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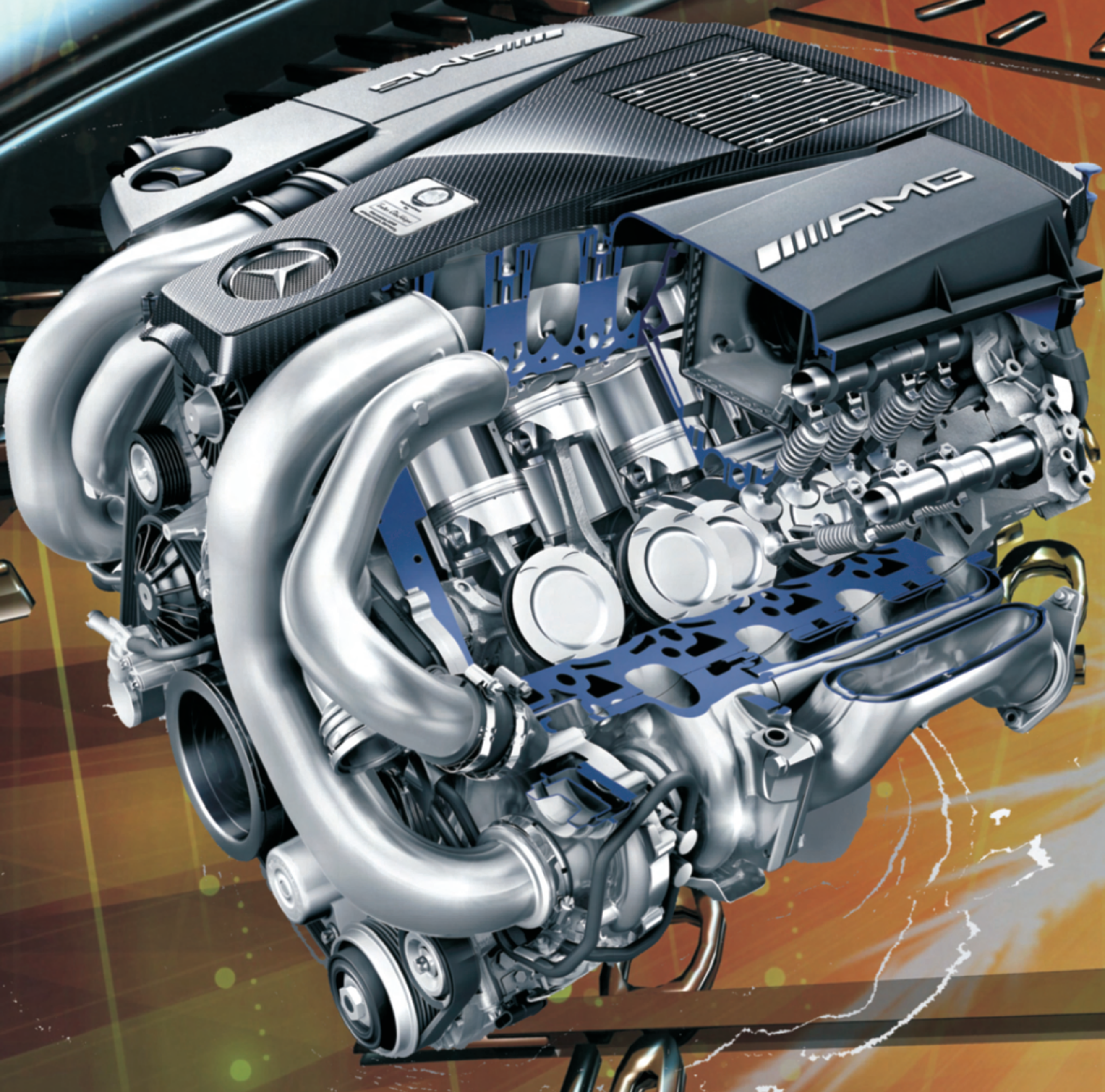

COMBUSTION ENGINES

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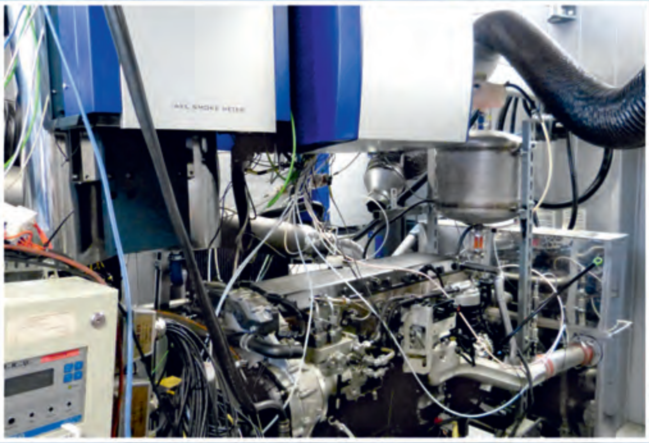
LD and HD engines development and reliability

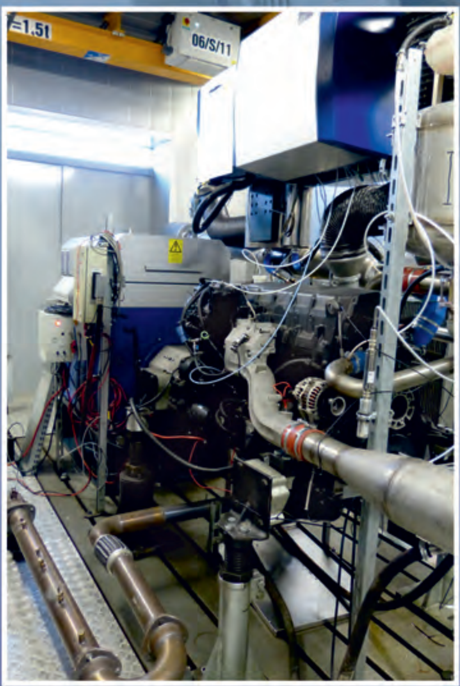


Engine validation

- durability tests
- thermal tests
- NVH & special tests
- emissions tests on chassis dyno and on the road (RDE-PEMS)
- quality & cost reduction tests
- oil & fuel tests
- aftertreatment tests

Base engine calibration

- initial calibration verification
- actuator calibration
- injection and air path strategy calibration
- engine protection calibration
- full load calibration
- emission optimization



Base hardware development

- component matching
- calibration refinement for new components functionality
- functional tests

Aftertreatment development tests

- NSC+DPF Euro 6 development
- SCR and SDPF Euro 6 development
- TWC+GPF Euro 6 development
- particle number and size distribution testing
- ammonia dosing for SCR applications
- catalytic converter ageing tests

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Cover/*Okładka*
I – Mercedes-AMG GLE 63: 5.5-litre V8-biturbo engine
(*fot. media.daimler.com*), background (© Kovalenko – *Fotolia.com*)
IV – The integrated starter-alternator (ISG)
(*fot. media.daimler.com*)

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Ameya JOSHI

CE-2016-306

Directions in vehicle efficiency and emissions

This paper provides a general review of light-duty (LD) and heavy-duty (HD) regulations, engine technology, and key emission control strategies. The US is placing a stronger emphasis on laboratory emissions, and the LD regulations are about an order of magnitude tighter than Euro 6, but Europe is focusing on real-world reductions. The California HD low-NO_x regulation is advancing and may be proposed in 2017/18 for implementation in 2023+. The second phase of US HD greenhouse gas regulations propose another 25-30% tightening beyond Phase 1, beginning in 2021. LD and HD engine technology continues showing marked improvements in engine efficiency. LD gasoline concepts are closing the gap with diesel. HD engines are demonstrating more than 50% BTE using methods that can reasonably be commercialized. LD and HD diesel NO_x technology trends are also summarized. NO_x storage catalysts and SCR combinations are the lead approach to meeting the LD regulations. Numerous advanced NO_x technologies are being evaluated and some promise for meeting the California HD low NO_x targets. Oxidation catalysts are improved for both diesel and methane oxidation applications. Gasoline particulate filters (GPF) are the lead approach to reducing particles from gasoline direct injection (GDI) engines. They reduce PAH emissions, and catalyzed versions can be designed for low back pressure. Regeneration largely occurs during hot decelerations.

Key words: *greenhouse gases, vehicle emissions, regulations, engines, aftertreatment, NO_x, diesel oxidation catalyst, selective catalytic reduction, diesel particulate filter, gasoline particulate filter*

1. Introduction

The challenges are significant in reducing vehicular criteria pollutants and greenhouse gases to meet tightening regulations around the world. Multitudes of papers and presentations are given annually to advance the understanding and technologies.

This paper focuses on recent key developments related to emissions for both diesel and gasoline engines in the automotive and heavy-duty markets. It begins with an overview of the major regulatory developments covering criteria pollutants and CO_2. Then, a high-level review is provided of engine technologies, starting with light-duty gasoline and diesel engines, and then heavy-duty diesel engines. In this section, only broad developments are covered with the intent of summarizing the directions and emissions challenges for exhaust technologies. Next, the paper covers lean NO_x control, oxidation catalysts, diesel and gasoline PM filters, and closes with representative papers on gasoline emission control.

This review is not intended to be all-encompassing and comprehensive. Representative papers and presentations were chosen that provide examples of new, key developments and direction.

2. Regulations

Figure 1 shows the relative light-duty (LD) gasoline vehicle tailpipe non-methane hydrocarbon (NMHC) and NO_x regulations for representative regions around the world. The emerging US Tier 3 regulations, which started phase-in in California (regulation LEV3) in 2015, are the tightest in the world, and are 85% to 90% (for diesel) tighter than the current Euro 6 regulations. The US also has much tighter durability requirements of 240,000 km versus 160,000 km for Europe. For the first time, China is proposing deviating from the European regulations with their China 6b regulations, which are 1/3 of the Euro 6 standards, proposed for 2023. Given the relative size and dominance of these two markets, it seems likely the rest of the world will eventually follow. Additionally, further tightening in the US is possible with California recently laying out a regulation roadmap for 2025+ suggesting converting the fleet average NMHC + NO_x emissions of the 18 mg/km shown in the figure to a cap.

Europe also sees a need to reduce vehicular emissions, but is emphasizing tighter enforcement of current regulations by incorporating a real-driving emissions (RDE) regulation for NO_x from light-duty diesel (LDD) and particles from gasoline direct injection (GDI) vehicles. Implementation is scheduled to begin in September 2017 with emissions being measured on roads using portable emissions monitoring systems (PEMS). By 2021, the RDE effective emissions are expected to be similar to the dynamometer certification limit values, versus values that averaged ~6x measured on 38 Euro 6 cars tested using the RDE protocol (1).

For heavy-duty (HD) vehicles, the Euro VI regulations allow 10 mg/kWh PM (particle mass) and 460 mg/kWh NO_x on the world-harmonized heavy-duty transient cycle. The US regulations are 30% looser on PM but about 40% tighter on NO_x using the US transient cycle. Europe also added a particle number standard of 6 x 10^{11} particles/kWh on the transient cycle, essentially forcing the use of diesel particulate filters (DPF). Although not required to meet the PM regulation in the US, all heavy-duty trucks use DPFs to meet all aspects of the regulation. California is investigating further tightening the HD regulations by as much as an order of magnitude in the 2023-2027 timeframe, and the US EPA (Environmental Protection Agency) is considering following.

Shifting to greenhouse gases, Figure 2 shows a comparison of LD CO_2 regulations around the world [2]. In this case

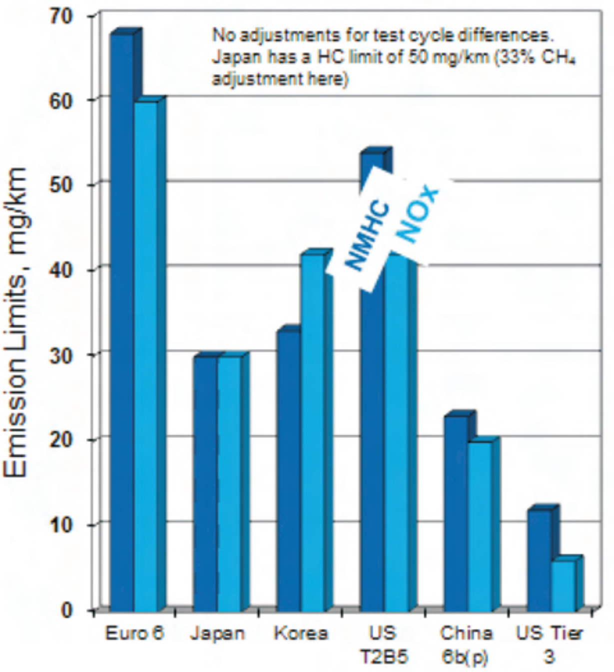

Figure 1. Relative comparison of key gasoline LD vehicle non-methane hydrocarbon (NMHC) and NO_x emissions regulations for key world markets

Europe takes the lead, wherein the US generally harmonizes with a five-year delay. However, again in real-world driving the emissions improvements are different. European real-world CO_2 emissions as indicated using fuel consumption records on 600,000 vehicles were compared to certification values measured on the NEDC (New European Drive Cycle) [3]. The study found that model 2001 cars were emitting about 8% more CO_2 than indicated on the test cycle. But in 2014 this gap increased to 40%, with virtually no real-world CO_2 emissions improvements for models 2010 to 2014. The researchers attribute 75% of the 2014 gap to testing the vehicles on the dynamometer using the favorable end of allowable tolerances and procedures during certification testing. In the US, one estimate [4] is that automakers will need to triple their annual rate of improvement in vehicle efficiency (traction energy/fuel energy; ~22% in 2015) from 0.3% per year to 0.9% per year to meet the 2025 regulations.

On the HD side, the final stage of the US Phase 1 HD greenhouse regulation starts in 2017. The EPA (Environmental Protection Agency) finalized a Phase 2 rule that will build upon this and be phased in from 2021 through 2027 [5]. The main features of the rule are:

- Maintain separate engine and vehicle standards, but re-weigh test cycles to better-reflect real-world operation. Engines should improve fuel consumption by ~4-6% from 2017 to 2027.
- Regulate trailers using a computer model of technology options such as aerodynamics, rolling resistance, and weight reduction.
- Include transmissions using modeling or integrated powertrain testing.
- Improved vehicle simulation model to regulate vehicle technologies.
- 18 vocational vehicle categories.
- Chassis dyno confirmation of reductions for some classifications.
- Regulate natural gas emissions from the crankcase and LNG (liquid natural gas) tanks.

Total CO_2 reductions from the large line-haul freight trucks and trailers is on the order of 25% from the 2017 Phase 1 baseline.

3. Engine developments

Figure 3 shows estimates of CO_2 reductions, emissions issues, and the status of representative LD engine technologies, relative to the basic turbo-charged direct-injection gasoline engine. Given the expense and market resistance to EV technologies (only < 5% hybrid market penetration 18 years after the first introduction), it seems reasonable that engine technology will be developed to the maximum practical potential and be combined with hybridization.

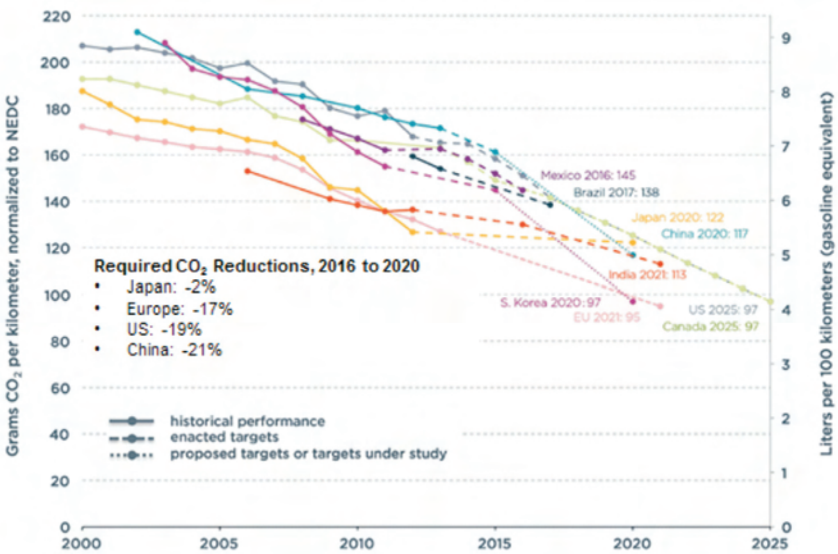

Fig. 2. Comparison of LD CO_2 regulations around the world [2]

Figure 4 summarizes improvements and normalized cost of powertrain technologies to bring a Euro 5 platform to the EU and US CO_2 standards of 2020-22 [6]. Gasoline engines are closing the CO_2 gap with diesel. However, the incremental cost of the diesel improvements is considerably less than that of gasoline once a diesel powertrain investment is made. Also, hybridization is generally more expensive than engine improvements.

The impact of advanced engine concepts will affect exhaust gas temperatures, highlighting the challenge of increasing engine efficiency while reducing criteria pollutants. This can especially be problematic for diesel engines. Pischinger [7] nicely summarizes the relationship between time, fuel consumption reductions and exhaust gas temperatures for the 2 liter class engines at a medium load point. Post-turbo temperatures dropped a remarkable 220°C (480°C to 260°C) from 2005 to 2015 while BSFC (brake specific fuel consumption) dropped 5%.

	CO_2 Reduction	Emissions Issues	Status
GDI base, turbo, stoich	0	PN	Implemented
Cylinder de-activation	5-8%	-	Implemented
Homogeneous Lean SI	5-10%	Lean NOx	Development
HEV (additive to others)	7-30%	-	Implemented
Downsize GDI, 18→24 bar BMEP high CR, Miller stoic	10-15%	PN	Implementing
d- and c-EGR	10-15%	Cold start, controls	Implementing
CR~17, S/B~1.5, c-EGR, 2-stage boost,stoich, Miller.	15-20%	-	Adv Eng
Lean-burn GDI	10-20%	Lean NOx, PN	Implementing
Light-duty diesel	15-20%	Lean NOx	Implemented
GDI, Down Size (40%), mHEV, SChrg, turb-comp	20-25%	-	Development
Compression ignition DI gasoline	15-25%	Lean NOx, LT HC	Adv Eng
2-stroke opposed piston diesel	25-35%	Lean NOx	Development

Fig. 3. Estimated CO_2 emissions reductions, criteria pollutant issues, and status for representative LD engine technologies

The most efficient engine to ever reach the development stage is the 2-stroke opposed piston diesel engine. Independent modeling work [8] shows a 13-15% incremental fuel consumption reduction relative to a state-of-the-art 2020 diesel 1.2 liter engine, confirming earlier reports from developers [9].

Moving to HD engines, the US EPA Phase 2 HD GHG proposal [5] lists some potential engine technologies and implementation timing needed to meet the regulation. Figure 5 shows the projected technologies and GHG reductions for the largest truck engines. Technologies that will be implemented at the highest rate by 2024 are reducing friction and other parasitic losses, improved aftertreatment, reduced pumping losses, and improved combustion. The incremental hardware cost relative to 2017 levels associated with these items is estimated by the EPA to be about $400-500 at maturity.

To help move these engine technologies forward, the US Department of Energy SuperTruck Program is now closing [10]. Common features independently developed by each of the four program participants to achieve 50% BTE engines (brake thermal efficiency = energy to crankshaft/energy in fuel) under road loads are:

- Engine efficiency: high efficiency turbochargers, friction reduction, reduced ancillary losses.
- Fuel Injection: high-pressure common rail.
- Combustion: higher compression ratio, optimized piston bowl redesign.
- Waste Heat Recovery: Rankine cycle.
- Selective Catalytic Reduction (SCR) for NO_x: higher efficiency deNOx, low ΔP.

Although Rankine cycle waste heat recovery gives the largest fuel savings, and it was used by all four participants to achieve 50% BTE, the other technologies are enough in combination to achieve the program goals.

Supplemental Emissions Test (SET) Mode	SET Weighted Reduction (%) (2020-2027)	Market Penetration (2021)	Market Penetration (2024)	Market Penetration (2027)
Turbo compound with clutch	1.8%	5%	10%	10%
WHR (Rankine cycle)	3.6%	1%	5%	15%
Parasitic Friction (Cyl kits, pumps, FIE), lubrication	1.4%	45%	95%	100%
Aftertreatment (lower dP)	0.6%	45%	95%	100%
EGR Intake & exhaust manifolds Turbo/VVT Ports	1.1%	45%	95%	100%
Combustion FI Control	1.1%	45%	95%	100%
Downsizing	0.3%	10%	20%	30%
Weighted reduction (%)		1.5%	3.7%	4.2%

Fig. 5. Projected large truck engine fuel consumption reductions (relative to 2017 engines) [5]

4. NO_x control

Light-duty diesel NO_x control is being driven by the Euro 6 regulation (80 mg/km NO_x on the World-Harmonize Light-Duty Test Cycle, WLTC), but the emerging RDE regulations are requiring even more NO_x control, with conformity factors of 2.1x (multiple of the certification testing; 168 mg/km) in September 2017 and 1.5x (120 mg/km) in September 2020 for new engines. The current US regulations are about 50% tighter on a fleet average basis, but cars can certify higher as long as other cars (e.g., gasoline) certify lower than the average. The emerging US LD NO_x regulations are about an order of magnitude lower than Euro 6.

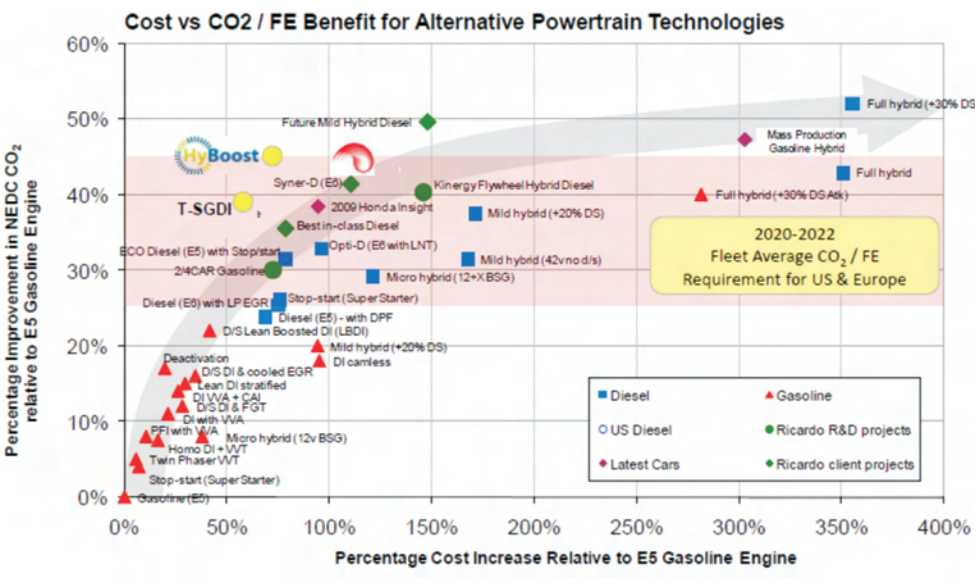

Fig. 4. Estimates of CO_2 reductions and costs relative to a Euro 5 gasoline car [6]

The leading NO_x architecture for both LD markets is the NO_x storage catalyst (NSC) followed by an SCR catalyst either coated on a diesel particulate filter (DPF) or downstream from it, or both [11]. The NSC has good low-temperature performance, and generates NH_3 during the rich desorption portion of the operating cycle, to replace or supplement urea injection to the SCR catalyst. Figure 6 shows some of the architectures [12]. Using only the NH_3 coming from the NSC, a "passively" operated NSC+SCR system (no urea) reduces NO_x nearly 80% on the WLTC, with all the cold start NO_x reductions coming from the NSC, and only 7% of the total reductions coming from the SCR unit. Larger cars or higher-load operation may require urea as an addition NH_3 source. With urea-based NSC+SCR systems, upwards of 90-95% cycle averaged deNOx efficiencies can be achieved. In city driving cycles the NSC removes about 2/3rd of the treated NO_x, with the urea-SCR taking up the remaining third. Even on a highway cycle, the NO_x burden is roughly evenly split between the NSC and SCR. For cold start applications, it is beneficial to locate the SCR catalyst as close to the engine as possible, so SCR catalyst coated onto the DPF is preferred.

Passive NO_x adsorbers (PNA) release the NO_x thermally (T > 180°C) rather than chemically (rich-lean cycling). In one study [13], about 10% of the engine NO_x was removed on the NEDC, all of it in the cold start portion, by the passive NO_x adsorber and converted in the SCR. NO_x emissions are 25% lower than if a DOC (diesel oxidation catalyst) was used instead of the NO_x adsorber. Improvements are coming. When palladium is added to a ZSM-5 zeolite, NO_x can be stored at 50°C and released at 250-400°C [14]. The zeolite also adsorbs hydrocarbons, and it is thought the released HCs help in NO_x reduction.

In the heavy-duty sector, the aftertreatment architecture has been essentially unchanged since about 2010: DOC+ +DPF+SCR+ASC (ammonia slip catalyst). These systems are now achieving > 96% cycle-averaged deNOx efficiencies on the cold and hot start composite transient cycles. However, to meet the future California HD low-NO_x regulations that are being discussed with minimized GHG impacts, > 99% deNOx efficiency will be needed. In an

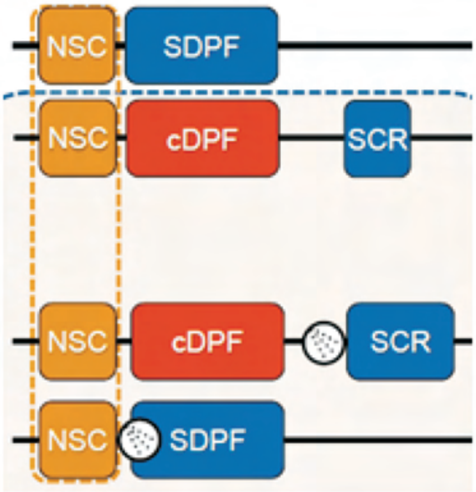

Fig. 6. Some of the LDD aftertreatment system designs for Euro 6c (RDE) [12]

interim report of a technical feasibility study, 20 mg/bhp-hr NO_x was achieved in composite (cold plus hot start) US HD transient testing using a burner rig simulator of engine exhaust conditions [15]. Technologies employed included improved engine calibration, auxiliary heating during the cold start and low-load periods, PNA, SCR+DPF, heated

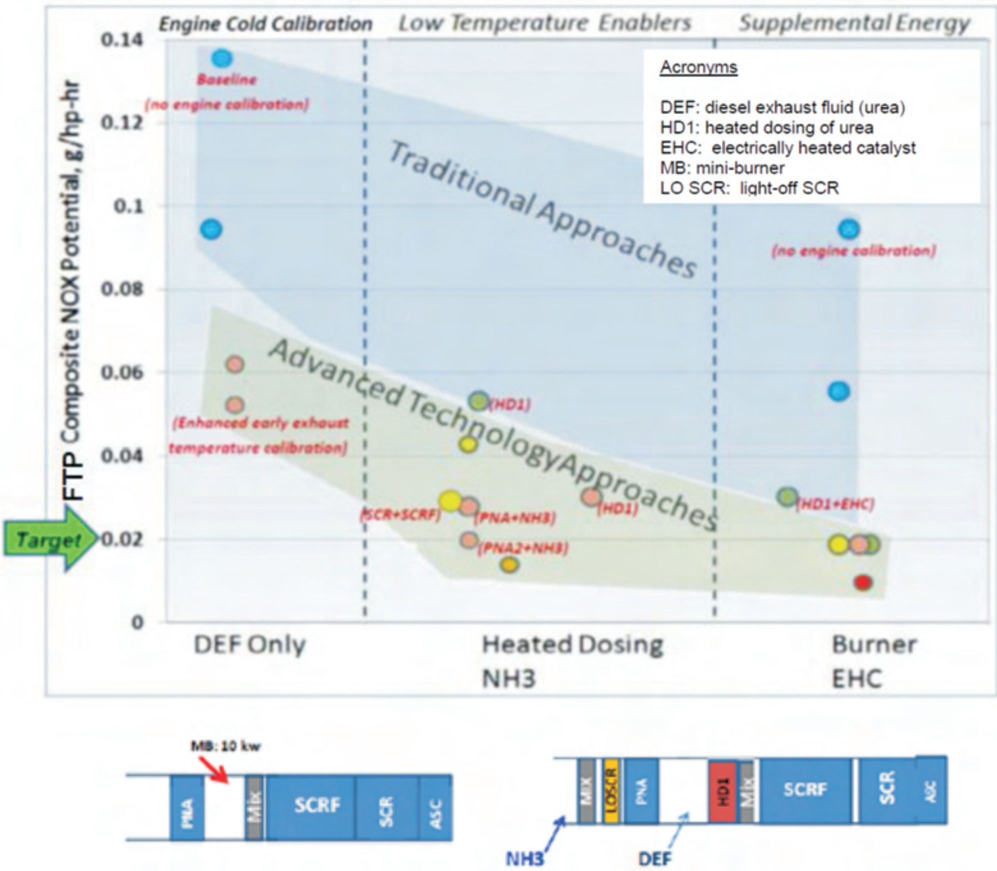

Fig. 7. Preliminary burner rig results and two HD systems delivering the lowest NO_x [15]

urea or gaseous NH_3 injection, more SCR volume, and/or a light-off SCR catalyst. Figure 7 shows some results and the two lowest-configurations with the lowest NO_x.

5. Oxidation catalysts

Diesel oxidation catalysts (DOCs) play the role of pre-conditioning the exhaust for the complex downstream components. As such, DOCs are being designed for specific applications. Fundamentals are still being developed.

DOC formulations balance the palladium and platinum levels for optimum performance. The precious metal ratio, hydrocarbon and CO oxidation characteristics, and NO_2 formation were simultaneously simulated and tested in a light-duty DOC [16]. They looked at the LD application with a constant PGM (platinum group metals) loading of 4.2 g/liter (120 g/ft^3). Increased platinum content improves n-$C_{10}H_{22}$, lean C_3H_6, and CO oxidation (except 100% Pt); but also NO oxidation, and the reduction back to NO by C_3H_6 and CO. Conversely, reactions promoted by increasing or pure palladium are CO and methane oxidation, C_3H_6 steam reforming, and rich C_3H_6 oxidation. A similar study [17] looked at HD applications. The results show a strong dependence of the NO oxidation on the catalyst oxidation state for different Pt-Pd DOCs. A model was developed and a case study demonstrated the capabilities of the model in designing an appropriate DOC for a given application.

Methane oxidation is important for natural gas engines, and can limit the application of these engines in Europe due to regulatory limits of 160 mg/kWh total HC on the transient cycle for compression ignition, and 500 mg/kWh methane for spark ignition engines. Methane is difficult to oxidize and the best commercial catalysts need T > 350°C to convert 50% of the methane. However, it was recently reported [18] that a platinum-palladium catalyst on a titania and ZSM-5 zeolite support that dropped this temperature to < 250°C.

6. Gasoline particulate filters

Converse to the US, the European Union has implemented a particle number (PN) standard for gasoline direct injection engines, 6E12 particles/km, tightening to 6E11 particles/km in 2017. In addition, the European Commission is likely to recommend maintaining these values in RDE testing, after taking into account measurement error. Improved fuel injection and other engine methods can be used to help meet these standards [19], but these methods can fail to meet the regulations as the engine ages, if engine deposits form [20], or if the car is driven in somewhat more aggressive drive cycles or is not warm [11]. Alternatively, gasoline particulate filters (GPFs) provide a robust solution. Further, poly-aromatic hydrocarbons may be strongly associated with the particles, and GFPs greatly reduce these [11]. Hence, GPFs are a leading technology being evaluated to meet the European and proposed Chinese PN regulations.

Earlier GPF work focused on bare filters, but high porosity filter substrates can make adding a three-way catalyst to the filter attractive [21]. Back pressure with a “four-way catalyst” is only 10% more than that of the base TWC system [22]. Engine performance impacts after 160,000 km is minimally affected [21], with only 2.5% loss of peak power and < 1% loss of peak torque, with no deterioration in fuel consumption.

Regarding filter regeneration, a GPF was preloaded with a representative soot surrogate and installed in the underfloor (UF) position on a car [23]. Figure 8 shows actual and simulated results. The soot is mainly burned during the lean decelerations. At 30 km/h there was no soot burn, but nor was there soot accumulation. Also shown in the figure is a simulated case when the filter is in the close-coupled (CC) position. Soot burn is rapid due to the higher temperatures.

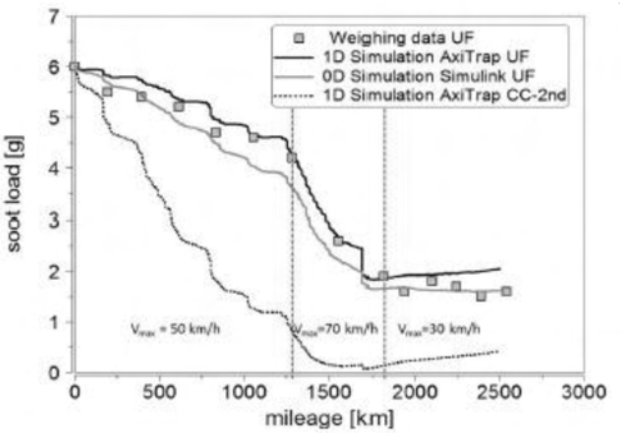

Fig. 8. Measured and simulated burning of soot in under-floor GPFs for three different average speed regimes [23]

7. Conclusions

The LD regulations in representative markets are compared. The emerging US Tier 3 regulations (starting in 2017) are about an order of magnitude tighter than the current Euro 6 regulations. Europe is shifting focus to real-world driving emissions (RDE) for LD diesel NO_x and GDI (gasoline direct injection) PN (particle number) in 2017. China has been following the EU, but is proposing standards for 2023 that are 1/3 of Euro 6. LD GHG (greenhouse gas) regulations are also compared, with Europe implementing the tightest regulations. However, real-world reductions in the EU are significantly less than indicated by the regulation.

Europe and US currently have similar HD regulations, but California will be tightening down on NO_x beginning in about 2023-27. The US EPA Phase 2 HD greenhouse gas standards for 2021-27, calling for a nominal 4-6% tightening on engine CO_2 and 15-25% for the whole truck, depending on class.

Gasoline engines are developing rapidly, slowly closing the gap with diesel, but LDDs are making incremental gains that are very cost effective versus other options automakers have. Exhaust temperatures are decreasing as engine efficiency improves. There are numerous incremental strategies are being used on HD engines to approach or attain 50% BTE.

Leading lean NO_x reductions for heavy- and light-duty diesel engines is generally reviewed. SCR filters are central to the LD for meeting the EU RDE and US Tier 3 regulations. LD systems are using NO_x storage catalysts (NSCs) for cold start and downstream SCR systems on filters and/or in traditional flow-through designs. Advanced prototype HD systems are being evaluated for meeting the California HD low-NO_x objectives. Some achieve < 20 mg/bhp-hr NO_x on a simulated HD FTP transient cycle.

Understanding on diesel oxidation catalysts continues to evolve. LD and HD simulations enable proper design to meet a variety of needs. An experimental catalyst was reported that oxidizes methane at ~250°C, about 100°C lower than the best commercial catalysts.

Gasoline particulate filters (GPFs) are essentially needed to meet the Euro 6c and RDE regulations coming in 2017. Toxic PAH (polycyclic aromatic hydrocarbon) emissions are reported from GDI vehicles and reduced using GPFs. GPF regeneration is characterized. Almost all the required burning of soot occurs during lean decelerations. Soot levels on GPFs reach an equilibrium loading in urban driving.

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Performance of a drop-in biofuel emulsion on a single-cylinder research diesel engine

Current targets in reducing CO_2 and other greenhouse gases as well as fossil fuel depletion have promoted the research for alternatives to petroleum-based fuels. Pyrolysis oil (PO) from biomass and waste oil is seen as a method to reduce life-cycle CO_2, broaden the energy mix and increase the use of renewable fuels. The abundancy and low prices of feedstock have attracted the attention of biomass pyrolysis in order to obtain energy-dense products. Research has been carried out in optimising the pyrolysis process, finding efficient ways to convert the waste to energy. However, the pyrolysis products have a high content in water, high viscosity and high corrosiveness which makes them unsuitable for engine combustion. Upgrading processes such as gasification, trans-esterification or hydro-deoxynegation are then needed. These processes are normally costly and require high energy input. Thus, emulsification in fossil fuels or alcohols is being used as an alternative.

In this research work, the feasibility of using PO-diesel emulsion in a single-cylinder diesel engine has been investigated. In-cylinder pressure, regulated gaseous emissions, particulate matter, fuel consumption and lubricity analysis reported. The tests were carried out of a stable non-corrosive wood pyrolysis product produced by Future Blends Ltd of Milton Park, Oxfordshire, UK. The product is trademarked by FBL, and is a stabilized fraction of raw pyrolysis oil produced in a process for which the patent is pending. The results show an increase in gaseous emissions, fuel consumption and a reduction in soot. The combustion was delayed with the emulsified fuel and a high variability was observed during engine operation.

Key words: *pyrolysis oil, emulsion, wood pyrolysis, engine testing*

1. Introduction

Global energy demand concerns and the increased levels of greenhouse emissions to the atmosphere, particularly CO_2, have drawn attention into research for alternative energy vectors. Biomass has been broadly considered as an option due to its abundancy and availability all over the world, low prices, renewability and zero CO_2 emissions while the use of waste materials such as, cooking oil has been studied as part of the solution for fossil fuels as well as to solve or palliate the uncontrolled disposal of these toxic substances [3].

Several techniques have been investigated to transform these waste materials and biomass into valuable biofuels: i) physio-chemical conversion processes, ii) biochemical conversion process and iii) thermochemical conversion processes [1]. Amongst thermochemical processes are pyrolysis, gasification and liquefaction [1, 4]. The advantages of pyrolysis over other techniques are the insignificant production of toxic components, less energy consumption and the solid waste formed is disposable [3].

Pyrolysis is the thermal decomposition of organic material in absence of oxygen [1–3, 5]. It can be divided in conventional pyrolysis whether an electrical heating resistance is employed for the process or microwave pyrolysis, a more energy efficient approach [3]. The main products of the pyrolysis process are bio-oil, bio-char, methane, hydrogen, carbon dioxide and carbon monoxide [1, 6]. The proportion of these products will depend on the feedstock, the technique/method used (temperature, heating ramp and residence time) [2, 7] and the feedstock pretreatments (thermal, biomass, chemical and physical) [2, 3, 5] and therefore, no agreement is found in the literature in the products concentrations [3]. Depending on the technique, pyrolysis can be divided in slow, fast and flash pyrolysis [1, 2]. The resultant product will again depend on the trade-off between the temperature, heating rates, pressures, residence time leading to different biomass yield products [1–3]. Fast pyrolysis is currently the most widely used due to the high percentage of bio-oil, also known as pyrolysis oil (PO): 60% yield in bio-oil, 20% biochar and 20% syngas [1].

However, the energy content of bio-oil compared to petroleum derived fuels is nearly half [1] or one third of the fossil fuels [8] , between 15–20 MJ/kg [2] due to the high water content, 30–40% [1]. Upgrading processes, such as stem reforming, gasification or transesterification are needed due to the high moisture, high viscosity, solid content, chemical instability and high corrosiveness [9]. Despite these disadvantages, lower toxicity products, good lubricity and greater biodegradation makes pyrolysis oil an attractive solution to petroleum depletion [10].

An alternative process to these upgrading techniques is emulsification of PO in diesel for use in compression ignition engines [11, 12]. Frequently emulsions of standard pyrolysis oil contain substantial amount of water, have low calorific value, are unstable and have high particulate content [11, 12]. However, FutureBlends have developed an oil capable of improving or overcoming these drawbacks. The product is known as advanced pyrolysis oil (APO™).

Previous attempts to test PO in diesel engines showed limited operation time due to the poor volatility, high viscosity (up to 4 times higher than diesel [8]), high corrosiveness, cooking [8, 14] and low cetane number [8]. Yang et al. [15], fast-pyrolysed coffee bean residue to obtain a bio-oil which was emulsified with diesel at two different percentages: 5% PO-95% diesel and 10% PO-90% diesel. A reduction of NO_x emissions was found when increasing the PO content. However, CO, CO_2 and smoke levels were higher when compared to diesel. The emulsified blends extended the ignition delay and the pre-mixed combustion, a typical trend when the fuel cetane number is reduced. Kim et al. [8]explored the direct use of wood pyrolysis oil on a single-cylinder diesel engine. With this aim, butanol was blended to reduce the viscosity of the fuel and 5% of two cetane improvers, polyethylene glycol 400 (PEG-400) and 2-ethylhexylnitrate (2-EHN) were added. Three percentages of PO were tested, 10%, 20% and 30% PO, the percentage of butanol was reduced without modifying the 5% content in cetane improvers. The results showed that the PO delayed the combustion and increased considerably the fuel consumption. Particulate number emissions were increased with the higher content in PO as well as unburnt hydrocarbons and NO_x for the majority of the blends and engine conditions tested. A reduction in HCs and CO was reported at low engine loads (IMEPs) and the 30% blend was capable of reducing slightly NO_x emissions. On the other hand, the thermal efficiency was improved around 3% with the use of PO-butanol blends. Hossain [16] studied blends with dried digestate with butanol (10, 20, 30% vol.) and waste cooking oil in a multi-cylinder diesel engine. The viscosity was reported to be 5–7 times higher and heating value 17% lower than diesel. The ignition delay was increased and the engine stability particularly at high loads as well as the thermal efficiency were affected negatively. CO emissions were reduced although CO_2 and fuel consumption were increased up to 5% and 19% respectively on a volumetric basis. Smoke levels were reduced 44%. The comparison between researches is therefore challenging due to the different feedstocks and approaches used to burn the PO in diesel engines and for these reasons, no agreement in the effect of PO in gaseous emissions or engine combustion is found.

The aim of this research work is to analyse combustion performance, gaseous emissions, particulate matter and lubricity of APO™ in diesel emulsion in a research single cylinder, direct injection, naturally aspirated compression ignition engine.

2. Experimental set-up

2.1. Engine

The engine used in this study is an air-cooled single cylinder, direct injection and naturally aspirated compression ignition engine. The experimental engine test rig consists of an air cooled Thringe Titan thyristor-type DC electric dynamometer coupled to a load cell to load and motor the engine. The standard injection timing is 22 Crank Angle Degree (CAD) Before Top Dead Centre (bTDC) as set by the manufacturer. The engine oil temperature, recorded using a K-type thermocouple, was used to check that the engine was fully warm as a means to reduce test-to-test variability. The technical data and engine characteristics are given in Table 1. The in-cylinder pressure traces were acquired using a Kistler 6125B quartz type pressure transducer with a Kistler 5011 charge amplifier at crank shaft positions determined using a 360-ppr incremental shaft encoder (Baumer BDK 1605A360-5-4). The data acquisition and combustion analysis were carried out using in-house (University of Birmingham) developed LabVIEW software running a National Instruments (PCI-MIO-16E-4) data acquisition board. Output from the analysis of engine cycles included the in-cylinder pressure, indicated mean effective pressure (IMEP), percentage coefficient of variation (COV) of IMEP values and percentage COV of peak cylinder pressures, average crank angle for ignition delay, and other combustion characteristic information. To reduce the noise in the data signals and acquisition system, the data is collected for a number of cycles (i.e. 100) and then averaged. The COVs of IMEP and peak cylinder pressure were used as criteria for combustion stability (cyclic variability). Fuel consumption was measured volumetrically.

Table 1. Engine specification data

Number of cylinders	1
Bore/stroke	98.4 mm/101.6 mm
Displacement volume	733 cm^3
Compression ratio	15.5:1
Rated power (kW)	8.6@2500 rpm
Peak torque (Nm)	39.2@1800 rpm
Injection system	Three holes pump-line-nozzle
Injection timing (°bTDC)	22
Maximum injection pressure (bar)	180
Engine piston	Bowl-in-piston

2.2. Fuel properties

The tests were performed of a stable non-corrosive wood pyrolysis product produced by Future Blends Ltd of Milton Park, Oxfordshire, UK emulsified in diesel. The product is trademarked by FBL, and is a stabilized fraction of raw pyrolysis oil produced in a process for which the patent is pending. The components of the pyrolysis oil used to produce the the APO™ are presented in Table 2.

The values in Table 2 vary with the biomass feedstock used, the temperature and time of processing and the condensation methods used to quench the reaction. The values cited are in the middle range from many production experiments.

With almost 30% mass fraction water, the higher heating value is similar to the starting wood at 15–17 MJ kg^{-1}. However the high acid fraction makes for a pH of < 2.5, and solid char and mineral matter makes the PO abrasive – with poor fuel qualities. Future Blends has followed a strategy of modifying the production and processing of the PO to improve the quality. APO™ is produced by a process that removes the sugar components (for sale as feedstock to produce ethanol), and retains the aromatic and phenolic based lignin fraction. The loss in yield relative to the original PO is partly compensated for, by the much higher high heating value of this fraction relative to the sugar fraction (27 MJ kg^{-1} vs 16 MJ kg^{-1}).

Table 2. Component Fractions of Pyrolysis Oil meeting the requirements of ASTM D7544-12 Standard Specification for Pyrolysis Liquid Biofuel – Grades G and Grade D

Components	Mass fraction (%)
Water	27
Ether soluble organics (aldehydes, ketones, phenolicmonomers)	21
Light fatty acids – mainly aceticacid (HAc)	5
Ether insoluble organics (anhydrosugars/oligomers, hydroxy acidswith C > 10)	28
Lignin derivatives, polymerization products and solids	15
n-hexaneextractives – e.g. hydrocarbons, terpenes	4

Both the hot vapour filtration and APO™ processes are the focus of current patenting action. In Table 3, the properties of APOTM are presented.

Table 3. APO™ Properties

Property	Unit	Value
Carbon	Mass fraction (%)	62.6
Hydrogen	Mass fraction (%)	7.4
Oxygen	Mass fraction (%)	30
Higher Heating Value (HHV dry basis)	MJ kg^{-1}	27.0
Water	Mass fraction (%)	< 2
Density	kg m^{-3}	1150
DynamicViscosity @ 40 degC	mPa s	270
TAN number	KOH g kg^{-1}	< 40
Conradson Carbon	Mass fraction (%)	16
Flash Point (estimated)	Celsius	70

Stability tests were carried out for the APO™ and no changes in viscosity of the APO™ were found in 672 hours. In the standard corrosion test a polished mild steel rod is immersed in the material for 24 hours did not corrode.

Two batches of APO™/diesel emulsions were provided to the University of Birmingham in order to analyse the performance of the fuel during engine operation. Gaseous emissions, PM emissions, volumetric fuel consumption and in-cylinder pressure were evaluated. Three engine conditions were selected: 1500 rpm – 8 Nm, 1500 rpm –15 Nm and 1500 rpm – 25 Nm. The blends tested are the following:

Batch (i): 20% APO, 8% surfactant and 72% diesel. The emulsion was prepared in a Silverston High Shear Mixer. The viscosity of the emulsification was too high for automotive applications. Therefore, in the following batches several APO™ percentages were tested.

Batch (ii): The concentration of APO™ in diesel fuel was modified in order to study the effect of fuel composition on engine stability: a) 15% APO™, 8% surfactant, 77% diesel and b) 20% APO™, 8% surfactant, 72% diesel.

The base fuel used for both campaigns was an Ultra Low Standard Diesel (ULSD) provided by Shell Global Solutions, UK. Properties of the base fuels are summarised in Table 4.

Table 4. Properties of ULSD EN590 fuels. Batches (i) and (ii)

Property	Method	Unit	Diesel
Density at 15°C	DIN EN ISO 12185	kg/m^3	834.5
Kinematic viscosity at 40°C	DIN EN ISO 3104*	mm^2/s	2.78
CFPP	DIN EN 116	°C	–27
Cloud Point	DIN EN 23015	°C	–8
50% v/v	DIN EN ISO 3405	°C	270.6
90% v/v	DIN EN ISO 3405	°C	331.5
Lower Calorific Value		MJ/kg	42.7

2.3. Emission analysis

2.3.1. Gaseous emissions

A MKS MultiGAS 2030 FTIR analyser (Fourier Transform Infrared Spectroscopy) was used to analyse the gas components of the engine exhaust. To obtain the gas information, the FTIR analyser emits at once a beam that contains several frequencies of light to measure how much of that beam is absorbed by the sample then, the beam is modified to involve different combination of frequencies. This process will be repeated until the several data points have been scanned. These data points will be used to infer what the absorption (of the sample) is at each wavelength and therefore confirm the sample species. The MKS MultiGAS 2030 FTIR analyser is capable of measuring gaseous species including NO, NO_2, N_2O, NH_3, HCs, CO, CO_2 and H_2O (except for N_2, H_2 and O_2).

2.3.2. Particulate Matter

A TSI scanning mobility particle sizer (SMPS) 3080 electrostatic classifier is employed to establish the particle size distribution. This is comprised of an electrostatic classifier series 3080, a 3081 Differential Mobility Analyser (DMA) and a model 3775 Condensation Particle Counter (CPC). The CPC that forms part of the SMPS system has a particle count accuracy of ±10% for particle concentrations lower than $5x10^4$ particles/cm^3 and ±20% for particle concentrations lower than 10^7 particles/cm^3. The flow rate and sheath rate were 6 and 0.6 L/min respectively. The particulate size distribution obtained for these stings ranges from 10 nm to 406.8 nm. The scan time is 120 seconds per sample. Hydrocarbon condensation and nucleation was minimised by controlling the temperature in the dilution process.

2.4. Lubricity analysis

Lubricity properties of PO samples were performed on High Frequency Reciprocation Rig (HFRR). The schematic of the equipment is shown in Figure 1. The test specimens comprised of a 6 mm diameter steel ball and steel disc. All the tests were conducted according to the EN ISO 12156-1:2006 standard (ISO12156-1, 2006). The fuel temperature maintained at 60°C and the volume of the fuel was 3 ml. A humidity and temperature controlled cabinet was employed to assure the appropriate conditions of the sample according to the standards. During the test, the disc was fully submerged in PO while the upper specimen was loaded with a 200 g mass and subjected to a reciprocating motion with frequency of 50 Hz during 75 minutes [17, 18].

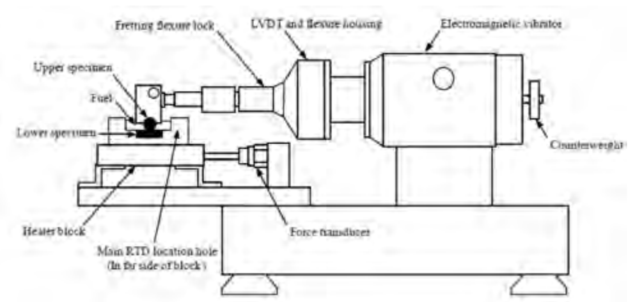

Fig. 1. Schematic Diagram of HFRR [18]

To investigate the wear scan diameter (WSD) of the ball in micrometres, an optical microscope was used together with 100x magnification lens. The average WSD was calculated and corrected to normalise for the standard water vapour pressure of 1.4 kPa. This considers the effect of the air conditions on the fuel's lubricating performance while the HFRR was operating, as defined by ISO 12156-1. The wear scan diameter was corrected considering the relative humidity and the temperature. All of the lubricity experiments were repeated twice and repeatability was demonstrated to be less than 20 μm. The equipment was calibrated prior the test to assure the accuracy of stroke length.

