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Trends in Automotive Emission Legislation: Impact on LD Engine Development, Fuels, Lubricants and Test Methods: a Global View, with a Focus on WLTP and RDE Regulations

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

Keywords Exhaust emissions · Emissions control · IC engines · RDE · WLTP

1 Introduction: Background and Content

The most important factor affecting the development of powertrains used in road vehicles is currently the emission of harmful exhaust compounds and the ways in which these emissions can be reduced.

The second most important factor is in reducing greenhouse gas emissions, particularly CO_2 emitted by motor vehicles, which is also a political priority due to CO_2's impact on global warming. In recent years, at the UNECE forum, within the GRPE group, working on the harmonisation of regulations of motor vehicles, the informal working groups (IWG) WLTP, PMP, EVE and others, as well as in the European Commission (WLTP 2nd act, RDE), have been working on the new WLTP emission test methodology—a new global harmonised laboratory test method and RDE—a method of testing emissions in road conditions using portable PEMS analysers.

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

The issues of harmful emissions, especially:

a) Nitrogen oxides (NO_x) from vehicles powered by compression ignition engines (CI), which for vehicles meeting Euro 3, Euro 4, Euro 5 and Euro 6b standards, proved to be significantly greater in actual conditions of road use than in homologation laboratory measurements.
b) Particulate matter (whether quantified by mass—PM, or number—PN) in exhaust gases, not only from vehicles with CI engines, where the introduction of DPF filters has practically resolved this problem, but also from vehicles with spark ignition engines (SI), especially ones equipped with direct gasoline injection into the combustion chamber (GDI) that produce large amounts of particles of very

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

c) Non-exhaust particulate emissions, originating from other components such as brakes and tires, as well as volatile compounds emitted from the materials in new vehicles (Vehicle Internal Air Quality)

d) Carbon dioxide (CO_2) and fuel consumption (which is also related to global demand for fuel, energy security and plans for a decarbonised economy [2]) occurring in real world driving conditions,

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

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

Now that it has become apparent that emissions of some compounds (especially NO_x, but also particulates and other pollutants, as well as CO_2), measured in actual conditions can be much higher than emission results from laboratory tests, measurement methods are subject to further change. This applies to both laboratory methods (e.g. new research procedures prepared by the EU/UN-ECE: WLTP/GTR15 [4] or US EPA: CFR 1065/1066), as well as emission and fuel consumption tests in real driving conditions (the test procedure prepared by the European Commission—RDE), which is so important that the RDE method has become an integral part of the procedure for testing emissions from motor vehicles. In September 2017, the EU introduced the requirements of WLTP and RDE to the new approval regulations referred to as Euro 6d-TEMP (as a transitional phase leading into Euro 6d), which completely changed the approach to the approval and certification of vehicles.

2 Organisation of the 6th International Exhaust Emissions Symposium

During the years 2010, 2011, 2012, 2014 and 2016, BOSMAL Automotive Research and Development Institute Ltd. (hereafter "BOSMAL") organised five international symposia on vehicular exhaust emissions, covering issues related to limiting emission of harmful exhaust emissions from automotive sources and their impact on the development of vehicle powertrain design, exhaust after-treatment systems, the development of fuels, lubricants and new test methods [5], as this subject is vitally important for the further development of the motor industry globally, in Europe and in Poland (the country playing host to a high number of automotive manufacturing centres). These symposia were very popular among professionals in the automotive and fuel industries, both foreign and domestic, who participated extensively in their deliberations.

On 14–15 June 2018, BOSMAL together with the Polish Scientific Society of Combustion Engines (hereafter "PTNSS", from its Polish acronym) was the organiser and host of the sixth iteration of the event—*The 6th International Exhaust Emissions Symposium,* with the event entitled "*Trends in automotive emissions legislation: impact on LD engine development, fuels, lubricants and test methods – a global view, with a focus on WLTP and RDE regulations*". The technical programme for the symposium was organised and prepared by the International Organising Committee, headed by Dr. Piotr Bielaczyc (BOSMAL/PTNSS), which also included well-known specialists in the field from various European countries and the USA.

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

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

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

The important goals of this symposium were integrating of the scientific and academic communities with the automotive industry (both in Poland and abroad), facilitating the

establishment of new contacts, exchanging of knowledge on many issues and promoting the achievements of Polish scientific and research institutions active in this field, especially BOSMAL.

The journal *Combustion Engines*, the website *DieselNet.com* of Canada, the Polish-language journal *Przegląd Techniczny* and the Polish *Gazeo.pl* gaseous fuels internet portal provided the media patronage for the event.

