 2009/40/EC and includes only smoke (opacity) test for diesel vehicles. In general, there is no correlation between PM/PN emissions and smoke.

On-Board Diagnostics (OBD): There is only a PM limit for OBD (12 mg/km for light-duty vehicles and 25 mg/km for heavy-duty). NRMM do not have OBD requirements.

Low (ambient) temperature test (Type 6): Regulation 2017/1151 refers to UNECE Regulation 83. There is no PM or SPN limit.

## 3. PMP current activities

The following sections will summarise the progress on the topics that PMP deals with. Most topics relate to light-duty and heavy-duty vehicles. Nevertheless they are applicable to other vehicle categories as well.

### 3.1. Volatile Particle Remover (VPR) calibration

SPN23 systems consist of a Volatile Particle Remover (VPR), that dilutes the sample and removes volatiles, and a Condensation Particle Counter (CPC) that counts particles > 23 nm [4]. There are some concerns with respect to the accuracy of the instrument calibrations, and accordingly the comparability of results obtained using different commercial systems. A VPR inter-laboratory correlation study was launched in 2011 aiming at the assessment of the different VPR calibration procedures established by the different manufacturers. The “golden” VPR was a prototype two stage ejector system with an intermediate evaporation tube. The “golden” Aerosol Generator was a graphite spark generator. The “golden” instrumentation also included a CPC [17].

The average Particle Number Concentration Reduction Factor (PCRF) at 30, 50 and 100 nm values determined at eight of the total eleven laboratories using the golden instrumentation agreed within ±5%, but three laboratories measured systematically higher values (10%, 20% and 40%, respectively) (Fig. 1). This overestimation was most probably related to a backpressure build-up at the exit of the second ejector, as verified in the lab with the highest overestimation.

The graphite particles produced from the Golden aerosol generator were found to be thermally stable. However, they were highly charged and when not neutralized, the size classified particles contained a large fraction of larger particles. On the other hand, thermally treated 30 nm particles of diffusion flame soot generators CAST (Combustion Aerosol Standard) still shrunk in the VPRs. It was recommended that a low cut-off size CPC is employed when CAST or NaCl particles are employed in PCRF calibrations.

The inter-laboratory exercise also showed that an accurate calibration of the VPR with polydisperse aerosol (using SMPS) was difficult and required that the concentration was at levels that would freeze coagulation.

At PMP meetings the VPR calibration topics were discussed and the following conclusions were taken in order to reduce the permitted flexibilities [18]:

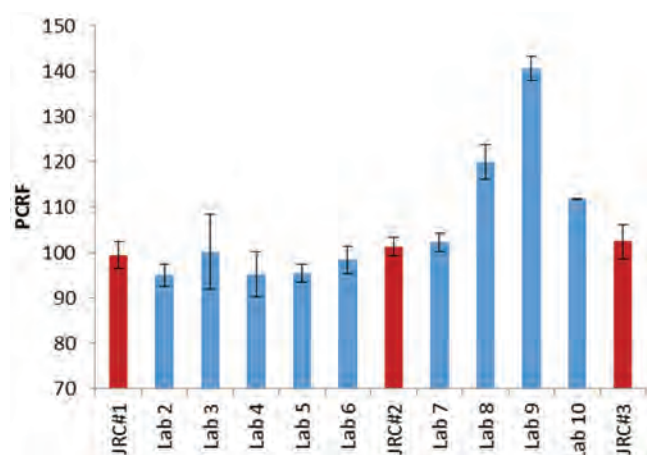


Fig. 1. Average Particle number Concentration Reduction Factors (PCRf) at 30, 50 and 100 nm graphite particles with the Golden aerosol generator and the Golden CPC at different laboratories [17]

- The reference CPC should have counting efficiency at 23 nm > 90%. It should be also calibrated for linearity.
- When the two CPCs method is used for calibration of VPRs, the two CPCs should be inter-calibrated.
- The stability of the aerosol during the VPR calibration should be improved from 10% to 5%.
- For the polydisperse validation a Count Median Diameter (CMD) and a Geometric Standard Deviation (GSD) should be defined. At the moment the suggestion is 45–55 nm and 1.6–1.8.
- The tetracontane requirements are easy to pass and a polydisperse test should be added: 1 mg/m<sup>3</sup> of alkane or emery oil is the suggestion.

### 3.2. CPC calibration

The legislation does not define a calibration aerosol for CPCs and studies have shown that it has an influence on the counting efficiencies [19]. An inter-laboratory calibration exercise for engine exhaust CPCs was launched in 2016 to assess the repeatability and reproducibility of soot-like aerosols. During this exercise, three CPCs and one soot generator were circulated among 7 laboratories in Europe. The circulated instruments were compared with in-house reference counters and in-house spark-discharge soot, diffusion flame soot, silver nucleation and emery oil generators [21].

Figure 2 summarises the results. At the plateau region there was no significant difference between aerosols. At 70 nm the CPC efficiency was 2–3% below its maximum counting efficiency with soot-like aerosol, while with emery oil even at 55 nm the efficiency was maximum. At 23 nm the soot-like aerosol average counting efficiency was between 27.0% and 32.0%, while emery oil averaged 49.3%. At 41 nm the soot efficiencies were between 77.2% and 79.7%, while with emery oil 91.5%. The variance among in-house soot generators was on the same level as emery oil (3.1 percentage points at 55/70 nm) at all particle sizes; however, the variability with emery oil was due to a drift of the CPC. The main conclusion was that soot-like aerosol from diffusion flame and spark-discharge generators is a suitable candidate for the harmonization of particle number calibrations in automotive exhaust applications;

however, there are still concerns whether it can reach the same levels of accuracy as the emery oil.

Interestingly, only half of the laboratories calibrated the circulating 10 nm CPC, indicating that the calibration at that size with soot-like particles is more challenging.

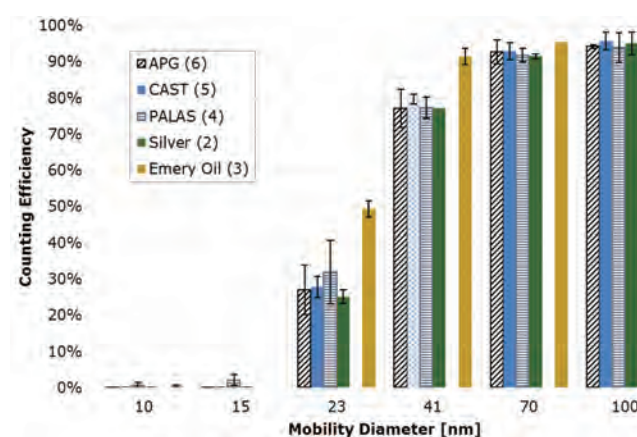


Fig. 2. Calibration results of the golden CPC with various particle generators across Europe. Number in brackets indicates number of laboratories [21]. APG = AVL Particle Generator (thermally stable CAST)

At PMP meetings the CPC calibration topics were discussed and the following conclusions were taken to reduce the permitted flexibilities [18]:

- The reference CPC should be calibrated according to ISO 27891.
- The slope should remain 0.9 to 1.1, but the residuals check should be reduced to  $\pm 4\%$  (from the slope).
- The CPC slope calibration k factor should be included (and reported).
- The ISO 27891 should be adopted with application notes when some parts are not applicable.

At the moment the prevalent view is that the calibration material should be soot-like and other materials should be adjusted to soot.

### 3.3. Regeneration

The emissions during regeneration events are taken into account by weighing the final emissions with the emissions during regeneration events and the regeneration frequency. At the moment this applies to heavy-duty and NRMM, but not to light-duty vehicles. The main reason is that during the PMP investigations and the light-duty inter-laboratory correlation exercise, it was found that the contribution of the regeneration emissions was negligible [21]. However, later studies showed that is not necessarily true for other more aggressive cycles including prolonged operation at motorway driving conditions [22]. The SPN23 emissions during phases with regeneration can exceed many times the Euro 5b PN limit. Subsequently, DPF sizes, filtration characteristics and material options have evolved, and more complex NO<sub>x</sub> and PN aftertreatment combinations are being employed. PMP investigated whether these changes require modifications to the regulatory procedure to adequately measure particles from regenerations [23], and whether there are any particular issues not to include regeneration in light-duty legislation.

Figure 3 (upper panel) shows the emissions of a vehicle during a regeneration event, measured with various instruments connected to the dilution tunnel (CVS). The total PN concentration (including volatiles), as measured by an Engine Exhaust Particle Sizer (EEPS) > 6 nm exceed  $10^7$  p/cm<sup>3</sup>. The SPN23 concentration is around  $10^4$  p/cm<sup>3</sup>, while SPN10 reaches  $10^6$  p/cm<sup>3</sup> at the beginning of the regeneration and stabilises at  $10^4$  p/cm<sup>3</sup> after 10 min. The SPN3 concentration is much higher for the whole regeneration event. It is important to note the robustness of the PMP protocol: The SPN23, SPN10, SPN3 emissions are not affected by a 10 times change of the PCRf (200 to 2000) during the test. Additionally, another system with catalytic stripper and a 10 nm CPC measured similarly with the PMP system and a 10 nm CPC (within experimental uncertainties and particle losses corrections). What is interesting though is that when the test was repeated with some instruments connected to the tailpipe (no instruments available at the CVS), the high sub-23 nm particles were not seen (Fig. 3 lower panel). For this test the accumulated soot/material was less.

The main conclusion is that the PMP methodology is robust enough to measure emissions during regeneration events (note that a PCRf of 1000 is recommended) [24]. The conclusion applies also to 10 nm measurements, although some concerns were raised for formation of “non-volatile” particles due to desorption of material from the vehicle or the tube between the vehicle and the CVS due to the high exhaust gas temperatures. Thus, it is important to properly precondition the vehicle and facilities before regeneration tests, in order to ensure minimum contribution from previous vehicles.

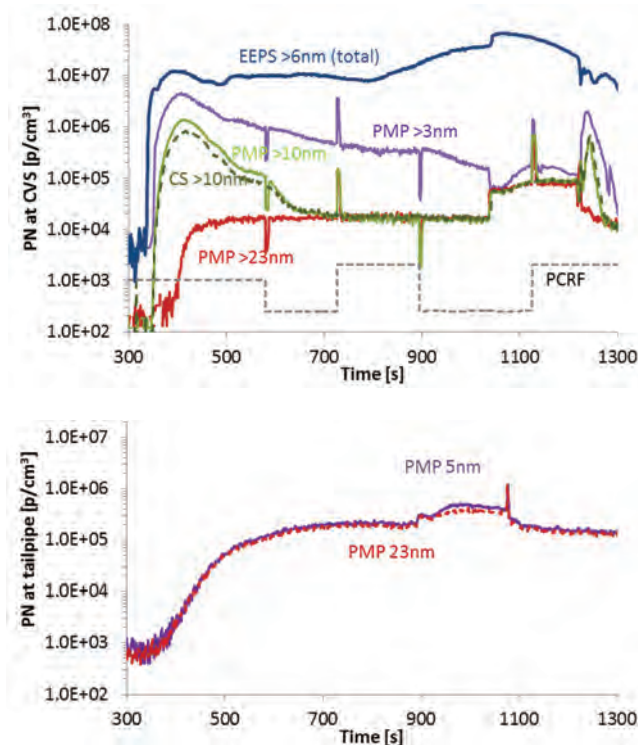


Fig. 3. PN emissions during triggered/forced regeneration with the vehicle parked. Upper panel: Measurements from the CVS. Lower panel: Measurements from the tailpipe (subsequent test) [25]

The emissions during regeneration events are taken into account by the  $K_i$  factor ( $i = \text{SPN23}$  in this case):

$$M_{pi} = (M_{si} D + M_{ri} d) / (D + d) \quad (1)$$

where:  $M_{si}$  are the mean emissions of compound  $i$  without regeneration (p/km),  $M_{ri}$  are the mean emissions of compound  $i$  during regeneration (p/km),  $M_{pi}$  are the mean emissions of compound  $i$  (p/km),  $d$  is the number of complete applicable test cycles required for regeneration,  $D$  is the number of complete applicable test cycles between two cycles where regeneration events occur.

$$K_i \text{ (factor)} = M_{pi}/M_{si} \quad (2)$$

$$K_i \text{ (offset)} = M_{pi} - M_{si} \quad (3)$$

The  $K_i$  factor is not included in the light-duty regulation and there is no information in the literature about SPN. Table 2 summarises the results of the PMP Golden vehicle [21], presented data [26] and a few more internal JRC data. The followed procedure was not exactly the one prescribed in the regulation (continuous cycles until regeneration). Between regeneration events different cycles were conducted (even on road tests), thus the  $K_i$  factors are approximations, but nevertheless realistic. No vehicle exceeds the SPN23 limit even when considering the regeneration events. However, there are vehicles that remain more than one order of magnitude below the SPN23 limit, and others that are close to the limit. The range of the  $K_i$  factors (0–91) or offset (0– $4.9 \times 10^{11}$  p/km) is very wide.

Table 2. Estimation of  $K_i$  factors for regeneration [21, 26]. All vehicles equipped with DPF

Vehicle	$M_{si}$ [p/km]	D [km]	$M_{ri}$ [p/km]	D [km]	$M_{pi}$ [p/km]	$K_i$	$K_i$ offset [p/km]
Euro 4*	$1.3 \times 10^{11}$	1000	$1.3 \times 10^{11}$	11.0	$1.3 \times 10^{11}$	1.0	0
Euro 5	$2.0 \times 10^{10}$	250	$2.0 \times 10^{12}$	23.2	$1.9 \times 10^{11}$	9.4	$1.7 \times 10^{11}$
Euro 5	$2.0 \times 10^{11}$	250	$1.4 \times 10^{12}$	11.0	$2.5 \times 10^{11}$	1.3	$5.1 \times 10^{10}$
Euro 6	$5.5 \times 10^9$	300	$6.9 \times 10^{12}$	23.2	$5.0 \times 10^{11}$	91	$4.9 \times 10^{11}$
Euro 6	$2.0 \times 10^{10}$	800	$2.0 \times 10^{10}$	23.2	$2.0 \times 10^{10}$	1.0	0
Euro 6	$1.0 \times 10^{11}$	500	$4.0 \times 10^{12}$	23.2	$2.7 \times 10^{11}$	2.7	$1.7 \times 10^{11}$
Euro 6	$2.0 \times 10^{10}$	450	$2.1 \times 10^{11}$	11.0	$2.5 \times 10^{10}$	1.2	$4.5 \times 10^9$
Euro 6	$6.7 \times 10^{10}$	450	$1.9 \times 10^{12}$	23.2	$1.6 \times 10^{11}$	2.3	$9.0 \times 10^{10}$
Euro 6	$2.7 \times 10^{10}$	250	$7.9 \times 10^{10}$	11.0	$2.9 \times 10^{10}$	1.1	$2.2 \times 10^9$

\* Golden PMP vehicle provided by AECC

### 3.4. Sub-23 nm instrumentation

A feasibility study [27] concluded that regulating below 10 nm is not recommended due to extreme particle losses in the commercial systems at the sub-10 nm range and the possibility of artefacts (re-nucleation or pyrolysis). For > 10 nm measurements, a catalytic stripper and/or high dilutions are recommended in order to reduce the possibility for re-nucleation and growth of re-nucleated material. Updating existing systems to measure below 23 nm (e.g. from 10 nm) is possible without big investment costs.

After the JRC feasibility study, preliminary draft technical specifications were based on existing PMP systems with the only additions (still draft) [28]:

- PCRf at 15 nm
- CPC with 50% (or higher) at 10 nm

The main open questions are:

- Should the catalytic stripper be obligatory or not? If yes, what are the minimum technical specifications of the catalytic stripper?
- How to take into account the particle losses below 30 nm? Is an additional PCRF at e.g. 15 nm enough? Should the mean PCRF include the 15 nm point (weighted or not)?

Obviously, in case of lowering the lower detectable size, the material for both PNC and VPR calibration has to be re-investigated and the calibration procedures need to be updated. Additionally, the SPN-PEMS specifications have to be adjusted accordingly.

Figure 4 presents the penetration curves of two commercial systems (one with evaporation tube [29] and the other with catalytic stripper [30]) and the difference between them when measuring particles of different count median diameters (CMD). The difference becomes important (> 10%) when the CMD becomes smaller than 30 nm.

In order to avoid uncertainties for size distributions with low CMD or more complicated approaches like in aviation, the easiest way is to include the 10 nm CPC in addition to the 23 nm CPC. This would increase the investment costs of the OEMs, but has the advantage that the > 23 nm approach could remain and the sub-23 nm information could be used separately (e.g. regulating in addition a maximum sub-23 nm fraction or level). With two CPCs the sub-23 nm concentration can be estimated as follows:

$$(\text{SPN}_{10}-\text{SPN}_{23}) \times \text{PCRF}_{15} / \text{PCRF} \quad (4)$$

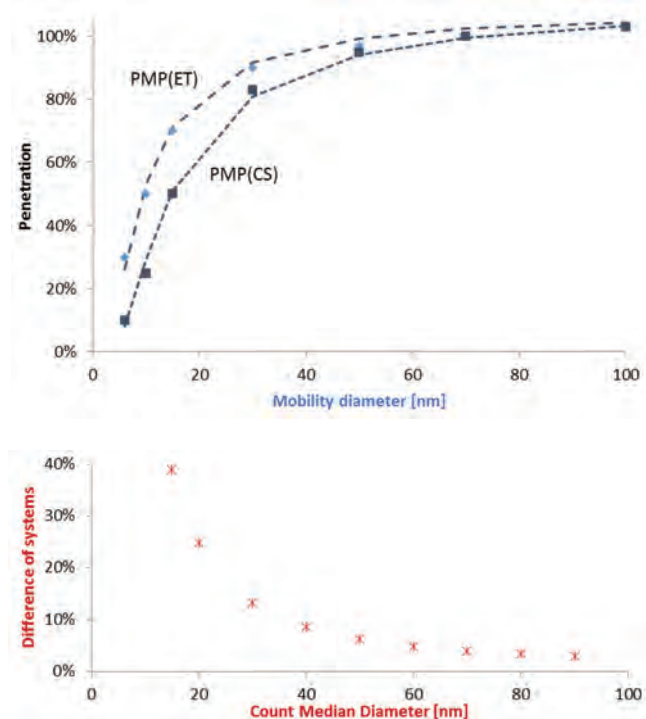


Fig. 4. Upper panel: Counting efficiency in function of monodisperse mobility diameter of two VPRs of PMP systems with Evaporation Tube (ET) [29] or Catalytic stripper (CS) [30] (examples). Lower panel: Difference of the two systems for various polydisperse size distributions with various Count Median Diameters (CMD)

### 3.5. Sub-23 nm round robin

In order to assess the repeatability and reproducibility of the SPN10 (and SPN23) method an inter-laboratory exercise was organised at the end of 2017. Two golden PMP systems (from different manufacturers) measured both from 10 nm and 23 nm and were compared with the lab systems measuring from 23 nm and additionally from 10 with two golden CPCs (from different manufacturers). The golden car was a GDI without particle filter. The testing started at JRC, Italy in October 2017 and the European part finished in June 2018.

The first results are promising and showed similar variability between 10 nm and 23 nm CPCs connected to systems with catalytic strippers [31].

### 3.6. Sub-23 nm monitoring

One major task of JRC is to monitor new technologies regarding existence of sub-23 nm particles. There are various JRC updates on the topic for light-duty [30, 32], L-category [15], heavy-duty [33]. Figure 5 summarises emission levels of various vehicle categories based on a few studies that focused on the most recent technologies: Euro VI heavy-duty vehicles, Euro 5 and Euro 6 light-duty vehicles (cold start included in the test cycle), Euro 2 and Euro 3 mopeds and motorcycles (cold start weighted 30%). Based on these results the sub-23 nm fractions are:

- 60–100% for spark ignition engines (natural gas, port fuel injection, mopeds and motorcycles)
- < 50% for diesel engines with or without DPF.

The conclusion of this study is that the solid sub-23 nm fractions can be significant; however, the sub-23 nm absolute emission levels might be low. For example, PFI vehicles are typically below the SPN limit even when including the sub-23 nm fraction. Thus, for regulatory purposes the current methodology still captures high emitters for most of the cases (i.e., a vehicle that passes with the 23 nm CPC would also pass with the 10 nm CPC and vice versa).

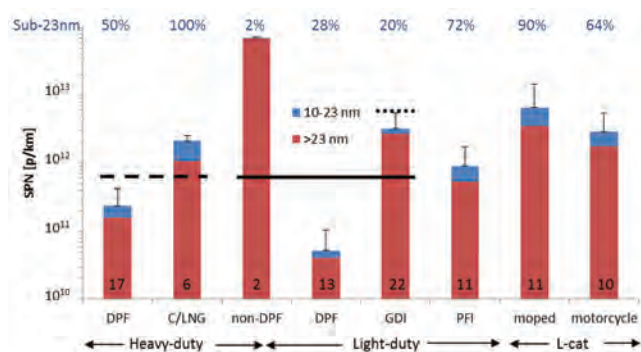


Fig. 5. Overview of emission levels of different current vehicle categories, based on JRC measurements [15, 30, 32, 33]. Error bars show one standard deviation (only positive side) for the number of vehicles shown in each bar. Horizontal lines give the European regulated SPN limits for SPN > 23 nm. Note that for the GDIs of this figure the limit was 6x10<sup>12</sup> p/km (dotted line). The dashed line shows a limit of 6x10<sup>11</sup> p/km. However, the SPN limit applies only to heavy-duty engines (not vehicles) and is expressed in p/kWh. All tests were conducted at temperatures around 23°C

### 3.7. Low temperatures measurements

The emissions during low ambient temperatures (Type 6 test) of Regulation 2017/1151 refer to the UNECE Regulation 83. No SPN23 emissions are covered. The topic is

under discussion for the next revision of WLTP focusing on an engine/vehicle technology independent test procedure covering all pollutants (including SPN23). The PMP contribution was only to ensure that SPN23 are feasible without any particular requirements. The WLTP revised version will require that no condensation takes place until the measurement of the SPN23 (or PM) at  $-7^{\circ}\text{C}$ .

Figure 6 summarises JRC results of the last years on the topic. The emissions are always higher at lower ambient temperature when there is no particle filter. When there is a particle filter (DPF or GPF) the emissions are usually higher but not always. Nevertheless, in this case, they remain below the  $6 \times 10^{11}$  p/km limit.

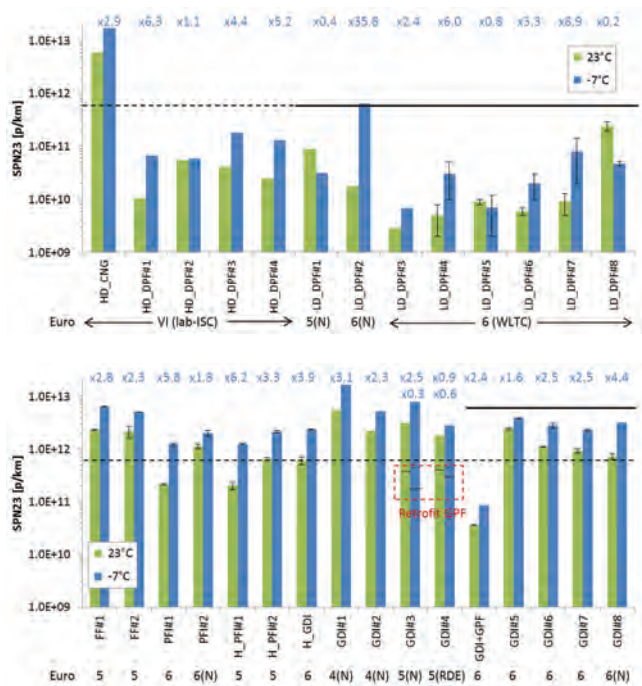


Fig. 6. Emissions from various vehicles at  $23^{\circ}\text{C}$  and  $-7^{\circ}\text{C}$ . Upper panel: Heavy-duty (HD) vehicles and light-duty (LD) diesel vehicles. Lower panel: Gasoline light-duty vehicles. Data from [22, 32–37]. The solid line show the applicable limits of  $6 \times 10^{11}$  p/km for diesel light-duty vehicles and  $6 \times 10^{12}$  p/km for GDIs. Dashed lines are aid to the eye. The SPN limit applies only to heavy-duty engines (not vehicles) and is expressed in p/kWh. “N” for NEDC. Euro level is shown at the lower part of the figures. Ratio of  $-7^{\circ}\text{C}$  to  $23^{\circ}\text{C}$  SPN23 emissions is given at the upper part of the figures

### 3.8. Raw exhaust sampling via fixed dilution

For type approval of light-duty vehicles raw exhaust sampling is not allowed. For heavy-duty vehicles proportional partial flow sampling systems are necessary for transient cycles. The reason is that proportional sampling is needed for the filter mass method to be equivalent to the full dilution method. However, the SPN method measures in real time, thus SPN emissions can be calculated if the exhaust flow rate is known. The investigations on the topic will follow these steps:

- Collection of experimental data (comparisons of CVS, partial flow systems and raw exhaust measurements with fixed dilution).
- Theoretical uncertainty analysis.
- Decision on technical specifications, in case raw exhaust sampling is proven to be robust and accurate.

The plan is to start with the heavy-duty evaluation because the conditions there are more extreme compared to light-duty vehicles (exhaust gas temperatures, high bio-fuel content, passive regenerations, pressure pulsations etc.) [38, 39].

Figure 7 summarises the experimental data available in the literature until today. The studies that were found are:

- JRC study with a Euro III engine equipped with different DPFs and a US2007 engine [40].
- PMP Heavy-duty inter-laboratory exercise [41]
- OEMs SPN PEMS validation [12]
- MAN study with a Euro VI diesel and a Euro VI CNG engine [42]
- CUMMINS study with Euro VI engines [43]
- HORIBA study with a DPF equipped engine [44]
- JRC light-duty SPN PEMS study [45]

In general the mean differences between raw exhaust (tailpipe) sampling and CVS or PFDS are within 30%.

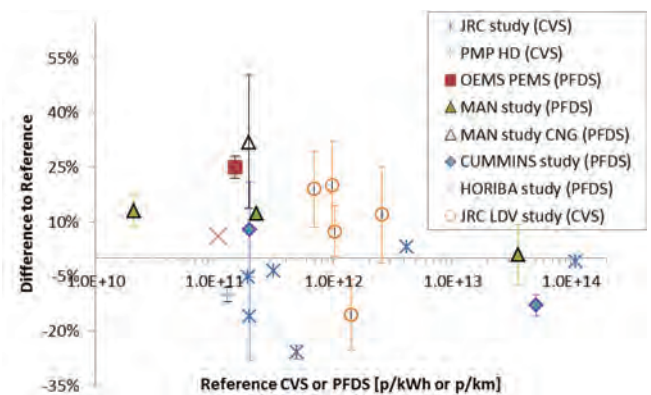


Fig. 7. Differences of SPN23 systems at the tailpipe from SPN23 systems at the CVS or PFDS. Each point is an engine with at least 3 tests. Error bars show one standard deviation of the differences

## 4. SPN PEMS

The interest for developing a procedure for on road testing of light-duty vehicles using Portable Emission Measurement Systems (PEMS) for SPN23 was announced in November 2012. In April 2013 the kick-off meeting took place. The group worked intensively and continuously until the end of 2015 on this issue. This work was independent from PMP activities.

### 4.1. Theoretical evaluation

In a preliminary study [46] a theoretical evaluation was conducted and showed that Diffusion Chargers (DCs) could be an acceptable alternative to CPC-based systems, if an extra uncertainty of around 50% when compared to CPCs would be acceptable. Based on the findings of that study, the minimum required specifications of the DCs were drafted.

### 4.2. JRC experimental evaluation: Phases I and II (light-duty)

At a next step (end of 2013) various prototype SPN23 PEMS (based on DCs) were evaluated in a chassis dynamometer lab to assess and validate the application and performance of portable SPN23 instrumentation [47]. The systems were measuring from the tailpipe and were compared to reference SPN23 systems (i.e. PMP compatible) at

the tailpipe and the full dilution tunnel with Constant Volume Sampling (CVS).

The results from three GDIs and one DPF equipped vehicle showed that the best performing SPN-PEMS (DC-based) was up to 100% higher when compared to the reference system at the dilution tunnel (CVS). Based on the findings of the previous studies, the technical requirements of the SPN-PEMS were drafted.

In the second evaluation Phase (which started in September 2014 and lasted till the end of that year) 8 SPN-PEMS (5 of them DC-based) were compared with legislation compliant SPN systems connected to the tailpipe and the dilution tunnel (CVS) [45]. The results of 7 GDIs, 3 PFIs, 2 DPFs, 3 motorcycles and 1 moped, confirmed the findings of Phase I: Diffusion Charging (DC) based systems are a feasible option to measure SPN. The best performing SPN-PEMS (DC-based, the same as in Phase I) had differences from the reference instrument at the dilution tunnel within 50% (with only a few exceptions).

However, one CPC-based SPN-PEMS, which arrived later in the program, had behaviour equivalent to the reference systems and better real time comparability with the reference systems compared to the DC-based systems. Further evaluation of the system after the campaign with another 10 vehicles confirmed these findings [45]. Based on the experimental data new and stricter efficiencies for SPN-PEMS were recommended for the technical requirements in order to reduce the measurement uncertainty of DCs at the CPC levels.

#### 4.3. Inter-laboratory correlation exercise (light-duty)

The inter-laboratory exercise, which took place between September 2015 and December 2015 (one more lab measured in May 2016), aimed to assess the accuracy and precision of the method using two different SPN-PEMS (one DC-, and one CPC-based) on one Golden Vehicle in different laboratories across Europe directly involving other stakeholders, such as industry and technical services.

The SPN-PEMS DC-based deviation from PMP-CVS ranged from -34% to 53%, while SPN-PEMS CPC-based deviation from PMP-CVS ranged from -40% to 46% [48]. However, it should be noted that the main reason for these deviations was that some of the PMP-CVS systems were over- or underestimating (i.e., probably they had calibration issues).

#### 4.4. JRC experimental evaluation (heavy-duty)

At the end of September 2015, in a heavy-duty vehicles PEMS meeting, it was decided to evaluate the particle number method, because the filter based PEMS method was not sensitive enough. The kick-off meeting was held in Ispra (Italy) in October of 2015. JRC evaluated some SPN PEMS instruments in the lab and on the road at different ambient temperatures from February until June 2016 [11] and then the commercial instruments in September 2016 [49]. The differences of the SPN-PEMS to the reference system at the dilution tunnel (PMP-CVS) were found within 35–50% for temperatures > 0°C for both DC- and CPC-based systems.

#### 4.5. OEMs validation exercise

After the JRC evaluation, the European Automobile Manufacturers Association (ACEA) started the validation

phase testing an even wider range of engines and vehicles. One SPN PEMS (CPC-based) instrument was also circulated to all participants to evaluate the measurement uncertainty of the methodology with SPN PEMS. The two CPC-based PEMS had mean differences compared to the reference PMP systems of better than 20% with a standard deviation of 22%. The two DC-based systems had mean differences of 80% and decrease to less than 40% when a PMP correction was applied or if only emission levels >  $3 \times 10^{11}$  p/kWh were considered [12].

A theoretical study on the maximum expected uncertainty found a margin of around 63% [50]. Half of this uncertainty comes from the particle detector (33%) and up to 25% due to particle losses and dynamics, especially for CNG engines.

Figure 8 summarises, as an example, the results of the CPC-based SPN PEMS for all campaigns.

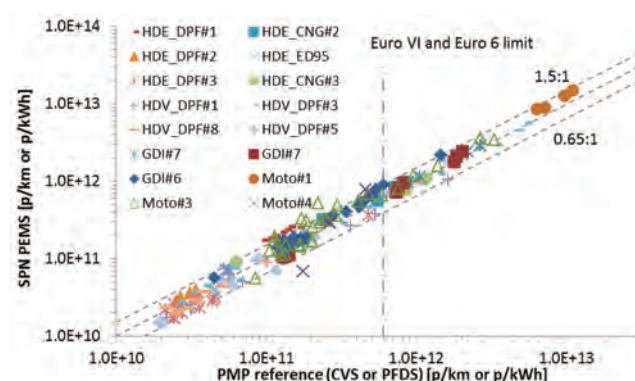


Fig. 8. Summary of L-category, light-duty and heavy-duty results for a CPC-based SPN PEMS compared to reference PMP systems at the full dilution tunnel (CVS) or proportional partial flow dilution systems (PFDS). Each point is a test cycle. Data from [11, 12, 45]

### 5. Horizon 2020 projects

One of the challenges identified in the GV-02-2016 Call ‘Technologies for low emission light duty powertrains’ was to create opportunities for real breakthrough research by addressing the need of the legislation and automotive industry for a sound metrological base for exhaust particles < 23 nm and by supporting the translation of findings into practice. Special attention should be paid on particle emissions of positive ignition engines under real driving conditions, since the emissions measured during the certification process do not always represent these in real world conditions. Three projects focus on the development of measurement systems (DownToTen [51], SUREAL-23 [52], PEMS4Nano [53]) with similar objectives:

- Investigate and quantitatively describe the nature and the characteristics of nanoparticles < 23 nm (formation, origin, physical and chemical character);
- Develop and set up a synthetic aerosol bench – similar to synthetic exhaust gas bench – and use it for fundamental studies at instrument level. Facilitation of metrology and evaluation purposes;
- Evaluate existing, proposed and under development particle measurement instruments against rigorous criteria for the measurement of the sub 23 nm particles, with emphasis on the performance within the demanding and hostile environment of PEMS;

- Analyse exhaustively and compare a large number of possible sampling and sample conditioning configurations (including dilutors, catalytic stripper, evaporation tube, thermodenuder, Constant Volume Sampling (CVS)). Benchmark them against a well-defined set of criteria (incl. losses, efficiencies, uncertainty, repeatability, reproducibility, robustness etc.) and under varying conditions of challenging aerosol from a variety of sources. Select the most promising combinations for further usage;
- Set-up an appropriate Particle Number – PEMS demonstrator that will materialise the findings and suggestions with respect to PN detection and sampling and conditioning;
- Use the above to measure a number of current and future engine and vehicle technologies as well as state-of-the-art exhaust aftertreatment systems in the laboratory and in real world conditions.
- Develop and propose an appropriate sampling and measurement methodology for the sub 23 nm particles both in the laboratory and real driving conditions to be employed during engine and vehicle type approval.

The progress of the projects is presented at the PMP meetings since October 2016.

## 6. New Periodical Technical Inspection (NPTI)

An initiative of VERT, launched in November 2016, addresses the needs of tamper-proof methods for exhaust assessment [54]. The initiative focuses on "New periodic technical inspection" (NPTI). The initiative is supported by the European Union as well as the governments of Germany, the Netherlands, Belgium, and Switzerland. The VERT/TNO NPTI proposal with the particle number test in idle run for diesel vehicles is summarised in a White Paper [55]. It is assumed that the process will be suitable with minor if any modifications also for petrol engines. The instrumentation is still under development. The first results are promising. Instruments in their prototype stage are already capable of recognizing vehicles that have been manipulated using partial bypass that resulted in SPN23 emissions close to maximum allow type approval levels (i.e.  $6 \times 10^{11}$  p/km) (see Fig. 9) and present a satisfactory correlation with SPN PEMS compliant instrumentation. Work on the testing procedure and pass/fail limit is still on going. This work is also under the evaluation of the Roadworthiness Technical Working Group which focuses on the roadworthiness aspects of tampering with exhaust emission control systems.

In September 2017 the Federal Council in Germany passed a law which demands periodical technical inspection of tailpipe emission applicable since January 2018 for gaseous pollutants (but currently no  $\text{NO}_x$ ) and from January 2019 for particles.

Figure 9 summarizes the results from different studies:

- TNO study at low idle with three vehicles [56]
- JRC NPTI instruments pre-evaluation with one DPF equipped vehicle with bypass at low idle [57]
- SPN-PEMS evaluation study using idle data of the NEDC and WLTC [45].

The results show a medium correlation between emission levels during type approval cycle (NEDC or WLTC) and low idle emissions even with SPN-PEMS instruments. The scatter further increases when first generation NPTI instruments are included. Any low idle limit has to take into account this scatter, but the technical specifications of NPTI instruments should have acceptable uncertainty, with low cost.

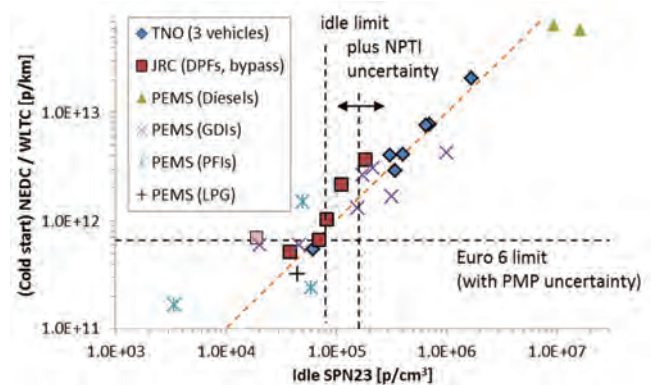


Fig. 9. Emission factor (#/km) during NEDC or WLTC vs raw exhaust concentration (#/cm<sup>3</sup>) measured during low idle with different PMP or SPN-PEMS instruments based on the PEMS project (Chapter 4). TNO data from [56]. JRC data and NPTI uncertainty estimation from [57]

## 7. Market surveillance

After the VW scandal a European Type Approval Authorities Experts Group (TAAEG) was set [58, 59] to ensure uniform application of the requirements for motor vehicles within the Community type-approval system, and to facilitate the exchange of information and experience regarding the implementation of type-approval legislation for vehicles. From the discussions of this group and with the contribution of the JRC, the Commission has published a guidance note to evaluate emissions strategies and to detect the presence of defeat device [60]. From this guidance, several requirements were included in the RDE regulation, with for instance the requirement of the manufacturer to provide to the Granting Type approval Authorities (GTAA) the extended documentation describing the auxiliary emission strategy of its vehicle (included in RDE 3<sup>rd</sup> package). Additionally, this guidance defined the requirements for an efficient in-service conformity checking, many of which have been included in the RDE 4, voted in May 2018.

In parallel, a revision of the EU type-approval framework was voted in 19 April 2019 that will replace Directive 2007/46/EC. Member states will be able to take measures (including ordering vehicle recalls and revoking type-approval certificates) against non-compliant vehicles sold in their national markets, instead of having to wait for the type-approval authority of the country that issued the vehicles' type-approval certificate to take action. The new type-approval framework introduces also an effective market surveillance system to control the conformity of vehicles already in circulation. The new Regulation for type-approval and market surveillance of motor vehicles will enter into force on September 2020, and the first in-service conformity testing in September 2019. While the focus is mostly  $\text{NO}_x$  and  $\text{CO}_2$ , SPN is also being checked through

this new in service conformity process, as all the regulated pollutants.