3. Results

3.1. Combustion analysis

The in-cylinder pressure recorded from the combustion of the two fuels at the three engine conditions is presented in Figure 2. For low loads (8 and 15 Nm) the pyrolysis blend reduced the pressure inside the combustion chamber, however, at the highest load the trend is reverted. The Coefficient of Variance (COV) of Indicated Mean Effective Pressure (IMEP) for the three engine conditions is presented in Figure 3. It can be noted that for 8 and 15 Nm, it was below 5% and similar to diesel. However, the stability at the highest engine load was above the acceptable limits.

The rate of heat release (ROHR) or fuel oxidation rates is proportional to the mass fraction burnt (mfb) and describes the combustion history of the fuel. This parameter is also related to the local pressure and temperature conditions in the combustion chamber which govern the formation mechanism of the pollutant emissions. Figure 4 shows the results for the three loads, diesel and pyrolysis oil fuels. The PO blend delayed the start of the combustion and produced a higher peak at the beginning of the combustion, known as premixed combustion. Due to this high peak in heat release the local pressure and temperature conditions will promote the formation of NO_x. Due to the higher viscosity and physical properties of the PO fuel the auto ignition is delayed leading to more premixed combustion and thus, NO_x.

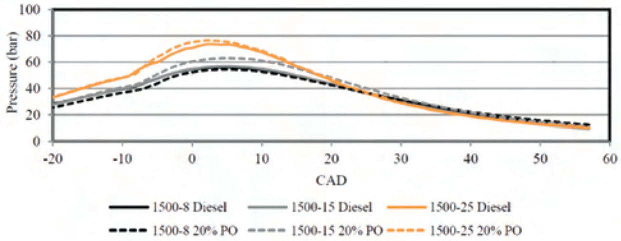

Fig. 2. In cylinder pressure results for diesel and pyrolysis fuel

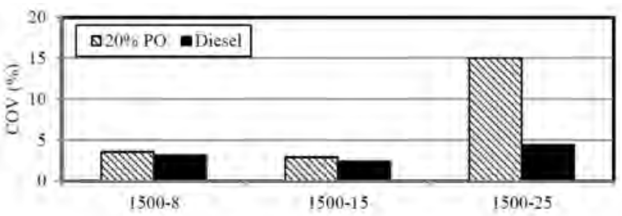

Fig. 3. COV of IMEP

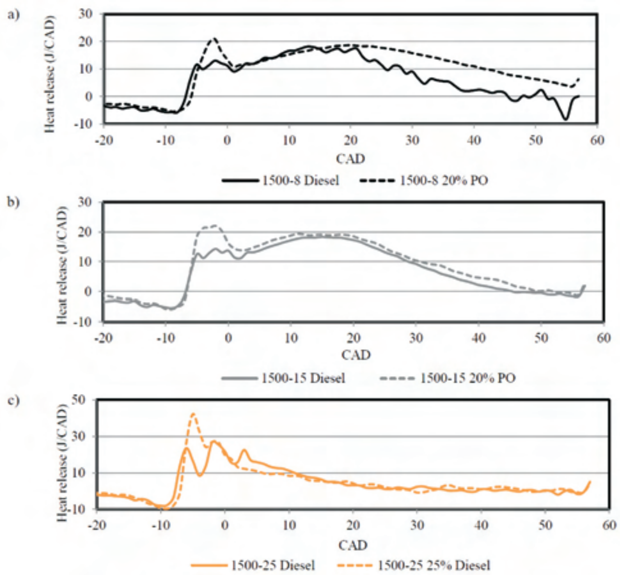

Fig. 4. ROHR: a) 1500-8, b)1500-15 and c) 1500-25 (rpm-Nm)

3.2. Gaseous emissions

3.2.1. Batch (i)

NO_x emissions

Figure 5 presents the results obtained for NO_x emissions. As the engine load is increased, the NO levels are higher as the in-cylinder temperature and the fuel demand to achieve this condition are also higher. On the other hand, the trend in NO_2 emissions is opposite, as the thermal conditions inside the cylinder favours the NO formation processes. N_2O emissions are low for both fuels, although its emission must be considered due to its high greenhouse effect potential and detrimental effects on human health. The pyrolysis oil-diesel blend shows to produce slightly higher levels of NO_x (NO, NO_2 and N_2O) than the diesel fuel for all the studied conditions. The physical properties of the fuel (i.e. viscosity) play a significant role on fuel injection, atomization and vaporization processes and therefore, combustion and pollutant emission formation.

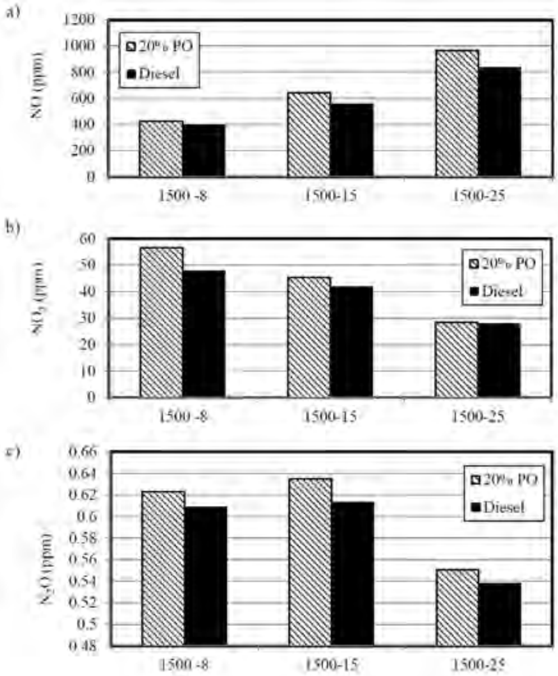

Fig. 5. NO_x emissions: a) NO (ppm), b) NO_2 (ppm and c) N_2O

<u>Carbonaceous gaseous emissions</u>

Similarly to NO_x emission trends, the same trend was observed for CO and THC emissions, Figure 6. The combustion of the pyrolysis blend produced a larger amount of CO and also slightly increased concentration of unburnt hydrocarbons, particularly a low load where the combustion chamber is cold and the hence the available heat to drive the complete oxidation of fuel.

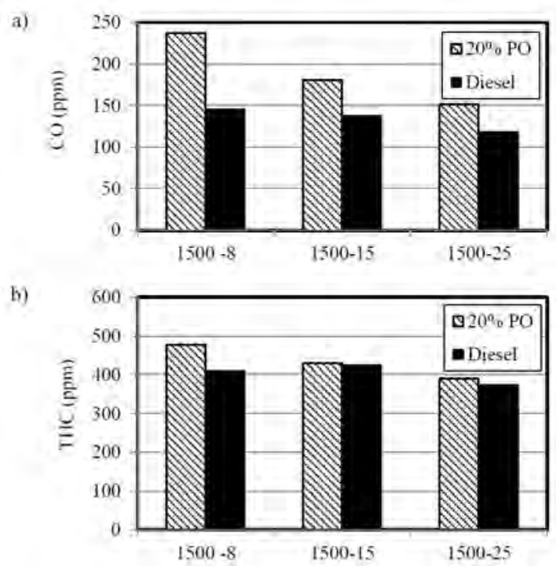

Fig. 6. CO emissions [ppm] and THC [ppm]

During the engine operation with the fuel blend some issues with the engine stability were noted. The engine torque and speed could not be maintained at the set-values. As a consequence, higher fluctuations in gaseous emissions were observed, particularly for THC. The comparison between diesel and PO THC emissions against time is depicted in Figure 7 a and b, respectively.

The presence of heavier HCs in the pyrolysis oil can lead to lower combustion efficiency and reduced engine thermal efficiency. In addition, fuel properties such as the lower calorific value of the oxygenated components can increase the fuel consumption. These reasons explain the increase in CO_2 levels seen from the combustion of the pyrolysis blend, Figure 8.

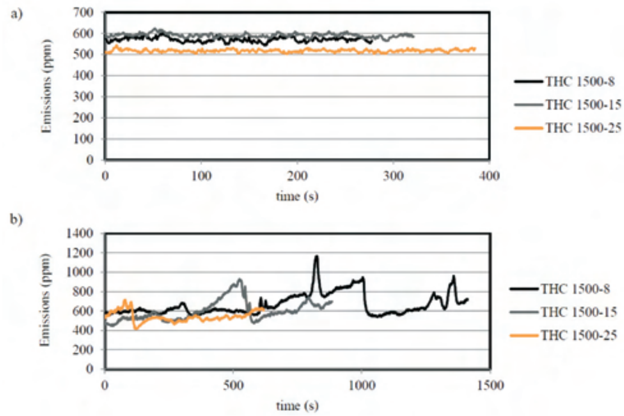

Fig. 7. THC against time: a) Diesel and b) Pyrolysis oil (PO)

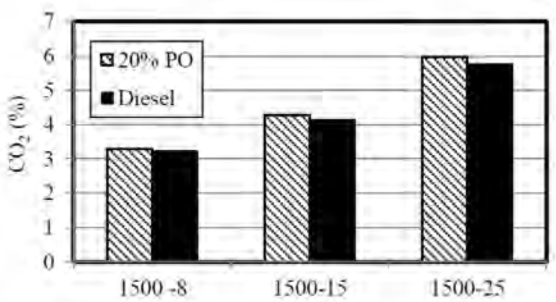

Fig. 8.Carbon dioxide results

3.2.2. Batch (ii)

Similarly to the previous Batch (i), the combustion of the emulsified fuel resulted in an increase of NO, NO_2 and N_2O emissions, Fig. 9. In general in addition to fuel chemistry (oxygen content and flame temperature) the modified combustion patterns obtained with the fuel blend (Fig. 4) can explain the increased NO_x emissions formation. Parameters such as fuel density, viscosity, heating value and distillation point are all affecting the injection timing, rate and fuel penetration.

<u>Carbonaceous emissions</u>

The combustion of pyrolysis blend increased the CO levels emitted when compared to diesel fuel, a trend that is similar to the earlier campaign (Fig. 10). Regarding THC,

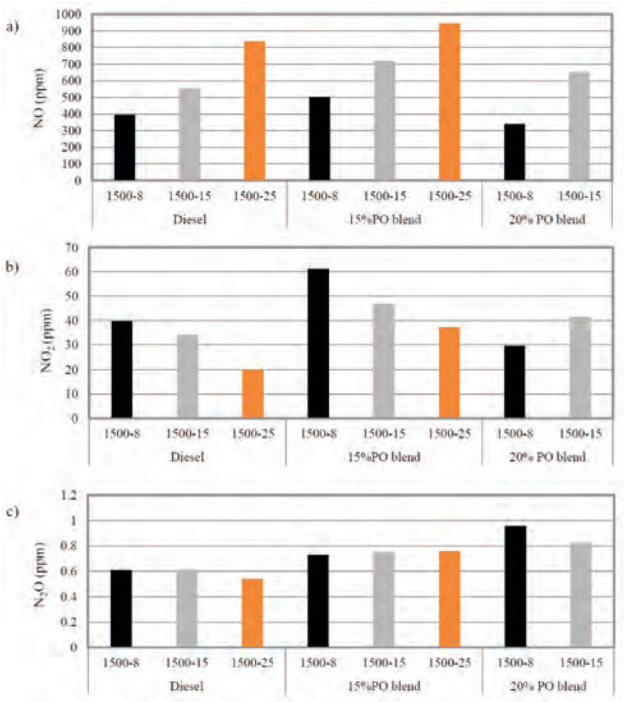

Fig. 9. Nitrogen emissions: a) NO, b) NO2 and c) N2O

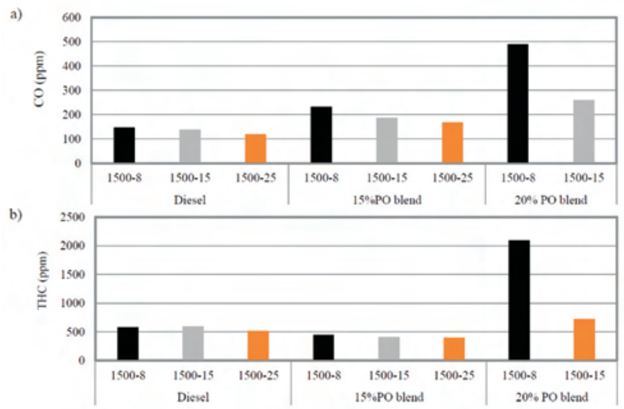

Fig. 10. Carbonaceous emissions

15% PO combustion reduced slightly THC concentration. However, for the 20% PO blend the THC levels are increased significantly, particularly at low load. The lower in-cylinder temperature and the presence of heavy hydrocarbons in the fuel blend and therefore, higher viscosity can be disadvantageous for the liquid fuel spray patterns. The engine stopped during the 20% PO blend test and the engine could not be restarted until the injection system was cleaned using diesel. In addition, the fuel separation (tar layer at the bottom and a blend of the light hydrocarbons from the PO and diesel) observed in the tank can suggest that this fuel separation can also occurred during the injection process, meaning that: i) there is a fuel capable to provide normal operation of the engine and ii) there is a fuel with physical properties that are not optimum for internal combustion engines.

3.3. Particulate Matter emissions

Similar trends in PM emissions were obtained as well. Figure 11 shows the PM total number emissions for both PO blends and diesel baseline. The presence of PO aids in PM reduction, especially at higher loads, due to the presence of oxygen in the PO formula and the water cooling effect can also play an important role. However, at low loads PM total concentration was similar both diesel and PO blends.

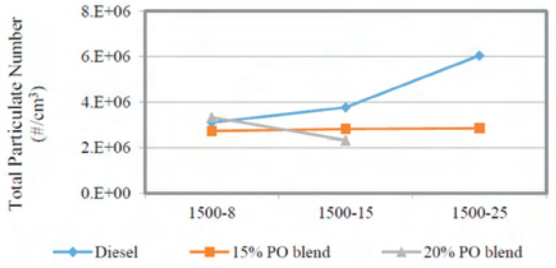

Fig. 11. PM total number

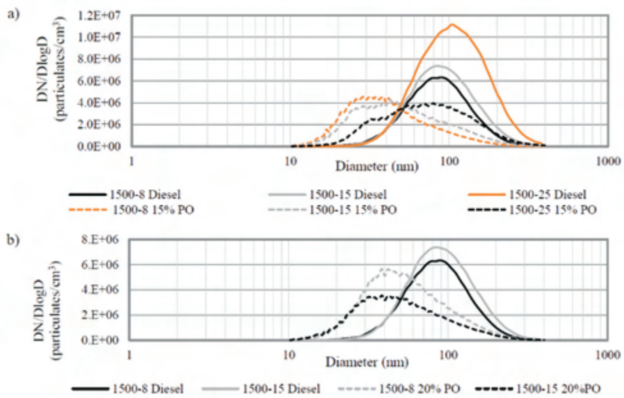

Fig. 12. PM emissions Batch (ii): a) 15% PO blend and b) 20% PO blend

Analysis the particulate size distribution (Figure 12), it can be observed that the PO blend reduced significantly larger particulates, accumulation mode, however, The combustion of both blends produced a peaks centred between 25–30 nm for 15% and 30–35 nm for the 20% blend. The size of these particulates suggests that they are composed mainly by heavy unburnt hydrocarbons. At the highest load, the PM diameters measured are similar to diesel particulates. Therefore, PO blend forms less soot, but the presence of heavy hydrocarbons in the base fuel increases the level of nucleation mode particulates (small PM).

3.4. Fuel consumption

The results for the fuel consumption are reported in Figure 13. Due to the lower heating value (high water content) the fuel consumption increased when using PO blends.

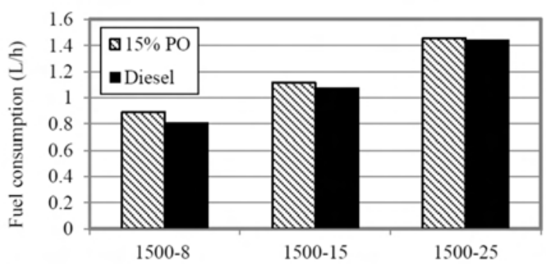

Fig. 13. Fuel consumption

3.5. Lubricity

ULSD Sample which used as a Reference Diesel fuel is supplied by Shell Company by specified lubricity number. Its lubricity with ASTM D6079 Standard is 284 µm. A pre-test of lubricity for this fuel was performed three times, where results were 276, 267 and 285 µm and the average is given as a result in Table 5.

Figure 14 is one sample of Wear Scar Diameter Measurement, which was repeated two times, and then average value is considered as a corrected wear scar diameter.

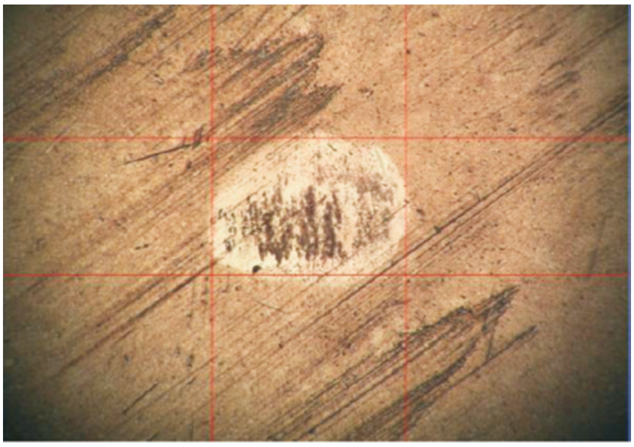

Fig. 14. Example of WSD(µm)

The lubrication properties of pyrolysis oil samples were investigated by using HFRR (PCS Instrument). Table 5indicates comparison of Lubricity properties of Pyrolysis oils compared to ULS Diesel Sample. Figure 15 shows the measured tribological properties obtained from the HFRR tests for the fuels. ULSD sample was tested three times for calibration and to investigate its accuracy. In addition, HFRR tests for PO blends were repeated twice and the mean value is reported. All fuels accomplished the ASTM D6079 Standard as all WSD were far below 520 µm.

Table 5. Corrected Wear Scar Diameter (µm)

Fuel Types	Corrected Wear Scar Diameter (µm)
ULSD	276
PO 15% Batch 1	314.5
PO 15% Batch 2	281
PO 20% Batch 2	186

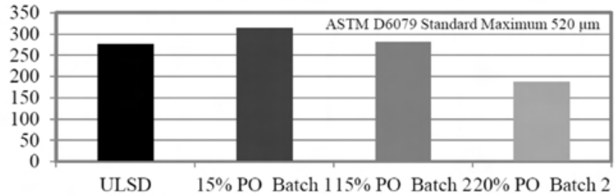

Fig. 15. Corrected Wear Scar Diameter (µm)

4. Conclusions

The feasibility of PO-diesel blends in a research single cylinder diesel engine has been investigated.

Gaseous emissions (NO_x, CO, THC and CO_2) were generally increased with the increasing percentage of PO in the blended. Total PM emissions were reduced up to 52% at high loads, although no significant difference was observed at low loads. The presence of oxygen in the molecule can aid to reduce PM formation and promote PM oxidation during the expansion stroke. However, the increased levels of THC led to an increase in the nucleation mode. In addition, the COV and engine stability was deteriorated due to the higher viscosity and other physical properties of the fuel leading to high uncertainties in the results.

No significant differences were found in the WSD between 15% PO blend a diesel. A reduction of 32% in the WSD was observed for the 20% PO blend.

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This project could not have been completed without the efforts of the FBL staff in producing the APO – Sanjeev Gajjela, Jose Medrano, Javier Gonzalez and Haonan Wu.

Abbreviations

2-EHN	2-Ethyl Hexyl Nitrate
APOTM	Advanced Pyrolysis Oil
bTDC	Before Top Dead Centre
CAD	Crank Angle Degree
COV	Coefficient of Variance
HFRR	High Frequency Reciprocating Rig
IMEP	Indicated Mean Effective Pressure
PEG-400	Polyethylene Glycol 400
PM	Particulate Matter
PO	Pyrolysis Oil
THC	Total Hydrocarbons
ULSD	Ultra Low Sulphur Diesel
WSD	Wear Scan Diameter

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

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

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

1. Introduction

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

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

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

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

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

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

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

2. Tested vehicles

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

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

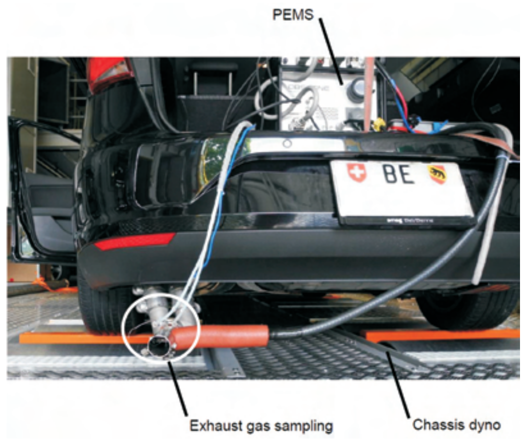


Fig. 1. Test vehicle with installed PEMS on chassis dynamometer

Table 1. Data of tested gasoline (GDI) vehicle

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

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

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

Table 2. Data of tested Diesel vehicles

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

3. Test equipment

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

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

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

– regulated gaseous components:

exhaust gas measuring system Horiba MEXA-7200

CO, CO_2… infrared analysers (IR)

HCFID... flame ionisation detector for total hydrocarbons

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

NO/NO_x... chemoluminescence analyser (CLA)

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

4. Nanoparticle analysis

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

For the dilution and sample preparation an ASET system from Matter Aerosol was used (ASET … aerosol sampling and evaporation tube). This system contains:

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

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

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

5. Test procedures

Driving cycles on chassis dynamometer

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

Table 3. Overview of used measuring systems

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

PN – Particles Number
OBD – On Board Diagnostics
EFM – Exhaust Flow Meter
OBS-one – H_2O monitored to compensate the H_2O interference on CO and CO_2 sample cell heated to 60°C
AVL Move – dry to wet correction applied

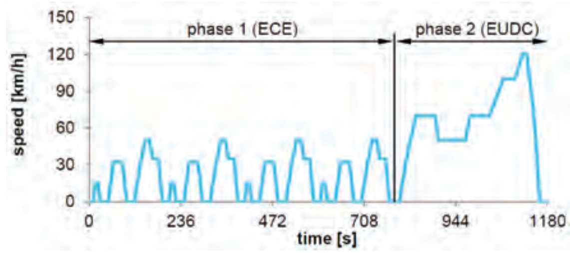


Fig. 2. NEDC European driving cycle

The first NEDC of each test series was performed with cold start (20-25°C) and further cycles followed with warm engine. Between the cycle always 3 minutes of constant speed 80 km/h in 4[th] gear were performed as conditioning.

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

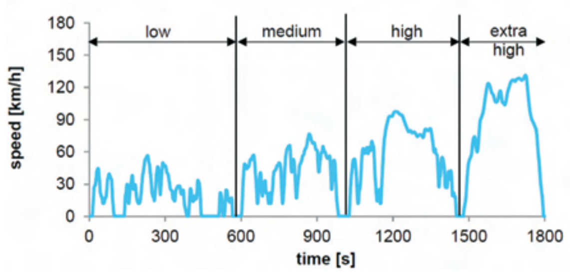


Fig. 3. WLTC driving cycle

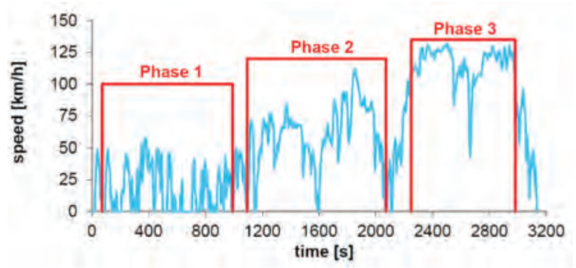


Fig. 4. CADC driving cycle

On-road testing

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

5. Results

Comparisons of PEMS on chassis dynamometer

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

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

What can be the reasons of these deviations?

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

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

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

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

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

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

In order to exclude the influence of volumetric flow (V_{exh}) and density (ρ_x) the concentrations of CO_2 were correlated: integral averages measured with PEMS against the bag-concentrations (diluted) recalculated to the non-diluted concentrations at tailpipe. This is represented at the bottom of Fig. 6 as CO_2 in [%].

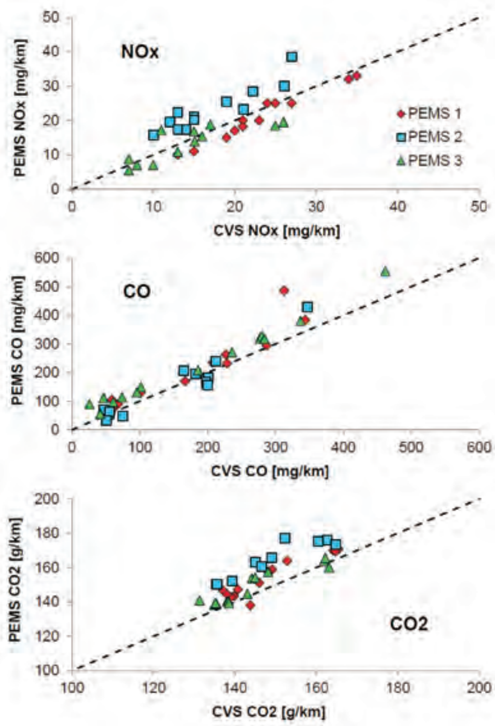


Fig. 5. Correlations of emissions measured with PEMS and with stationary CVS-installation in all investigated driving cycles: NEDC cold, NEDC, WLTC, CADC

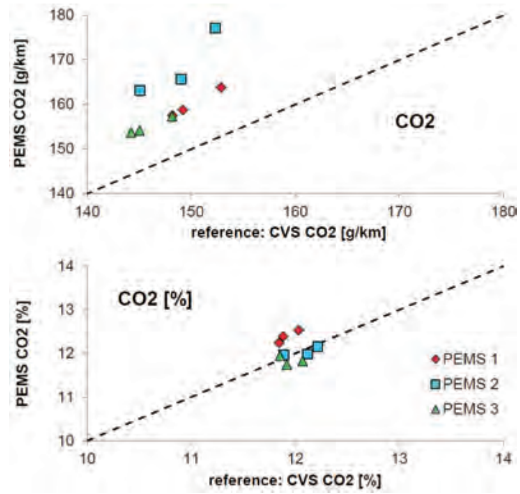


Fig. 6. Correlations of emissions measured with PEMS and with stationary CVS-installation in NEDC cold

The comparison of concentrations indicates much better correlations.

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

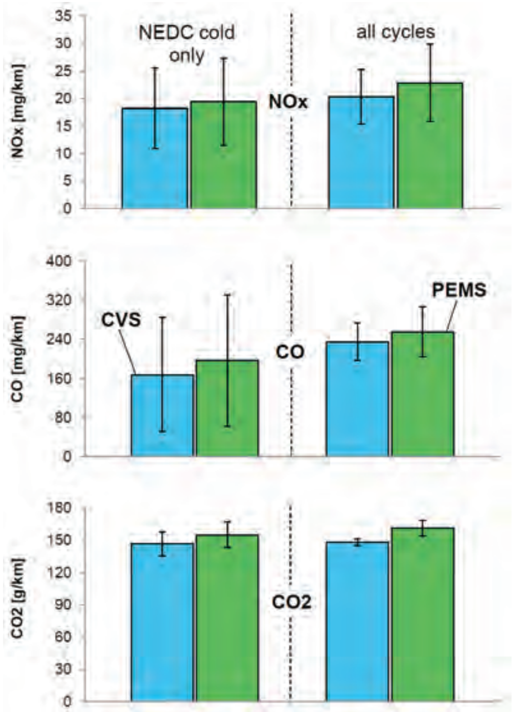


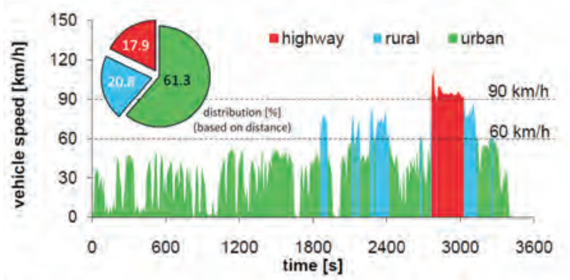
Fig. 7. Comparisons of average results: CVS versus all PEMS's

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

Road tests and comparisons with chassis dynamometer GDI car

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

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



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

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

The distinction between the driving modes: urban, rural, highway is performed by the evaluating program according to the RDE requirements (see next section). All cycle parts below 60 km/h are considered as "urban" all intervals with [60 km/h < 90 km/h] are rural and all driving with vehicle speeds v > 90 km/h is highway.

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

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

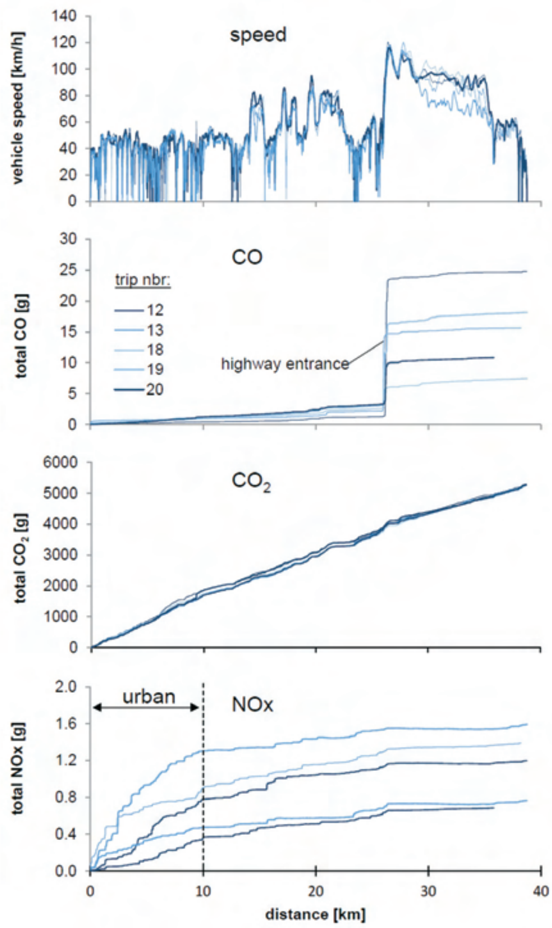


Fig. 9. Comparison of accumulated results from five road trips

From all performed trips can be followed that:

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

– CO results show more dispersion – the level of CO emissions for the whole road trip is below 300 mg/km, a sudden acceleration during the measurement can influence greatly the final results.
– The vehicle has not constant NO_x emissions. This tendency is confirmed by the comparison of the results in different cycles with different instruments.
– CO and NO_x measured levels are relatively low (concentrations not represented here: NO_x average < 50 ppm; CO average < 300 ppm).
– The results from the PEMS3, which has no EFM (Exhaust mass Flow Meter), are similar to the results of other measuring systems.

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

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

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

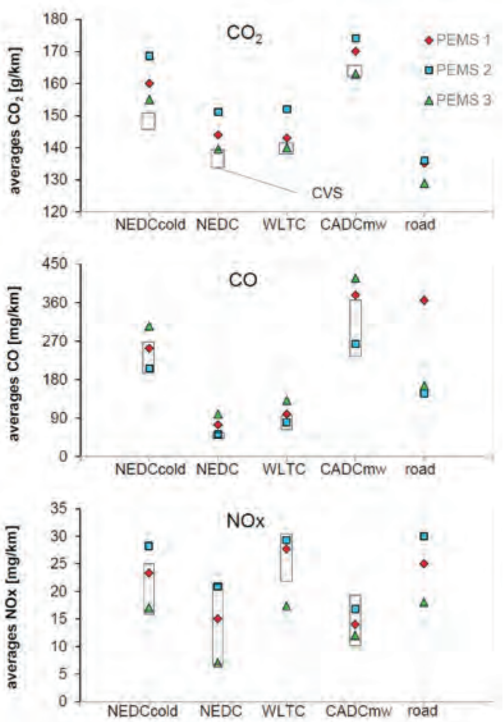


Fig. 10. Comparisons of average values between road trips and cycles on chassis dynamometer. PEMS 1, 2, 3; Seat Leon 1.4 TSI Euro 5b

Testing of Diesel cars with PN-PEMS

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

Figure 11 illustrates an example of correlation of results obtained with CPC (according to PMP) and with NM3. A very good correlation of both measuring systems is demonstrated. The ability of NM3 to show higher peaks during the transients and also higher average values in the driving cycles is to explain with the fact, that NM3 is more sensitive in the lowest size range below 23 nm.

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

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

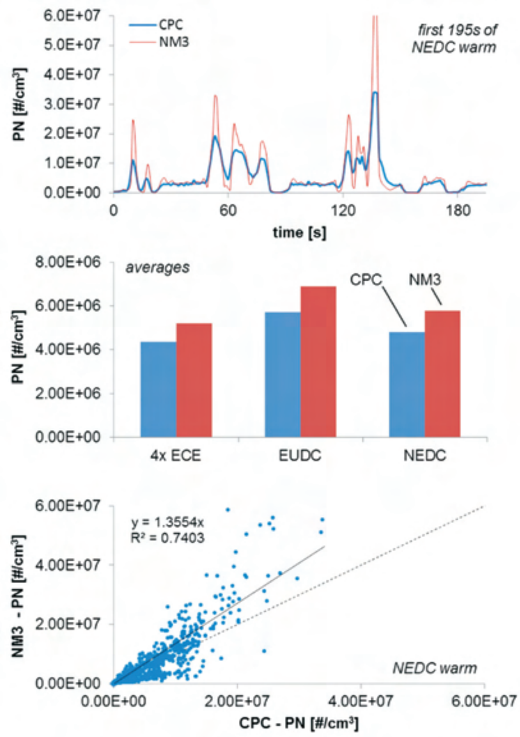


Fig. 11. Particle counts concentrations measured simultaneously at tailpipe with NanoMet 3 (NM3) and with CPC

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

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

Figure 13 shows in WLTC another example of DPF efficiency: vehicle 1 with a high quality DPF represents the average particle counts reduction rate (PCRR) relatively to the highest emitting vehicle 3 of 99.998%. The damaged DPF is visible with PCRR = 48.786%.

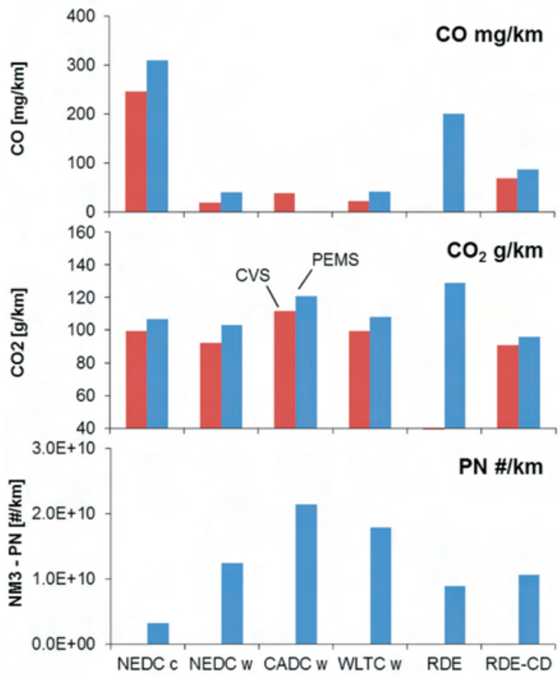


Fig. 12. Emissions of a modern diesel passenger car (Euro 6b) in different driving cycles and in real driving

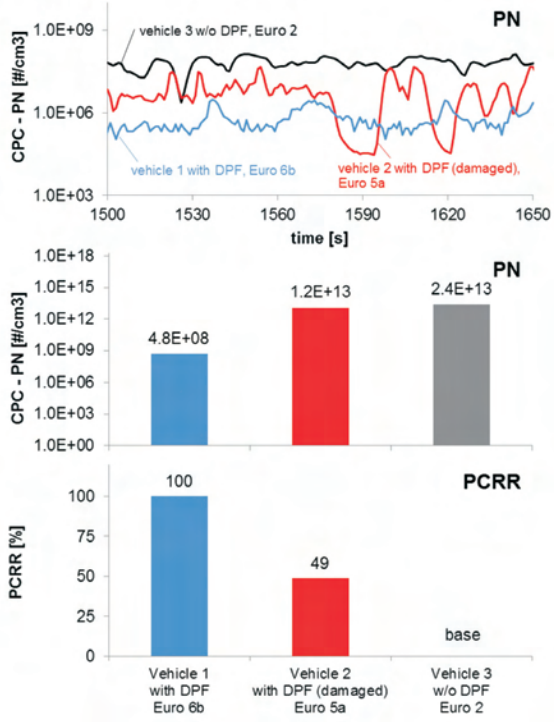


Fig. 13. Effects of DPF on Diesel Passenger Cars in WLTC (hot) Succes of DPF Technology

RDE requirements for road testing

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

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

An extract of the requirements regarding trip validation is:

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

6. Conclusions

Following conclusions can be mentioned:

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

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

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

Acknowledgement

The authors express their thanks to the Swiss Federal Office of Environment BAFU, Dr. M. Schiess and Mr. G. D'Urbano and to the Laboratories for Testing Materials, EMPA, Mr. Ch. Bach and Mr. Th. Büttler for support and collaboration.

Abbreviations

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

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Investigations of emissions of reactive substances NO_2 and NH_3 from passenger cars

Public concern and complaints regarding ambient air in zones of dense traffic pertains to two compounds of nitrogen, nitrogen dioxide (NO_2) and ammonia (NH_3); both are toxic and strongly irritant, such that legal limitations are under discussion. This paper contributes to measuring methods as already in part proposed by GRPE subgroup WLTP-DTP (Worldwide Light Duty Test Procedures – Diesel Test Procedures) for NO_2.

Despite legally lowered NO_x emission levels, lumping both, NO_2 and NO, levels of NO_2 have risen in cities and agglomerations as a result of both, deployed catalytic exhaust after-treatment devices and low sulphur Diesel fuels. In present tests two different combinations of NO_2 measuring methods as proposed by WLTP were checked on Diesel cars for practicability in handling and accuracy. These integral, indirect methods ($NO_2 = NO_x – NO$) have been found as useful tools for estimate of NO_2 and with use of appropriate analyzers a satisfactory accuracy was attained.

Furthermore, attention was brought to ammonia (NH_3) emitted by gasoline engines with three way catalysts (TWC) which ought not to be ignored while on the other hand SCR systems for Diesel engines are strictly regulated. Emission levels of more recent TWC turned out to be mostly below 20 ppm NH_3. Vehicle of older technology exhibited significantly higher levels, about 10 times more.

As chemical reactions depend on pressure and temperature (= i.e. flow condition in CVS-tunnel) as well as concentrations, doubts need to be considered on accuracy of results based on chemical reactive substances. Nevertheless, clear tendencies regarding changes of concentrations of NO_2 and NH_3 along the path-way could not be observed.

Key words: *exhaust emissions, reactive substances NO_2 and NH_3*

1. Introduction

Nitrogen dioxide NO_2 and ammonia NH_3 are not limited by the present exhaust gas legislation for passenger cars and the possibilities of limiting them are discussed.

Some increase of atmospheric pollution by NO_2 can be observed in the dense traffic areas, in spite of general reduction of NO_x [1–3]. It is due to the combined effect of an increased proportion of Diesel vehicles with oxidation catalysts (DOC) or with passive DPF regeneration systems (CSF) in the fleet, together with the use of low sulphur fuels. Oxidation catalyst, often used as a key element of the DPF regeneration concept, increase the ratio of NO_2/NO_x in the exhaust gas, which is of big concern, since NO_2 is more toxic than NO [1]. Some particulate filters technologies are especially problematic as they form NO_2 on purpose to regenerate the filter continuously.

Several contributions on NO_2-production in the Diesel aftertreatment systems and on the NO_2 measuring procedures were performed by the authors in the past [4, 5].

From them, as well as from experiences of other authors [6–8], it can be generally stated, concerning the NO_2 emission of Diesel engines, that:

– with Pt-coated catalyst (DOC), or with catalyzed soot filter (CSF), there is a maximum of NO_2/NO_x-ratio typically when exhaust gas temperatures range around 350°C; there is a higher potential for NO_2-formation with higher Pt-content in the coating,
– lower NO_2-productions appear with higher spatial velocity,
– higher S-content in the fuel also causes a lower NO_2-production (this by directly influencing the catalysis and by quicker ageing of the catalyst),
– weaker catalytical activity and consequently lower NO_2-concentration appear with used DOC/DPF and/or when these devices are loaded with soot.

Modern gasoline cars are equipped with three way catalysts (TWC), which efficiently convert NO_x and the resulting amount of NO_2 is negligible.

It was nevertheless stated and analyzed in several test programs of the Swiss Federal Laboratories EMPA that gasoline vehicles may emit quite considerable peak values of Ammonia NH_3 [9–11]. This happens especially during Lambda deviations to the rich mixture in dynamic engine operation.

High NH_3 emission peaks may occur with modern NO_x-storage catalysts, when switched to rich operation for deNOx-regeneration [12]. Ammonia originates in the atmosphere from natural and anthropogenic sources and it has a relatively short life time in the range of hours. It reacts with nitrogen oxides and sulphur oxides forming ammonium nitrate and sulphate.

In near exposure NH_3 is toxic and has to be minimized.

Both compounds NO_2 and NH_3 are reactive and the question appears how should they be measured?

In WLTP there are some proposals of measuring NO_2 from bags and from diluted gas.

In the present project direct measurements (from undiluted and diluted exhaust gas) were performed at different sampling points in the exhaust- and CVS- system and in different operating conditions. These results were compared with the simultaneous measurements from diluted gas in the sampling bags.

The project was financially supported by the Swiss Federal Offices of Environment (BAFU) and of Roads (ASTRA) and was a contribution to WLTP in collaboration with the EC Joint Research Center Laboratories, JRC, Ispra, Italy.

2. Tested vehicles

Two Diesel cars were used to investigate NO_2 emissions.

Figure 1 shows the vehicles on the chassis dynamometer and Table 1 represents the most important data of the vehicles. The Opel was used twice in different testing periods (9 months apart). The results will be defined as vehicle 1 and vehicle 2.

Fig. 1. Diesel vehicles for research of NO_2

Table 1. Data of Diesel vehicles

Vehicle	Vehicle 1 and 2 Opel Astra DI16V	Vehicle 3 BMW 320d
Cylinder	4	4
Overall displacement [cm^3]	1994	1995
Power [kW]	60	110
Injection type	DI	DI
Fuel	Diesel	Diesel
Weight empty [kg]	1390	1600
Transmission	m5/front	m6/rear
Matriculation	20.01.1998	30.09.2004
Turbocharging	yes	yes
Exhaust aftertreatment	DOC	DOC
Emission level	Euro 2	Euro 4

Three gasoline cars were used to study the release of NH_3. Figure 2 and Table 2 represent these vehicles. The Renault is representing an older TWC technology with Lambda control.

Fig. 2. Gasoline vehicles for research of NH_3

Table 2. Data of Gasoline vehicles

Vehicle	Renault 18 Break vehicle 4	Volvo V60 T4f vehicle 5	Peugeot 306 Break 1.6 vehicle 6
Cylinder	4	4	4
Overall displacement [cm^3]	2164	1596	1587
Power [kW]	74	132	72
Injection type	MPI	DI	DI
Fuel	Gasoline	Gasoline	Gasoline
Weight empty [kg]	1110	1554	1250
Transmission	m5/front	a6/front	m5/front
Matriculation	01.04.1985	27.01.2012	2001
Turbocharging	no	yes	no
Exhaust after-treatment	TWC	TWC	TWC
Emission level	Euro 0	Euro 5	Euro 3

The fuels used were from the Swiss market, summer quality:
– Diesel S<10 ppm according to SN EN 590 and
– Gasoline RON 95 according to SN EN 228

The lube oils were not changed and not analyzed.

3. Test Methods and Instrumentation

The vehicles were tested on a chassis dynamometer, each one at the same operating conditions and with warm engine (see "Test procedures").

3.1. Chassis dynamometer

The following test systems were used:
– Roller dynamometer: Schenk 500 G5 60
– Driver conductor system: Tornado, version 3.3
– CVS dilution system: Horiba CVS-9500T with Roots blower
– An automatic air conditioning in the hall (concerns the intake- air of the engine and the dilution air of CVS).

The driving resistances of the test bench were set according to the legal prescription.

To study NO_2 emissions at constant speeds and sometimes in WLTC the driving resistance was increased to obtain a higher exhaust temperature near to the maximum of NO_2 production.

3.2. NO_x and NH_3 analysis

The chemiluminescence measuring method uses the effect that during the oxidation of NO to NO_2 by means of ozone O_3, a part of NO_2 is emitting a luminous radiation. This chemiluminescence signal is detected photo-electrically. When O_3 is present in excess the signal is proportional to the NO concentration of the sample gas.

In order to measure NO_2 in the sample gas, it has first to be converted into NO. To accomplish this chemical reduction the sample gas is passed through a converter heated to more than 400°C.

Modern converters contain metallic active material, which allows better selectivity of NO_2. Since sample gas normally contains both NO and NO_2, it is possible to measure the sum $[NO] + [NO_2] = [NO_x]$ in the converter channel.

One of the used NO_x-analyzers, the Horiba chemiluminescence analyzer (CLA) – not heated is equipped with one converter and can selectively indicate NO, or NO_x.

Another NO_x-measuring system used is the EcoPhysics CLD 822 CM hr. (chemiluminescence detector), a heated analyzer with heated measuring line. This detector is equipped with a double reactor chamber and with two $NO_2 \rightarrow NO$ converters and allows simultaneous readings of NO, NO_x and NO_2.

Both analyzers were systematically calibrated with the zero and span-gases and fulfilled all quality requirements.

The third measuring system used was the FTIR (Fourier Transform Infrared) Spectrometer (AVL SESAM), which offers the possibility of simultaneous, time-resolved measurement of approx. 30 emission components – among others: NO, NO_2, NO_x, NH_3 and N_2O.

The FTIR measuring principle is a measurement with IR light. Contrary to NDIR with a narrow wave length area by means of an optical filter, the scan area of the IR wave length by use of the FTIR measuring principle is large. The principle of FTIR is that the gas to be analyzed is led through a cuvette with an IR light source at one end that is sending out scattered IR light, and a modulator that "cuts" the infrared light into different wave lengths. At the other end of the cuvette a detector is measuring the amount of IR light to pass through the cuvette. Like the NDIR measuring principle, it is the absorption of light at different wave lengths that is an expression of the concentration of gases to be analyzed. By data processing, Fourier Transformation mathematics is used to turn the measured absorption values into gas concentrations for the analyzed gases. As the light, when using the FTIR measuring principle, is modulated into many different wave lengths, it is possible to analyze many different gases in the same instrument.

FTIR is calibrated by the data processing software and it does not need the continuous calibration.

The detection limit for all NO_x measuring systems is in the range of 0.5 to 1.0 ppm, which for the investigated vehicles and the applied driving cycle is equivalent of 0.01 to 0.02 g/km.

4. Test procedures

The vehicles were tested on a chassis dynamometer at two constant speeds 30 km/h and 50 km/h and in the dynamic driving cycle WLTC (Worldwide Light Duty Test Cycle), always with warm engine. As conditioning and warm-up the first 1000s of WLTC (part 1 and part 2) were used.

The exhaust gases were measured with FTIR at different sampling positions (SP) along the exhaust flow path and also from the bags. At the end of the CVS-tunnel and in the bags CLD and CLA were also used.

The sampling positions were: tailpipe, tube to CVS (non-diluted), CVS after dilution and CVS at the end. The resulting dilution factors (DF) were for vehicle 1 at 30 km/h in the range of 9 and at 50 km/h in the range of 6.

At constant operation the measuring system was switched from SP to SP. The dynamic cycles were performed for each SP successively.

In this way the thermal state of the engine and exhaust was repetitive and responded to the operating conditions.

4.1. NO_2 sampling positions

Figure 3 represents the sampling positions for Diesel vehicles. SP1 and SP2 are for undiluted and SP3 for diluted gas. The braking force of the chassis dynamometer was increased at constant speeds to obtain the maximum possible NO_2-values and to make better visible the investigated effects. In the driving cycle WLTC this simulation of slope was not done (except of one trial with the Opel with a slope

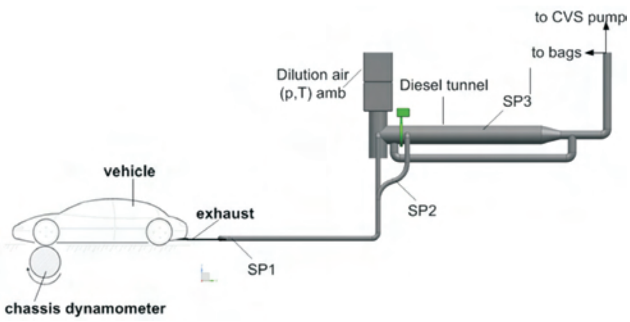

Fig. 3. Sampling positions SP for Diesel vehicles – testing NO2

of 3%). The slope at constant speeds was 3% for vehicle 1 and 2 and it was 5% for vehicle 3. The slope (the braking force) was adjusted for each vehicle in order to obtain higher temperatures of the DOC and significant NO_2-concentrations at 30 km/h.

4.2. NH_3 sampling positions

Figure 4 represents the sampling positions for gasoline vehicles. SP1 and SP2 are for undiluted and SP3, SP4 and SP5 for diluted gas.

The braking resistances were not increased i.e. responded to the horizontal road.

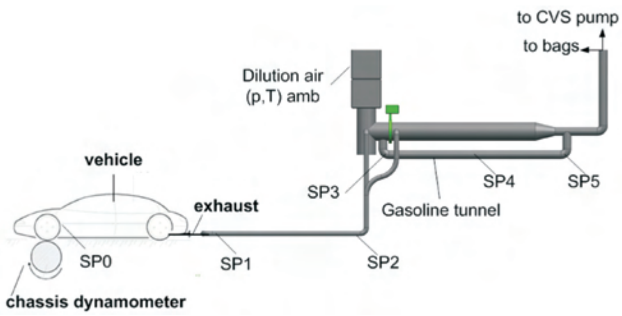

Fig. 4. Sampling positions (SP) for Gasoline vehicles – testing NH_3

4.3. Driving cycle

In terms of the driving cycles an approach to find a homogenized world-wide driving cycle was started with the on-going development of the harmonized WLTP world-wide light duty test procedure. The WLTC (world-wide light duty test cycle) should represent typical driving conditions around the world and is developed based on combinations of collected in-use data and suitable weighting factors by an expert group from different countries. This cycle has been used also in this study, Fig. 5. It represents different driving situations, like urban, rural, highway and extra-highway.