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

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

3 Global Trends in Reducing Emissions from Internal Combustion Engines Used in Road Transport: the Symposium's Technical Content

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

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

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

a) "General automotive exhaust emissions"
b) "CO_2, GHG & Air Quality (including particulate matter)"
c) "Emissions reduction technologies & aftertreatment"
d) "Test methods: laboratory based and RDE-PEMS"
e) "Fuel and Alternative powertrains"

3.1 Symposium Sessions

Individual sessions were chaired by well-known experts on car emissions representing various countries and firms/institutions.

3.1.1 First Session

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

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

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

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

Dr. Bielaczyc's presentation also highlighted the impact of new emission testing methods on the development of automotive engine structures and future trends in vehicular powertrains. Despite the low esteem in which diesel engines are held by many, manufacturers of these engines have already developed solutions based on SCR catalytic systems, which can ensure that this engine type has very low emissions of both PM/PN and NO_x.

A new trend in engine design is "rightsizing", as well as an ongoing convergence of spark ignition and compression ignition engine technology, with differences now much smaller than in the past (turbocharging, direct injection, compression ratio). The aforementioned trends were presented in the context of ongoing LDV powertrain development in the EU (Fig. 1).

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

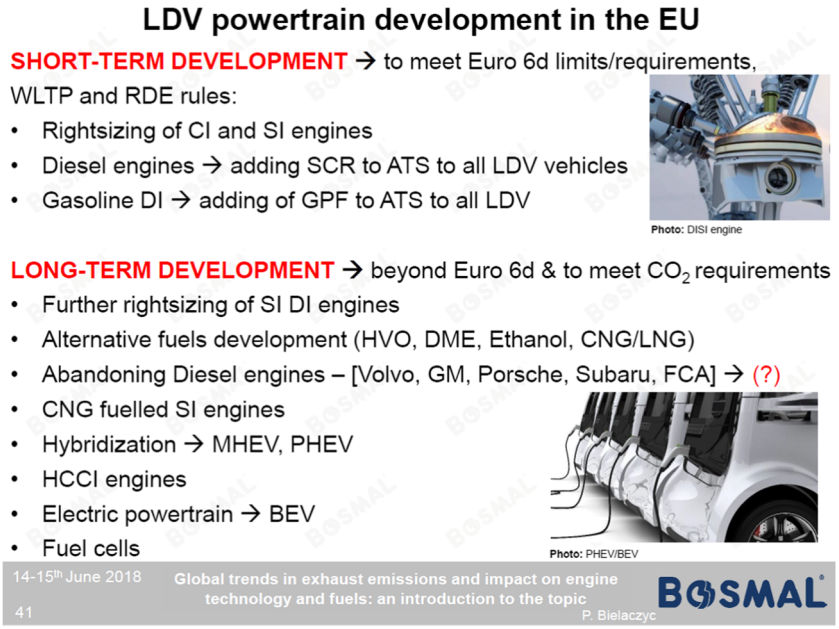

Fig. 1 Technical trends in engine and after-treatment design for LDV

do appear particularly negative; however, when compared to WHO concentration limits, it becomes clear that the EU has a serious problem with exposure of its population to certain pollutants (Fig. 2). In recognition of the contribution of road vehicles to this situation, changes are currently underway to the way in which vehicles are approved for sale in terms of their exhaust emissions.

Subsequent changes in test procedures will result in the fourth RDE package, which will also introduce tests of cars in use, to be performed by independent accredited laboratories as well as the vehicle manufacturers. The analysis of the next emission regulations, described as "post-Euro 6"—and even "Euro 7"—has begun, which are to bring the same test methods and limits for all types of engines and fuels (a philosophy known as "fuel-neutral" or "technology-neutral", which already exists in the USA).