## 8. Non-exhaust particle emissions

There is currently no regulation related to brakes particle emissions neither in Europe nor in any other part of the world [61]. This is due to several reasons with the most important being the lack of accurate scientific data on the relative contribution of brake wear particles to overall PM<sub>10</sub> pollution, the inaccurate – and sometimes outdated – brake wear PM<sub>10</sub> and PM<sub>2.5</sub> emission factors reported in the literature as well as the lack of health studies directly linking brake wear particles to adverse health effects [62]. The PMP group is currently working on the development of a standardized test procedure for sampling, measurement and characterization of brake wear particles. The main goal of the methodology is to provide researchers and interested parties with a commonly accepted procedure for assessing real-world brake particle emissions. The first step of the procedure includes the development of a real-world braking test cycle. Real world PM and PN emission factors can be reported only if real world driving and braking conditions are examined. The analysis of the WLTP database showed that in many cases the driving conditions applied by researchers to study brake wear emissions were substantially different from real world driving and braking situations [63]. Further comparison of real-world driving and braking data with existing industrial braking cycles showed that the latest are very aggressive and in any case not representative of real world conditions [64]. For all these reasons it was decided to go towards the development of a completely new real-world braking test schedule. At the same time, the PMP is working on the development of a suitable methodology for sampling brake wear particles as well as on selecting the most suitable existing methods for brake wear particles' measurement and characterization. For that reason, a dedicated Task Force has been created within the PMP with the aim of accelerating the work [65]. The focus of the Task Force is on developing a methodology suitable for PM and PN concentration measurement. This is necessary as there is a great diversity among the published results. The Task Force includes representatives from the brake industry, OEMs, instrument manufacturers, regulatory bodies and universities/research institutes thus ensuring a holistic as well as a thorough technical support. The cycle was circulated through the PMP website in July 2018 and the goal is to deliver the proposed methodology by the end of the current mandate in June 2019. Figure 10 presents some PM mass and SPN results. Although the PM mass emissions over WLTCs can exceed the vehicle exhaust PM limit, the SPN emissions are very low.

Regarding tyre wear particles there is no regulation related to its particle emissions neither in Europe nor in any other part of the world [61]. Except for the reasons listed above and which also apply to tyre wear particle emissions, there is the issue of the direct dependence of tyre wear emissions to the type of road/pavement which makes it more difficult to regulate [68]. The PMP communicated the difficulties to the GRPE and made clear that a full scale investigation of the tyre related open issues would require a time and resource consuming large scale experimental

project. Neither the PMP, nor the JRC, had the necessary resources to perform such an experimental project. The GRPE decided to continue monitoring on-going projects and published data regarding the physical nature and size distribution of particle emissions from tyre wear and committed to eventually provide a report to GRPE on the investigation status and recommended next steps. In the meantime, JRC decided to perform a joint study with the Swedish National Road and Transport Research Institute (VTI) with the aim of exploring whether there is a relation between the Treadwear Rating (TWR) declared by the manufacturers at the sidewall of the summer tyres and the tread mass loss of the tyre. The relation between the TWR and the generation of tyre wear dust in the form of PM<sub>10</sub>, PM<sub>2.5</sub> and (S)PN concentration were also explored. The results of this study have been presented at the 47<sup>th</sup> PMP Meeting and will serve as a starting point for the discussion which will follow in order to come up with a recommendation for the next steps. The initial idea is to bring to the GRPE the need for the development of a standardized methodology for measuring the abrasion of the tyres. Such a methodology would give the opportunity to study not only tyre wear particle emissions but also emissions of other pollutants (i.e. microplastics).

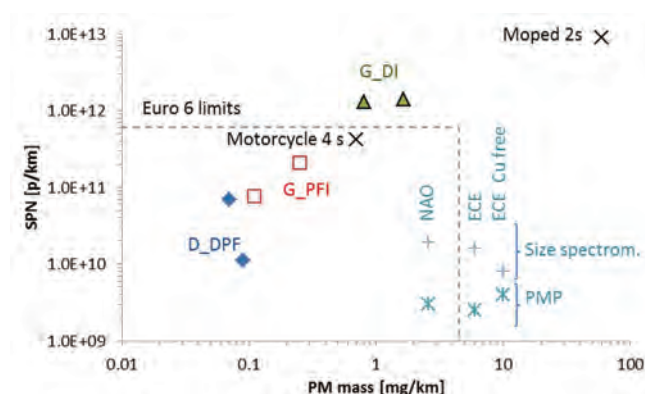


Fig. 10. PM mass and SPN measurements from a dilution tunnel using series-production pads from European market (ECE) and of non-asbestos organic (NAO) type (US market) with or without copper (Cu free). Results from [66, 67]. Results from exhaust emissions of various vehicles is also given for comparison [30]

## 9. Next steps: Post Euro VI and Euro 6

The major issues the last years were the development of more representative test cycles and procedures (WLTP) and on-road testing of vehicles. Even though RDE and WLTP were introduced, many other challenges lay ahead: Increased use of alternative fuels, electrification, the use of new technologies, increasing connectivity and automation and the advancement of measurement techniques, raise the need to evaluate what pollutants should be regulated in the future and how. Some of the main issues to be addressed, and closely related to SPN emissions, are:

- Review of the existing emission limits: Is there a need for a further reduction?
- Unregulated pollutants, including lower detected particle size.
- Full exploitation of on-board diagnostics and on-board monitors.

- Review of all existing tests (necessity, international harmonisation).
- Review of test cycles (mostly relevant for NRMM).
- Durability requirements review.
- Anti-tampering protection (especially at software level).
- Non-exhaust emissions.
- Interior vehicle air quality.
- Harmonization of regulations.

However, it is too early to foresee any directions, because it is still brainstorming and collection of input period.

## 10. Conclusions

The European vehicle emissions regulation includes a solid particle number > 23 nm (SPN23) limit for light-duty, heavy-duty on-road, and non-road mobile machinery (NRMM). For L-category vehicles at the moment the SPN emissions are being monitored by JRC.

In-Service Conformity testing includes SPN measurements with Portable Emissions measurement Systems (PEMS) for light-duty and heavy-duty vehicles. The additional uncertainty of SPN23 PEMS is covered with a so-called Conformity Factor (CF) that includes a margin for the instrument uncertainty. The uncertainty was based on theoretical and experimental evaluation at JRC and other laboratories.

The main topics that are under discussion at the moment are:

*Calibration procedures:* Some requirements that can be narrowed have been identified for both VPR and CPC calibrations. A very important finding is that soot-like aerosol is a suitable candidate for CPC calibration harmonizing the material for the various applications (VPR, CPC, PEMS).

*Regeneration:* The investigations confirmed that PMP systems can be used without any artefact issues during regeneration events of light-duty vehicles. Today there are no particular concerns that including the  $K_i$  factor will result in high emissions for DPF equipped vehicles. However this will be important if the emission limit is decreased.

*Sub-23 nm feasibility:* The feasibility study summarised that lowering the current lowest detectable size of 23 nm down to 10 nm is possible without large investment costs. An inter-laboratory exercise with prototype systems is currently on-going to confirm the theoretical assumptions. The two main open questions are 1) whether a catalytic stripper should be obligatory or not, and its specifications, and 2) how to take into account the losses at the sub-23 nm range. A simple solution could be to leave the PCRf as it is

today. A more accurate solution is adding a 10 nm CPC to the existing 23 nm CPC. However the feasibility of such solution for regulatory purposes has to be discussed.

*Sub-23 nm monitoring:* The sub-23 nm fraction is relatively high for spark-ignition engines exceeding 60%. However, at the moment the 23 nm lower detectable size captures the majority of vehicles exceeding the legislation limit.

*Low temperatures testing:* The testing is possible. At  $-7^\circ\text{C}$  the emissions increase by a factor of > 2 in most cases without a particle filter.

*Raw exhaust sampling:* Preliminary literature overview showed that raw exhaust systems are within 30% of regulated systems. A more detailed experimental investigation is foreseen in the near future.

*SPN-PEMS:* The experimental uncertainty of the systems (plus the raw exhaust sampling) is around 50–60% today. Next steps include extension of PEMS testing to regulations that have a SPN laboratory limit (e.g. heavy-duty engines and NRMM).

*NPTI:* The on-going activities regarding new periodical technical inspection for particle number are promising. It seems feasible to measure at idle with sensors and identify a mal-functioning DPF. The technical specifications are being drafted and extension to gasoline engines is under-going.

*Non-exhaust emissions:* A test cycle has been prepared for brake wear emissions and the sampling methodology is under discussion. Tyre wear emissions will be investigated in more details the future.

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## Conflicts of Interest

The authors declare no conflict of interest.

## Disclaimer

The opinions expressed in this manuscript are those of the authors and should in no way be considered to represent an official opinion of the European Commission. Mention of trade names or commercial products does not constitute endorsement or recommendation by the authors.

## Nomenclature

ACEA	Association for Emissions Control by Catalyst
CAST	Combustion Aerosol Standard
CF	Conformity Factor
CMD	Count Median Diameter
CNG	Compressed Natural Gas
CPC	Condensation Particle Counter
CS	Catalytic Stripper
CVS	Constant Volume Sampler
DC	Diffusion Charger
DPF	Diesel Particulate Filter

ED95	95% Ethanol fuel
EEPS	Engine Exhaust Particle Sizer
ET	Evaporation Tube
EU	European Union
GDI	Gasoline direct Injection
GRPE	Working Party on Pollution and Energy
GSD	Geometric Standard Deviation
GTR	Global Technical Regulation
HD	Heavy-Duty
HDE	Heavy-Duty Engine

HDV	Heavy-Duty Vehicle	PN	Particle Number
ISC	In-Service Conformity	PTI	Periodic Technical Inspection
JRC	Joint Research Centre	RDE	Real-Driving Emissions
LD	Light-Duty	SPN	Solid Particle Number
NEDC	New European Driving Cycle	TAAEG	Type Approval Authorities Experts Group
NPTI	New periodic Technical Inspection	TWR	Treadwear Rating
NRMM	Non-Road Mobile Machinery	UN	United Nations
NRSC	Non-Road Steady Cycle	UNECE	United Nations' Economic Commission for Europe
NRTC	Non-Road Transient Cycle	VERT	Verification of Emission Reduction Technologies
OBD	On-Board Diagnostics	VPR	Volatile Particle Remover
OEM	Original Equipment Manufacturer	WHSC	Worldwide Harmonized Stationary Cycle
PCRF	Particle number Concentration Reduction Factor	WHTC	Worldwide Harmonized Transient Cycle
PEMS	Portable Emissions Measurement System	WLTC	Worldwide harmonized Light-Duty Transient Cycle
PFDS	Proportional partial Flow Dilution System	WLTP	Worldwide harmonized Light-Duty Test Procedure
PFI	Port Fuel Injection	WMTC	Worldwide harmonized Motorcycle Transient Cycle
PM	Particulate Matter		
PMP	Particle Measurement Programme		

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## Testing and evaluating real driving emissions with PEMS

*Testing of real driving emissions (RDE) with portable emission measuring system (PEMS) in an appropriate road circuit became an obligatory element of new type approval of passenger cars since September 2017.*

*In several 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. Particle number measuring systems (PN PEMS) were also included in the tests.*

*The present paper informs about influences of E85 on RDE on two flex-fuel-vehicles, discusses some aspects of different ways of evaluation with different programs, shows comparison of different types of PN PEMS and represents the effects of simulation of slope on the chassis dynamometer.*

**Key words:** RDE evaluation, RDE with Ethanol, PN PEMS, simulation of slope and normality of RDE results.

### 1. 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) [1–3]. 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 behavior and the course of the route during the RDE test. [6–8].

There are new requirements and challenges for all market participants: the industry has to adapt the R&D processes of engines, [9–11]; the measuring technics, including PN PEMS are continuously improved and developed, [12, 13] and 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].

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.

Several countries have objectives to substitute a part of the energy of traffic by ethanol as the renewable energy source and some manufactures introduced the FFV (Flex-Fuel Vehicles) variants and published extensive information about their R&D and performances: GM/Saab [15, 16]; Toyota [17]; VW [18]. The RDE with two FFV's and especially with E85 were investigated in the present work.

### 2. Test installation

#### 2.1. 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<sub>2</sub>...infrared analysers (IR)
  - HC<sub>FID</sub>...flame ionization detector for total hydrocarbons
  - CH<sub>4FID</sub>...flame ionization detector with catalyst for only CH<sub>4</sub>
  - NO/NO<sub>x</sub>...chemiluminescence analyzer (CLA)

The dilution ratio DF in the CVS-dilution tunnel is variable and can be controlled by means of the CO<sub>2</sub>-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 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.

#### 2.2. GAS PEMS and PN PEMS

An information about the used Horiba Gas PEMS and about the gas measuring installation of the chassis dynamometer is given in Table 1.

As PN PEMS for Real Driving Emissions two systems were used and compared:

- NanoMet3 from TESTO (NM3). This analyzer works on diffusion charging (DC) principle, has an integrated sample conditioning system, as described above for chassis dynamometer and it indicates the solid particle number concentration and geometric mean diameter in the size range 10–700 nm.

– Horiba OBS-ONE PN measurement system (OBS-PN). This analyzer works on the condensation particles counter (CPC) principle, has an integrated sample conditioning system (double dilution and catalytic stripper ViPR, 350°C) and it indicates the summary PN concentrations in the size range 23 to approximately 1000 nm.

Both systems present several advantages like compactness, robustness, fast on-line response and both are recognized for legal testing purposes.

Table 1. Overview of used measuring systems

	HORIBA MEXA 7200	HORIBA OBS ONE
	4x4 chassis dyno CVS	PEMS <sup>Ⓞ</sup> wet
CO	NDIR	heated NDIR
CO <sub>2</sub>	NDIR	heated NDIR
NO <sub>x</sub>	CLD	CLD
NO	CLD	CLD
NO <sub>2</sub>	calculated	calculated
O <sub>2</sub>	-	-
HC	FID	-
PN	not measured	-
OBD logger	-	yes
GPS logger	-	yes
ambient (p, T, H)	yes	yes
EFM	-	pitot tube

OBS - one H<sub>2</sub>O monitored to compensate the H<sub>2</sub>O interference on CO and CO<sub>2</sub> sample cell heated to 60°C

### 3. Test procedures

#### 3.1. Driving cycles on chassis dynamometer

The vehicles were tested on a chassis dynamometer in the dynamic driving cycle WLTC, Fig. 1,

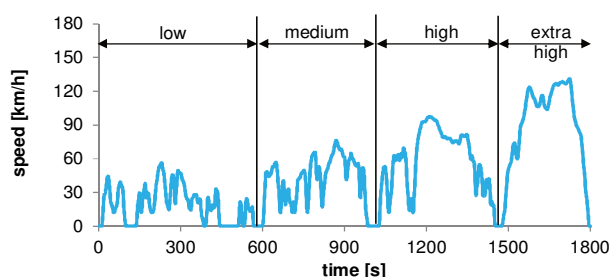


Fig. 1. WLTC driving cycle

For the research about „slope” a part of real world cycle (like in Fig. 2) was reproduced on the chassis dynamometer.

For the research with different fuels important objective was to always keep the same procedure of changing the fuel quality. The fuel change was performed at the day preceding the tests. The fuel tank was emptied and filled with the new fuel. Than the vehicle was pushed on the chassis dynamometer, cold-started and driven in one WLTC as condi-

tioning. Than the vehicle stayed on the chassis dyno until the next test-day.

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

#### 3.2. 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 1.5 h duration and parts of urban, rural and highway roads. Figure 2 represents an example of a road trip from the PN PEMS test program.

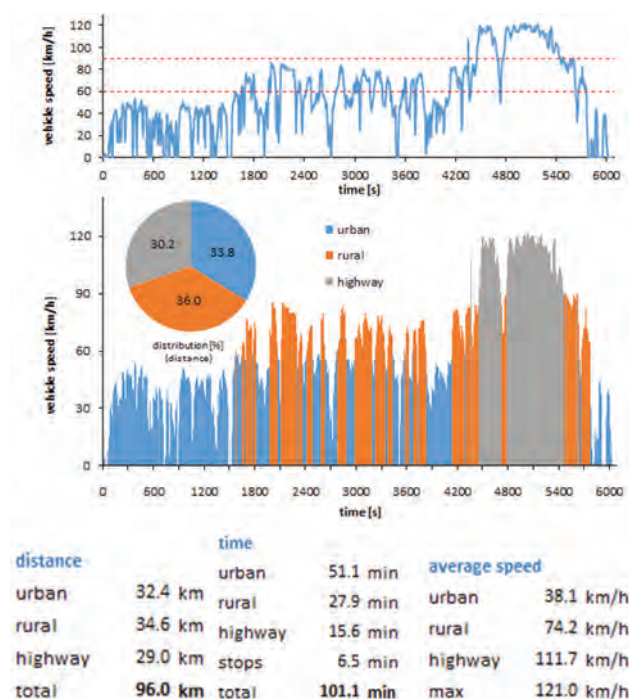


Fig. 2. AFHB, road trip for RDE

#### 3.3. Test vehicles and fuels

The tests were performed with two Euro 5 flex fuel vehicles: Volvo V60 (GDI) and Audi A4 TFSI (GDI).

Both vehicles were equipped with PEMS and tested on-road with E0 & E85. Fig. 3 shows the vehicles in laboratory and Table 2 gives the most important data.

Table 2. Data of tested vehicles

Vehicles	Volvo V60 T4F FFV gasoline (V1)	Audi A4 2.0 TFSI FFV gasoline (V2)
Number and arrangement of cylinder	4 in line	4 in line
Displacement cm <sup>3</sup>	1596	1984
Power kW	132 @ 5700 rpm	132@4000 rpm
Torque Nm	240 @ 1600 rpm	320@1500 rpm
Injection type	Direct injection (DI)	Direct injection (DI)
Curb weight kg	1554	1570
Gross vehicle weight kg	2110	2065
Drive wheel	Front-wheel drive	Front-wheel drive
Gearbox	a6	m6
First registration	2012	2010
Exhaust	Euro 5a	Euro 5

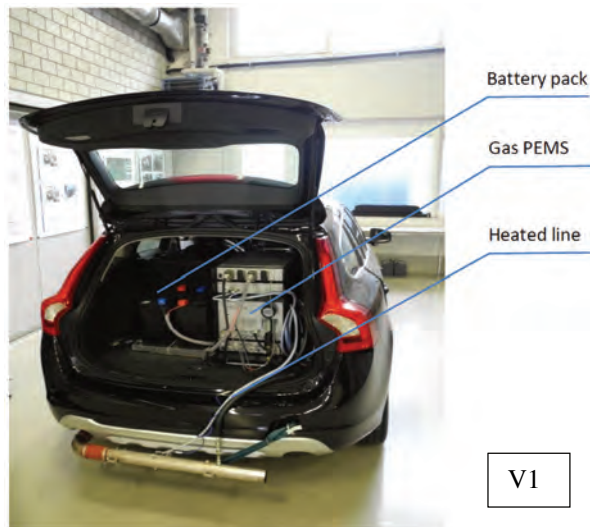


Fig. 3. Tested vehicles (FFV) equipped with PEMS

### 3.4. Fuels

The gasoline used was from the Swiss market, RON 95, according to SN EN228. For the tests a charge of fuel was purchased to keep always the unchanged chemistry.

As a further variants of fuels E10 and E85 were used. These are respectively blends with: 90% v gasoline and 10% v Ethanol, or with 15% v gasoline and 85% v Ethanol. The blend fuels were prepared on the basis of E85 purchased on the Swiss market.

Table 3 summarizes the most important parameters of the fuels.

Table 3. Parameters of used fuels

		Gasoline	Ethanol C <sub>2</sub> H <sub>5</sub> OH	E10	E85
Density 15°C	[g/cm <sup>3</sup> ]	0.737	0.789	0.742	0.781
Stoichiometric air/fuel ratio	[-]	14.6	9.0	14.0	9.8
Lower calorific value	[MJ/kg]	43.0	26.8	41.3	28.9
Boiling point	[°C]	30-200	78.5		
Research octane nbr.	[-]	95	110		
Latent heat of evaporation	[kJ/kg]	420	900		
Oxygen content	[%m]	< 5	34.8		

## 4. Results and discussions

### 4.1. Ethanol blend fuels

Figure 4 represents the comparisons of average emission values from the operation with gasoline, E10 and E85 in WLTC warm. These results are averages of 2 cycles. The warm-up procedure was always by means of a preliminary cold started WLTC.

The particle counts emissions are generally significantly reduced with Exx (more than 1 order of magnitude).

CO-emissions are clearly reduced with increasing Exx-content. For NO<sub>x</sub> no regular tendencies with E10 & E85 are visible. Nevertheless, this is strongly dependent on the electronic control of this FFV and the indicated differences of few [ppm] can also be an effect of emitting dispersion.

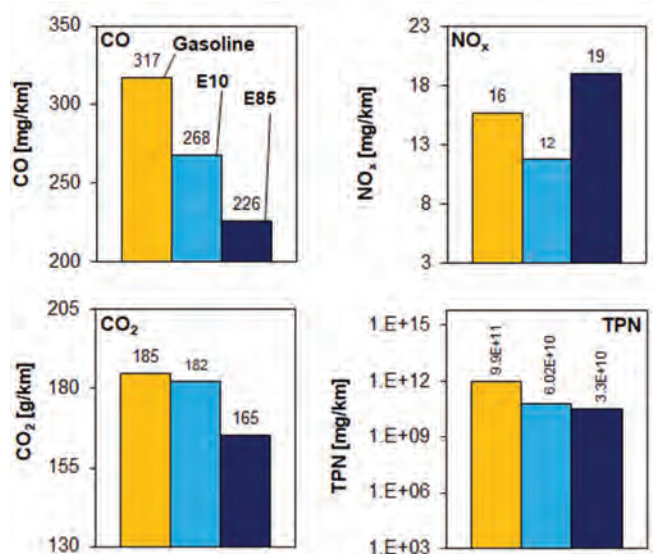


Fig. 4. Average emissions in WLTC warm, with gasoline E10 &amp; E85 V1: Volvo V60 T4F, 3WC

With each vehicle three RDE tests were performed with E0 and E85. Figures 5, 6, 7 and 8 show the cumulated results of NO<sub>x</sub>, PN, CO<sub>2</sub> and CO. The tendencies are similar as in WLTC:

- E85 instead of E0 reduces significantly NO<sub>x</sub>-emission; there is a certain dispersion of results, but this tendency is clearer than in WLTC and it is similar for both vehicles,
- PN is strongly reduced with E85 for both vehicles, which confirms the previous experiences on chassis dynamometer with vehicle V1,
- E85: CO<sub>2</sub> is only slightly reduced with V1 and more clearly with V2,
- E85: CO is not reduced with V1 but clearly reduced with V2 – it can be remarked that the acceleration events, very often in the last high-speed part of the cycle, can significantly contribute to the increase of cumulated emission.

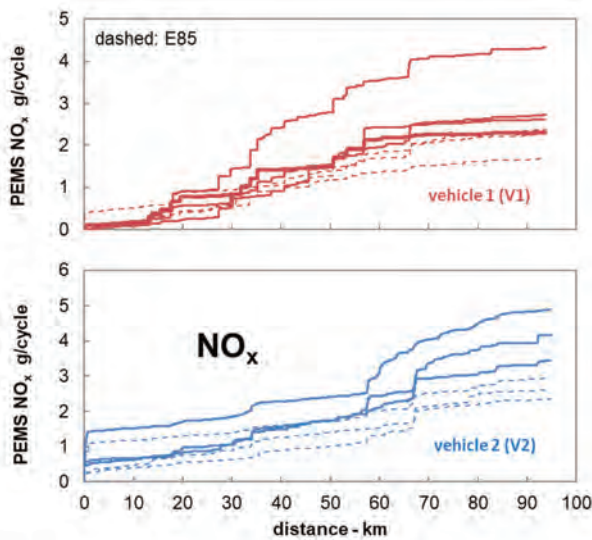


Fig. 5. NO<sub>x</sub> – Emissions during RDE with E0 and E85; Volvo V60 Flexfuel (V1); Audi A4 Flexfuel (V2)

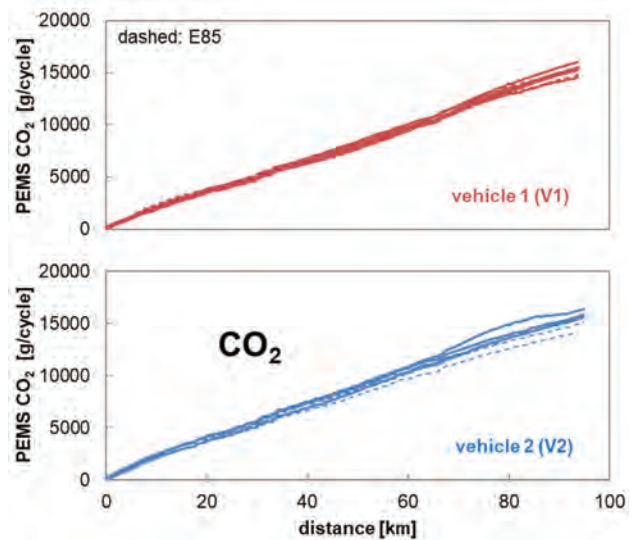


Fig. 7. CO<sub>2</sub> – Emissions during RDE with E0 and E85; Volvo (V1); Audi (V2)

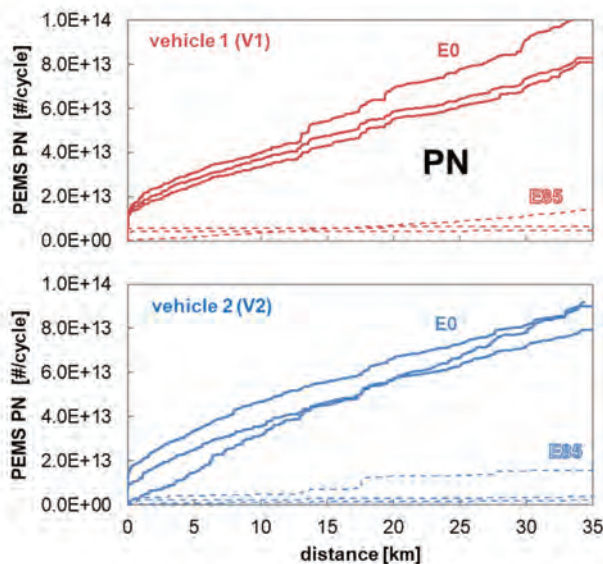


Fig. 6. PN – Emissions during RDE urban part with E0 and E85; Volvo (V1); Audi (V2)

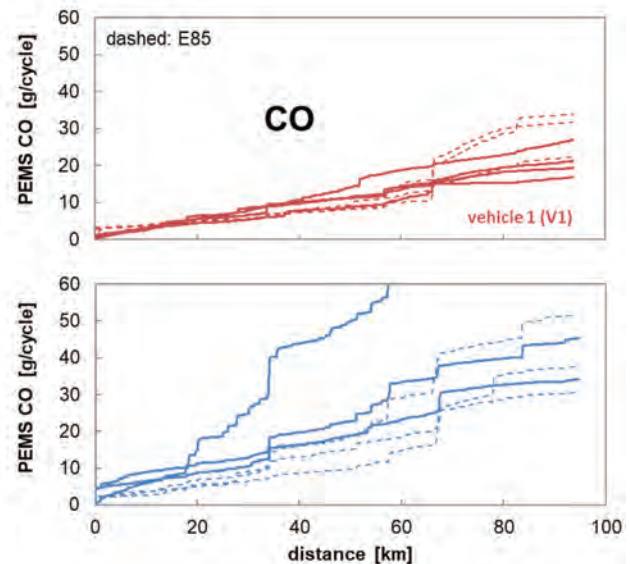


Fig. 8. CO – Emissions during RDE with E0 and E85; Volvo (V1); Audi (V2)

#### 4.2. Evaluations with EMROAD

Research of data evaluation was performed with the objective to indicate the influences of different evaluation ways on the results and their relationships.

All this research was performed for both vehicles, but only with the data from gasoline operation.

Figure 9 shows an example of comparisons of results NO<sub>x</sub> & CO in one of three RDE-attempts with both vehicles. The results are evaluated with EMROAD MAW-method (moving averaging windows) and with integration (integral average values). The cold start results are considered, or excluded (as cold start & warm-up are considered, either the period from engine start to reach 70°C coolant temperature, or a time period in maximum 5 min).

The integral values (INT) indicate higher emissions (NO<sub>x</sub> & CO) with cold start, than without cold start; this for both vehicles in the entire cycle and in the urban part. This is a usual very well-known result.

The MAW-method in contrary indicates much smaller differences “with/without cold start” for vehicle V2 and for vehicle V1 even lower CO- and NO<sub>x</sub>-values with cold start. The main reason for that is in the weighing and validation of the windows (MAW). Additionally, it must be remarked that the absolute values of the CO- and NO<sub>x</sub>-emissions are very low and the differences “with/without cold start” are insignificant.

##### 4.2.1. Influence of weighing and validation on RDE results

The characterization of normality and completeness of a RDE trip is graphically represented in Fig. 10.

The “normality” of the windows is concluded by comparing their CO<sub>2</sub> distance-specific emissions with a reference curve. The test is complete when the test includes enough normal windows, covering different speed areas (urban, rural, motorway).

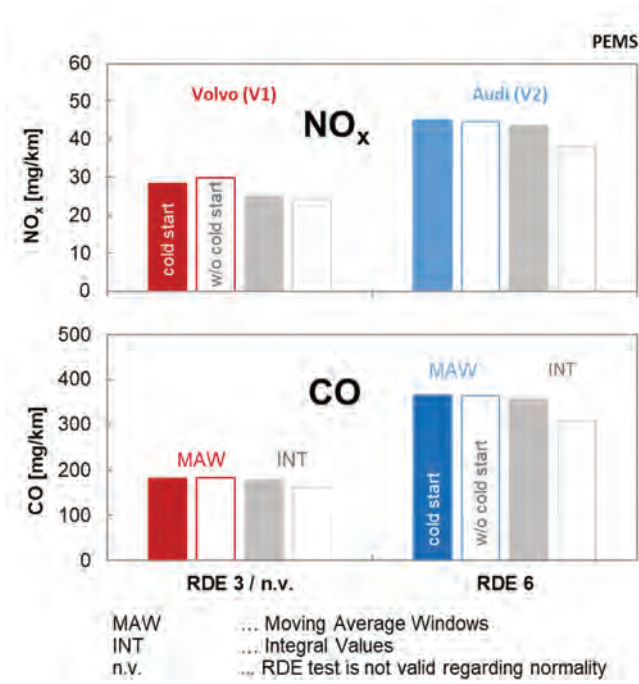


Fig. 9. Influence of cold start on emission results RDE – MAW and integral values

The reference dynamic conditions of the test vehicle are set out from the vehicle CO<sub>2</sub> emissions versus average speed measured at type approval (WLTC) and referred to as “vehicle CO<sub>2</sub> characteristic curve”.

During the MAW evaluation the following steps are performed:

- Step 1 Segmentation of the data
- 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.

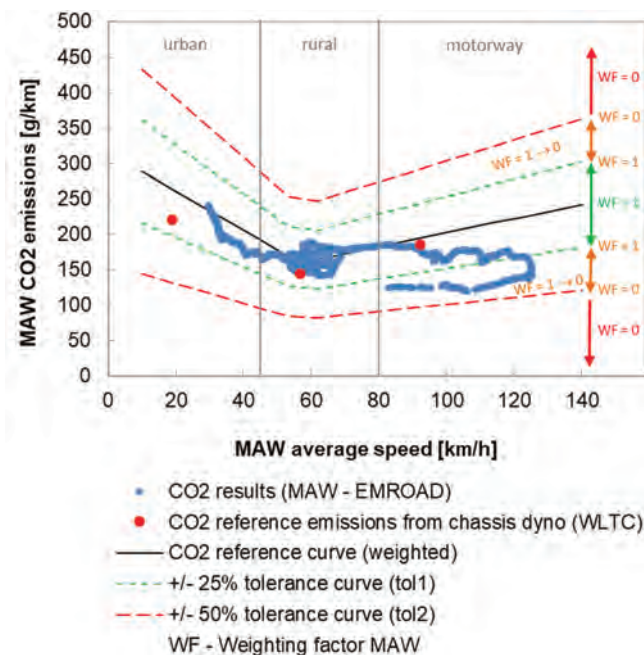


Fig. 10. Characterization of the normality and completeness of a RDE trip

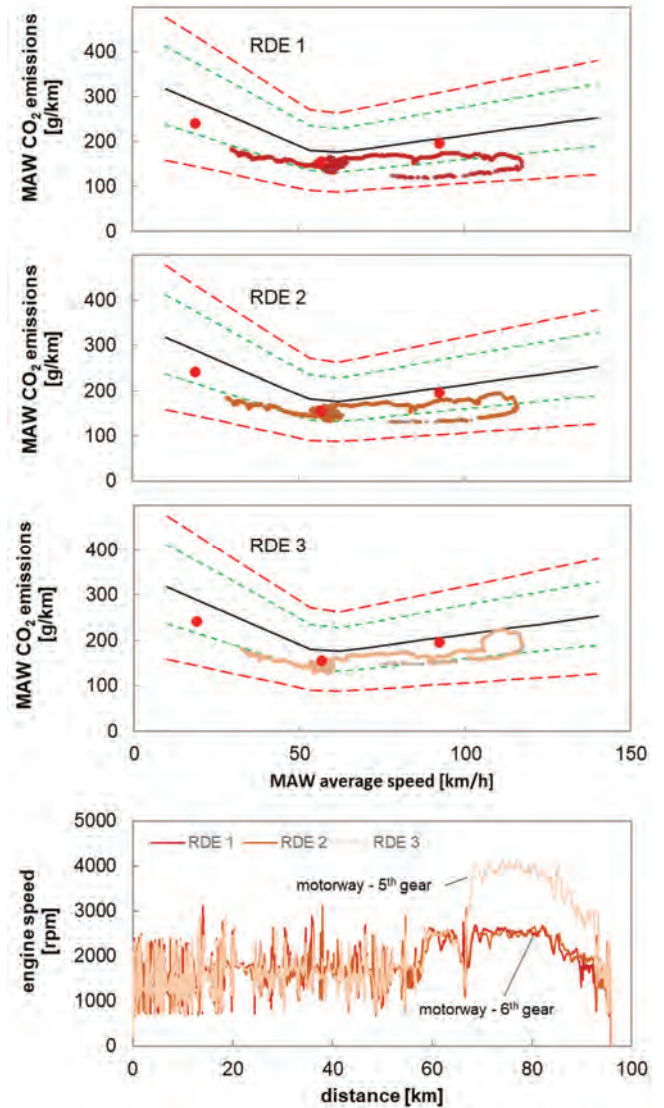


Fig. 11. RDE normality results and vehicle engine speed; Volvo (V1)

The following data are not considered for the calculation of the CO<sub>2</sub> 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 previously excluded are included in evaluation since September 2017
- vehicle ground speed < 1 km/h
- any section of the test during which the combustion engine is switched off.

In Fig. 11 such CO<sub>2</sub> characteristic curves are represented for two of three evaluated trips of vehicle V1. The trips and their dynamic conditions are not entirely normal, since the characteristic curves are exceeding the primary tolerance of ±25% (of the average WLTC-CO<sub>2</sub>-values).

The operation of this vehicle V1 in the urban part (at lowest speeds) is not dynamic enough and the program sets for these windows weighting factors WF < 1. At the highest speeds, there are also windows passing over the primary tolerance, because of not sufficient engine load. (The maximum speed on Swiss highway is limited to 120 km/h and

the last part of the highway in the RDE circuit is going downhill).

In the 3<sup>rd</sup> trip, “RDE3”: in the highway part of cycle the automatic gear was limited to select only the 5th speed. This increased the fuel consumption and the CO<sub>2</sub> emission in this part of the cycle and it moved the characteristic curve (MAW CO<sub>2</sub> vs. MAW speed) in the primary tolerance domain of ±25%.

Summarizing these examples, it can be remarked that: the normality and weighing of the windows have an influence on the final emission results and the characteristic curve of the trip (CO<sub>2</sub> vs. speed) is recommended to be inside of the primary tolerance band of ±25% with WF = 1.

### 4.3. Comparison EMROAD vs. CLEAR

Both evaluation methods and programs – EMROAD (MAW) and CLEAR (PB – Power Binning) were used and accepted in the EC-legislation.

The power binning method classifies the instantaneous emissions of the pollutants  $m_{\text{gaz},i}$  (g/s) into several power classes according to the corresponding power at the wheels. The method checks that a sufficient number of events fall within each class. The method applies to the total trip and to the urban part ( $v_i \leq 60$  km/h).

The actual wheel power  $P_{w,i}$  can be either measured by a torque-meter or calculated from instantaneous CO<sub>2</sub> emissions, using the vehicle-specific CO<sub>2</sub> lines (“Veline”) based on WLTC data ((EU) 2016/646 of 20 April 2016).

The maximum wheel power class is the highest class which includes the 90% of the rated engine power as declared by the manufacturer.

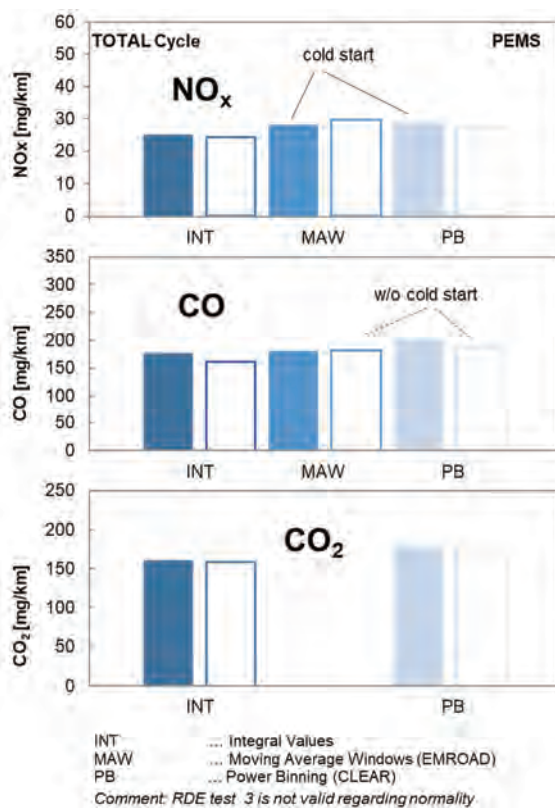


Fig. 12. Comparison of results with and without coldstart RDE - Integral values, MAW and PB; Volvo (V1)

In the present work the results of all evaluation methods (INT/MAW/PB) were compared in 3 RDE tests with and without cold start.

Figure 12 gives an example of this comparison in one of the performed tests. For the same test, there is a dispersion of NO<sub>x</sub>- and CO-results in the scattering band of approximately ±7%.

The results with consideration of cold start are with INT & PB higher, than without cold start. For MAW-method the weighing factors of a non-valid cycle cause the lower emissions with cold start (see previous section).

Fig. 13 shows the distribution of power classes and the NO<sub>x</sub>/CO-emissions per class in the three RDE-trips. It can be remarked that the power class distribution, is very well repetitive, while the emissions (here especially in the test “RDE2”) can scatter considerably.

Summarizing: both methods EMROAD and CLEAR have similar but not identical results. In the last amendment to Euro 6 including RDE4 (March 2018) was stated, that the results of both evaluation methodologies were not consistent enough and the CLEAR methodology was deleted.

### 4.4. Simulation of slope on chassis dynamometer

Sometimes in the research activities, the on-road driving cycle is registered and reproduced on the chassis dynamometer. A simulation of slope in WLTC with constant slope (+/- 2%) in the entire cycle was performed in [19]. An increase of CO<sub>2</sub> & NO<sub>x</sub> with increased slope and no influence of slope on PN were found.