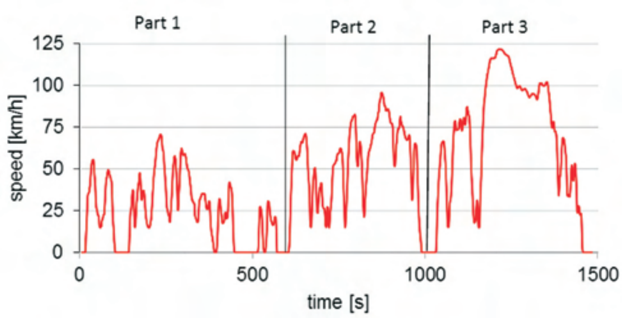

Fig. 5. WLTC driving cycle

5. Results

5.1. NO_2 Emissions of Diesel vehicles

In some test series the driving resistances were increased (simulation of slope) in order to increase the NO_2-values and to better study the NO_2 transport.

Figure 6 represents the NO_2-concentrations (ppm) at v = 30 km/h, at different sampling positions (SP) and in bags. The increased driving resistance (3% slope) was applied for both vehicles. (Remember that vehicle 1 and vehicle 2 is physically the same car, but used in different test sessions, 9 months apart).

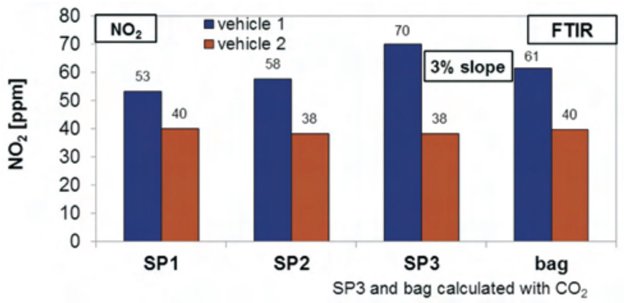

Fig. 6. NO_2-Emissions at different SP's and v = const 30 km/h

The tendency of increasing NO_2 from SP1 to SP3 for vehicle 1 is not confirmed for vehicle 2.

At sampling position SP3 the exhaust gas is diluted and the dilution factor (DF) is calculated with CO_2 concentration.

The estimate of values from diluted gas is influenced by the dilution factor (DF). Tests were performed with DF calculated from CO or NO, but the lowest dispersion was found for CO_2. This dispersion is in the range of ±3%.

In both tests the results from bag-measurement are similar to those of different sampling positions (SP).

The concentrations of N_2O and NH_3 (not represented here) were negligible, ($N_2O \sim 2$ ppm, $NH_3 < 0.3$ ppm mostly zero).

Comparing the repetition results with Opel Astra after 9 months (vehicle 2) with the previous results (vehicle 1) clear differences of NO_x- and NO_2-emissions were found.

The NO_2-differences are represented in Fig. 6. As a reason for these differences the EGR-valve is considered. The tested car is equipped with EGR-valve, which, according to the state of deposits, can vary on resulting EGR-rate at similar operating conditions of the engine. In reality the car was used at mostly low operating profiles before the 1st test campaign and it was used over longer periods at high operating profiles before the 2nd test campaign.

To confirm the hypothesis about the EGR-valve fouling the pneumatic control of this valve was deactivated for some tests and showed the expected impacts on NO_2 and NO_x.

The increased NO_2-emission of vehicle 1 from SP1 to SP3 in Fig. 6 may be explained with the influence of EGR-valve over the measuring time at v = const (over 1 h). The bag-values (as average) confirm the values at SP1, SP2 and SP3.

The question: "what happens with NO_2, if we increase EGR-rate at steady state operation?" cannot be simply answered, because there is an interference of contradictory effects at certain operating conditions, like reducing NO_x (and NO_2), but increasing the exhaust temperature (t_{exh}) and with it a possible increase of the $NO \rightarrow NO_2$ conversion in the catalyst, if the t_{exh}-range was below the NO_2 maximum production. This topic offers questions for further investigations.

For legislation or for the real world application nevertheless a dynamic operation is required.

In order to show the influences of slope and of EGR some repetitions of WLTC's were performed, one of them with deactivated EGR.

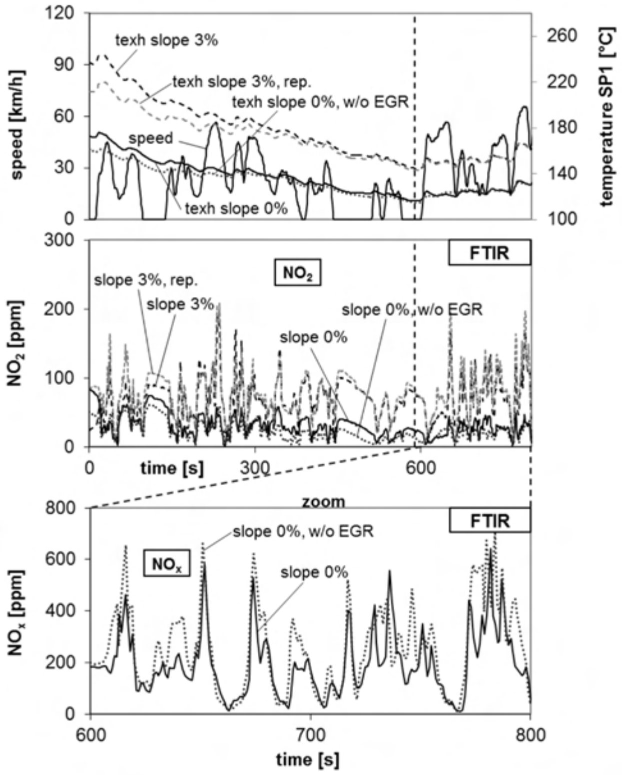

Fig. 7. NO_x and NO_2-emissions in WLTC with and w/o EGR, with slope 3% and w/o slope, vehicle 2, SP1

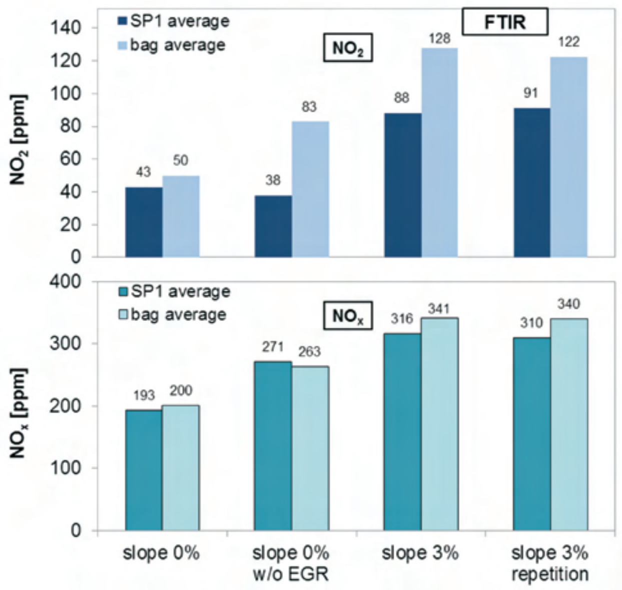

Fig. 8. NO_x and NO_2-emissions in WLTC with and w/o EGR, with slope 3% and w/o slope, vehicle 2

Figure 7 shows the traces of NO_2 and NO_x in a part of WLTC, at SP1, performed with and without EGR and with and without slope. A slope of 3% causes clearly higher exhaust temperature, in average, an increase of about 50°C was observed. Deactivated EGR increases the NO_x-peak values.

In the phases of zero-load (ex. 450–500 s) in the driving cycle NO_2-concentration increases depending on the temperature of the oxidation catalyst (maximum of NO → NO_2 conversion in the temperature range 300–350°C). With slope of 0% these NO_2-values are lower and DOC temperature is cooler. Without EGR NO_2-emission in the mentioned time-interval is lower than with EGR.

The repetitivity of t_{exh}- and NO_x-time plots is good.

Figure 8: a comparison of average NO_2- and NO_x-values in WLTC confirms: both emissions are higher at higher engine load (slope 3%); deactivated EGR increases NO_x and decreases (or keeps constant) NO_2 at tailpipe (SP1), but in the bags NO_2 w/o EGR increases.

There is for this vehicle and this configuration of exhaust gas lines and sampling a tendency of outstandingly higher NO_2-values measured in the bag. This suggests a supplementary NO_2 production in the bag.

Nevertheless, there are other possible reasons for deviations between undiluted (SP1) and diluted (bag) results. These reasons are: estimate of the dilution factors and the possible fluctuations of emission source during the long time of test (measuring at each SP one WLTC after the other). With these reasons the authors explain the differences of NO_x between SP1 and bag.

The comparison of results at different SP's at 50 km/h for all 3 vehicles is given in Fig. 9.

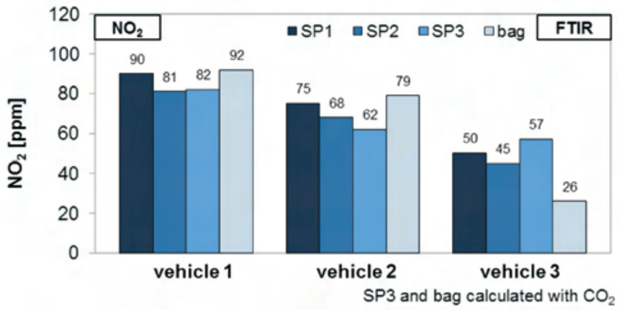

Fig. 9. Comparison of NO_2-results at different SP's and 50 km/h

There are no clear tendencies and small differences between the values at SP1, SP2 and SP3. It can be supposed, that this is more an effect of emission fluctuation during the time of switching the sampling sonde from SP1 to SP3, than any reactivity effects of NO_2. On one side, the vehicle speed is not absolutely constant, but fluctuates by approximately ± 1 km/h, on the other side, there are no clear, repetitive, regular effects showing increasing, or decreasing NO_2, which would be an indication of reactivity.

The bag-values are for vehicle 1 and 2 in the range of SP-values, while for vehicle 3 they are much lower.

The NO_2-emissions of vehicle 2 were on average lower during the repetition tests than for vehicle 1. This is explained with the cleaner EGR-valve (after more high-load operation) – the driving resistance was the same (3% slope). For vehicle 3 a slope of 5% was applied.

Figure 10 compares the results from FTIR in WLTC. In the bags, after dilution, there is for vehicle 1 and 2 some generations of NO_2- an effect, which is confirmed in repetition tests. Vehicle 1 was driven with 3% slope, while vehicle 2 with 0% slope, which is the reason for different NO_2-levels. For vehicle 3 there is generally a decline of the NO_2-values along the gas way and the total average (over the cycle), the bag-value is lower, than value at the tailpipe (SP1).

It can be summarized for the investigated diesel vehicles that the NO_2-concentrations in bags are generally higher for vehicle 1 and 2 and generally lower for vehicle 3, than the tailpipe values (SP1).

According to the conditions of flow, temperature and concentrations the NO_2 can be increased or reduced in the bags. The condition and functionality of EGR-valve offer further influences on NO_2.

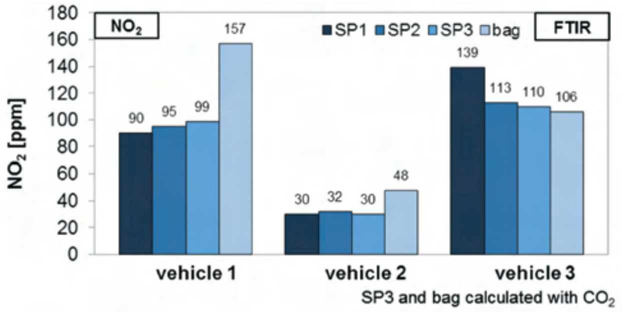

Fig. 10. Comparison of NO_2-results in WLTC at different SP's

5.2. WLTP-DTP measurement guidelines

The guidelines proposed by WLTP for NO_2 legal measuring procedures consider the feasibility with the present installations (CVS) and analyzers.

Two methods set-up #1 and #2 are possible to perform with the present equipment. They propose an indirect estimate of NO_2 by measuring continuously NO (with CLD) during the driving cycle and measuring NO_x from the bag. With the consideration of all necessary corrections NO_2 = = NO_x – NO. Set-up # 1 uses for all measurements one kind of analyzer whereas set-up #2 uses two analyzers.

In the applied method with 2 CLD-analyzers (set-up #2) the FTIR, or CLA were used as one of the CLD's in the present tests. CLD and CLA can be considered as equivalent systems, concerning the measuring principle and the calibration.

Figure 11 shows the comparisons of NO_2-results obtained in the WLTC warm with all vehicles and with different measuring methods: WLTP-DTP set-up #1 and #2 and time-resolved measurements with FTIR and CLD Eco.

Table 3. Measuring constellations according to WLTP-DTP in Fig. 11

Variant	Measurement	
	NO modally in CVS	NO_x in bags
Set-up 1: CLA	CLA	CLA
Set-up 1: CLD	CLD	CLD
Set-up 2: FTIR & CLA	FTIR	CLA
Set-up 2: CLD & CLA	CLD	CLA
Set-up 2: CLA & FTIR	CLA	FTIR

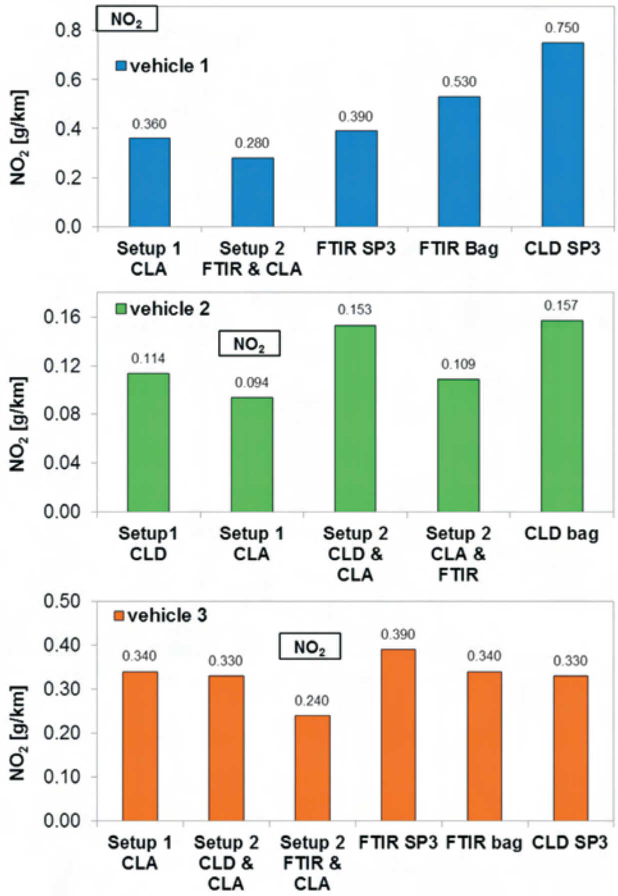

Fig. 11. Comparison of NO_2-results measured according to WLTP with different sets of analyzers

Table 3 explains the different variants of measuring constellations of set-ups #1 and #2, which are represented in Fig. 11.

There are different factors influencing the results (Fig. 11). For vehicle 1 the big dispersion of estimated NO2 is first of all an effect of varying EGR during the different tests – especially for "FTIR Bag" and for "CLD SP3" – test series with highest NO_2-values.

It has been found, that FTIR, due to its internal calibration indicates usually slightly higher NO- and NO_x-value, than CLD or CLA. This can partly explain the lower value of "set-up 2 FTIR and CLA", where FTIR measured on-line "NO" and CLA was used for bag "NO_x". (In the descriptions of set-up 2 in this figure the 1st system was used for on-line NO measurements and the 2nd system was used for summary bag NO_x).

For vehicle 2 there are two groups of NO_2-values: in the range of 100 mg/km and 150 mg/km. The dispersion of each group is quite little and the difference between them is a result of combination of emitting and of measuring dispersion. The average NO_2-level is clearly lower than for vehicle 1, but the interference, or irregularities of the EGR-valve cannot be excluded.

For vehicle 3 there is especially low NO_2-value for "set-up 2 FTIR and CLA". It comes out, that FTIR should not be used in set-up 2 together with another measuring principle (CLD or

CLA). If the results with FTIR would be left out of consideration, the remaining results with CLA and CLD are well corresponding to each other with a relative dispersion of 3%.

From these considerations, it can be said, that when there is a constant emission level of the car and if no FTIR (in this case) is used for set-up #2, the WLTP set-up #1 and #2 yield similar NO_2-results. These results are comparable with the off-line measurements from the bag or with the on-line time-resolved and integrated measurement in the diluted gas in CVS tunnel (SP3).

The use of "mixed" measuring techniques for set-up #2, like CLD and FTIR is not recommendable.

Figure 12 represents the integral average NO_x-values in WLTC (warm) obtained with different analyzers at SP3 (in diluted gas). This example shows vehicle 1 (with 3% slope) and vehicle 3 (0% slope). The analyzers are: FTIR, CLD (heated), CLA (cold) and bags (FTIR).

It can be remarked, that the cold measurement with CLA indicates overall the lowest NO_x concentrations. The integrated FTIR on-line measurements show for both vehicles higher values than those from bags.

The differences of some [ppm] are small but they can influence the estimate of low concentrations of NO_2, which is calculated as: $NO_2 = NO_x - NO$. These results confirm the recommendation of using the same type of measuring system for NO_2-estimates with set-up #2.

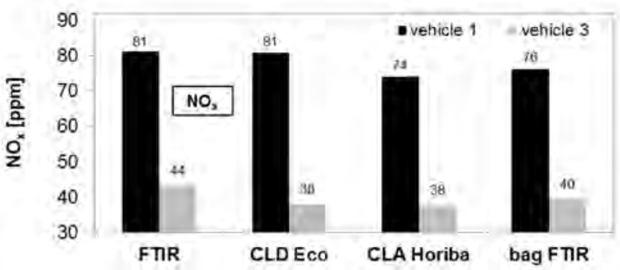

Fig. 12. NO_x in diluted gas (at SP3) with CLA-Horiba, CLD Eco. and FTIR in WLTC

5.3. NH_3 emissions from gasoline vehicles

Comparisons of NH_3-emissions of all vehicles (vehicle 4, 5 and 6) at all sampling positions are represented in Fig. 13 for 30 km/h and in Fig. 14 for 50 km/h. The average level of NH_3 of vehicle 4 (with older technology) is clearly higher, than for both newer vehicles.

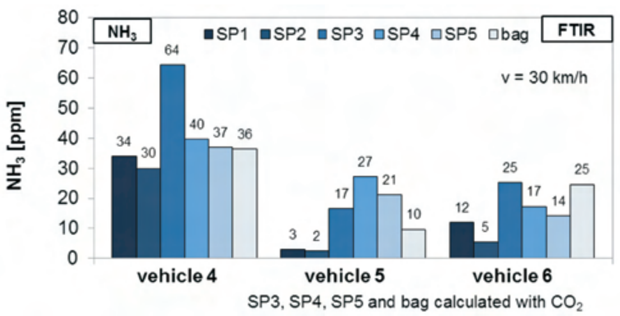

Fig. 13. Comparison of NH_3-concentrations (ppm) at constant speed 30 km/h

For vehicles 5 and 6, there are generally increased values of NH_3 at SP3 and the following SP's (calculated with DF). SP3 is the first measuring position after the dilution of gas.

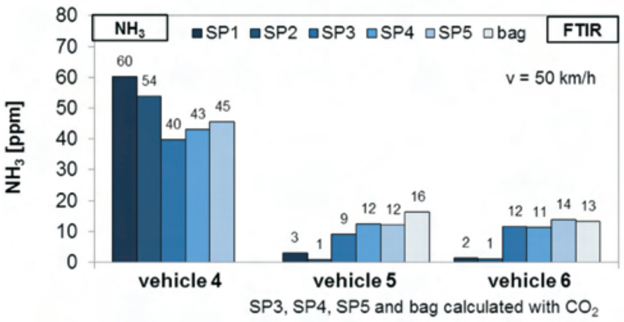

Fig. 14. Comparison of NH_3-concentrations (ppm) at constant speed 50 km/h

Figure 15 shows an example of time courses of diluted and undiluted emissions of NH_3 and N_2O during the test of vehicle 5 at v = 30 km/h. The time intervals of measurements and of switching the sampling sonde between the sampling positions (SP's) are visible. The undiluted values are obtained by multiplying the diluted values with DF.

At 50 km/h two CVS flows and consequently two dilution factors DF have been applied – Fig. 16 represents the integral average values. It can be seen, that with a double DF the values at SP3 to SP5 and bag are also nearly doubled. This means, that the low NH_3-values which were measured in diluted gas were at the detection limit of the FTIR and did not represent the real NH_3-concentrations any more.

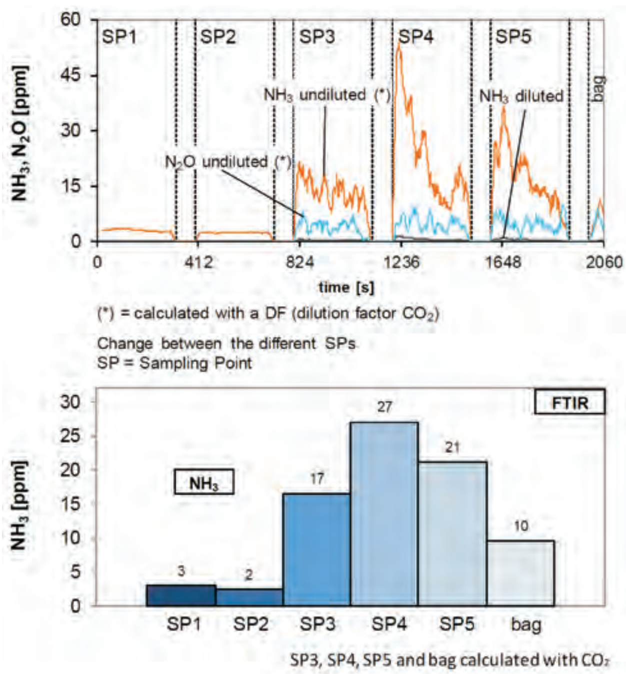

Fig. 15. Influence of dilution on NH_3-emissions at v = const 30 km/h vehicle 5; DF: 34.1

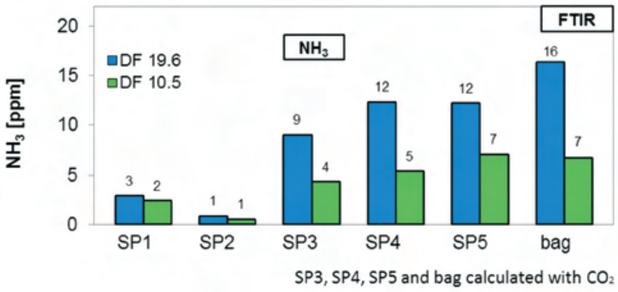

Fig. 16. Influence of dilution factors on NH_3-emissions at v = const 50 km/h vehicle 5; DF: 19.6 and 10.5

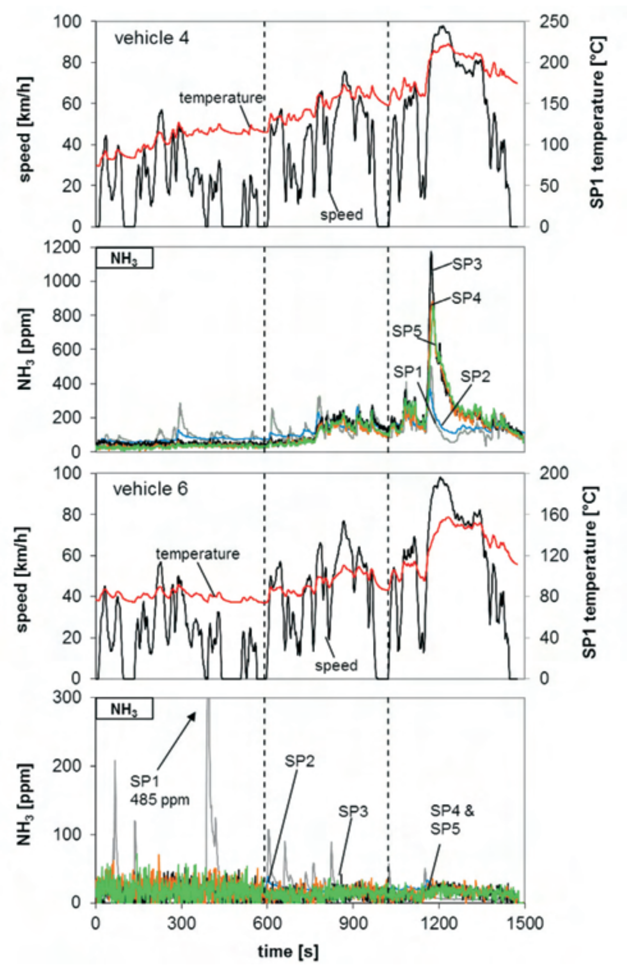

Fig. 17. NH_3-emissions in WLTC warm

This influence – measurements at the detection limit – is believed to be the major reason of non-valid results from diluted gas. The other postulated reasons – inhomogeneities in the flow, reactivity and store-release of NH_3 – are at these low concentrations most probably of lower importance.

Figure 17 represents the NH_3-concentrations in the WLTC for vehicles 4 and 6. Concentrations were measured at different sampling positions in undiluted (SP1 and SP2) and in diluted (SP3, 4 and 5) exhaust gas. There are some high peaks of NH_3, which occur systematically in all tests of the same vehicle and in the same operating profile of the cycle, like for vehicle 4 near to 1170 s. These peaks are the results of rich Lambda-excursions connected with higher exhaust gas temperatures. Another type of NH_3-spikes arrive randomly (only in one measurement) and are an effect of stochastic "release" from the exhaust system, like for vehicle 6 near to 400 s. They are most probably originating from the store-release effects of NH_3 and/or of NH_3 precursor substances.

Figure 18 compares the results of all gasoline vehicles (vehicle 4, 5 and 6) in WLTC, as integral average values. There is again a higher NH_3-emission level of the older vehicle 4.

There is a very good repetitivity of results (from SP to SP) for vehicles 5 and 6 from on-line measurements.

The bag values of the newer vehicles with relatively low emissions level tend to be higher than the average of all SP's. For the high emitting vehicle it is an inverse tendency: the bag value of this vehicle is substantially lower than on-line data would suggest. This indicates a tendency of reduction of NH_3 in the bag in case of high emission and increase of NH_3 in the bag in case of low emission.

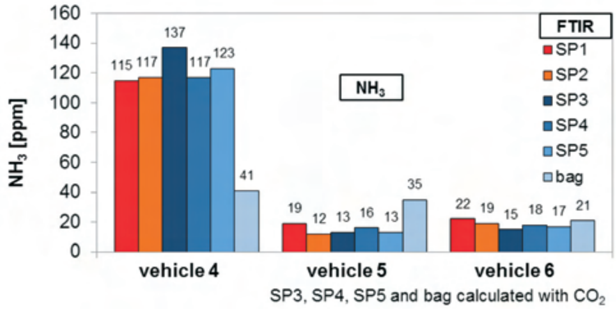

Fig. 18. Comparison of NH_3-results in WLTC

6. Conclusions

After investigations and repetitions of tests with Diesel and gasoline vehicles the following can be concluded:

<u>NO_2 from Diesel cars with oxidation catalyst</u>

- At steady state operation, the NO_2-concentrations in bags are generally higher for vehicle 1 and 2 and generally lower for vehicle 3, than the tailpipe values (SP1).
- According to the conditions of flow, temperature and concentrations in CVS-tunnel (due to different dilution factors with different vehicles) NO_2 can be increased or reduced in the bags, albeit based on the present results it is supposed, that the emission fluctuations during the measuring period constitute the principal influence on the observed effects.
- The present NO_2-results at constant speed operation do not indicate any regular, systematic changes of concentrations from SP to SP, which would indicate a chemical reactivity. Further research in this respect is recommended.
- The WLTP set-up #1 and #2 yield similar NO_2-results, like the direct measurement from the bag, or like the time-resolved and integrated measurement in the diluted gas in CVS tunnel; this on the condition, that no emission changes occur in the test period and unified, well calibrated measuring systems are used.
- The investigated indirect, integral WLTP – NO_2-measuring methods have been found as useful tools to estimate the NO_2-levels.

– Comparisons of NO_2-levels with other vehicles are not recommendable, since the present research was focused on the testing procedures and the NO_2-emissions of vehicles were increased by increasing the driving resistances of chassis dynamometer.

<u>NH_3 from gasoline cars with TWC</u>

– The vehicle with older technology had an approximately 10x higher NH_3-emission level, than the newer vehicles.
– In single phases of the WLTC the relationships of bag-values and the average SP-values are varying: there is a tendency of lower NH_3 in the bag for high emitting case and a tendency of slight increasing NH_3 in the bag for the low emitting cases.
– The results from diluted gas (also bag-values) in WLTC correspond better with the results from undiluted gas than at constant speeds; this is because of different emission profiles and different estimates of dilution factors in both operating modes.
– In certain acceleration events of WLTC high peaks of NH_3 emissions are observed; some of these peaks are repetitive (originating from rich Lambda-excursions) and some of them are stochastic (originating from store-release effects of NH_3).
– Emission level of newer vehicles, regarded as average of all SP's, is mostly below 20 ppm NH_3.
– The NH_3-concentrations in diluted exhaust gas in CVS-tunnel (SP3, SP4, SP5) and in bag are for modern, low-emitting vehicles close to the detection limit of FTIR and the results are biased from detector noise.
– The direct, undiluted measurement of NH_3 at tailpipe (SP1) can be recommended as the best variant. This direct measurement avoids the possible problems of: detection limit, contamination from dilution air, adsorption/desorption in CVS-tunnel and artefacts in the bag.

The present paper contributes to the experiences and knowledge about testing and emissions of NO_2 and NH_3 from passenger cars.

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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 institutions BAFU, ASTRA, EMPA, AEEDA, TTM, AFHB.

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Definitions/Abbreviations

AEEDA Association Europeenne D'Experts en Depollution des Automobiles
AFHB Abgasprüfstelle FH Biel, CH
ASTRA Amt für Strassen (CH)
BAFU Bundesamt für Umwelt, (FOEN)
CLA chemiluminescent analyzer
CLD chemiluminescent detector
CVS constant volume sampling
DF dilution factor
DI Direct Injection
DOC Diesel Oxidation Catalyst
DTP Diesel Test Procedures
EC European Commission
ECE Economic Commission Europe
ECU electronic control unit
EGR Exhaust gas recirculation
EMPA Eidgenössische Material Prüf- und Forschungsanstalt
FOEN Federal Office of Environment (BAFU), CH
FTIR Fourier Transform Infrared analyzer
GRPE Groupe Rapporteurs Pollution Energie (UNO ECE)
HC unburned hydrocarbons
HD heavy duty
IR infrared
JRC EC Joint Research Center
NDIR non dispersive infrared
NO nitrogen monoxide
NO_2 nitrogen dioxid
N_2O nitrous oxide
NO_x nitric oxides
OBD on-board diagnostics
SP sampling position
texh e xhaust temperature
TTM Technik Thermische Maschinen, CH
TWC three way catalyst
ULSD ultra low sulphur Diesel
VERT Verification of Emission Reduction Technologies
WLTC worldwide harmonized light duty test cycle
WLTP worldwide harmonized light duty test procedure

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On line engine oil consumption monitoring via the gaseous total sulfur signal SO_2 in the raw exhaust of the engine utilizing the sensitive ion molecule reaction mass spectrometry

The dynamic monitoring of oil consumption in IC engines is approached with various techniques ranging from radioactive counting to detection of halogenated tracer compounds or polyaromatic hydrocarbon tracers, to monitoring unburned hydrocarbons as residues from engine oil.

This article discusses the method of gaseous SO_2 measurement in raw exhaust it's benefits and limitations of today's status. Modern engines consume about 2 to 5 g/h of engine oil under low and medium load but consumption may go up to 130 g/h in negative load conditions. Particulate filters must be desulfated every 5000 km even when sulfur free fuel is in use. For the oil measurement in the raw exhaust all possible Sulfur compounds are converted to SO_2 in a hot oxidizing atmosphere. Additional pure oxygen in the form of ozone is added to the oxidizer for very low lambda engine conditions and the conversion of sulfur on particulates into SO_2. A sensitive mass spectrometer operating in an ion molecule ionization mode measures gaseous SO_2 from concentrations of 0.02 ppm to 50 ppm in measurement cycles from 2 Hz to 0.2 Hz depending on if long term measurement or dynamic operation is chosen. Technical description of pressure reduction, gas transfer, oxidation efficiencies and lower detection levels of the instrumentation are given as well as data on a complete engine map and data on reproducibility of the SO_2 method are presented.

Key words: *engine oil consumption, oil consumption monitoring, spectrometry*

1. Introduction

Downsizing of engines in cylinders and capacity, increasing compression ratios and MEPs, turbocharging, reduction of piston friction, use of CNG as modern fuel: all these strategies result in elevated temperatures of engine parts and engine oil, reduced oil viscosity, elevated blow by rates, and hence increasing oil loss of modern IC engines. Nitrogen traps as well as particulate filters reduce their operation efficiencies by the adsorption of sulfur compounds along their active sites of the catalyst and so complex desulfation strategies must be applied in today's after gas treatment technologies. Even when sulfur free fuel is used the amount of sulfur given by engine oil loss makes desulfation steps necessary every 5000 km of driving. Desulfation is typically achieved by injection of fuel or as post injection, however the amount of hydrocarbons must be chosen in a way that only SO_2 desorption takes place and not reduction of sulfur into H_2S. This would cause a severe odor problem and hence extensive testing is necessary. The reduction of any sort of sulfur in the raw exhaust is of high priority in engine development.

Monitoring engine oil consumption in dynamic measurements was performed since the 1970s with radioactive tracers added to the engine oil (J. Meyer – General Motors [1]). As radioactive materials were banned in many research facilities over the years many researchers in the past 20 years tested various non-radioactive oil tracer methods like pyrene added to engine oil and being detected by a laser ionisation mass spectrometer (Püffel Thiel BMW [2–4]), addition of dibromnaphtalene (V&F) [5]. Matz and Gohl (TU Hamburg Harburg) [6] developed aE oil consumption monitoring method based on measurements of high molecular weight hydrocarbons in the raw exhaust. The SO_2 method as described in detail below was developed by Rabl and Artmann (University Regensburg) [7] but also developed by other researchers like Moteur Moderne, Ford, Turkey, Da Vinci [8] Emission Services, or Horiba, Japan [9]. Still today there are no clear preferences of one or the other method of monitoring and depending on engine types and fuel used one or all methods may work for oil consumption monitoring. To us the SO_2 method seams to be the most reliable and easiest to use technique as should be shown below.

Tracers in engine oil bear two intrinsic problems. First, they must withstand the high combustion temperatures in the cylinder in order not to oxidize and so to change their chemical structure and the second restriction is their single boiling point temperature, compared to a boiling point curve from 200 to 400°C of the engine oil. Low boiling point tracers will be distilled out of the oil over operating time and thereby reduce the concentration in the oil and high boiling point compounds like pyrene cannot be detected well at low oil temperatures and more at low exhaust gas temperatures.

The survival of tracers at high combustion temperatures may be tackled with inorganic halogenated compounds but halogenated compounds may form aggressive acids that are not welcome by engine operators.

Another approach is the addition of aromatic compound like pyrene that have very high flame resistance but also have high boiling points and will condensate at low oil temperatures and low engine load applications.

There are specific compounds in the engine oil that are not present in fuels and hence could be detected in the raw

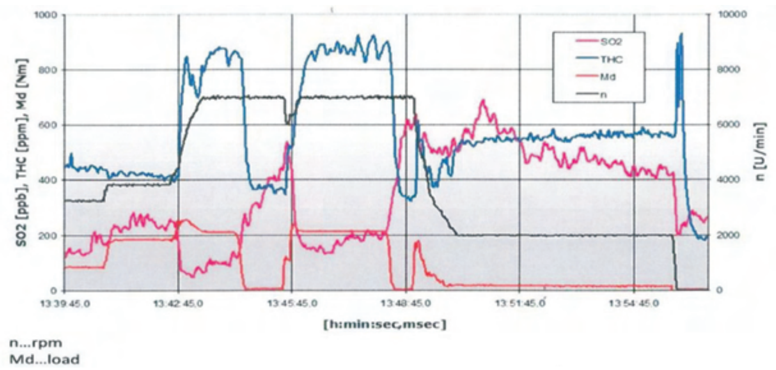


Fig. 1. Measurement of oil throw limit at high rpm and transition from high load to no load

exhaust gas as information of engine oil loss. Zinc and phosphorus additives in engine oil would represent specific markers of engine oil if they came in a gas phase but they are not; they leave the combustion zone in oxidized states with no gaseous vapor pressure and condense along surfaces.

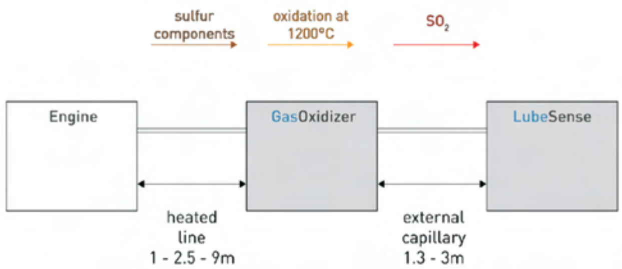
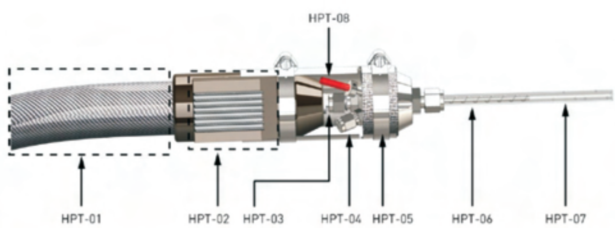


Fig. 2. Schematic setup for oil consumption measurement

Organic sulfur additives to engine oil leave the combustion chamber as gaseous sulfur compounds, mainly as SO_2. Under some combustion conditions like in very low lambda burning as in negative load operation of the engine H_2S, CH_3SH is formed, in soot formation conditions sulfur attaches to particulates and in very high temperature flames carbon monoxi sulfide COS may be formed. All these gaseous sulfur compound may add up to 3% next to SO_2 as main Sulfur emission. Since oil transport into the combustion chamber is in both liquid and vapor form, a consistent sulfur concentration in the oil is required in order to assume that consumed oil in the exhaust that has the same concentration of sulfur as in the original oil.



Connector	Description	Connector	Description	Connector	Description
HPT-01	Body of heated gas transfer line	HPT-04	Connection for HPT calibration port	HPT-07	Gas extraction probe
HPT-02	Power supply heated gas transfer line	HPT-05	Stabilization frame for Heated Probe Tube	HPT-08	Power supply for Heated Probe Tube
HPT-03	Mounting point for Heated Probe Tube	HPT-06	Heating wire Heated Probe Tube		

Fig. 3. Connector layout for V&F heated prove tube in oil consumption measurement

2. Exhaust gas extraction from engine and pressure regulation

Sample gas should be taken in front or after turbo charger and long stretches of cast iron manifold should be avoided. Cast iron has a strong tendency to store SO_2 by adsorption and so memory effects can be seen at changing temperatures of cast iron (stainless steel does not store SO_2). The gas extraction has a heated tip reaching into the manifold and a heated ceramic filter. This assures high enough temperatures of the gas to avoid condensation at low exhaust gas temperatures.

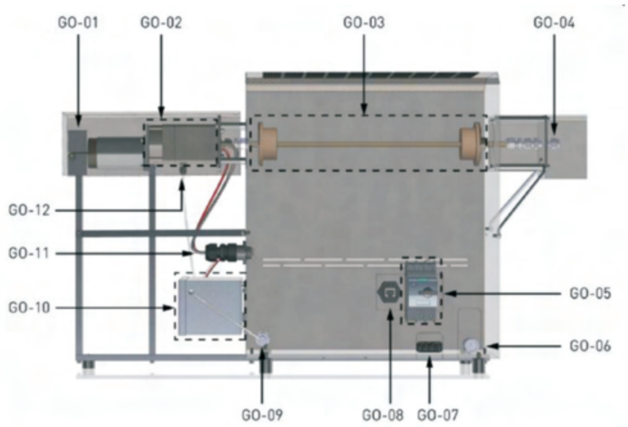
Right after the gas extraction a fast pressure regulator keeps a constant gas flow rate of 1 liter per minute in the pressure range from 0.3 to 8 bar of manifold pressure.

3. Back-flash and calibration gas inlet

Behind the front tip of the gas probe gas can be added to the gas transfer line. This done out of 2 reasons. First a back flash gas can keep the gas line clean from soot and condensation water during engine stop or cold start and secondly SO_2 calibration gas may be flushed through the gas line. By activating the calgas two features of the transfer line may be verified. First the degree of contamination. The analyzing system has a t_{90} gas response time of 50 msec oxidizer has a response time of 300 msec. In case the response time on SO_2 becomes more than 2 seconds a contamination of the gas line mostly by soot particles is indicated. Another important check with SO_2 calgas added at the tip of the transfer line is the measurement of the overall gas travel time from manifold to analyzer. This time becomes important when dynamic and instationary time resolved oil consumption is measured. As the electric signals of mass fuel flow and engine air flow are ahead of the SO_2 gas signal a correction of this travel time must be done in the calculation of mass output of oil.

4. Oxidizing oven

H_2S, COS,CS_2 and sulfur bound on particulates can be oxidized to pure SO_2 gas phase in a high temperature O_2 containing environment. Temperatures generated by a heated filament along a ceramic tube must be in the range of 1200 deg and residence time of the exhaust gas at these temperatures should be no less than 20 msec. A constant flow of exhaust gas between 1 to 2 liters per minute allows the necessary residence time in the hot oxidizing zone. For engine operating conditions below lambda 1 where the residual oxygen concentration in the raw exhaust goes to zero, additional oxygen must be added to the oxidizing chamber. An additional gas flow of pure O_2 controlled by a mass flow controller at 60 ml per minute is added to the sample gas and is sufficient to guarantee enough oxygen even under Lambda 4 operating conditions.



Connector	Description	Connector	Description	Connector	Description
GO-01	Mounting point for heated gas transfer line	GO-05	Automatic circuit breaker	GO-09	Ozone Generator inlet connector
GO-02	Pressure reducer and mixing chamber	GO-06	100% Oxygen inlet	GO-10	Ozone Generator
GO-03	High temperature zone with alumina rod	GO-07	Power cable port	GO-11	Mixing chamber heating connector
GO-04	Mounting point for AirSense external capillary	GO-08	Optional: RJ45 communication port	GO-12	Ozone Generator outlet connector

Fig. 4. Connector layout for V&F heated prove tube in oil consumption measurement

Fig. 5. Mass spectrometer

5. The monitor

The instrument in use is based on an ion molecule reaction mass spectrometer described in [10, 11].

A high vacuum chamber houses electromagnetic devices that separate ions of different molecular weight and count these ions in short (msec) time intervals. The formation of ions from the sample gas molecules is achieved by charge exchange from an ion beam to the neutral molecules in two body collisions. This technique suppresses background matrix interferences to a minimum and realizes a high linearity over 4 orders of magnitude. The ion counting system enables either very low detection levels 10 ppb at 3 sec or a high time resolution of 100 ppb at 300 msec.

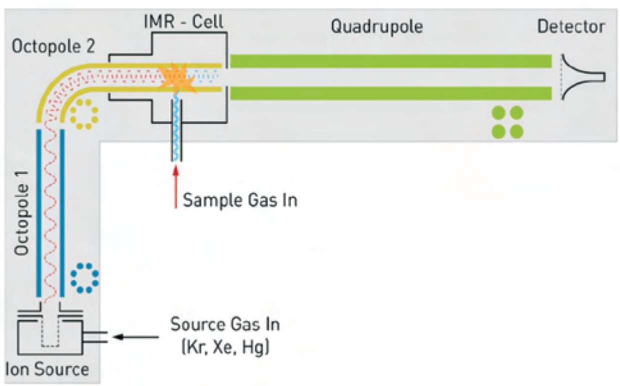


Fig. 6. Principle of mass spectrometer measurement

6. Measurement boundary requirements

To properly measure the amount of oil consumed the other sources of sulfur should be minimized, or better still, eliminated. There are two other sources that can alter the amount of sulfur present in the exhaust gases: air and fuel. Air contributes very little sulfur to the combustion products. However the common gasoline that is purchased at the pump may have a relatively higher amount of sulfur. So for this method low sulfur research gasoline which has a sulfur percentage of less than 2 ppm has to be used. The oil consumption rate is calculated from mass flow rate of fuel and air, and total sulfur concentration in oil, fuel, air and exhaust gas. At higher sulfur levels there will be a higher offset in the SO_2 signal and the resolution of SO_2 measurement related to engine oil is diminished.

Sulfur content in CNG gas may be determined easily by running CNG fuel air mixture through the oxidizer and measuring the SO_2 level.

For long term experiments a supply of fuel should be stored as there are variations of sulfur content in online fuel supply lines.

6.1. Sulfur defined engine oil

Standard engine oil has a sulfur content from 3000 to 5000 ppm. For very sensitive oil consumption measurements

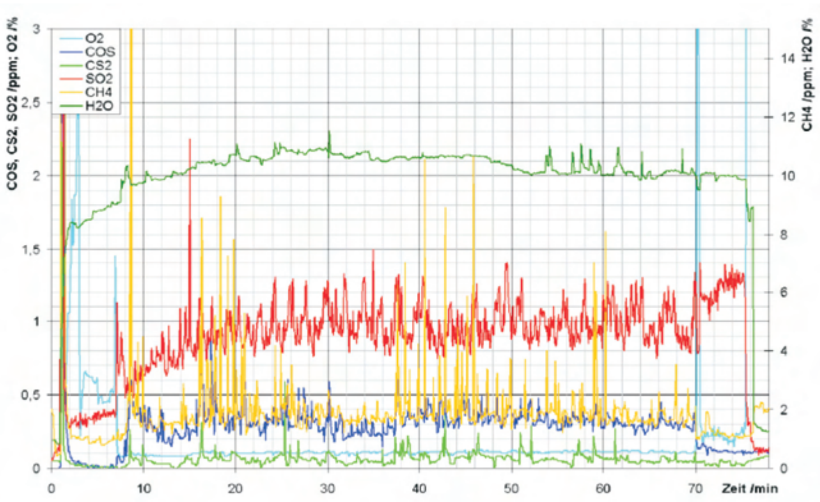


Fig. 7. Distribution of sulfur compounds in the raw exhaust of a normal aspirated engine (Rabl, Artmann FH Regensburg)

a content of 10000 ppm is desirable and may be purchased from companies like Lubrizol. In any case a proper sulfur analysis of the engine oil is desirable. After changing to a fresh oil the engine should run for 3 hours to standardize the sulfur components in the oil. From experience it is known that engine oil slowly diminishes the sulfur content after 30 to 50 hours of operation. In cases where heavy fuel contamination of the engine oil is an issue the sulfur content should be analyzed in 10 hour operating periods.

Fixed values of mass flow or online data are given to the monitoring instrument in order to convert the ppm signal of SO_2 into g/h or g/kWh signals.

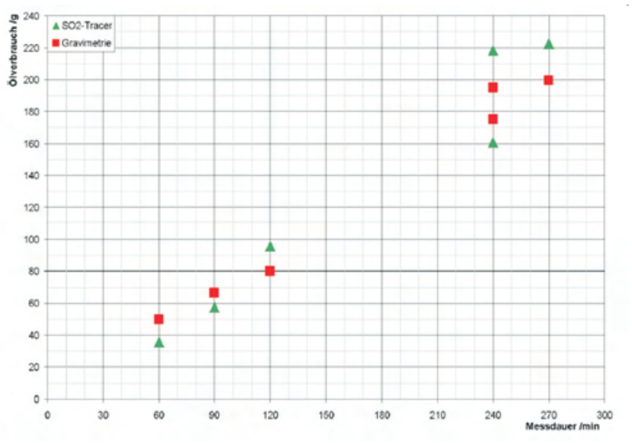


Fig. 8. Comparison of gravimetric and SO_2 measurements (Artmann, Rabl, FH Regensburg)

6.2. Measurement examples

The picture below shows a time resolved measurement of various molecular gaseous compounds from the raw gas of a normal aspirated engine running in unstable combustion caused by a high throughput of oil. The graph shows that within several sulfur compounds SO_2 is by far the highest signal in the raw exhaust. The oxidizing oven does convert all of CS_2, H_2S and COS into SO_2.

7. Comparison and difference of the SO_2 method against gravimetric measurements

The classic way to obtain oil consumption of an engine is running the engine for a length of time, typically 10 hours and then draining the engine oil pan. Determining the difference in weight before and after should describe the engine's oil consumption. For some measurements like the one shown below (Rabl, Artmann) the two methods show good agreement. For other operating conditions this cannot be the case. The basic difference of the gravimetric method compared to all tracer methods where the oil loss is measured by a signal in the raw exhaust is:

Tracer methods show the amount of oil passing the combustion region as a positive signal, whereas the weight loss of engine oil is a negative signal. Not only are oil leaks on engine seals included in the gravimetric signal, but also aldehydes that can be formed in the oil and result in sludge sticking to the oil pan and it also includes oil dilution by fuel input to the oil that may even result in a weight gain of the engine oil.

Gravimetric determination of oil consumption gives an integral signal of oil loss over the period of time. This is a disadvantage in developing engine components to minimize oil loss. Tracer methods, especially the SO_2-method allows a dynamic study of oil loss under transient engine conditions.

Oil loss of engines are measured with different test procedures. In engine development a comparison between a standard piston, piston rings and liner is made against modified parts in another cylinder of the same engine. Large engines like ships and power generator engines are operated in stationary modes in various load conditions and so the values are given in g/kWh. The oil consumption may reach up to 100 kg of oil in 24 hours. For small engines there are test cycles in use like the " Tokyo test" where the engine in operated between idle and low load, low rpm sequences for 20 min time intervals. Other tests use the standard FTP test as is seen below. The figure below expresses the characteristic reproducibility of test runs.