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

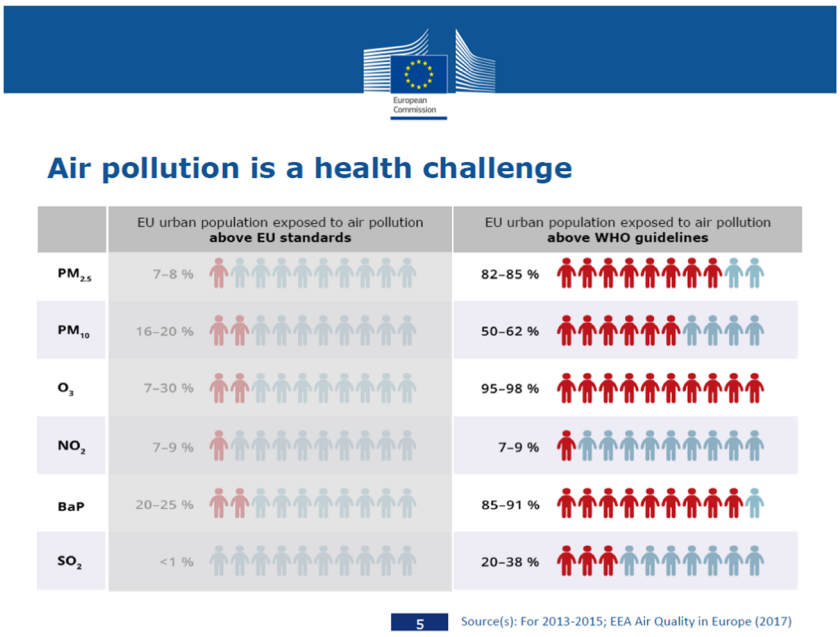

Fig. 2 Exposure to "excessive" levels of pollutants in ambient air is a strong function of the definition of "excessive" levels

some tentative conclusions to be drawn regarding future emissions limits for the EU (Fig. 3).

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

3.1.2 Second Session

In the second session, covering greenhouse gas (GHG) emissions, CO2 emissions and particulates, Dr. Barouch Giechaskiel (JRC-Ispra, Italy) presented two reports prepared by teams of specialists from the European Union's JRC Ispra research centre in Italy. He presented the problem of differences in the results of measurements of CO2 emissions in type approval tests using to the NEDC cycle and under real driving conditions, as well as the methods of compensating for these differences after the alteration of the test procedure via the WLTP

This topic was also touched on by Prof. Luciano Rolando from Turin University of Technology, who stated that CO_2 emissions according to the WLTC cycle can be 10 to 24% higher using the WLTP procedure as opposed to the NEDC, due to the higher energy demand in this cycle; however, the engine efficiency also has to be taken into consideration (Fig. 4). The European Commission proposes to further reduce the average CO_2 emissions of cars by 15% in 2025 and by 30% in 2030 in relation to the level from 2021 (though some parties continue to lobby for even higher reductions).

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

3.1.3 Third Session

The third session, concerning emission reduction methods and catalytic exhaust gas after-treatment systems, consisted of two parts and had the largest number of presentations. It was opened by Dr. Ameya Joshi (Corning, USA), who gave a speech about the methods for limiting engine emissions through catalytic systems, also for hybrid powertrains in which the TWC and other catalytic reactors may undergo cooling when the combustion engine is not running. He also talked about the possibilities of increasing the efficiency of car

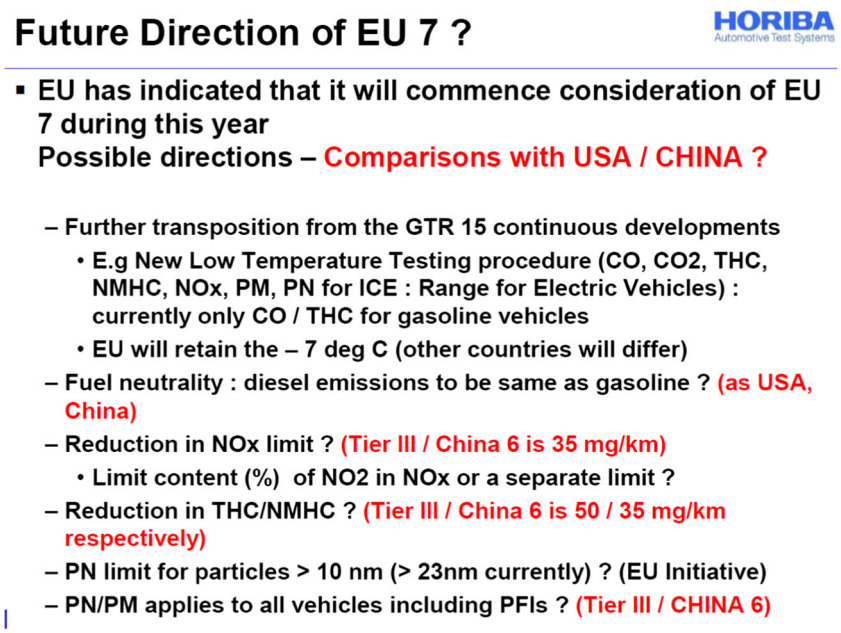

Fig. 3 Comparisons and observation of EU/Chinese/US emission limits in the context of the upcoming Euro 7 emission standard