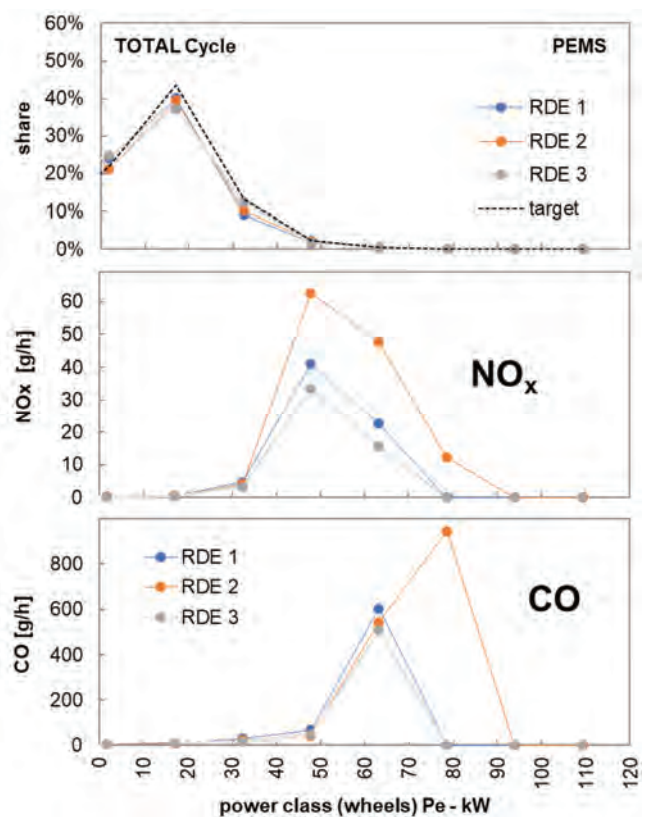


Fig. 13. Power binning results for 3 RDE-Measurements; Volvo (V1)

In the present work, a part of the RDE-cycle with mostly variable altitude, approximately 8 min. was selected, Fig. 14. The variable slope in this “sub-cycle” was programmed in the chassis dynamometer control system and the tests with this sub-cycle were performed on the vehicle V1. The performance of such a cycle needs a certain preparation and increased attention of the driver.

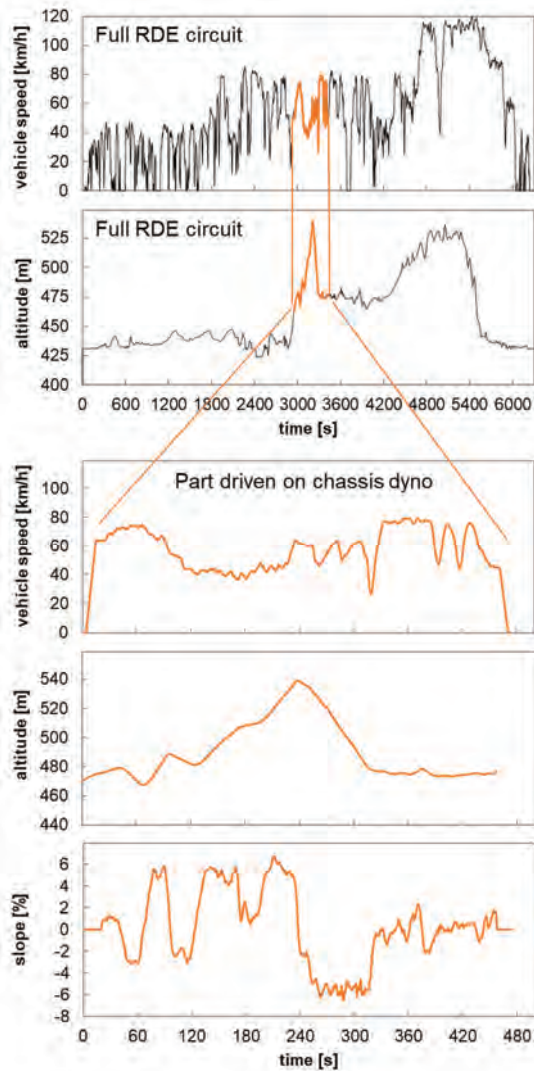


Fig. 14. RDE circuit and part used for chassis dynamometer measurement; HORIBA OBS One; Volvo (V1)

Figure 15 shows the average results with/without slope simulation, obtained with both systems: GasPEMS and bags (CVS). The slope simulation yields higher values of CO, CO<sub>2</sub> & fuel consumption, the NO<sub>x</sub>-values nevertheless are not influenced. Both measuring systems indicate similar absolute values of results.

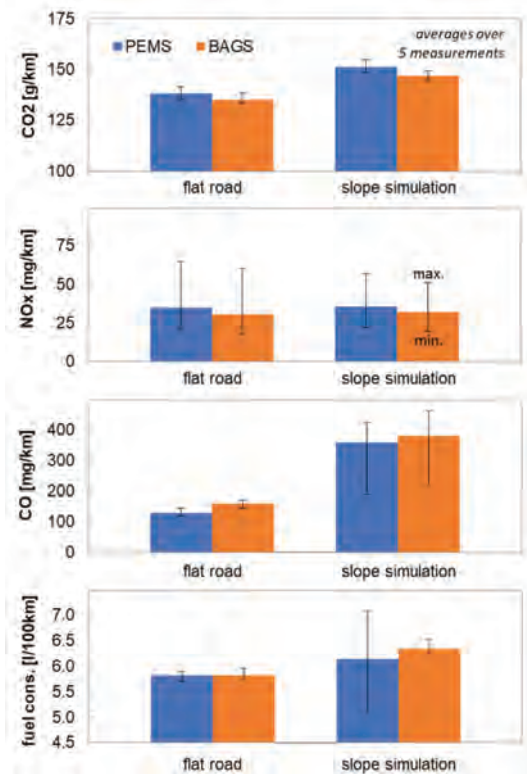


Fig. 15. Influence of real slope simulation on chassis dynamometer exhaust emissions; HORIBA OBS One; Volvo (V1)

#### 4.4.1. Comparisons of PN-PEMS

During the investigations with simulation of slope following PN measuring systems were included with sampling at tailpipe (TP): CPC, NM3 and OBS-PN (see explanations in section 2).

Figure 16 shows the average results of 5 trials with/without slope simulation. Both PN-PEMS indicate nearly the same PN-values but both systematically slightly lower, than CPC-readings. NM3 shows a higher dispersion of results.

The simulation of slope has no influence on the PN emissions.

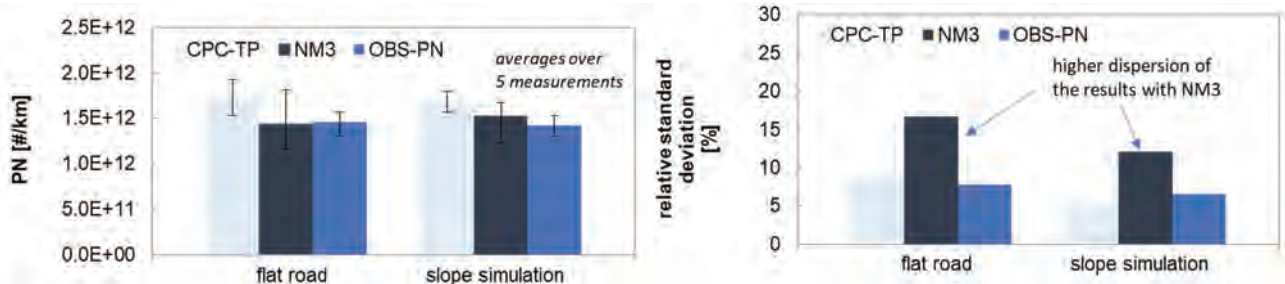


Fig. 16. Simultaneous measurements of PN at tailpipe with ViPR+CPC3790, NM3 and OBS-PN on chassis dynamometer; HORIBA OBS One; Volvo (V1)

## 5. Conclusions

Following conclusions can be mentioned:

### 5.1. E0 & E85

- The use of E85 fuel is advantageous for emission reduction: with E85 there is reduction of NO<sub>x</sub> and PN for both investigated vehicles in all driving conditions.
- The volumetric fuel consumption with E85 is generally higher, due to the lower heat value of this fuel.
- Both vehicles attain similar levels of emissions at the end of RDE cycle, while the dispersion of results for each vehicle/fuel variant is much larger than on the chassis dynamometer (in WLTC).

### 5.2. Evaluations with EMROAD

- The normality and weighing of the windows have an influence on the final emission results and the characteristic curve of the trip (CO<sub>2</sub> vs. speed) is recommended to be inside of the primary tolerance band of ±25% with WF = 1.

- Including the cold start in the evaluation, generally increases the emission results, but in case of non-valid trip and weighing of the windows (MAW) this effect can be weakened or even inversed.

### 5.3. EMROAD vs. CLEAR

Both methods of evaluations of results EMROAD and CLEAR have similar but not identical results. The CLEAR methodology was deleted in the last version of RDE legislation (March 2018).

### 5.4. Slope and PN-PEMS

- The slope has an impact on emissions of CO and CO<sub>2</sub> (fuel consumption) and it should be considered during the reproduction of RDE driving cycles on the chassis dynamometer.
- Nanoparticle emissions are principally independent on slope.
- Both investigated PN PEMS working with different measuring principles (DC vs. CPC) indicate nearly the same PN-values.

## Nomenclature

AFHB	Abgasprüfstelle FH Biel, CH	NO	nitrogen monoxide
ASTRA	Amt für Strassen (CH)	NO <sub>2</sub>	nitrogen dioxide
BAFU	Bundesamt für Umwelt, (Swiss EPA)	N <sub>2</sub> O	nitrous oxide
CD	chassis dynamometer	NO <sub>x</sub>	nitric oxides
CLA	chemiluminescence analyser	n.v.	non-valid
CLD	chemiluminescence detector	OBD	on-board diagnostics
CLEAR	RDE evaluation program from TUG with PB	OBS-ONE	Horiba Gas PEMS
CPC	condensation particle counter	OBS-PN	Horiba PN PEMS
CVS	constant volume sampling	OP	operating point
DAQ	data acquisition	PB	Power Binning
DC	diffusion charging	PEMS	portable emission measuring systems
DF	dilution factor	PMP	EC Particle Measuring Program
DI	Direct Injection	PN	particle number
DiSC	diffusion charge size classifier	PN-PEMS	PEMS with PN measuring device
E0	gasoline (zero Ethanol)	RDE	real driving emissions
E85	85% vol. Ethanol	TC	thermoconditioner
EC	European Commission	TFZ	Technologie- und Förderzentrum für Nachhaltigkeitsforschung, Straubing, D
ECE	Economic Commission Europe	TP	tailpipe
ECU	electronic control unit	TUG	Technical University Graz
EFM	exhaust flowmeter	TWC	three way catalyst
EMROAD	RDE evaluation program from JRC with MAW	V1	vehicle 1
GDI	gasoline direct injection	V2	vehicle 2
GMD	geometric mean diameter	ViPR	nanoparticle sample preparation with volatile particles remover
HC	unburned hydrocarbons	WLTC	worldwide harmonized light duty test cycle
INT	integral average values	WLTP	worldwide harmonized light duty test procedure
JRC	Joint Research Centre (EC)	3WC	three way catalyst
LFE	laminar flow element		
MAW	moving averaging windows		
MFS	mass flow sensor		
NM3	NanoMet3		

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## Methodology of electric motor testing on the hybrid engine test bench

*This paper presents a basic methodology and equipment setup used for an electric motor designed for light-duty vehicles, testing on a hybrid engine test bench equipped with an active AC dynamometer. The methodology used during the test was based on the appropriate regulation (UN-ECE Regulation 85). An example of mechanical performance measurements is presented, as well as an overall layout of the measurement devices used for testing, including a scheme detailing all electrical connections between the equipment employed during the test. The paper takes into consideration the necessity of development and subsequent improvements of the methodology employed during testing of e-motors, which due to the highly changeable and competitive automotive environment, will undoubtedly have a gradually increasing share and significance in the automotive industry.*

Key words: *e-motor, electric motor, hybrid engine test bench, testing methodology and equipment, active AC dyno, UN-ECE Regulation 85*

### 1. Introduction

The high prices of fossil fuels on the global markets, growing demand for green and low-carbon energy, as well as fierce competition and more and more stringent emission legislation have exerted great pressure on automakers and manufacturers, forcing them to search for and implement new, more efficient powertrain solutions focused on reduced fuel consumption and emission levels [4, 6].

The most reasonable solution seems to be small displacement engines, however, as it is now known, they are not the most optimal ones. Simultaneously, further optimization of existing internal combustion engine solutions generates great costs and seems to be quite limited from the technical point of view [5]. Now it is seen that automakers are more and more interested in implementing electric engines in the way of hybrid applications or pure electric drivetrains equipped with very sophisticated control units [3, 9]. According to the ERTRAC study, powertrain electrification is the main leverage to reduce global CO<sub>2</sub> emissions from transport sources [12] and only a high level of electrified vehicles in fleet mix show a chance to meet the decarbonization challenge in European Union presented in the EU Transport White paper to reduce the overall CO<sub>2</sub> tank-to-wheel emissions by 60%, based on 1990 emission level [7].

At the end of the 19<sup>th</sup> century and at the beginning of the 20<sup>th</sup> century, electric cars constituted a significant part of the fleet. Despite many advantages, electric motors have lost the battle with the internal combustion engine. The biggest disadvantages were low range and limited battery capacity as well as the substantial weight of the battery itself [9, 14]. The internal combustion engines of the day offered greater power and mileage. Additionally, the introduction of the electric starter to the market made the starting procedure of combustion engines much easier than previously (when manual cranking had been quite normal) [14].

At present, the development and introduction of innovative electronic solutions have made electric motors better, quieter and much more powerful. Currently, in the era of

increasing requirements of emission standards, electric engines are once again the center of attention, making up a crucial development point for the entire automotive industry [3, 5, 9].

The market share of hybrid-electric vehicles was rising slowly in the last years to 1.8% of all new cars sold in the European Union in 2016. Plug-in-hybrid and electric vehicles were at about 1% among all vehicles sold in 2016 [11]. Current European electric-vehicles sales are of about 1.5% of all new vehicle registration and can rise to about 5% in 2021 and to bigger percentage in next years to 2025, when a significant uptake of the electric vehicle market is to be expected [3].

At present four type of electrified drivetrains that use electric motors are considered in modern vehicles: HEVs (Hybrid electric vehicles), PHEVs (Plug-in hybrid electric vehicles), BEVs (Pure battery electric vehicles), and HFCEVs (Hydrogen fuel cell electric vehicles) [1, 9]. Electric (battery) powertrain consists of onboard high-energy battery or supercapacitor, or both of them, electric energy converters (Inverter), electric motor and drivetrain system [1, 14]. Energy and power demand must be sufficient to deal with:

- The air drag that is proportional to vehicle frontal area, air drag coefficient and the square of the speed.
- Rolling resistance that is proportional to vehicle mass and rolling resistance coefficient.
- Gravity at ascends.
- Other power losses (internal and external) e.g. due to wear.
- Provide power to on-board equipment and sub-systems e.g.: lights, air conditioning (A/C) system, radio, power drives, electronic control units, etc. [14, 17].

Currently, the 2<sup>nd</sup> generation of PEV technology is under development, with improved batteries, more driving mileage, followers adequate infrastructure. The 3<sup>rd</sup> generation of PEV is planned for 2020–2025 time frame, with improved batteries and vehicles to make core market for PEVs competitive [6]. The main challenges of vehicle electrification are currently following [1]:

- Solution to environmental performance,
- Cruising range, battery charging time,
- Infrastructure,
- Cost/affordability.

Apart from the on-going improvements of electric vehicles technology making EVs competitive with the conventional ICE vehicles on multiple markets some legislators and R&D organizations are constantly working on test methods and test equipment assigned for this type of vehicles and powertrains.

The concept of testing and quantifying the performance of the electric motors in the industry is not new, but due to the growing popularity of this type of the engines in the automotive industry (hybrid and electric solutions), it is undoubtedly necessary to get familiar with the requirements and research methodology. Test method related to pure electric vehicles, hybrid electric and compressed hydrogen fuel cell hybrid vehicles were part of the works on new WLTP (Worldwide harmonized Light vehicles Test Procedures) carried out by Informal Working Group (IWG) on WLTP of United Nation Economic Commission for Europe (UN ECE), Inland Transport Committee, World Forum for Harmonization of Vehicle Regulation (GRPE). Results of those works were introduced to the Global Technical Regulation (GTR) no. 15 of UN ECE in Annex 8. Currently, Proposal for Amendment 4 to GTR 15 for WLTP test procedure is under discussion [13]. Another IWG – Electric Vehicles and Environment (EVE IWG) of this UN ECE World Forum is working on the development of new UNECE GTR determining test methods for the main issues related to EV vehicles as [16]:

- Power determination of the electrified vehicles.
- Electrified vehicle durability issue (continuing research on EV battery performance and durability).
- Methods of quantifying the energy consumption.

## 2. Electric motor testing methodology on test bench for a hybrid powertrains

### 2.1. Methods of electric moto testing UN ECE

#### Regulation No. 85

The existing test methodology is widely described in the UN-ECE Regulation 85 [15]. This regulation requires to obtain and map the power curve as a function of the engine or electric motor speed in terms of the power at full load indicated by the manufacturer for internal combustion engines or electric drivetrains. The regulation determines also the measurement of the maximum 30 minutes power of electric drivetrains intended for the propulsion of motor vehicles of categories M and N1 [15].

Within its structure, UN-ECE Regulation 85 defines the main definitions and related technical concepts. In the case of electric motors, electric drivetrains are composed of controllers and a motor and can be used for propulsion of vehicles (as the sole means of propulsion). The “net power” is defined as the power obtained on a test bench at the end of the crankshaft or its equivalent at the corresponding engine or motor speed, with the auxiliaries [15].

UN-ECE Regulation 85 also specifies the auxiliaries used during the tests determining its position and locations on the test bench and also specifying some overall technical

conditions. The regulation specifies especially the cooling conditions that need to be maintained during the test. According to the regulation, the electric drivetrain shall be equipped with auxiliaries (radiator, fan, fan cowl, pump, thermostat in case of liquid – cooling or air filter, cowl, blower, temperature adjustment system in case of air cooling). The radiator, the fan, the fan cowl, the water pump and the thermostat shall be located on the test bench in the same relative position as when mounted on the vehicle. The cooling-liquid circulation shall be activated by the drivetrain water pump only. Cooling of the liquid may be produced either by the drivetrain radiator, or by an external circuit, provided that the pressure loss of this circuit and the pressure at the pump inlet remain substantially the same as those of the drivetrain cooling system. Where the fan, radiator and fan cowl cannot conveniently be fitted into the test cell, the power absorbed by the fan when separately mounted in its correct position in relation to the radiator and cowl (if used), shall be determined at the speed corresponding to the motor speeds used for measurement of the motor power, either by calculation from standard characteristics or by means of practical tests. This power, corrected to standard atmospheric conditions should be deducted from the correct power. It is notable that the electric drivetrain shall be supplied from a DC voltage source with a maximum voltage drop of 5% depending on time and current (periods of less than 10 seconds excluded) [15].

UN-ECE Regulation 85 also determines the approval of the propulsion system within its net power measured in accordance with the specified procedure. As mentioned previously, the net power is the power obtained on the test bench on the crankshaft at the specified engine speed together with auxiliary equipment. It is notable that net power is determined under atmospheric reference conditions. The maximum 30-minute power is the maximum net power of the electric motor which the drive system can produce (on average) over a period of 30 minutes [15].

According to UN-ECE Regulation 85, the determination of net power proceeds as follows: the engine and its set of devices must be conditioned at 25 ( $\pm 5$ )°C for at least two hours. The net power test is performed at the maximum setting of the power regulator. Before starting the test, the engine operates on the test bench for three minutes, generating a power equal to 80% of the maximum power at the speed specified by the manufacturer. The measurements are made at different engine speeds to accurately determine the power curve between zero and the maximum speed recommended by the manufacturer [15].

The determination of the maximum 30-minute power in accordance with the regulation is conducted as follows: the engine and its set of devices must be conditioned at 25 ( $\pm 5$ )°C for at least four hours. The electric motor works on the test bench with the power recommended by the manufacturer to obtain the maximum 30-minute power. The engine speed must be within the range for which the net power exceeds 90% of the maximum power measured in accordance with the regulations. The engine speed in the point of the determination of the 30-minute power should be recommended by the manufacturer. Engine speed and power must be recorded and post-processed accordingly to

the requirements in the regulation. The power must be within  $\pm 5\%$  of the power at the start of the test. The maximum 30-minute power is the average power obtained within thirty minutes of the start of the test [15].

UN-ECE Regulation 85 specifies the data evaluation methodology. In encapsulated form, the net power and the maximum 30 minute power of the electric motor specified by the manufacturer are accepted if for maximum power the results differ by no more than  $\pm 2\%$  and for other measuring points on the power curve by no more than  $\pm 4\%$  from the values measured by the technical service on the unit under test submitted for testing. It is notable that the e-motor speed tolerance is  $\pm 2\%$ .

It is worth mentioning that all the such performed at BOSMAL incorporating the measurements of the net power and the 30-minute net power was conducted in accordance with the latest version of UN ECE Regulation No. 85 (i.e. revision 1, supplement 6, paragraphs 5.3.1 and 5.3.2) [15]. The work directly referred to net power and torque measurements, determination of 30-minute net e-motor power and the proper and adequate interpretation of the results obtained.

## 2.2. Test bench for internal combustion engines (ICEs) and hybrid powertrains as the indispensable equipment for e-motors testing

Nowadays special dedicated engine test stands using alternating current (AC) dynamometers are widely used during the testing of internal combustion engines (ICE) and hybrid powertrains. In general, this type of the engine test bench with an active AC dynamometer can also be used during testing of entire vehicle drivetrains.

The engine test stand with an active AC dynamometer installed at BOSMAL, together with all equipment designed for research, development and type approval is dedicated to performing research activities in the range of testing and operational simulations of light (LD), medium (MD) and heavy-duty (HD) engines fueled with a gasoline, diesel fuel, LPG, CNG, synthetic fuels and biofuels, as well as hybrid and fully electric solutions. The drivetrains which it is possible to test can be a classic engine unit consisting of an internal combustion engine (ICE) only, but also hybrid drivetrains and finally entirely electric motors equipped with the associated control hardware. The engines tested on such a test bench are able to be operated and tested under steady state, transient and dynamic (fast-changing) conditions. This approach incorporating a specific list of a highly advanced equipment is fully consistent with current automotive trends appearing on the market which are noticeably focused on hybrid and electric motors applications [8].

It is noteworthy that BOSMAL laboratory has currently on its disposal one the abovementioned test stands equipped with an active engine dynamometer with an asynchronous AC motor and a power unit assigned for electric motors (shown in Fig. 1 and Fig. 2). This equipment configuration gives wide possibilities to test both internal combustion engines and hybrids consisting of both the internal combustion engine and electric motors, but also enables testing of electric motors themselves. In the case of testing hybrid or electric motors, a common, superior automation surveillance system gives the ability to perform dynamic tests and

perform all the measurements requested by the related regulations (e.g. UN-ECE Regulation 85) [8].



Fig. 1. The equipment used during testing: PUMA Open software (updated to version 1.5.5)

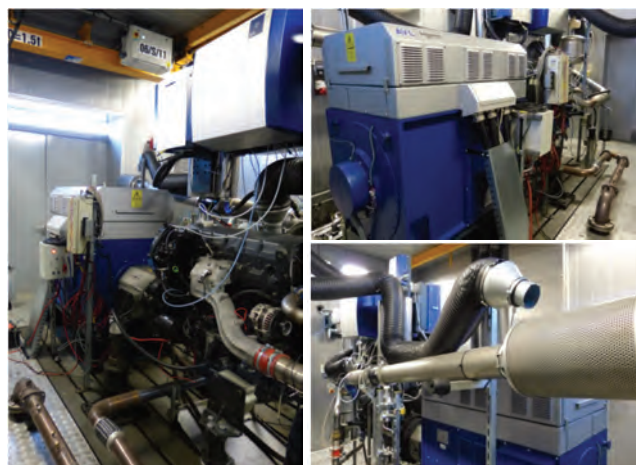


Fig. 2. The equipment used during testing: active AC dynamometer and auxiliaries

It is evident that dynamic tests are currently indispensable in development studies and for type approval, as well as in durability research. A dedicated test stand for testing of hybrid and electric drivetrains facilitates execution of tests in accordance with the applicable regulations and standards, but also gives the ability to prepare any programmable tests according to any requirements – which is extremely important from the research and development point of view. An example of such a practical application is a simulation of the behavior of the hybrid drivetrain system in real working conditions while operating in a vehicle.

## 2.3. The problematic issues occurring during e-motors testing

Electric drivetrains in automotive applications contain an e-machine, power electronics, an energy storage device, charging electronics, transmission and some peripheral equipment. The challenges for e-machines in vehicular applications are extensive and they have to meet many requirements, for example: high efficiency, low cost and weight, dynamics, packaging, high power, climatic robustness, acoustic behavior and EMC, thermal robustness

and mechanical stability [10]. In the past many direct-current motors were used in electric vehicles. Today the most usable technology are permanent magnet synchronous machines (PSM) and asynchronous machines (ASM), or sometimes also electrically excited synchronous machine (ESM) [10].

The research and development field reports that testing the e-motors is strictly connected with the certain problems related with the signal measuring nature, efficient data post-processing and transparent final data evaluation methodology. Some major problems are briefly mentioned below and detailed in the literature [2, 10]:

- Fast switching inverters and the power analysis reliability in terms of sufficient sampling rates;
- A dynamic, fast-changing and transient nature of e-motor testing in all operational conditions;
- The necessity of permanent monitoring of the current harmonics;
- The issues related with a raw data storage, data post-processing and high data accessibility methods.

The abovementioned problems during e-motor performance measurements are strictly related to the hardware and software used and also with their technical potential. In this context, the power analyzer units used must be dedicated and optimized for automotive application purposes indicating satisfactory technical parameters. For that reason, a great amount of costs must be necessarily borne by automotive research and development institutes just in order to be equipped with the highest quality equipment ensuring a highly reliable data recording and enabling transparent final data evaluation.

#### 2.4 Testing equipment and capabilities used during the test

The test stand employed during the e-motor tests incorporated an active alternating current (AC) dynamometer with maximum power of 220 kW, a power battery unit, AVL e-storage with a nominal power of 160 kW to supply the e-motor, and power analyzer (Yokogawa WT 1800) for voltage and current measurement. The AVL e-storage DC power unit featured an output voltage range of 8–800 V and a maximum current output of 600 A. The test stand was controlled by the AVL PUMA Open automation platform. Additionally, the motor required connection to an external liquid cooling system with the PID temperature and flow control and not to exceed 60°C (measured at the motor outlet). Dielectric transformer oil was used as a coolant due to the direct winding cooling solution employed.

The mechanical performance of an electric motor in terms of net torque  $T = f(n)$  and power  $P = f(n)$ , was measured at the motor crankshaft over the entire speed range. The e-motor as installed on the test bench is depicted in Fig. 3. The inlet and outlet of the oil cooling system as well as the main electrical connections are depicted in Fig. 4.

The equipment used during testing: PUMA Open software, AVL e-storage (power battery unit), power analyzer (Yokogawa unit) and electric inverter (coolant pump speed control) are shown in the following figures: Fig. 5, Fig. 6, Fig. 7 (respectively).

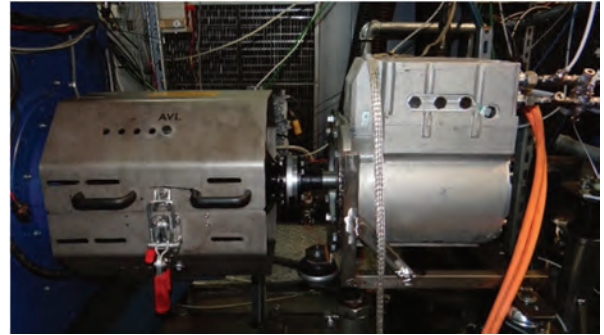


Fig. 3. The e-motor installed on the engine test bench equipped with an active AC dyno

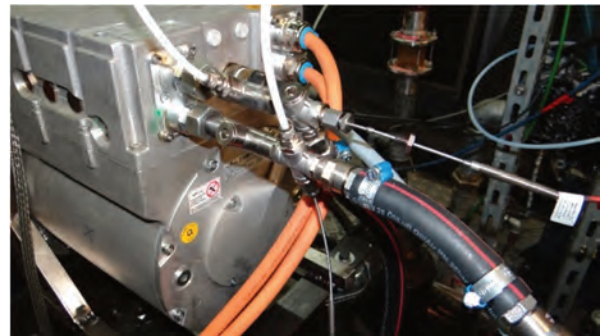


Fig. 4. The motor oil cooling system in/outlet and the electrical connections



Fig. 5. The equipment used during testing: AVL e-storage (power battery unit)



Fig. 6. The equipment used during testing: power analyzer (Yokogawa unit)



Fig. 7. The equipment used during testing: the electric inverter (coolant pump speed control)

BOSMAL's overall capabilities and functionalities in terms of testing e-motors are enumerated below. As mentioned above, at this point, BOSMAL has at its disposal a hybrid test cell (no. 19) which is equipped with an up-to-date e-storage unit and a portable low voltage battery emulator. The test bench software incorporates the following functionalities and has the following characteristics [8]:

- AVL PUMA OPEN 1.5.3
- AVL iGEM
- AVL ISAC
- AVL InMotion

AVL e-storage DC Power Unit is characterized by the following parameters:

- Nominal capacity: 160 kW
- Output voltage: 8-800 VDC
- Output current (max): 600 A
- Permanently fixed on test bench no. 19

A regatron low voltage battery emulator is characterized by the following parameters:

- Nominal capacity (max): 20 kW
- Output voltage: 65 V
- Output current (max): 385 A
- Portable unit (mobile usage)

### 2.5. Testing methodology and description of the unit under test

The main aim of the test activities was to measure and validate the mechanical performance of an electric motor in terms of net torque  $T = f(n)$  and power  $P = f(n)$  measured at the motor crankshaft over the entire speed range. The secondary activities were to determine the nominal power value generated at rated speed and verify its stability over time. This is referred to as the 30-minute net power test with 1 Hz data acquisition, which was conceptualized as a verification of measured/declared nominal power values over 30 minutes (criterion: within  $\pm 5\%$  tolerances) [15]. The measurement of mechanical performance was conducted in the speed range of 0–6000 rpm with a step of  $\Delta n = 250$  rpm. The measurement of net torque and power values were taken as an average of 30-second steps [15]. In parallel to the mechanical power on the motor's shaft, the electric active power was also measured using a Yokogawa power analyzer.

As mentioned above, the measurements of the net power and the 30-minute test were conducted in accordance

with UN ECE Regulation No. 85, revision 1, supplement 6, paragraphs 5.3.1 and 5.3.2 [15].

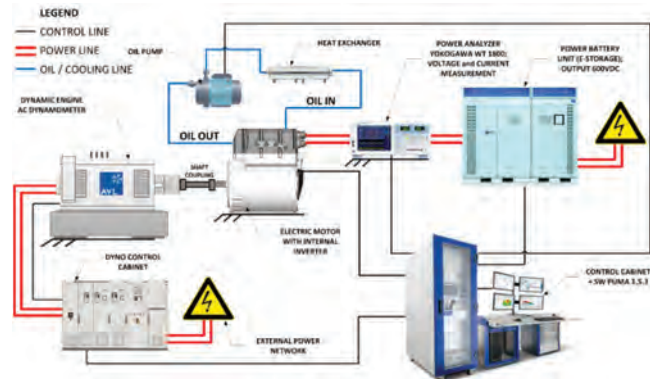


Fig. 8. The overall concept of the electrical connections and the equipment employed during the testing

The unit under test was a PMSM (permanent magnet synchronous three-phase alternating current (AC) motor), mono unit (one motor integrated with the onboard inverter electronics), with 6 poles. Nominal supply voltage was 600 volts direct current (VDC) and an additional 9–32 VDC power supply was used for the control electronics. The basic characteristics of the electric motor were the following: operating speed range 0–6000 rpm, nominal net power 80 kW at 6000 rpm and maximum overload power 88 kW available for maximum 15 seconds. In essence, the electric motor was supplied with 600 volts direct current (VDC) from the AVL e-storage DC power unit. It is notable that the electric motor was internally integrated with the control unit incorporating the following functionalities: controlling the inverter which converts direct current into alternating current and is responsible for starting and driving the motor, protection functions (motor temperatures, overload, overcurrent and overvoltage), communication/diagnostic interfaces and digital I/O (inputs / outputs) to interface with external control systems. The electric motor was interfaced with the test bench control system using CAN bus and digital I/O. The overall concept of the electrical connections and the layout of the equipment employed during the tests are depicted in Fig. 8.

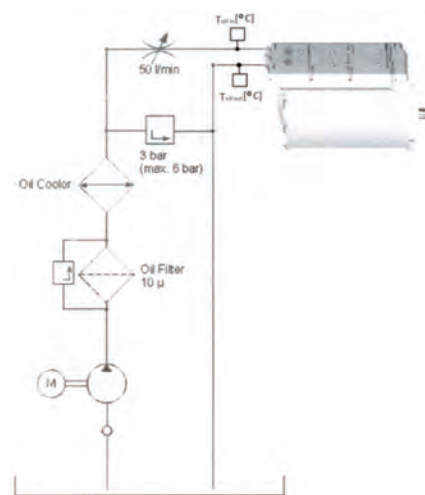


Fig. 9. The external circuit of the cooling system applied in the tested e-motor

As mentioned above the e-motor was connected to the external liquid cooling system in which the coolant temperature and flow were monitored and operated by the PID controller. The scheme showing the external circuit controlling the proper oil recirculation and at the same time the cooling functionality has been depicted in Fig. 9.

## 2.6. Example of test results

The basic characteristic of the electric motor is presented on Fig. 10. The measurement of mechanical performance was conducted over an entire operating speed range of 0–6000 rpm with a step of  $\Delta n = 250$  rpm. The measurements of net torque and power values were taken as an average of 30 seconds steps. The motor characteristic can be distinguished into a part of constant torque (250 Nm) in a range of 0–3000 rpm and the part of constant power (80 kW) between 3000–6000 rpm.

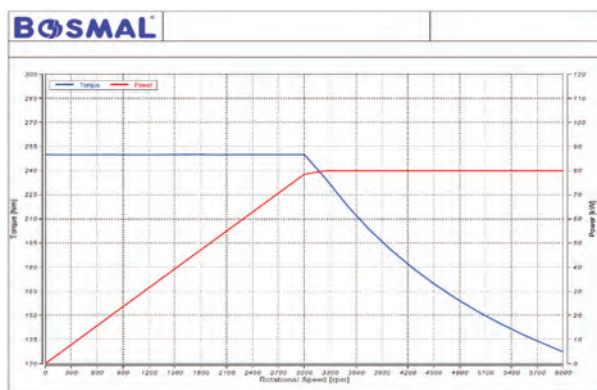


Fig. 10. E-motor rated power and torque characteristic as a function of speed,  $T = f(n)$ ,  $P = f(n)$

The next test activities were a determination of the nominal power value generated at rated speed and verifying its stability over the set period of time. This is referred to as 30-minute net power test with 1 Hz data acquisition, which was comprehended as a verification of measured to declared nominal power value over 30 minutes and within  $\pm 5\%$  tolerances [15]. The results are presented in Fig. 11.

## 3. Conclusions and summary

The tests conducted as well as the methodology and related equipment employed have led to the following overall conclusions, as described below:

- due to the constantly rising share of electric motors in the automotive industry, demand for the type of tests presented above will grow significantly;
- test benches for testing combustion engines can be adapted for electric motor tests, following implementation of an additional set of measuring equipment and specified power supply units;

## Nomenclature

AC	Alternating Current
A/C	Air Conditioning
ASM	Asynchronous Machine
BEV	Battery Electric Vehicle
CAN	Controller Area Network
CNG	Compressed natural gas

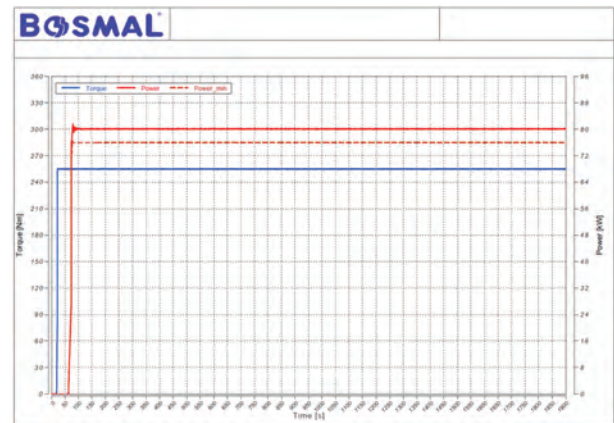


Fig. 11. E-motor nominal power verification as a function of time (30 minutes),  $P_{max} = f(t = 1800 \text{ s})$

- testing e-motors' performance involves many problematic issues related to the signal measuring aspect, efficient data post-processing and transparent final data evaluation methodology;
- the tests conducted the incorporated determination of net power and torque measurements, as well as the so-called 30-minute net power test in accordance with UNECE Regulation 85;
- the electrical and mechanical performance results presented allowed determination of the overall electric motor efficiency over the entire speed operating range, the results of what will be presented in future publications;
- the electrical power used for supplying the motor can be recovered – to a great extent – by using an active AC dynamometer;
- the overall energy balance for an electric motor is much more advantageous than in case of combustion engines – a point which will be further investigated and discussed in the future.

It is noteworthy that some of the abovementioned conclusions will be undoubtedly expanded and put under detailed investigation during future tests.

Summarizing, electric motor testing for automotive applications is a new and quite complex issue. It is noteworthy that developing a dependable and credible test methodology for electric motor testing reveals great significance from the research and development point of view, especially taking into consideration the fact that electric motors will make up a substantial and still increasing share of drivetrains used in the automotive industry in the future.

## Acknowledgement

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ESM	Electrically Excited Synchronous Machine	MS/s	Mega-samples/second
EVE	Electric Vehicles and Environment (IWG of GRPE)	PEV	Pure electric vehicle
GRPE	The Working Party on Pollution and Energy	PHEV	Plug-in hybrid electric vehicle
GTR	Global Technical Regulation (of UN ECE)	PID controller	Proportional–Integral–Derivative Controller
HFCEV	Hydrogen fuel cell electric vehicle	PMSM (PSM)	Permanent Magnet Synchronous Motor
HD	Heavy duty engine	SW	Software
I(t)	Current in the function of time	U(t)	Voltage in the function of time
I/O	Digital inputs/outputs	UN-ECE	United Nations Economic Commission for Europe
ICE	Internal Combustion Engine	VDC	Volts Direct Current
IWG	Informal Working Group (of GRPE)	WLTP	Worldwide harmonized Light vehicles Test Procedure
LD/LDV	Light-duty engine/light duty vehicle		
LPG	Liquefied petroleum gas		
MD	Medium duty engine		

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CE-2018-304

## Engine-generated solid particles – a case study

Current ecological trends and resulting legislation like European emissions standards Euro 6d or Best Available Techniques are setting new challenges in the field of environmental protection. Since the problem of emissions of particulate matter from diesel engines was solved by the application of diesel particulate filters (DPFs or FAPs) and due to the global dominance of gasoline fuelled passenger cars, particular concern has been focused on improvement of emissions performance of gasoline vehicles, including hybrids, as well as heavy-duty and non-road vehicles. This paper presents the results of preliminary studies on the chemical and physical properties of gasoline engine-generated particles, including nanoparticles. SEM images were presented which allowed identification of the character of particulate matter and estimates of the dimensions of particles. Moreover, the particles were found to be composed of different elements, including Cu, Si, Na, Ca, Zn and P, pointing to the origination of these particles from the pistons and lubricant additives.

Key words: engine emissions, particulate matter, nanoparticles, SEM, morphology

### 1. Introduction

Levels of pollution in the ambient air are a significant subject of environmental studies [1, 2]. Emissions related to transportation are of special concern both of scientific, industrial and governmental representatives. The reason for this is that road pollution is a kind of low-stack emission; it is emitted at the level of the human respiratory tract. Legislation motivated by public health concerns forces engine and vehicle designers to overcome the increased emission of harmful compounds and include high efficiency exhaust gas aftertreatment systems in their designs.