8. Conclusion

The SO_2-monitoring technique in the raw exhaust with an oxidation chamber between gas extraction and analyzer for a complete conversion of sulfur-containing molecules and particulates into SO_2 is more and more accepted by engine developers as the most universal technique. The disadvantage of need of sulfur free or very low and constant sulfur levels in the fuel is compensated by a simple calibration procedure. Other tracer methods suffer in complex calibration procedures or nonlinear loss of tracer during operation. Over the past years sensitivity and selectivity of the SO_2-detection method was improved. Matrix effects of fuels like

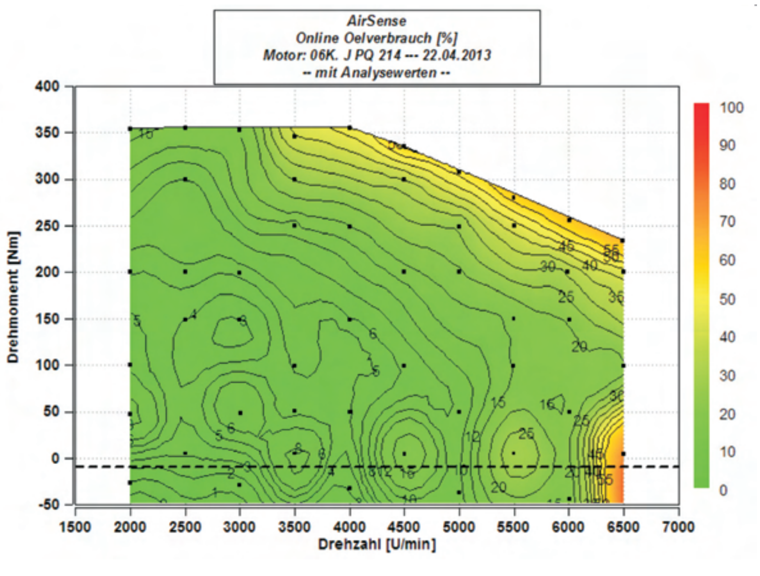


Fig. 9. A map of stationary operating points of rpm against torque of a engine (courtesy of Audi)

O_2 and water content were eliminated, as especially was the particulate load under rich operating conditions by the high temperature oxidizer concept with the addition of ozone. A special high temperature pressure reduction system allows to extract low flow volumes of 1 to 3 l/min gas from high pressure regions before turbocharger. Zero and calibration gas is directly fed into the onset of the probe line, hence gas travel times can be measured accurately and contamination of gas lines is detectable without decoupling the system from the engine. The highly sensitive ion molecule mass spectrometer setup is built with sulfur free components for low background signals and the additional control of H_2O signal and O_2 signal (50 sec measure time) assures that no water condensation along the gas lines and connectors (H_2O signal spikes when droplets are formed) occurs and that there is always enough oxygen present even under very rich engine operating conditions. A further development within engine oil analysis bears the measurements of water and aldehyde content in engine oil for a on line determination of oil degradation over operating time of the engine.

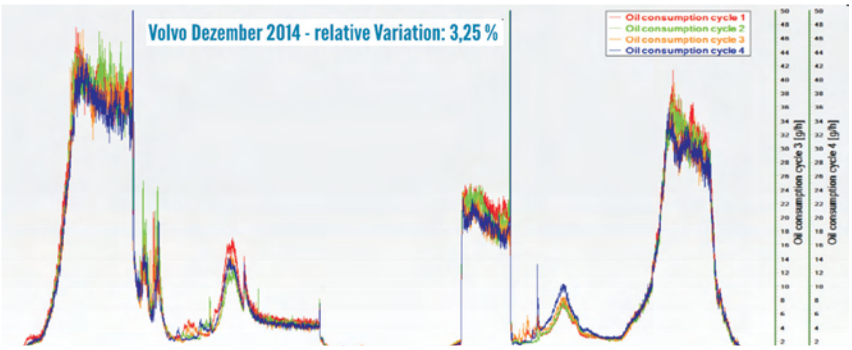


Fig. 10. Repeatability oil consumption in test cycles

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Ethanol as an automotive fuel – a review

Usage of ethanol as a fuel has been known for hundreds of years. However, recently usage of ethanol and its blends as a road transport fuel has increased and interest in its use is growing. There are a lot of pros and cons connected with using ethanol, which are described in this paper. This paper reviews current knowledge on using ethanol in spark ignition engines. The fuel is described in the context of future opportunities. A significant part of the paper is dedicated to the analysis of ethanol and its blends' impact on regulated and unregulated exhaust emissions, including laboratory results obtained by BOSMAL from chassis dynamometer testing of European vehicles.

Key words: *SI engine, alternative fuel, biofuel, ethanol, bioethanol, ethanol-gasoline blend, exhaust emission*

1. Introduction

1.1. Ethanol: history and basic information

Biofuels are becoming more and more popular and ethanol is no exception; it is becoming important in the automotive industry. There are multiple reasons for this situation:

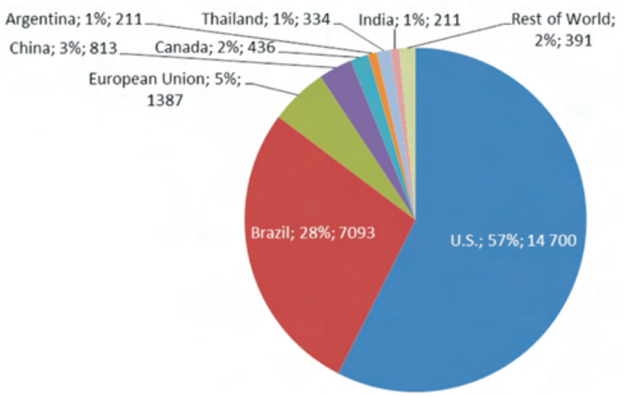

Fig. 1. Worldwide ethanol production in 2015 [32]

- Policy:
  - international security,
  - national security,
  - public policy,
  - environmental policy.
- Economy:
  - international prices,
  - investment regimes,
  - Sustainable development.
- Energy:
  - energy mix,
  - renewable energy usage
  - energy infrastructure
  - energy efficiency,
  - energy innovations and R&D.

Ethanol and its blends are major fuels for many countries and they are the widely used biofuels. The global leader in ethanol production is the USA; in 2014 more than 54 million litres were produced there. The second biggest producer is Brazil with 23 million litres. Europe holds 3rd place; further details can be found in (Fig. 1) [32].

Using ethanol as a fuel for engines is not a new idea. It was first used in American Samuel Morey's ethanol-turpentine internal combustion engine [24]. Many early build automobiles at the beginning of the 20th century ran on ethanol. Engine designers found advantages of ethanol in comparison to gasoline, being mostly interested in adding alcohol to gasoline and thermal engine efficiency consequence and operational stability [7, 35].

Beginning of ethanol large scale production in US and EU is attributed to the 1920's when in 1925 Henry Ford published article where he sad that future fuels will be produced from plant waste and fermented fruits. In 1928 started first ethanol based Polish fuel production which was blend of 30% ethanol and 70% gasoline [35]. After second War World because of high production cost and low crude oil prices ethanol was not popular. Concept of using ethanol as a fuel came back during fuel crisis in 1970's. It is assumed that in that time US could produce up to 190 million litres of ethanol per year [13].

Since the 1990s, emission standards have become more and more stringent, resulting in the fact that ethanol has been the subject of a lot of studies focussing on emission impacts and exhaust gas components. Recent studies have focused on the issue of necessary modifications to adapt gasoline engine to ethanol or gasoline-ethanol blends [7, 8].

Nowadays, world production and transport consumption of ethanol has a growing trend. Most actual trend is a production second generation of bioethanol from non-food feedstock. Motivating factor of ethanol fuel development are government support and grants. [28] Ethanol implementation is a complex subject involving political, legislative, economic, logistical, technical and environmental dimensions [7, 33, 38]. Ethanol could provide multiple positive effects – e.g. energy security due to independence from crude oils, higher engine efficiency due to high compression ratio or reducing concentrations of harmful exhaust gas components [7, 37, 39].

1.2. Ethanol production processes and the ILUC issue

Ethanol could be produced from crude oil, but is commonly produced using biomass. Ethanol produced from biomass is often called bioethanol. Bioethanol can theoretically limit greenhouse up to 87% over conventional fossil fuel, but this is strongly connected with production process and the feedstock [19]. Bioethanol is divided into first and second generation due to biomass from which is produced. First generation is produced from sugar rich edible feedstocks. In the USA it is mostly corn; in Brazil sugar cane. Second generation is produced from non-food feedstock (cellulose, organic waste, food crop waste. [16, 22, 34]. Transfer from first to second generation is forced by ILUC considerations.

Many croplands which were previously used for food cultivation were transferred to ethanol feedstock production. Because food croplands are still necessary other land types like forest and grasslands which transform high level of CO_2 are transformed to agricultural production, which could increase the atmospheric CO_2 level. Due to that facts and second generation biofuel process technology issues Europe Parliament reduced advanced biofuels goals. Energy from first generation biofuels produced on agricultural land shall be no more than 7% of the final consumption of energy in transport in the Member States in 2020 year (previous goal were 10%). In this context and low crude oil prices development of ethanol engines will probably slowdown in Europe. Outside Europe applications of ethanol itself and its blends with gasoline in the transportation sector are the most widespread in Brazil (E5–E85, E100), USA, Thailand (E75) and China [7, 14, 17, 18], although in China ethanol faces competition from its close relative methanol.

2. Ethanol fuel properties

Ethanol is a primary alcohol, is the second simplest alcohol, often abbreviated as C_2H_5OH. It is volatile, flammable, transparent, colorless liquid. Ethanol produced from biomass could be fully biodegradable and renewable [16, 22]. Another advantage is that it has high octane number in comparison to gasoline. Ethanol very easy absorb water which make it problematic to storage. Moreover, it has a higher density and viscosity than gasoline [22, 29, 31] and is generally more penetrative

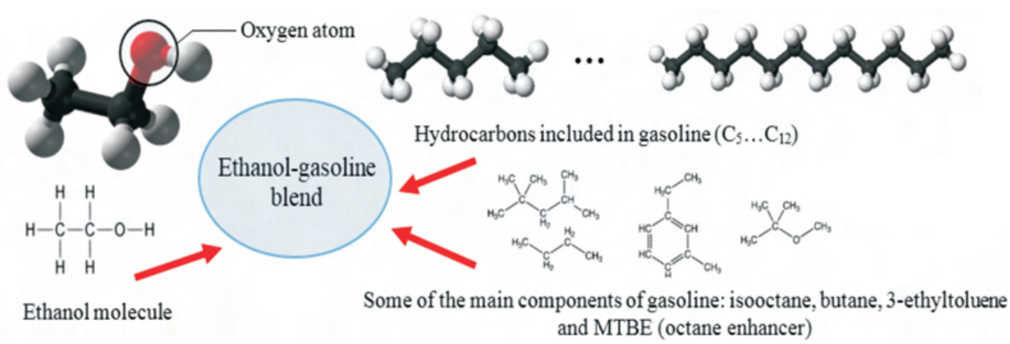

Fig. 2. A comparison of the ethanol molecule and compounds contained in standard gasoline [3]

Table 1. The physicochemical properties of ethanol and gasoline [7]

Parameter	Unit	Gasoline	Ethanol (E100)
Chemical formula	–	Mainly hydrocarbons: C5-C12	C_2H_5OH
Molecular mass	[kg kmol^{-1}]	114.15	46.07
Specific gravity	[kg m^{-3}]	0.7–0.78	0.794
Density at 15°C	[kg/m^3]	750–765	785–810
Kinematic viscosity	[mm^2/s]	0.494	1.221
Heating value	[MJ/kg]	42.7	26.8
Latent heat of vaporization	[kJ/kg]	380–400	900–920
Volatility index	–	> 840	< 234
Lubricity* (PN-ISO 12156-1)	[μm] *	≈ 760	< 600
Vapor pressure (at 37,815 °C)	kPa	53–0	17
Research Octane Number (RON)	–	95	108.6–110
Auto-ignition temperature	[°C]	257	425
AFR ratio	–	14.2–15.1	8.97
C:H ratio	–	0.53	0.33
Carbon content	[% mass]	87.4	52.2
Oxygen content		Negligible	34.7
Hydrogen content		12.6	13
Water content		Negligible	0.5–5 (depending on quality and storage conditions)
Solubility in water	[%]	0	100

Table 2. The physicochemical properties of selected ethanol-gasoline blends [7]

Parameter	Unit	E10	E50	E85
Volumetric percentage of each compound	[v/v]	10% ethanol 90% gasoline	50% ethanol 50% gasoline	85% ethanol 15% gasoline
Density at 15°C	[kg/m³]	756	772.4	788.9
Vapor pressure (at 37.815°C)	[kPa]	57.8	51.4	32.5
Heating value	[MJ/kg]	41.24	33.72	30.38
Volatility index	–	903	714	234
Lubricity* (PN-ISO 12156-1)	[µm*]	823	724	636
Research Octane Number (RON)	–	96.6	103.2	106.8
C:H ratio	–	0.51	0.44	0.36
Hydrocarbon content:	% (v/v)	40.8	25.2	8.5
– olefin hydrocarbons		10.5	5.7	1.6
– aromatic hydrocarbon		30.3	19.5	6.9
Benzene content		0.67	0.38	0.13
Compounds contain oxygen		13.31	51.16	85.74

through physical barriers [1]. Ethanol has higher energy density than gaseous fuel and relatively low carbon to hydrogen ratio (0.33) and is partially oxidized.

Theoretically, ethanol combustion produces only two products – CO_2 and H_2O:

$$C_2H_5OH + 3O_2 \rightarrow 2CO_2 + 3H_2O + \text{heat}$$

Unfortunately, the reduced H_2 content reduce also calorific value of fuel [2, 20, 22, 29]. Ethanol is more often splash blended with gasoline to form ethanol-gasoline blends (see Figure 2), than using neat. Volumetric percentage is defined by number following the letter "E" in its name. For example, commonly used in Brazil E85 means that it is ethanol gasoline blend with 85% volume of ethanol. Physicochemical properties of neat ethanol and its blends with gasoline are shown in Table 1 and Table 2.

3. Ethanol impact on vehicles

3.1. Regulated exhaust gaseous emissions

For many years BOSMAL has conducted research on ethanol blends' use as a fuel and the resulting missions. Samples of results obtained in those research programs are presented in the following section.

Regulated emissions can be defined as emissions for which limits exist in the EU's Euro 6 standard (HC, NMHC, CO, NO_x for all SI vehicles, along with PM and PN for vehicles with direct injection engines), in addition to CO_2 (which is regulated separately and is subject to fleet average limits). Regulations require testing of vehicles on a chassis dynamometer under laboratory conditions. Most of BOSMAL's studies have been carried out on unmodified gasoline vehicles. Because of start-up difficulties, drivability and material compatibility issues tested were only low-to-mid ethanol blends up to E50. The only exception was testing E85 in unmodified non-FFV. It managed to execute the NEDC driving cycle but some drivability issues were observed and there were excessive HC emissions during the UDC phase of the cycle.

Bielaczyc et al. [9, 10, 12], tested unmodified small-displacement European passenger cars running over the NEDC in the field of regulated emissions, CO_2 and fuel consumption. With increasing ethanol content up to 50% HC and CO are going down. Opposite situation is with NO_x which were growing up to E25 (see Figure 4). In study [11] HC and emission data were similar for blends E5, E10 and E25. Emissions were non-linear in the range E5–E85. In results from [10] there is no correlation between HC and CO emissions performance. The latest investigation [13] proved a part of previous conclusion and finally that blends higher than E25 does not change anything or are unpredictable.

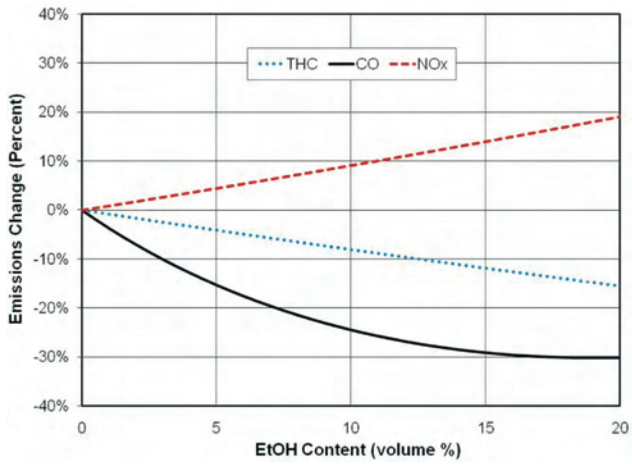

Fig. 3. Trends of emissions of THC, CO and NO_x over the range E0–E20. Note that the figure shows trends, rather than raw results (taken from [15])

In literature can be found similar analysis. Crawford an co-authors [15] published results from analysis of fuels E0 to E20 shown in Figure 3. THC and NO_x characteristic are linear. THC decrease. Together with Ethanol content, opposite situation is with NO_x which increase. Decrease of CO is logarithmic

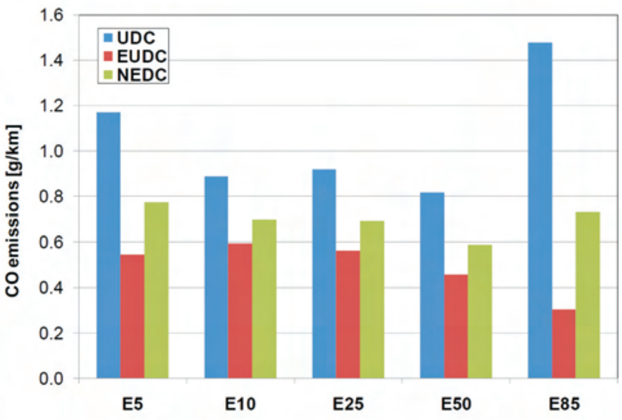

Fig. 4. Exhaust emissions of CO from an unmodified car running over the NEDC on various ethanol blends [27]

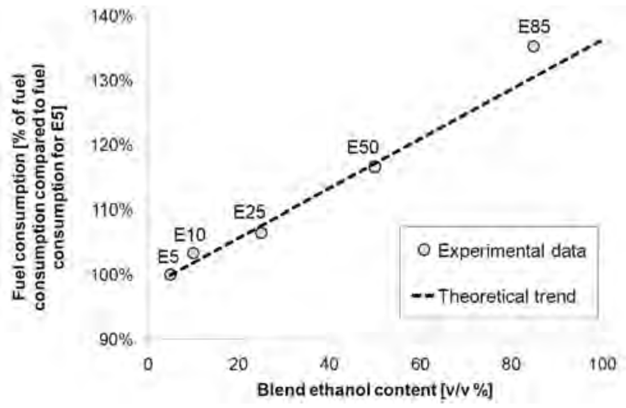

Fig. 5. Fuel consumption for an unmodified car running over the NEDC on various ethanol blends [27]

3.2. CO_2 emissions and fuel consumption

Emission of CO_2 is primary parameter which is always measured in emissions tests. The carbon weight fraction of E85 is lower than that of E0. That suggest that CO_2 emissions should be lower. However E85 has much lower energy content. Due to that fact decrease of CO_2 is not so obvious. Fuel consumption is linearly growing together with increase of ethanol content and the same decrease of energy (Figure 5). E85 fuel consumption is slightly out of that trend. It is connected with combustion difficulties confirmed with high CO (Figure 4) and HC emissions. The same situation was confirmed again by BOSMAL in [12].

Yanowitz & McCormick [40] examined a wide range of data running E85 on FFV and presents them compared to standard petrol in FFV and non-FFV cars. They proved that emissions could be reduced by 10% of NMHC, 10% of CO and 18% NO_x but CH_4 emissions is increased by around 100%.

3.3. Exhaust emissions of particulate matter

Vehicles with SIDI engines are tested on PM emissions limit since Euro 5 standard implementation. Now Euro 6 standard limits also PN in such an engines. Figure 6 demonstrate tailpipe PN emissions rates during FTP cycle for two fuels, E0, E45. Showed cycle is split into two parts (UDC and EUDC). As usual, emissions correlate with acceleration. Emissions peaks are much smaller with E45 fuel but level of decrease is not the same during all the cycle. Study of PM and PN emissions with different ethanol blends were made also by Marciq et al. Measurements were based on turbocharged direct injection gasoline LDV with two different engine calibrations, A – Figure 7 and B – Figure 8 (changed ECU parameters: fuel pressure, fuel injection, spark timing etc.). Used fuels were E10, E17, E32, E45 and E85. Test were made using two measurement methods, by sampling directly from the tailpipe and through sampling dilution tunnel. Test cycle was based on FTP cycle with three phases: cold start, urban, and hot start. PM measurements test methods were filter and DMM, which measure total PM (including soot and semivolatiles), agree is about 15%. It can be sad that with ethanol content increase, PN and PM emissions decrease.

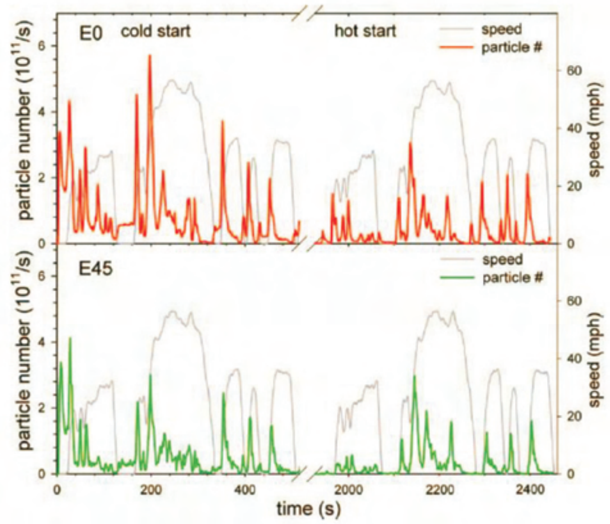

Fig. 6. Gasoline direct injection engine vehicle PN emissions under transient FTP cycle. Top E0 fuel; bottom E45 fuel [27]

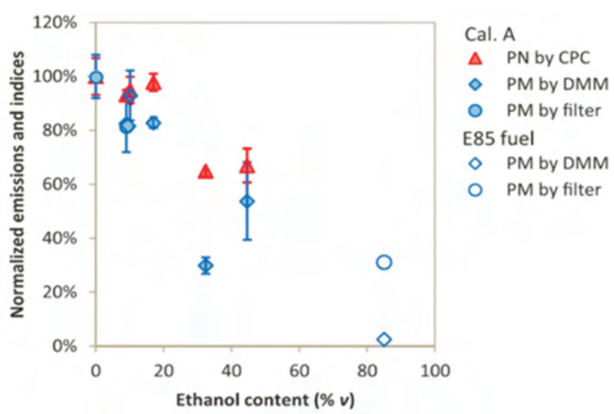

Fig. 7. Vehicle PN emissions and PM emissions by DMM and by filtration, on FTP cycle for vehicle calibration A [21]

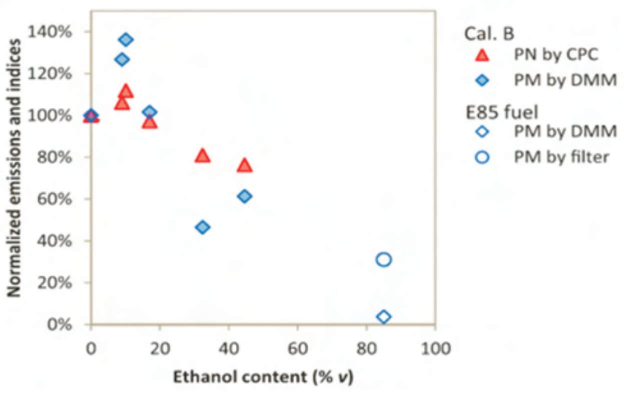

Fig. 8. Vehicle PN emissions and PM emissions by DMM and by filtration, on FTP cycle for vehicle calibration B [21]

Similar tests were performed by BOSMAL (Figure 9 and Figure 10) [9] where PM and PN were measured with UDC and EUDC cycle. BOSMAL test does not shows the same linearity. It should not be assumed that higher ethanol content always gives lower PM and PN emissions. Bielaczyc et al. [11] checked PN and PM emissions of SIDI vehicles in NEDC cycle with E5–E50 fuels. It is hard to find any emission vs ethanol content characteristic. Only decrease PN emission characteristic in EUDC cycle is visible (Figure 9 and Figure 10). Testing PM emissions at a temperature of 7°C showed a decrease in PM with increasing ethanol content.

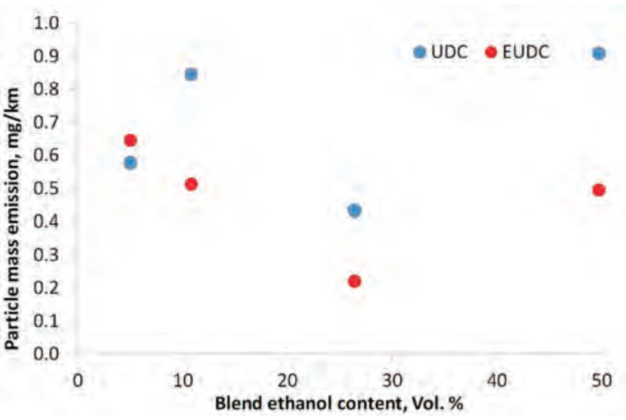

Fig. 9. Vehicle PM emissions on UDC and EUDC cycle [9]

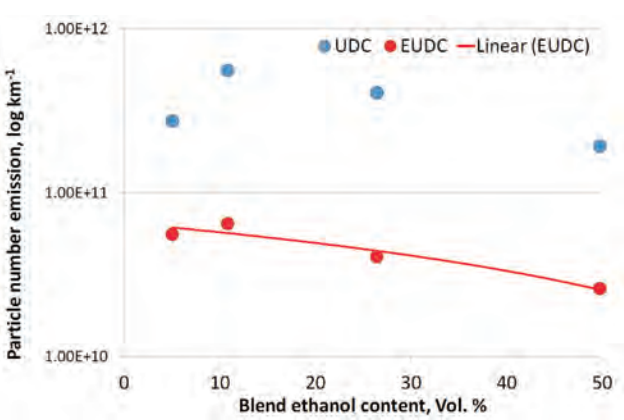

Fig. 10. Vehicle PN emissions on UDC and EUDC cycle [9]

3.4. Unregulated exhaust emissions

In this paper as "unregulated emissions" is described any measurable exhaust emissions which measurement are not standardized by Euro 6 legislation. That emissions are interesting for several reasons such additional information about pollutants and control of them. They can be included into new emissions standard in future like it took a place with particle matter and number emissions of gasoline engines. It also gives information about air quality and combustions as well as aftertreatment system processes. In studies of ethanol as a fuel often measured unregulated exhaust emissions are formaldehyde, acetaldehyde and ethanol itself. It seems obvious that with increasing ethanol content in the fuel increase also emission of ethanol [40]. Have been reported that ethanol emissions increase linearly together with ethanol content by [25].

Interesting is fact that ethanol emissions is detected running also on E0 [9, 26]. Ethanol emissions during NEDC cycle for different ethanol blend is presented in Figure 11. Emissions of aldehydes (formaldehyde and acetaldehyde) could be emitted as a result of partial oxidation of alcohol molecules therefore emissions of them from ethanol fuels are much higher in comparison to E0 where they are very low. Several studies have shown that formaldehyde emissions are very low [7] and it is hard to observe any correlation [5, 9]. However, acetaldehyde emissions are easy to detect and there is a clearly visible correlation with ethanol content especially following cold start of the engine [9]. Other unregulated compound were detected, including ammonia, alkanes and aldehydes, nitrogen monoxide and nitrous oxide.

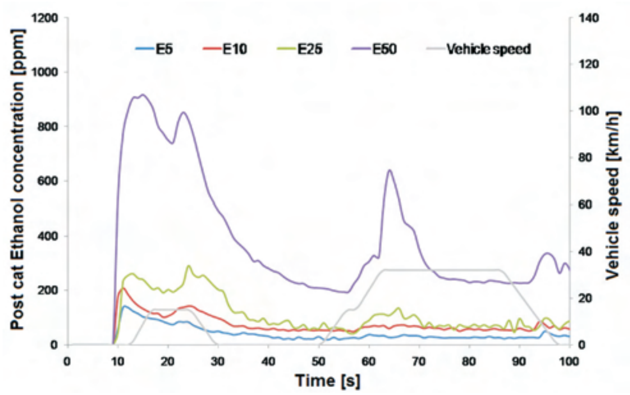

Fig. 11. Pre cat ethanol concentrations for various blends over the first 100 seconds of the NEDC (source: BOSMAL data – see [9] for commentary)

4. Summary and additional considerations

Due to political and economic factors biofuels and ethanol continue to grow their automotive market share. Probably because of ILUC issue increase market share of ethanol will be temporary slowed down in the EU. Accelerated growth of bioethanol engine technology and its increased market share is expected after development of 2nd generation of bioethanol technology. On the other parts of world will be still major substitute to gasoline, especially to unstable political situation in the middle east. Long-term projections of US Energy Information show that E85 is expected to take a 37% share of US domestic ethanol production by 2035 [32, 33].

Using of ethanol and its blends as a fuel seems to have potential. Several emissions are decreased by using fuel which contain ethanol. There are proven emission reduction of HC, CO, THC, NMHC. Some of them stayed on the same level or even increase, especially NO_x, but can be decreased by new engine technology and calibration possibilities connected with ethanol properties. The authors have in mind here downsizing associated with a high degree of turbocharging, variable compression ratio, DISI engines, redesigned after-treatment systems and ECU management. Recent modelling [36] indicates that ethanol could have significant GHG reduction potential in Europe, provided that vehicle hardware is set up to take advantage of all that ethanol can offer (in particular its high octane number).

To provide fuel with high content of ethanol there are still much research priorities that are very necessary in order to increase both the engineering and political decision-political processes [7, 8].

Further details and experimental results can be found in BOSMAL's publications on this topic – inter alia: [3–12, 30].

Nomenclature

DMM	Dekati Mass Monitor
ECU	Engine Control Unit
EUDC	Extra-Urban driving cycle
FFV	Flexible Fuel Vehicle
HC	Hydrocarbons
ILUC	Indirect Land Use Change Issue
NEDC	New European Driving Cycle
NMHC	Non-methane hydrocarbons
PM	Particle Mass
PN	Particle Number
SIDI	Spark Ignition Direct Injection
THC	Total Hydrocarbons
TWC	Three Way Catalyst
UDC	Urban Driving Cycles
LDV	Light Duty Vehicle
LPG	Liquified Petrolum Gas

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CE-2016-339

PEMS-based investigations into exhaust emissions from non-road and rail vehicles

At the beginning of the twenty-first century, one of the major challenges of humanity was to reduce the negative effects of civilization development. Besides the engines used in road vehicles there is a large group of engines for non-road applications. This group includes motor propelled vehicles not used on the road NRMM (Non-Road Mobile Machinery). Engines of these vehicles, among all of the non-road applications, are characterized by very specific working conditions that do not allow for them to be qualified for propulsion engines. The main problem with these vehicles is the particulate matter and nitrogen oxides emission. Rail vehicles operating conditions these requirements take by the similar way, as having a wide range of rolling stock markedly alters the environmental impact of these vehicles. Thus it becomes necessary to consider the issue of the method of evaluation of engine emissions in rail vehicles in terms of their actual operating conditions. Thus, efforts to assess the actual level of emissivity for rail vehicles and attempts to improve it are necessary and justified.

Key words: *non-road vehicle, rail vehicles, pollution emissions, real driving emissions, portable emissions measurement systems*

1. Introduction

1.1. General characteristic of non-road engines

Engines of non-road applications constitute a wide group that includes engines of: handheld portable devices (lawnmowers, chainsaws), power generators and non-road vehicles (otherwise referred to as NRMM – Non-Road Mobile Machinery). The NRMM vehicle group includes construction machinery, farm tractors and machines as well as special purpose machinery. The NRMM engines are a vast group among the non-road engine group (Fig. 1). The engines of these vehicles are characterized with very specific operating conditions, which is why they cannot be classified as traction engines.

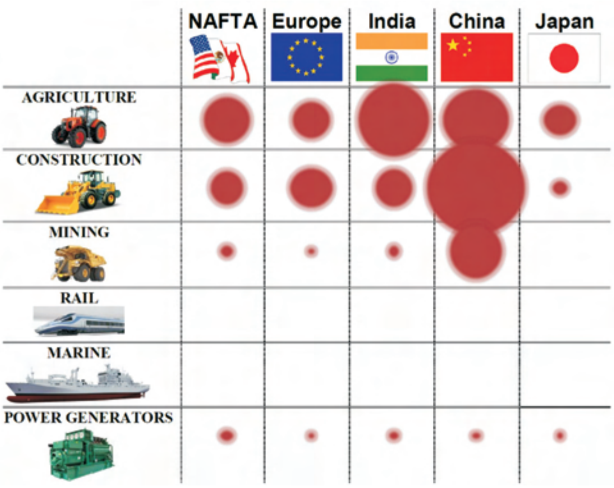

Fig. 1. The share of non-road engines in selected regions of the world [3]

A recent increase in the sales of NRMM vehicles has been greater than that of heavy-duty vehicles (HDV) (Fig. 2) [1]. The advancement of the transport infrastructure and the development of cities result in a continuous increase in the sales of construction machinery worldwide. A similar situation is observed in the farm tractor and machine market. The advancement and modernization of the farms resulted in an increased number of farm vehicles and machinery. A good example is Europe, where the number of operated farm tractors grew significantly in past decades [16]. A great influence on the number of NRMM vehicles have the emerging markets such as China, India and Eastern Europe. It is forecasted that this trend will continue in the coming years.

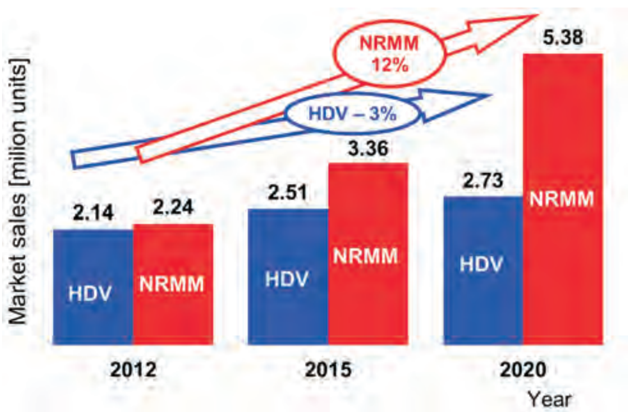

Fig. 2. Sales of HDV and NRMM vehicles (2020 – forecasted) [2]

The main problem in relation to the NRMM vehicles is the emission of particulate matter (PM) and nitrogen oxides (NO_x). The scale of the problem is well depicted by the situation in Germany, where the share of PM in the exhaust emissions from engines of non-road applications has for years been maintained on a steady level of approx. 50% (Fig. 3) [4]. The share of the emission of NO_x from the engines of non-road applications in Germany is lower compared to that of PM and amounts to approx. 15%, which is still a high value (Fig. 4). When it comes to the application of diesel engines constituting the main powertrain of NRMM vehicles, their impact on human health and environment is quite important. In its report published in 2012, International Agency for Research of Cancer (IARC), one of the agencies of World Health Organization (WHO) informed that diesel exhaust gas is carcinogenic [5]. Because of the number of diesel engines, the potential related to the reduction of exhaust emissions from this group of vehicles is the main research goal of this work.

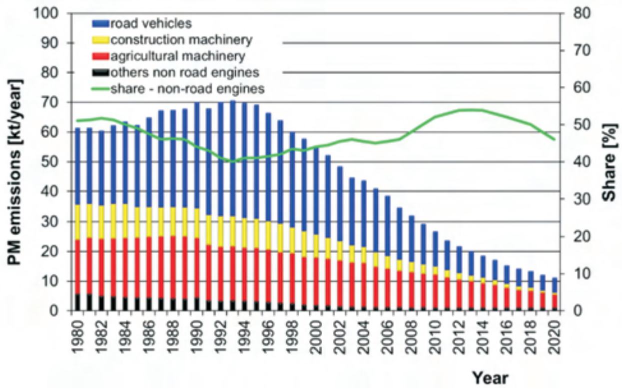

Fig. 3. Emission of PM from the engines operated in Germany (2014-2020 – forecast) [4]

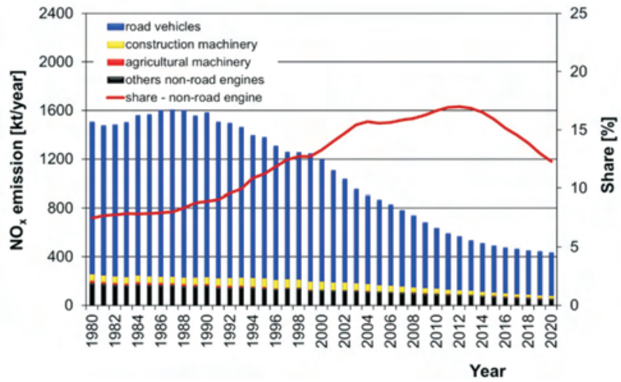

Fig. 4. Emission of NO_x from the engines operated in Germany (2014-2020 – forecast) [4]

1.2. General characteristics of rail vehicles

Diesel direct injection rail vehicles traction engines still remain the main powertrain solution for these vehicles because of their unique advantages. Yet, the negative impact of these engines on the natural environment is significant (Fig. 5). In Poland there are many traction vehicles whose engines do not meet the exhaust emissions requirements.

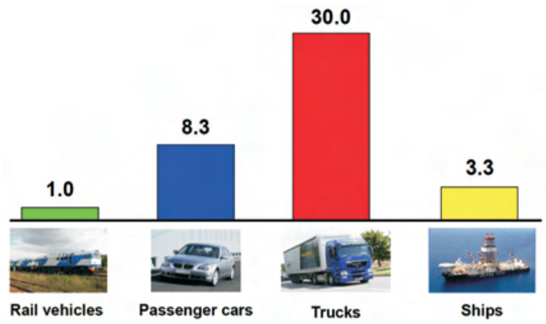

Fig. 5. Relative environment burden by the above means of transportation [22]

The influence of the locomotives on the natural environment depends on the characters of their operation. It is the locomotive operating conditions that decide about its unit fuel consumption, hence the exhaust emissions. The share of operation of a shunting locomotive at idle amounts to 51.6% of the total operating time, 33% of that time corresponds to 10% of the rated usable power and the outstanding shares are miniscule [21].

The ecological evaluation of diesel powertrains is extremely disadvantageous as compared to electric powertrains (Fig. 6). The damage done to the environment by the diesel traction vehicles in Poland when transporting cargo is four times higher than in the case of electric traction vehicles and 1.8 times higher that it is in the case of river transport but is 5 times lower than the damage done to the environment by heavy duty diesel vehicles. The exhaust emissions from non-road vehicles (rail vehicles also belong to that category) constitute a significant share in relation to the road vehicles [7-9].

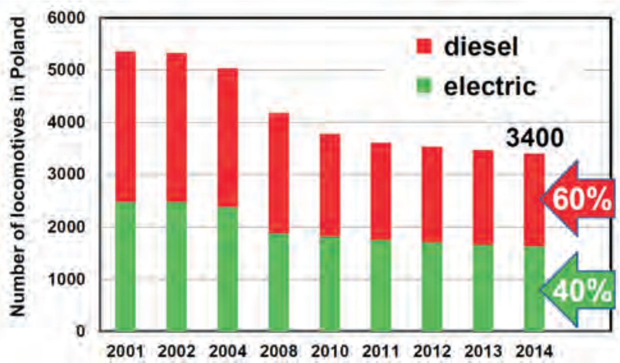

Fig. 6. The shares of diesel and electric locomotives in the rail rolling stock in individual countries

The study discusses the issues related to the ecological operation of rail vehicles. The evaluation of the level of environment friendliness is in most cases based on the comparison of the emission level of a traction combustion engine with the applicable exhaust emission limits. These values pertain to research tests of engines and vehicles. Under local (country) conditions of rail vehicles operation these requirements look a bit different because having a wide variety of rolling stock significantly changes the status of this kind of transportation in terms of environment friendliness. It is thus necessary to decide about the methodology of the evaluation of the rail vehicles emission level under real operating conditions. Hence, any actions aiming at the evaluation of the emission level of rail vehicles under real operating conditions are necessary and fully justified.

2. Potential of PEMS measurement

Aside from measurements performed on motor vehicles (including off-road) the system allows coordinating the exhaust emissions measurements from heavy-duty trucks, buses (including hybrid), construction and farm machinery (non-road), rail vehicles, ships and aircraft fitted with piston and jet engines (Fig. 7).

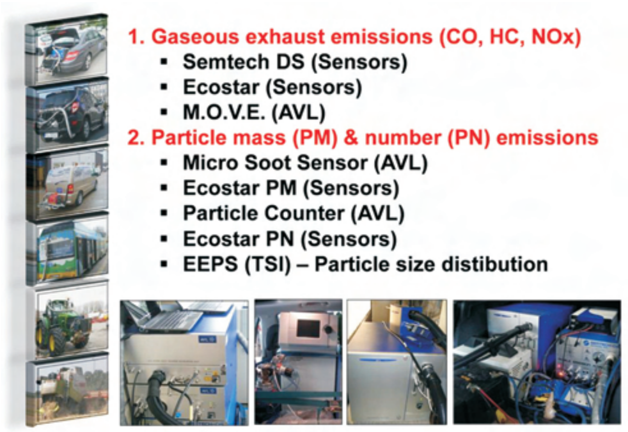

Fig. 7. Example applications of the PEMS equipment (PEMS components listed)

As for other applications of combustion engines in motor vehicles of the GVW exceeding 3500 kg (heavy-duty trucks and buses), off-road vehicles, construction and farm machinery (non-road), rail vehicles, ship and aircraft fitted with piston and jet engines – the engines are removed and tested on engine dynamometers [17, 18]. These engines operate under artificial conditions, usually much different than the actual ones. For the assessment of exhaust emissions after a certain period of operation the engine would have to be removed from the vehicle, which is technically and economically infeasible. The proposal to test vehicles using portable exhaust emissions measurement systems is a universal solution as it can be used in vehicles of all applications, where the same engines are applied.

A solution to this problem is the use of portable exhaust emissions measurement systems (PEMS). The system is composed of CO, CO_2, HC, NO_x and particulate matter measuring devices (equipment measuring particulate matter measures its mass, number and diameter). The system also acquires engine and vehicle operating parameters from the on-board computer (via CAN-bus).

The authors of the paper propose an introduction of an exhaust emissions conformity factor (CF) denoting the multiple of the increase or decrease of the exhaust emissions under actual traffic conditions compared to the homologation tests. Such an index has been defined for a given exhaust component (CF – exhaust emission conformity factor) [13]:

$$CF_j = \frac{E_{real,\,j}}{E_{(WHTC),j}} \tag{1}$$

where: j – exhaust component for which the emission index was determined, $E_{real,j}$ – emission under actual traffic conditions [g/kWh], $E_{WHTC,j}$ – emission measured in the WHTC test [g/kWh] (for heavy-duty vehicles).

The proposed exhaust emissions conformity factor will adapt the homologation emission values obtained in the tests to the actual traffic conditions of a vehicle. Hence, the conformity factor, referred to as ‘CF’, should be dimensionless and determined for different emission categories:

- passenger and light-duty trucks (up to 3500 kg) – for which the emission limits are prescribed in grams per kilometer [g/km],
- heavy-duty and non-road vehicles – for which the emission limits are prescribed in grams per kilowatt hour [g/kWh].

3. Exhaust emission form non-road vehicles in real operating conditions

3.1. NRMM real operating conditions and emissions

PEMS-based investigations under actual operating conditions allow determining the exhaust emissions and engine operating parameters such as engine load and speed in particular. Analyses of the conditions of actual operation of non-road engines confirm that most of them are specific and distinct compared to road vehicle engines [6, 12]. An example could be the engine of a farm tractor that operates under load characteristics during fieldwork, i.e. a constant operating speed varies in a narrow range, which mainly results from instantaneous and sudden load changes (Fig. 8). Figure 9 presents the view of the tractor during the tests with the hourly emission of NO_x shown on the tractor route. From this course, it clearly results that the emission remains on a steady level, except for instantaneous surges resulting from an increased load and while making U-turns, when the engine load and its speed change. Such a course of engine parameters is characteristic of a numerous group of NRMM vehicles [6].

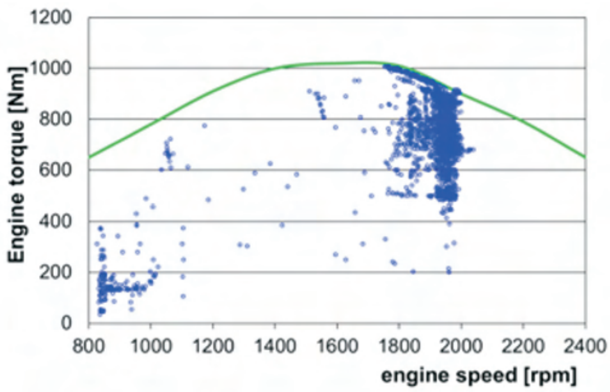

Fig. 8. Farm tractor engine parameters under actual operation (ploughing)

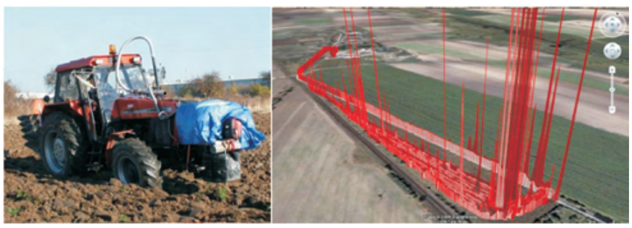

Fig. 9. Farm tractor during the tests under actual conditions of operation and the emission of NO_x shown on the tractor route

The performed tests for a large group of farm, forest and construction machines confirm that the main problem during the operation under actual conditions is the emission of PM and NO_x [11]. The legislation related to the NRMM exhaust emissions testing procedures has not yet been fully developed and established, but the European proposal of the future limits provides a CF for all exhaust components of 1.5. The CF obtained according to relation 1 confirms that for almost all tested vehicles the CF is greater than the proposed limit (Fig. 10). The forest harvester is an exception here, in which case the CF for both PM and NO_x is below the proposed limits. It is noteworthy that the CF for CO and HC for all tested vehicles is below the proposed CF limit.

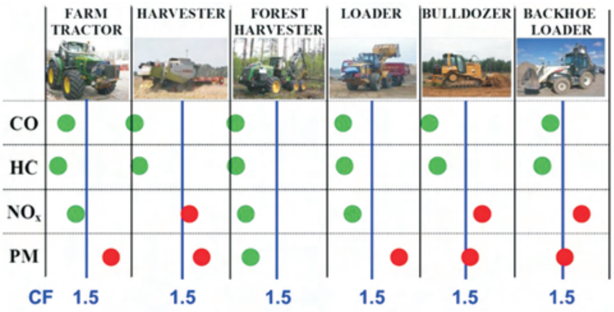

Fig. 10. CF for the investigated NRMM vehicles

3.2. Emissions standards for NRMM

One of the main goals of the EU directives was to set the admissible exhaust emission limits. Throughout the years, they became increasingly stringent. Despite the fact that the HDV and NRMM engines have similar characteristics and power outputs, the admissible limits for the NRMM are less stringent. A comparison of the admissible emission limits of PM and NO_x in the European legislation for the HDV and NRMM engines have been shown in Figures 11 and 12. The comparison pertains to the engines of the power output of 130–560 kW; this is a range of power output typical of heavy-duty diesel engines (HDD).

In the future, one should expect further tightening of the emission and fuel consumption (emission of CO_2) limits related to the NRMM engines [15]. This will ensure a modernization of the design of engines as well as the entire powertrains. The research and development centers are already working on such solutions. Intense works are under way on hybridization and electrification of NRMM powertrains [14, 19, 20].

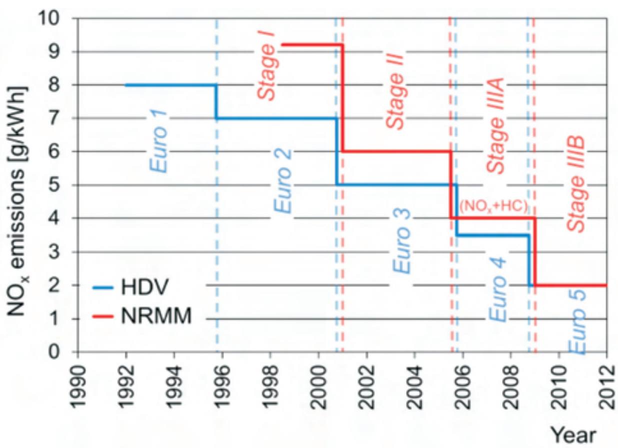

Fig. 11. Comparison of the admissible values of the NO_x emission for the HDV and NRMM engines (130–560 kW) [25]

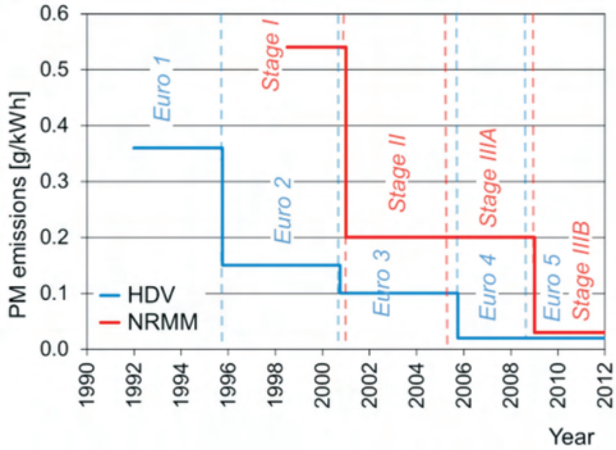

Fig. 12. Comparison of the admissible values of the PM emission for the HDV and NRMM engines (130–560 kW) [25]

A homologation stationary test for non-road engine applications is a NRSC (Non-Road Stationary Cycle) test [25]. This is an 11-phase test performed on an engine test bed. On its basis, the average emissions of individual exhaust components are determined. The characteristic share coefficients in each test phase are selected depending on the tested engine [25]. For the NRMM vehicles, the stationary test is ISO 8178-C1. Ever since the introduction of the Stage III emission limit, the exhaust emission measurements on NRMM vehicles have also been carried out in a dynamic NRTC (Non-Road Transient Cycle) test. The ISO 8178 test was renamed to NRSC (Non-Road Stationary Cycle). The NRTC test was developed jointly by the European and American legislators. For the tested engine, the NRTC is performed twice: for a cold and warm engine start. The final result is a weighted average with a share coefficient of 0.1 for the cold start test (in the US – 0.05) [25].

4. Exhaust emission from rail vehicles in real operating conditions

4.1. Diesel locomotives in passenger and cargo transportation in Poland and in the world

A characteristic feature of locomotives for passenger transportation is that they are designed to operate as slow and fast trains. They have a source of power for central heating of the train under low ambient temperatures (heating boilers, heat generators). The locomotives for passenger trains also have specific traction characteristics, particularly in terms of their operating speed. Cargo lugging locomotives do not have a heating system for the train cars and their traction characteristics should be described as high loads at low speeds. Universal locomotives have both characteristics of those designed for lugging cargo and passenger trains.

Shunting locomotives are designed to lug or push rail cars on the tracks, sidetracks and marshalling yards. We can also distinguish industrial locomotives that are practically shunting locomotives but some of them operate under specific conditions e.g. extreme air pollution (steelworks, coal grading sites, mines) and elevated temperatures (steelworks when transporting the products of the metallurgical process).

When it comes to the type of applied transmission of torque from the engine to the wheels (including its adjustment) we can distinguish locomotives fitted with mechanical hydraulic, (hydrostatic, hydrodynamic) and electric (direct current, alternating current) transmissions.

A significant share of this type of vehicles in the rolling stock certainly results from the advantages that this means of transport provides. Diesel locomotives have the following advantageous features as opposed to electric locomotives:

– Power supply independent from external sources, which is vital in case of natural disasters. Under such exceptional situations diesel locomotives can fully stand in for the electric ones,
– The possibility of implementing: innovative solutions in the powertrains of diesel locomotives, various types of energy conversion and electric transmissions,
– Diesel locomotives can operate under severe ambient conditions, which can be a serious problem for the electric locomotives,
– Diesel locomotives have a higher efficiency ($\eta_o = 0.26$) as compared to the electric locomotives ($\eta_o = 0.21$).

Polish Rail currently uses 12 series of regular gauge diesel locomotives of power outputs from 110 kW to 900 kW (Fig. 13 and Table 1). Each year the number of diesel locomotives gets reduced both in Poland and the EU member states because they are gradually being replaced by the electric locomotives (lower costs of operation on lines of higher train traffic) [9, 23].

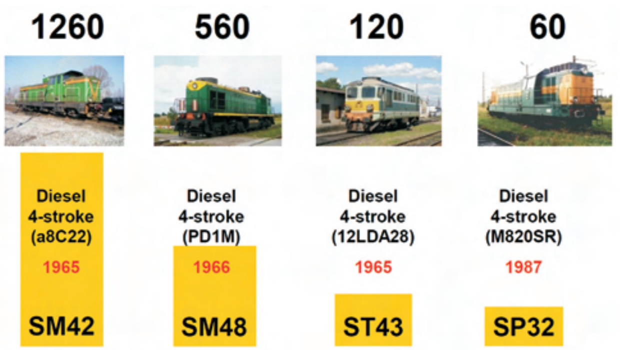

Fig. 13. Diesel locomotives in Poland

Table 1. Shunting locomotives operated in Poland [24]

No.	Series	Country of production	Engine type/ power [kW]	Service weight [Mg]	Maximum traction [MN]
1.	SM03	Poland	Diesel, 4-stroke/110	24	58.5
2.	SM30	Poland	Diesel, 4-stroke/257	36	75
3.	SM31	Poland	Diesel, 4-stroke/883	116	220
4.	SM40	Hungary	Diesel, 4-stroke/441	62	182.6
5.	SM41	Hungary	Diesel, 4-stroke/441	62	182.6
6.	SM42	Poland	Diesel, 4-stroke/588	70	228
7.	SM48	USSR	Diesel, 4-stroke/883	116	380

Until 2020 in Europe the number of diesel locomotives will drop but the number of diesel multiple units for local passenger transportation tasks will grow. The UIC analyses indicate that by 2020 the companies plan to purchase approximately 9000 new locomotives and 8500 diesel multiple units.

The development of the locomotives with respect to the fuels for their powertrains is in line with the development trends in road and non-road transportation not to mention the air transportation. Their development will much depend on the development of new technologies in land and air transportation and will seek advanced technologies that will ensure the optimum use of the energy supplied to the vehicles maintaining high safety of the realized transportation task and low emission level. The trends in the development of locomotives will be characterized by attempts to:

– Use modern engines in new and currently operated locomotives,
– Increase usable power output at a steady fuel consumption,
– Reduce exhaust emissions and noise level,
– Reduce heat emission from the engine,
– Optimize the design of the engine aggregates in terms of fuel consumption and the costs of production,
– Develop diesel-electric locomotive powertrains,
– Develop electric powertrains with a new generation of batteries and electric motors,
– Apply biofuels for use in diesel and diesel electric locomotives operated under various transportation and industrial tasks.

A wide application of microchip technologies in vehicles indicates that also in the locomotives such a technology will find its application for the control of the engine operation, safety systems and on-board diagnostics of the locomotive in the long term (realized similarly to the OBD systems On-Board Diagnostics) used in road vehicles.

4.2. Emission standards

European rail vehicles exhaust emission regulations are as follows: locomotives (including shunting locomotives) and railcars have been included in the UIC 624 charter. The admissible values of the emissions were established in 2001 and they are applicable to new railway vehicle engines. The applicable test is ISO 8178-F [18]. The regulations do not apply to special purpose locomotives (operated in refineries or mines) and traction engines of power output below 100 kW. The UIC I limits were applicable for all the engines until 31.12.2002, and from 1.01.2003 onwards (UIC II) a division applies to engines of power output up to 560 kW and engines above that value. The exhaust gas components that undergo the measurement were also changed. Exhaust gas opacity test has been given up in favor of the measurement of the PM level (UIC II as is in the case of the Euro standards). It is noteworthy that from 2008 the UIC limits have been getting closer to the level IV of the Euro standard (Fig. 14).

Emission standard	Valid from	NO_x [g/kWh]	HC [g/kWh]	CO [g/kWh]	PM [g/kWh]
Stage I	2001	9.2	1.3	5.0	0.54
Stage II	2002	6.0	1.0	3.5	0.2
Stage IIIA	2006	4.0		3.5	0.2
Stage III B	2010	2.0	0.19	3.5	0.025
Stage IV	2013	0.4	0.19	3.5	0.025
		–95%	–85%	–30%	–95%

Fig. 14. Emission standards [25]

4.3. Improving ecological parameters of rail vehicle diesel powertrains

Engine adjustment

The locomotive engine rebuilds results in a partial reduction of the exhaust emissions: the obtained results meet (with a sizable margin) the ORE B13 as well as the UIC standards (the latter only for the unit emission of carbon monoxide). This allows the evaluation of the appropriate adjustment of the supercharging pressure or maintaining excessive values thereof (which can be implied by high NO_x). The growth in the emission of hydrocarbons may result from the fact that the engine is not yet properly run in, but the results significantly exceed the admissible UIC limits. The course of the injection was improved (injection advance angle) which is confirmed by a lower emission of nitrogen oxides that meets only the ORE B13 standard (Fig. 15).

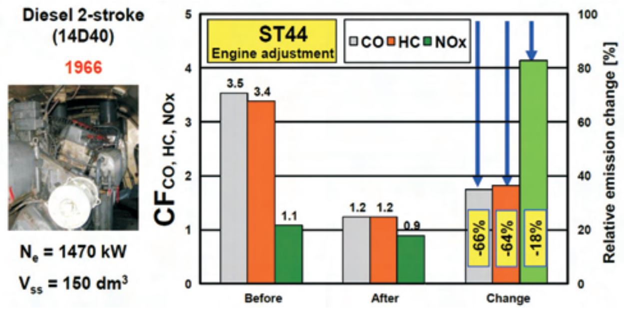

Fig. 15. ST44 cargo locomotive engine rebuild

Engine replacement

The change of the engine type results in considerable ecological benefits. In comparison to the standard 14D40 engine hourly emission of carbon monoxide was reduced by more than 80%. The emission of hydrocarbons was reduced by 36%. A small increase in the emission of nitrogen oxides was observed (4%), yet the 645E3B engine has a power output more than 50% higher than its predecessor (Fig. 16).

Changing rolling stock

The above-presented range of engine adjustments, their repairs and rebuilds does not exhaust the possibilities of reducing of the exhaust emissions from rail vehicles. The diesel engines of locomotives are mainly much worn out units of high power output. These engines often do not meet the exhaust emissions requirements. They are frequently subjected to tune-ups and rebuilds in order to improve their ecological parameters. The situation with light railcars is a bit different. In this field heavy duty vehicle engines are used – high load diesel engines of maximum capacity of 25 dm³.

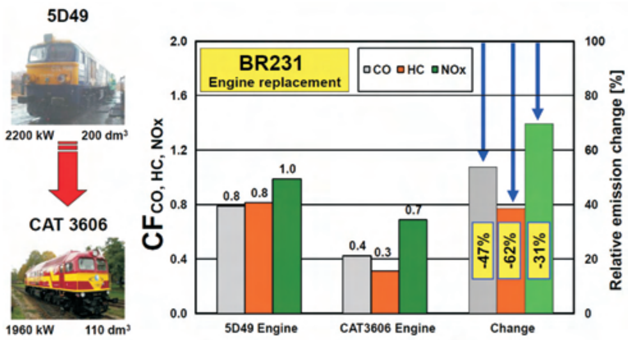

Fig. 16. Replacement of worn out locomotive engines with new designs

Because of the possibility of replacing of the deteriorated locomotives operating in passenger traffic the ecological indexes of railcars have been presented. The currently imported single, double or tri articulated railcars largely contribute to the reduction of the exhaust emissions. Following the conducted tests we can reduce the emission of carbon monoxide by over 90% when using these vehicles. Because the engines fitted in these vehicles are newer it is possible to reduce the emissions of hydrocarbons from 70% to over 90%. The emission of nitrogen oxides in the worst scenario is reduced by 50%. It is also possible to reduce this emission by more than 95% (Fig. 17).

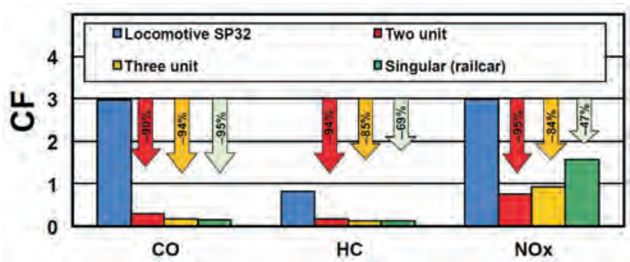

Fig. 17. The proposal of changes of the rolling stock

The SM42 locomotives mainly used in shunting could be replaced by bimodal tractors designed for shunting rail-road cars (both wide and narrow gauge). The emission tests were carried out through comparing the locomotive and the bimodal tractor of the power output of approximately 100 kW. Due to the different values of the tracting force of these vehicles the analysis of the emissions was performed with the assumption of a much-extended operating time of the bimodal tractor. As a result of such an analysis the emission of carbon monoxide was lower by more than 90%. The hourly emission of hydrocarbons was also more than 90% lower. The emission of nitrogen oxides under such conditions was lower by more than 80%. The PM emission was lower by 70% in its hourly emission (Fig. 18).

The presented possibilities of reduction of the exhaust emissions need indicating the ecologically prevailing direction. To this end, these proposals were juxtaposed using the multiplicity factor in the emission level as the indicator.

A very advantageous is the proposal of using railcars. The application of these railcars results in a reduction of nitrogen oxides by almost 4 times, hydrocarbons – 5 times and carbon monoxide as much as 10 times (Fig. 19). Thanks to the presented solutions it is possible to reduce the adverse impact of diesel locomotives on the environment.

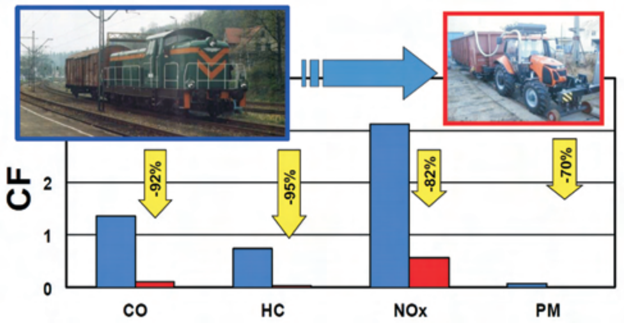

Fig. 18. Replacement of diesel locomotives with light railcars

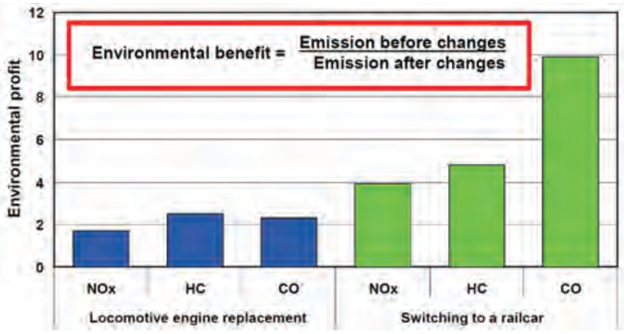

Fig. 19. Ecological benefit: the multiplicity of the ecological benefit of the most efficient solutions

The economic benefits of the application of the methods and measures reducing the negative impact of rail vehicles on the environment are:

- Reduction of fuel consumption up to 50%,
- Reduction of the lubricant consumption up to 70%,
- Increase of the locomotive power output 60%,
- Extension of the active operation period by at least 20 years,
- Extension of the rebuild intervals,
- Reduction of the malfunction index 2.5 times,
- Self-financing of the investment in the period of approximately 10 years.

Besides, particularly advantageous are the economic effects of replacing of the diesel locomotive by bimodal vehicles (Fig. 20):

- The purchase price of the bimodal vehicle is three times lower as opposed to the cheapest shunting locomotive,
- The operating costs of operation of the tractor are six times lower as compared to the locomotive,
- Tractive properties are three times higher,
- The vehicle can be operated without additional permits on own sidetracks,
- The railway and tramway infrastructure including the on-site organization activities can be mechanized,
- Used on-road vehicles can be adapted for the purpose of rail and road vehicles,
- The vehicles can be purchased at competitive prices.

The replacement of shunting locomotives with a bimodal tractor in a double work shift system guarantees a return of the expenditure within two years.

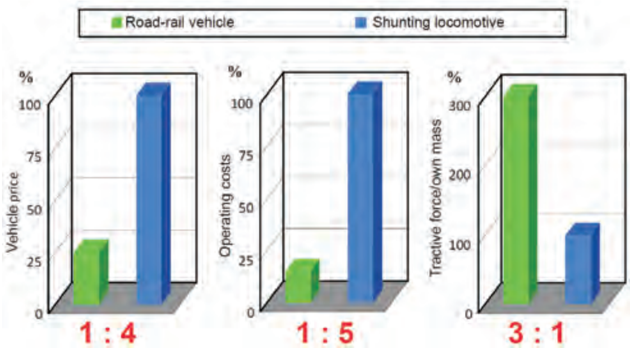

Fig. 20. Comparison of the advantages of the bimodal tractor and a diesel shunting locomotive

5. Conclusions

The reduction of exhaust emissions requires a continuous search for new solutions in both engine design and methods of engine testing. A factor stimulating this development is the exhaust emission legislation. The advancement of exhaust emission measurement techniques provides new possibilities of engine testing particularly under actual conditions of operation (RDE). One may suppose that this method will become prevalent and will gain in significance. The aim of the legislators and manufacturers should be the acknowledgment of the RDE measurements as one of main methods of homologation testing. Works aiming at introducing such changes should be completed as soon as possible and the enforceability of the implemented legislation should be global.

The performed investigations confirm that for NRMM engines the main problem is the emission of NO_x and PM. The improvement of engines of these vehicles should be directed towards reduction of the said exhaust components. In this respect, the portfolio of possible solutions is quite large, which is confirmed by the solutions implemented on road vehicles. Such solutions can then successfully be transferred to NRMM vehicles.

The here presented possibilities of changes to the traditional railway vehicles i.e. modernization, replacements of the old diesel engines with more technologically advanced units and the use of light railcars and special purpose vehicles (bimodal tractors) required indicating the ecologically prevailing trends. The knowledge of how the railway vehicles affect the environment required an actual evaluation of the real operating conditions and determining of the exhaust emissions under these conditions. It is possible only having considered their specific operation. This task is particularly complex as diesel locomotives do not have identical load histograms – variable operating conditions generated variable values of the exhaust emissions. In order to obtain the full ecological ‘picture’ of the condition of the diesel locomotive units a mobile testing laboratory was built for the exhaust emission testing.

The most efficient method of limiting of the negative impact of rail vehicles on natural environment is to replace the locomotive engine or replace the locomotive itself with light railcars. Other methods of reducing of the exhaust emissions such as engine tune-up or engine rebuilds do not bring expected results.

According to the newly developed test the exhaust emissions from locomotives used for: passenger trains – are lower by 20–40% for all the exhaust components, shunting – are lower by approximately 50%, cargo trains – have no significant differences.

The replacement of diesel locomotives with light railcars results in a significant reduction of the exhaust emissions: carbon monoxide by 90–95%, hydrocarbons by 69–94%, nitrogen oxides by 47–95%.

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CE-2016-340

Selected remarks about RDE test

New test procedures for determining exhaust emission from passenger vehicles will be introduced in 2017. For several years, the European Commission has been developing new procedures, which aim is to perform tests in road conditions. The purpose is to determine the real values of emissions, which are not always reflected by the level of emissions obtained in the laboratory. Proper and accurate procedures for determining emissions in real traffic conditions (RDE – Real Driving Emission) have not yet been approved (as opposed to Heavy Duty Vehicles for which such conditions already exist), but there are proposals that are currently being analyzed by major research centers in Europe. There are many differences between those proposals such as determining road emission or research methodology related to emission measurement of hydrocarbons. The work compares the results of emissions measured in road tests using the latest legislative proposals related to passenger cars. The results are shown in relation to the used measurement method: classic method of determining exhaust emission; uses all measurement data determining the mass of harmful compounds and distance travelled during the test; method of averaging the measuring windows (MAW – moving average windows), also in the literature called EMROAD method, which determines the measurement windows (on the basis of carbon dioxide emissions from the WLTC test) and on its basis determines the road emission in RDE test; generalized method of instantaneous power (Power Binning), known in the literature as CLEAR – Classification of Emissions from Automobiles in Real driving, determines road emissions on the basis of generalized instantaneous power during the RDE test.

Key words: *exhaust emission, passenger cars, real driving tests*

1. Introduction

Emission standards are established for the control of pollutants emitted from motor vehicles throughout the world. Most regions also set the limits on carbon dioxide emissions, which are directly related to fuel consumption [1]. Exhaust emissions are measured in laboratory conditions (for passenger cars on the chassis dynamometer) in a fixed certification test. This part of the certification process of the vehicle is responsible for its "environmental performance" and is the same for all cars. The chassis test is responsible for the "most likely" road conditions, and performing the same tests for all vehicles allows for the comparison of the emission results between them. Nowadays, however, more and more attention is given to road tests (which is already reflected in the proposed European Union emissions regulations) known as RDE tests using PEMS type mobile research equipment (Portable Emission Measurement System). Recent research on emissions from vehicles in traffic conditions, performed with the use of mobile measurement systems, reflect the actual ecological performance of vehicles. Most attention is given to the possibility of using such tests to calibrate the engines in such a way to reduce emissions not only during the certification tests, but also in the entire range of engine operation. The authors of paper [11] pointed out that new research in real traffic conditions, currently simulated in various research tests (NEDC – New European Driving Cycle [16], CADC – Common Artemis Driving Cycles, WLTC – Worldwide Harmonized Light vehicles Test Cycle [15]), may increase the emissions of nitrogen oxides from road vehicles. They postulated that in order to reduce that increase it is necessary to make changes in the vehicles software, stating that these changes will be successful only for vehicles equipped with petrol engines. Vehicles fitted with compression-ignition engines will require further investments to increase the effectiveness of the exhaust gas aftertreatment through the use of new methods of reducing the concentration of nitrogen oxides (eg. using an SCR system – Selective Catalyst Reduction).

Authors of the article [9], who compared road emissions in real traffic conditions with the use of PEMS analyzers with results obtained using the program COPERT [12], arrived at the same conclusions. It was found that in the speed range of 20-120 km/h calculation results obtained by using the COPERT program are higher by about 10% for such quantities as fuel consumption and the emission of hydrocarbons to the values from road tests. However, with regard to the emission of nitrogen oxides the data from COPERT are understated by about 30%.

Comparative emission studies of Euro 5 emission class vehicles carried out in the laboratory on a chassis dynamometer [7], in various driving tests (e.g. NEDC, CADC and the WMTC – Worldwide Motorcycle Test Cycle) also confirmed the results previously stated. The authors used CADC and WMTC as tests in which the specificity of changes in speed corresponds to the test in real traffic conditions. It was found that for vehicles with petrol engines emissions of carbon monoxide does not exceed 1 g/km (permissible Euro 5 limit is also 1 g/km), emission of hydrocarbons does not exceed 10% of the limit (0.1 g/km) and the emission of nitrogen oxides is equivalent to approximately 20% of the limit value (0.06 g/km). The authors pointed out that vehicles with compression-ignition engines far exceed the permissible emission limits of nitrogen oxides – the obtained values exceed the exhaust emissions limit approximately 4 times (emission limit values for nitrogen oxides in Euro 5 is 0.18 g/km).

Studies in road conditions draw attention to significant emissions of particulate matter, mainly in the nanoparticle range from combustion engines also those powered by alternative fuels (e.g. natural gas) [13] (2015). The article highlights the significant mileage of the vehicles using alternative fuel, which in turn results in up to 8-fold increase in emitted particle number for vehicles with a mileage of 500,000 km compared to the vehicles with mileage of 75,000 km. The article confirmed in RDE tests, with different road traffic characteristics, that vehicles powered by compressed natural gas emit larger amounts of nitrogen oxides in comparison to vehicles powered by spark-ignition engines.

With regard to the accuracy of measurements in actual traffic conditions the final result depended on the operating conditions of the vehicle and the engine (including the speed of other vehicles, road surface, the capability of the driver and the driving style and other aspects of road traffic). These conditions are unpredictable and can significantly affect the outcome of the emissions measurement. From the data found, among others, in publications [6, 17], it follows that the greatest impact on the achieved emission results are: thermal state of the vehicle (engine), average speed, driving dynamics and road topography.

The impact of road conditions on the emission results was the subject of article [14], which studied SUVs with petrol engines and automatic transmission under the conditions of varying slope of the road. The authors have attempted to estimate the emission changes of individual components depending on the angle of road inclination. The authors demonstrated that the change in the road slope of 10% resulted in a 2-fold change in the emissions for vehicles with spark ignition engines and a 1.5-fold change in emissions for vehicles with compression-ignition engines.

Starting from 2017, the process of type approval of new passenger car models in the European Union will include a procedure for measuring emissions in real traffic conditions. EU regulation (715/2007/EC [5] and 692/2008 [4]) for RDE tests is a response to the results of studies [8, 10], relating to increased emissions of nitrogen oxides from vehicles equipped with compression ignition engines, despite such vehicles meeting the acceptable standards in laboratory tests. Under the new rules [3] for all new type approvals from September 2017, and in the case of newly registered car models from September 2019, the emissions of nitrogen oxides measured in traffic conditions will not be allowed to exceed 2.1 times the maximum limit (for Euro 6 that is 80 mg/km), or 168 mg/km. However, since January 2020 for a new type approval (and since January 2021 for new model registrations) this ratio will be reduced to 1.5, which means that the maximum emission of nitrogen oxides cannot exceed 120 mg/km (Fig. 1).

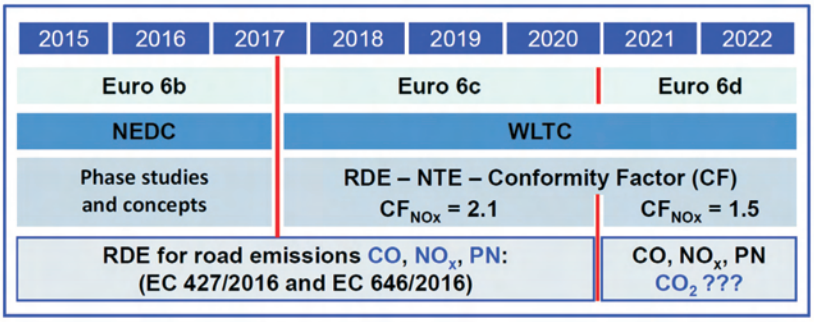


Fig. 1. RDE tests requirements in Europe [2, 3]

Parameters of road tests cannot be arbitrary, and to determine the emissions one of the proposed methods of measurement will be used [3]:
– method of moving average windows (MAW – Moving Average Windows); also referred to as EMROAD in the literature, developed by the JRC,
– method for categorizing power (Power Binning); in literature referred to as CLEAR – Classification of Emissions from Automobiles in Real driving, developed at the Graz University of Technology.

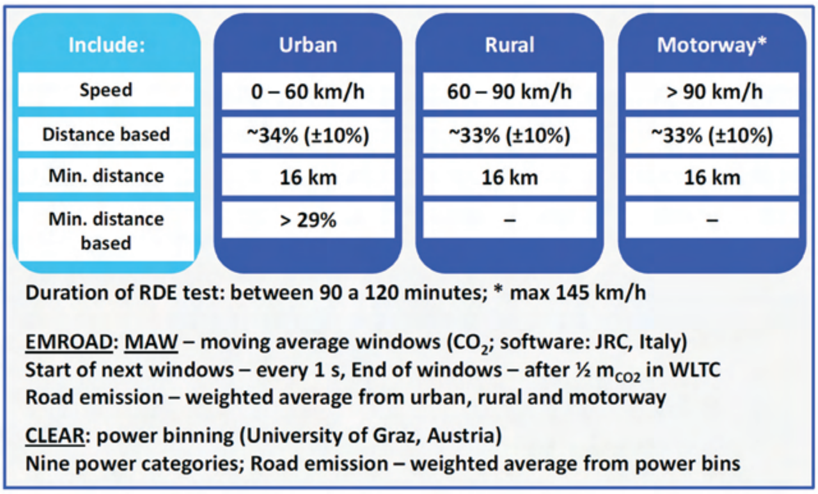


Fig. 2. Requirements of the test drive cycle [3]

The test route is selected in such a way that the test was carried out continuously, and the data was continuously recorded to achieve the minimum duration of the study. An external power supply provides electricity to the PEMS system, and not from a source receiving energy directly or indirectly from the tested vehicle engine. PEMS installation was carried out in such a way to ensure the least possible influence on the vehicle emission performance, its operation or on both of these factors. Efforts should be made to minimize the weight of the installed equipment, and potential changes in the aerodynamics of the test vehicle. RDE studies should be carried out on weekdays, on paved roads and streets (i.e. off-road driving is not permitted). Prolonged idling after the first ignition of the internal combustion engine at the start of the emission test is to be avoided (Fig. 2 and Fig. 3).

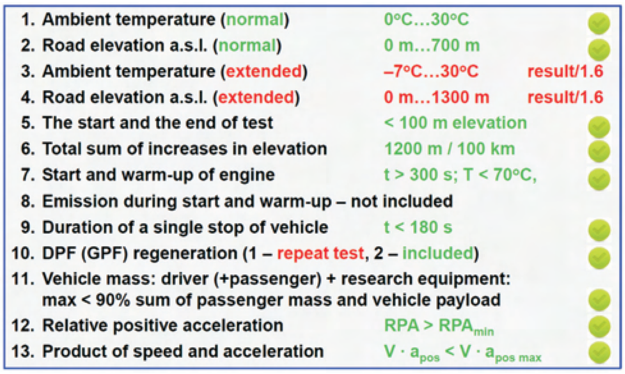


Fig. 3. Specific requirements of the test drive cycle [3]

2. Methodology

The tested objects were cars, the characteristics of their drive units are shown in Table 1. They were equipped with gasoline and diesel engines; characterized by exhaust emissions in line with the Euro 6 regulations. Despite the differences in the engine types and displacements, similar curb weight of vehicles was a common feature. The aim of the study was to determine the interdependence of the road emissions of compounds contained in vehicles exhaust gases (separately for the gasoline and diesel engines).

A Semtech DS mobile analyzer by Sensors and Engine Exhaust Particle Sizer 3090 were used for measuring the concentration of harmful substances in the exhaust gas. They facilitated the measurement of harmful gaseous compounds and particulate matter in accordance with the requirements of the standards mentioned earlier. Additionally data directly from the vehicle's diagnostic system and a GPS location signal were transmitted to the central unit of the analyzer.

Table 1. Characteristics of engine/vehicle used in testing

Parameter	Gasoline	Diesel
Cylinder number, arrangement	4, in series	4, in series
Displacement [cm^3]	1984	1968
Emission class	Euro 6	Euro 6
Max. power [kW] at [rpm]	169 / 4700–6200	135 / 4000
Max. torque [Nm] at [rpm]	350 / 1500–4400	380 / 1750–3000
Fuel injection	Direct injection	Common Rail
Vehicle curb weight [kg]	1349	1354

Table 2. Test route characteristics

Test parameters	Vehicle A Gasoline	Vehicle B Diesel	Relative difference $\frac{(A-B)\times 100\%}{½(A+B)}$
Total time [s]	5349	5209	2.65
Maximum speed [km/h]	147.9	133.3	11.36
Average speed [km/h]	33.73	34.51	–2.28
Distance [km]	50.116	49.936	0.43

Road emission measurements were made in the actual traffic conditions when driving in urban, rural and motorway roads; tests were performed three times, and the partial results presented are examples; the end results are the averages of all the results obtained (Table 2). Research route was chosen for a variety of driving conditions to take account of the varying: urban, rural and motorway topography and their impact on the value of the emission of gaseous components of exhaust gases. Analysis of changes in route elevation reveals a small variation, as well as elevation differences within values permitted by the norms (Fig. 4).

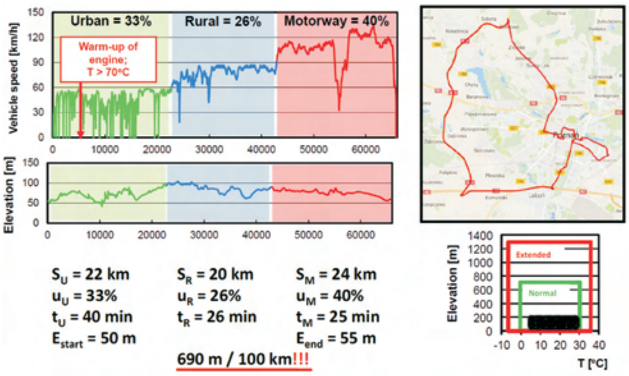


Fig. 4. Changes in road elevation and the vehicle speed (diesel engine) during the test

3. Result analysis

3.1. Analysis of all measurement data

The recorded changes of individual pollutants concentrations allowed to determine the relations characterizing the effect of the dynamic engine characteristics on harmful compounds emission, taking into account the results of the entire route measurement. The dynamic engine characteristics are included in an indirect way, using the distribution of the whole range of speeds and loads in real traffic conditions for making graphs of the emission intensity of the chosen components of combustion gases. This data was presented on the engine characteristic in the speed and load boxes (Fig. 5 and Fig. 6).

On the basis of the previously obtained measurements of harmful compounds emissions and using the knowledge of the distance traveled by the vehicle, instantaneous conformity factors values CF (Conformity Factor) were determined, which are defined as the ratio of road emission of the component, and the emissions specified by the legislation

$$(CF = b_{RDE}/b_{norm}).$$

The road emission values designated for the vehicle with the gasoline engine from the route tests are as follows (Fig. 7a): emission of carbon monoxide was 216 mg/km, emission of nitrogen oxides was 56 mg/km, emission of hydrocarbons was 83 mg/km, emission of carbon dioxide was 117 g/km. Compliance of road emissions with the specified Euro 6 limits was observed for all exhaust components tested. The values of the indicators were as follows (Fig. 7b): the conformity factor of carbon monoxide was 0.22, the conformity factor of nitrogen oxides was 0.89, the conformity factor of hydrocarbons was 0.83. The analysis of the data shows that the values of road emissions obtained in actual operation are not exceeded for vehicles with gasoline engines.

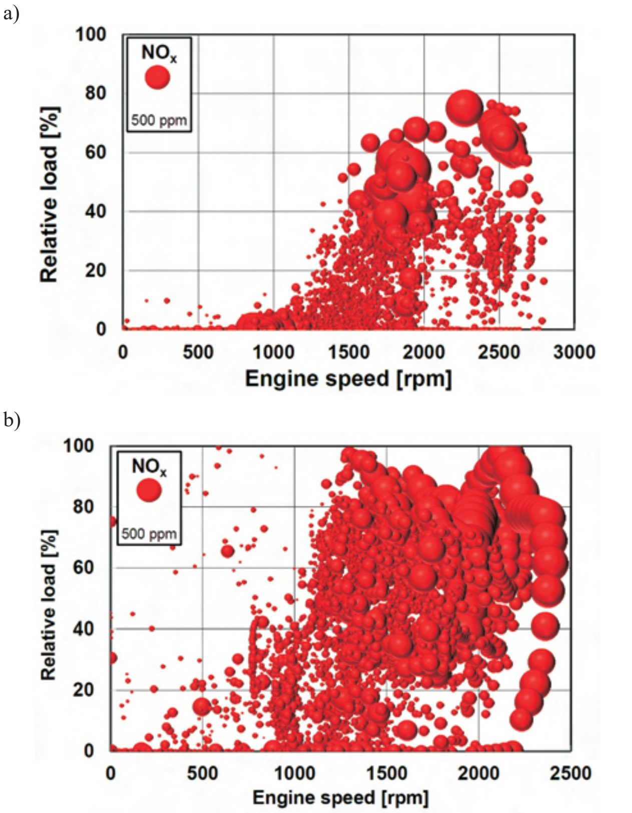


Fig. 5. The nitrogen oxides concentration relative to the engine operating parameters during the RDE test: a) gasoline engine, b) diesel engine

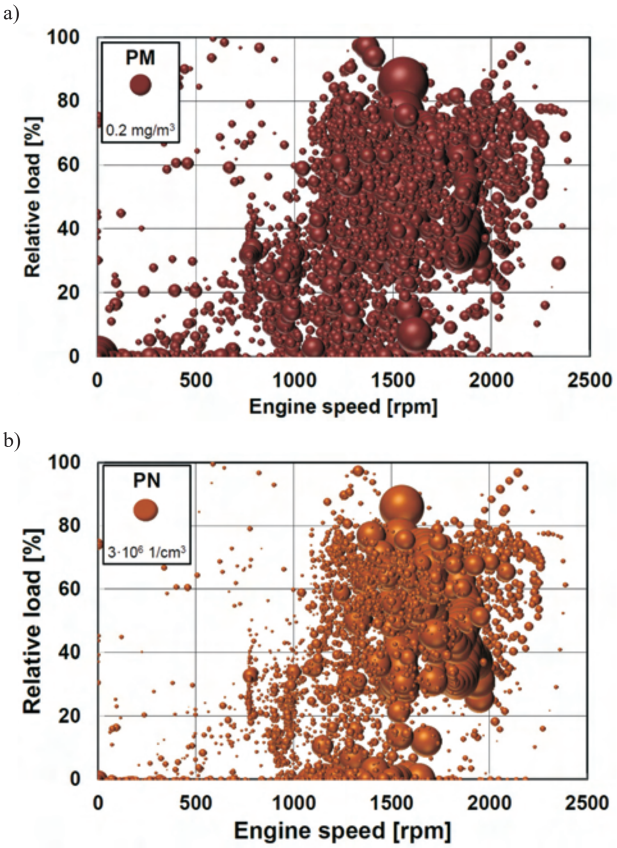


Fig. 6. Emission intensity by mass (a) and the number (b) of particles related to engine operating parameters during the RDE vehicle test (diesel engine)

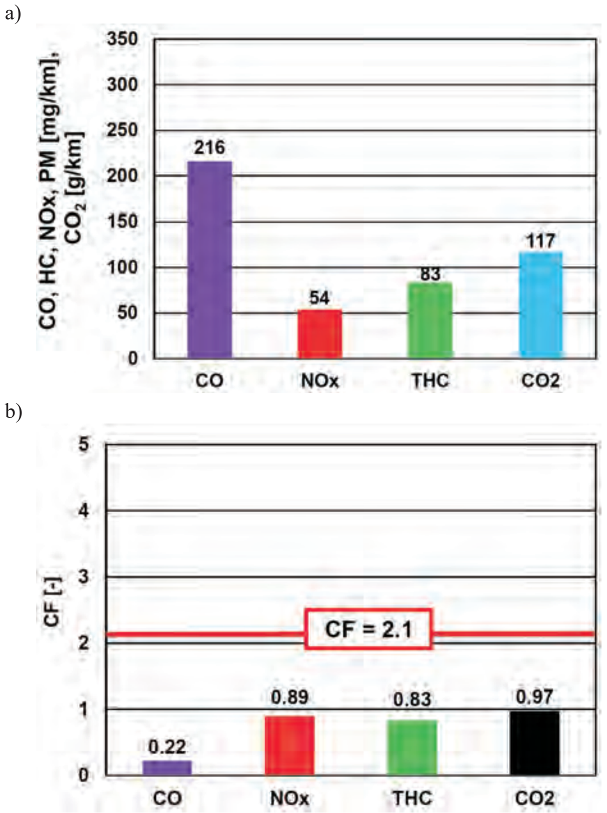


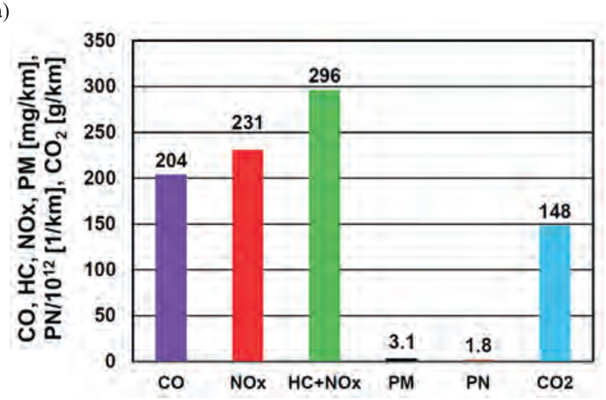
Fig. 7. Road emission values (a) and conformity factors (b) determined during road tests for a vehicle equipped with a gasoline engine (all results)

The road emission values determined for vehicle with a diesel engine from a drive on the test route are as follows (Fig. 8a): emission of carbon monoxide was 204 mg/km, emission of nitrogen oxides was 231 mg/km, emission of the sum of the nitrogen oxides and hydrocarbons was 296 mg/km, emitted particulate mass was 3.11 mg/km, and emitted particle number was $1.8 \cdot 10^{12}$ 1/km, emission of carbon dioxide was 148 g/km. Conformity factors specified for the vehicle fitted with a diesel engine are different in nature compared to those for an Gasoline engine. The emission values specified in Euro 6 standard were significantly exceeded for the of the value of sum of nitrogen oxides and hydrocarbons, as well as for nitrogen oxides alone and for particle number.

The values of the conformity factors were as follows (Fig. 8b): the conformity factor of carbon monoxide was 0.41, the conformity factor of nitrogen oxides was 2.89, the conformity factor of the sum of nitrogen oxides and hydrocarbons was 1.74, the conformity factor of particulate mass was 0.69, and the conformity factor of particle number was 2.99.

The analysis of the data shows that the road emission values obtained in actual operation do not exceeded the limits for vehicles with gasoline engines, while for diesel engines the emission of the sum of nitrogen oxides and hydrocarbons, emission of nitrogen oxides and the particle number (the latter rate due the regeneration of the particulate filter during testing) are all exceeded.

a)



b)

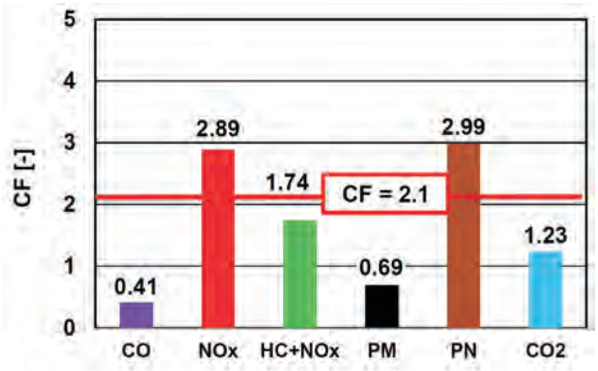


Fig. 8. Road emission values (a) and their respective conformity factors (b) determined during road tests for a vehicle equipped with a diesel engine (all results)

3.2. Moving average windows method

The first step in determining the road emissions with the new test procedure is to determine the validity of the test method (Fig. 9). The following issues must be considered:

- route length; for the conducted road tests the length was: 17.16, 13.69, 20.83 km, which adds up to 51.68 km (one of the values does not lie within the required test range),
- test duration, which has to be between 90 and 120 minutes; the conducted test took 87 minutes (thus the value does not meet the test requirements),
- time period during the test when the engine is not warmed up yet; the time for this test was 5 minutes (this value is acceptable for the test),
- the share of individual test stages in the whole test: urban drive was 33.20%, rural drive was 26.49%, and motorway drive was 40.31% (all obtained values meet the requirements of the test),
- the average speed in urban drive must be between 15 and 40 km/h; the test reached a value of 16.09 km/h (value lies within test limits),
- share of speed over 145 km/h on the motorway; this speed was not exceeded in the test (the value meets the test requirements),
- share of drive time with speed over 100 km/h on the motorway section must be at least 5 minutes; the test reached the value of 9.28 minutes (the value is acceptable),
- the share of time spent stationary during urban drive section must be between 6 and 30%; in test this value was 45.32% (the value does not meet the test requirements),
- the altitude difference between the starting and ending point of the test drive must be less than 100 m; the value reached in the test was 7.6 m (the value is acceptable).

a)

Trip characteristics	Urban	Rural	Motorway	Complete
Trip distance	> 16 km	> 16 km	> 16 km	
	16.58	11.54	23.18	51.30
Total trip duration				90-120 min
				89
Cold start duration				min 5 min.
				5
Distance share	29-44%	23-43%	23-43%	
	32.33	22.49	45.18	100.00
Average speed	15-40 km/h			
	14.69	72.85	118.35	34.58
Motorway speed above 145 km/h			< 3%	
			0.00	
Motorway speed above 100 km/h			>= 5 min	
			9.45	
Urban stop time				6-30%
				47.72
Start and end points elevation absolute difference				<= 100 m
				7.10
RPA	0.17	0.06	0.05	
95th percentile Speed*Acc	10.01	10.63	20.79	

b)

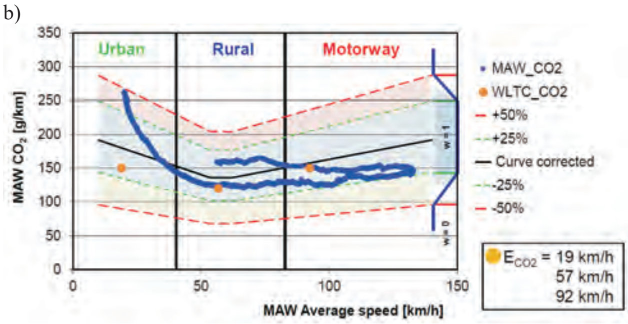


Fig. 9. Characteristics of the test route for a vehicle with a diesel engine (a) and CO_2 characteristic curve (b)

The obtained road emission values of pollutants (carbon monoxide and nitrogen oxides) for a vehicle with a gasoline engine were used to determine the conformity factors, whose maximum value as of 2020 will be 2.1 (factor value was obtained by dividing the measured road emission value by the emission limit b_{CO} equal to 1000 mg/km or by the emission limit of NO_x equal to 60 mg/km); The following values were obtained:

- road conformity factor of carbon monoxide: in the urban section – 0.092, in the rural section – 0.189, on the motorway – 0.229; average measured value during the test was 0.169 (Fig. 10a);
- road conformity factor of nitrogen oxides: in the urban section – 0.374, in the rural section – 0.726, on the motorway – 1.198; average measured value during the test was 0.762 (Fig. 10b).

For the vehicle with the diesel engine the following values were obtained:

- road conformity factor of carbon monoxide: in the urban section – 0.2, in the rural section – 0.174 on the motorway – 0.656; average measured value during the test was 0.342 (Fig. 11a);
- road conformity factor of nitrogen oxides: in the urban section – 1.165, in the rural section – 1.314, on the motorway – 4.391; average measured value during the test was 2.279 (Fig. 11b);

a)

b)

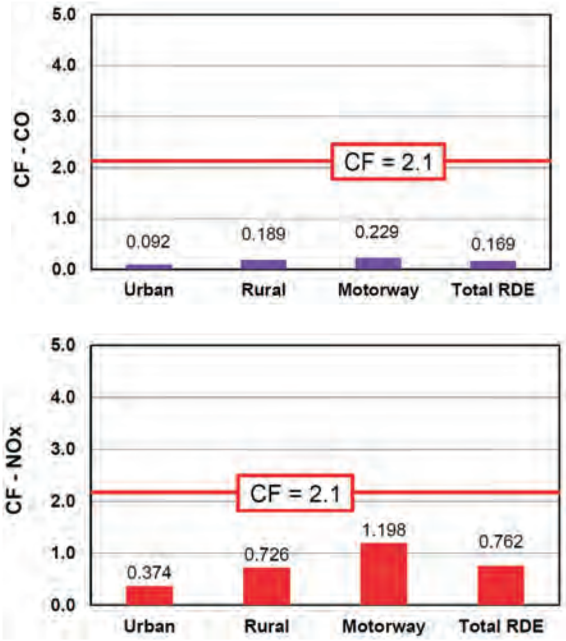


Fig. 10. Conformity factors of carbon monoxide (a) and nitrogen oxides (b) obtained in each test section for vehicle with a gasoline engine

a)

b)

c)

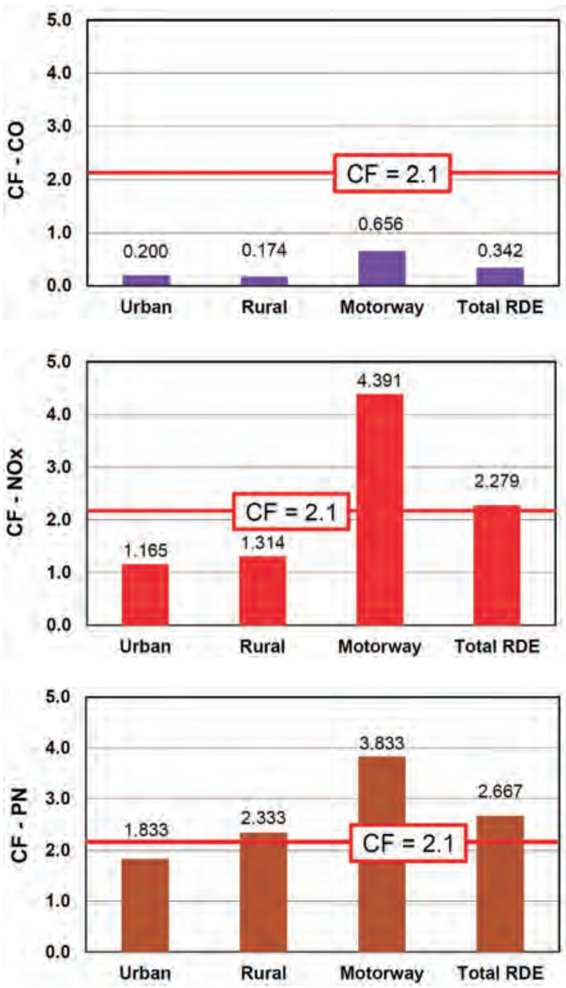


Fig. 11. Conformity factors of carbon monoxide (a) nitrogen oxides (b) and particle number (c) obtained in each test section for vehicle with a diesel engine

– road conformity factor of particle number: in the urban section – 1.833, in the rural section – 2.333, on the motorway – 3.833; average measured value during the test was 2.667 (Fig. 11c).

3.3. Power binning method

The power binning method uses pollutants emission concentrations, which are classified in accordance with the corresponding power at the wheels, and then using weighting factors to determine the emission values of the RDE test. Power bins and their corresponding share of time in the RDE test were established so as to be representative of each LDV (Table 3).

Table 3. Normalized shares of power for vehicle in an urban environment and the entire RDE test

Power bin	P_{norm} [–]		Share [%]	
	from (>)	to (≤)	urban	whole test
1		–0.1	21.98	18.5611
2	–0.	0.1	28.79	21.8580
3	0.1	1.0	44.00	43.4500
4	1.0	1.9	4.74	13.269
5	1.9	2.9	0.45	2.3767
6	2.9	3.7	0.045	0.4232
7	3.7	4.6	0.040	0.0511
8	4.6	5.5	0.004	0.0024
9	5.5		0.0003	0.0003

The values of P_{norm} are normalized using the equation:

$$P_{norm} = \frac{P_{RDE}\,[kW]}{P_{NEDC}\,[kW]} \tag{1}$$

where: P_{RDE} – power at the wheels at that point in time of the RDE test [kW], and P_{NEDC} [kW] is the power at the wheels of the test vehicle in a type approval test on a chassis dynamometer.

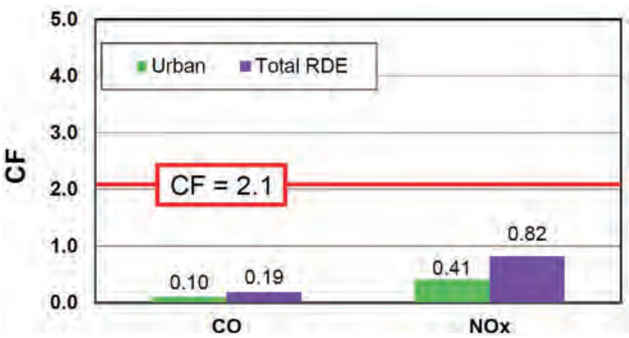
The end emission result is achieved by determining the product of road emissions in every power bin and the share of time of each bin in the entire test drive (Fig. 12). For a vehicle with a gasoline engine the following estimates of road emissions (CF) were obtained: carbon monoxide – 0.10 (in the urban section), and 0.19 (whole RDE test) and the conformity factor of nitrogen oxides – 0.41 and 0.82, in the urban section of the test and the whole RDE test respectively. For a vehicle with a diesel engine the conformity factor values were as follows: carbon monoxide 0.23 and 0.35, nitrogen oxides 1.31 and 2.40 and particle number of 2.12 and 2.82, in the urban section alone and the whole test respectively.