The social awareness of emission intensity and air quality is still increasing. From the physical and chemical (or even mechanical) point of view, the combustion processes of organic fuels occurring both in furnaces and the combustion chambers of vehicular engines will never run with emission of a mixture of only carbon dioxide and water vapour as the result. Exhaust gas consists of hundreds (or even thousands) of groups of chemicals and limits for some of them have been defined by various legal polices. The remaining part of exhaust gas components is unregulated. Moreover, among raw exhaust components, gaseous chemicals and solid particles may be distinguished. The components of solid particles – depending on the conditions of the combustion processes – may occur both in the gaseous and PM-bound forms. These aspects cause studies on exhaust emission to constitute a great challenge for chemists and engine designers.

Particulate matter (PM) is an agglomeration of solid particulates suspended in the atmosphere. Particulate matter is characterized by different chemical and physical properties depending on the aerodynamic diameter size of their idealised spherical volumes, and are also characterized by their origin [3]. Once emitted to the atmosphere, particulate matter undergoes many transformations, such as coagulation and condensation, which lead to changes in the physical and chemical character of aerosols. The formation of particulate matter begins with a nucleation process which occurs in the presence of so-called gaseous precursors, like

SO<sub>2</sub> or volatile organic compounds (VOCs). Aerosols may be transported long distances and be gravitationally deposited or removed via rainfall [4]. Atmospheric aerosols are a mixture of particulate matter from many different sources – natural and anthropogenic, with the latter category including material from both stationary and mobile sources [5]. This paper deals with studies on engine generated particulate matter from mobile sources (road vehicles).

Actions resulting in decreased harmful exhaust emissions from combustion engines have been undertaken for decades and have chiefly relied on the application of three ways catalysts (TWCs) and diesel oxidation catalysts (DOCs), followed by Diesel particulate filters (DPFs) [6]. Selective catalytic reactors (SCR), gasoline particulate filters (GPFs) or lean NO<sub>x</sub> trap systems are quite new solutions fitted to recent Diesel and gasoline engines (Fig. 1a and Fig. 1b).

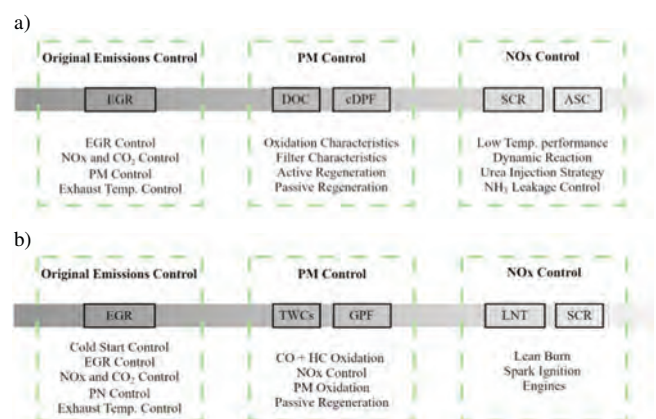


Fig. 1. Technical points of a) diesel engine after treatment system; b) gasoline DI engine after treatment system

Further concern centred on solid particles present in exhaust gas, which resulted in the implementation of new emission standards (Euro 5) where limits for the emission

of particulate matter mass (PM) and particulate matter number (PN) were set as  $4.5 \text{ mg}\cdot\text{km}^{-1}$  and  $6\cdot 10^{11} \text{ \#}\cdot\text{km}^{-1}$ , respectively. (Previously, Diesel engines had been subject to mass-based PM limits for emissions of particulates, but with much higher emissions limits and no PM limit). The highest concentrations of PM were reported for diesel engines, for reasons linked to the properties of that fuel and the Diesel cycle, as well as the full roll-out of direct injection for all modern Diesel engines. Therefore, diesel particulate filters (referred to as DPF or FAP) are currently installed to all new diesel-fuelled vehicles. According to the latest update of emission legislation set out in September 2017, newly-produced vehicles should be tested in real driving conditions as part of the type approval procedure [7], later extending to surveillance of vehicles currently in circulation. The abovementioned exhaust aftertreatment systems for control of particles (DPF/FAP, GPF) are mostly designed to work in a “storage and release” manner. This phenomenon is considered a significant source of NPs emission [8, 9]. The “storage and release” principle relies on regeneration events, which are expected to be more common in real driving conditions due to engine loading and the fact that the temperature of exhaust gas and thus the aftertreatment system elements is continuously changing [8].

This work aimed to identify the main challenges concerning research on solid particles generated by gasoline and new advanced vehicular engines on the basis of literature and own preliminary studies.

## 2. Nanoparticles – physical and chemical properties

A nanoparticle is considered as a particle whose aerodynamic diameter does not exceed 100 nm. In some literature references nanoparticles are described as such particles, but with a diameter range from 10 to 23 nm. This is mostly combined with legal requirements which currently specify the obligatory to control the level of particles emitted of diameter ( $23 \text{ nm} - 10 \text{ \mu m}$ ). Nowadays, due to the minute size of NPs, research on automotive generated particles is focused on the development of methods enabling the characterization of NPs in terms of their physical and chemical properties [10, 11]. Nanoparticles which are the part of the nucleation mode are the subject a great attention of scientists and engine designers, mainly due to their strong impact on human health [12]. They are able to diffuse through the skin and be transported by the blood reaching the most vital systems and organs.

Similarly as in the atmosphere, nanoparticles, once generated as a result of favourable conditions in an engine combustion chamber undergo reactions of accumulation and coagulation changing the size of spheres and changing the chemical and physical properties [10]. It is believed that the increasing concentration of  $\text{SO}_2$  and the increase of  $\text{SO}_2$  conversion enhance NPs' formation [8]. This stage of NPs' formation is known as nucleation. While NPs consist of water, sulphur compounds and hydrocarbons, larger particulates (accumulation mode and upwards) are made of solid agglomerated soot, which as a material is extremely effective at absorbing and adsorbing organic and inorganic exhaust components (Fig. 2).

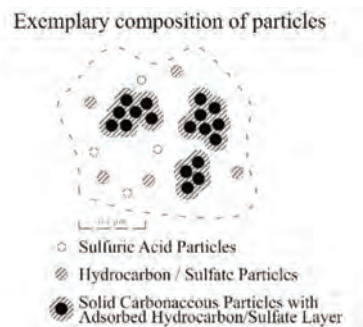


Fig. 2. Typical composition and structure of engine exhaust particles [10]

The influence of the fine solid particles on human health increases in inversely proportion to their size. Research confirms that particles from the  $\text{PM}_{2.5}$  category are characterized by greater health affect than  $\text{PM}_{10}$ . Particles under a diameter of  $2.5 \text{ \mu m}$  are able to penetrate the blood-air barrier (alveolar–capillary barrier) and to circulate with the blood throughout the human body [12]. Engine generated particles are mostly composed of soot and elemental carbon, which are materials with excellent absorptive properties. As a result, such particles are carriers of absorbed and adsorbed chemicals, including carcinogenic and mutagenic products of chemical reactions occurring in the combustion chamber. Benzo(a)pyrene is the most well-known polycyclic aromatic hydrocarbon (PAH); however, new advance instrumental methods allow investigation of nitric (nitro-PAHs) and oxidative (oxy-PAHs) derivatives of PAHs which are considered more dangerous than PAH themselves [13]. The World Health Organization (WHO) has estimated that PM is responsible for about 3% of deaths caused by failure of the respiratory system and 5% of deaths caused by lung cancer [14]. The mechanisms of NPs' negative impacts on human health are still the subject of many studies. One such mechanism relies on the strong impact of organic matter's oxidative stress on an organism's cells [15].

## 3. Nanoparticles' morphology

SEM analyses allow the morphology and dimension of NPs to be studied. Solid particles' morphology and external structure were analysed using a field emission scanning electron microscope (SEM, FEI Versa 3D) equipped with an energy dispersive X-ray spectrometer (EDS, EDAX Apollo XP) for qualitative physicochemical analysis. SEM observations were carried out without conductive coating at high vacuum mode, using a secondary electron (SE) or backscattered electron detector (BSE) at an acceleration voltage of 5 kV. EDS analyses were performed an acceleration voltage of 20 kV. For efficient generation of X-rays, the overvoltage must be not less than twice the critical ionization energy of the elements of interest [16].

Figure 3 (a, b) and Figure 4 (a, b) present electronic microscopic images of two samples of soot particles sampled on glass-fibre filters during a laboratory emission test (WLTP) of a passenger car with a 1.4 litre gasoline engine. The images were taken at different magnifications. Figure 3a shows particles of ca.  $5 \text{ \mu m}$  of size. There are rather spherical in shape and seem to be a separate body beyond the rest of particulate matter. The higher magnification

image (Fig. 3b) presents the rare filament-like particles containing branched structures with very low dimensions of ca. 50 nm. Engine exhaust particles show a strong tendency to accumulate in loose, powdery, brittle agglomerates varying in size. All particle fractions contained nanoparticles down to 100 nm in the form of agglomerates. The size of these structures is probably even lower, however at this point more exact analysis of the scales present was not possible.

Figures 4a and 4b similarly show the particles generated during operation of gasoline engine. The content of oxygenated additives in the fuel were different comparing to the test mentioned previously. This information is reserved by the fuel producer. Figure 4a presents a particle of an irregular shape, yet with rather smooth surface. The higher magnification image showed that this surface is rather lumpy, consisting of many minute particles (of 30–70 nm dimension) combining in larger agglomerates. Moreover, as noted by Yang et al. (2016), the nanostructure of particulate matter is highly dependent on the fuel oxygen content [17].

Nanoparticles are usually generated in high-temperature well-premixed processes. These conditions are favourable for soot particles to coalesce in the form of chains. Accord-

ingly to the studies of Potenza et al. (2019), the coalescence of particles is possible due to the pressure of charged radicals in the flame. As the flame extinguishes, the free charges disappear and chains coalesce resulting in larger agglomerates [18].

#### 4. Nanoparticles' chemical composition

In order to pinpoint the dangers posed by nanoparticles and to accurately recognize solutions enabling the reduction of NP emissions, it is necessary to characterize their chemical composition. Solid particles, regardless of the size mode, are mainly made of organic and inorganic fractions. The organic fraction mainly consists of elemental carbon (EC) and organic carbon (OC). Organic matter is a mixture of hundreds (or even thousands) of organic compounds, beginning with n-alkanes, ending with more complex structures as polycyclic aromatic hydrocarbons (PAHs), their oxygen and nitric derivatives, aldehydes, hopanes and steranes [19, 20]. The inorganic fraction mostly consists of metals and non-metals and are the effect of material attrition or grinding [20]. The chemical composition of NPs differs depending on many factors, like the fuel used or the engine operating parameters [11, 21].

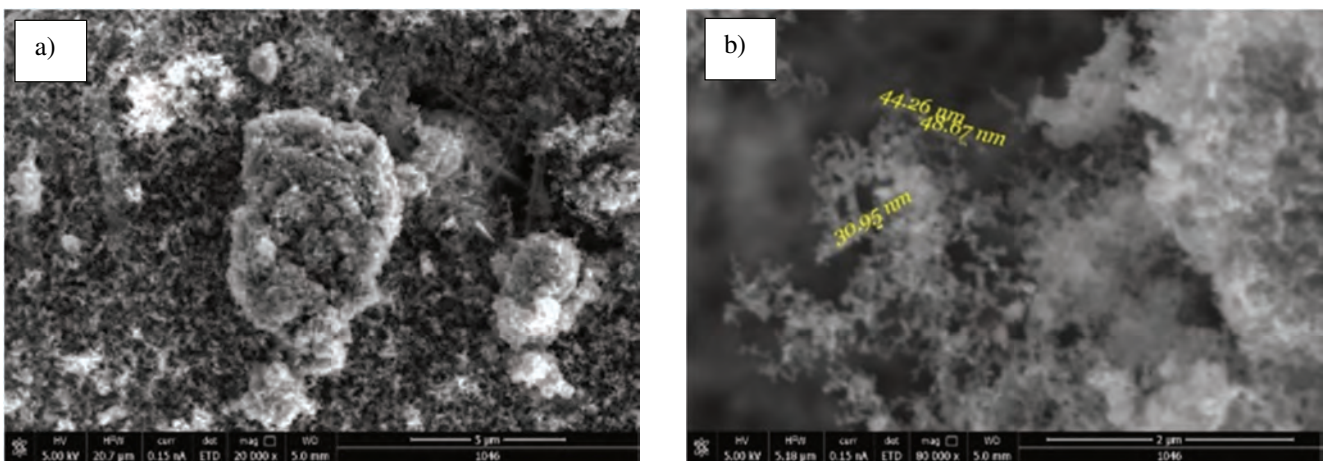


Fig. 3. SEM images of engine generated particles at different magnifications (a: 20 000 x; b: 80 000 x)

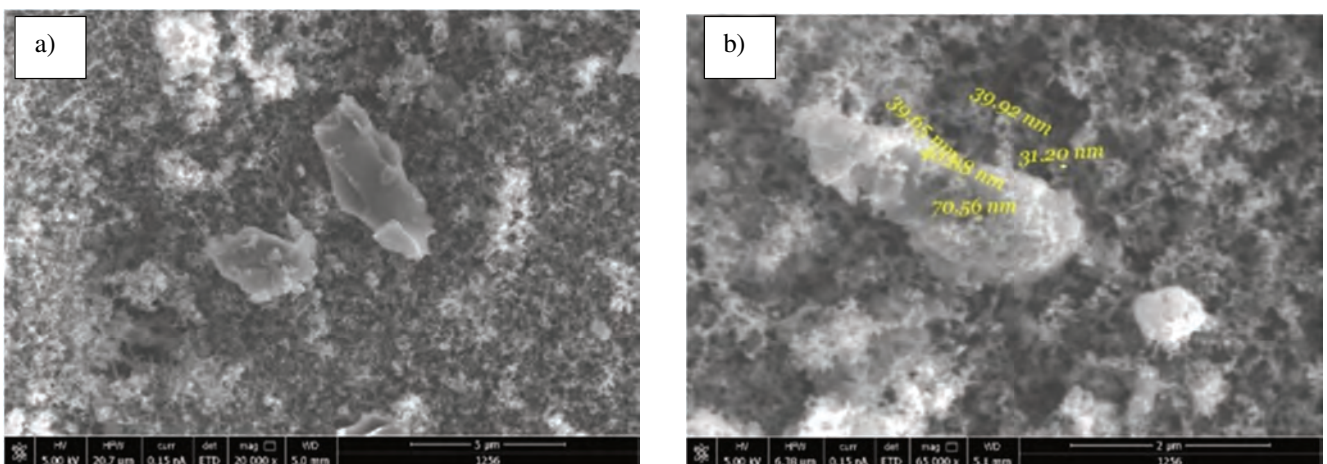


Fig. 4. SEM images of engine generated particles at different magnifications (a: 20 000 x; b: 65 000 x)

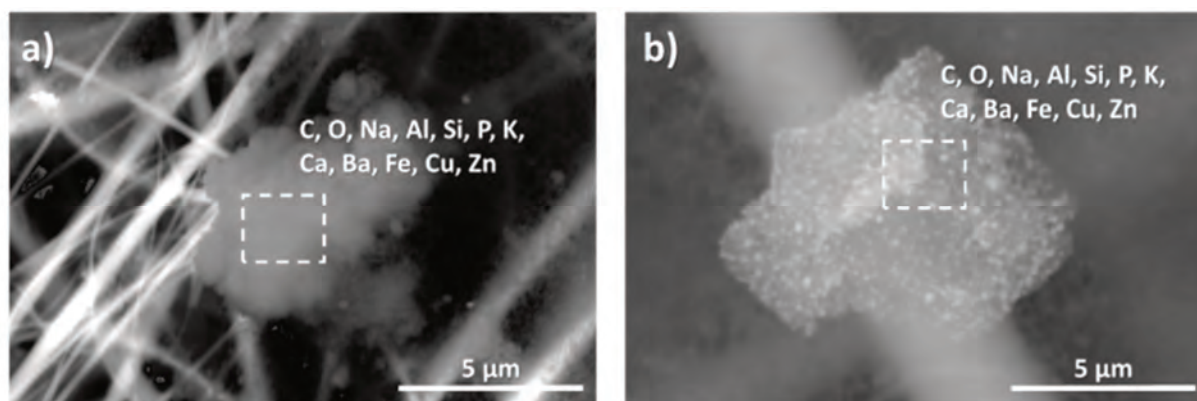


Fig. 5. BSE micrographs of particles with areas for EDS analysis marked a) sample no. 1046 b) sample no. 1256

Figure 5 shows BSE micrographs with results from the qualitative analysis of chemical composition of particulate matter from a gasoline fuelled engine. EDS analysis revealed the presence of Na, Ca, K, P, Zn, Cu, Ba and S in all fractions, which come from lubricant additives and minor Fe, Al, Si elements [18, 22]. The elements can be a part of aluminosilicate, which is composed of Si, Al, Ca, K and minor levels of Na, Mn and Zn [23]. Moreover, Cu and Si are rather bonded into an alloy, being the composite used in pistons ( $\text{AlSi}_{12}\text{Cu}_3\text{Ni}_2\text{Mg}$ ). The areas rich in Ba presented chemical associations of barite ( $\text{BaSO}_4$ ). The presence of these particles is related to non-exhaust vehicular emissions mainly from brake pads' abrasion emissions. Given that asbestos has been substituted in the compositions of such components, it could explain the sulphur and oxide content associated with these phases which are rich in barium [24]. As the sample was taken from exhaust gas, the presence of material related to brake dust suggests a substantial contribution of particulate from ambient air in the exhaust gas; this material appears to enter the engine with the intake air. Such a phenomenon underlines the need for careful consideration of the precise origin of particulate present in vehicular exhaust, as well as the need for chemical analysis at the nano scale, right down to analysis of individual parts of a structure.

To deepen the studies, TEM and XPS analysis of engine-generated particles and their morphology and chemical composition demanded. These techniques will allow the process of nanoparticles formation to be traced and to find out the valency of elements detected, which would give detailed information on the chemical composition of nanoparticles.

### 5. Parameters influencing NP emissions

Considering NPs of automotive origin, they primarily originate from the powertrain as the result of incomplete fuel combustion process. While leaving the exhaust pipe, due to the temperature gradient or reactions with other substances, some of the exhaust components may undergo aerosol transformations (i.e. condensation reactions), leading to the formation of secondary NPs. Beyond combustion generated NPs, there are also nanoparticles being the result of lubricating oil consumption and road traffic wear, which is the combined physicochemical alteration of material from tires, brakes, clutch mechanisms and the road surface itself.

The share of the fine particles whose material origin lies in the engine lubricant can reach up to 30% of total engine-related solid nanoparticles [25–28]. The share of the solid particles emitted whose material origin lies in the oil can be measured by analysis of the zinc and molybdenum concentration. Both metals are present in the quite high amounts in the engine lubricant but they are absent in the fuel; therefore it is estimated that average share for solid nanoparticles is about 10–20%. Additionally, the literature shows that motor oil is responsible for even 30% of the produced higher hydrocarbons (which are not included in the solid NP fraction). This is caused by their high activation energy for the combustion reaction (at least in comparison to fuel), due to which their combustion during engine combustion cycle is difficult [28, 29]. To estimate NP emissions originating from the engine oil, it is possible to use measurements of hopanes and steranes in the exhaust [30].

Road traffic wear NPs might be a result of tires grinding on the road and brake pads grinding on brake discs [31]. In light duty vehicles two types of brakes are currently installed: drum and disc. Drum brakes represent older technology; they are heavier and require a greater surface for a sufficient braking force. Moreover, due to their closed construction they often overheat, which decreases their effectiveness. Disc brakes are gaining popularity due to their lower weight, greater resistance to overheating due to their open construction and shorter braking distances [31]. Research has shown that new disc brakes generate more solid particles ( $\text{PM}_{10}$  and smaller) during to their break-in period. The chemical composition of such PM strongly depends on the material which brakes are constructed of, i.e. iron and copper particles originating from the brake pads or other solid metal particles from the disc. The braking process may be responsible for as much as 50% of the non-exhaust road traffic emissions [32]. The amount of solid nanoparticles originating from the tires depends on tyre hardness and road abrasiveness. The literature reports that over a distance of 1 km  $1 \cdot 10^{11}$  solid nanoparticles of this type can be emitted [10, 33] and thus the level of NPs of this type is often broadly comparable to the level of exhaust NPs. As mentioned previously, the presence of material assumed to drive from brakes in exhaust particulate complicates the situation regarding qualitative chemical analysis, as a single particle could contain a cocktail of elements deriving from many different sources (fuel, lubricant, engine hardware, intake air particulate).

In Scandinavian countries, especially in the winter, tires with studs are often used for the purposes of obtaining better grip on a road covered by snow or a layer of ice. Containing tungsten carbide, cobalt or copper, such studs may contribute to NP formation at the tyre-road interface [34]. Elements linked to road salt may also be detected in chemical analyses of exhaust particulate.

Returning to combustion-generated NPs, engine architecture is an important factor influencing the concentration of emitted NPs. The application of gasoline direct injection technology improves fuel consumption and power density, but on the other hand, causes the generation of higher amount of NPs comparing to the amounts of NPs generated where port fuel injection technology is applied (all other factors being equal) [27]. The elevated emission of NPs is probably the result of incomplete combustion in an engine chamber [10, 29]. To reduce emissions, the number and size of the cylinders was reduced in many designs. This trend is called *downsizing*. However, current technological development requires the optimization of engines from many points of view simultaneously (fuel consumption, emissions, drivability, durability), which is leading to a trend to maintain (or even increase) engine power while simultaneously lowering the emission. This trend conflicts to a degree with designs featuring lower numbers of cylinders and small engine displacements and so a new trend has been observed: the *rightsizing* trend [7].

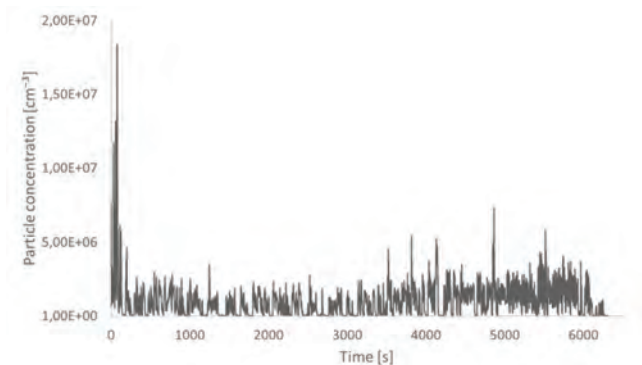


Fig. 6. Particle concentration during a 2-hour real driving (RDE) test with a GDI vehicle with no GPF installed [37]

Cold start of an engine, low temperature of the after-treatment and an aggressive driving style are also factors influencing the intensity of NP emissions. Engine cold start occurs after a period of cooldown, where the powertrain is working below the optimal thermal states. This temperature strictly influences the distribution of lubricating oil in an engine [35, 36]. Research conducted by BOSMAL on GDI vehicles with no GPF installed proved the domination of a cold start during real driving tests. PN concentrations were higher during cold start than during the next 2 hours of driving, even though later sections include high speed driving (Fig. 6). Various devices with different measuring ranges are available for quantifying PN; particles in the range 10–23 nm are not counter by standard laboratory PN counters, yet the “missing” particles account for no more than 15% of the total for modern GDI vehicles [37].

Similarly, the research conducted by BOSMAL on Diesel-fuelled vehicles with DPFs proved that 57% of total PN were emitted during the first km of a cold start driving cycle at low ambient temperature ( $-7^{\circ}\text{C}$ ), while at warmer ambient temperatures ( $+25^{\circ}\text{C}$ ) 13% of total PN were emitted during the first km of driving. These numbers were lower for another vehicle without a DPF; 15% of the total PN quantity was emitted during the first km at  $-7^{\circ}\text{C}$  and 8% of the total PN were emitted over that distance at  $+25^{\circ}\text{C}$  [37]. Thus, lower ambient temperatures cause the NP emissions profile to become more “cold start-heavy”. However, DPF-filtered PN levels are low and there can be considerable variation on behaviour from test to test and vehicle to vehicle.

Exhaust aftertreatment technologies based on filters (DPF, GPF) might be thought to be immune from cold start effects, yet cold start engine operation can still influence their performance. Firstly, cold devices have not yet expanded to their equilibrium volume seen under hot conditions and so there can be some leakage of unfiltered exhaust around the edge of the monolith or through cracks within it, which later close up as the monolith undergoes thermal expansion. Secondly, passive regeneration (unaided oxidation of soot trapped on the filter, especially on the upstream filter face – closest to the engine) is extremely unlikely to occur when the temperature of the system is low (i.e. immediately following cold start). And finally, cold start engine operation (especially at very low ambient temperatures) and driving during warmup generate greater amounts of soot than under other driving conditions, thereby increasing the need for more DPF frequent regenerations (and thus increasing total NP emissions because of the emissions associated with regeneration). For a GPF (where there is no active regeneration strategy), a build up of soot on the filter increases the backpressure, leading to increased fuel consumption and ultimately to more frequent regenerations (and thus increasing total NP emissions in the long term).

Such effects are of considerable importance in areas of low average ambient temperatures, especially in cold seasons. It was reported that the decreased temperature down to  $-7^{\circ}\text{C}$  may cause a 60–160% increase of NP emissions compared to the emission intensity at  $23^{\circ}\text{C}$  [29]. Ambient temperature aside, an aggressive driving style (i.e. high engine speeds and loads) causes increases in NP emissions [26]. Similarly, vehicle mass is an important factor influencing both pollution emission and fuel consumption (FC). It was reported that FC increases by 6–7% with an elevation of vehicle mass for each 100 kg, which intensifies the emission of NPs.

## 6. Conclusions

There are many possibilities to reduce NP emissions associated with road transport. They include both technological aspects such a powertrain designs featuring advanced aftertreatment systems, production of new advanced fuels, as well as changes in social awareness such as promotion of eco-driving styles and propagation of information on the effects of NP pollution on the environment and human health.

It might appear that the problem of exhaust NP emissions from internal combustion engine-powered road transport has already been solved and that there is no need for further

investigations. However, technological development both in the vehicle and engine industries, analytical chemistry and even medicine has proved the multi-disciplinary character of the problem. Thus, studies combining all three abovementioned disciplines remain in demand. The investigation of gaseous emissions is also a significant topic in this field, as they are the effect of preliminary processes of particle formation and thus might give more precise information on the biological impacts of PM and its origin.

Current EU legislation on emissions from light duty road vehicles covers emissions of CO<sub>2</sub>, NO<sub>x</sub>, hydrocarbons and non-methane hydrocarbons, PN and PM. The technological development of instrumental techniques has enabled

the detection of many other exhaust components which might significantly affect the human health which are not regulated by EU, US or other legislation. This creates some challenges both for engine and aftertreatment designers, fuel producers and scientists studying air quality and human health. The physicochemical laboratory methods used to generate the sample results presented in this paper represent a promising avenue for further research in the field of vehicular NP emissions.

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### Nomenclature

AD	aerodynamic diameter	OC	organic carbon
ASC	ammonia slip catalyst	oxy-PAH	oxidative derivatives of PAH
BSE	backscattered electron detector	PAH	polycyclic aromatic hydrocarbons
DI	direct injection	PM	particulate matter
DOCs	diesel oxidation catalysts	PN	particulate number
DPFs	diesel particulate filters	RPM	revolutions per minute
EC	elemental carbon	SCR	selective catalytic reduction
EDS	energy dispersive X-ray spectrometer	SE	secondary electron detector
EGR	exhaust gas recirculation	SEM	scanning electron microscopy
FAPs	<i>filtre à particules</i>	TEM	transmission electron microscopy
FC	fuel consumption	TWCs	three ways catalysts
GDI	gasoline direct injection	VOCs	volatile organic compounds
GPF	gasoline particulate filter	WHO	World Health Organisation
LNT	lean NO <sub>x</sub> trap	WLTC	Worldwide harmonized Light vehicles Test Procedures Cycle
nitro-PAH	nitric derivatives of PAH	XPS	X-ray photoelectron spectroscopy
NP(s)	nanoparticle(s)		

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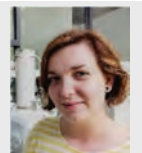
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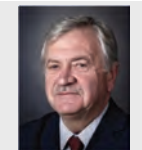
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## Observations from PEMS testing of combustion engines of different applications

*The article compares data obtained in road tests with the latest legislative proposals relating to various applications of internal combustion engines. Passenger car emission tests have been performed several times on the same test route in accordance with the RDE procedure guidelines, for which a dozen or so criteria must be met, including the distance of each of the drive sections, their in the drive time and the dynamic characteristics of the drive. The analysis was also based on a two-dimensional operating density characterization, presented in the vehicle speed-acceleration coordinates. As a result, it was possible to compare dynamic properties, operating time density and, thus, to check the validity of conducted drive tests in terms of their feasibility and emission values. An exhaust emission related comparison of three types of powertrain have been presented: gasoline, diesel and hybrid in the RDE tests. The authors proposed a new form of presenting the road exhaust emissions results in relation to the carbon dioxide emission, referred to as a standardization of the emission results. The exhaust emissions from city buses fitted with different powertrains tested on an actual bus route and in the SORT test were also compared.*

Keywords: *exhaust emission, passenger cars, road tests, Real Driving Emissions*

### 1. Introduction

Currently, a trend towards a more global consideration of environmental threats from the automotive industry can be observed. The provisions approving the use of vehicles (type approval tests and production compliance), periodic technical inspections and legal acts related directly and indirectly to the production, use and management of used products and waste treat the issues of environmental protection in a more comprehensive manner. Over the past years, there have been various systems for vehicle exhaust emissions measurement and control in individual countries, however a widespread unification began more recently [1, 5, 25, 34].

The dynamic development of transport in the last decades is an important factor in the world economic development and at the same time a significant source of problems related to it, especially significant on the local scale, especially in large urban agglomerations. The negative effects of transport are noticeable both for the natural environment and society. The widespread development of this sector has allowed society to overcome a significant barrier to civilization development, the effects vary depending on the level of economic development, level of advancement and use of various transport sectors, geographical location (mainly climate), as well as the sensitivity of the environment.

Preventing threats from transport from occurring, and when it is not possible – limiting their environmental impact, as well as the scale and scope of negative effects is extremely important [41]. Appropriate activities should be taken at administrative levels of authority, local governments as well as in the private sector. It is necessary to introduce appropriate legal and administrative regulations, provide adequate financial resources and human potential for the development of new technologies, spatial planning, rational design and maintenance of infrastructure, as well as for educating the public and rationalizing transport tasks.

The growing number of vehicles in the world and the rising pollution levels lead to an increase in the requirements placed to reduce exhaust emissions. Additionally the current level of technology advancement and technology in the industry, including all types of transport, increases the quality level of emission measuring devices [4, 8, 9]. In order for products to meet these requirements to an appropriate extent regarding the periodically changing regulations, the industry focus had to shift towards this aspect. Exhaust emission testing bears a significant level of complexity. Current emission analyzers require specific laboratory conditions, and type approval procedures include tests on engine and chassis dynamometers. Those, however, do not reflect the actual emissions in real operating conditions. The results of latest tests conducted in real conditions indicate that for some exhaust components this emission is higher by several hundred percent in case of both gas compounds [18, 21, 28] and particulates [32, 35, 39]. As a result, there is a visible trend towards the implementation of emissions measurement in real operating conditions for conventional [2, 23, 29] and hybrid vehicles [36, 40] as well as for two- and three-wheeled vehicles [38].

The fuel crisis of the 1970s made the world realize that the natural energy resources are limited. Nowadays, exceeding the ecological barrier is more and more often considered to be more dangerous than the depletion of fuel resources [6], especially since the issues of environmental protection in the world energy policy are not given due urgency in some countries. The increase in the world's vehicle number leads to significant amounts of carbon dioxide, but it also depend on the types of transport and their use. In line with the European Union strategy, in force since 1995, the average level of carbon dioxide emissions from vehicles has been reduced to 130 g/km in 2015, and in 2020 this level in Europe is to be down to only 95 g/km [13].

The main research and development direction for manufacturers of vehicle drive systems, is a system based on the cooperation of a combustion engine and electric drive, i.e.

hybrid drive (Fig. 1). Hybrid vehicles currently have a noticeable share in the car market [3]. In the span of the next 15–20 years, hybrid drives should reach about 25% share of all new vehicles sold in the European Union. At the same time, other modern drive systems, such as the classic electric drive that draws energy from batteries and fuel cells, are expected to gain several percent of the market share.

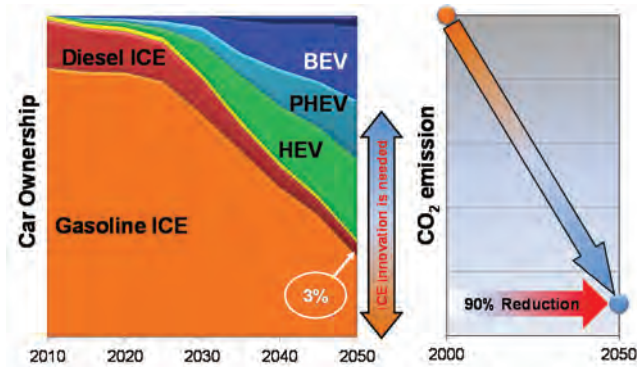


Fig. 1. Future power source trend and CO<sub>2</sub> target [12]

The key technological factors for the development of internal combustion engines can be assessed in three aspects [19, 26, 29–32]:

- exhaust emission tests in RDE (Real Driving Emissions) traffic conditions, which results in the extension of the repeatable dynamometer tests by tests performed in various road conditions (Fig. 2),
- lowering the limit values of carbon dioxide emission will cause electrification of vehicle drives, which will force conventional combustion engines to reduce fuel consumption and increase their efficiency,
- lower exhaust emissions limits of harmful compounds result in a further reduction of NO<sub>x</sub> emissions for Diesel engines, while for SI engines with direct fuel injection a significant issue is the reduction of the number of particles.



Fig. 2. Poznan University of Technology – large experience in RDE measurements [24]

## 2. Validation of RDE procedure requirements

The research route on which the tests were performed was designed to meet the European Commission require-

ments as described in the regulations [10, 11]. 8 measurement cycles were made while meeting the real driving conditions requirements in urban, rural and motorway areas in and around the city of Poznan. The average distance traveled was 80 km (Fig. 3, Table 1).

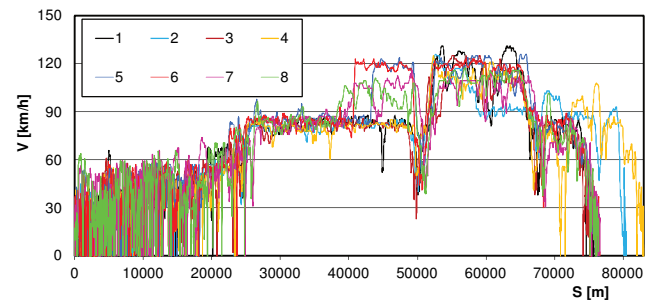


Fig. 3. All RDE tests were characterized by similar parameters and had similar speed profiles

Tab. 1. Drive cycle parameters (acceleration, constant vehicle speed, braking, stop) relative to the average value

Test number	Share [%]			
	a > 0	V = const	a < 0	V = 0
Test 1	20	39	20	21
Test 2	20	51	19	10
Test 3	22	41	20	17
Test 4	21	41	20	18
Test 5	23	34	23	19
Test 6	26	34	26	14
Test 7	33	21	30	16
Test 8	32	17	31	20
Average	24.6	34.7	23.6	16.9

Analysis of the route distance data in the urban section showed that the drive No. 2 had the largest distance covered, while the shortest was drive No. 4, however the length values of all drive cycles were within the acceptable range, i.e. they were greater than 16 km (Fig. 4a). Route data analysis for the rural section indicated that the longest route was travelled during drive No. 2, and the shortest for drive No. 8. The distances covered in all drive cycles were within the acceptable range, i.e. they were greater than 16 km (Fig. 4b). The motorway section was the longest for the drive No. 8, and the shortest for the drive No. 1. The route distances for drives No. 1 and 3 were too small. The remaining drives were within the acceptable range, i.e. their distance was longer than 16 km, and the average was 24.66 km (Fig. 4c).

The urban drive section time density was the highest for the drive No. 3, and the smallest – for the drive No. 2. The time density of the urban part of all drives (except for the drive No. 2) were all within the valid range of 29–44% (Fig. 5a). Time density of the rural section of the drive was the highest for the drive No. 1, and the lowest – for the drive No. 8. But these values were only deemed acceptable for drives No. 5–8 as being in the range of 23–43%. The remaining drives did not meet this requirement and were thus deemed invalid (Fig. 5b).

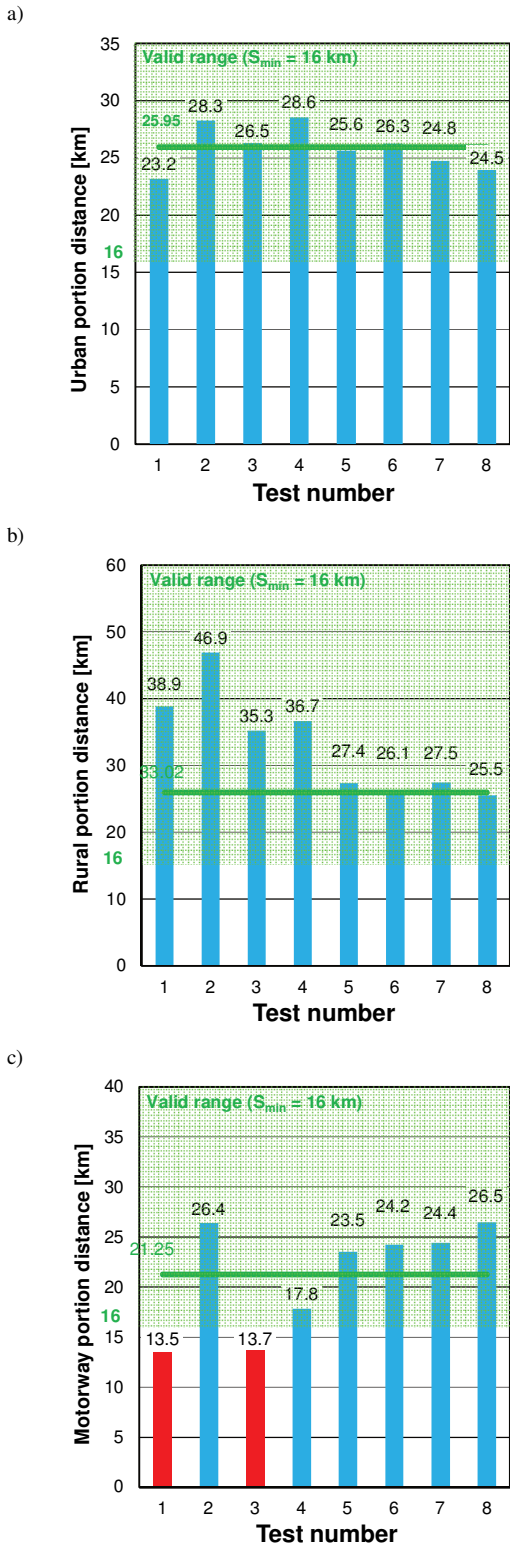


Fig. 4. Comparison of urban (a), rural (b) and motorway (c) section distances with a minimum value (required) for all drives as well as the average

The highest time density value for the motorway section drives data analysis was found for drive No. 8, and the smallest – for drive No. 1. The rural section time density values were in the valid range of 23–43% for all drives except the drives No. 1, 3 and 4 (Fig. 5c).