4. Conclusions

By comparing the conformity factors (CF) of emissions in RDE tests the following values were obtained:

– For the vehicle with the gasoline engine: the obtained conformity factor values for carbon monoxide emission were 0.22, 0.17 and 0.19 (using all measurement data,

a) b)



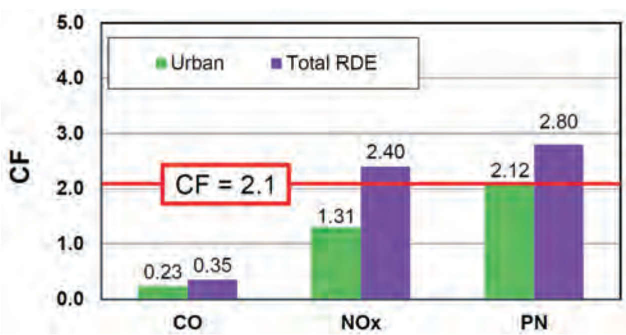


Fig. 12. Conformity factors of carbon monoxide and nitrogen oxides from gasoline vehicle (a) and carbon monoxide, nitrogen oxides and particle number for a diesel vehicle (b)

using the method of moving average windows and using the method of power binning respectively) – the resulting relative difference was 30%; for the emission of nitrogen oxides obtained values were 0.89, 0.76 and 0.82 (for the respective methods) – and the obtained relative difference was 17% (Fig. 13);

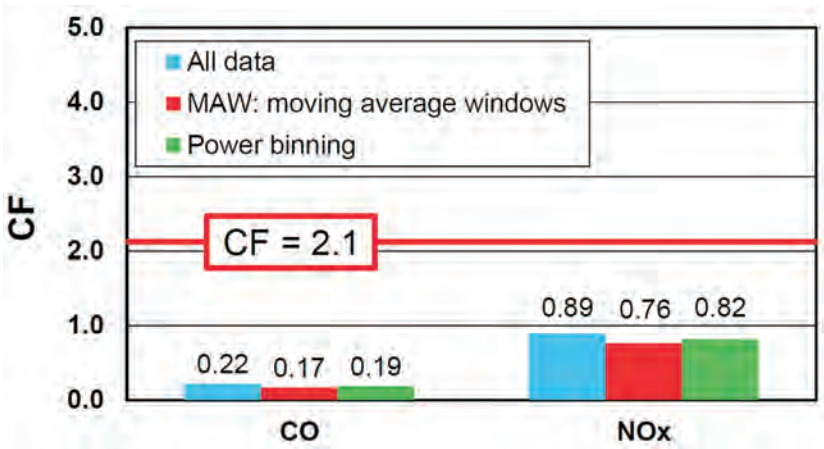


Fig. 13. Conformity factors of carbon monoxide and nitrogen oxides emissions from tests employing different methods of processing results (gasoline engine)

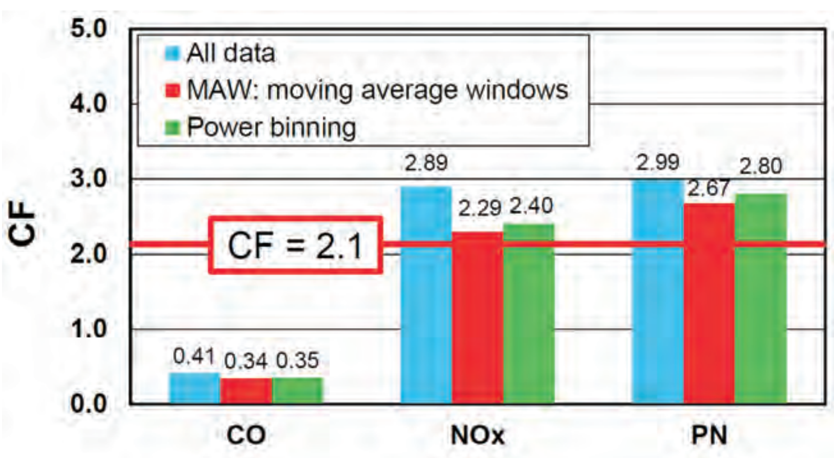


Fig. 14. Conformity factors of carbon monoxide, nitrogen oxides and particle number emissions from tests employing different methods of processing results (diesel engine)

– For the vehicle with the diesel engine: the obtained conformity factor values for carbon monoxide emission were 0.41, 0.34 and 0.35 (using respective methods) – the obtained relative difference was 20%, the obtained conformity factors of nitrogen oxides had a value of 2.89, 2.29 and 2.40 – the obtained relative difference was 27%, and the conformity factor value of particle number was 2.99, 2.67 and 2.80 – the obtained relative difference was 12% (Fig. 14).

Based on the pollutants emission results and conformity factors it should be concluded that road emission conformity factors of CO and NO_x are not exceeded for the vehicle powered by a gasoline engine, while for the vehicle powered by a diesel engine, it was found that limit values were exceeded for emission of nitrogen oxides (CF_{NOx} = 2.29–2.89, with the limitation CF_{NOx} = 2.1 for all result analysis methods) and for particle number (CF_{PN} = 2.67–2.99, with the limitation CF_{PN} = 2.1). It should be noted that the highest values of emission were obtained using all the measured data. This is mainly due to the fact that this method does not rejected any sections of the test (in the moving average windows method for example: stationary measurements lasting more than 3 minutes are discarded – and for this method the lowest values of emission were achieved). Using the method of power binning produced conformity factors that are between the minimum (moving average window method) and the maximum obtainable value from all the measurement data. However, this is the most complex method, as it requires knowledge of such things as: factors determining the power used in the test on a chassis dynamometer and road emissions of carbon dioxide in the various phases of the certification test for cars, specified by the Euro 6 norm.

Nomenclature

PB	Power Binning
CADC	Common Artemis Driving Cycles
CF	Conformity Factor
CLEAR	Classification of Emissions from Automobiles in Real driving
COPERT	Computer Programme to calculate Emissions from Road Transport
EMROAD	software (Excel add-in) used to analyze on-road emissions data measured with Portable Emissions Measurement Systems
HDV	Heavy Duty Vehicles
MAW	Moving Average Windows
NEDC	New European Driving Cycle
PEMS	Portable Emission Measurement System
RPA	Relative Positive Acceleration
RDE	Real Driving Emission
SCR	Selective Catalyst Reduction
WLTC	Worldwide Harmonized Light vehicles Test Cycle
WLTP	Worldwide Harmonized Light vehicles Test Procedure
WMTC	Worldwide Motorcycle Test Cycle

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Current directions in LD powertrain technology in response to stringent exhaust emissions and fuel efficiency requirements

The major global automotive markets have all set limits for exhaust emissions from new road vehicles, which have become increasingly stringent over the past few decades. There is also considerable pressure to reduce fuel consumption and CO_2 emissions – around 80% of all new passenger cars sold globally are subject to some kind of energy efficiency regulation. Such legal requirements necessitate extensive R&D and testing and the entire field is undergoing a period of rapid change. Despite a recent trend towards harmonisation, at present significant regional differences exist, which vary from the analytical laboratory methods specified, the list of regulated pollutants, the numerical values of the emissions limits and the test cycles employed for engine and chassis dynamometer testing of vehicles and their powertrains. Here the key points are reviewed and strategies and technologies employed to deal with these emissions challenges are discussed. Incoming automotive emissions regulations including the WLTP and Real Driving Emissions are discussed and in conclusion likely directions in powertrain technology are identified.

Key words: *LD engines, powertrain technology, exhaust emissions, emissions standards, WLTP, RDE*

1. Introduction

Notwithstanding decades of improvement in the industry, concern over the impact of vehicles on air quality remains high. Emissions of greenhouse gases from road vehicles remain very high on the political agenda; emissions of particulate matter are coming under increasing scrutiny as a form of pollution with wide-ranging negative impacts; concern over NO_x emissions is very high; certain as-yet unregulated gaseous emissions are potential air quality risks. Looking to the longer term, the security of the oil supply and broader energy usage concerns have become very much part of the automotive development landscape.

Fig. 1. Main drivers of powertrain development [9]

Concern over gaseous and solid pollutants – perhaps most infamously CO_2 – has become a concern for all major global markets, not just the United States and European Union. Among the main drivers that influence vehicle technology and powertrain development are emissions regulatory development in the EU, USA and Asia (mainly Japan, China, India), GHG (mainly CO_2) emissions reduction which is aligned with fuel consumption/fuel economy (FC/FE) and has an influence on consumption of energy resources (Fig. 1) [9].

The response to this has been the introduction of various pieces of legislation, some imposing increasingly strict emissions limits; others various mandates, incentives and quotas regarding fuel consumption and the types of fuels used. Now, following revelations that emissions from real vehicle usage are generally poorly reproduced in the laboratory, test methods themselves are changing: first in the laboratory (e.g. the WLTP/C – GTR15; USA CFR 1065/1066 procedures); furthermore, real driving emissions have increased in importance to the point where RDE/PEMS measurements are now a legal requirement in the EU (although so far only for monitoring purposes). Randomised laboratory test cycles, once considered a viable approach for particle number measurements, now look very unlikely to be implemented in view of progress with PN PEMS.

The introduction of particle number limits and increased scrutiny of particulate emissions from engine types other than Diesel represents a somewhat new and challenging direction in emissions testing and control. These factors exert massive pressure on vehicle and engine manufacturers (both light duty and heavy duty), their suppliers and the oil and fuel industries. Reduction of harmful emissions, today especially NO_x for diesel LD engines and PN for gasoline DI engines are among the main drivers influencing personal transport development (Fig. 1). Other, allied fields such as R&D and fuel additive and lubricant suppliers also find themselves subject to the same forces. Many of the afore mentioned problems are shared by the various strands of the industry – passenger car and light commercial vehicle/heavy duty/

off road/marine – and many of the proposed strategies and technical solutions have multi-segment applicability.

However, the market is dictated not only by political and technical factors, but also by consumer demands, which themselves also evolve. Something both legislators and the general public have in common is the goal of reducing fuel consumption, without any sacrifices in terms of durability or safety. Responding to this pressure, a broad range of advanced engine technologies, catalytic aftertreatment systems, revised fuel types, bespoke lubricants and friction inhibitors, etc. have been introduced. These strategies are often interrelated: low sulphur fuel is required for aftertreatment system compatibility; advanced engine design has impacts on required lubricant properties, etc. Fundamental changes to the propulsion strategy for on-road vehicles (e.g. fuel types/the implementation of advanced electromechanical systems – hybrids) represent a revolution in the industry. All these advanced technologies must be developed, tested, approved and certified. As explained in later sections of this paper, recent changes mean that these processes are no longer confined to the laboratory.

2. Development of global emissions rules

2.1. General approaches of modern emission standards

After about 50 years of vehicular emissions regulation and control, today there are many different emissions standards, test procedures and limits mandated in the main automotive markets such as the EU, USA, Asia (mainly Japan, China and India), Brazil and other countries (Fig. 3). Emissions standards are built on four pillars: tailpipe limits for harmful pollutants, test procedures that describe the test methodology, the driving cycle used on a chassis dynamometer in emissions laboratory in prescribed test conditions, equations describing the calculation of test results, including corrections for temperature and humidity (inter alia) and weighting factors (in certain cases) [1, 12, 17, 26].

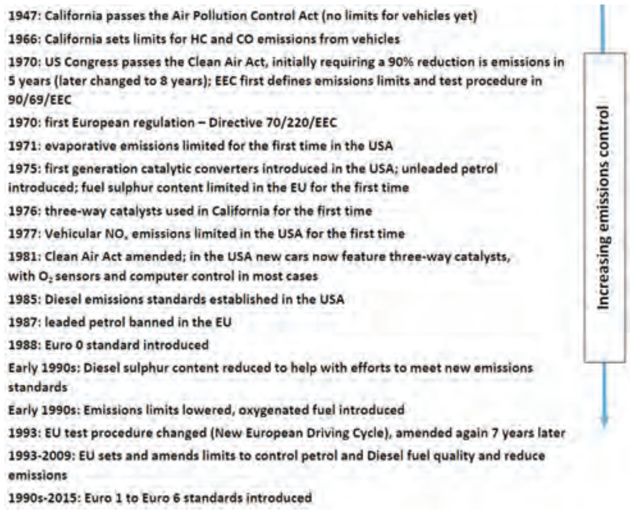

Fig. 2. Milestones in emissions regulation and emissions control [9]

Global harmonization of automotive emissions regulations remains a distant prospect, but it is now often mentioned that harmonization of emissions procedure and protocols could bring benefits for automotive OEMs and customers – customers today are not getting value from region-to-region variation [26]. The first step in this direction could be UNECE GRPE programme on the introduction of World Light-duty Vehicles (harmonized) Test Procedure WLTP that was carried out over 2007-2015 (for

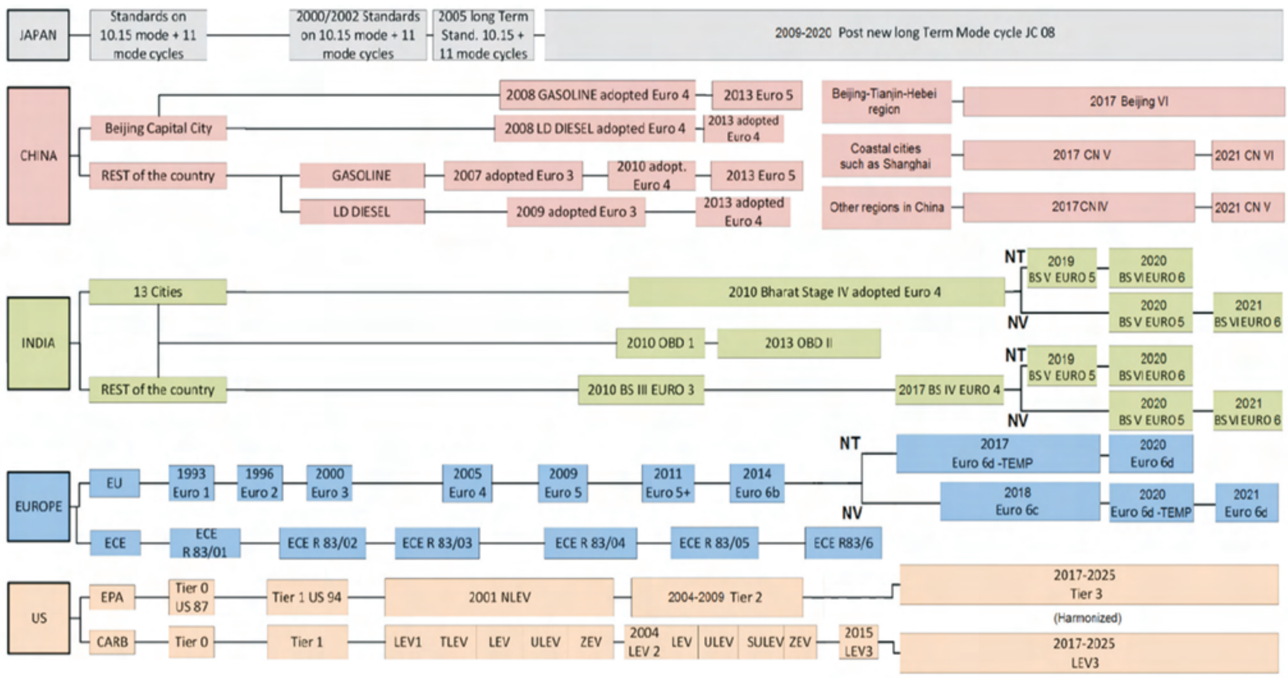

Fig. 3. Development trends in emissions regulation on the main automotive markets

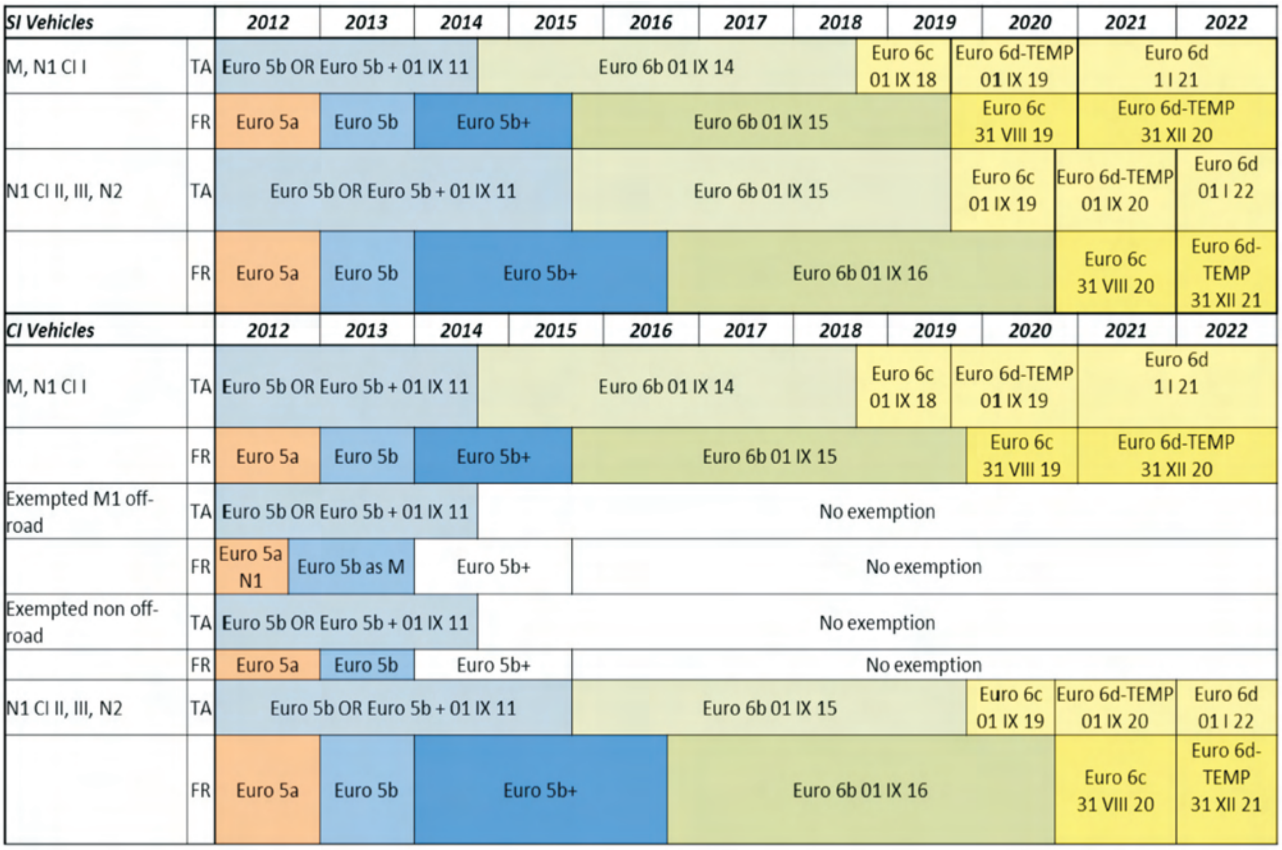

Fig. 4. Emissions reduction path in European Union countries

* WLTP, earliest expected application in Europe: September 2017. ** RDE, Euro 6c without quantitative RDE requirements, Full RDE test is applied at Euro 6d

the first step) by the EU, Japan, India, China, and Korea, with the support of other countries, (including the USA) and finalized via a new UNECE emissions regulation (GTR15, published in 2014) which defines the test procedure based around the WLTC.

Test cycle and a technical specification; in line with a "split level approach" [12], limits will be set during the transposition to national legislation in the EU and some Asian countries.

2.2. European Union

The new framework for vehicle type-approval proposed by the European Commission would harmonise enforcement practices across EU member states and shift the focus from pre-production to in-service conformity and market surveillance [14].

The emissions reduction pathway in the EU, with phase-in dates for new emissions limits Euro 6c, Euro6d-Temp and Euro 6d are presented in Fig. 4. The latest emissions standards were presented in the Commission Regulation (EU) 2016/646 of 20 April 2016 amending Regulation (EC) No 692/2008. The main issues for Euro 6 regulations are the following:

<u>Euro 6c</u> – Full Euro 6 emission requirements but without quantitative RDE requirements, i.e. Euro 6b emission standard, final particle number standards for PI vehicles, use of E10 and B7 reference fuel (where applicable), assessed on the regulatory laboratory test cycle, with RDE testing for monitoring only (no NTE emission limits applied);

<u>Euro 6d-TEMP</u> – Full Euro 6 emission requirements, i.e. Euro 6b emission standard, final particle number standards for PI vehicles, use of E10 and B7 reference fuel (where applicable), assessed on the regulatory laboratory test cycle, with RDE testing with NTE limits based on temporary conformity factors;

<u>Euro 6d</u> – Full Euro 6 emission requirements, i.e. Euro 6b emission standard, final particle number standards for PI vehicles, use of E10 and B7 reference fuel (where applicable), assessed on the regulatory laboratory test cycle, with RDE testing with NTE limits based on final conformity factors.

2.3. USA (including California)

In general it can be stated that California is the "home" of exhaust emissions legislation and control, with the Californian approach continuing to influence the rest of the US and the rest of the world. As early as 2007 fourteen US states other than California had implemented Californian legislation, at least in part. But in the United States, the Environmental Protection Agency (EPA) has the statutory authority under the Clean Air Act (CAA) to regulate greenhouse gas (GHG) emissions.

In 2012, the EPA, in coordination with the National Highway Safety Administration (NHTSA) and the California

Air Resources Board (CARB) issued a Final Rulemaking (FRM) for Light-duty Vehicle Greenhouse Gas Emissions. In this FRM, the EPA set tailpipe emission standards for all light-duty vehicles from 2017 MY (Model Year) through 2025 MY. The regulation also tightens sulphur limits for gasoline. Both the certification limits (Bins) and the fleet average standards are expressed using the sum of NMOG + NO_x emissions (Fig. 5). The required emission durability has been increased to 150,000 miles or 15 years, whichever comes first. Gasoline vehicles are tested – for exhaust and evaporative emissions – using gasoline containing 10% ethanol (E10) [11].

Tier 3 Certification Bin Standards [FTP, 150.000 mi]				
Bin	NMOG+NOx [mg/mi]	PM 1) [mg/mi]	CO [g/mi]	HCHO [mg/mi]
Bin 160	160	3	4,2	4
Bin 125	125	3	2,1	4
Bin 70	70	3	1,7	4
Bin 50	50	3	1,7	4
Bin 30	30	3	1,0	4
Bin 20	20	3	1,0	4
Bin 0	0	0	0	0

1) In MY 2017-20 PM standard applies only to that segment of a manufacturer's vehicles covered by the percent of sales phase-in for that model year

Fig. 5. US federal exhaust emissions standards [11]

There was also a general concerns about setting standards so far into the future, that were mainly focused on the development of technology by automotive OEMs and consumer acceptance of this new technologies. To support automotive OEMs, the EPA formally adopted in its regulations a Mid-term Evaluation (MTE) which has been designed to assess only the feasibility of the 2022 MY to 2025 MY standards. The standards from 2017 MY to 2021 MY already fixed and cannot be changed [25].

California applied emissions standards called LEV. LEV III standards were finalized December 2012 with phase-in 2015-25. Beginning 2020 all vehicles need to be certified to LEV III (Fig. 6).

LEV III FTP STANDARDS

Passenger Cars and Light Duty Trucks ≤ 8.500 lbs

Durability Vehicle Basis (mi)	Vehicle Emission Category 1)	NMOG+ NOx (g/mi)	CO (g/mi)	Formaldehyde (mg/mi)	Particulates 2) (g/mi)
150.000 (optional)	LEV160	0,160	4,2	4	0,01
	ULEV125	0,125	2,1	4	0,01
	ULEV70	0,070	1,7	4	0,01
	ULEV50	0,050	1,7	4	0,01
	SULEV30	0,030	1,0	4	0,01
	SULEV20	0,020	1,0	4	0,01

Fig. 6. California LEV standards [11]

2.4.China, India and Japan

China, which has become the largest global automotive market, has introduced a very ambitious emissions reduction programme since 2013 that has lead to significant reductions in automotive emissions, especially in large urban agglomerations, by introducing rules similar to Euro 4, 5 and 6, introducing also WLTP rules and even Californian LEV III standards in Beijing (Fig. 3) [34].

India is following the EU emissions reduction programme via the introduction of BS IV (Bharat Stage 4), BS V and BS VI rules (which are similar to Euro 4, Euro 5 and Euro 6), with an intermediate phase between BS V and VI as short as possible (Fig. 3)

Japan has its own emissions regulation named "Post new long term regulation" and its own Japanese test cycle – JC 08, which replaced the old Mode 10.15 and Mode 11 test cycles (Fig. 3). Japan is also very active at the UN ECE GRPE informal group that is developing the new WLTP test procedure with the intention to implement the WLTC test cycle and the entire WLTP procedure in Japanese emissions regulation. (As Japanese traffic and speed limits do not permit the high speeds typical of European/North American motorways, the Extra High phase of the WLTC will not be used for testing in Japan.)

3. Development of emissions test methods

3.1. New light duty world harmonized test procedure – WLTP

In November 2007 the World Forum for Harmonization of Vehicles Regulations (WP.29) of the UNECE on GRPE session established an informal group to prepare a road map for the development of a World-harmonized light-duty vehicle test procedure (WLTP). The development of the WLTP comprised two main elements:

- Development of a harmonized driving cycle representative of world average driving conditions (internally referred to as the DHC – Informal Subgroup on the Development of the WLTP Test Cycle – see Fig. 7)
- Development of a harmonized test procedure that sets the conditions, requirements, tolerances, etc. for the emissions test, test equipment and instruments (internally referred to as the DTP – Informal Subgroup on the Development of the WLTP Test Procedure)

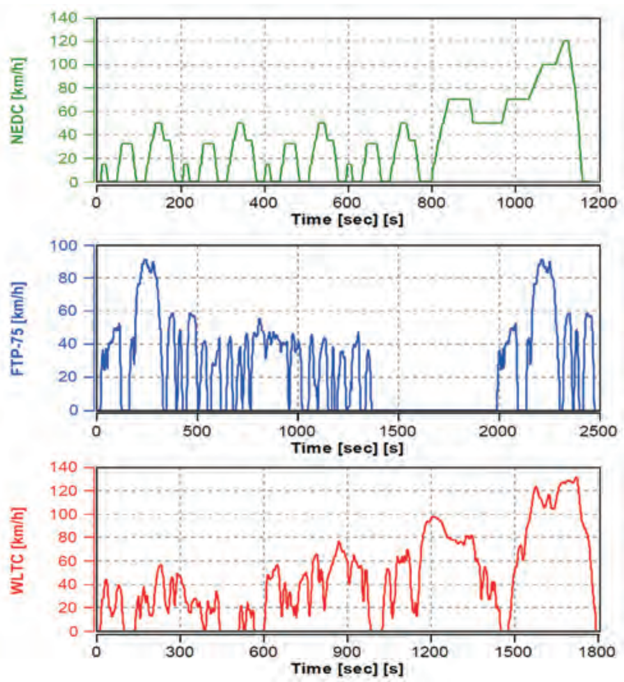

Fig. 7. The WLTC driving cycle in comparison to the NEDC and FTP-75

At its November 2007 session, WP.29 decided to set up an informal WLTP group under GRPE to prepare a roadmap for the development of the WLTP. After various meetings and intense discussions, WLTP informal group presented in June 2009 a first road map consisting of 3 phases.

(a) Phase 1 (2009–2014): development of the worldwide harmonised light duty driving cycle and associated test procedure for the common measurement of criteria compounds, CO_2, fuel and energy consumption (Type 1 test of EU type approval procedure).

(b) Phase 2 (2014–2018): low temperature/high altitude test procedure, durability, in-service conformity, technical requirements for on-board diagnostics (OBD), mobile air-conditioning (MAC) system energy efficiency, off-cycle/real driving emissions.

(c) Phase 3 (2018+): emission limit values and OBD threshold limits, definition of reference fuels, comparison with regional requirements.

The term 'WLTP' has been in use for some years, but very recent developments and formalisations in the development of this programme mean that it in fact it is use only as unofficial name. GTR 15 ('Global Technical Regulation No. 15') has come into being and so 'GTR 15' is now a more appropriate term for developments and planned implementations in this area. The main planned target is regarding CO_2 emissions and fuel consumption, since at the Euro 6 level emissions limits for regulated pollutants are not cycle-specific and there is no political mandate to change emissions limits to "match" the test cycle – a significant consideration (see Fig. 8).

EU institutions are currently working on transposition and implementation of WLTP regulation from UN ECE GTR 15 to European legislation. In the EU the WLTP is being prepared as a new implementing and amending regulation of co-decision EC No. 715/2007 that will eventually replace EC No. 692/2008 (NEDC), the well-known regulation currently used. The WLTP will be introduced via a new implementing Regulation 201a/xxx (after finishing all steps of acceptance procedure and possible changes in European Union institution), which is planned to replace Regulation (EC) 692/2008. This new Regulation 201a/xxx will also change the emission type definition for vehicles in this way that any first time official emissions testing of vehicles for the WLTP inevitably creates new emission type approvals (TA), regardless of whether the vehicles have already a previous emission type approval according to the implementing provisions of Regulation (EC) 692/2008 or not [28].

This means that vehicles type approved to the WLTP after 1 September 2017 will have to comply with RDE requirements (PEMS testing), with step 1 not-to-exceed (NTE) emission limits. Since type approval to the WLTP is mandatory for all new vehicles as from 1 September 2018, all vehicles not fulfilling the RDE step 1 requirements would have to be tested for the WLTP before 1 September 2017 or could not be sold anymore after 1 September 2018.

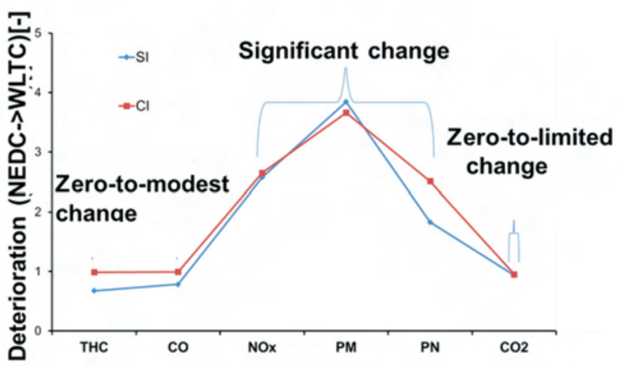

Fig. 8. Emissions over the WLTC compared to the NEDC for a pool of European SI and CI vehicles [8]

The new test cycle WLTC (World Light-duty Test Cycle) that will be introduced in WLTP regulation and is already specified in GTR15 is very different from the current NEDC cycle as it is more transient and somewhat similar to the US FPT 75 cycle. However, various factors determine the fuel consumed over a driving cycle, of which the cycle itself is but one factor. For pollutants other than CO_2 the picture is even more complex (Fig. 8). As a basic starting point, it is helpful to compare different cycles' speed traces by eye. Figure shows the speed traces for the NEDC, FTP-75 and WLTC test cycles. (Note that the three traces do not have common x axes.) Note also that for the FTP-75 the long period of vehicle standstill (ending at around 2000 seconds) is not idling, but engine shutoff ("hot soak"), during which exhaust gas is not sampled. The FTP-75 is the cycle with the longest history – automotive emissions legislation and prescribed test methods have a long history. The need to have stable test conditions and for results to be reproducible in any properly-equipped laboratory was considered a strong enough argument for automotive emissions legislation to only apply in laboratory contexts. However laboratory test cycles are not enough in achieving the general goals of reducing harmful emissions and fuel/energy consumption. Because the current test procedure, based on the NEDC cycle run under laboratory conditions, in outdated and there can be large (even huge) discrepancies between laboratory test results and real world emissions, a new WLTP methodology requires many modifications in the emission test procedure as well as in the emission testing laboratory (Fig. 9). The most important of them are [5, 12, 27]:

Related to the test cycle:

– WLTC (Worldwide harmonized Light duty Test Cycle)
– Different for 4 vehicle classes, depending on the power/weight ratio and max. speed
  - More dynamic, less idling, longer (20 → 30 min), higher average speed (34 → 46 km/h). and higher max speed (120 → 131 km/h).
  - Individual shifting points for each vehicle with a manual transmission.

Related to road load simulation for testing

– More realistic road load determination and simulation, to eliminate fuel consumption optimization.

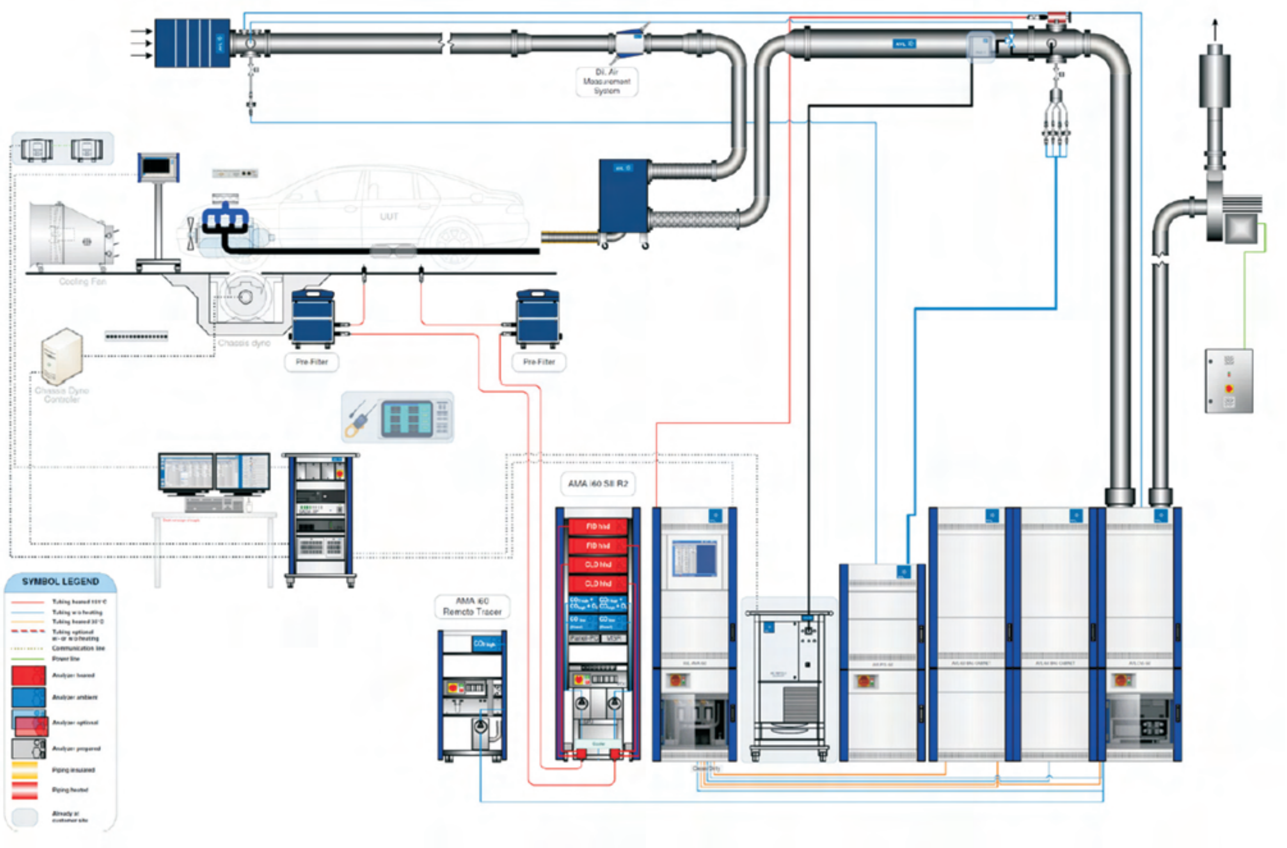

Fig. 9. BOSMAL – New Euro 6c/6d emission testing laboratory that meets WLTP/GTR15 testing requirements

– Test of a “Low CO_2” and “High CO_2” vehicle per vehicle family and interpolation using those results.

Vehicle preparation and conditioning

– 23°C test and soak temperature. ±3°C (5 min running average) during soak, ±3°C at test start and ±5°C during the test (2 Hz data)
– Electrical energy flow evaluated for the 12 V vehicle battery and correction of CO_2/FC accordingly. For that reason, it is strictly forbidden to charge the battery before a type approval test.

Test and measurement procedure

– Bag analyzing sequence optimized (calibration and checks once per test run)
– PM/PN measurement using dilution tunnel, particulate filters and number measurement for gasoline engines as well,
– PM/PN Background correction (optional)

While the fundamental approach of using a chassis dynamometer and emissions sampling bags remains unchanged, all the updated and new elements of GTR15 have a substantial impact on laboratory design (see Fig. 9).

3.2. Real driving Emissions (RDE)

The term real driving emissions (RDE) has been deployed to refer to efforts to reduce the disconnect between laboratory testing (and results) and real world scenarios. A considerable body of evidence attests to the fact that laboratory test procedures, particularly type approval, represent a best- case scenario and that a range of emissions (including, perhaps most controversially, CO_2/fuel consumption) are considerably higher in real life than in laboratory tests. Equipment is now available to measure emissions in the field and this will soon be a legal requirement for passenger cars sold in the EU; the USA already has such requirements in place for heavy duty vehicles. However, much remains to be done to characterize the correlation between real world emissions and laboratory emissions [30]. Additionally, despite recent changes in the legislation, some details remain at least somewhat uncertain regarding RDE and RDE testing. RDE is intended to exist in parallel with WLTP legislation and measurements will be carried out in on-road driving with different conditions. Emissions which will be evaluated in RDE testing of LDV are: NO_x, CO and CO_2, later on also PN. It is scheduled to be introduced with Euro 6c and Euro 6d limits. CO will be recorded and it may be subject to a limit at a later date [3, 19, 31].

To make an engine RDE-compliant can mean higher CO_2 emissions (and thus higher FC). RDE standards are a challenge that requires the introduction of additional technologies [27].

The European commission has provided conformity factors for RDE tests. Throughout the normal life of a vehicle type approved according to [34], its emissions determined in accordance with the RDE requirements (Annex to the regulation) and emitted during any possible RDE test performed in accordance with the requirements of the Annex, shall not be higher than the following not-to-exceed (NTE) values:

$$NTE_{pollutant} = CF_{pollutant} \times TF(p1,\ldots, pn) \times EURO\text{-}6$$

The temporary RDE conformity factor CF for NO_x emissions may equal 2.1 from 2017. The final CF effective from 2020 (Euro 6d) in the EU represents very stringent limits 1.5, because the 0.5 margin is close to the accuracy of current PEMS test equipment, but it will be implemented to satisfy boundary conditions [26, 27].

According to vehicle manufacturers, the NO_x CF should not be lower than 3, to satisfy all boundary conditions such as varying temperature, wind, humidity and driving behaviour. It is worth noting that the RDE test procedure does not correct for ambient humidity (in contrast to laboratory emissions measurements).

Table 1. Conformity factor CF pollutant for the respective pollutant

Pollutant	Mass of oxides of nitrogen (NO_x)	Number of particles (PN)
CF pollutant	1 + margin*, with margin = 0.5 upon request of the manufacturer, the following temporary conformity factors may apply: 2.1	to be confirmed… latest proposal: 1 + margin, with margin = 0.5
*"margin" is a parameter taking into account the additional measurement uncertainties introduced by the PEMS		

The main differences between both test methods introduced are following [9, 12, 19, 23]:

WLTC:

- Realized on the conditioned chassis test stand → relatively better repeatability
- Less dependent on external factors
- Customized gearshifts – good flexibility
- Commences from cold start

RDE:

- Emissions related with real-life conditions
- Road profile, road surface quality, actual ambient conditions, traffic congestions and driver's behaviour (eco-driving, neutral, aggressive) determine final parameters of the test (constant speeds, acceleration rates) and final emission levels
- Relatively worse repeatability
- Ideal flexibility (usage of all gears)
- Complex procedure of data acquisition and its final validation and post-processing
- Cold start excluded (although this exclusion is under discussion and cold (and even hot) starts will likely be included in future) [13].

Under discussion and investigation by the EU's Joint Research Center (JRC) is also introducing rules for RDE testing of hybrid vehicles [14, 19].

Following the 1st and 2nd packages, at least two further packages will be voted on and eventually adopted in EU countries

3rd package:

Conformity Factor for Particle Number (PN) on-road emissions [18],

real-driving emissions after engine start ("cold-start RDE") [13],

RDE testing procedure for hybrid and light commercial vehicles [14],

Ki values for regenerating systems,

Others: consideration of the volatility of gasoline fuel on PN/ consideration of LD Commercial Vehicles / consideration of Small Volume Manufacturers and Ultra-Small Volume Manufacturers / requirements to publish the RDE CFs in the certificate of conformity

4th package:

In-service-conformity tests,

Some other issues raised over the past few months

Future steps

2016-2017: Reviewing RDE procedure and adapting provisions to ensure practicality and effective emissions testing [19]

4. Particulate emissions – focus on the DI SI (gasoline) issue

As a combustion-propelled mechanical system with many moving parts, of mass of at least 1000 kg, moving over suboptimal terrain at speeds of up to around 40-50 meters per second, particulate emissions from vehicles are an inevitability – and not only from the engine (Fig. 10). The issue of nanoparticle emissions from internal combustion engines has evolved greatly over the years – both in terms of the emissions levels (which have now been reduced by orders of magnitude in many cases) and the scope of interest (no longer limited to Diesel engines). Concurrently, new test methods have been devised and a large body of toxicological evidence has been accumulated on the impact of such emissions. Legislation has evolved significantly in response to changes in technology and scientific information on the adverse effects of particulate; direct injection petrol engines are now a the focus of upcoming changes in European legislation (Table 2). Now that DPFs have made emissions from CI engines so low, it is natural that attention turns to other sources of particulate. SI engines remain the most widely used engine type for LD vehicles and more and more SI engines feature direct injection. The market share of direct injection SI engines (DISI) has grown rapidly; in the 2011 the new vehicle market share for the EU was 20% and 15% for the USA and has since grown further.

Advantages of DISI engines over PFI engines include:

- Potential for improved fuel efficiency,
- Better control over the injection process and fuel dosing,
- Certain emissions benefits, for example during start-up.

Disadvantages of DISI engines include:

- Emissions of particulate matter, which are generally much greater than from PFI engines (Fig. 11)

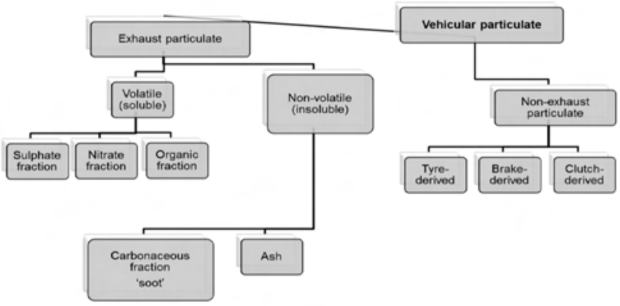

Fig. 10. The range of particulate emitted by a vehicle with an ICE

The causes of higher particulate matter emissions from DISI engines [2, 6, 7, 21, 24]:
– Slow burning pool fires formed on the wetted cylinder head and wall
– Imperfections in the injection spray cone
– Complex gasoline volatility effects
– Liquid fuel impingement on cold surface of the combustion chamber and pistons [2] – much worse at low ambient temperatures (Fig. 13) [6].

Table 2. Global limits for exhaust emissions of particulates from LDV and PC

Jurisdiction / legislative stage	PM [mg/km]*	PN [#/km]	Applicable test cycle
EU / Euro 5a	5.0	–	NEDC
EU / Euro 5b	4.5	6.0×10^{11}	NEDC
EU / Euro 6b	4.5	6.0×10^{11} 6.0×10^{12}	NEDC
EU / Euro 6c	4.5	6.0×10^{11}	NEDC/
WLTC			
EU / Euro 6d	4.5	6.0×10^{11}	WLTC
EPA / Tier II ("full useful life", 8 bins)	0.0–12.43	None	FTP-75
EPA / Tier II ("full useful life")	1.86	None	FTP-75
CARB / Exhaust Mass Emission Standards (2015)	6.21	None	FTP-75
CARB / Particulate Standards (2017)	1.86	None	FTP-75
CARB / Particulate Standards (2028)	0.62	Will be included	FTP-75
Japan / Post New Long Term	5.0	None?	JC08
China / CN6a (2019)	4.5	6.0×10^{11}	WLTP
China / CN6b (2022)	3.0	6.0×10^{11}	WLTP

Despite conceptual similarities to the Diesel engine, engine out emissions from DISI engines are normally 1-2 orders of magnitude below engine out emissions from CI engines; significant numbers of particles are below 20 nm in terms of their electrical mobility diameter (Fig. 12) [7, 8, 24].

The EU, EPA, CARB and Japan have set limits for solid emissions from vehicles featuring DISI engines (albeit not always technology-specific).

The limits are connected with mass emissions of PM. PN so far only targeted in EU legislation.

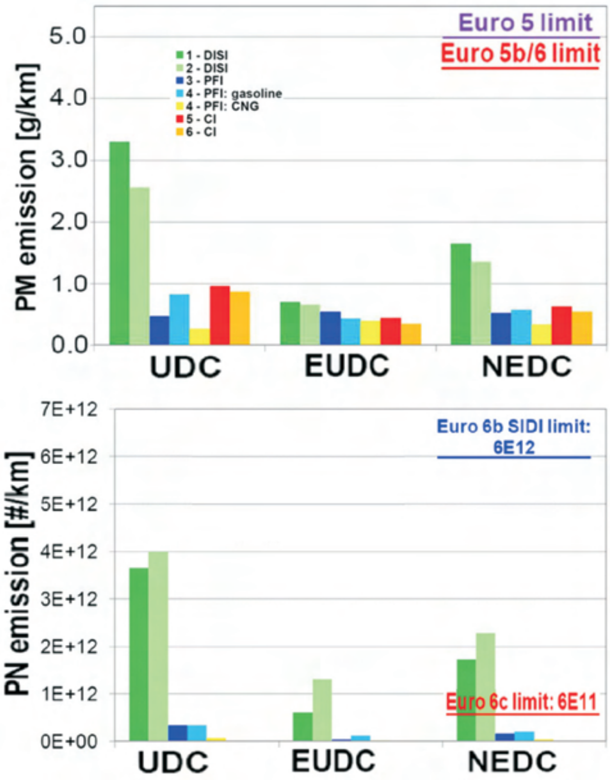

Fig. 11. PM and PN emissions from a range of vehicles, including two SIDI vehicles [7]

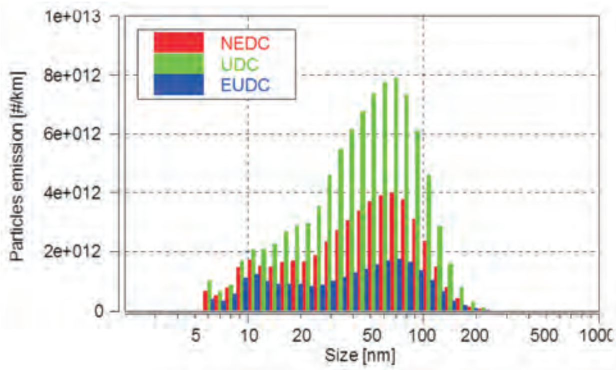

Fig. 12 Size distribution of particles emitted by a direct injection petrol vehicle

Another important issue discussed at the UNECE GRPE sessions and other forums is introduction of measurement of sub 23 nm particles currently not measured according to the PMP procedure (Fig. 12) [29].

There are some potential issues connected with measurement of particles in exhaust gas, the most important of which are:
– Particle number (PN) measurements during regeneration phases,
– Measurements of sub 23 nm particles especially in the context of the incoming WLTP cycle and DISI engines equipped with GPFs (see Fig. 11),
– Further improvements to the calibration procedure:

- existing systems with small modification can measure below 23 nm,
- however, below 10 nm the measurements will have high uncertainty,
- for > 10 nm measurements small differences can exist (e.g. at cold start),
- including information on the size distribution,

– PN counting from raw exhaust via fixed dilution
  - Interest in this approach confirmed by some engine manufacturers and some instrument manufacturers
  - The 01 Series of amendments to Reg. 132 already includes such a possibility but the procedure has not been defined

– Viability of the filter method for measuring extremely low emissions (cf. CARB LEV III 1 mg/mile).

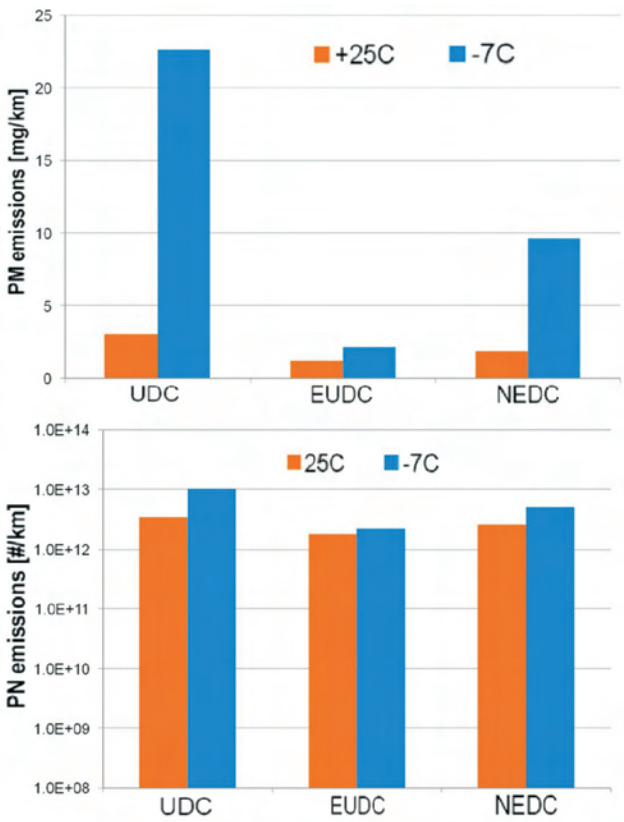

Fig. 13. PM and PN emissions from a SIDI vehicle tested at two ambient temperatures [7]

5. CO_2 emissions reduction

Greenhouse gas emissions have become a real issue. New passenger cars sold in 2015 emitted (over the NEDC) on average 119.6 g CO_2/km (10 g CO_2/km below 2015 target). 13.7 million new cars were registered in 2015 – a 9% increase in comparison to 2014. The EU wants to limit CO_2 to 95 g CO_2/km in 2021. The Global Fuel Economy Initiative (GFEI) "50 by 50" is an initiative jointly launched by UNEP (UN Environment Program), IEA (International Energy Agency), ITS (International Transport Forum), FIA Foundation. It calls for cars worldwide to be made 50% more fuel efficient by 2050, along with interim targets [10]. In Europe even full transport decarbonisation in the EU by 2050 is also under discussion, and exporting that technology to other large emitters [22].

Current official EU rules for CO_2 limitation are following:

– EC 443/2009 regulates the average specific emission of CO_2 for each manufacturer for NPC registered in EU in each CY

– Permitted CO_2 emissions = 130 g/km [NEDC] + 0.0457 * (vehicle mass [kg] – 1,372 [kg])

– 2020 target 95 g CO_2/km in 2021 – application of WLTP after 2017

Official US rules:

– 2 sets of parallel standards, namely:
  - CAFE – Corporate average standards adopted by NHTSA
  - GHG – Green House Gas standards adopted by EPA

– MY 2022 – 25 Mild Term Evaluation (MTE) made by EPA. The MTE will commence in early 2016 and issued a final determination by April 2018 with final standards to follow.

– EPA and CARB GHG regulations are harmonized from 2017-2025.

– Other countries with CO_2 (or fuel economy) limitations: Japan, Brazil, PR of China, South Korea, Taiwan.

Diesel cars sold in the EU are still in the majority (52% of total sales), but this share has shown a tendency to decline this year. The average CO_2 emissions intensity (over the NEDC) in 2015 was [33]:

– petrol fuelled cars: 122.6 CO_2/km

– Diesel fuelled cars: 119.2 g CO_2/km.

Hybrids and battery-electric vehicles (178 100 cars) constituting 1.3% of total sales 57 000 pure battery-electric vehicles were registered – a 50% increase in comparison to 2014 [33].

6. Engine technology and aftertreatment systems developments trends

6.1. Engine technology trends

It has been confirmed by many experts from the EU, USA and Asia that internal combustion engines (ICEs) remain the main solution for transportation needs (especially for LDV); considerable progress has been made in reducing emissions and fuel consumption, but these goals need to be harmonised and pursued simultaneously, with "engine + aftertreatment + fuel + lubricant" considered as a single system, along with all interactions between elements of this system. [9, 16, 17, 26]. Light duty and Heavy duty engine and emissions control technologies continue to evolve at a fast pace, showing market improvements in engine efficiency. LD gasoline engine concepts are achieving 45% BTE (Brake Thermal Efficiency) and closing the gap to Diesel engines. Current HD diesel engines are currently already demonstrating 50% brake thermal efficiency (BTE) and proposals have been developed to reach up to 55% BTE [20, 26].

Changes in world-wide emissions regulations, especially the introduction of WLTP and RDE, first in the EU, perhaps later also in other continents, will lead to major changes in

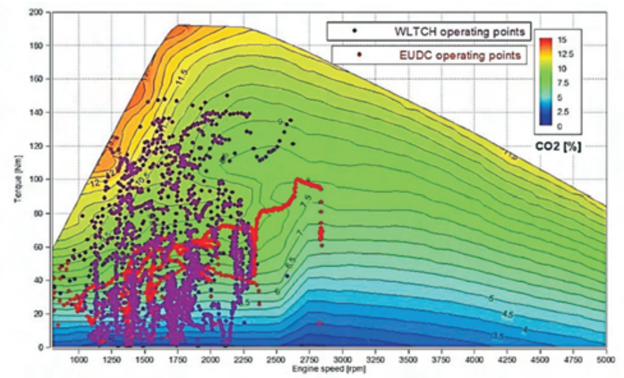

Fig. 14. CO_2 emissions measurements under the GTR 15 regime: NEDC vs WLTC

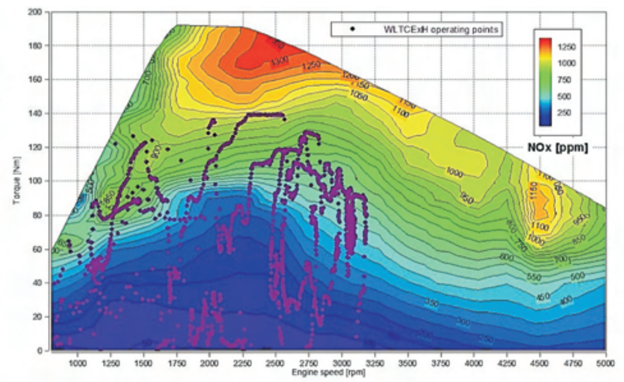

Fig. 15. NO_x [ppm] emission measured during engine map on the engine test bench with indicated WLTC operating points

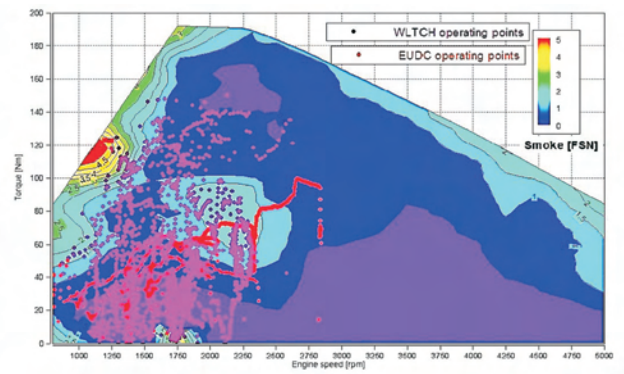

Fig. 16. Smoke [FSN] emission measured during engine map on the engine test bench with indicated NEDC operating points

engine technology, control strategy and calibration. The test cycle is an important change (particularly given the differences between the WLTC and the NEDC), but the test cycle is only part of the story. More important are changes in testing conditions, especially road load simulation, inertia setting, etc. (Figs 14–16).

But the new RDE test method introduction scheduled from 2017 will have an even higher influence on engine technology and sizing. The trend for the past few years has been one of downsizing (reduction of engine displacement, number of cylinders, dimensions and overall weight), as a consequence of CO_2 reduction trend is introduced in a synergy of many other technologies, such as: direct injection technology for both CI and SI engines, modulation of the compression ratio (variable CR), boosting technology – mainly 1-or 2-stage turbocharging, optimization of the engine's controlling algorithm by adding many new parameters that influence the calibration, valve actuation technology, special dedicated exhaust aftertreatment systems as a combination of multiple different catalysts/traps or specially catalysed filters like SDPFs. (Fig. 17).

However, small, downsized European Diesel engines, when driven at higher loads than current tests require (Fig. 15), exceed permitted levels of NO_x emissions, mainly due to the higher combustion temperatures generated by turbocharging. In the case of downsized gasoline engines (especially DI versions) fuel efficiency is much lower and particulates emissions become higher.

However, today engine manufacturers have to switch back to bigger engines – i.e. to upsize their engines again and to move from engine downsizing to engine rightsizing (in effect increasing the engine displacement and sometimes the number of cylinders) in order to be able to meet RDE requirements with low CFs – particularly for NO_x (Figs 14–16).

The new, wider areas of the engine map which must be optimised concerning the emission of regulated pollutants are a very important factor in powertrain design, as shown in Figs 17–18.

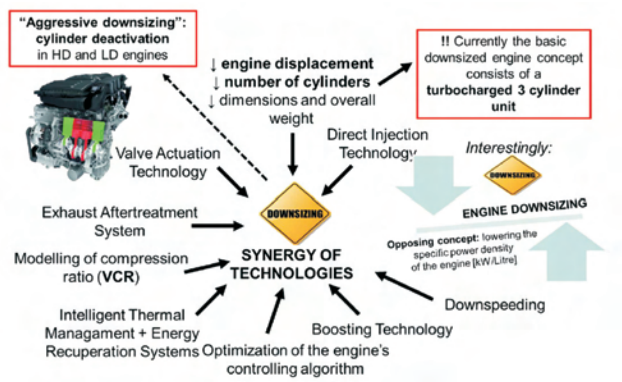

Fig. 17. Engine technology trends – a summary of the past few years

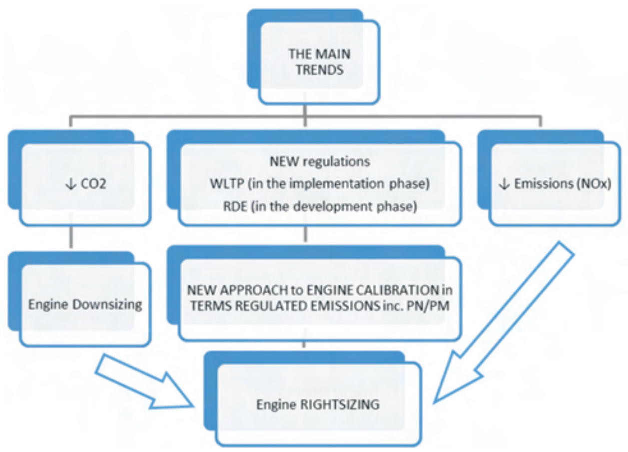

Fig. 18. Engine technology trends – the new tendency: rightsizing

6.2. Aftertreatment systems for CI and SI DI engines

Over the last decade exhaust aftertreatment systems of CI engines used in LD and HD vehicle applications have been developed significantly. Diesel engines feature a close coupled oxidation catalyst (DOC) for conversion of HC and CO & diesel particulate filter (DPF) to reduce particulate mass and number, in conjunction with Selective Catalytic Reduction (SCR) for NO_x reduction. Alternatively, CI engines can be found with close coupled Lean NO_x Trap (LNT – sometimes also called an NSC – nitrogen storage catalyst), with the functionality of an oxidation catalyst (DOC), and NO_x trap. The first system (SCR) was mainly used in high displacement LD engines > 3.0 dm^3, while the second (LNT) can be seen in smaller diesel LD engines. Vehicle weight can be used as the criterion for choosing which type of DeNOx strategy is appropriate (Fig. 19).

SCR is preferred for HD vehicles because of its weight and volume. {DOC + DPF + SCR + CUC} is quite large (its size is 850 x 700 x 700 mm for a 400 kW engine) but it's able to meet CF = 1.5. Another reason why it is used in HD vehicles is different type of driving in comparison to LD vehicles. HD vehicles undergo fewer cold starts and their engines are often used under steady state conditions with predictable load.

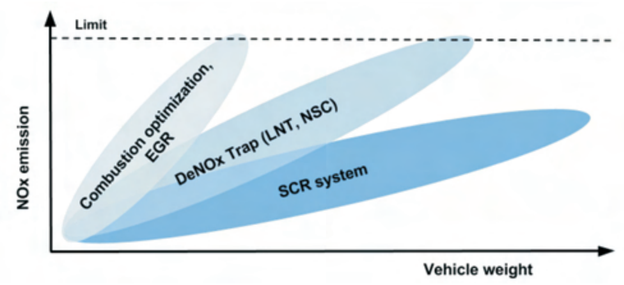

Fig. 19. Exhaust aftertreatment strategies for CI engines

After the introduction of the new WLTP procedure that will be introduced in 2017 and new RDE on-road emissions procedure in a similar time-frame to ensure that real-world emissions will be aligned with laboratory performance and emission of vehicle emissions legislation become again a critical driver for emissions control technology for LD vehicles.

The low conformity factors (CF) for LD vehicles, now confirmed (NO_x) or drafted (PN), will certainly exert pressure on engine aftertreatment technologies both in LD and HD engines. Relatively low or very low CFs will cause substantial changes in technology. SCR or SDPF has to be used in all LDV powered by diesel engines to meet Euro 6c or Euro 6d standards. ATS solutions would need to be "combined" in configurations, as follows (Fig. 20):

– {DOC + DPF + SCR (mandatory)}
– {DOC + SDPF + SCR},
– {LNT + DOC + SDPF}, for smaller LDVs with CI engines

As a consequence, there would be:

– more ATS systems,
– larger ATS components,
– greater AdBlue consumption,
– possibly greater fuel consumption/CO_2 emissions.

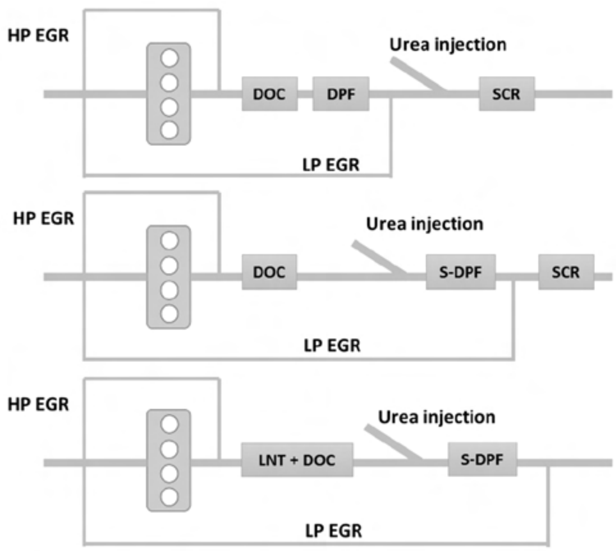

Fig. 20. Emission control technologies for LDV TDI to meet RDE NO_x limits (source: AECC, 2016)

In the case of gasoline engines (SI) in LDV the main catalyst technology used to emissions control is the Three-Way Catalyst (TWC) that operates in a closed-loop system including a lambda or oxygen sensor to control the air-to-fuel ratio in the SI engine. TWCs are an efficient solution for gasoline port fuel injection engines (PFI), but in the case of direct-injection engines (DI), which are promoted in the EU due to their better fuel efficiency, this solution can't be sufficient to meet new Euro 6c PN limit of 6 x 10^{11} #/km. For SI DI engines ATS solutions would need to be "combined" in configurations, as follows:

– {TWC + GPF} for SIDI stoichiometric engines,
– {TWC + LNT + GPF} for SIDI lean burn engines.

A few vehicle OEMs in Europe have already announced that all SIDI LDVs produced from 2017 will be equipped with GPF filter. Among them are: VW, Mercedes and Renault.

7. Engine fuel and oil development

Since fuel and lubricants are of vital importance – to the point where they can be considered to be powertrain components – R&D work on fuels and lubricants has become arguably as important as research on engine hardware, etc. As well as technical and engineering requirements, there is strong pressure to switch to fuels which are cleaner and more sustainable in terms of life-cycle emissions. The most obvious candidates in this area are natural gas [4] and biofuels – one of the main trends for both petrol and Diesel is an increasing proportion of biofuels blended into the mix in many jurisdictions – ethanol in the case of petrol and FAME in the case of Diesel, although other options exist. Obviously, the function to be played by lubricants is that of reducing friction and avoiding engine damage, with additional obligations in terms of heat transfer and the removal of deposits, in some cases. All three of these roles can have an influence on fuel consumption. There is a delicate balance to maintain regarding keeping friction low while ensuring long-term durability and engine performance. Finally, lubricants must also be compatible with the vehicle's aftertreatment system.

In 2015 a new fuel-related initiative was announced in the USA, called the 'Co-Optima' programme [15]. This Co-Optimization initiative aims to simultaneously transform both transportation fuels and vehicles and their powertrains in order to maximize performance and energy efficiency, minimize environmental impact, and introduce the adoption of innovative combustion strategies in IC engines [32]. One of the important targets is to develop higher octane gasoline (e.g. 100 RON) that facilitates better engine efficiency [26].

8. Summary

As a result of the topics explored in the preceding sections of this paper, certain conclusions can be drawn, bearing in mind that the currently situation is highly dynamic and that the pace of change is very fast.

In view of the fact that both the WLTP and RDE testing will be introduced in the EU it is prudent to ask whether they will have the desired effect: a measurable impact on air quality. Given that the changes will apply only to new registrations, it is to be expected that there will be some considerable temporal lag in terms of the impact of RDE-compliant vehicles on air quality. On the subject of RDE-complaint vehicles, there are good reasons to believe that the required changes could increase CO_2/FC and thus it there could be a situation in which the EU might have to moderate its expectations in terms of reduced CO_2/FC in light of more stringent emissions requirements. In the USA, the recent trend has been towards zero emissions, with CO_2/FC a lesser priority. Whether this trend continues, or whether CO_2/FC will become more important, remains to be seen. Regarding emissions limits in general, limits are now so low (particularly US limits: LEV/Tier III), that the physical lower limits for emissions from conventional combustion engines are being approached; the accuracy of the measurement technique has a progressively greater impact on progressively lower emissions. This leads to two closely related questions: *will emissions limits go any lower?* and *can emissions limits go any lower?*

The same applies to gravimetric particulate matter emissions limits – modern emissions levels are low and legal limits are also low – the sensitivity of the technique is questionable at these levels and PM testing is now effectively a pass/fail type test. Particle number (PN) has higher resolution and is a more effective tool for legislators, but at present this test is only carried out on vehicles with direct injection engines. Leading the way, China plans to mandate this type of test (and limit) for all vehicles apart from those running on CNG – this approach is ahead of the EU and the US and it remains to be seen how widely PN limits will be applied internationally over the coming years. Given that exhaust particulate emissions are now so low (at least by mass), surely it is pertinent to pay close attention to vehicular non-exhaust particulate emissions (which are of a similar order of magnitude to exhaust particulate emissions).

While at present no CF has been proposed for FC, this topic is of great interest to consumers. RDE testing includes requirements to monitor CO_2 and the ubiquity of the internet means that such data will probably find their way into the public sphere. However, consumers may still treat such data with suspicion, and yet the results of RDE testing could affect buying habits and thereby the engines offered in the EU (and even beyond).

Trends in engine offerings are not set in stone and manufacturers may change their strategies in light of the factors and pressures discussed above. Specifically, it is possible that some engine design trends from recent years will slow down, stop, or even reverse. For example, Dieselisation (especially for small PC) in the EU and in the US (where the share is currently very low). Downsizing and turbocharging (at least the more aggressive types of turbocharging) may become a less attractive option, especially in view of the fact that downsized turbocharged engines tend to produce more NO_x and that their FC benefits are often lower in RDE testing than over the NEDC. It is noteworthy that in the EU emissions limits themselves are not changing – rather, the conditions under which those limits must be met are being broadened – and therein lies the challenge for engine designers and powertrain engineers. Changes in global emissions regulations, focusing currently mainly in Europe more on NO_x and PN emissions than on CO_2 (as was the case in previous years), have a great influence on engine size and technology. Automotive OEMs have to move from "downsizing" engine concepts – which are good for low CO_2 emissions, but very problematic for NO_x emissions, not only for Diesels but also for GDI engines – to a new "rightsizing" concept that should give further consideration to the difficult NO_x-PN-CO_2 trade-off (amongst other factors). The next few years should bring some new "rightsized" engine families to the market, perhaps first in Europe, but later on also in Asia and the USA. This diametrically opposing strategy appears to be a good technical solution, but the marketability and attractiveness of such engine offerings may not be a simple task.

In an era of globalisation, transnational vehicle manufacturers and increasing integration of markets, it is perhaps surprising that there are so many differences between exhaust emissions legislation in different jurisdictions. The EU has already harmonised the requirements of all 28 member states, but one day harmonisation between the EU, US and even Japan may be possible.

This paper has focused mainly on engine and aftertreatment hardware, but the ultimate source of energy (fuel) is also important. Alternative fuels aside, it may be possible to radically decrease CO_2 emissions and FC by improving "conventional" fuel types – 100 RON fuel is a promising direction and something vehicle manufacturers would like to see, but global availability remains a distant goal.

While the subject matter of this area of discussion is of a technical/engineering nature, the dimensions of the argument extend well beyond the technical arena: legislation is changing (and has already changed); rapid changes in the strategies pursued by vehicle and engine manufacturers could have significant socioeconomic impacts; buying habits and whether consumers can be persuaded to upgrade to new, fuel efficient vehicles are naturally of economic importance. Finally, there is the *raison d'etre* of the entire topic: the environment, specifically urban air quality and anthropogenic greenhouse emissions.

Abbreviations

ATS	Aftertreatment system
BS	Bharat Stage
CAFE	Corporate Average Fuel Economy
CARB	California Air Resources Board
CF	Conformity Factor
CRF	Code of Federal Regulations
CI	Compression Ignition engine
CNG	Compressed Natural gas
CUC	Clean Up Catalyst
DI engines	Direct Injection engines
DISI	Direct Injection Spark Ignition engines
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
EPA	Environment Protection Agency
FAME	Fatty Acid Methyl Ester
FC	Fuel Consumption
FIA Foundation	Fédération Internationale de l'Automobile Foundation
FRM	Final Rule Making (USA)
GDI	Gasoline Direct Injection engine
GFEI	Global Fuel Economy Initiative
GHG	Greenhouse Gas
GTR15	Global Technical Regulation No. 15
HDV	Heavy Duty Vehicles
ICEs	Internal Combustion Engines
IEA	International Energy Agency
ITS	International Transport Forum
JC	Japanese test Cycle
LDVs	Light Duty Vehicles
LNT	Lean NOx Trap
MAC	Mobile Air-Conditioning
MTE	Midterm Evaluation (USA)
MY	Model Year (USA)
NEDC	New European Driving Cycle
NHTSA	National Highway Traffic Safety Administration
NMOG	Non-Methane Organic Gases
NPC	National Population Commission
NSC	Nitrogen Storage Catalyst
NTE limits	Not-To-Exceed limits
OBD	On-Board Diagnostics
OEMs	Original Equipment Manufacturers
PEMS	Portable Emissions Measurement System
PFI	Port Fuel Injection engines
PM	Particulate Mass
PMP	Particulate Measurement Programme
PN	Particulate Number
R&D	Research and Development
RDE	Real Driving Emissions
RON	Research Octane Number
SCR	Selective Catalytic Reduction
SDPFs	DPFs with SCR coating
SI	Spark Ignition engine
TWC	Three-Way Catalyst
UN ECE GRPE	the Working Party on Pollution and Energy of United Nations Economic Commission for Europe
UNEP	United Nations Environment Program
US FTP-75	United States Federal Test Procedure
WLTC	Worldwide harmonized Light vehicles Test Cycle
WLTP	Worldwide harmonized Light vehicles Test Procedures
WLTP-DHC	Informal Subgroup on the Development of the WLTP Test Cycle
WLTP-DTP	Informal Subgroup on the Development of the WLTP Test Procedure

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CE-2016-342

Trends in automotive emissions, fuels, lubricants, legislation and test methods – a global view, with a focus on the EU & US – Summary of the 5th International Exhaust Emissions Symposium (IEES)

The field of vehicular exhaust emissions is experiencing wide-ranging and rapid changes. 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 being increasingly stringent, the list of parameters subject to legal limits are slowly expanding – and, most importantly, these limits must be met under a wide wide range of conditions. A range of strategies are available to overcome these difficulties, which was explored during the 5th International Exhaust Emissions Symposium (IEES) hosted at BOSMAL in May 2016. This paper reports and summarises the topics of the 5th IEES and attempts a synthesis on the current status of the field and what the coming years may hold for the automotive and fuel industries and other allied fields.

Key words: *exhaust emissions, emissions standard, RDE, WLTP, WLTC, biofuel, exhaust aftertreatment systems, fuel, lubricant*

Introduction

One of the most important factors influencing socioeconomic development and improvement of quality of life is the development of means of transportation and energy sources (fuels) – first of all with mineral liquid fuels, but also with alternative fuels. However, such development causes negative effects like air pollution from gaseous emissions and particulate matter originating from engines (but also from other vehicle systems). The influence of those harmful factors remains significant.

The problem of reducing greenhouse gas emissions (especially CO_2), emitted by road vehicles is very high on the political agenda, limits for particulate emissions are also being tightened; in the USA particulate mass (PM) and in Europe, especially the number of particles (PN), emissions of which will be limited for spark ignition engines with direct injection (DI SI).

These compounds are regarded as pollutants with far-reaching negative impacts on the environment. In the case of NO_x, the problem is wide deviations in the results of laboratory measurements and on-road measurements using PEMS systems. A potential danger is also the emission of harmful compounds which are not yet subject to legal limits. The issue of harmful emissions (and fuel consumption, which is connected also with global demand for fuel and energy security) occurring in real traffic conditions is a priority of the automotive sector, especially in the European Union and the United States. It is also a subject of public debate with the participation of international organizations that deal with emissions and emissions testing (e.g. the ICCT).

The response of legislative institutions dealing with this subject has been the introduction of many legal acts determining the permissible emissions of vehicles and methods for their measurement, some imposing increasingly stringent limits on emissions of various harmful compounds, a number of other mandatory guidelines, incentive plans for reducing fuel consumption and the introduction of low-carbon fuels and alternative fuels. Now, in light of revelations that emissions of certain compounds measured in real conditions are poorly reflected in laboratory tests (especially NO_x), measurement methods will change. This concerns both laboratory methods (e.g. the new test procedures prepared by the UN-ECE – WLTP/ GTR15; or the US EPA – US 1065/1066), as well as emissions and fuel consumption measurements under real-world conditions (real driving emissions, RDE). RDE measurements have turned out to be so important that that test method is to become an integral part of the test procedure

Front page of symposium programme

PTNSS BOSMAL Bielsko-Biała, Poland

5th International Exhaust Emissions Symposium 19-20 May 2016

Final Programme

Thursday, 19 May 2016

- **08:00 - 09:00** - Registration

Welcome & Opening Address
- **09:00 - 09:10** - **Prof. Jerzy Merkisz (PTNSS), Dr. Arkadiusz Stojecki (BOSMAL) & Dr. Piotr Bielaczyc (International Organising Committee)** [10]

Session 1: The Automotive Emissions Landscape in the US and the EU
Chairs: Wolfgang Thiel (TRT, Germany) & Piotr Bielaczyc (BOSMAL, Poland)
- **09:10-09:40** - **Dr. Piotr Bielaczyc (BOSMAL, Poland)** – Which strategy is better for emissions control - the EU or the US?: an introduction to the question [30]
- **09:40-10:20** - **Dr. Vicente Franco (The ICCT Europe, Germany)** – A comparison of emission standard design and enforcement approaches in the EU and US [40]
- **10:20-10:50** - **Giovanni D'Urbano, (FOEN, Switzerland)** – Swiss approach and experience in controlling air pollution emissions from internal combustion engines and gas turbines [30]

- **10:50-11:30** - **Coffee break, poster presentation [40]**

- **11:30-12:00** - **Kurt Engeljehringer (AVL, Austria)** – Global emission regulations and testing methods on the local differences [30]
- **12:00-12:30** - **Dr. Miriam E Gerlofs-Nijland (National Institute for Public Health and the Environment, the Netherlands)** – Adverse health effects of traffic-derived emissions - the impact of biofuel [30]

- **12:30-13:30** - **Lunch, poster presentation** [60]

Session 2: Emissions Reduction Technologies and Strategies
Chairs: Tim Johnson (Corning, USA) & Piotr Bielaczyc (BOSMAL, Poland)
- **13:30-14:15** - **Keynote: Dr. Timothy Johnson (Corning, USA)** – Directions in vehicular emissions and efficiency [45]
- **14:15-14:45** - **Mike Douba (Center for Transportation Research, Argonne National Laboratory, USA)** – Testing PHEVs and BEVs to determine expectations in reduced emissions and fuel usage [30]
- **14:45-15:05** - **Prof. Federico Millo (PoliTo, Italy)** – Modelling of LNT and SCR on filter for passenger car applications [20]

- **15:05-15:45** - **Coffee break, poster presentation** [40]

- **15:45-16:05** - **Dr. Gerhard Schopp (Continental, Germany)** – Calibration and validation of engine management systems with respect to actual and future exhaust emission legislations [20]
- **16:05-16:25** - **Dr. Claus Goersmann (Johnson-Matthey, UK)** – Low carbon transport 2050: Powertrain options [20]

Session 3: Real Driving Emissions
Chairs: Wolfgang Thiel (TRT, Germany) & Vicente Franco (ICCT Europe, Germany)
- **16:25-16:55** - **Helge Schmidt (TUV, Germany)** – Real Driving Emissions - status of discussion and practical experience [30]
- **16:55-17:10** - **Prof. Gordon Andrews (University of Leeds, UK)** – Real world SI vehicle emissions in low speed congested traffic [15]
- **17:10-17:25** - **Prof. Gordon Andrews (University of Leeds, UK)** – Real world emissions performance of a HDD truck with urea SCR NO_x control [15]
- **17:25-17:45** - **Prof. Jerzy Merkisz (BOSMAL/Poznan University of Technology, Poland)** – Investigations on exhaust emission from off-road vehicles and rail vehicles using PEMS [20]
- **17:45-18:00** - **Michael Heuser (Sensors Europe GmbH, Germany)** – Advances in PN PEMS [15]

- **20:00** - **Symposium Dinner and Musical Soiree at Palac Kotulinskich**

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5th International Exhaust Emissions Symposium 19-20 May 2016

Friday, 20 May 2016

Session 4: Particle Matter Emissions and their Measurement and Control
Chairs: Wolfgang Thiel (TRT, Germany) & Piotr Bielaczyc (BOSMAL, Poland)
- **09:00-09:30** - **Prof. William Northrop (University of Minnesota, USA)** – Semi-volatile particulate matter from low temperature Diesel combustion using conventional and alternative fuels [30]
- **09:30-10:00** - **William Silvis (AVL Inc., USA)** – Making sense of PM measurement at 1 mg/mi, 6E11 #/km [30]
- **10:00-10:20** - **Dr. Topi Ronkko[1], Jenni Alanen[1], Erkka Saukko[1], Kati Lehtoranta[2], Timo Murtonen[2], Hilkka Timonen[3], Risto Hillamo[3], Dr. Panu Karjalainen[1], Heino Kuuluvainen[1], Juha Harra[1], Prof. Jorma Keskinen[1] (1:Tampere University of Technology, Finland; 2: VTT Technical Research Centre of Finland; 3: Finnish Meteorological Institute)** – Nanoparticles in natural gas engine exhaust [20]
- **10:20-10:35** - **Dr. Jonna Kannosto, Dr. Mikko Moisio, Ville Niemela, Henna Isherwood (Dekati, Finland)** – Gravimetric PM filter results can be improved with integrated real time particle concentration measurement [15]

- **10:35-11:15** - **Coffee break, poster presentation** [40]

Session 5: Fuel and Lubricant Development in Light of Emissions Requirements and Industry Trends
Chairs: Amanda Lea-Langton (University of Manchester, UK) & Sabina Kawczak (PKN Orlen, Poland)
- **11:15-11:45** - **Keynote: Dr. Thomas Wallner (Center for Transportation Research, Argonne National Laboratory, USA)** – Co-optimization of fuels and engines [30]
- **11:45-12:05** - **Thomas Hartmann, Uwe Lutz, Mathias Lohman, Marc Walter, (BASF SE, Germany)** – Impact of soot formation on lubricant ageing in DISI engines [20]
- **12:05-12:25** - **Knut Skardalsmo (Skardalsmo Fuel Consulting, Norway)** – Bridging the gap to the hydrogen economy [20]
- **12:25-12:45** - **Dr. Heather Hamje (CONCAWE, Belgium)** – Studies of fuel effects in modern Diesel passenger cars [20]
- **12:45-13:00** - **Prof. Miroslaw Wyszynski (University of Birmingham, UK)** – Gaseous and particulate emissions from a diesel fuel emulsion containing up to 20% of pyrolysis oil obtained from woody biomass [15]
- **13:00-13:20** - **Giovanni Cecconello (Petronas, Italy)** – Engine oil advanced technologies for FE improvement in modern HD applications [20]

Symposium summary and closing
- **13:20-13:30** - **Dr. Piotr Bielaczyc, on behalf of the International Organising Commitee** [10]

- **13:30-14:30** - **Lunch** [60]

- **14:30-16:30** - **Tour of BOSMAL's laboratories**
Guide: Wojciech Trybus, Testing Laboratory Director, BOSMAL

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The symposium programme

emission cars – the EU has made big steps regarding plans to introduce RDE to the approval procedures of cars from 2017; such tests and the accompanying emissions conformity factors will be mandatory, rather than any kind of "optional extra". However, as always, the automotive market is not shaped only by political and technical factors, but also by customer requirements, which themselves also evolve. Both legislators and the general public have a common goal of reducing fuel consumption, without sacrificing durability or safety. Also, the increased media interest in the issue of exhaust emissions from modern cars (especially Diesels) increases the pressure on everyone involved in legislating, meeting and testing emissions. The response to that is a wide range of advanced engine technology, catalytic aftertreatment systems, the development of fuels, lubricants and oils that reduce friction, and so on.

These solutions are often correlated: exhaust gas after-treatment systems require fuel with low sulphur content, advanced engine design defines the parameters of oil, etc. Fundamental changes in the powertrain (new energy sources, advanced electromechanical systems: hybrids) are a revolution in the industry. Requirements that emissions are below the prescribed level under almost all operating conditions may force the introduction of new technical solutions, or at least require extensive modification of current solutions. All of these new and modified technical solutions need to be de-

Prof. Jerzy Merkisz and Dr. Piotr Bielaczyc delivering the opening address

Wolfgang Thiel (TRT Engineering, Germany) during the opening presentation veloped, tested, approved and certified – and, in light of RDE requirements – not only in the laboratory.

Symposium organisation

Seeing that this subject is important for the further development of the automotive industry on a global scale as well as in the European Union and Poland, in the years 2010, 2011, 2012 and 2014 BOSMAL Automotive Research and Development Institute Ltd in Bielsko-Biala organized four international symposia on the problems of exhaust emissions from automotive sources. These symposia interested professionals from the automotive industry and academia, both foreign and from Poland, who willingly and frequently participated in the discussions. On 19-20 May 2016 BOSMAL and the Polish Scientific Society of Combustion Engines (PTNSS) was the organizer of the 5th International Exhaust Emissions Symposium. The organization and the programame of the symposium were prepared by the International Organizing Committee, headed by Dr. Piotr Bielaczyc (BOSMAL/PTNSS), with well-known specialists from the USA, Switzerland, the UK, Germany and Italy.

This is the fifth meeting in Bielsko-Biala with leading experts in this field from the US and Europe who discussed the American and European strategies for the development of low emitting vehicles, the latest trends in legislation and methods of emissions testing, the development of vehicular engines, fuels and lubricants. The aim of the meeting was to compare the factors mentioned above and discuss the possibility of legislation harmonization in the US and the EU, which would increase the possibility of control in certifying vehicles; the event also aimed to foster integration of the scientific community and the automotive industry at home and abroad, exchange of knowledge on many issues, as well as promoting the achievements of Polish research institutes in this field, particularly BOSMAL.

Media partners of the symposium included: "Combustion Engines" – a scientific journal published by PTNSS, "DieselNet" of Canada, "Przegląd Techniczny" and the "Gazeo" internet portal, the latter two from Poland.

Giovanni D'Urbano (FOEN, Switzerland) delivering his presentation on Swiss emissions standards

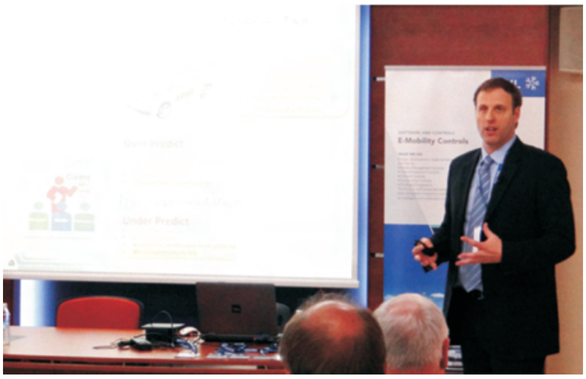
The symposium was attended by over 140 delegates, representing of 68 companies from the automotive and fuel industry, associated international organizations such as the ICCT and CONCAWE, research institutes and international academia from 20 countries (Japan, the USA, Canada, the UK, Spain, Portugal, Italy, Switzerland, Austria, Luxembourg, Denmark, Belgium, Germany, the Netherlands, Norway, Finland, France, Slovakia, the Czech Republic and Poland).

Symposium guests were welcomed by BOSMAL Director Dr. Arkadiusz Stojecki; the symposium was opened by Prof. Jerzy Merkisz, President of PTNSS.

Symposium content

During the symposium 25 presentations were delivered on the impact of harmful emissions on human health, internal combustion engines, the development of vehicular powertrains, development of fuels and motor oils by well-known automotive exhaust emissions experts – see the full programme presented in the introduction. Additionally, there were 12 posters presented by specially invited experts from the field. The invited speakers presented during the five plenary sessions on the following topics: 'The Automotive Emissions Landscape in the US and the EU', 'Emissions Reduction Technologies and Strategies', 'Real Driving Emissions', 'Particulate Matter Emissions and their Measurement and Control' and 'Fuel and Lubricant Development in Light of Emissions Requirements and Industry Trends'. Setting both the scene and the tone for the symposium, the symposium's opening presentation was given by Dr. Piotr Bielaczyc of BOSMAL, who presented the most important technical, political and economic factors that currently affect the development of the automotive industry in the world, presented the history of the issue and attempts to regulate over the years, not only in the EU but also in the United States, China and India. He paid attention to current, real problems not completely taken into account by emissions regulations. He emphasized the problem of high emissions of NO_x from modern diesel engines, the problem of particulate matter also emitted by spark ignition engines with direct injection and variance between actual measurements of fuel consumption and CO_2, and those resulting from the NEDC cycle. The difference here reaches 30-50%. The problem of the road-laboratory gap regarding particulates and NO_x will probably be solved by RDE, but the suitability of RDE for CO_2 measurements remains unclear. Typically, CO_2 emissions over the new cycle (WLTC) and the present cycle (NEDC) do not differ significantly; applying

Dr. Miriam Gerlofs-Nijland (National Institute for Public Health (RIVM) in Netherland) during a speech on the health consequences of emissions in road traffic



Mike Douba (Argonne National Laboratory, USA) delivering his presentation on test procedures for hybrids

the full WLTP [procedure] improves the situation somewhat (mainly due to the redefined test inertia), but the road-laboratory gap has not yet been closed when it comes to CO_2/FC. A number of questions asked in the summary of the opening presentation were touched upon and answered by presenters in further presentations. These theses for further discussion were:

- Will the introduction WLTP / RDE meet expectations and will have a measurable impact on air quality? After how many years will the results will be visible?
- Will the EU reduce its expectations for reducing fuel consumption and CO_2 emissions in the light of the more restrictive emission standards?
- Will the US continue its policy of aiming for zero emissions, or will fuel consumption become a bigger problem?
- Can emissions limits be reduced any further?
- Will PM/PN limits eventually apply to all vehicles? What about particles not originating from the combustion engine?
- Will consumers accept higher but more realistic fuel consumption; will it change the habits of buyers and engine offerings?
- Is it probable that the trends of recent years slow down/ stop /reverse? Specifically:
  – Dieselisation – is the trend in the EU reversing? Is there scope for increased market share in the USA?
  – Downsizing/turbocharging
- What are the effects of current problems? How will the automotive industry survive?
- How to solve the problem of high NO_x emissions inherent in downsized engines?
- When will it be possible to harmonize regulations in the USA, the EU (and beyond)?
- Is it possible to drastically reduce CO_2 emissions through improvement of conventional fuel types?
  – 100 RON – when could it be available on a global scale?

Legislation and proscribed test methodologies regarding exhaust emissions in the US and the EU

In the first session on regulations and methods of emissions testing the following individuals presented (inter alia): Dr. Vicente Franco (the ICCT, Germany), Kurt Engeljehringer (AVL, Austria), Giovanni D'Urbano (FOEN, Switzerland) who spoke about trends in reducing global emissions and their impact on measurement procedures and equipment.

Participants during the coffee break, viewing the climatic chamber (with 4WD chassis dynamometer) at BOSMAL

Multiple presenters emphasized the fact that in the US the key elements of type approval include compliance testing of new and in-use vehicles, vehicle recalls and financial penalties, and a dedicated agency independent of local government (the EPA). The EU does not have many of these aspects – most significantly, there is no central authority responsible for the type approval and enforcement of regulations; nor is the creation of such an entity likely in the near future. Responsibility for these functions rests with individual member states. There is no harmonized approval system for the whole EU to organise vehicle recalls. (Recalls in the case of non-compliance with emissions standards are a true rarity in the EU, in contrast with the USA.) During the symposium it was highlighted that another problem is the lack of legal uniformity and regional variations in the interpretation of EU regulations, as a result of which it is difficult to say whether the ECU software used by some companies (for example) is actually breaking the rules or not. In spite of the frequency with which "defeat devices" are mentioned (in particular in recent months), there is a surprising lack of consensus on what such devices are and what kind of specific language could be used to ban them. Upcoming changes including RDE regulations will partially improve the situation in the EU, but without a centralized European body for approval of vehicles the US approach to the problem will continue to be more thorough. Experts discussed the incoming method for the measurement of emissions under actual driving vehicle on the road – RDE. The main objection regarding RDE is that measurements may be unreliable because of the very high number of external influencing factors. According to research by AVL (for example), NO_x emissions can be measured with an accuracy of ±28%. There was much discussion of the WLTC chassis dynamometer driving cycle proscribed by the WLTP procedure (as described in UNECE GTR 15), which will soon replace the NEDC (as described in UNECE Regulation No. 83) and the cycles used in certain Asian countries.

China, which is always inspired by European emission standards, is currently planning to introduce China 6a, which is equivalent to Euro 6, but later China 6b is even twice as stringent. If fully implemented, it would mean that China would have the most stringent standards in the world, tested over the WLTP – a situation which would have appeared highly unlikely only a few years ago.

There were conversations on engine control strategies, which have significantly overtaken the development of

Prof. William Northrop (University of Minnesota, USA) during his presentation on particulates from low temperature combustion

legal requirements for type approval in Europe. In order to protect some engine and aftertreatment components, certain systems may be deactivated under certain conditions (e.g. EGR at cold start). In the EU, such control strategies are manufacturer secrets, while in the US such actions must be authorized. Federal US legislation also requires that vehicles are tested over multiple driving cycles, which include hot starts – in contrast to the EU, where there is one test cycle which always commences from a cold start. (This is another example of the thoroughness with which US emissions limits are enforced, for the time being without resorting to RDE testing.)

William Silvis (AVL Inc., USA) during his wide-ranging presentation on particulate emissions measurements

Dr. Miriam Gerlofs-Nijland (National Institute for Public Health and the Environment - RIVM, Netherlands) presented important information regarding the influence of the toxic compounds emitted by engines fuelled by biodiesel on living organisms.

Methods of reducing engine emissions

The second session, focusing on emission reduction methods, was opened by a keynote delivered by Dr. Tim Johnson (Corning, USA). Among other topics, he talked about the possibilities for increasing the efficiency of vehicular engines.

The rather impressive figure of 45% thermal efficiency has been reached, but further development in this area is still possible. Figures which a few years ago seemed obtainable only in CI engines are now being reached in SI engines, although many of these engines are experimental and not market-ready; part-load efficiency remains an area for improvement. Naturally, a large part of Dr. Johnson's keynote was dedicated to exhaust gas aftertreatment systems (selective catalytic reduction (SCR), SCR on filter (SCR-F), passive NO_x absorbers (PNA), methane oxidation catalysts and gasoline particulate filters (GPF)). An important element for reducing emissions is the engine control strategy employed by the ECU – the calibration method of which was presented by Dr. Gerhard Schopp (Continental Powertrain, Germany). Due to the rapid development of the market for electric and hybrid vehicles there are doubts about that how to measure their actual emissions. The problems and future plans for emission measurement methods of hybrid vehicles have been presented by an expert from the US, a government research laboratory Mike Douba (Argonne National Laboratory, USA). Dr. Claus Goersmann (Johnson-Matthey, UK) presented his analysis of and predictions for future vehicles powered by low carbon fuels, which can reduce fuel consumption and CO_2 emissions by up to 15%. It was highlighted that diesel engines – recently so heavily criticized – should remain an important source of power due to their high efficiency. In spite of the growing popularity of electric vehicles, in 2025 97% of vehicles will still be powered by an internal combustion engine. That is why it is important to develop carbon production of alternative fuels and biofuels of low carbon intensity, as well as electricity from renewable sources.

Dinner and musical soiree at Kotuliński palace at the end of the first day of the symposium

Giovanni D'Urbano (FOEN, Switzerland) presented Switzerland's approach to emissions reduction. Mainly EU standards are employed in Switzerland, in some cases made more stringent, e.g. with reduced limits for emissions of particulate matter from construction machinery.

Real-world emissions measurements: RDE testing

The third session related to RDE. The first RDE package has recently been published in Commission Regulation (EU) 2016/427; others are being finalised. Still under discussion is the matter of including cold start emissions, test procedures for hybrids and particle number measurements (RDE PN). Key findings and observations were presented by Helge Schmidt (TÜV Nord, Germany).

RDE tests that will be introduced to new approvals from September 2017 (with a conformity factor (CF) of 2.1) and next from January 2020 (CF = 1.5) require testing of the vehicle on the road using a portable emissions measurement system (PEMS). The route for the RDE includes driving in city traffic (urban), extra-urban and motorway. The route

Dr. Vicente Franco (The ICCT Europe, Germany) during his presentation on emissions standards in the EU and US

Guests during the coffee break, in the background the 500e electric car developed by BOSMAL

used by TÜV Nord is 83 km long and the test lasts 105 minutes (i.e. mean speed 57 km/h – higher than the equivalent values for WLTC and the NEDC).

Methods of determination and reducing particulate emissions

The fourth session of the symposium focused on emission of particles, methods of their determination and control. Special attention was paid to mechanisms of particle formation. Prof. William Northrop (University of Minnesota, U.S.A.) showed the associations of solid particles emission in low temperature combustion processes. Biofuels were included in his considerations as well. He found that low temperature combustion leads to a decrease in soot emissions; however, the emission of CO and HC increases. Another American expert, William Silvis (AVL Inc., U.S.A.) presented advanced methods of solid particle emission measurement, allowing detection even where the particle population is very low, a pertinent point in view of future legislation (specifically California LEV III, which will limit gravimetric particulate emissions to 1 mg/mile). The topic of nanoparticles was also expanded upon by Dr. Topi Ronkko (Tampere University

Kurt Engeljehringer (AVL, Austria) during his presentation on global emissions regulations and emissions measurement methods

of Technology, Finland). He reported that the mean aerodynamic diameter of particles occurring in the exhaust gas of an engine running on CNG is lower than 10 nm. Dr. Mikko Moisio (Dekati, Finland) presented an advanced method of particle mass measurement based on a diffusion charger with electrometer.

Development of fuels and lubricants for engines

The last, but just as important, part of the symposium dealt with the development of engine fuels and lubricants and their interactions with other powertrain systems. As expected, the topics of mineral oil-based fuels and possibilities for improvement of their properties, alternative fuels, biofuels and their manufacturing processes/technologies, possibilities of their application and compatibility with present infrastructure and vehicles were widely discussed – a keynote presentation was delivered by Dr. Thomas Wallner (Argonne National Laboratory, USA) on the US Department of Energy (DoE)'s project entitled: "Co-Optima (Co-optimization of engine fuels)", aiming at acceleration of the implementation of improved conventional fuels, low-cost and sustainable biofuels and highly efficient, low emitting engines for vehicle propulsion. Knut Skaardalsmo (Skaardalsmo Fuel Consulting, Norway) focused on the promising possibilities of methanol as an automotive fuel. Notably, methanol (CH_4O) may be obtained from natural sources and has the lowest carbon-to-hydrogen ratio of any liquid fuel. Dr. Heather Hamje (CONCAWE, Belgium) and Prof. Mirosław Wyszyński (the University of Birmingham, UK) presented the impact of advanced engine fuels on the emission of regulated and unregulated exhaust gas components. The part of the session on lubricants included the impact of soot on engine oil and the role played by low viscosity oil in fuel economy efforts. Representing Petronas (Italy), Giovanni Cecconello mentioned the topic of the development of low-viscosity oils (SAE 0W-20), providing low friction losses in internal combustion engines, in the context of engines powering heavy-duty vehicles. At this point it is worth recalling that diverse branches of the industry (e.g. light duty, heavy duty, motorsport, etc.) share certain problems and that solutions developed for a given branch can sometimes be transferrable to other branches – as an example, SCR for NO_x control has its origins in non-mobile applications.

Dr. Thomas Wallner (Argonne National Laboratory, USA) during his keynote presentation on the US Co-Optima programme

Summary and Conclusions

The 5th International Exhaust Emission Symposium referred to the all questions related to the emission of hazardous exhausts emissions from automotive sources, including observations and conclusions on the present and future legislative landscape on emissions and fuel economy, methods of emissions reduction and the development of research methods to aid in those goals.

The reduction of emissions of hazardous and toxic compounds is currently important – a reduction in emissions of solid particles (both in terms of mass and number), a decrease in real-world NO_x emissions, as well as meeting all demands during new types of tests (such as the WLTP and RDE) are the main challenges for the automotive industry caused by political, socioeconomic and technical factors. Fulfilling emission limits over the WLTC, as well as during RDE testing, is a very complicated and expensive process for vehicle producers, demanding increased investments into R&D, which for years has been among the main targets of BOSMAL, currently the largest R&D institution of this type in central/eastern Europe.

On the other side of the equation, legislators working on the implementation of advanced research methods and emission norms in Europe and elsewhere have to follow (and even anticipate) rapid developments in electronics and the computerization of modern vehicles, and to implement vehicle type approval and in-use conformity procedures to ensure openness, clarity and to avoid conflict between vehicles manufacturers, vehicle users and regulatory authorities. Finally, it is worth recalling that while real-world exhaust emissions (e.g. NO_x, PN) cannot be measured by the average driver, real-world FC is automatically measured and displayed (and sometimes later shared on the internet) and this topic is of growing interest to consumers.

All presentations given during the 5th International Exhaust Emission Symposium (5th IEES), together with accompanying material, have been archived in the official conference proceedings entitled: Symposium Proceedings – "Trends in automotive emissions, fuels, lubricants and test methods – a global view with focus on the EU & US", ISBN No 978–83–931383-9-5 and in the Book of Abstracts, ISBN No 978-83-946334-0-0, published by BOSMAL on CD, together with movie reportage on DVD. Addy Majewski of DieselNet (Canada) prepared a summary/analysis of the symposium, which is available online [14]. A summary of the symposium has also been published in the Polish journal "Przeglad Techniczny".

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The 5th International Exhaust Emissions Symposium
19-20 May 2016, BOSMAL, Bielsko-Biala (Poland)

Trends in automotive emissions, fuels, lubricants, legislation and test methods – a global view, with a focus on the EU & US

Presentation abstracts

WHICH STRATEGY IS BETTER FOR EMISSIONS CONTROL – THE EU OR THE US?: AN INTRODUCTION TO THE QUESTION

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Keywords: exhaust emissions, emission standards, emissions legislation, test procedures

The major global automotive markets have all set limits for exhaust emissions from new road vehicles, which have become increasingly stringent over the past few decades. There is also considerable pressure to reduce fuel consumption and CO_2 emissions – around 80% of all new passenger cars sold globally are subject to some kind of energy efficiency regulation. Such legal requirement necessitate testing. Despite a recent trend towards 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 employed for engine and chassis dynamometer testing of vehicles and their powertrains. Here the key points are reviewed and strategies and technologies employed to deal with these challenges are discussed. Automotive emissions regulation processes are discussed and a question is posed – which is the better approach for emissions control?

VEHICLE EMISSION STANDARD DESIGN AND ENFORCEMENT APPROACHES IN THE EU AND US

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Keywords: compliance and enforcement, emission standards, US, EU, defeat devices

In the wake of the Volkswagen scandal, real-driving emissions and compliance and enforcement are emerging as key development areas for emission regulations in the EU). Whereas the US regulatory framework dealt successfully with the VW defeat device issue via minor adaptations, the problem of real-world diesel NO_x is expected to drive more fundamental, overdue changes in the EU. The new framework for vehicle type-approval proposed by the European Commission would harmonise enforcement practices across EU member states and shift the focus from pre-production to in-service conformity and market surveillance. In combination with future improvements to RDE testing, this has the potential to become a world-class vehicle emissions regulatory framework (one that could serve as a second template, along with the US regulatory framework, for other key vehicle markets, namely China and India). But the success of such an approach is not to be taken for granted, as it will largely depend on the ability of the European regulators to compel manufacturers to provide detailed, justified descriptions of their emission control strategies while providing them guidance on how the regulations should be interpreted. Also, in-use testing programs, an adequate penalty system in case of noncompliance, increased transparency, and the faculty to perform random checks and integrate evidence from non-government parties are thought to be important aspects of robust vehicle emission regulation.

SWISS APPROACH AND EXPERIENCE IN CONTROLLING AIR POLLUTION EMISSIONS FROM INTERNAL COMBUSTION ENGINES AND GAS TURBINES

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Keywords: Switzerland, air pollution control, legislation

Swiss air pollution control policy is based on two major principles in environmental protection. The first of which, the "polluter pays principle" is written in our constitution and puts the burden of environmental cost directly on the polluter. The second principle, the "precautionary principle" is laid down in the Swiss environmental protection act and allows for preventive action. Together, this means

that Swiss environmental policy must demand the use of Best Available Technology (BAT) in all areas. To fulfil this task, Switzerland has introduced national measures but also seeks international collaboration and harmonization. This includes groundwork at UNECE level, like for example the particle number measurement procedure (PMP), which already has or is going to be implemented in diesel and gasoline passenger car, heavy duty engines, nonroad engines as well as stationary engines regulations. Moreover, Switzerland is committed to reduce real-life NO_x emissions from combustion engines using different fuels (diesel, gasoline, natural and biogas) through effective national and international regulations.