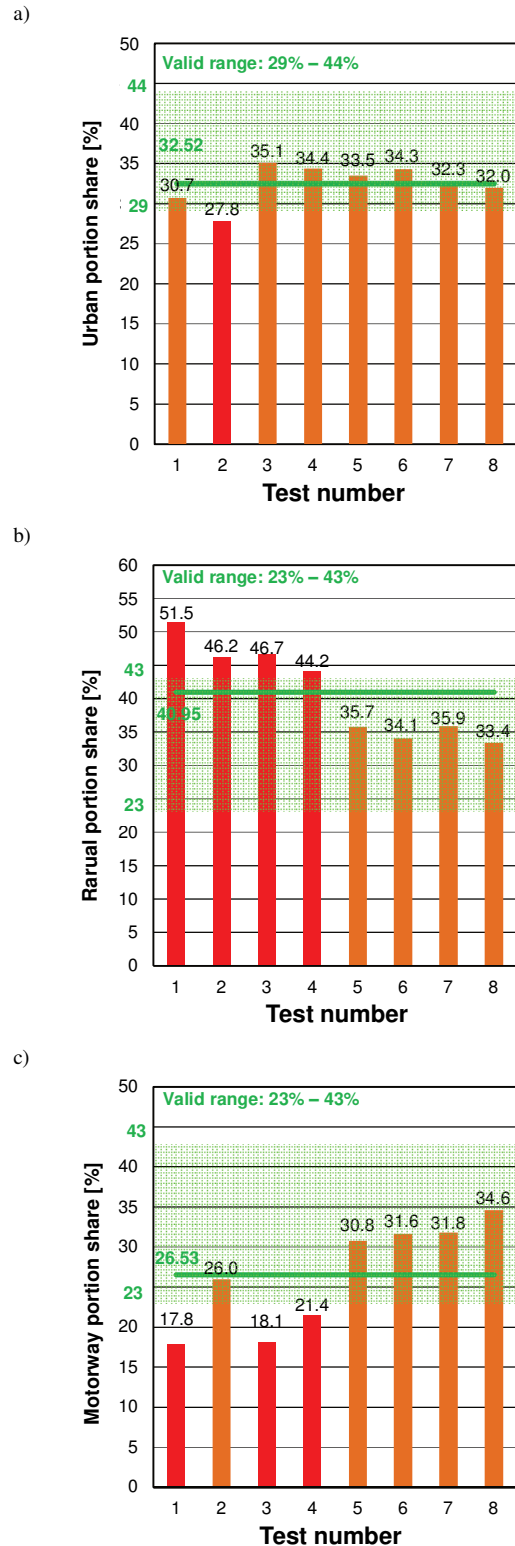


Fig. 5. Comparison of the urban (a), rural (b) and motorway (c) sections share in the drive cycles with the limit values (required) indicated for all drive cycles as well as the average value

The average speed data analysis in the urban section showed that the highest speed was found for drive No. 2, and the smallest speed for drive No. 1. The average speed values of all drives are within the required range, i.e. from 15 km/h to 40 km/h (Fig. 6a). The drive cycle duration was the longest for the drive No. 4, and the shortest for the drive



For all the drive cycles the largest operating time density for the vehicle was observed for the idle mode and the average speed value range ( $V = 24$  m/s for  $a = 0$  m/s<sup>2</sup> except for drive No. 7). This is the result of a constant driving speed in the rural area. For the valid drives, variable acceleration values in the range ( $-0.4$  m/s<sup>2</sup>,  $0.4$  m/s<sup>2</sup>) are visible in the vehicle operating characteristic.

The drives labelled 5–8 were all valid and for these drives average values were determined, which were marked as "reference" (Fig. 8).

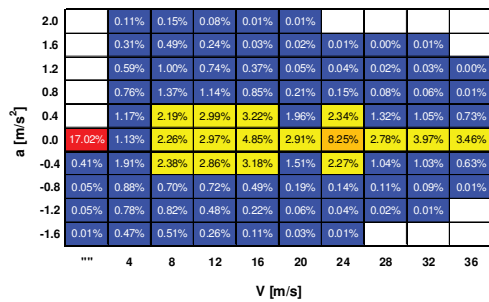


Fig. 8. Vehicle's operating time density in individual speed and acceleration intervals for the "reference" drives

The road emission values were determined using previous research with simultaneous measurement of exhaust emissions. Due to the fact that the tests were performed for a vehicle with a Euro 6b emission class gasoline engine (without a particle filter – GPF), the emission of carbon dioxide, carbon monoxide, hydrocarbons, nitrogen oxides and the number of particles was measured (Fig. 9). The obtained results were presented for all eight drives with the indication that the first four drives did not meet the formal requirements of the test drive cycle (marked in red), however, this fact did not invalidate the road emission results that can be obtained from them. Invalid drives are marked in red, while the parameter value range for a drive to be valid (as for drives marked 5–8) is marked in green.

The emission limits shown in Fig. 9, marked as Euro 6d-Temp, refer to future emission standard (coming into force on 1.09.2017), where the emission limits are provided as:

- for nitrogen oxides at 2.1,
  - for particle number at 1.5
- relative to the emission value limits of Euro 6b.

Analysis of individual pollutant emission values indicates a similar nature of the obtained data, which is discussed below.

The maximum road emissions value of carbon monoxide (Fig. 9) for valid drives was 356 mg/km (drive 8), and the minimum value is 264 mg/km (drive 6). Drive No. 6 was characterized by a low RPA (Relative Positive Acceleration) value from among the valid drives. Obtained road emission values did not exceed the limit values, specified in the Euro 6b standard for passenger vehicles equipped with gasoline engines (1000 mg/km) for all performed drive tests.

The emission of nitrogen oxides (Fig. 10) changed (for drives compliant with the RDE requirements) from 39.7 mg/km (drive 5) to 44.9 mg/km (drive 8). Road emissions

values in all drives did not exceed the permissible limit, i.e. 60 mg/km.

The character of the particle number road emission was similar to the previous results (Fig. 11): the highest value was obtained for drive No. 8 ( $4.3 \cdot 10^{12}$  1/km), while drive No. 6 had the lowest value ( $2.5 \cdot 10^{12}$  1/km).

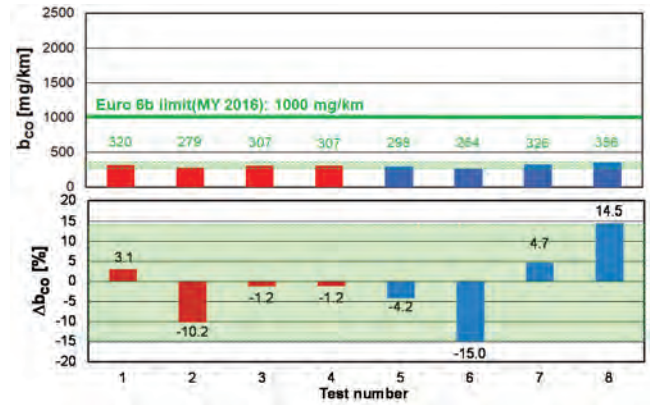


Fig. 9. Carbon monoxide road emissions and relative error for all completed drives; invalidated drives are marked in red, while the parameter value range of valid drives (5–8) is marked in green

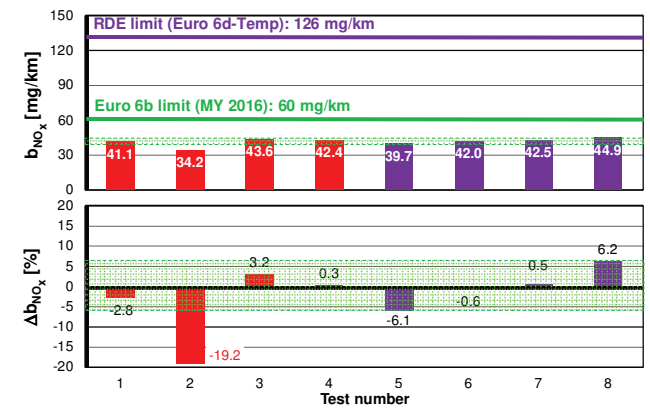


Fig. 10. Road emission of nitrogen oxides and relative error for all drives

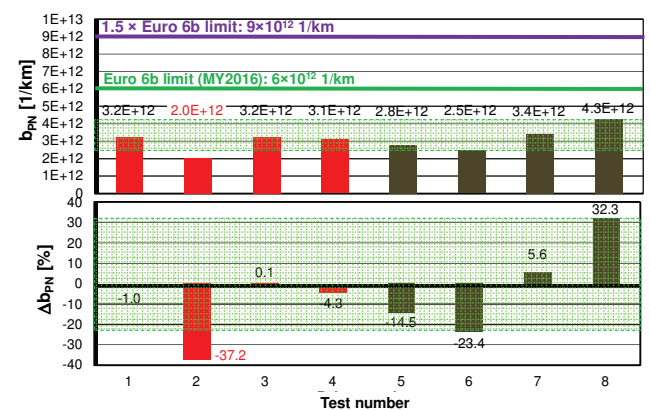


Fig. 11. Particle emission number and relative error for all drives

In order to compare the value ranges in individual road exhaust emissions, a relative error was determined for each component of the road emission in each drive, as described by the formula:

$$\Delta b_j = \frac{b_{j,avg(5-8)} - b_j}{b_j} \quad (1)$$

where:  $b_{j,avg(5-8)}$  – average road exhaust emissions value from drives 5–8,  $b_j$  – individual pollutant road emission value.

Analysis of individual relative errors values allows the following relationships to be found:

- the relative error of carbon monoxide road emissions values between individual drives does not exceed 15%; all drives were within this range (including the drives that failed to meet the RDE requirements). In this case, the highest relative error values (i.e. 14.5% and –15%) were obtained for the valid RDE tests. The relative error of carbon monoxide road emissions for invalid tests was lower than in the case of valid ones, i.e. carbon dioxide emission values obtained from the tests not meeting the RDE requirements were mostly similar to each other – in contrast to the values obtained in the tests that were valid for the RDE procedures;
- the relative error value of nitrogen oxides road emissions between individual drives did not exceed about 6%; all drives were in this range – except for drive No. 2 (not meeting RDE requirements), whose result was reported to be lower by about 20% from the average value of the valid drives. At the same time, there is no unambiguous trend in the values of relative error for invalid drives;
- the nature of the relative particle number error confirms the previous results, that the relative error between individual valid drives is the largest and exceeds 30%; all drives were in this range – except for drive No. 2.

The analysis of individual requirements specified in Regulations 2016/427 [11] and 2016/646 [12] confirmed the validity of the RDE test procedure for four out of eight performed drive tests. Invalid drives were characterized by either too short drive distance, too small share of driving in particular test sections, too long time spent idle in the urban section and too low driving dynamics in the rural part.

The analysis of the test results does not allow to unambiguously determine the errors and uncertainties of the obtained emission results with the assumed number of road test errors made.

However, it should be noted that the highest values of road exhaust emissions were obtained for drives in which the urban section share was small but with a large share of the motorway section. This shows a significant impact of RDE test sections on the road emission results, where a high engine load is used, and the exhaust emission intensity is greatest (as well as the of exhaust aftertreatment systems efficiency not being at maximum).

The conducted research lead to determining the scatter of the obtained exhaust emission results for RDE tests performed in accordance with the European Union procedures. The results scatter values (for passenger vehicles with direct fuel injection gasoline engines, meeting the Euro 6b standard) were as follows:

- for carbon monoxide road emissions results the scatter was  $\pm 15\%$ ,

- for nitrogen oxides road emissions results the scatter was  $\pm 6\%$ ,
- for particle number road emissions results the scatter was  $\pm 32\%$ .

However, the issue of a greater impact of the RDE test section or driving dynamics (defined by indicators of relative positive acceleration or the product of velocity and acceleration) on the exhaust emission values was not resolved in this research. Describing and testing these relations will be the subject of further research using passenger cars powered by various fuels and hybrid vehicles.

### 3. Hybrid, Diesel and Gasoline vehicles in the RDE tests

Three vehicles were used for the exhaust emission tests in real traffic conditions. The same vehicle models of the same manufacturer were tested, but they had different drive system solutions. The first car was a hybrid vehicle, equipped with a spark-ignition engine with an indirect multipoint gasoline injection and a displacement of 1.8 dm<sup>3</sup>, working in parallel with an electric motor. The second of the tested vehicles was equipped with a compression-ignition engine with common rail direct injection with a turbocharger, with a displacement volume of 1.4 dm<sup>3</sup>. The last tested vehicle had an MPI gasoline engine with a displacement of 1.6 dm<sup>3</sup>.

The research goal was to determine the average road exhaust emission values of all measured components for each of the tested vehicles in urban, rural and motorway driving conditions, with the use of the developed Excel spreadsheet, that was used to convert the raw data according to the EMROAD method, as proposed by the European Commission.

The traffic conditions for each of the tested vehicles were very similar (Fig. 12). The similarity results mainly from the guidelines on the conditions and dynamics of the test drives, as listed in the regulations of the European Commission [8–11]. The tested vehicles passed almost the same distances in individual driving sections. Each vehicle covered a distance of about 27 km in urban driving section. Distance travelled by vehicles in rural driving section was shorter than in the urban section and amounted to approx. 25 km. The distance covered by cars while driving on the motorway was the shortest and ranged from 22 to approx. 23 km. For urban driving, Driving at speeds below 60 km/h was considered a part of the urban drive section, for the rural drive section all the drive time moving at speeds between 60 and 90 km/h was used, and for the motorway section it was driving at speeds above 90 km/h. The vehicle drive speed characteristics do not differ much, because the test drives were performed on the same route and because the drives needed to meet the requirements for the distance traveled within each drive section (minimum 16 km for each of the three sections). The average speed of urban driving (marked in green) was about 50 km/h for each of the tested vehicles. The average speed of driving in the rural section (marked in blue) was approx. 80 km/h for all vehicles. The average speed of all tested vehicles in motorway driving was about 110 km/h. None of the vehicles moved at speeds exceeding 120 km/h during the RDE test.

The hybrid vehicle has met the requirements for dynamic drive conditions. Both the values of relative positive acceleration (RPA) and the 95<sup>th</sup> centile of the product of speed and acceleration did not exceed the minimum and maximum limit for individual driving categories respectively (Fig. 13). The minimum required number of one hundred and fifty sets of data with acceleration values  $a_i > 0.1 \text{ m/s}^2$

for each drive section was also met. The value of RPA was  $0.19 \text{ m/s}^2$  for urban driving,  $0.056 \text{ m/s}^2$  for rural driving, and  $0.044 \text{ m/s}^2$  for motorway driving. The 95<sup>th</sup> centile value of the speed and acceleration product of was  $10.2 \text{ m}^2/\text{s}^3$  for urban driving,  $15.1 \text{ m}^2/\text{s}^3$  for rural driving and  $16.5 \text{ m}^2/\text{s}^3$  for motorway driving.

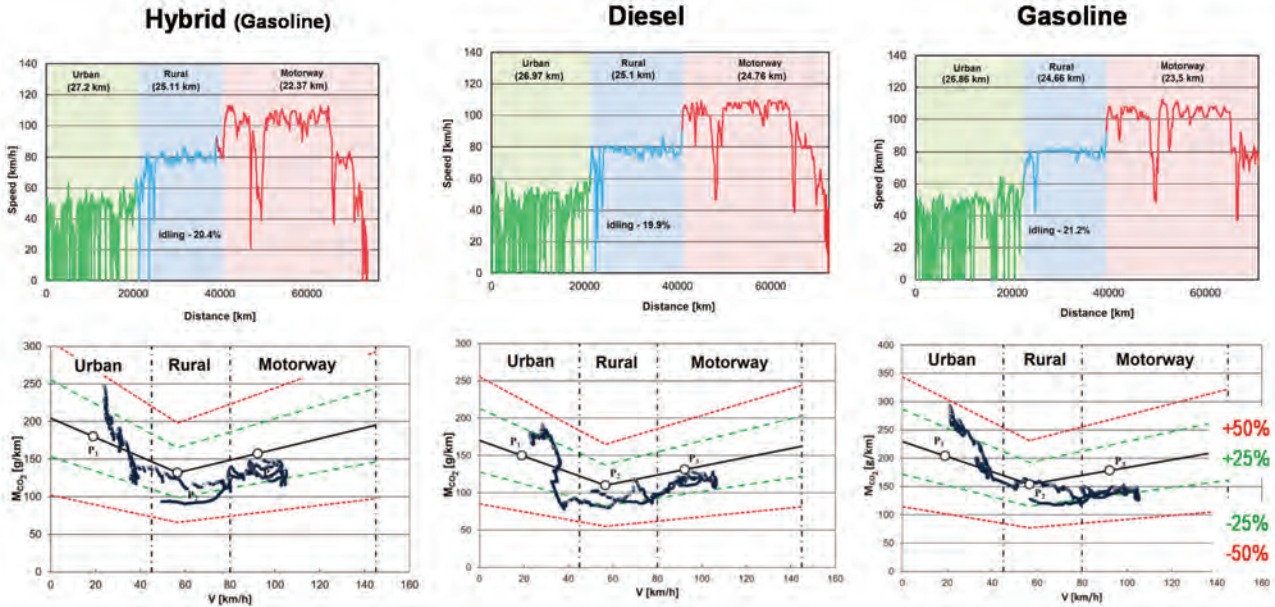


Fig. 12. Comparison of the traffic conditions for each of the tested vehicles

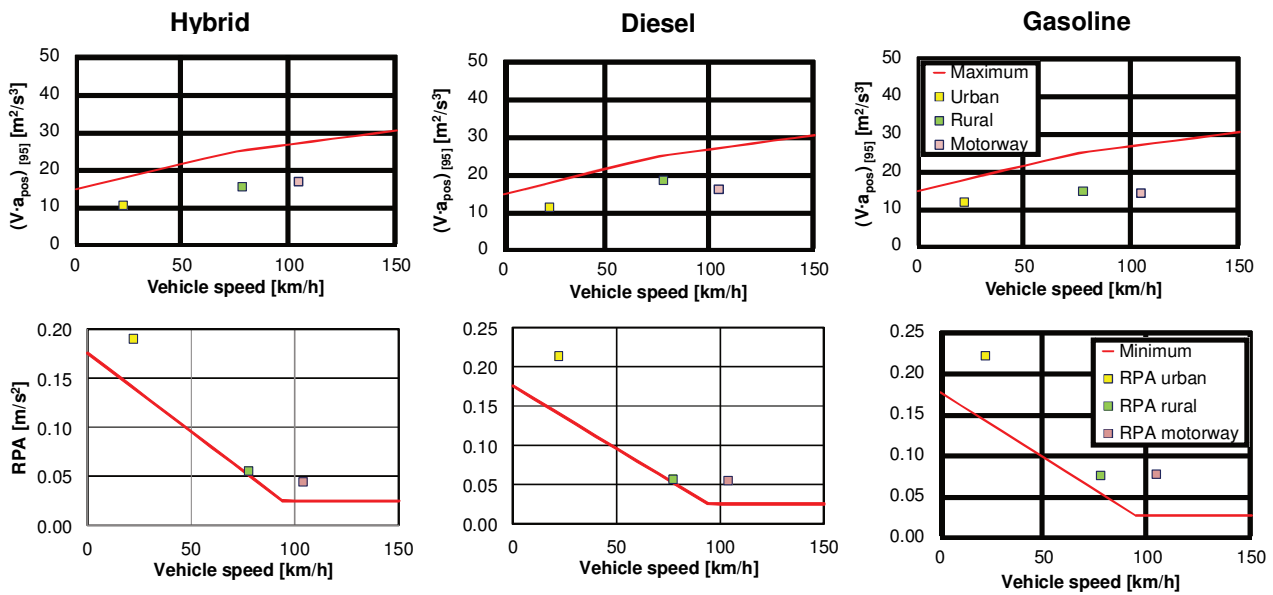


Fig. 13. Comparison of the drive dynamics conditions for each of the tested vehicles

The diesel vehicle test drive results met the requirements for dynamic conditions for the relative positive acceleration (RPA) and the 95<sup>th</sup> percentile of the velocity and acceleration product for each drive section. For urban driving the RPA value was  $0.21 \text{ m/s}^2$ , for rural driving it was  $0.06 \text{ m/s}^2$  and for motorway driving it equaled  $0.05 \text{ m/s}^2$ . The value of the 95<sup>th</sup> centile ( $v \cdot a_{\text{pos}}$ ) reached  $11.0 \text{ m}^2/\text{s}^3$  for urban driving,  $18.1 \text{ m}^2/\text{s}^3$  for rural driving and  $15.78 \text{ m}^2/\text{s}^3$  for motorway driving.

The drive made with the vehicle with an SI engine met the drive dynamics requirements. Both the values of the relative positive acceleration (RPA) and the values of the 95<sup>th</sup> centile of the product of velocity and acceleration for each drive section were within the calculated limit values. In addition, the number of data sets with acceleration values  $a_i > 0.1 \text{ m/s}^2$  exceeded 150 for each the urban, rural and motorway drive sections. The value of RPA for urban driving was  $0.22 \text{ m/s}^2$  for rural driving it was  $0.08 \text{ m/s}^2$ , and

0.07 m/s<sup>2</sup> for motorway driving. The values of the 95th centile of the velocity and acceleration product ( $v \cdot a_{pos}$ ) for urban, rural and motorway sections were respectively 11.4 m<sup>2</sup>/s<sup>3</sup>, 14.3 m<sup>2</sup>/s<sup>3</sup> and 13.8 m<sup>2</sup>/s<sup>3</sup>.

The average CO road emission from the hybrid vehicle for the RDE test has been shown (Fig. 14). The largest average CO emission was recorded for urban driving and it reached approximately 0.28 g/km. Very similar values were obtained for CO emissions for rural and motorway sections. With the EMROAD method, they are equal to 0.098 g/km and 0.087 g/km respectively, and for the method using all data: 0.08 g/km and 0.07 g/km. The average carbon monoxide emission in the whole RDE test was 0.15 g/km. The differences in the emissions obtained by the two methods are small – in urban drive sections it is only 0.003 g/km. The largest difference is in the case of CO emissions is for rural driving – 0.018 g/km. The CO road emission, calculated using the EMROAD method, is higher for all drive sections and for the entire drive cycle.

The average road emission of carbon monoxide from a vehicle with a CI engine was the largest when driving in the urban section. The emission obtained using the EMROAD method is 0.030 g/km and is 0.005 g/km lower than the value obtained by the all data method. A similar noticeable difference appears in the case of rural driving emissions, except that in this case the emission determined by the EMROAD method is higher by 0.004 g/km than the second method and equals 0.013 g/km. The average CO road emission in motorway driving was the smallest and for both methods it amounted to 0.011 and 0.010 g/km. While in the whole RDE test, the average CO emission reached 0.018 and 0.019 g/km for the two methods.

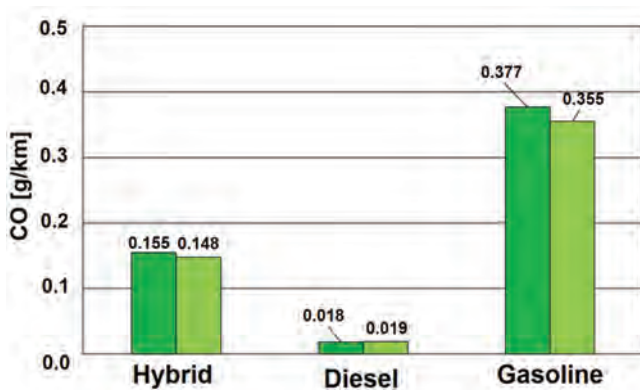


Fig. 14. CO road emission for each of the vehicles in the whole RDE test (EMROAD and all data)

The carbon monoxide road emission for the gasoline powered vehicle determined in individual drive sections varies significantly depending on the method used. In the case of urban driving, the emission determined by the moving averaging window method was 0.32 g/km while for the classical method it was 0.47 g/km, which means that the emission determined by the classical method is more than 30% greater. The emission for the rural drive section does not differ so much between the methods, it is similar and reaches approx. 0.4 g/km. For motorway driving, the difference in road emission values obtained by the two methods

is the greatest. The exhaust emission value obtained by the EMROAD method is 0.45 g/km and is three times greater than the exhaust emission determined by the classical method. Despite very large differences in CO emission indications in individual sections, the average road emission of carbon monoxide in the whole RDE test is almost identical for the EMROAD method and the classical method, and reaching 0.36 and 0.38 g/km respectively.

The determined average CO road emission is presented in the form of CF factors and referred to the permitted CF value (Fig. 15). The current regulations do not specify the absolute value of the CF<sub>CO</sub> emission index, but it should appear in future amendments to the regulations. Temporarily, the EC Regulation only recommends the registration of emission data, but as part of the analysis of the test results, a CO emission index limit of 2.1 has been established.

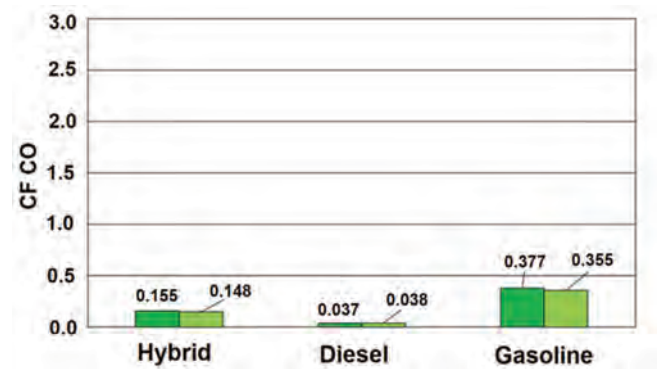


Fig. 15. Values of carbon monoxide emission factors for each of the vehicles in the whole RDE test (EMROAD and all data)

The hybrid vehicle emitted the most nitrogen oxides in the motorway drive section – approx. 0.024 g/km. Differences in relation to emissions in other categories were small. The average NO<sub>x</sub> road emission in the rural section was 0.02 g/km for the EMROAD method and 0.022 g/km for the method using all data. The smallest average road emission was recorded for urban driving and it was 0.0185 g/km for the EMROAD method and 0.02 g/km for the method using all measurement data. Interestingly, the emission determined with the use of all measurement data is greater than that determined by the moving averaging windows method, which is different from previous measured exhaust components. The average road emission of NO<sub>x</sub> in the entire RDE test is equal to about 0.22 g/km (Fig. 16).

The average road emission of nitrogen oxides from the vehicle with a CI engine was the greatest for urban driving and equalled 0.90 g/km with the EMROAD method and 0.82 g/km with the all data method. The smallest emission value was recorded for rural driving and reached 0.36 and 0.32 g/km for the two methods. In motorway driving, differences in exhaust emissions between the two methods were small and it could be said that the average emission was 0.5 g/km. In the whole RDE test, the average NO<sub>x</sub> emission was 0.588 g/km for the moving averaging windows method and 0.56 g/km for the method using all the measurement data.

The results of average  $\text{NO}_x$  emissions for a SI vehicle obtained by the two different methods for individual drive sections as well as the entire RDE test do not differ so much in the case of CO emissions. The highest average road  $\text{NO}_x$  emission was recorded for urban driving, with values of 0.017 and 0.020 g/km for the moving averaging windows method and the method using all measurement data respectively. The emission of nitrogen oxides in the urban drive section was the smallest among all the sections and reached 0.011 g/km for the EMROAD method and 0.009 g/km for the other method. For motorway drive section the emission results for both methods were almost the same at approx. 0.012 g/km. In the whole RDE test, the average  $\text{NO}_x$  emission ranged from 0.013 to 0.014 g/km.

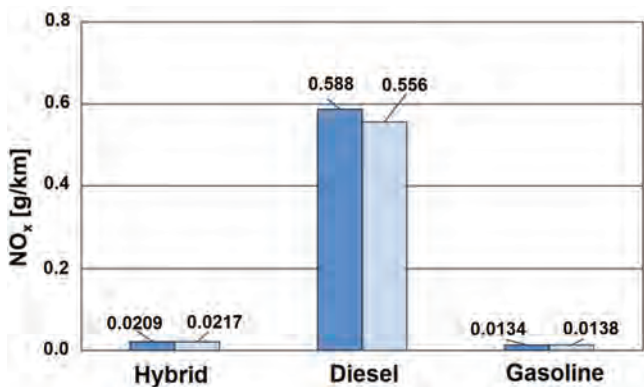


Fig. 16. Road  $\text{NO}_x$  emission for each of the vehicles in the whole RDE test (EMROAD and all data)

The Euro 6 standard specifies that the  $\text{NO}_x$  road emission from the tested vehicle must not exceed 0.06 g/km. The EC Regulation states that for RDE road tests the  $\text{NO}_x$  emission is not to exceed the  $\text{CF}_{\text{NO}_x}$  factor equal to 2.1, which means that emissions in real driving conditions must not exceed 0.126 g/km (Fig. 17). The  $\text{CF}_{\text{NO}_x}$  emission factors for individual drive sections are very small and range from 0.31 for urban driving to 0.40 for motorway driving. The  $\text{CF}_{\text{NO}_x}$  factor for the whole test drive is approx. 0.35, which means that the Euro 6 limit has not been exceeded.

The nitrogen oxide emission conformity factor for the CI vehicle clearly exceeded the legal limit value in both urban and motorway driving. For urban driving, the tested vehicle exceeded the emission limit by up to five times. And for motorway driving, the value of the  $\text{CF}_{\text{NO}_x}$  factor ranged depending on the analysis method from 2.74 to 2.83. The smallest values of this factor were achieved when driving in rural areas and did not exceed the maximum permitted value of 2.1, but they are still greater than 1, which means that the emission limit itself was exceeded. The average value of the  $\text{NO}_x$  emission conformity factor in the whole RDE test exceeded 3, therefore, the vehicle emits more than three times more nitrogen oxides in real driving conditions than allowed in the type approval tests on the chassis dynamometer.

The  $\text{NO}_x$  emission factors obtained for an SI vehicle did not exceed the limit value of 2.1 in any drive section nor in the whole test. What is more the  $\text{CF}_{\text{NO}_x}$  factor did not ex-

ceed 1, which means that in real driving conditions the vehicle did not exceed the legal emission limit value.

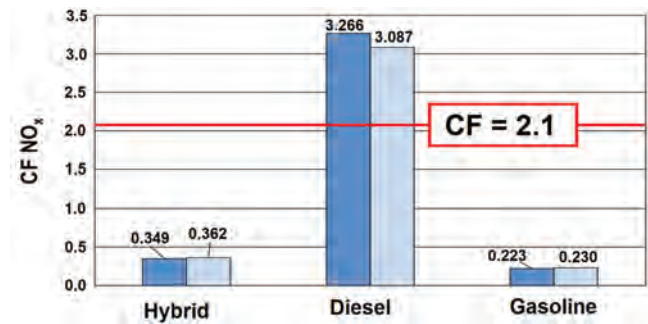


Fig. 17. Values of nitrogen oxide  $\text{CF}$  emission conformity factors for each of the vehicles in the whole RDE test (EMROAD and all data)

The particle number emissions from the tested hybrid vehicle vary greatly depending on the vehicle category considered (Fig. 18). In the case of particle emissions, differences in the results between the two measurement data analysis methods are noticeable. The highest emission values were recorded for the vehicle moving in urban areas. In this case, the emission determined based on all data was  $1.7 \cdot 10^{12}$  1/km, while the emission obtained with the EMROAD method was lower and reached the value of  $1.4 \cdot 10^{12}$  1/km. As part of the rural drive section, the emission determined using the moving averaging window method was higher at  $5.2 \cdot 10^{11}$  1/km, while the emission obtained by the second method was  $3.4 \cdot 10^{11}$  1/km. The particulate matter emission determined for the motorway section has reached the same values for both methods and was equal to  $5.5 \cdot 10^{11}$  1/km. The average particle number road emission in the entire RDE test was higher for the method using all measurement data and reached the value of  $9.1 \cdot 10^{11}$  1/km, while the emission value obtained by the EMROAD method was  $8.4 \cdot 10^{11}$  1/km.

The differences in the numerical emission of particles obtained by the two methods for the CI engine are not as large as in the case of particle emissions from the hybrid vehicle. The biggest difference is noticeable in the case of PN emissions for urban driving. The emission determined by the EMROAD method was  $1.4 \cdot 10^{12}$  1/km and was  $2 \cdot 10^{11}$  1/km greater than the emission obtained by the second method. The average particle number emission in urban driving was very similar for both analysis methods and reached the value of approx.  $5.7 \cdot 10^{12}$  1/km. For motorway driving, the average PN emission value was again similar for both methods and amounted to approx.  $4.2 \cdot 10^{12}$  1/km. In the whole RDE test, the diesel vehicle emitted  $8.1 \cdot 10^{12}$  1/km according to the EMROAD method and  $7.7 \cdot 10^{12}$  1/km for the other method.

The PN emission determined for a vehicle with a gasoline engine in the urban section using the all data method was  $1 \cdot 10^{12}$  1/km and was more than 1/3 higher than the emission obtained with the EMROAD method. On the other hand, the road emission of PN in the rural section was greater for the moving averaging windows method at  $9.2 \cdot 10^{11}$  1/km, while the method of all measurement data obtained the value  $8.4 \cdot 10^{11}$  1/km. In the case of motorway section, the average PN road emission determined using the

EMROAD method is more than double that of the second method and amounts to  $9 \cdot 10^{11}$  1/km. Similarly to the case of CO emission results, the emission for the whole RDE test obtained using both methods is similar, despite large differences in values for individual drive sections. The average PN emission in the test was  $8.2 \cdot 10^{11}$  1/km according to the moving averaging window method and  $7.6 \cdot 10^{11}$  1/km for the second method.

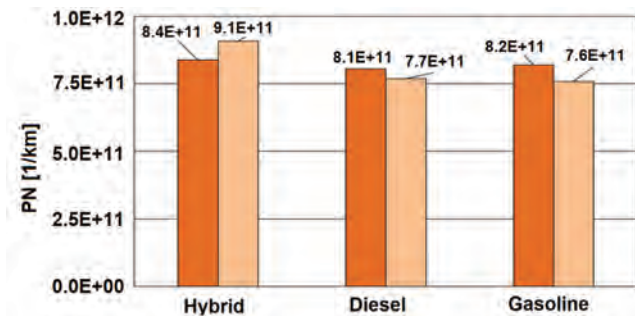


Fig. 18. Particle number emission for each of the vehicles in the whole RDE test (EMROAD and all data)

Although the particle number emission is a problem for gasoline engines mostly limited only to solutions with direct gasoline injection, and the tested vehicle was equipped with an MPI gasoline engine, it was assumed for the test results analysis that the vehicle is subject to the numerical limit of particle emission equal to  $6 \cdot 10^{11}$  1/km. The adopted limit applies to vehicles with SI DI engines starting from September 2017, replacing the temporary limit of  $6 \cdot 10^{12}$  1/km. The  $CF_{PN}$  particle number emission factor has not yet been announced, but in the future it is expected to be 1.5. As part of the analysis of particle emissions,  $CF_{PN}$  emission conformity factors for each drive section were calculated and compared to the mentioned limit value of 1.5.

The hybrid vehicle exceeded the particle matter emission factor only in the urban drive section. According to the method using all measurement data, the factor was exceeded almost twice – and reached the value 2.91. In the EMROAD method, this factor was 2.37. For this vehicle driving in the rural and motorway sections, the PN emission factor was less than 1, meaning that the road emission did not exceed the limit of  $6 \cdot 10^{11}$  1/km. The  $CF_{PN}$  value for the whole test drive was equal to 1.5 according to the method using all data and 1.40 according to the EMROAD method, which means that the number of particles the vehicle emitted in the entire test was close to the emission limit value defined for standard RDE tests (Fig. 19).

The  $CF_{PN}$  values for individual drive sections and for the entire test for a diesel vehicle are very similar to those of the  $CF_{PN}$  for a hybrid vehicle. The permitted limit value of 1.5  $CF_{PN}$  is exceeded only in the case of urban driving and reaches a maximum value of 2.36 according to the moving averaging windows method. In the rural and motorway sections, the emission factor value does not exceed 1, which again means that the average particle number emission in these sections does not exceed the limit specified in the Euro 5 standard. The PN emission factor for the whole RDE test of the diesel vehicle was on average around 1.3, i.e. the emission exceeded the limit value of the Euro 5

standard, but it did not exceed the allowed PN emission deviation of the emission conformity factor in real driving conditions.

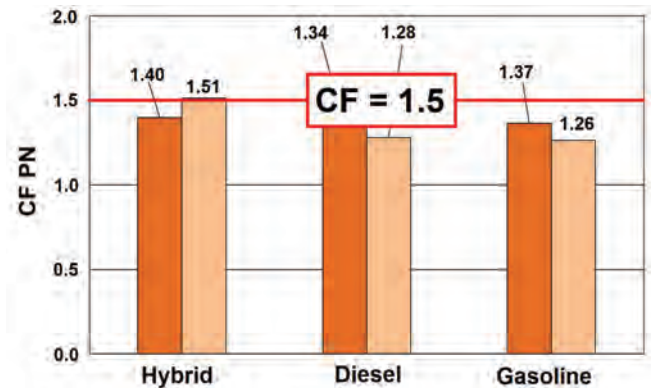


Fig. 19. Particle number emission conformity factor values for each of the vehicles in the whole RDE test (EMROAD and all data)

The test results showed that the diesel vehicle indeed emitted more than three times more nitrogen oxides than the current standard allows, thus exceeding the permissible value of the  $CF_{NOx}$  emission factor, which confirms the results of many domestic and foreign research centers [11, 16, 20]. Both the tested hybrid vehicle, equipped with an SI engine and a vehicle equipped with only a gasoline engine, exceeded the limit of particle number emission, but their emission did not meet the minimum values set in the form of conformity factors, or exceed them. The hybrid vehicle and the gasoline vehicle were equipped with an indirect, multi-point gasoline injection, and thus the PN emission limit does not apply to these vehicles. The vehicle with the diesel engine, like the other vehicles, also exceeded the PN emission limit, but its emission factor did not reach the maximum permissible value. The average CO road emission from all vehicles in individual driving sections and in the whole RDE test was small and did not exceed the limits set by the standards. The average  $NO_x$  road emission from the hybrid vehicle and the gasoline vehicle was relatively small, both in individual drive sections and in the entire RDE test and also did not exceed the Euro limits.

#### 4. Standardization of exhaust emission results – relation to carbon dioxide road emission

The performed emissivity verification tests of passenger cars with internal combustion engines (Gasoline, Diesel, complying with Euro 3–Euro 6 emission limits) in real driving conditions constituted the first verification of the value and usefulness of the developed tool – a universal on-board exhaust emissions measurement system. Determining the emissivity in road conditions and comparison with the values of road carbon dioxide emissions made it possible to determine the coefficient of Standardization of Exhaust Emission (SEE).

$$\text{Real road emission [g/km]} = \frac{m_{RDE} - \text{mass emission [g] (PEMS)}}{S - \text{distance [km] (OBD, GPS)}}$$

$$SEE [\%] = \frac{\text{Real road emission [g/km]}}{\text{CO}_2 \text{ real road emission [g/km]}}$$

Analysis of the data presented in Fig. 20 and 21 shows that the coefficient values obtained in real operation are smaller the higher the vehicles emission class. For gasoline engines, the SEE index for the emissions of carbon monoxide, hydrocarbons and nitrogen oxides ranges from 0.001% to 0.5% (Fig. 20). For CI engines, the SEE index related to the emission of carbon monoxide, hydrocarbons, nitrogen oxides and particulate matter ranges from 0.01% to 4% (Fig. 21).

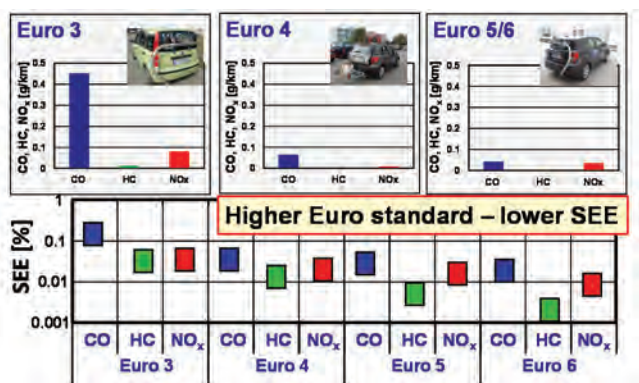


Fig. 20. Gasoline PC – standardization of exhaust emission

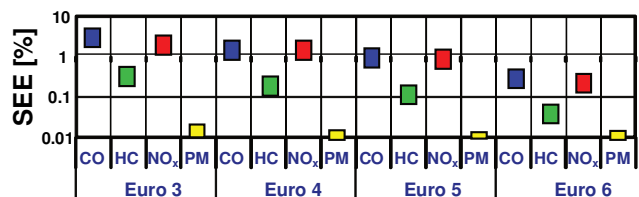


Fig. 21. Diesel PC – standardization of exhaust emission

Comparison of these results indicates that the SEE coefficient for vehicles with Diesel engines reaches values around 10 times greater than for vehicles with Gasoline engines.

### 5. Exhaust emission tests for city buses

Urban public transport plays an important role for cities and their inhabitants in many ways. It ensures a more economic use of natural resources and is less harmful to the environment than individual automotive transport. Public transport is therefore the main pillar of urban mobility for the future. However, this is only possible if urban public transport vehicles are low-emission. A large part of the city public transport is ecological in many ways already. Road transport is responsible for around 54% of nitrogen oxide emissions and 10% of particulate emissions. The reduction of these two components of exhaust emissions as well as carbon dioxide (fuel consumption) is currently the key issue in the development of urban bus drives [7, 15, 20]. The Polish market of urban buses numbers around 12,000 and has been quite stable for several years (50% of the vehicles used are 10 years or younger). However, it should be men-

tioned that there is an increasingly frequent replacement of the old bus fleet with modern (hybrid and electric) solutions, which is related to the EU transport decarbonization plan (Fig. 22). This plan assumes that by 2030, the emission of carbon dioxide in transport will decrease by over 9% (and by 2050 by more than a half). It should be mentioned that only in 2015 Solaris sold 1,300 low-floor buses with various types of drives (including 946 to foreign markets). Intensive efforts are also made towards the implementation of hybrid and electric buses for mass production (fueled by fuel cells for example) [14, 16].

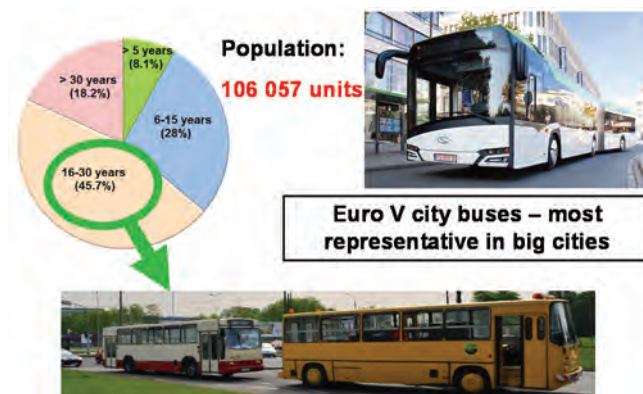


Fig. 22. Buses in Poland (2016)

There exist legal, scientific and technical actions related to reducing the negative impact of these transport modes on the human environment in Poland as well as all around the world. Positive results of activities in this field are noted, including introducing further legal regulations to contribute to the protection of the environment. Such activities are also observed in relation to mass transport means – city buses, and especially to the drive systems used in them. As a result of such activities, more ecological constructions for city bus drives are being developed, as well as their continuous improvement in terms of reduced emissions and fuel economy [17, 22, 27].

The tests used municipal buses with similar functional properties. The first test vehicle was equipped with a conventional drive system with a Diesel engine, the second with a hybrid drive in serial configuration, and the third with an SI engine powered with compressed natural gas (Table 2). To prepare vehicles for testing, a replacement load was used to reflect the load generated by passengers during daily use.

The tests of specific exhaust emission and drive system operating parameters were performed in the SORT drive tests (Fig. 23) and in real operating conditions (Fig. 24). Measurements in standardized tests covered the test drive cycles SORT 1, SORT 2, as well as SORT 3, where three tests were performed. The requirements listed by the methodology developed by UITP were met. The selection of test routes No. 1, 2 and 3 was made with the assumption that they would be as close as possible to the SORT tests in terms of the nature of the route (urban conditions of different traffic intensity and suburban conditions) as well as the vehicle speeds obtained. In these test cycles, three tests were performed for each of the test vehicles. Exhaust emis-

sion measurements on the city bus line were made during the rush hour, when the buses operate the stops at the highest frequencies. The results presented in the article are only referenced to the SORT 2 test, as it was found that this test reflects the conditions of city buses operation the most of the three tests performed.

Tab. 2. Technical characteristics of vehicles used for tests

Parameter	DIESEL	HYBRID	CNG
Type/fuel	4-stroke, R6, DIESEL		4-stroke, R6, SI/CNG
Displacement [L]	9.2	! 6.7 (Serial)	8.9
Maximum power [kW]/[rpm]	265/1900	209/2300 + (SE 240 kW)	239/2000
Maximum torque [N·m]/[rpm]	1450/1100–1700	1008/1200–1800	1356/1300–1400
Exhaust aftertreatment	SCR/DPF		TWC
Emission standard	Euro V-EEV		

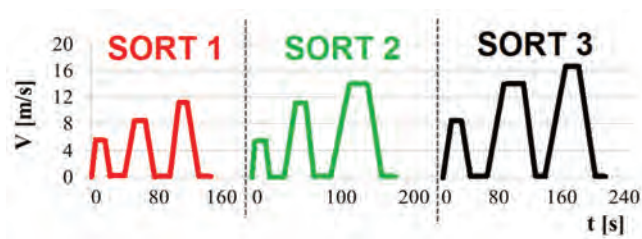


Fig. 23. Standardized on-road test: 1 – urban + heavy traffic, 2 – urban, 3 – suburban

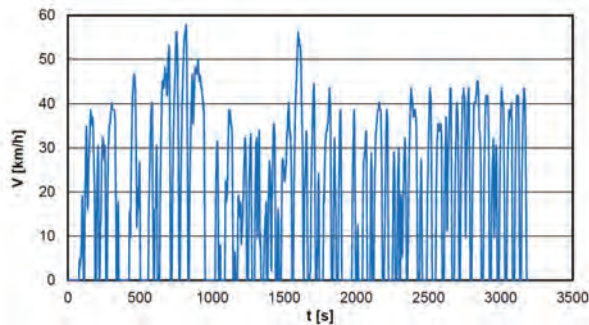


Fig. 24. Vehicle speed characteristic on the city buses test route

The analysis of the internal combustion engines dynamic operating conditions in real operation can be simplified to the analysis of a given parameter in the vehicle speed-acceleration coordinates. This approach is similar to the analysis of the engines static characteristics in the coordinates of the engine-load and speed. If the entire vehicle with the drive system is treated as a "closed object" (a so-called black box), then making such an assumption allows analysis of selected exhaust emission components regardless of internal changes taking place in the considered system. This assumption does not exclude the simultaneous collection of the drive system operating data (including the engine speed and load obtained from the on-board diagnos-

tic system). The description of any parameter, e.g. the emission intensity of a given exhaust component, in coordinates, e.g. vehicle speed–acceleration was made using two-dimensional probability density histograms, which constitute a record of the duration of individual engine load being in a given interval or their share of the total duration. Although such characteristics do not take into account the dynamic properties of the engine, defined on the basis of engine control-torque relationship, the published optimization results based on their use indicate that such simplification is acceptable.

In order to compare the share of bus operating time in the selected speed and acceleration intervals, differences were determined between these values as obtained in tests on the route No. 2 and in the SORT 2 drive test (Fig. 25). Analysis of the graphs indicates that for the conventional vehicle the average value obtained was 1.5%. For the intervals described by the parameters (0 m/s; 0 m/s<sup>2</sup>) and (6–10 m/s; 0–0.8 m/s<sup>2</sup>), as well as (12–14 m/s; –1.6–0.8 m/s<sup>2</sup>) the largest differences of more than 5% were found.

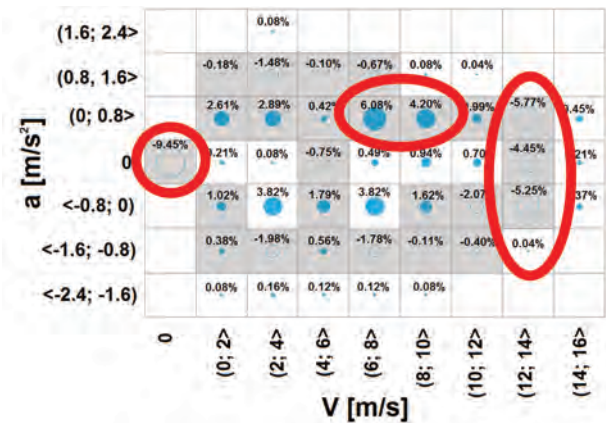


Fig. 25. Difference in the operating time density of test vehicles between measurements on the test route and in the SORT 2 test, shown in the speed and acceleration intervals for the vehicle with a CI engine

The conventional bus drive system (Fig. 26) in the city road tests spent 9% less time in the interval (600 rpm, 800 rpm) and (0 N·m; 200 N·m) as well as 3.8–5.6% in the (1400 N·m; 1600 N·m) load interval.

Analysis of the measured exhaust components emission intensity, presented in the engine speed and load intervals, allows to find the impact of the combustion engine operation parameters on the exhaust content of individual harmful components. For a conventional bus the highest intensity of carbon monoxide emission occurred in the full range of recorded speed values with a load greater than 1200 N·m – the average value of this parameter is 196 mg/s (Fig. 27). Such a distribution of data is primarily the result of the engine characteristics, where at high load the injected fuel dose did not mix properly and incomplete combustion occurred. In a vehicle equipped with a hybrid drive, the emission intensity of the carbon monoxide depends mainly on the torque generated by the engine. For the third test vehicle, the content of the analyzed compound was mainly influenced by the rotational speed of the crankshaft, and to a lesser extent the engine load. For the interval of the

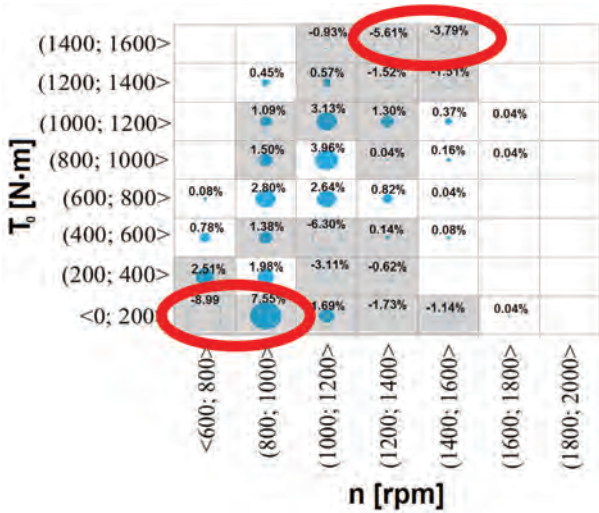


Fig. 26. Difference in the operating time density of test vehicles between measurements on the test route and in the SORT 2 test, shown in the engine speed and load intervals

highest torque value, an average value of 295 mg/s carbon monoxide emission was measured.

A strong dependence of the nitrogen oxides emission intensity on the engine load can be seen for the conventional bus (Fig. 28). The highest values of the exhaust component were observed in the interval where torque was greater than 1200 N·m, where the average emission intensity measured reached 169 mg/s. The hybrid vehicle also shows a significant importance of the engine rotational speed on the emission of this component. In the engine speed interval of up to approximately 1,400 rpm, the NO<sub>x</sub> emission intensity values did not exceed 140 mg/s, which was the result of the electric system being used in the vehicle. Electric energy accumulated in batteries and supercapacitors effectively supported the operation of the internal combustion engine. The average nitrogen oxide emission intensity in the speed interval above 1600 rpm, for loads greater than 400 N·m, was 267 mg/s. Such high values were obtained mostly due to the parameters of the engine used in this vehicle, which had the lowest rated power among the tested vehicles. In a hybrid bus, due to the very high efficiency of the catalytic

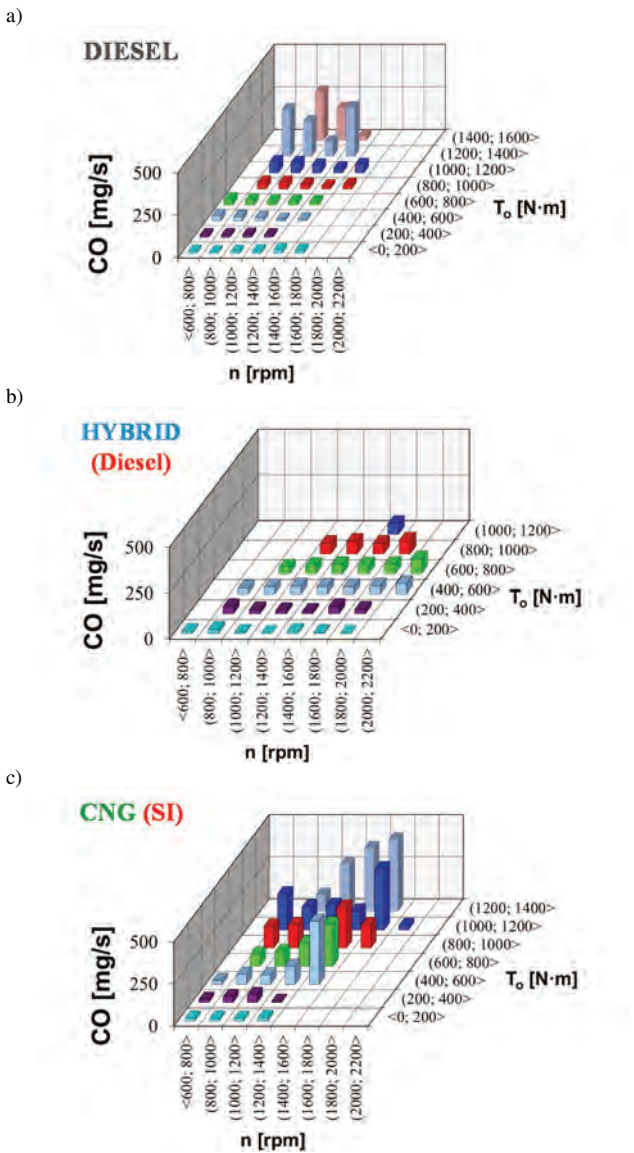


Fig. 27. Carbon monoxide emission intensity in road tests: a) bus with a diesel engine, b) hybrid bus, c) bus powered by natural gas

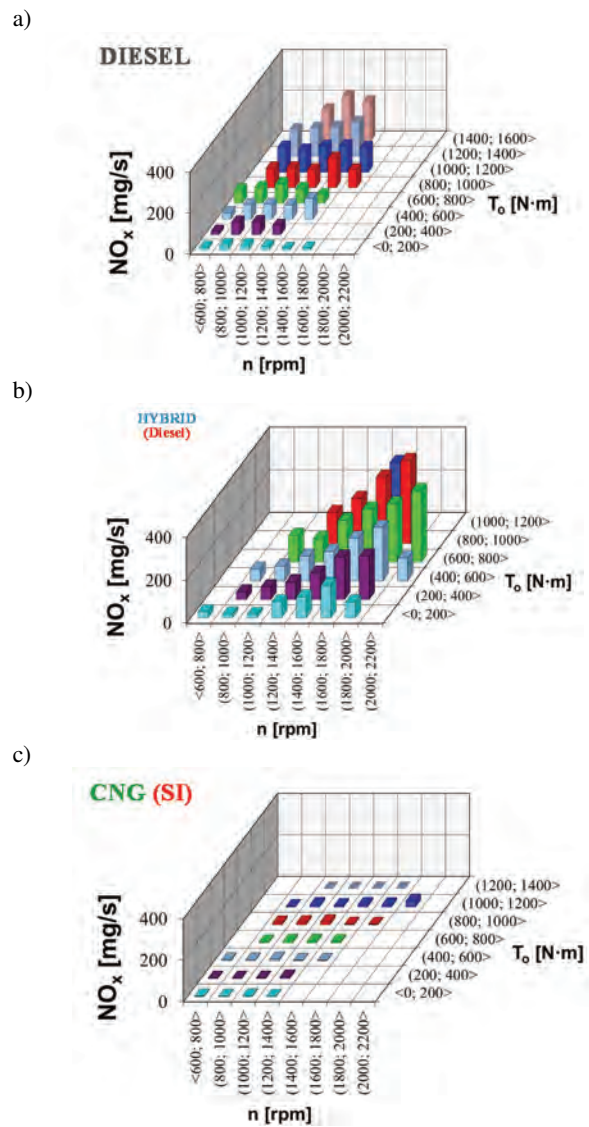


Fig. 28. Nitrogen oxides emission intensity in road tests: a) bus with a diesel engine, b) hybrid bus, c) bus powered by natural gas

converter used in the reduction of nitrogen oxides, the maximum emission intensity of the analyzed exhaust component did not exceed 28 mg/s.

Based on the obtained specific exhaust emission results it is possible to refer their value to the emission limits that these test vehicles meet (Euro V–EEV). In order to do this, the emission conformity factor CF has to be determined. Since the CNG alternative fuel bus achieved CO emission values that were significant among the tested exhaust emissions in relation to the legislative guidelines, whereas for the vehicles with SI engines a similar situation occurred for the NO<sub>x</sub> emission values, further considerations were focused on these two exhaust compounds.

The specific CO emission conformity factors (Fig. 29) show that the vehicle with a conventional drive obtained values greater than 1 in both the SORT 1 test and on test route No. 1, which means that the legal emission limits were exceeded. For the hybrid bus the calculated CF<sub>CO</sub> factors were in the range of 0.14–0.85 for all measurement drive cycles. The exhaust emission values obtained for the third vehicle were greater than 1 in four cases (maximum 1.68 for the SORT 1 test).

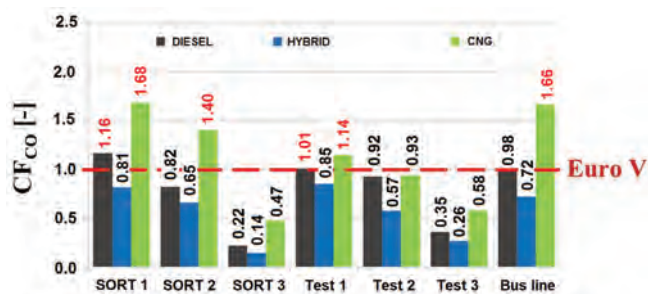


Fig. 29. Carbon monoxide emission conformity factor CF<sub>CO</sub> obtained from measurements in real operating conditions and the Euro V–EEV emission limits

For the CF<sub>NO<sub>x</sub></sub> factors it can be stated, that the smallest values were found for a bus powered by compressed natural gas and they were within the range of 0.16–0.32 (Fig. 30). Tests of the conventional vehicle powered with diesel oil have shown, that the exhaust emission limits were exceeded in the standardized SORT 1 and SORT 2 drive tests, on test route No. 1, as well as on the municipal bus line. The highest obtained values of the CF<sub>NO<sub>x</sub></sub> factor (from 1.76 to 3.36) were observed for a hybrid bus in all analyzed test drive cycles. A major influence on this distribution of results were the exhaust gas aftertreatment systems placed in the exhaust systems of these vehicles. The first and second tested buses used the SCR system that did not reduce NO<sub>x</sub> continuously, but the degree of conversion depended on multiple factors, including exhaust mass flow and exhaust temperature.

The specific exhaust emission values are determined in type approval tests using the net engine performance parameters measured at the end of the crankshaft or its equivalent. In real operating conditions, the internal engine resistance is expressed as a percentage – one specific value for the entire engine speed range. However, it should be noted that this is a certain simplification affecting the final results of the research.

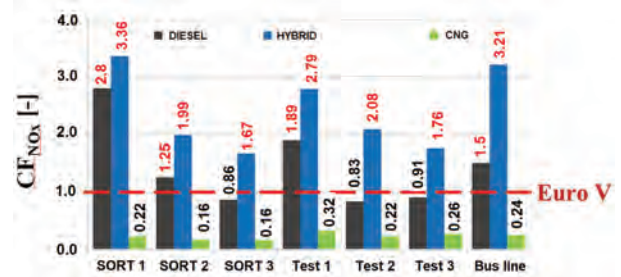


Fig. 30. Nitrogen oxides emission conformity factor CF<sub>NO<sub>x</sub></sub> obtained from measurements in real operating conditions and the Euro V–EEV emission limits

## 6. Conclusions

Having a developed concept and research methodology for measuring exhaust emissions in real operating conditions for all means of transport equipped with combustion engines, using on-board diagnostics systems and measuring emissions while driving, is a modern achievement. In addition to emission measurements from motor vehicles (as well as off-road vehicles), exhaust emission measurements are also coordinated for trucks, buses, including hybrid vehicles, construction and agricultural machines (non-road), rail vehicles, ships, boats and aircraft with piston and jet engines. These activities assess the on-board emissions using measuring devices referred to as PEMS (Portable Emission Measurement System). These include devices for measuring gaseous exhaust emissions (CO, CO<sub>2</sub>, HC, NO<sub>x</sub>) as well as particulate matter (including mass, number and size distribution) [23, 37], and at the same time using data acquisition systems – collecting registered engine and vehicle operating parameters using on-board diagnostic systems or black boxes. The latter were introduced to vehicles through the development and implementation tests of on-board recording devices in motor vehicles.

The current level of measurement technology related to exhaust emission testing allows testing emission from means of transport in real operating conditions. The biggest disadvantage of such tests is the high cost of the measuring equipment and its adaptation to the vehicle exhaust systems and use in vehicles. Such measurements are currently carried out in all countries where environmental protection is a priority in order to compare the measuring capabilities of various measuring devices for various vehicles. As a result, the move towards legally acknowledging the measurement of vehicle exhaust emissions in real operating conditions is perceived as the final test to verify the vehicle as a whole in terms of its exhaust emissions. This type of research allows to determine the level of emission values of individual exhaust components in real driving conditions. In addition, they enable assessing the operational characteristics of the tested means of transport in terms of the operating time density for the engine load intervals and determining the engine operating conditions together with their share in the total operating time during the test. Such information may be compared to the results obtained using stationary engine and vehicle test procedures, which in the future may further the optimization of the engine operating points that are used in various modes of transport.

*The study presented in this article was performed within the statutory research (contract No. 05/52/DSPB/0260).*

## Nomenclature

a	acceleration	MPI	multi point injection
a <sub>pos</sub>	positive acceleration	NEDC	new European driving cycle
b	road exhaust emissions value	OBD	on-board diagnostics
CF	conformity factor	PEMS	portable emission measurement system
CI	compression ignition	PHEV	plug-in hybrid electric vehicle
CNG	compressed natural gas	PMP	Particle Measurement Programme
DI	direct injection	PM	particle mass
EEV	enhanced environmental friendly vehicle	PN	particle number
EMROAD	methods used to analyze on-road emissions data collected with portable emissions measurement systems	RDE	real driving emissions
EOBD	European on-board diagnostic	RPA	relative positive acceleration
EU	European Union	S	distance
Euro	standard emissions	SI	spark ignition
GPF	gasoline particle filter	SORT	standardised on-road test cycles
GPS	global positioning system	SSE	standardization of exhaust emission
HEV	hybrid electric vehicle	u	share
ICE	internal combustion engine	UITP	international association of public transport
GPF	gasoline particle filter	WLTC	worldwide harmonized light vehicles test cycle
		V	velocity

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## Trends in automotive emissions legislation: impact on LD engine development, fuels, lubricants, and test methods – a global view, with a focus on WLTP and RDE regulations – Summary of the 6th International Exhaust Emissions Symposium (IEES)

*Among the drivers influencing vehicular powertrain development, the field of vehicular exhaust emissions is experiencing wide-ranging and rapid changes. New emissions regulations such as Euro 6d and new test methods (RDE and WLTP) are the main challenges for the automotive industry caused by political, socioeconomic and technical factors. Air quality is very high on the political agenda and pressure remains to limit and reduce greenhouse gas emissions from the road transport sector. In addition to limits becoming increasingly stringent, the list of parameters subject to legal limits are slowly expanding – and, most importantly, these limits must be met under a wide range of conditions. A range of strategies are available to overcome these difficulties, which was explored during the 6th International Exhaust Emissions Symposium (IEES) hosted at BOSMAL in June 2018. This paper reports and summarises the topics of the 6th IEES and attempts a synthesis on the current status of the field of IC engines, hybrid powertrains and electric vehicles and what the coming years may hold for the automotive and fuel industries and other allied fields.*

Key words: *global trends of exhaust emissions, emissions standard, IC engines, RDE, WLTP, WLTC, test methods, fuel development, hybrid and electric vehicles*

### 1. Introduction

The most important factor affecting the development of drive systems in motor vehicles is currently the emission of harmful exhaust compounds from motor vehicles and the ways in which these emissions can be reduced.

The second most important factor is in reducing greenhouse gas emissions, particularly CO<sub>2</sub> emitted by motor vehicles, which is also a political priority due to CO<sub>2</sub>'s impact on global warming. In recent years, at the UNECE forum, within the GRPE group, work on the harmonisation of regulations of motor vehicles, the informal working groups (IWG): WLTP, PMP, EVE and others, as well as in the European Commission (WLTP 2nd act, RDE) have been working on the new WLTP emission test methodology – a new global harmonised laboratory test method and RDE – a method of testing emissions in road conditions using portable PEMS analysers.

Emission limits of particulate matter and nitrogen oxides have also tightened, and are being treated as a form of pollution with a significant negative impact on the environment [1].

The issue of harmful emissions, especially:

- a) Nitrogen oxides – NO<sub>x</sub> from vehicles powered by compression ignition engines (CI), which for vehicles meeting Euro 3, Euro 4, Euro 5 and Euro 6b standards, proved to be significantly greater in actual conditions of road use than in homologation laboratory measurements,
- b) Particulate matter (whether quantified by mass – PM, or number – PN) in exhaust gases, not only from vehicles with CI engines, where the introduction of DPF filters has practically resolved this problem, but also from vehicles with spark ignition engines (SI), especially ones equipped with direct gasoline injection into the combustion chamber (GDI) that produce large amounts of parti-

cles of very small diameters, so-called nanoparticles, which are very harmful to living organisms,

- c) Non-exhaust particulate emissions, originating from other components such as brakes and tires, as well as volatile compounds emitted from the materials in new vehicles (Vehicle Internal Air Quality)
- d) Carbon dioxide (CO<sub>2</sub>), and fuel consumption (which is also related to global demand for fuel, energy security and plans for a decarbonised economy [2]) occurring in real world driving conditions,

are becoming a priority for the automotive sector, especially within the largest markets of the European Union, Japan, China, India and other Asian countries, South Korea, Brazil and the United States [3]. The development of engines and powertrains, and especially the possibilities of electronic control, have far outstripped the development of approval regulations in Europe, which has led to differences in emission measurements.

The response from the official legislative institutions dealing with this subject was the introduction of many legal acts specifying maximum levels of permissible exhaust emissions and test methodologies to quantify those emissions. Some pieces of legislation have imposed increasingly stringent emissions limits for individual harmful compounds; other have imposed series of mandatory guidelines for testing fuel consumption, as well as incentive plans for the introduction of low-carbon fuels and alternative fuels.

Now that it has become apparent that emissions of some compounds (especially NO<sub>x</sub>, but also particulates and other pollutants, as well as CO<sub>2</sub>), measured in actual conditions can show a poor correlation with emissions results from laboratory tests. Measurement methods are subject to further change: this applies to both laboratory methods (e.g. new research procedures prepared by the EU/UN-ECE: WLTP/GTR15 [4], or US EPA: CFR 1065/1066); as well

as emission and fuel consumption tests in real driving conditions (the test procedure prepared by the European Commission – RDE), which is so important that the RDE method has become an integral part of the procedure for testing emissions from motor vehicles. In September 2017 the EU introduced the requirements of WLTP and RDE to the new approval regulations referred to as Euro 6d-TEMP (as a transitional phase leading into Euro 6d), which completely changed the approach to the approval and certification of vehicles.

## 2. Organisation of the symposium

During the years 2010, 2011, 2012, 2014 and 2016, BOSMAL Automotive Research and Development Institute Ltd (hereafter BOSMAL), organised five International Symposia on vehicular exhaust emissions, covering issues related to limiting emission of harmful exhaust emissions from automotive sources and their impact on the development of vehicle powertrain design, the development of fuel technology, engine oils, exhaust gas treatment systems and new research methods [5], as this subject is vitally important for the further development of the motor industry globally, in Europe and of course in Poland. These symposia were very popular among professionals in the automotive and fuel industries, both foreign and domestic, who participated extensively in their deliberations.

On 14-15 June 2018, BOSMAL together with the Polish Scientific Society of Combustion Engines (PTNSS) was the organiser and at the same time hosted the next, being the sixth, international symposium on automotive exhaust emissions – *The 6th International Exhaust Emissions Symposium entitled: "Trends in automotive emissions legislation: impact on LD engine development, fuels, lubricants and test methods – a global view, with a focus on WLTP and RDE regulations"* (Fig. 1).

The programme for the symposium was organised and prepared by the International Organising Committee headed by Dr. Piotr Bielaczyc (BOSMAL/PTNSS), which also included well-known specialists from the USA, Switzerland, the UK, Germany and Italy.



Fig. 1. Logo of the 6th Exhaust Emissions Symposium

It was the sixth time that leading experts from the USA and Europe met in Bielsko-Biala to discuss various aspects such as: the science of exhaust emissions and their control, socio-political aspects (i.e. pressure to limit real emissions from transport sources), legal and technical aspects (the impact of new global WLTP and RDE vehicle emission test methodologies), the development of powertrain design and optimisation, new "low-carbon" types of motor fuels, hybrid and electric powertrains, and trends in the development and testing processes for road vehicles, their powertrains, fuels and lubricants.

Discussions included the possibility of harmonising global regulations on emission reduction through the widespread introduction of the WLTP methodology requirements and also on the introduction of WLTP and RDE requirements for approval tests in the European Union from 1.09.2017, which significantly increased the mandate and powers of the authorities approving test facilities and certifying vehicles.

New (or improved) emission reduction methods, new solutions introduced to internal combustion engines and hybrid powertrains were discussed, as well as new emission test methodologies and the equipment needed for such tests. Advanced engine fuels/lubricants and alternative fuels' technical development were also topics discussed at length during the two-day event.

An important goal of this symposium was also the integration of the scientific and academic communities with the automotive industry (both in Poland and abroad), facilitating the establishment of new contacts, the exchange of knowledge on many issues, as well as promoting the achievements of Polish scientific and research institutions active in this field, especially BOSMAL.

This journal, the website *DieselNet* of Canada, the Polish journal *Przegląd Techniczny* and the Polish *Gazeta* gaseous fuels internet portal provided the media patronage for the event.

More than 120 delegates participated representing 68 automotive and fuel industry companies, the European Commission (DG GROW from Brussels and the JRC Ispra Research Center), the US Government Research Center – Argonne National Laboratory near Chicago, research institutes and industrial research centres from the automotive and fuel industries, and an international academic community from 17 countries (USA, UK, Spain, Greece, Italy, Switzerland, Austria, Luxembourg, Denmark, Belgium, Germany, the Netherlands, Sweden, Finland, France, Slovakia, the Czech Republic and Poland). The final programme (Fig. 2) contains details of all technical presentations and other information on the event.

Symposium guests were welcomed by BOSMAL Director Dr. Arkadiusz Stojekki (Fig. 3). The symposium was formally opened by Prof. Jerzy Merkisz (of PTNSS, Poznan University of Technology and BOSMAL), acting in his capacity of PTNSS president. Commencing the first technical session, the chairman of the International Organising Committee (BOSMAL's Dr. Piotr Bielaczyc) gave a preliminary presentation mentioning the symposium's main topics and setting the scene for the presentations and deliberations which followed.

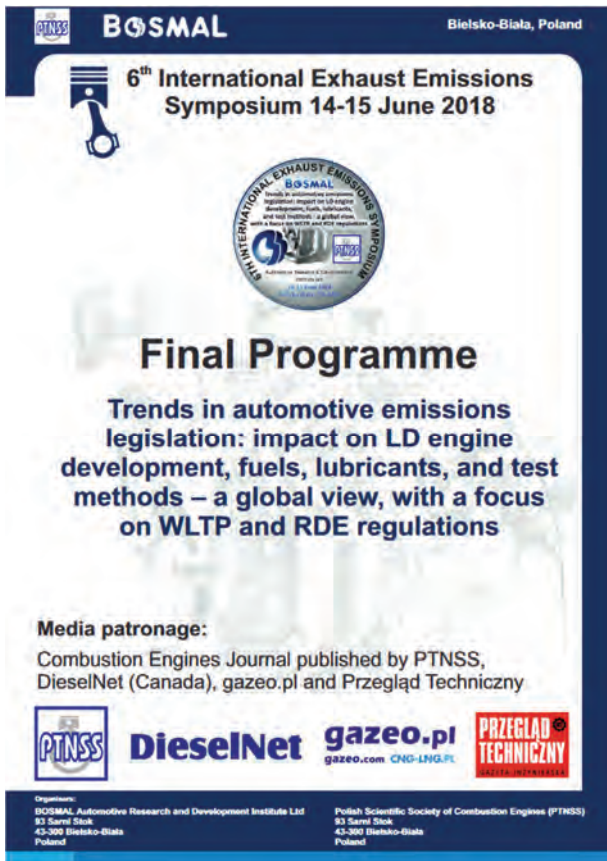


Fig. 2. First page of the Final Programme of the 6th Exhaust Emissions Symposium



Fig. 3. BOSMAL director Dr. Arkadiusz Stojeccki and Dr. Piotr Bielaczyc at the beginning of the event

### 3. Global trends in reducing emissions from internal combustion engines used in road transport

Twenty five presentations were delivered during the symposium by well-known experts on emissions of harmful exhausts from motor vehicles, combustion engines, powertrain development (including hybrid and full electric), fuels and engine oils and development of research methods.

Furthermore, the invited American and European specialists presented nine technical posters.

Presentations were delivered during five plenary sessions covering various issues, with the following titles:

- a) "General automotive exhaust emissions",
- b) "CO<sub>2</sub>, GHG & Air Quality (including particulate matter)",
- c) "Emissions reduction technologies & aftertreatment",
- d) "Test methods: laboratory based and RDE-PEMS",
- e) "Fuel and Alternative powertrains".

#### Symposium Sessions

Individual sessions were chaired by well-known experts on car emissions: Wolfgang Thiel (Germany), Les Hill (UK), Amanda Lea-Langdon (UK) and Piotr Bielaczyc.

##### 3.1.1. First Session

The first session was in relation to general aspects of vehicular emissions and global standards for their reduction.

The discussions during this first session included the new method for measuring emissions under real road driving conditions – RDE, as well as a newly-introduced chassis dynamometer WLTP procedure described in UNECE Regulation GTR 15, which has replaced the NEDC cycle in use since 2000.

A comparison of emissions standards in the EU, USA, China, Japan, and India was presented. One of the presentations on this subject of the symposium was delivered by Dr. Piotr Bielaczyc (BOSMAL), who presented the most important technical, political and economic factors that currently affect the development of global road transport.

Global trends in reducing emissions from vehicles using the example of the European Union, Japan, USA, China and India were also discussed, as well as the main features of new EU emission standards – WLTP – developed by the GRPE (UNECE) and RDE groups, which were introduced into the EU approval requirements as the emission level Euro 6d-TEMP from 1<sup>st</sup> September 2017, through Commission Regulations (EU) 2017/1151 and 2017/1154.

Dr. Bielaczyc's presentation also highlighted the impact of new emission testing methods on the development of automotive engine structures and future trends in vehicular powertrains. Despite the low esteem in which Diesel engines are held by many, manufacturers of these engines have already developed solutions based on SCR catalytic systems, which can ensure that this engine type has very low emissions of both PM/PN and NO<sub>x</sub>.

A new trend in engine design is "rightsizing", as well as an ongoing convergence of spark ignition and compression ignition engine technology, with differences now much smaller than in the past (turbocharging, direct injection, compression ratio).

In the first session devoted to the regulations and methods of emission testing, further reports were presented by: Dr. Vicente Franco (European Commission, Belgium; Fig. 4) who presented the issues of air protection against pollution from automotive sources in the European Union (EU Clean air policy) and the latest data on the implementation of WLTP and RDE regulations in the European Union as tools to meet those aims.

Subsequent changes in research procedures will result in the fourth RDE package, which will also introduce tests of cars in use, to be performed by independent accredited

laboratories as well as the vehicle manufacturers. The analysis of the next emission regulations, described as ‘post-Euro 6’ – and even ‘Euro 7’ – has begun, which are to bring the same test methods and limits for all types of engines and fuels (a philosophy known as ‘fuel-neutral’ or ‘technology-neutral’, which already exists in the USA).

Les Hill (Horiba, UK; Fig. 5) presented trends in reducing emissions on a global scale as well as their impact on measurement procedures and the requirements for test equipment and methods. The US has introduced EPA Tier 3 and CARB LEV-III (in California) requirements, regulations on greenhouse gas emissions (GHG) and procedures defined in CFR Part 1065/1066 which are still being continually updated.

Japan plans to introduce testing methods based on the WLTP procedure (3-phase test without driving speeds > 100 km/h) and RDE tests for vehicles with CI engines. China and India likewise plan to introduce similar standards as in the EU, based on WLTP tests and methodology, and also RDE in the future. Thus, the precedent for RDE testing to expand from its point of origin in the EU to other legal jurisdictions over the next few years appears clear; particularly significant are the plans for introduction of rigorous RDE requirements by the large (and growing) markets of China and India. The formation of a new UN-ECE Informal Working Group for Global RDE reflects this situation.



Fig. 4. Wolfgang Thiel (TRT Engineering, Germany) and Dr. Vicente Franco (European Commission, Belgium) during the first session



Fig. 5. Les Hill (Horiba, UK) delivering his presentation

### 3.1.2. Second Session

In the second session, covering greenhouse gas (GHG) emissions, CO<sub>2</sub> emissions and particulates, Dr. Barouch Giechaskiel (JRC-Ispra, Italy; Fig. 6) presented two reports prepared by teams of specialists from the European Union’s JRC Ispra research centre in Italy. He presented the problem of differences in the results of measurements of CO<sub>2</sub> emissions in type approval tests using the NEDC cycle and under real driving conditions, as well as the methods of compensating for these differences after the alteration of the test procedure via the WLTP.

This topic was also touched on by Prof. Luciano Rolando from Turin University of Technology who stated that CO<sub>2</sub> emissions according to the WLTC cycle can be 10% to 24% higher using the WLTP procedure as opposed to the the NEDC, due to the higher energy demand in this cycle. The European Commission proposes to further reduce the average CO<sub>2</sub> emissions of cars by 15% in 2025 and by 30% in 2030 in relation to the level from 2021 (though some parties continue to lobby for even higher reductions). Dr. Amanda Lea-Langdon from the University of Manchester in the UK presented the methodology and some results of advanced optical measurements of solid particles.