GLOBAL EMISSION REGULATIONS AND TESTING METHODS ON THE LOCAL DIFFERENCES

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Keywords: exhaust emissions, emissions limits, emissions testing, Euro 6, WLTP, real driving emissions (RDE)

Exhaust emissions testing and emissions limits have a long history. Recent studies have confirmed that in-use performance is not always as good as what has been measured in the laboratory. Electronic control of the powertrain is the main controlling factor in this emissions performance – exhaust emissions from a modern car are about 80% software and 20% physics. Older approaches such as testing over a well-defined test cycle are beginning to be replaced with newer approaches, including not-to-exceed testing and real driving emissions. The WLTP is also being introduced – a well-defined laboratory test cycle which nevertheless attempts to create more realistic vehicle operating conditions and close multiple loopholes in the NEDC. Thus, the industry faces a range of emissions-related challenges. AVL has a platform of tools to enable vehicle manufacturers to meet these new, demanding emissions requirements.

ADVERSE HEALTH EFFECTS OF TRAFFIC-DERIVED EMISSIONS – THE IMPACT OF BIOFUEL

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Keywords: air pollution, toxicity, traffic, engine exhaust emission, biofuel blends

For many years, automotive emissions have been the dominating source suspected to contribute to adverse health effects of air pollution. This has led to increasingly tighter emissions standards and with that advances in engine and emission control technologies and increased use of new (bio)fuels. Consequently, emissions have set to change substantially now and in the years ahead. However, these factors will not only influence the emissions but will also lead to changes in the chemical composition and the toxicity of engine exhaust emissions. Examples will be shown on the implications of these factors on the toxicity and health risk associated with tailpipe emissions. Focus will be on the impact of increasing the blend ratio of biodiesel on engine emission associated toxicity. This review of the toxicological assessments of emissions from biofuels and blends shows the importance of an effective hazard identification methodology for risk assessment to reveal the impact of biofuel (blends).

DIRECTIONS IN VEHICULAR EMISSIONS AND EFFICIENCY

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Keywords: greenhouse gases, vehicle emissions, engines, aftertreatment, NO_x, particulate, PM, hydrocarbon, diesel oxidation catalyst, selective catalytic reduction, diesel particulate filter, three way catalyst

Powertrain technology is developing very rapidly as a result of pollutant and greenhouse gas regulations. Europe is implementing real driving emissions (RDE) standards with the conformity factors for light-duty diesel NO_x ramping down to 1.5X by 2021. The US is placing a stronger emphasis on laboratory emissions, but the LD regulations are about an order of magnitude tighter than Euro 6. The California HD low-NO_x regulation is advancing and may be proposed in 2017/18 for implementation in 2023+. Beijing, China, and India have proposed Euro 6 type regulations for implementation in the 2017-20 timeframe. The second phase of US HD greenhouse gas regulations propose another 25-30% tightening beyond Phase 1, beginning in 2021.

LD and HD engine technology continues showing marked improvements in engine efficiency. LD gasoline concepts are achieving 45% BTE (brake thermal efficiency or net amount of fuel energy gong to the crankshaft) and closing the gap with diesel. Projections indicate tight CO_2 regulations will require some degree of hybridization and/or high-performing diesel engines. HD engines are demonstrating more than 50% BTE using methods that can reasonably be commercialized; and proposals are developed for reaching 55% BTE.

Lean NO_x SCR technology trends emphasize durability, N_2O, and greatly reduced emissions. Diesel PM (particulate matter) reductions are evolving around the nature of soot and the distribution in the filters. Gasoline direct injection (GDI) particulates carry PAHs (polycyclic aromatic hydrocarbons) through the three way catalyst, but filters can remove most of them. Gasoline particulate filter regeneration is now better understood. Improved understanding of oxidation catalyst formulations are reported with further quantification of the impact of precious metal formulations. Finally, three-way catalysts understanding of the catalyst-support interactions, and the introduction of a low-mass cellular substrate that improves TWC cold start performance are recent advances.

TESTING PHEVS AND BEVS TO DETERMINE EXPECTATIONS IN REDUCED EMISSIONS AND FUEL USAGE

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Keywords: hybrids, electric vehicles, testing

Standardized vehicle test protocols provide the procedures and calculation methods for repeatable laboratory determinations of fuel economy and emissions representative of actual driving. Over time, new cycles and sophisticated adjustment factors were added to better match lab results to "real-world" observations. Procedures were heavily modified for Hybrid Electric Vehicles (HEVs), Plug-in Hybrid Electric Vehicles (PHEVs), and Battery Electric Vehicles (BEVs). HEV testing accounts for changes in battery energy states. PHEV procedures separately characterize the charge-depleting driving mode and account for its partial fraction of total expected driving. And procedures for BEVs capture efficiency and range without requiring a test burden far beyond standard vehicle testing. These new procedures must properly account for different energy sources and complex powertrain operation so that fair comparisons of different technologies can be made. Concepts like the "Utility Factor" are used for both PHEVs and BEVs to account for variations in range. The three important considerations of vehicle efficiency: Petroleum use, CO_2 emissions, and fuel costs, scale with "MPG" for any vehicle using only petrol-derived fuel. However, these three metrics diverge when dealing with plug-in vehicles ("MPGe" offers no useful information). The blended type PHEV is the most difficult to characterize in testing and to express with final results because engine use is uncertain without testing many variations in driving styles. Although some progress has been made, the test procedures and tools available to fully characterize blended PHEVs does not yet exist. Recommendations to improve this shortfall are given.

MODELLING OF AFTERTREATMENT SYSTEMS FOR NO_x CONTROL FOR DIESEL PASSENGER CAR APPLICATIONS

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Keywords: diesel aftertreatment, modelling, NO_x emissions

Tighter emission regulations invoke the necessity of adopting advanced aftertreatment systems. Lean NO_x Traps (LNTs) and Selective Catalytic Reduction (SCR) catalysts are most promising technologies for controlling NO_x emissions in diesel passenger car applications. Therefore, computationally efficient numerical models of aftertreatment devices for NO_x emissions are nowadays being actively investigated, aiming to achieve not only reliable predictions of their abatement efficiency under different operating conditions, but also for optimization and model-based control systems. In this context, fast running global reaction mechanisms are developed and calibrated according to suitable test protocols using synthetic gas benches. Calibrated models are afterwards validated according to engine-out emission data under real driving cycle conditions. These models can then be transferred to reduced order models using reasonable assumptions to be implemented in real time applications such as Engine Control Units (ECU) and Hardware in Loop (HiL) systems, thanks to their lower computational requirements.

CALIBRATION AND VALIDATION OF ENGINE MANAGEMENT SYSTEMS WITH RESPECT TO ACTUAL AND FUTURE EXHAUST EMISSION LEGISLATIONS

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Keywords: combustion engine managements, calibration

Ever stricter emission limits, the introduction of fuel consumption limits and the demand for higher engine performance, makes the use of innovative and complex engine technologies necessary.

This requires also higher accuracy from the Soft Ware for Engine Control and its Calibration. Beside the calibration of many, partly new control functions for exhaust aftertreatment and On Board Diagnosis (OBD), the accurate tuning of the so-called basic functions play a major role. That is mainly air path, fuel path, torque model and boost procedure control. This is an absolute necessary precondition to be able to fulfil the most stringent emission and OBD legislations.

A further topic that should not be underestimated is the increasing number of vehicle variants, whereas the number of engine variants decreases at the same time. This results in the fact that a given engine is used in a very high number of vehicle variants, e.g. vehicles with different weight or different power output. In order to keep the overview, consequent calibration data reuse and a very well structured working method is needed.

The lecture should demonstrate, how Continental master this challenges in calibration of engine management systems for combustion engines.

LOW CARBON TRANSPORT 2050 – POWERTRAIN OPTIONS

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Keywords: GHG Emissions, 2050, powertrain options

At the 2015 United Nations Conference on Climate Change in Paris 177 parties agreed to keep the increase in global average temperature well below 2°C above pre-industrial levels. In order to achieve this goal, green-house gas emissions need to be massively reduced by 2050. This includes enormous green-house gas and especially CO_2 emission reductions for the transport sector. Possible powertrain options to achieve future targets include internal combustion engines with de-carbonized liquid fuels, hybrid and plug-in hybrid vehicles as well as fuel cell electric and battery electric vehicles.

FROM LABORATORY TO ROAD – REAL DRIVING EMISSIONS

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Keywords: real driving emissions, NEDC, RDE

In European emission type approval during the past years the exhaust emission limits have been reduced significantly. Although air quality was improved from 1990 on, a high percentage of the European population is exposed to air pollutant concentrations above European limit values, mainly on particles, nitrogen dioxide (NO_2) and ozone (O_3).

Exhaust emissions of passenger cars and light duty trucks in Europe are measured by using the "New European Driving Cycle" (NEDC) under well-defined ambient conditions in a laboratory. The NEDC represents only a small part of all driving conditions in real traffic. On 03.02.2016 the European Parliament decided that exhaust emissions in real traffic (Real Driving Emissions = RDE) shall be measured in Europe by using Portable Emission Measurement Systems (PEMS). Due to European air quality regulations NO_x emissions are the main issue of RDE. European Commission is also interested in particle measurement especially on gasoline cars with direct injection.

When measuring emissions in real traffic numerous influencing factors have to be considered. Besides variable ambient conditions changing traffic situations affect the results of such measurements. This complex set of influencing factors has to be ad-dressed by defining route requirements and boundary conditions. An elaborate data evaluation has been created. While the Moving averaging windows method (MAW; or EMROAD by JRC) is based on CO_2 emissions, for the Standardized wheel power frequency distribution method (SPF; or CLEAR by TU Graz) the wheel power is used for normalizing exhaust emissions.

Due to the fact that RDE are measured in real traffic, this new method will be challenging for all parties involved.

REAL WORLD SI VEHICLE EMISSIONS IN LOW SPEED CONGESTED TRAFFIC

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Keywords: congested traffic, emissions, PEMS, FTIR

Air quality in urban areas of cities exceeds European limits and the present work studied the traffic emissions in a congested area of Leeds where local air quality measurements showed exceedances of European NO_2 standards. The traffic in the locality was highly congested with average speeds that varied during the day and over several days from 5 to 30 kph. 29 hot start journeys were compared with 8 cold start journeys and the average journey emissions in g/km were correlated as a function of the average journey velocity. Traffic conditions varied from 1000 vehicles per hour to 200 vehicles per hour on a single lane road in one direction. A Temet Gasmet FTIR PEMS was used in a Euro 4 SI Mondeo vehicle. At high average speed and low congestion emissions were low and for hot starts were below the legislated emissions. At high (< 20 kph) average speeds CO_2 emissions were below those on the test cycle, but were much higher than on the test cycle with high congestion low speed journeys. With cold start in congested traffic the emissions were much higher than for hot start and well in excess of the legislation. The cause of the increase in emissions at low average journey speeds was the increase in the number of stop/starts and the high acceleration rates at each start. The number and magnitude of these events were much higher than on the NEDC. Proposals for Real Driving Emissions, RDE, in Europe are to concentrate on high average in driving in cities where air quality exceedances occur and are unlikely to be difficult for vehicle emissions control technologies to achieve low emissions. Real congested traffic is a much greater emissions control challenge and is the cause of air quality exceedances, current RDE proposals do not address these issues.

REAL WORLD EMISSIONS PERFORMANCE OF A HDD TRUCK WITH UREA SCR NO_x CONTROL

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Keywords: RDE, SCR, NO_x emissions, PEMS

A Mercedes Benz AXOR-C6x2 with a Mercedes-Benz OM457LA Euro V engine with urea SRC NO_x control was investigated using real world driving with a cold start. The journey was 33 km long and included a motorway section with local roads from the depot to the motorway and to the delivery point at the other end. Six repeated journeys were made under different local traffic conditions. It took 500-700s to reach 200°C at the catalyst and there was evidence during downhill motorway driving of the catalyst cooling when the engine was not fuelled, this resulted in increased NO_x emissions. NO_x emissions were relatively high for much of the journey, indicated a poor performance of the urea SCR NO_x control in this real world driving. The Temet FTIR PEMS system was used for exhaust emissions measurement with the Horiba OBS pitot tube exhaust mass flow measurement system. The emissions during the long cold start dominated the overall journey emissions. CO and THC emissions were high during acceleration transients and indicate poor control by the catalyst.

INVESTIGATIONS ON EXHAUST EMISSION FROM OFF-ROAD VEHICLES AND RAIL VEHICLES USING PEMS

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Keywords: exhaust emissions, off-road vehicles, rail vehicle, real driving emission (RDE)

One of the most significant aspects of exhaust emission testing is the adopted methodology. In recent years, methods of exhaust emission testing under actual operating conditions (RDE – Real Driving Emission) have been developing rapidly. Such a measurement method is very complex but is the only way to provide invaluable information on the actual on-road exhaust emissions, not obtainable under laboratory conditions. Tests conducted under actual vehicle operation provide cognitive and development prospects. No other testing methodology enables such full exploration of the relations occurring between the exhaust emissions and almost all operating parameters of vehicles and their engines. Therefore, RDE studies are gaining in importance and in the coming years they will be introduced to the type approval procedures. This applies to road and off-road vehicles. Off-road and rail vehicles are a group whose numbers significantly increased in the recent years, it is expected that this trend will be maintained in subsequent years. Experts agree that for these groups of vehicles the internal combustion engines will be the main source of power for a number of years. The presentation shows past experience in RDE research conducted for the engines of off-road vehicles, mainly construction and agricultural machines and engines of rail vehicles. Examples of toxic fumes emission results from the selected construction and agricultural machines and locomotives engines. These results are shown using an indicator (CF – Conformity Factor) for each tested compound. The results provided in the presentation show that emissions under real operating conditions differ from emissions measured in laboratory tests. It should also be noted that despite the several years of experience of many research centers continuing RDE research of off-road and rail motor vehicles is fully justified, there are still many issues concerning the procedures and conditions for research that require further testing.

ADVANCES IN PN PEMS

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Keywords: PN PEMS, PMP, CPC, Real Driving Emissions

In preparation of the new RDE – LDV Commission Regulation (EU) 2016/427, the EC – JRC has been evaluating candidate technology platforms for on-board particle number measurements. These technologies have included diffusion-charge (DC's) – and condensation particle counter (CPC) – based solutions. Intermediate results shown to participants of the evaluation´s first phase led to the consideration of developing a CPC-based device.

The disadvantages of DC´s and the difficulties to operate commercially available CPC´s on vehicles in terms of mitigating the safety concerns of the operating fluid, meeting the thermal requirements, having appropriate thermal sample conditioning of the aerosol and operating under the challenging environment (for example, shock, vibration and altitude) has necessitated the development of a new portable mixing-type CPC with sample conditioning similar to that used in the reference PMP devices.

The compact 12V device comprises a modular heated line (100°C), a heated primary dilution system (100°C, nominally set at 15:1) a volatile particle remover (VPR, heated catalyst ca. 300°C), a secondary diluter system (30-70:1) and a mixing-type CPC operating using n-Butanol.

This system has been characterized in accordance with the EU PMP guidelines and shown to meet the required criteria: removal of volatiles, particle size penetration efficiency and linearity. In addition to these criteria, the system has been evaluated over a range of real-world driving conditions (notably, vibration, temperature and altitude) for any additional error sources.

Research studies comparing the PN PEMS device against reference PMP systems throughout Europe, South Korea and the US have shown deviations in a range two PMP compliant systems would differ from each other and smaller.

SEMI-VOLATILE PARTICULATE MATTER FROM LOW TEMPERATURE DIESEL COMBUSTION USING CONVENTIONAL AND ALTERNATIVE FUELS

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Keywords: low temperature combustion, nanoparticles, semi-volatiles

Low temperature combustion (LTC) operation in compression ignition engines can simultaneously reduce NO_x and soot emissions but is known to result in higher CO and hydrocarbon (HC) emissions compared to conventional mixing controlled combustion. Dual fuel LTC combustion, coined Reactivity Controlled Compression Ignition (RCCI) has similar emissions trade-offs but has the advantage of higher thermal efficiency and load range. Oxygenated alternative fuels used as the low reactivity fuel in RCCI can also lead to near-zero carbonaceous soot emissions. Although these techniques are effective at nearly eliminating soot from engines, gas-to-particle conversion processes can produce semi-volatile nanoparticles that nucleate and grow once diluted and cooled in the primary exhaust plume. Our research involves the characterization of semi-volatile particles from LTC modes. Results show that semi-volatile particles in the primary exhaust are highly dependent on dilution conditions and that solid soot particles are not necessarily nucleation sites for particle growth. In all cases, high molecular weight hydrocarbons play a crucial role in heterogeneous nucleation of nanoparticles upon primary dilution. Modelling supports the experimental finding that smaller particles in the distribution are made of lower volatility material than large particles. More critically, the research shows that although the conditions in the primary exhaust plume are suitable for condensation onto existing particles, saturation ratios of UHC compounds are not high enough to homogeneously nucleate particles.

MAKING SENSE OF PM MEASUREMENT AT 1 MG/MI, 6E11 #/KM

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Keywords: particulate matter (PM)

The regulators in the US are once again considering to lower the allowable emissions of particulate matter from passenger cars, perhaps to 1 mg/mile. There is both concern that the current reference method for this measurement may not be up to the task, and uncertainty about the implications of other available metrics for a combustion aerosol. So it is interesting to review the nature of the engine aerosol, how the metrics of mass, size and number relate to each other in characterizing it, and to assess information from recent studies on the capabilities of the reference methods as well as other instruments that are more precise.

NANOPARTICLES IN NATURAL GAS ENGINE EXHAUST

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Keywords: fine particle emission, nanoparticle formation, natural gas engine

Increased availability and smaller emissions have increased the attractiveness of natural gas in internal combustion engine applications both in transport and energy sectors. In this study [1], the natural gas engine nanoparticle emissions and particle formation were studied using instrumentation capable to measure particle concentration and size distribution down to 1 nm. Measurements were conducted in an engine laboratory at two different engine loading conditions. The test engine was a gasoline engine that was modified to run with natural gas. Results indicate that especially the nanoparticles smaller than 10 nm should be taken into account when the natural gas engine exhaust particle number is evaluated. These particles seem to be initially formed at high temperature, i.e. in the engine cylinders or their vicinity, and grew in particle size in the exhaust sampling process.

Reference:

[1] Alanen, J., Saukko, E., Lehtoranta, K., Murtonen, T., Timonen, H., Hillamo, R., Karjalainen, P., Kuuluvainen, H., Harra, J., Keskinen, J., Rönkkö, T. The formation and physical properties of the particle emissions from a natural gas engine. Fuel. 2015;162,155-161.

GRAVIMETRIC PM FILTER MEASUREMENT RESULTS CAN BE IMPROVED WITH SIMULTANEOUS REAL TIME PARTICLE CONCENTRATION MEASUREMENT

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Keywords: PM filter, mass, gravimetric measurement

Gravimetric measurement is standard measurement method in engine measurements and it's used a lot in different research. Particle mass in exhaust has been reduced a lot in recent years and therefore it is more difficult to make reliable gravimetric measurements. In filter measurements, if one measurement differs from the others it's difficult to know if unequal result is real change in sample or some problem in filter weighing of handling process. When real-time concentration signal is measured simultaneously with filter, measurement weighing result can be verified using real time signal. Real time instruments are typically used in particle emission R&D and research work is conducted with non-regulated real-time instruments like CPC, MSS, ELPI®+, DMM, EEPS and others. However these are research instruments and need quite a lot of knowledge of usage. There is clear need of easy to use real time instrument to qualify the gravimetric filter mass results.

Dekati Ltd. has integrated real-time PM detector with a standard gravimetric PM filter holder. The assembly is approximately the same size as a normal PM filter holder and it fits directly into all existing PM filter sampling systems (CVS or partial flow diluters). Furthermore, it tolerates 47°C cabinet temperature and provides both a gravimetric PM mass result and second-by-second mass related accumulation data collected on a 47 mm filter.

The system consists of a traditional 47 mm filter holder and a parallel electrical detection part. The electrical detection part consist miniature diffusion charger and electrometer for a real-time signal and it's equipped with own pump so that normal PM filter flow rate is unchanged. The whole system is fully automated and battery-powered to maximize usability. In addition to replacing the filter there are no other requirements for cleaning.

In this work, we explain the system operating principle and show specifications for both gravimetric and real-time PM data measurements. We show how to use new filter holder assembly in engine measurements and present measurement data from laboratory aerosols and vehicle particle emission measurements. We also present challenges in comparing diffusion charger and gravimetric PM results and discuss other possible measurement applications like PEMS and gravimetric measurement quality assurance.

FUEL-ENGINE CO-OPTIMIZATION

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Keywords: internal combustion engine, efficiency, optimisation

Decades of dedicated work to maximize efficiency have refined engines to the point where major improvements require innovative approaches that look at the entire system. The Fuel-Engine Co-Optimization initiative aims to simultaneously transform both transportation fuels and vehicles in order to maximize performance and energy efficiency, minimize environmental impact, and accelerate widespread adoption of innovative combustion strategies. This research and development (R&D) collaboration between the U.S. Department of Energy (DOE), nine national laboratories, and industry is a first-of-its-kind effort to combine biofuels and combustion R&D, building on decades of advances in both fuels and engines.

The Fuel-Engine Co-Optimization initiative takes a three-pronged, integrated approach including engines designed to run more efficiently on affordable, scalable, and sustainable fuels, fuels designed to work in high-efficiency, low-emissions engines and marketplace realities that can shape the success of new fuels and vehicle technologies with industry and consumers.

The goal of the Fuel-Engine Co-Optimization initiative is to arm U.S. industry with the R&D needed to reduce petroleum consumption by billions of barrels a year, deliver tens-of-billions of dollars in cost savings annually via improved fuel economy, dramatically decrease transportation-sector criteria pollutants and greenhouse gas emissions, accelerate the speed of advanced biofuels deployment, enhance energy security through more effective uses of diverse domestic energy sources and spur U.S. economic and technological vitality.

IMPACT OF SOOT FORMATION ON LUBRICANT AGING IN DISI ENGINES

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Keywords: DISI engine, soot accumulation in lubricant

In comparison to PFI engines, direct injection gasoline engines prone to emit soot particles.

The particles in the exhaust gas could be treated with a gasoline particle filter, but how about the particles smuggled into the engine oil?

What quantity of soot could be detected after a long-term accumulation and is there an impact on injector cleanliness?

BRIDGING THE GAP TO THE HYDROGEN ECONOMY

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Keywords: methanol, hydrogen, renewable, fuel, NOx, Sulphur, emissions, energy

Methanol, also known as methyl alcohol or wood alcohol, is a chemical with the formula CH_3OH. It has been given attention as a low carbon alternative fuel because it can be synthesized from a number of feedstocks. Beyond the possibility of producing methanol with renewable resources, methanol is an environmentally interesting fuel due to its low Sulphur, NO_x, and particulate emissions.

Today methanol is generally produced using natural gas as a feedstock. Methanol is however very interesting as an alternative low-carbon fuel because it also can be produced from renewable feedstocks such as municipal waste, industrial waste, biomass, and even carbon dioxide.

The Swedish ferry and freight operator Stena Line has successfully retrofitted one of its vessels for using methanol as a solution to low sulfur fuel requirements. This is the world's first and only vessel running on methanol. Additionally, a number of chemical carriers are also being designed to be able to run on methanol. Today methanol is only employed on a significant basis as a transportation fuel for cars in China, where it is inexpensive and readily available.

By using exhaust heat and a catalyst Methanol can easily be split into CO and H_2 and the energy content of these products are approximately 20% higher than the liquid fuel. This can only be done effectively on methanol due to the lack of carbon-carbon bonds. Hence, methanol is an interesting fuel for e.g. gas turbines used as range extenders in hybrid vehicles.

STUDIES OF FUEL EFFECTS IN MODERN DIESEL PASSENGER CARS

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Keywords: Diesel, fuel properties, EN590, emissions

Certain diesel fuel specification properties are considered to be environmental parameters according to the European Fuels Quality Directive (FQD, 2009/EC/30) and previous regulations. These limits included in the EN 590 specification were derived from the European Programme on Emissions, Fuels and Engine technologies (EPEFE) which was carried out in the 1990's on diesel vehicles meeting Euro 2 emissions standards. These limits could potentially constrain FAME blending levels higher than 7% v/v. In addition, no significant work has been conducted since to investigate whether relaxing these limits would give rise to performance or emissions debits or fuel consumption benefits in more modern vehicles. Over the last few years Concawe have carried out a number of studies to evaluate the impact of specific diesel properties on emissions and fuel consumption in Euro 4, Euro 5 and Euro 6 light-duty diesel vehicle technologies with a range of aftertreatment systems. The tests have mainly been conducted using two driving cycles, a cold New European Driving Cycle (NEDC) and a hot Worldwide harmonised Light duty Test Cycle (WLTC), which is considered closer to real driving. Apart from FAME type and content and its effect on aftertreatment systems, more recently other properties (Poly-Aromatic Hydrocarbon (PAH) content, density, and cetane number) have been studied. Results of emissions testing will be presented and discussed including effects of the above fuel properties on particulates, NO_x, fuel consumption, energy consumption and CO_2 emissions.

PERFORMANCE OF A DROP-IN BIOFUEL EMULSION ON A SINGLE-CYLINDER RESEARCH DIESEL ENGINE

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Keywords: pyrolysis oil, emulsion, wood pyrolysis, engine testing

Current targets in reducing CO_2 and other greenhouse gases as well as fossil fuel depletion have promoted the research for alternatives to petroleum-based fuels. Pyrolysis oil (PO) from biomass and waste oil is seen as a method to reduce life-cycle CO_2, broaden the energy mix and increase the use of renewable fuels. The abundancy and low prices of feedstock have attracted the attention of biomass pyrolysis in order to obtain energy-dense products. Research has been carried out in optimising the pyrolysis process, finding efficient ways to convert the waste to energy. However, the pyrolysis products have a high content in water, high viscosity and high corrosiveness which makes them unsuitable for engine combustion. Upgrading processes such as gasification, trans-esterification or hydro-deoxynegation are then needed. These processes are normally costly and require high energy input. Thus, emulsification in fossil fuels or alcohols is being used as an alternative.

In this research work, the feasibility of using PO-diesel emulsion in a single-cylinder diesel engine has been investigated. In-cylinder pressure, regulated gaseous emissions, particulate matter, fuel consumption and lubricity analysis reported. The tests were carried out of a stable non-corrosive wood pyrolysis product produced by Future Blends Ltd of Milton Park, Oxfordshire, UK. The product is trademarked by FBL, and is a stabilized fraction of raw pyrolysis oil produced in a process for which the patent is pending. The results show an increase in gaseous emissions, fuel consumption and a reduction in soot. The combustion was delayed with the emulsified fuel and a high variability was observed during engine operation.

ENGINE OIL ADVANCED TECHNOLOGIES FOR FE IMPROVEMENT IN MODERN HD APPLICATIONS

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Keywords: fuel economy lubricants

Fuel consumption reduction in heavy duty vehicle applications is becoming every year more important and restrictive for both OEMs and final end-users due to the evolution of emissions legislation. A saving of just 0.5% fuel for a 300 units fleet of long haul trucks (150,000 km/year) means more than 100'000€ saved per year. This target of fuel consumption reduction can be achieved and measured on a 6-cylinder 11 and 13lt HD Diesel engine thanks to the application of a low viscosity SAE 0W-20 formulated engine oil, resulting from the active and intensive technical partnership between Petronas and FPT Industrial. The development history of such low viscosity HD lubricant is presented, including an overview about preliminary tribology tests carried out for the evaluation of the base oil and the additive package in terms of lab bench screening, anticipating the assessment phases at the engine dyno and field vehicle test for final candidate.

The 5th International Exhaust Emissions Symposium 19-20 May 2016, BOSMAL, Bielsko-Biala (Poland)

Trends in automotive emissions, fuels, lubricants, legislation and test methods – a global view, with a focus on the EU & US

Poster abstracts

TESTING EMISSIONS OF PASSENGER CARS IN LABORATORY AND ON-ROAD (PEMS, RDE)

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

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

In the present paper, the results and experiences of testing different PEMS on the chassis dynamometer and on-road are presented. The investigated PEMS were: Horiba OBS ONE, AVL M.O.V.E and OBM Mark IV (TU Wien).

In the first part of work the measuring systems were installed on the same vehicle (Seat Leon 1.4 TSI ST) and the results were compared on the chassis dynamometer in the standard test cycles: NEDC, WLTC and CADC.

As reference, the results of the stationary laboratory equipment (CVS and Horiba MEXA 7200) were considered.

In the second part of work the nanoparticle emissions of three Diesel cars were measured with PN-PEMS.

For the real-world testing a road circuit was fixed: approximately 1h driving time with urban/rural and highway sections. Comparisons of results between the PEMS and with stationary reference system show different tendencies, depending on the considered parameter (NO_x, CO, CO_2) and on the test cycles. In this respect all investigated PEMS show similar behavior and regarding over average of all parameters and tests no special preferences or disadvantages can be declared.

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

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

INVESTIGATIONS OF EMISSIONS OF REACTIVE SUBSTANCES NO_2 AND NH_3 FROM PASSENGER CARS

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Keywords: NO_2, NH_3, emissions

Public concern and complaints regarding ambient air in zones of dense traffic pertains to two compounds of nitrogen, nitrogen dioxide (NO_2) and ammonia (NH_3); both are toxic and strongly irritant, such that legal limitations are under discussion. This paper contributes to measuring methods as already in part proposed by GRPE subgroup WLTP-DTP (Worldwide Light Duty Test Procedures – Diesel Test Procedures) for NO_2.

Despite legally lowered NO_x emission levels, lumping both, NO_2 and NO, levels of NO_2 have risen in cities and agglomerations as a result of both, deployed catalytic exhaust after-treatment devices and low sulphur Diesel fuels. In present tests two different combinations of NO_2 measuring methods as proposed by WLTP were checked on Diesel cars for practicability in handling and accuracy. These integral, indirect methods ($NO_2 = NO_x – NO$) have been found as useful tools for estimate of NO_2 and with use of appropriate analyzers a satisfactory accuracy was attained.

Furthermore, attention was brought to ammonia (NH_3) emitted by gasoline engines with three way catalysts (TWC) which ought not to be ignored while on the other hand SCR systems for Diesel engines are strictly regulated. Emission levels of more recent TWC turned out to be mostly below 20 ppm NH_3. Vehicle of older technology exhibited significantly higher levels, about 10 times more.

As chemical reactions depend on pressure and temperature (= i.e. flow condition in CVS-tunnel) as well as concentrations, doubts need to be considered on accuracy of results based on chemical reactive substances. Nevertheless, clear tendencies regarding changes of concentrations of NO_2 and NH_3 along the path-way could not be observed.

IMPROVED SOOT MEASUREMENTS WITH AN ENGINE EXHAUST PARTICLE SIZER

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Keywords: Engine Exhaust Particle Sizer, inversion matrix, particle size distribution

The Engine Exhaust Particle Sizer™ spectrometer (EEPS, Model 3090, TSI Inc.) is widely used to measure the size distribution of fast changing exhaust particles at ambient pressure in engine research and development. It can provide particle size, number and mass at different locations in the combustion process. The EEPS records particle size distributions (PSD) at a rate of 10 Hz, allowing for the measurement of transient events. Another instrument, the Scanning Mobility Particle Sizer spectrometer (SMPS; TSI Inc.) is widely considered the standard in measuring submicrometer aerosols, yet measurements with it take comparatively long to complete a size distribution scan. It has been reported that discrepancies exist between PSDs measured by the EEPS and those measured by an SMPS [1, 2]. These discrepancies were shown to be more severe for aerosols composed of agglomerates - such as soot from engine exhaust – than for compact, nearly spherical, aerosols. TSI has developed two new matrices to improve the agreement between EEPS and SMPS measurements, especially at larger particle sizes. One of these matrices is for compact aerosols (IM-compact), the other one for soot-like agglomerate aerosols (IM-soot), including diesel emissions. We will present EEPS results using both new matrices compared to an SMPS [3, 4].

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COMPARING EXHAUST EMISSIONS OF A NON-ROAD MOBILE MACHINE WITH DIESEL AND HVO FUELS UNDER REAL-WORLD AND LABORATORY CONDITIONS

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Keywords: real-world emissions, diesel engine, HVO, exhaust emissions, particle size distribution, NOx

Non-road mobile machines powered by diesel engines are widely used in many different agricultural, construction and forest work. For example, in Finland the number of non-road machines constituted around 30% of all mobile on-road and non-road diesel engines in 2014. Their emissions accounted for 23%, 59%, 31% and 42% of yearly mobile diesel engine emissions of CO_2, HC, NO_x and PM, respectively. Due to adverse health effects and climate warming potential, the emissions of non-road mobile machinery are regulated. Particle number emission limit is included in the proposed Stage V (2019) emissions standards. To mitigate exhaust emissions, alternative fuels, such as biodiesel (FAME) and hydrotreated vegetable oil (HVO) have been developed for diesel engines. Laboratory measurements have shown that CO, HC, PAH, PM and particle number emissions reduced while NO_x emissions increased when tractors operated with FAME compared to diesel fuel. HVO offers some advantages over FAME, including higher cetane number, better storage stability, less cold operability and deposit problems [1]. Compared to fossil fuel, besides HVO has been observed to reduce the emissions of NO_x, PM, CO and HC, also soot particle number, sulphuric acid and subsequent nucleation mode particle emissions reduced. Mobile non-road diesel engine exhaust emissions were studied by chasing a tractor on-road with mobile laboratory Sniffer [2], and by repeating the same transient test on an engine dynamometer. Additionally, non-road steady state tests were carried out. The engines were equipped with an oxidation catalyst and a selective catalytic reduction (SCR) system. They were fuelled by fossil diesel with ultra-low sulphur content and HVO.

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[1] Kuronen M, Mikkonen S, Aakko P, Murtonen T. Hydrotreated vegetable oil as fuel for heavy duty diesel engines. SAE Technical Paper Series 2007;2007-01-4031.

[2] Pirjola L, Parviainen H, Hussein T, Valli A, Hämeri K, Aalto P et al. "Sniffer" – a novel tool for chasing vehicles and measuring traffic pollutants. Atmos. Environ. 2004;38:3625-3635.

ON LINE ENGINE OIL CONSUMPTION MONITORING VIA THE GASEOUS TOTAL SULFUR SIGNAL SO2 IN THE RAW EXHAUST OF THE ENGINE UTILIZING THE SENSITIVE ION MOLECULE REACTION MASS SPECTROMETRY

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Keywords: engine oil, oil consumption, sensitive ion molecule reaction mass spectrometry

The dynamic sensing of oil consumption in IC engines is approached with various techniques ranging from radioactive counting to halogenated tracer compounds in engine oil, to polyaromatic hydrocarbon tracers, to monitoring unburned hydrocarbons as residues from engine oil.

This article discusses the method of gaseous SO_2 measurement in raw exhaust its benefits and limitations of today's status. Modern engines consume about 2 to 5 g/h of engine oil under low and medium load but consumption may go up to 130 g/h in negative load conditions. All possible Sulfur compounds in the raw exhaust are converted to SO_2 in a hot oxidizing atmosphere. Additional pure oxygen in the form of ozone is added to the oxidizer for very low lambda engine conditions. A sensitive mass spectrometer operating in a ion molecule ionization mode measures gaseous SO_2 from concentrations of 20 ppb to 50 ppm in measurement cycles from 2 Hz to 0.2 Hz depending if long term measurement or dynamic operation is chosen. Technical description of pressure reduction, gas transfer, oxidation efficiencies and lower detection levels of the instrumentation are given as well as data on a complete engine map and data on reproducibility of the SO_2 method are presented.

ANALYSIS OF DIESEL INJECTOR DEPOSITS

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Keywords: Diesel injector deposits, analytical techniques, Diesel combustion

Diesel injector deposits have been a focus of investigation for several years and there is ongoing work into understanding their formation and composition. Increasingly sophisticated analysis techniques are available to enable understanding of the composition and formation of diesel injector deposits. As fuel, lubricant and engine technologies develop, it will continue to be necessary to invest in the development of these techniques as well as others, in order to ensure that potential issues of deposit formation can be avoided or mitigated. This work considers four of the techniques that are available to engineers in order to better understand the structure and composition of injector deposits. These are FTIR, XPS, SEM and TEM. The type of information available from each is described. Use of a combination of techniques is recommended in order that elemental, chemical and structural information can be determined.

THE INFLUENCE OF THE UREA DOSING METHOD ON THE NO_x REDUCTION RATIO IN THE SELECTIVE CATALYTIC REDUCTION

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Keywords: nitrogen oxides, selective catalytic reduction, ammonia, urea, adblue

The purpose of this study was to prepare an experimental system of dosing urea solution in the gas phase and conduct a research program on its influence on a selective catalytic reduction converter. The main concept of the system was a pre–treatment of urea solution prior to introduction into the exhaust gas stream, through evaporation and initialization of the conversion process into ammonia. The study was conducted on the exhaust aftertreatment system of a modern diesel engine equipped with a oxidation converter, particulate filter and SCR system. The performance of the SCR converter supplied by the experimental vapour phase dosing system was then compared to the standard solution of liquid phase dosing . Particular attention was paid to the determination of the physical state of the reducing agent on the SCR converter's performance.

In order to compare conversion efficiency of the SCR converter over a wide range of exhaust gas temperatures, a special steady–state test procedure was developed. In addition to that, a series of highly dynamic tests were run, considering both cold- and hot-start engine conditions.

A significant increase in the conversion efficiency of nitrogen oxides at a given constant α dosing value was found. The results obtained indicate a high potential to increase the efficiency of the SCR converter using gas–phase urea and provide a good basis for further scientific – research works on this type of concept.

TRANSIENT ANALYSIS OF BOTH LAMBDA AND EGR VALUES MEASURED LOCALLY WITH CRANK ANGLE RESOLUTION IN IC ENGINES USING A FIBER OPTIC SENSOR

Stefan Seefeldt, Olaf Thiele, Joachim Deppe, Juergen Pfeil, Christian Disch, Thomas Koch, Anna Glodek, Radoslaw Boba

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Keywords: IR absorption, lambda, exhaust gas (EGR), fuel density, transient, IC engine, ICOS

The reduction of fuel consumption and a simultaneous minimization of air pollution species, i.e. NO_x, soot particles, are of highest interest today and in future. Only a detailed understanding based on transient measurements of processes taking place in internal combustion (IC) engines under real (production engine, transient operation) conditions allows a successful improvement of the state of the art engine concepts, like DI, HCCI. In this work we report about the latest results obtained from non-intrusive infrared (IR) absorption measurements by an Internal Combustion Optical Sensor (ICOS) with high time (crank angle) resolution applied in IC engines. Transient information of fuel densities with corresponding derived λ-values and traces of exhaust gas recirculation rates (EGR) are analyzed in the context of fuel injection, expansion, compression, ignition and combustion phases. Additional indication values, like in-cylinder pressure and light emission curves sampled simultaneously are analyzed and compared. Effects of fuel droplet and soot particle formation as well as misfire phenomena are reported. The fiber optical sensor technique was originally designed for investigations in spark ignited engines using spark plug probes. The availability of minimally invasive probes without spark plug capabilities makes this technology available for measurements in modern Diesel engines, too.

VISUALISATION OF SOOT FORMATION IN A DISI ENGINE FOR DIFFERENT FUEL INJECTION STRATEGIES AND IN COLD START CONDITIONS WITH THE AID OF ENDOSCOPIC COLOR IMAGING

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Keywords: soot formation, spray and combustion visualization, transient, IC engine

Soot formation is not only an issue for Diesel engines but also for Gasoline combustion. The formation of soot inside an internal combustion engine can have a number of sources, which cannot be identified easily by analyzing only the exhaust emissions or pressure signals. In the presented work soot formation was visualized using the simple but very effective method of endoscopic imaging inside an internal combustion engine. High speed (crank angle resolved) color imaging was used to visualize entire combustion cycles. This enabled the direct correlation of spray injection strategies to the formation of soot on the piston surface as a result of piston wetting. Additionally soot formation processes for engine cold start were analyzed using low speed (crank angle-phase locked measurements) imaging.

MASS SPECTROMETRY: IS THIS ANALYTICAL TOOL FOR THE SELECTIVE HYDROCARBON ANALYSIS ON DIESEL ENGINES SUITABLE?

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Keywords: mass spectrometry, ion molecule reaction, selective hydrocarbon analysis

The aim was to find a measurement system which is able to detect selectively the main components of hydrocarbons in diesel exhaust. The measurement system is to be used for the hydrocarbon sensor development and the catalyst assessment.

The choice fell on a mass spectrometer from the company V&F. It works with the reagent gases mercury (Hg), xenon (Xe), krypton (Kr) and it is based on ion molecule reactions. Depending on the reagent gas, a low ionization energy in comparison with the traditional electron impact ionization is be used. This soft ionization method offers a fast, selective and mostly interference free measurement of the species.

After fundamental studies of the interference by fragmentation the three components acetylene, ethylene and propene were set for the further measurements. On the engine test bench engine operating points as the cold start, the DPF regeneration and desulfation of the NO_x storage catalyst were examined. With the mass spectrometer could be demonstrated that quantitative statements are possible after a calibration. Molecules with no interference and single interference can be measured without limitation. Molecules with multiple interference must be considered and evaluated with caution. The species of acetylene, ethylene and propene add up a large part of the total hydrocarbon concentration. Furthermore, the mass spectrometer has a fast response even at transient conditions.

GEOCHEMICAL MARKERS AND POLYCYCLIC AROMATIC HYDROCARBONS IN PARTICULATE MATTER EMITTED FROM DIESEL ENGINES

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Keywords: persistent organic compounds, diagnostic ratios, geochemical ratios, CI

Particulates contained in exhaust gases deriving from diesel engines running on engine and chassis dynamometers were investigated. The research comprised qualitative as well as quantitative analysis of polycyclic aromatic hydrocarbons (PAHs) and also biomarkers contained in dichloromethane extracts. Analysis was conducted with use of Gas Chromatography with Flame Ionization Detector (GC-FID) and Mass Spectrometer (GC-MS) as detectors. On the basis of analysis results, the groups of PAHs characterized by the same number of rings (2 or 3, 4, 5 or more) were defined. Also diagnostic ratios (DR) along with geochemical ratios of selected biomarkers and alkyl aromatic hydrocarbons have been calculated. On this basis a geochemical interpretation, showing that geochemical features are unequivocally connected to the emission of fossil fuels and biofuels burned in diesel engines, has been developed. The exothermic combustion is limited to compounds of low molecular weight, which reveals that the applied methodology enables source identification of coexisting PAHs, as well as geochemical markers in the particulate matter emitted in exhaust gases.

ONLINE ANALYSIS OF LUBRICATING OIL DILUTION BY FUEL

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Keywords: oil dilution, fuel dilution, lubricating oil, measurement technology

In gasoline engines the catalyst heating and the warm-up phase, in particular during a cold start, increases the problem that fuel is applied to the cylinder wall. Thereby, a part of the fuel is mixed with the engine oil. The consequence is a change of the physical and chemical properties of the oil. In the worst case, lubrication is reduced, which could result in engine damage. By variation of the injection timing and injection pressure the oil dilution can be reduced.

At the University of Applied Sciences Regensburg a measurement technology has been developed, which allows a quantitative determination of the time course of fuel entry into the engine oil and desorption in stationary and transient operating points.

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DEADLINES

January 31, 2017	–	Abstract submission
February 15, 2017	–	Notification of abstract acceptance
March 31, 2017	–	Papers submission
April 30, 2017	–	Notification of paper acceptance
June 27-29, 2017	–	CONGRESS PTNSS 2017

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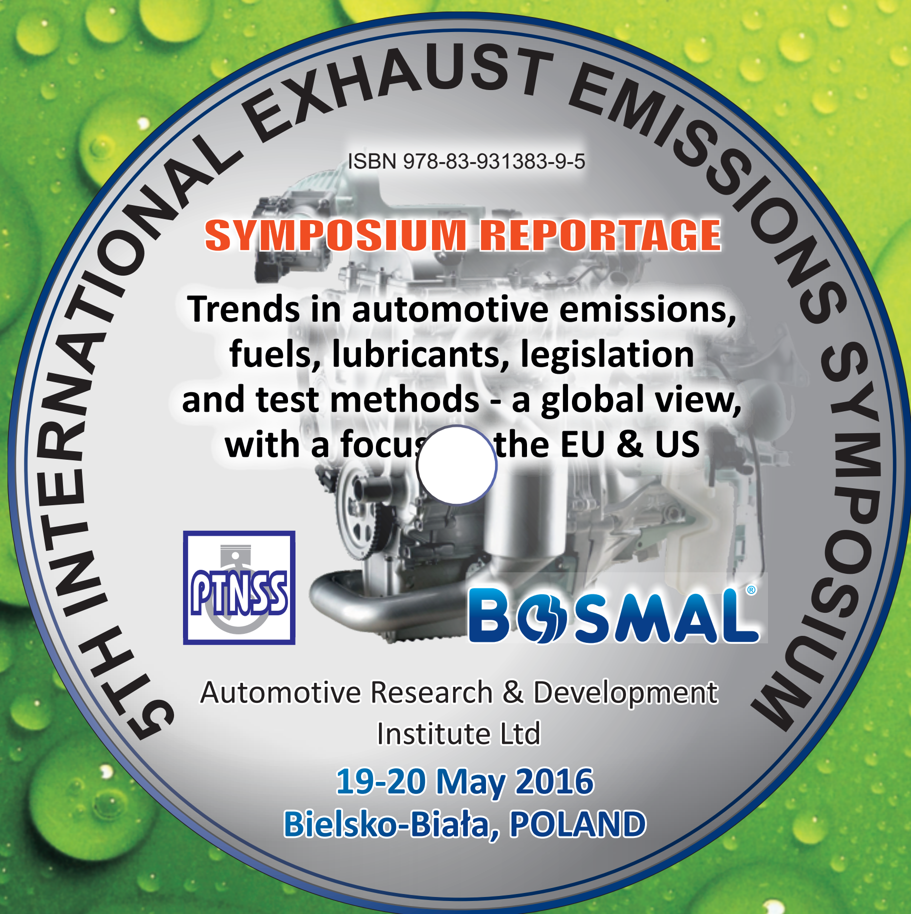
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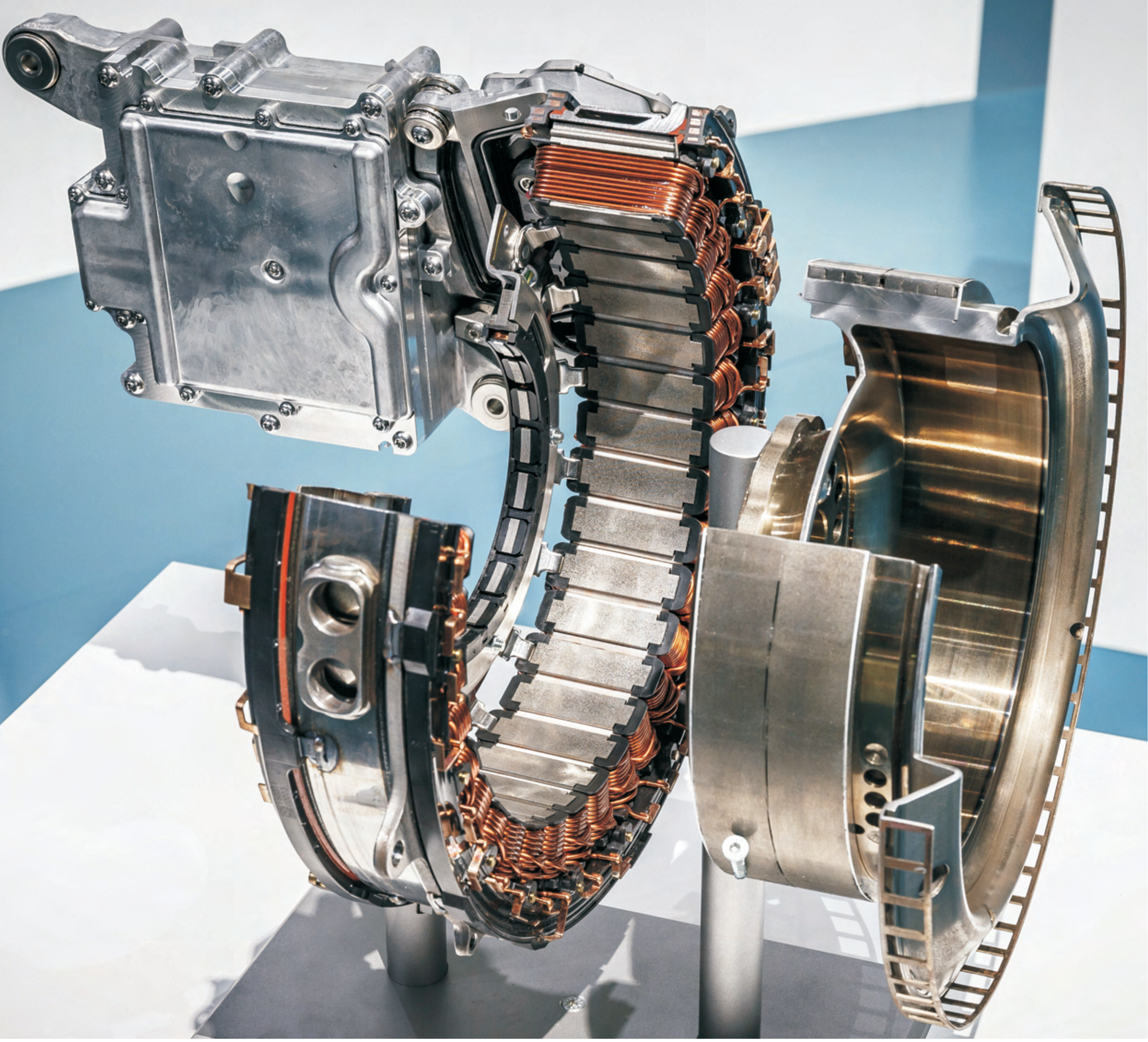

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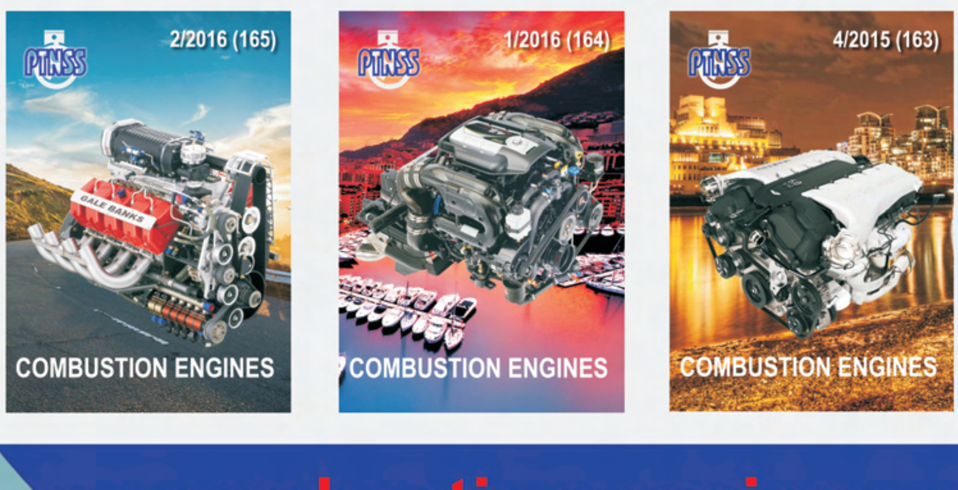

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