In his second contribution to the debate, Dr. Giechaskiel presented the work of the PMP group on measurements of PM/PN emissions and on the extension of the testing methodology of the number of nanoparticles (PN) for the current cut-off point of 23 nm down to 10 nm, to assess the emission of these particles which are currently not subject to limitation, which is significant especially in the case of gasoline and gaseous-fuelled engines. He also discussed the work of the PMP team on the introduction of methods testing and measuring the emission of particles generated from the brake discs and pads in cars and the planned work for new emission standards at the post-Euro 6 level.



Fig. 6. Dr. Barouch Giechaskiel – (EC JRC-Ispra, Italy) delivering his presentation

### 3.1.3. Third Session

The third session, concerning emission reduction methods and catalytic exhaust gas aftertreatment systems, consisted of two parts and had the largest number of presentations. It was opened by Dr. Ameya Joshi (Corning, USA), who gave a speech about the methods for limiting engine emissions through catalytic systems, also for hybrid power-

trains in which the TWC and other catalytic reactors may undergo cooling when the combustion engine is not running. He also talked about the possibilities of increasing the efficiency of car engines. 45% thermal efficiency has already been achieved for SI engines, but further development in this field is still possible – currently a level of 55% for the CI engines used in HD applications are being worked on. A significant part of his report was devoted to catalytic aftertreatment (SCR, SCRF, PNA, methane oxidation catalysts) as well as multi-component systems of catalytic reactors and filters which can allow engines to meet legal emissions requirements under a wide range of operating conditions.

Kurt Engeljehring (AVL, Austria; Fig. 7) spoke about the influence of RDE emissions standards on the development of research methods on both engine and chassis dynamometers. To meet the RDE standards, ECU adjustments must be performed on both engine dynos and verified on the chassis dyno in emission testing laboratories where RDE tests performed on the road are reproduced.

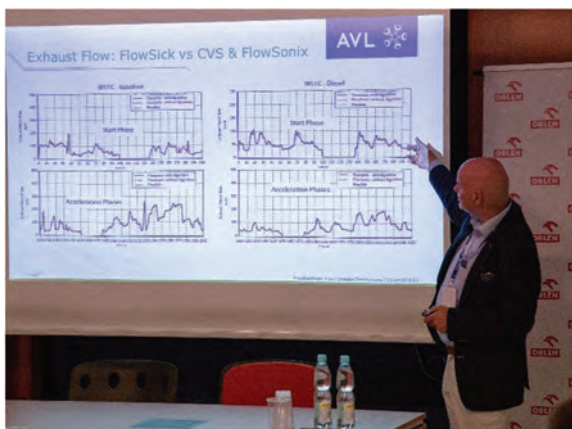


Fig. 7. Kurt Engeljehring (AVL, Austria) delivering his presentation

An important element of the strategy of reducing emissions by internal combustion engines is advanced engine control systems in cars – made possible by ECUs, whose calibration methods were presented by Dr. Marcos Alonso Baez (Nissan Technology Center, Spain; Fig. 8). This method is based on ECU modelling in terms of RDE emission requirements and is referred to as MBC (model based calibration). It allows optimising of the ECU function that controls the operation of the engine and its systems in terms of low  $\text{NO}_x$ , CO,  $\text{CO}_2$  emissions, real road emissions and reduces the time needed for dyno testing.

Jon Andersson (Ricardo, UK) presented the research program conducted for the CONCAWE association, concerning the possibility of reducing real road emissions by diesel-powered cars in terms of Euro 6d standards through the use of advanced SCR, SCRF and LNT catalytic systems in various configurations. The presented solutions show the possibility of fulfilling the limits of PN and  $\text{NO}_x$  emissions by a car with a CI engine in various driving cycles, including those with high energy demand (WLTC, US06, RDE).

A properly selected SCR system ensures very low  $\text{NO}_2$  emissions from the vehicle, far below the limits and requirements for Euro 6d. He emphasised that Diesel engines

– recently much criticised for their environmental performance – should remain an important source of propulsion due to their high efficiency and existing catalytic solutions, allowing significant reduction of  $\text{NO}_x$  emissions and the ability to meet emission limits also in RDE tests while maintaining their high efficiency and low  $\text{CO}_2$  emissions.



Fig. 8. Dr. Marcos Alonso Baez (Nissan Technical Centre Europe, Spain) delivering his presentation

Dr. Katarzyna Matusik (Argonne National Laboratory, USA; Fig. 9) presented advanced methods of testing fuel atomisation by injectors used in SI and CI engines using X-ray and photon synchrotron diagnostics. This methodology allows for very accurate analysis of fuel atomisation through injector holes, stream shape, evaluation of cavitation problems, accurate hole geometry measurements and many quantitative other analyses of the atomisation of the fuel.



Fig. 9. Dr. Katarzyna Matusik (Argonne National Laboratory, USA) delivering her presentation

Dr. Tue Johannessen (Aminnex, Denmark) and Dr. Toni Kinnunen (Proventia, Finland) presented the possibilities of using advanced SCR catalytic systems to reduce  $\text{NO}_x$  emissions in the captive fleet (i.e. currently used LD, HD vehicles and buses). This method is referred to as retrofitting and enables older vehicles to meet new emission standards at Euro 6 (LD) and Euro VI (HD) levels. This could significantly reduce the actual emissions from millions of vehicles with CI engines currently in use on Europe's roads. Examples of applications of this technique can be found in many cities in Germany and Scandinavia, as well as London buses. Maciej Hadryś (Mahle, Poland) presented new piston

design solutions for SI and CI engines that allow their overall temperatures to be lowered and for better temperature distribution on the piston surface.

Paolo Patroncini (4-e Consulting, Italy) presented the development of “P-2 Architecture”, modelling and design of hybrid powertrains for NRMM and off-road vehicles. For these types of vehicles and machines hybrid systems can be a promising solution. The first hybrid drive of this type is to be presented by the company 4-e Consulting and the University of Parma in November 2018.

The last two presentations in this session concerned particulates. The first covered methods for measuring the amount of soot in the DPF filter in CI engines using a special soot sensor developed by a team from the University in Thessaloniki, Greece, which can also be part of the OBD system. The reports as well as the problems with the accuracy of particle number measurements and calibration of devices used for this were presented by Prof. Savas Geivanidis the University in Thessaloniki.

The second presentation emphasised that PN measurement is one of the most difficult measurements in the field of automotive emissions testing. Work on this problem together with improving the accuracy of measurements and calibrations of measuring devices were presented by Alexander Terres (BMW/PTB, Germany; Fig. 10).



Fig. 10. Alexander Terres (BMW & PTB, Germany) delivering his presentation

#### 3.1.4. Fourth Session

The fourth session dealt with methods of automotive emissions testing, both in relation to laboratory tests and road tests using the RDE-PEMS method.

The new WLTP and RDE research methodologies were introduced in the provisions of Euro 6c and Euro 6d-TEMP and became applicable to new vehicle approvals from 1<sup>st</sup> January 2017.

The first RDE package was published two years ago in the Commission Regulation (EU) 2016/427 and the second and third package in the Commission Regulations (EU) respectively 2016/626, 2017/1151 and 2017/1154 respectively. Further updates are expected late in 2018, as well as in future years.

Dr. Sophie Kinnear (Jaguar Land Rover, UK; Fig. 11) presented a report on advanced testing laboratories used for testing exhaust emissions on a chassis dynamometer, and on test benches for testing entire propulsion systems together with the methods for correlation of results between these two types of test stands. She used the examples of her company's laboratories in Whitley, Coventry in the UK.



Fig. 11. Dr. Sophie Kinnear (Jaguar Land Rover, UK) delivering her presentation

Having extensive test bench capacity is now crucial to conduct development and adjustment of control systems for both internal combustion engines and associated systems (e.g. aftertreatment) in terms of meeting the requirements of the WLTP and RDE methodologies and new Euro 6d standards.

Sam van Goethem (TNO, the Netherlands) presented a new exhaust gas analyser for mobile measurements, referred to as SEMS (Smart Emissions Measurement System), based on sensors (as opposed to full chemical analysers), thermocouples and CAN bus connection via OBD II and J1939 interfaces. Such a system can measure fuel consumption, CO<sub>2</sub>, NO<sub>x</sub> and NH<sub>3</sub> emissions and may also be useful in the continuous monitoring of these parameters in a vehicle.

In this session, a report on RDE research was also presented by Prof. Jerzy Merkisz (here representing Poznan University of Technology), who is a well-known expert on real-time emissions measurements performed under real operating conditions. He presented the results of investigations into many types of vehicles and machines powered by internal combustion engines, obtained using PEMS mobile analysers: passenger cars and trucks, buses, working machines and off-road vehicles and even trains, ships and aircraft. He also presented revealing comparisons of actual exhaust emissions from various types of vehicles and working machines.

Professor Gordon Andrews (University of Leeds, UK; Fig. 12) emphasised the fact that the largest local air pollu-

tion levels are caused by traffic jams and sub-optimal or inadequate road layout, which is related to the low mean driving speed, the high frequency of stop events and the frequency and intensity of acceleration events, which often occur from idling. This is the main cause of high levels of air pollution in urban areas. Traffic conditions with very high emissions intensity and very low mean speed (below 15 km/h) are not included in the new WLTP and RDE tests. RDE tests of cars and heavy goods vehicles with an SCR catalytic system on congested roads in Leeds, UK as well as in China have shown that the highest emissions occurred when pulling away from a standstill and that the final emissions are correlated with the mean driving speed, a revelation which should be taken into account in further modifications to RDE regulations.

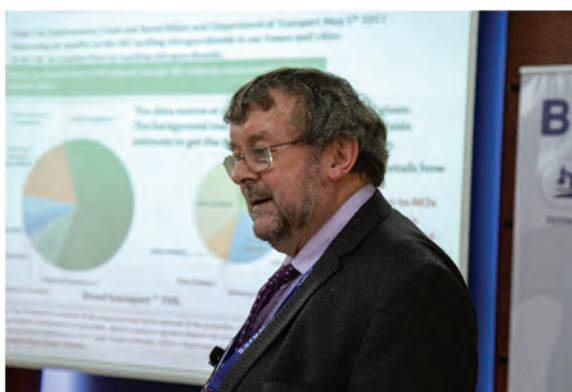


Fig. 12. Prof. Gordon Andrews ( University of Leeds, UK) delivering his presentation

### 3.1.5. Fifth Session

The fifth and final session concerned the development of motor fuels and alternative powertrains (here mainly electric vehicles).

Dr. Johannes Villinger (V&F, Austria) presented the possibility of using oxymethylether (OME) as a fuel for the possibility of improving the properties of alternative fuels and biofuels. He also presented the need for further work on the development of alternative fuels, despite the currently low prices of mineral fuels (those derived from crude oil/natural gas) and the possibility of improving the combustion process within the engine using additives for properly composed fuels. He presented the research possibilities of various advanced measuring instruments for exhaust gas composition analysis based on mass spectrometry for analysis of raw exhaust gas.

Another two consecutive reports were devoted to electric cars. This subject was discussed for the first time during the Exhaust Emissions Symposia at BOSMAL, however, it was justified by the increasing political pressure on the introduction of fully electric vehicles, and on the other hand the desire to thoroughly assess such propulsion systems both in terms of their ecological performance (so-called “source to wheel” analysis), as well as the advantages and disadvantages of this type of energy storage & propulsion system compared to conventional internal combustion engines (including hybrids) and liquid hydrocarbon fuels.

Dr. Piotr Bielaczyc (co-author Dr. Marek Ryłko – a well-known expert on hybrids and electric vehicles) presented a general report on the history, characteristics as well as the advantages and disadvantages of electric vehicle drives.

The first electric vehicles were built as early as 1830, much earlier than vehicles powered by internal combustion engines. Around the year 1910, electric vehicles were dominant on the passenger car market, but the introduction of an electric starter, which replaced the crank in cars with internal combustion engines, and on the other hand, the much higher price of electric cars caused a significant drop in interest in these cars. We are now observing a renaissance in interest for electric powertrains and vehicles, which can be a good solution, especially in crowded cities and heavily urbanised areas.

However, there are many barriers and disadvantages of these vehicles and one of the most important of these is the low energy density that can be stored in a lithium-ion battery, which is equivalent to only about 4% of the energy contained in liquid fuels. This means that the amount of energy that can be stored, for example, in a 125 kg battery corresponds to the same amount of energy contained in 4.5 litres of gasoline (i.e. ~10% of the capacity of a typical passenger car’s fuel tank).

Another problem is the infrastructure for charging electric car batteries. In the final presentation, Dr. Marek Sutkowski (Horus Energia, Poland) presented some insights into this subject. He explained that each car needs about 40 kWh of electricity to fully charge the battery, which corresponds to 8h of charging at 5 kW, or 30-40 minutes with a charging capacity of 100-150 kW (although in practice much more power – some 350 kW – would be recommended); such high power levels require special battery charging infrastructure, thus necessitating the construction of additional power plants and transmission lines in addition to the final charging points. A possible solution to this problem, according to the author, would be to build a network of charging stations based on generators equipped with large combustion engines that would be powered by Diesel or CNG. This, however, only confirms the thesis that the combustion engine is more universal than the electric motor, because it can convert the energy contained in the fuel into work by itself, without the need for large, heavy and costly energy storage systems.

## 4. Conclusions

During the 6th Symposium on Exhaust Emissions, all issues relating to the emission of harmful exhaust gases, greenhouse gases from automotive sources and the directions in which the development of vehicle’s drive based on both internal combustion engines, hybrid drives and electric motors are going were discussed.

Conclusions and observations regarding the current (Euro 6c, Euro 6d-TEMP, and Euro 6d in the European Union) and the future (planned post-Euro 6 and Euro 7) legal status limiting the emission of harmful and toxic exhaust components were presented.

Conclusions regarding the reduction of fuel consumption and emission of carbon dioxide (CO<sub>2</sub>), methods of reducing these emissions, development of test methodology for ex-

haust emissions from internal combustion engines used in motor vehicles and other means of transport as well as off-road vehicles and working machines were also discussed.

Reducing emissions of harmful compounds and toxic fumes, and now the especially important reduction of particulate matter (PM) in terms of their mass and number (PN) of emitted nanoparticles, reduction of real NO<sub>x</sub> emissions, as well as new tests and WLTP and RDE emission testing methodology are the main challenges for the automotive and motor industries caused by political, economic and technical factors.

The new WLTP and RDE research methods, which are a milestone in the development of vehicle tests which also require new engine designs and exhaust after treatment systems, are also the focus of certification authorities in other countries, notably Japan, China, India and South Korea. These countries plan to introduce them in the coming years. These works are also closely watched and partly supported by countries such as the USA and Canada.

New challenges currently faced by manufacturers of drive systems of motor vehicles, but also off-road vehicles and working machines, related to the decarbonisation of the economy, the need to reduce fuel consumption, which is equivalent to reducing greenhouse gas (GHG) emissions, especially CO<sub>2</sub>, caused the necessity of further development of various types of powertrains: both internal combustion engines, adapted to be fuelled with improved fuels of mineral origin, as well as new types of ecological and alternative fuels, hybrid systems, built from an internal combustion engine and an electric motor, especially in the Plug-in Hybrid system, as well as fully electric powertrains.

Currently, the development and introduction of innovative electronic solutions has made electric motors better, quieter and much more powerful and can be an independent or combined (hybrid) source of vehicle propulsion, which will be of great importance especially for vehicles used in city centres and heavily urbanised areas.

In the current era of increasingly stringent emission standards for the automotive industry, electric motors are again becoming a major main focus of attention, constituting an important development focus for the entire automotive industry.

In addition to continuous improvements in electric motor technology, making electric and hybrid vehicles more competitive compared to conventional internal combustion engines (ICEs) in many markets, lawmakers and research and development organisations are constantly working on test methods and test equipment for these types of vehicles and powertrains.

According to experts, despite the growing popularity of electric vehicles, over 90% of new vehicles will still be powered by an internal combustion engine in 2025.

Internal combustion engines – including Diesel engines – will continue to be the main source of power for motor vehicles and working machines for many years, due to their high efficiency, the ability to produce very clean engines, the availability of liquid and gas fuels, as well as the development of renewable fuel technologies and even synthetic fuels.

These motors will also be combined with electric motors as a hybrid unit in the future, which will have a great impact, especially on the specific applications of vehicles and working machines.

It is important to develop production technologies for low-carbon alternative fuels and biofuels, as well as electricity from renewable sources.

Compliance to the emission limits in the new WLTC cycles and measurements in real RDE traffic, as well as the introduction of new research methods for the study of hybrid and electric powertrains is a very complicated and expensive process for vehicle manufacturers, requiring increased investment in research and development and even entire new research laboratories, which is what BOSMAL has been doing for years, making it currently the largest research and development facility of its type in Central and Eastern Europe (Fig. 13).



Fig. 13. BOSMAL's climate-controlled 4WD chassis dynamometer for R&D and certification work on conventional, hybrid and fully electric powertrains

The process of testing and quantifying the efficiency of hybrid drives and electric motors in the automotive industry is based on conducting research on special test stands for development and calibration of drive systems based on the use of test cells similar to those for testing internal combustion engines equipped with dynamometers based on AC asynchronous motors. However, due to the growing popularity of electric motors in the automotive industry (hybrid and electrical solutions) it is undoubtedly necessary to develop an appropriate, systematic and coherent research methodology for researching and testing such engines. An instance of this is work on the research methodology for vehicles with electric, hybrid (Diesel-electric) and hydrogen fuel cells.

Experts participating in the symposium anticipated that in the coming years, intensive research and development will be carried out for the following types of vehicle drives, which will be produced in 2020-2025 and in later years:

- a) new types in internal combustion engines developed according to the “rightsizing” concept in LD and HD versions, which will aim to meet Euro 6d, post-Euro 6/Euro VI – Euro 7/Euro VII standards, also adapted to the new generation of motor fuels and alternative fuels (with the addition of HVO, ethanol/methanol, low carbon fuels, CNG, hydrogen and perhaps even other types), with mild hybrid systems or other hybrid systems used in the future
- b) a new generation of exhaust gas aftertreatment systems, especially SCR systems for CI engines and GPF filters for direct injection fuel injection engines (with highly refined and accurate Ad-blue dosing, filter regeneration, etc.),
- c) SI and CI engines developed for cooperation with electric motors in hybrid systems, especially Plug-in-hybrid, for various applications,
- d) hybrid powertrains for vehicles consisting of SI or CI engines and electric motors in various configurations and with different control systems,

- e) electric motors of various types used for powertrains of LD and HD vehicles with a maximum engine power of up to approximately 250 kW.

These types of powertrains will have to meet the new requirements which are included among others within UNECE regulations and European Union regulations, such as: GTR15 Regulations, with proposals for amendments to GTR15 (Proposal for Amendment 4 and 5 to Global Technical Regulation No. 15 (Worldwide Harmonised Light Vehicle Test Procedure (WLTP)), United Nations ECE/Trans/WP.29/GRPE/2018/1), newly developed by the GRPE (UN) group, GTR RDE Regulations, new research methods in the preparation of, among others, IWG group – Electric Vehicles and Environment.

The presentations, abstracts and posters submitted to the 6th IEES are included in conference materials entitled: “Symposium Proceedings – Trends in Automotive emissions legislation: Impact on LD engine development, fuels lubricants and test methods – a global view with focus on the WLTP and RDE regulations”, ISBN 978-83-946334-1-7, issued by BOSMAL on CD [6]; a printed Book of Abstracts is also available, ISBN 978- 83-946334-2-4 [7].

A film documenting and reporting on the symposium is archived on a DVD that will be attached to the Combustion Engines number 3/2018. A special edition of the journal Combustion Engines (3/2018) will also be released with articles and presentations from the symposium. Diesel Net (Canada) has prepared a report on the symposium, which is freely available online [8]. The summary of the symposium will also be included in the scientific journal Emission Control Science & Technology, an international journal published by Springer in New York, USA. Information and reports from previous iterations of the IEES (2010-2016) are available in previous issues of Combustion Engines, as well as in various volumes issued by BOSMAL and on the internet [9-25].

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# The 6<sup>th</sup> International Exhaust Emissions Symposium (IEES) 14-15 June 2018, BOSMAL, Bielsko-Biala (Poland)



*Trends in automotive emissions legislation: impact on LD engine development, fuels, lubricants, and test methods – a global view, with a focus on WLTP and RDE regulations*

## Presentation abstracts

**Piotr BIELACZYC** **CE-2018-310**  
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### **GLOBAL TRENDS IN EXHAUST EMISSIONS AND IMPACT ON ENGINE TECHNOLOGY AND FUELS: AN INTRODUCTION TO THE TOPIC**

Concern over the impact of exhaust emissions on air quality, greenhouse gas emissions and energy consumption is currently high. The automotive industry is undergoing a period of intensive change as a result of changes to the legal requirements on exhaust emissions. This situation is occurring in many markets worldwide. Some 80% of all new passenger cars sold globally are subject to some kind of energy efficiency regulation. Despite recent progress in harmonisation, at present significant regional differences exist, which vary from the analytical laboratory methods specified, the driving cycles, the list of regulated pollutants, the numerical values of the emissions limits and the test cycles mandated. The key points of new procedures are reviewed and strategies and engine/aftertreatment technologies employed to deal with these challenges are discussed. Automotive emissions regulation processes are discussed, with the aim of providing an introduction to the topic and asking key questions.

*Keywords: exhaust emissions, RDE, WLTP, aftertreatment, fuel*

**Vicente FRANCO** **CE-2018-311**  
European Commission, Directorate-General for Environment

### **AN UPDATE ON RECENT REGULATORY DEVELOPMENTS IN THE EU CLEAN AIR POLICY**

This presentation will provide an overview of the latest regulatory developments in the EU Clean Air Policy. 2018 will be an eventful year for EU vehicle emission regulations: the publication of the fourth package of the real-driving emissions (RDE) regulation and the second act of the Worldwide harmonized Light vehicles Test Procedure (WLTP) in the EU, and the approval of the new regulation of the approval and market surveillance of motor vehicles. These regulatory developments will bring substantially improved testing methods and changes in the attribution of market surveillance responsibilities—with corresponding improvements in the real-world emissions performance of

new light-duty vehicles and in the enforcement of existing limits. Work on new standards will also begin, to address the European Parliament's call for 'new technology-neutral Euro 7 emission limits applicable by 2025 for all light-duty vehicles'. In parallel, the Ambient Air Quality Directives will undergo an evidence-based 'fitness check' to assess whether they are fit for purpose, and to guide future action.

*Keywords: vehicle emission regulations, RDE, WLTP, air quality standards, emissions type approval*

**Leslie HILL** **CE-2018-312**  
HORIBA Ltd

### **A GLOBAL EMISSIONS LEGISLATION OVERVIEW**

The presentation will outline the current and future emissions legislation on a global basis. The predominant topic will be the future of the EU implementations of the WLTP and the latest LDV-RDE. In addition, other implementations of Real Driving Emissions will also be introduced. A short review will also look at other aspects of emissions legislation such as non-exhaust emissions sources that are currently under discussion.

*Keywords: emissions, legislation, implications, future*

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**K. ANAGOSTOPOULOS**  
**M. CLAIROTTE**  
**V. VALVERDE**  
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### **DEALING WITH THE GAP BETWEEN TYPE- APPROVAL AND IN-USE LIGHT DUTY VEHICLES FUEL CONSUMPTION AND CO<sub>2</sub> EMISSIONS**

There is increasing evidence suggesting that real world fuel consumption and CO<sub>2</sub> improvements in the last decade have been much less than those measured during type approval tests. Scientific studies have found that the offset

between officially reported values and real-world vehicle CO<sub>2</sub> emissions in Europe has constantly increased over the last years. The difference between officially reported and actual CO<sub>2</sub> emissions of vehicles has three main implications: a) it undermines the effectiveness of CO<sub>2</sub> Regulations in reducing greenhouse gas emissions in Europe, b) it distorts competition between vehicle manufacturers, and c) it undermines innovation.

As a fundamental step to deal with this issue the European Commission has already replaced the old and outdated test procedure used so far in the emission type-approval of vehicles with Worldwide harmonized Light vehicles Test Procedure (WLTP). Being a lab-based test-procedure, the WLTP, by its nature, can only cover part of the CO<sub>2</sub> gap. There is therefore increasing pressure to integrate the current type-approval system with additional measures based on real-world measurements.

This study presents experimental evidence on the variability of the CO<sub>2</sub>/fuel consumption of a vehicle, putting into question the idea that a single central estimate of these quantities may be sufficient. Two types of data sources have been used, namely the data collected during a period of 1 year from the same vehicle driven by different drivers, and the data collected from different vehicles tested by a few drivers on a limited number of routes. Combining the two sets of data in a proper statistical way allowed to merge the wide coverage of testing conditions of the first set with the wide coverage of vehicle technologies of the second set.

*Keywords: CO<sub>2</sub> emissions; fuel consumption; real-driving emissions; gap; light-duty vehicles; labelling*

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**CE-2018-314**

**AN INSIGHT INTO THE PROCEDURAL DIFFERENCES BETWEEN NEDC AND WLTP AND THEIR POSSIBLE IMPACT ON CO<sub>2</sub> EMISSIONS FROM THE TYPE-APPROVAL: CASE OF VEHICLES WITH INTERNAL COMBUSTION ENGINES**

In the last years the Type Approval (TA) procedure for passenger cars sold in Europe consisted of a laboratory test performed on a chassis dyno meter along the New European Driving Cycle (NEDC), throughout the CO<sub>2</sub> and pollutants emissions were measured. Different studies demonstrated the significant discrepancy between the TA test and the real world. Therefore, the European authorities decided to replace the NEDC with a new test procedure closer to real driving conditions called Worldwide Harmonized Light Vehicles Test Procedure (WLTP). The aim of this work is to address the effect of the WLTP introduction on vehicle CO<sub>2</sub> emissions with respect to the NEDC procedure through experimental and simulation assessments on two different Euro 5 vehicles equipped with Diesel and Gasoline engines, considering also the effect of the engine ther-

mal status and the impact of the stop-start. It was found that the higher test mass/RLs and cycle dynamics imposed by the WLTP generates an increase of 45% of the cycle energy demand, while the CO<sub>2</sub> growth is limited to 20%, highlighting the increase of the average efficiency of the internal combustion engine.

*Keywords: CO<sub>2</sub> emissions, type approval, WLTP, NEDC*

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**CE-2018-315**

**THE OPTICAL PROPERTIES OF VEHICLE GENERATED PARTICULATES**

Much is known about the role of greenhouse gases (GHG) in atmospheric chemistry, however atmospheric black carbon also makes an important contribution to the warming of the global atmosphere. This work investigates the optical properties of particulates which are shown to be affected by the proportion of black carbon linked to mixing state. Black carbon (BC) emitted from diesel engines, bio-fuel burning, wildfires, shipping and aircraft is known to absorb solar radiation in the atmosphere and have a strong warming effect on climate, particularly on local scales. However, strong uncertainties arise because the per-mass light absorption is strongly influenced by other materials, such as organics, co-emitted with the BC (known as the 'coating'). By studying emissions from a light-duty diesel engine rig using state-of-the-art, online single-particle instruments and comparing with equivalent ambient measurements in Manchester, we have shown that this enhancement in light absorption only occurs once the amount of coating relative to the BC reaches a certain threshold, which isn't normally the case for diesel emissions, except under cold start conditions.

*Keywords: black carbon, diesel particulates, atmospheric chemistry*

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**CE-2018-316**

## PARTICLE NUMBER MEASUREMENTS IN THE EUROPEAN REGULATIONS AND FUTURE ACTIVITIES

The solid particle number method was introduced in the European light-duty regulation for diesel vehicles to force the installation of the best-available technology at that time (i.e., wall-flow diesel particulate filters) without the uncertainties of the volatile nucleation mode and without the need of large investment for purchasing the equipment. Later it was extended to gasoline vehicles with direct injection engines, heavy duty engines (both compression ignition and positive ignitions) and non-road mobile machinery engines. Real Driving Emissions (RDE) testing on the road with Portable Emissions Measurement Systems (PEMS) for particle number (and NO<sub>x</sub>) during type approval and in-service conformity testing was recently (in 2017) introduced for light-duty vehicles, and is under discussion for heavy-duty vehicles in-service conformity testing.

This paper will summarize the existing legislation regarding solid particle number and discuss the on-going activities at a European level. The main focus at the moment is on improving the calibration procedures, and extending the lower detection size below 23 nm with inter-laboratory exercises. In parallel, discussions are on-going to introduce testing at low ambient temperature, regeneration emissions in the light-duty regulation, a particle limit for other technologies such as gasoline port-fuel injection vehicles, mopeds and motorcycles. A short overview of periodical technical inspection investigations and the situation regarding non-exhaust traffic related sources with special focus on brakes and tyres will be described.

*Keywords: vehicle emissions regulation, particle measurement programme (PMP), Portable Emission Measurement Systems (PEMS), Real Driving Emissions (RDE), periodical technical inspection, particle number, sub-23 nm*

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CE-2018-317

## AFTERTREATMENT TECHNOLOGIES TO MEET THE LATEST GLOBAL EMISSIONS STANDARDS

Countries all over the world are stepping up efforts to improve ambient air quality and limit CO<sub>2</sub> emissions. In the automotive sector, these are being enforced through a combination of mandated CO<sub>2</sub> or fuel economy targets and tighter tailpipe emission standards to minimize unburned hydrocarbons, NO<sub>x</sub> and particulates. Along with tighter limits, there is an increased emphasis on in-use compliance, via on-road testing under a broad range of driving conditions. OEMs are responding rapidly, and delivering cleaner and more fuel-efficient vehicles, via a combination of advanced engine technologies, powertrain electrification and after-treatment systems.

In this talk, we will provide an overview on recent advances in after-treatment systems technologies. The pursuit

of improved engine efficiencies has led to broad adoption of gasoline direct injection (GDI) technology. GDI engines emit higher particulates, which have motivated the development and likely adoption of gasoline particulate filtration (GPF) technology, which we will review in greater detail. Another challenge gaining importance is that of cold-start gas emissions. Gas temperatures are expected to decline with improved engine efficiencies and adoption of low-temperature combustion techniques. This emphasizes the role of improved catalysts in staying above the light-off temperature throughout the drive cycle. The coupling of conventional IC engines with electric motors also leads to the possibility of catalyst temperatures dropping below the light-out temperatures when the engine is turned off. Engine on-off events also lead to transient emissions, such that hybrids pose additional challenges for after-treatment systems. We review some of these challenges and solutions being proposed. We also cover some recent proposals for advanced diesel after-treatment solutions, especially in light of post Euro 6 regulations, for which discussions are expected to start this year.

*Keywords: exhaust emissions, regulated emissions, fuel economy, aftertreatment*

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CE-2018-318

## RDE DEVELOPMENT ON TESTBEDS

Complying with real driving emissions (RDE) legislation requires a massive increase in calibration effort, yet the RDE environment is characterized by highly unstable conditions which do not allow fair comparisons of emissions control systems and strategies to be made. This presentation examines the need to perform RDE development under laboratory conditions (i.e. on testbeds) and how this can be achieved using the latest testing hardware and software.

*Keywords: RDE, calibration, real world, test methods*

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CE-2018-319

## MODEL BASED CALIBRATION: A CHALLENGE FOR OPTIMAL EMISSIONS

As of today, 1.2 billion vehicles are being used over the world, with a continuous grow. A total volume of 2.5 billion vehicles are foreseen for 2050, reaching more than twice current quantity in 30 year time. Even though all vehicles in the market are compliant with the emission regulations, it is a fact that many cities suffer issues in terms of air quality, partially due to the use of the vehicles internal combustion engines (ICEs).

Several factors have contributed to reaching current situation concerning ICEs. Likely is that the regulation had not been fully representative of the real world conditions (regulation was mostly based on laboratory conditions rather than in actual vehicle usage) due to the availability and feasibility (accuracy) of measurement devices and test facilities.

Under that perspective and, to contribute to a sustainable society, several actions have been introduced from regulation and from Nissan point of view.

In terms of regulation, a much more realistic approach in terms of how emissions performance have to be evaluated has been introduced, either from a laboratory point of view (WLTP, Worldwide harmonized Light vehicles Test Procedures) or from a real vehicle usage perspective (RDE, Real Driving Emissions).

The mobility solution promoted by Nissan is based on two pillars. The first one is the widespread use of "Zero Emission" vehicles that produce no emissions, and the second one is the thorough improvement of thermal efficiency and emissions of vehicles equipped with internal combustion engines. Under this new scenario, achieving the new emissions performance requirements by the regulation and reaching lower levels of CO<sub>2</sub> emissions to achieve European's CAFE (Corporate Average Fuel Economy) targets has become a huge challenge to the OEMs.

The introduction of several new technologies to achieve both scenarios became mandatory. In practical terms, any single device affecting CO<sub>2</sub> and emissions has to be perfectly optimized under all working conditions (either engine working conditions and environmental conditions). Following conventional tuning methods, mostly based on the physical resources, would lead to an unacceptable development duration for the business. Therefore, introducing new tuning methodologies play a fundamental role in the new developments. The replacement of the physical engine by accurate mathematical models which allow most of the engine's tuning to optimize emissions and CO<sub>2</sub> performance has proven to be an efficient methodology to deal with the new challenges. Such a process is known as Model Based Calibration (MBC).

*Keywords: model based calibration, emissions, fuel consumption, engine model, dynamic modelling*

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CE-2018-320

**EURO 6 DIESEL EMISSIONS CONTROL SYSTEM  
APPROACHES & IMPACTS ON CHASSIS DYNO  
AND REAL-WORLD EMISSIONS: LATEST  
RESULTS FROM THE CONCAWE DIESEL  
EMISSIONS PROJECT**

Three diesel vehicles drawn from different sub-levels of the pre-Euro 6d-temp diesel fleet, and employing different emissions control technologies, have been tested on an EN590 compliant fuel. Technologies include LNT plus passive SCR, urea SCRf and urea SCRf with additional downstream secondary SCR. Emissions, including NO<sub>x</sub>, CO and PN have been determined and compared from different regulatory drive cycles tested on a state-of-the-art chassis dyno: NEDC, WLTC & US06, a demanding city-derived urban cycle, and also from moderate full and urban RDE conducted on UK roads. During all chassis dyno cycles, both lab-based analyzers and PEMS were operated in parallel, allowing correlations and compliance with regulatory requirements to be determined. The emissions impacts of specific aftertreatment technologies, including fNO<sub>2</sub> (fraction of NO<sub>2</sub> in NO<sub>x</sub>), over the various drive cycles, and operating conditions encountered within them, are considered and related to regulatory conformity factors. Results indicate that diesel vehicle technologies currently on the road are able to produce very low NO<sub>x</sub> emissions below CF = 1.5 under a range of demanding conditions.

*Keywords: RDE, Diesel, CF, NO<sub>2</sub>, Euro 6d*

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**USING X-RAY DIAGNOSTICS TO INVESTIGATE  
THE INTERNAL AND NEAR-NOZZLE FLOW  
IN GASOLINE AND DIESEL FUEL INJECTORS**

In an internal combustion engine, the role of the injector is to accurately and precisely meter fuel into a specified area at a commanded time. Because optimization of this injection process can improve fuel efficiency and mitigate exhaust emissions, substantial research has been dedicated to characterizing injectors, including their geometry, internal motion, and spray development. However, due to the inherent multiphase nature of the flow, experimental diagnostics can be challenging to perform. Visible light efficiently scatters from gas-liquid boundaries, making it difficult to optically probe the near-nozzle dense region of the spray. In addition, an injection event typically occurs within O(1) μs and features O(1) μm length scales, requiring time-resolved measurements at high spatial resolution in order to adequately resolve important dynamics.

Since X-rays interact relatively weakly with matter, they are not bound by the same scattering restrictions as visible light. In addition, third-generation synchrotron sources, such as the Advanced Photon Source (APS) at Argonne National Laboratory, provide penetrating x-rays at high flux that can be used to measure optically opaque samples at the length and time scales relevant to fuel injection systems. To this end, facilities at the APS, specifically the 7-BM beam-

line, have dedicated significant experimental time and effort to studying such multiphase flows.

We present a summary of the suite of x-ray diagnostic techniques available at the APS to investigate the internal and near-nozzle region of both gasoline and diesel injectors. The X-ray radiography technique measures time-resolved projected density fields as close as 0.1 mm from the injector tip. X-ray tomography produces high-resolution three-dimensional geometry of the injector, extending up to the sac region. The X-ray phase contrast imaging technique provides measurements of the internal motion such as that of the injector needle, as well as the extent of potential cavitation. In addition, ultra-small-angle X-ray scattering provides droplet size distributions to help better understand the degree and rate of atomization. The acquired X-ray data are useful for computational model development and validation in order to better predict the injection process.

*Keywords: fuel spray, synchrotron X-ray, injector, internal combustion engine*

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Amminex Emissions Technology A/S

### SOLID AMMONIA SCR TECHNOLOGY FOR NEAR-ZERO POLLUTING DIESEL VEHICLES

The massive NO<sub>x</sub> (NO<sub>2</sub>) urban air quality issues and aggressive CO<sub>2</sub> targets favor the use of SCR as a solution for good fuel economy and low NO<sub>x</sub> emissions. However, recent studies (JRC; Mendoza-Villafuerte et al., Sci. Tot. Envir., 2017) have documented that current some Euro VI solutions do not reach acceptable DeNO<sub>x</sub>-performance level in urban driving due to lack of urea dosing at low speed. To reach the full potential of ultra-low NO<sub>x</sub> via SCR-technology, two key options exist: a) Eliminating the portion of an exhaust temperature “window” where Ad-Blue®-SCR does not work (exhaust heating strategy) or b) unlock the full SCR performance potential by gaseous ammonia dosing – even below 150°C SCR temperature.

The high efficiency of the diesel engine naturally causes the exhaust to be ‘cold’ at low/medium load and the use of option (a) to enable full NO<sub>x</sub> reduction potential causes a significant fuel penalty (3–6%, e.g. Kufferath et al. (2018)). This presentation focuses on achieving an important step towards near-zero polluting diesel engines: Based on an aftertreatment configuration using solid ammonia storage technology (known as ASDS) combined with state-of-the-art DOC/DPF/SCR/ASC, it has been proven by independent testing that a ~10 ton city bus (4.5 liter non-EGR engine) in a low-speed London city cycle reaches a NO<sub>x</sub> reduction of 99.6% – or an absolute tailpipe level of 76 mg NO<sub>x</sub>/km from an engine-out level of 17.9 g NO<sub>x</sub>/km. Particle number is below Euro VI level via a conventional ceramic filter.

The results are linked to tight requirements for bus operation in London’s upcoming Low Emissions Zone: NO<sub>x</sub> levels must be below 500 mg NO<sub>x</sub>/km and on top of the

normal Euro VI NO<sub>x</sub> requirements there are special constraints on the content of NO<sub>2</sub>: Only 20% of NO<sub>x</sub> is allowed to be NO<sub>2</sub> (100 mg/km). Lastly, the impact of N<sub>2</sub>O on greenhouse gas effect must be below a 5% CO<sub>2</sub>-equivalent. Table 1 summarizes the key results in the London bus cycle (test segments with 16 and 10 km/h avg. speed) and the graph from the on-line monitoring system shows equal high performance in normal operation. The high “MinNO<sub>x</sub>”-performance is obtained without compromising ammonia slip levels and secondary emissions of N<sub>2</sub>O (less than 1% CO<sub>2</sub>eq) and NO<sub>2</sub> (10% of total NO<sub>x</sub>).

The outlook: With more than 99% reduction from a base Euro V engine, the goal of near-zero polluting diesels can be realized in normal operation without compromising CO<sub>2</sub> and the diesel engine combustion efficiency. The presentation will give more results from HD and LD segment and discuss this in relation to latest in-use conformity, China 6/VI and future Not-To-Exceed procedures for US-EPA.

Table 1. Emissions performance in low-speed London bus cycle. Low-emission zone requirements are tighter than current Euro VI: Specific NO<sub>2</sub> fraction (max. 20% of NO<sub>x</sub>) and limit on N<sub>2</sub>O level (less than 5% CO<sub>2</sub>-equivalent).

	NO <sub>x</sub>	NO <sub>2</sub>	CO <sub>2</sub>	CO <sub>2</sub> eq	NH <sub>3</sub>	NH <sub>3</sub>
Units:	g/km	g/km	g/km	g/km	ppm max	ppm avg
Analyser:	BAG	FTIR	BAG	Calculated	FTIR	FTIR
Target	0.5 g/km	0.1 g/km	Within +1% of base-line result (+2% accuracy)	< 5% of total CO <sub>2</sub> emissions (incl. N <sub>2</sub> O impact)	25ppm or lower	10 ppm or lower
Relative Limit	0.5	0.1	849	5%	25	10
Test level	0.076	0.007	805	0.77%	5.5	1.7
Pass/Fail	Pass	Pass	Pass	Pass	Pass	Pass

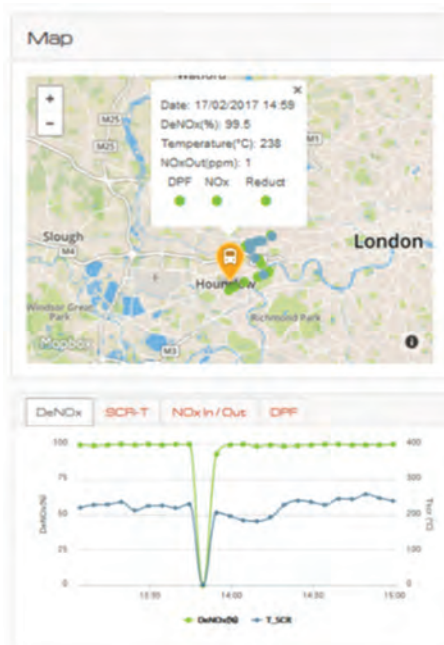


Figure 1. Example of live performance data (NO<sub>x</sub>Tracker) from vehicle in normal operation. High efficiency at or below 200°C

*Keywords: solid ammonia, ASDS, SCR, ultra-low NO<sub>x</sub>, urban driving*

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### MASS SPECTROMETRIC GAS ANALYSIS OF RAW GAS EMISSIONS FROM A DIESEL ENGINE FUELED WITH OME3-5 IN COMPARISON TO CONVENTIONAL DIESEL

#### Background

Polyoxymethylene dimethyl ethers (OMEs),  $\text{CH}_3\text{O}(\text{CH}_2\text{O})_n\text{CH}_3$  as OME1-6 are seen as very promising alternative fuels to diesel for HCIC engines, in respect to lowering  $\text{NO}_x$  and eliminating almost any soot formation in these engines. OMEs have low auto ignition temperatures, high energy densities, similar boiling points and are soluble in diesel. There are already numerous studies to OME combustion and emissions. According to Wang et.al OME3-5 blends improve efficiency and reduce emissions significantly.

We describe the chemical and kinetic properties of premixed flames and diffusion controlled flames and find the OME combustion as an intermediate condition of these combustion models. In a stoichiometric premixed flame the H, O and OH radicals are the driving force of the reactions. Once the temperature gets high enough (1000 K) the reaction  $\text{H} + \text{O}_2 \rightarrow \text{OH} + \text{O}$  is the main source of new radicals. The heat and the H radicals diffuse into the unburnt fuel air mixture. There the small number of H atoms gets amplified advancing the flame front ("flame speed") and in general the chemistry of the fuel determines the flame speed. Most fuels have similar flame speeds. A few odd cases are  $\text{H}_2$ ,  $\text{CH}_4$  and  $\text{C}_2\text{H}_2$ .  $\text{H}_2$  makes a much higher H concentration and  $\text{H}_2$  diffusion is fast,  $\text{CH}_4$  has to generate two  $\text{CH}_3$  radicals and is hence difficult to ignite and  $\text{C}_2\text{H}_2$  reacts much faster with  $\text{O}_2$  than other fuels do. In diffusion controlled flames there is a pyrolytic zone where the temperature rises sharply where CH, large and small fuel radicals dominate in front of the flame. For this case the flow of the fuel and the diffusion speed of H atoms determine the rate of reactions and this fact leads to different emission molecules and especially to soot and soot precursors in the exhaust.  $\text{C}_2\text{H}_4$ ,  $\text{C}_3\text{H}_6$ ,  $\text{CH}_4$  and  $\text{H}_2$  are the main products that burn in the flame.

#### Methods

The different raw gas emissions found from the combustion of diesel and OME3-5 were measured with a double mass spectrometer system based on Electron Impact – Mass Spectrometry (EI-MS) and Ion Molecule Reaction – Mass Spectrometry (IMR-MS). The technical realization and performance data (sensitivity 10 ppm to 100 Vol% for EI-MS; 0.1 ppm to 2500 ppm for IMR-MS, molecular mass range from 2 to 500 amu, measurement speed 20 ms for EI-MS, 2 ms to 500 ms per compound for IMR-MS, gas response times 25 ms t90 time, gas flow rates 250 ml/min,

calibration features direct or in reference to one molecule) are described. The EI-MS measures the main Vol% (bulk gas) components like  $\text{N}_2$ ,  $\text{O}_2$ ,  $\text{H}_2\text{O}$ ,  $\text{CO}_2$  and the low energy IMR-MS measures the main flame hydrocarbons  $\text{CH}_4$ ,  $\text{C}_2\text{H}_4$ ,  $\text{C}_3\text{H}_6$ ,  $\text{C}_4\text{H}_6$ , semi oxidized hydrocarbons like formaldehyde, acetaldehyde, methanol, vapor products of OME, soot precursor molecules  $\text{C}_2\text{H}_2$ ,  $\text{C}_3\text{H}_3$ ,  $\text{C}_3\text{H}_4$ ,  $\text{C}_6\text{H}_6$  and inorganic compounds NO,  $\text{NO}_2$ ,  $\text{SO}_2$  in the range from 1 ppm to 2000 ppm.

#### Results

For the operation with OME we found for no load as well as for full load between 5 ppm OME3 to 22 ppm OME1 gaseous emissions as evaporative losses in the exhaust gas. Under full load we found 280 ppm formaldehyde, 120 ppm acetaldehyde, 20 ppm methanol for diesel operation and 105 ppm formaldehyde, 40 ppm acetaldehyde, 25 ppm methanol for OME operation. The soot precursor compounds were under full load in diesel: 460 ppm  $\text{C}_2\text{H}_2$ , 110 ppm  $\text{C}_3\text{H}_4$ , and 24 ppm  $\text{C}_6\text{H}_6$ , and we found these emissions in OME to be below 5 ppm each. For  $\text{NO}_x$  the diesel operation gave 158 ppm NO and 40 ppm  $\text{NO}_2$  whereas the OME fuel gave 62 ppm NO and 140 ppm  $\text{NO}_2$  emissions.

#### Conclusion

Generally it may be stated that the properties of OME come close to requirements of future fuels.

*Keywords: OME, Diesel, Soot, EI-MS, IMR-MS*

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### PISTON EVOLUTION IN SPARK IGNITION ENGINES

Since the engines with spark ignition became more and more often charged, especially by turbochargers, expectation from mechanical parts of the unit also has changed. Pistons, as the moving component transferred the most, is becoming to be similar in some areas to diesel piston, later found the own path for better service. With this presentation I want to show that the transformation of piston never ends, also in petrol engines.

*Keywords: piston, piston design, spark ignition engine*

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CE-2018-325

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## OPERATION AND IMPLEMENTATION OF A RESISTIVE SOOT SENSOR FOR DPF HEALTH DIAGNOSTICS

Latest vehicle On-Board Diagnostic (OBD) systems are required by legislation to monitor the health of a Diesel Particulate Filter (DPF) by comparing its emissions over the type-approval driving cycle against a maximum allowable emission threshold (OTL). In order to achieve the required monitoring accuracy, cumulative resistive sensors are installed downstream the DPF of modern Euro 6 diesel engines. The usable signal of such sensors is the time needed for the surface of the sensor to be saturated with soot. This time is primarily inversely proportional to soot concentration. Since soot accumulation rate is governed by different physical phenomena, the behaviour of the sensor is also dependent, to a less extent though, on other parameters as well such as exhaust temperature and velocity. This presentation describes the mechanisms affecting soot accumulation rate and methods for simulating sensor behaviour by either mathematical or physical models. In addition, the way such signal can be used to assess the performance of a DPF over the type-approval driving cycles by collecting data under real driving conditions is also presented. The assessment is based on an actual resistive soot sensor available in market.

*Keywords: soot sensor, DPF, on-board diagnostics, type-approval, modelling*

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CE-2018-326

## SOLVING AIR QUALITY PROBLEMS IN CITIES BY RETROFITTING? OUR KEYS TO SUCCESS

The urban air quality has been widely discussed and debated during the last decades. It started mainly with the focus on fine particles and concern was in major cities in certain developing countries. Lately, more and more weight has been put on nitrogen oxides, also in European cities. Public and political pressure has been increasing within last years while additional studies on the current situation on air quality together with health risks has been published.

Emission sources of nitrogen oxides ( $\text{NO}_x$ ) are varying and they are complex in nature. The city traffic has shown to be one of the main reasons. As known today, older generation diesel vehicles are emitting lot of  $\text{NO}_x$ . The situation has believed to improve while newer fleet is taking place. But, unfortunately the progress has not been there as expected. The current knowledge on the difference between laboratory condition homologations and real world driving conditions is underlining the importance of improvements in exhaust emission reduction technologies.

Retrofitting of buses with improved emission after-treatment system has proven to be feasible and quick solution for reducing local  $\text{NO}_x$  emissions significantly. The comparison of new buses and the retrofitted ones clarifies

the need and opportunity of retrofit approach. Several case studies are presented, and some European city retrofit programs are referred to in this study.

*Keywords: retrofit, real driving emissions, PEMS, SCR, city bus*

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## HYBRID P2 ARCHITECTURE POWERTRAIN: AN OVERVIEW ABOUT INTEGRATION ON OFF-HIGHWAY VEHICLES TOWARD STAGE V EMISSION LEVEL

The Stage V emission regulation for Non Road Mobile Machinery has introduced a set of challenging limits, in particular for the internal combustion engines rated up to 56 kW. The improvement of combustion may be not sufficient to comply with these limits: as a result, the after-treatment system is bounded to become much more complex and expensive, requiring, as an example, the further adoption of a SCR system for  $\text{NO}_x$  reduction.

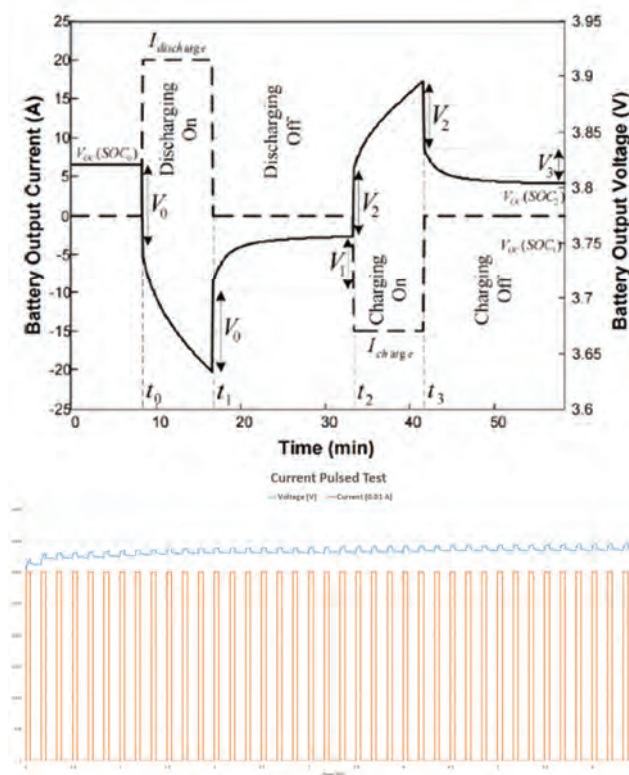
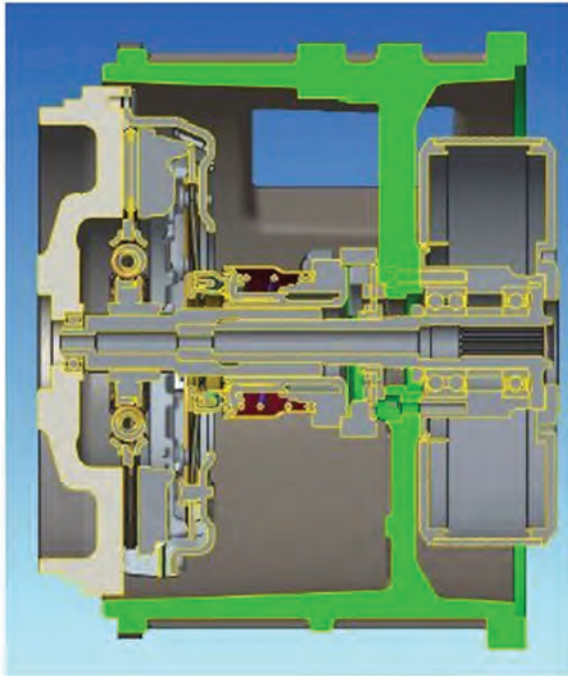
A viable alternative to the implementation of such a complex after-treatment system is to couple the ICE with an electric motor. Thanks to the electric assistance, the engine can operate at lower load, then at less critical conditions for pollutant emissions. Moreover, with a suitable battery pack, the vehicle can work for a short time in full electric mode (zero emissions) within buildings, in-door plants or in other highly populated areas.

The paper presents the development of a hybrid powertrain for non-road vehicles, made up of a specifically optimized Direct Injected Compression Ignition ICE, an AC electric motor with permanent magnet, an inverter, and a battery pack featuring the  $\text{LiFePO}_4$  technology. The multiple combinations and interactions among the components yield a wide range of opportunities for the use of this new hybrid machine, enabling not only a reduction of pollutant emissions at an affordable cost, but also a more efficient use of the energy.

The specific development of a hybrid system, that has a great complexity, requires the need of design tools that allow interaction between different kind components (mechanical, electronic, thermal, chemical, hydraulic) and permits to evaluate the overall performances of a vehicle according to the components specifications of such an heterogeneous nature.

The Model-Based Design technique, including the experimental test campaign on battery cells at different discharge rates and temperature sensitivity is the most used in this kind of environments. The behaviour of every component can be described mathematically, extrapolating a set of characteristic equations that distinguish it from others, and to be explained in elementary blocks thanks to specific

graphic and mathematical software modelling. The blocks that belong to every sub-systems can be connected to each other allowing an interaction between domains of different nature, in order to compose and simulate the whole generic system, that in this case is a whole hybrid vehicle.



*Keywords: hybrid powertrain, model-based simulation, non-road mobile machinery*

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### AUTOMOTIVE PARTICULATE NUMBER MEASUREMENTS: CALIBRATION, COMPARABILITY AND METROLOGICAL TRACEABILITY

Particulate number emissions from road vehicles are in the focus of the current EU legislation, because many European metropolitan areas struggle to fulfil air quality standards for particulate matter (PM). With the introduction of EURO 6d-temp in 2017, measurements of real driving emissions (RDE) with portable emission measurement systems (PEMS) were added to the type approval of passenger vehicles.

The legislation requires reliable and reproducible devices as well as comparability against stationary equipment for Particulate Number (PN). The PN counting setup compliant with Particle Measurement Programme (PMP) of the UNECE is based on a condensation particle counter (CPC). An accurate calibration procedure and traceability chain to metrological standards is important to be developed and implemented in order to reduce the measurement uncertainty and ensure compliance with emission regulation.

One task of the PMP is to improve instrument handling and calibration procedures for automotive particulate number emissions. In the framework of the PMP working group an inter-laboratory comparison exercise for CPCs was set up to identify possible "reference" aerosols to develop a standardized calibration procedure which could be used for stationary and mobile CPCs. The comparison was coordinated by the Joint Research Centre of the European Commission (JRC-Ispra), PTB, the German National Metrological Institute, and BMW.

This presentation introduces the current state of the standardization within the PMP working group for the calibration of PN devices for type approval, focussing on PMP-compliant devices with condensation particle counters. This is related to the results obtained from the inter-laboratory exercise, where e.g. the influence of the aerosol material on the measurement uncertainty of the calibration was analysed.

These results will be complemented by an overview of the current PN efforts and capabilities of NMIs, for example the first international metrological key comparison for particle number measurements. These demonstrate the degree of comparability of PN measurements and establish an uncertainty budget for metrological PN calibration pro-

cedures, which are essential in order to deliver metrological PN calibration services to industry or science.

*Keywords: particle number (PN), metrology, traceability, calibration*

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CE-2018-329

**FULL VEHICLE CHASSIS DYNAMOMETER  
TO POWERTRAIN TEST BED CORRELATION  
OF A MODERN GASOLINE AND A DIESEL  
POWERTRAIN CONFIGURATION**

The increasing complexity of powertrain systems coupled with the increasingly aggressive product development times of the modern automotive industry, generates a necessity for utilising test fields normally deployed earlier in the process. In this particular case, we examine a shift from chassis dynamometers (CD) to powertrain test beds (Vehicle in Loop and/or Powertrain in Loop). In addition, the current and future stringent emissions legislation warrants increased focus on ensuring quality, repeatability and robustness of data for validation test plans. This requires the same vehicle to be tested repeatedly under controlled boundary conditions, driving behaviours and road load conditions between the two test fields. The presentation examines various vehicle preparation, setup & commissioning tasks performed on a PTTB (Powertrain Test Bed), and shows a comparison of mass emission test results between a PTTB and a chassis dynamometer test field.

*Keywords: test methods, exhaust emissions, powertrain test bed, hardware-in-the-loop*

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CE-2018-330

**EMISSION MEASUREMENT SYSTEM:  
A FLEXIBLE SYSTEM FOR REAL-WORLD  
DRIVING EMISSION TESTS**

TNO has a track record of more than 30 years in light and heavy duty vehicles emission measurements and is responsible for deriving the emission factors for road transport in the Netherlands. During the last decade the gap between real-world driving emissions and test-bench tests became increasingly clear. To overcome this gap, all modern passenger cars and trucks in Europe have to undergo an on-road driving emission test with portable emissions measurement systems (PEMS). The currently used PEMS however, have some constraints, due to the large volume and operation effort. PEMS are meant for monitoring the emissions of a vehicle for a limited time. To cover real-world driving conditions, a longer, more diverse measurement is desirable.

To derive robust and reliable emission factors, TNO started in 2012 with the development of a simple and easy-to-use emission monitoring solution, applicable to both heavy and light duty vehicles: the Smart Emission Measurement System (SEMS). The developed methodology of deriving driving emissions has been constantly improved and validated against PEMS results in numerous measurement campaigns for on-road vehicles and non-road mobile machinery.

The present work outlines the development status of SEMS and TNOs track record towards true, real-world emission monitoring of transport.

*Keywords: real world emissions, SEMS, PEMS*

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CE-2018-331

**OBSERVATIONS FROM PEMS TESTING  
OF COMBUSTION ENGINES OF DIFFERENT  
APPLICATIONS**

The presentation discusses the ability to assess vehicle exhaust emissions under RDE procedures, such as test validity, verifiability and reproducibility of the results obtained in the same RDE test. An exhaust emission related comparison of three types of powertrain have been presented: gasoline, diesel and hybrid in the RDE tests. The author proposed a new form of presenting the results of road exhaust emissions in relation to the emission of carbon dioxide, referred to as standardization of emission results. The author also compared exhaust emissions from city buses fitted with different powertrains on actual bus route and in the SORT test. The environmental impact of aircraft emissions has been presented.

*Keywords: combustion engine, real world emissions, exhaust emissions, PEMS*

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CE-2018-332

**REAL WORLD DRIVING EMISSIONS  
IN CONGESTED TRAFFIC**

Driving modes in various European city real world drive cycles are compared and compared with the Leeds A660 Headingley route that passes a roadside air quality monitor that is non-compliant on NO<sub>x</sub> air quality is shown that this route is similar to other European cities in terms of number of stop/starts per km as a function of the mean velocity. It is also shown that the proportion of idle is similar to other cities with congested traffic and is much

larger than on test cycles. The large differences in congested traffic movement in large cities and that in the NEDC, WLTC and RDE routes that follow the boundaries of the RDE legislation is discussion. The large impact of congestion on emissions for SI and Diesel vehicles are demonstrated. It is also demonstrated that for uncongested journeys and for the cruise period of congested traffic journeys, the emissions meet the NEDC regulations. The lack of congested traffic driving in RDE compliant journeys means the cause of poor air quality in cities is not being addressed in this legislation.

*Keywords: combustion engine, real world emissions, exhaust emissions, PEMS*

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**CE-2018-333**

#### **FAST MEASUREMENT OF TRANSIENT GASEOUS POLLUTANTS FOR REAL-WORLD DRIVING EMISSIONS**

On-board versions of fast response gas analysers with millisecond response times enable the recording of high temporal resolution transient HC, CO, CO<sub>2</sub> and NO<sub>x</sub> emissions during cold start and pull-away, gear changes, speed bumps and other real world transient driving conditions. The emissions data has been correlated with on-board engine data available from the vehicle's electronic control unit to study the underlying causes of these short-duration events. Exhaust gas was sampled from before and after the catalyst to monitor catalyst efficiency and tailpipe breakthrough under certain conditions. High frequency detail allows accurate integration of pollutant concentration and measured engine exhaust mass flow. Various aspects of the vehicle's calibration are seen to contribute to the problematic short-duration bursts of tailpipe emissions which would not be visible with slower response analysers. Tests were initially performed on a 1.6 litre turbo GDI vehicle before comparison with a diesel vehicle and a plug-in hybrid vehicle. As well as correlating fast response emissions data with engine parameters, it is also possible to plot alongside high accuracy GPS data in order to discern emissions hot spots. This data is potentially important to bodies responsible for air quality control to drive future transport planning. It has been seen that many of the hotspots highlighted by a single vehicle emissions test match areas of repeated exceedance of local air quality limits.

*Keywords: real driving emissions, hybrid, air quality, NO<sub>x</sub>, transient*

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**CE-2018-334**

#### **ELECTRIC VEHICLES: CHALLENGES AND OPPORTUNITIES**

Concern over urban air quality, greenhouse gas emissions and energy efficiency considerations has greatly increased interest in electric vehicles in recent years. Electric vehicle can indeed offer notable advantages in some areas, but currently suffer from severe limitations in other areas, not least the lack of wide-scale refuelling infrastructure. The overall full life-cycle impact on electric vehicle on air quality, GHG emissions and energy consumption should be properly researched and fully considered in technical and political decision relating to such vehicles and their status on the market and on the world's roads. This presentation provides an overview of both challenges and opportunities relating to this topic.

*Keywords: electric vehicles, powertrain, zero emissions vehicle, charging infrastructure*

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**CE-2018-335**

#### **ELECTRIC VEHICLES – SOLUTION FOR LOWER EMISSIONS AND BETTER DRIVING ECONOMY**

Global trends to reduce driving emissions move car makers and car users into electrification. Hybrids, plug-in hybrids and electric vehicles are considered as the way to clean future transportation. Unfortunately at the moment these solutions are not as green as presented.

The real impact of electric vehicles on environment is very much dependant on power system portfolio. Countries like Norway use hydro-power and wind-power to produce electricity without emissions. On the other hand power systems build on coal-fired power plants produce significant environmental pollution.

The solution for the problem lies in alternate fuels. Such fuels can be used without harmful impact on environment and can enable power generation following increased demand for electric vehicle charging.

Presentation will compare emissions and driving cost of conventional cars and electrified ones. Additionally will present ideas for cleaner and more cost effective power generation.

*Keywords: electric vehicles, alternate fuels, emissions reduction, driving economy*

# The 6<sup>th</sup> International Exhaust Emissions Symposium (IEES) 14-15 June 2018, BOSMAL, Bielsko-Biala (Poland)

*Trends in automotive emissions legislation: impact on LD engine development, fuels, lubricants, and test methods – a global view, with a focus on WLTP and RDE regulations*



## Poster abstracts

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CE-2018-336

### TESTING AND EVALUATING REAL DRIVING EMISSIONS WITH PEMS

Testing of real driving emissions (RDE) with portable emission measuring systems (PEMS) in an appropriate road circuit became an obligatory element of new type approval of passenger cars since September 2017.

In several 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. Particle number measuring systems (PN PEMS) were also included in the tests.

The present paper informs about influences of E85 on RDE on two flex-fuel-vehicles, discusses some aspects of different ways of evaluation with different programs, shows comparison of different types of PN PEMS and represents the effects of simulation of slope on the chassis dynamometer.

The most important statements are:

- The use of E85 fuel is advantageous for emission reduction: with E85 there is a reduction of NO<sub>x</sub> and PN for both investigated vehicles in all driving conditions.
- The normality and weighing of the windows have an influence on the final emission results and the characteristic curve of the trip (CO<sub>2</sub> vs. speed) is recommended to be inside of the primary tolerance band of ±25% with WF = 1.
- Including the cold start in the evaluation, generally increases the emission results, but in case of non-valid trip and weighing of the windows (MAW) this effect can be weakened or even inversed.
- There are good correlations of results with PN PEMS working with different measuring principles (DC vs. CPC)
- Varying slope has clear influences on emissions and it should be considered, when reproducing the RDE-circuit on chassis dynamometer.

*Keywords: real driving emissions, PEMS*

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CE-2018-337

### THE MEANING OF BIO- AND CHEMOMARKERS IN EMISSION INVENTORIES

To understand the emission of particulate matter (PM) the receptor models are frequently applied. Receptor modelling is based on the relation of a chemical PM component with a specific emission source. The aim of future works of authors is to recognize the markers of the atmosphere pollution by particulate matter on the basis of detailed analytics of chemical properties of PM emitted from specific sources, i.e. stationary combustion processes emissions, vehicular and non-vehicular emissions and industrial emissions.

On the basis of so far acquired knowledge the PM is caused by both chemical and biological processes. It can be generated in natural and anthropogenic sources. For this reason the markers used in PM source apportionment techniques are frequently divided into bio- and chemomarkers. According to the literature biomarkers are the chemical substances that are resistant to biodegradation. However, in the literature there is a lack of detailed definitions of these terms and little is known about chemical markers of air pollution.

This work stands for the synthesis of the literature review on identification of bio- and chemomarkers of PM generated in combustion processes. The paper presents the qualification on determined in future analysis chemicals to both groups of markers.

*Keywords: particulate matter, emission, source apportionment, biomarkers, chemomarkers*

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CE-2018-338

### NEW CHALLENGES IN RESEARCH ON ENGINE-GENERATED SOLID PARTICLES

The levels of pollution in the ambient air are a significant subject of environmental studies. Moreover, social awareness of emission intensity and air quality is still increasing. From the physical and chemical (or even mechanical) point of view, the combustion processes of organic fuels occurring both in furnaces and combustion chambers of vehicular engines never run with emission of a mixture of carbon dioxide and water vapour as the result. Exhaust gas consists of hundreds (or even thousands) of groups of chemicals and limits for some of them tried to be regulated by the global polices. The remaining part of exhaust gas components is not limited. Moreover, among raw exhaust components gaseous chemicals and solid particles may be distinguished. The components of solid particles – depending on the conditions of the combustion processes – may occur both in gaseous and PM-bound forms. These aspects cause studies on exhaust emission to constitute a great challenge for chemists and engine designers. The actions resulting in decreased harmful exhaust emissions from combustion engines have been undertaken several years ago and relied on the application of three ways catalysts (TWCs) and diesel oxidation catalysts (DOCs). Selective catalytic reactors (SCR) or lean NO<sub>x</sub> trap systems are quite new solutions fitted to Diesel engines. Further concern was focused on solid particles which resulted in the implementation of new emission standards (Euro 6) where limits for the emission of particulate matter mass (PM) and particulate matter number (PN) were set as 4.5 mg·km<sup>-1</sup> and 6·10<sup>11</sup> #·km<sup>-1</sup>, respectively. The highest concentrations of PM were reported for diesel engines. Therefore, diesel particulate filters (DPFs or FAP) are currently installed to all new diesel-fuelled vehicles.

Nanoparticles are the subject of great attention of scientists and engine designers, mainly due to their strong impact on human health. They are able to diffuse through the skin and be transported by the blood reaching the most vital systems and organs. A key element of research on nanoparticles is the development of measurement systems. Research may be carried out in both theoretical and practical ways: theoretically by interrogating available databases; practically by street or tunnel measurements in a laboratory, or under real driving conditions via the application of portable emission measuring systems (PEMS). The challenges are the sizes of nanoparticles, their concentrations in a diluted exhaust stream during standard emission tests on a chassis dynamometer and the limits of detection of the equipment employed.

*Keywords: solid particles, particulate matter, nanoparticles, vehicle engine*

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## SYNCHROTRON X-RAY DIAGNOSTICS OF AUTOMOTIVE FUEL INJECTORS

One of the strategic goals of the Energy Efficiency and Renewable Energy Office (EERE) within the United States Department of Energy is the development of advanced combustion strategies as part of an initiative towards a global clean energy economy. To gain insight into how the fuel injection process can affect sustainable transportation technologies, EERE established a longstanding collaboration between Argonne's Energy Systems (ES) Division and the Advanced Photon Source (APS), a third-generation synchrotron facility that produces hard X-rays for experimental use. As part of this effort, EERE funded the outfitting of the 7-BM beamline specifically for carrying out research on fuel spray systems. Since its commissioning in 2011, 7-BM has evolved its earliest diagnostics and developed new techniques for studying fuel injection, with fuel spray research extending to neighboring beamlines that provide specialized capabilities.

Complementary to optical diagnostic techniques, utilizing X-rays to probe a dense sample such as a jet of fuel is advantageous because X-rays interact relatively weakly with matter, and therefore do not scatter in optically thick regions of the spray in the same manner that visible light does. In addition, the small probe size and high flux provided by the APS enable measurements at the length and time scales relevant to fuel injection systems. This poster summarizes the suite of X-ray diagnostic techniques available at the APS that can be used to investigate the internal and near-nozzle region of both gasoline and diesel injectors. The X-ray radiography technique measures time-resolved projected density fields as close as 0.1 mm from the injector tip. X-ray tomography produces high-resolution three-dimensional geometry of the injector, extending up to the sac region. The X-ray phase contrast imaging technique provides measurements of the internal motion such as that of the injector needle, as well as the extent of potential cavitation. In addition, ultra-small-angle X-ray scattering provides droplet size distributions to help better understand the degree and rate of atomization. All of these data may be used for computational model development and validation. With the help of high-performance computational resources available at Argonne, reliable simulations help paint a more complete picture of how the combustion process responds to varying conditions and design parameters, ultimately guiding researchers closer to finding the optimal combination.

*Keywords: fuel spray, synchrotron X-ray, diagnostic techniques, injector, internal combustion engine*

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CE-2018-340

**KEY PARAMETERS OF LI-ION CELLS AND BATTERIES ENSURING THE PROPER OPERATION OF ENERGY STORAGE FOR ELECTRIC VEHICLE PROPULSION**

Constant electric vehicles sales growth forces unceasing development of cell technology required for constructing traction batteries, which are one of the most important components of a vehicle powered by electrical energy. Li-Ion cells still have to be improved in areas of their key parameters, such as – energy density, high discharge and charge current in various low and high ambient temperatures, durability and capacity loss especially at low temperatures to ensure EVs' chances to be competitive with traditional vehicles with petrol engines, even in the city car category. For this reason, a series of tests has been specified in order to verify possible usage of different lithium-ion cells for electric vehicle propulsion. These tests were to reflect extreme conditions for road vehicles, which the energy storage has to withstand without a significant loss of its key parameters. Such a test program for estimation of the value of maximum discharge current for various types of cells at low and high temperature was developed by BOSMAL.

*Keywords: electric vehicles, energy storage, Li-ion cell, battery*

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**CE-2018-341**

**GASEOUS EMISSIONS FROM A HYBRID VEHICLE AND A NON-HYBRID VEHICLE MEASURED UNDER REAL URBAN DRIVING CONDITIONS**

Concern over vehicles' impact on urban air quality has never been higher. Urban driving conditions are suboptimal for conventional vehicles' exhaust emissions and fuel/energy consumption, for multiple reasons. This poster reports on a study which aimed to identify differences in gaseous exhaust emissions between a hybrid and a non-hybrid vehicle under real driving conditions using PEMS equipment. Tests conducted under specific and realistic urban driving conditions occurring in a Polish city. Significant differences in emissions profiles were identified and general conclusions on the causes were drawn.

*Keywords: real driving emissions, hybrid vehicle, urban driving, PEMS*

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**CE-2018-342**

**METHODOLOGY OF ELECTRIC MOTORS TESTING ON THE DYNAMIC ENGINE TEST BENCH**

This poster presents a basic methodology and equipment setup used for electric motor testing on a dynamic engine test bench. It has been shown based on an example of mechanical performance measurement, as well as an overall layout of the measurement devices used for testing.

Electric motor testing for automotive applications is a new and quite complex issue. It is noteworthy that working out a dependable and credible test methodology of the electric motor testing reveals a great significance from the research and development point of view especially taking into consideration the fact that the electric motors will make up a substantial and still increasing share in the automotive industry in the future.

*Keywords: electric motor, test method, engine test bench, UN ECE Regulation No. 85*

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**CE-2018-343**

**RD100 EASY SYSTEM**

OP SIS has long experience from environmental and gas emissions measurements, using the optical DOAS technology, (Differential Optical Absorption Spectroscopy). OP SIS has now started to use this technology for measuring real drive emissions from cars.

We have found a way to use this method for vehicles, which makes RDE tests easy and safe, to operate. The concentration of pollutants and volume flow are measured directly in an extension of the exhaust pipe. No exhaust gases need to be led into the car for analysis. The system takes only about ten minutes to install, and has a GPS to ensure that the ride meets the requirements for driving time, speed and distance. The system is also energy-efficient. A separate 12 volt car battery can operate the system for several hours.

*Keywords: real driving emissions, simple handling, safe system, high accuracy*



# VIII INTERNATIONAL CONGRESS ON COMBUSTION ENGINES

POLISH SCIENTIFIC SOCIETY  
OF COMBUSTION ENGINES

**17<sup>th</sup>-18<sup>th</sup> June 2019**

## Invitation and call for papers ANNOUNCEMENT 2

**PATRONAGE:**



### DEADLINES

- |                   |   |                                     |
|-------------------|---|-------------------------------------|
| January 31, 2019  | – | Abstract submission                 |
| February 15, 2019 | – | Notification of abstract acceptance |
| March 31, 2019    | – | Papers submission                   |
| April 30, 2019    | – | Notification of paper acceptance    |
| June 17-18, 2019  | – | CONGRESS PTNSS 2019                 |

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## TOPICS

The Congress will constitute an opportunity to discuss the latest achievements in such fields as design, manufacture, research and the ecological impact of internal combustion engines and fuels. The main topics of the Congress:

- Fuel injection systems and mixture formation
- Combustion processes control in SI and CI engines
- Engine thermal loading and utilization of heat released
- Alternative fuels
- Emission measurements and after treatment
- Alternative sources of power
- Engine testing, durability, reliability and diagnostics
- Modelling and optimization of engine processes
- Global trends in engine technology.

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Participants – the PTNSS member <sup>*)</sup>	950 PLN/220 €
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VIII International Congress on Combustion Engines will be held at the Cracow University of Technology, which is located in a Campus at Warszawska Street in Cracow.

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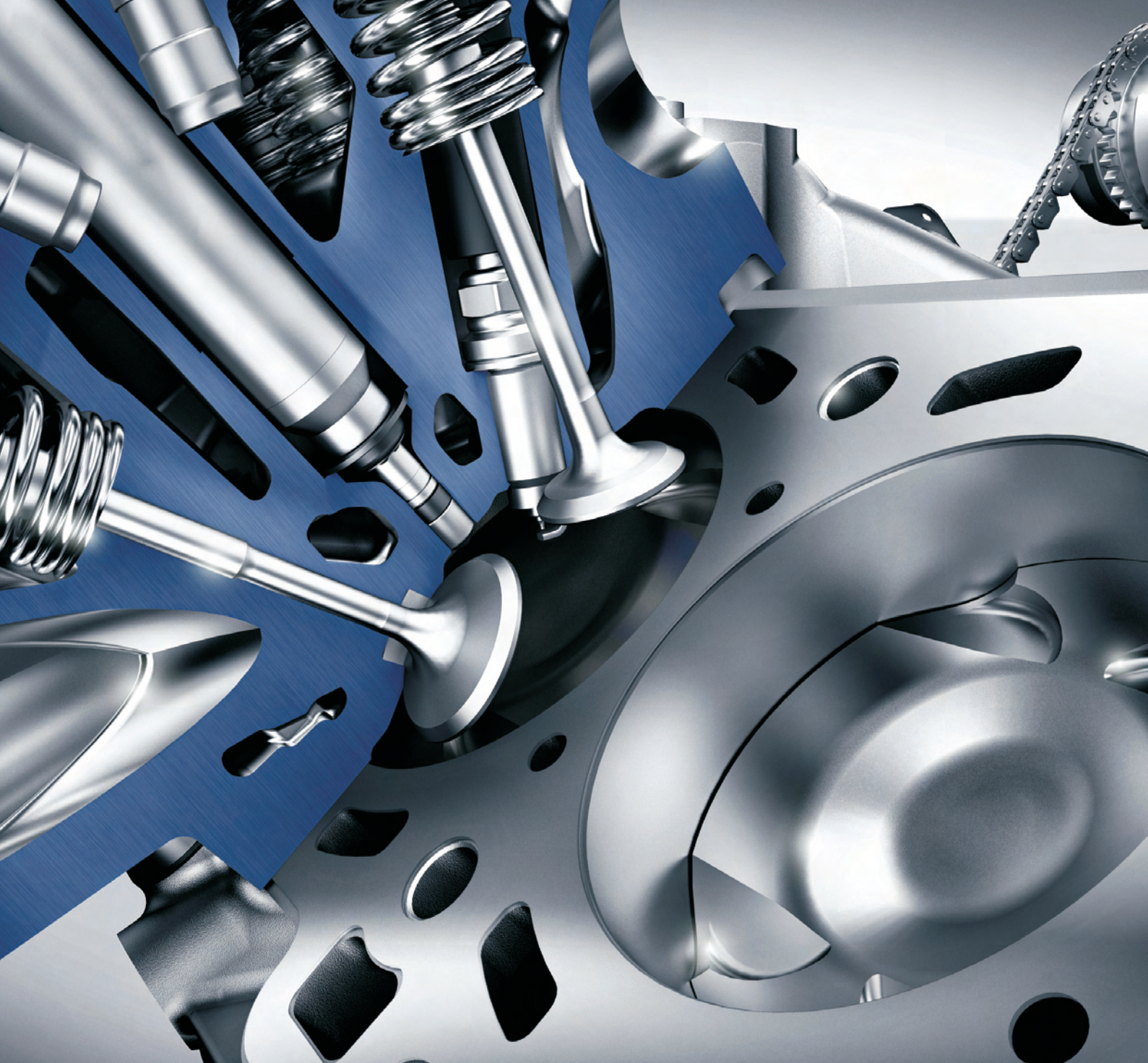
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Automotive Research & Development Institute Ltd  
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