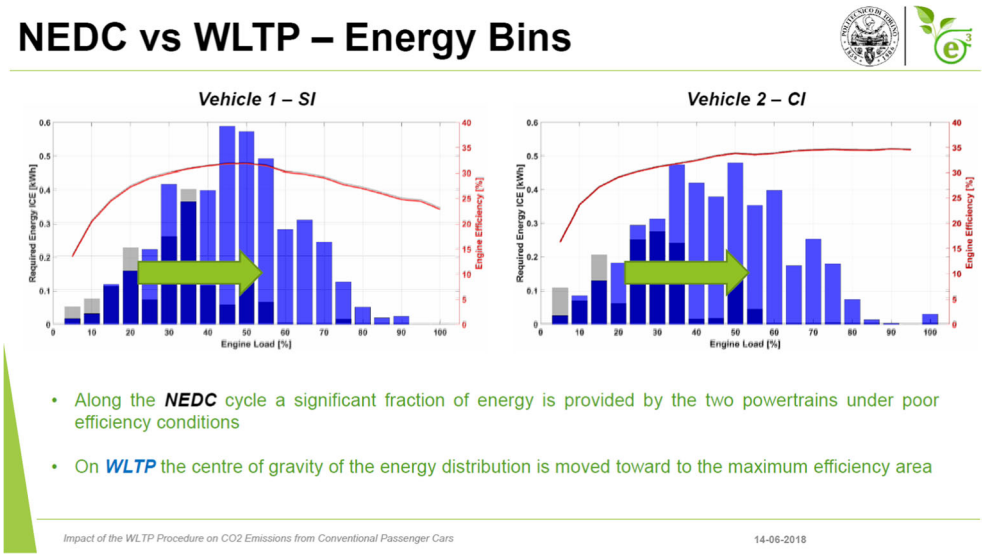

Fig. 4 Energy binning/engine efficiency comparison over the NEDC and WLTP for two sample vehicles

engines. 45% thermal efficiency has already been achieved for SI engines, but further development in this field is still possible—currently, a level of 55% for the CI engines used in HD applications is being worked on. A significant part of his report was devoted to catalytic after-treatment (SCR, SCRF, PNA, methane oxidation catalysts) as well as multi-component systems of catalytic reactors and filters which can allow engines to meet legal emissions requirements under a wide range of operating conditions (Fig. 5).

Kurt Engeljehringer (AVL, Austria) expanded upon the influence of RDE emissions standards on the development of test methods on both engine and chassis dynamometers. To meet the RDE standards, ECU adjustments must be performed on both engine dynos and verified on the chassis dyno in emission testing laboratories where RDE tests performed on the road are reproduced (Fig. 6).

An important element of the strategy of reducing emissions by internal combustion engines is advanced engine control systems in cars—made possible by ECUs, whose calibration methods were presented by Dr. Marcos Alonso Baez (Nissan Technology Center, Spain). This method is based on ECU modelling in terms of RDE emission requirements and is referred to as MBC (model based calibration). It allows optimising of the ECU function that controls the operation of the engine and its systems in terms of low NO_x, CO, CO_2 emissions, real road emissions and reduces the time needed for dyno testing.

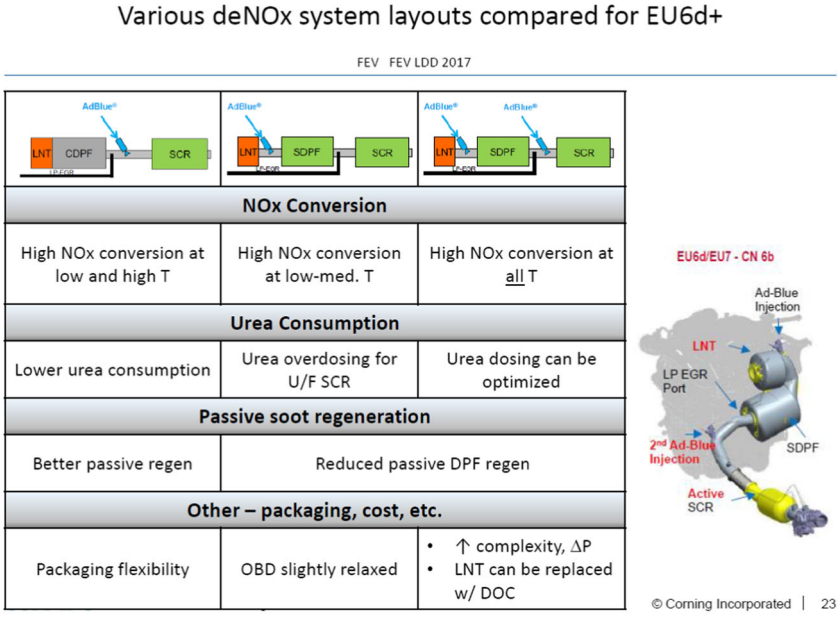

Fig. 5 Sample diesel ATS architectures for compliance with incoming and future emissions standards

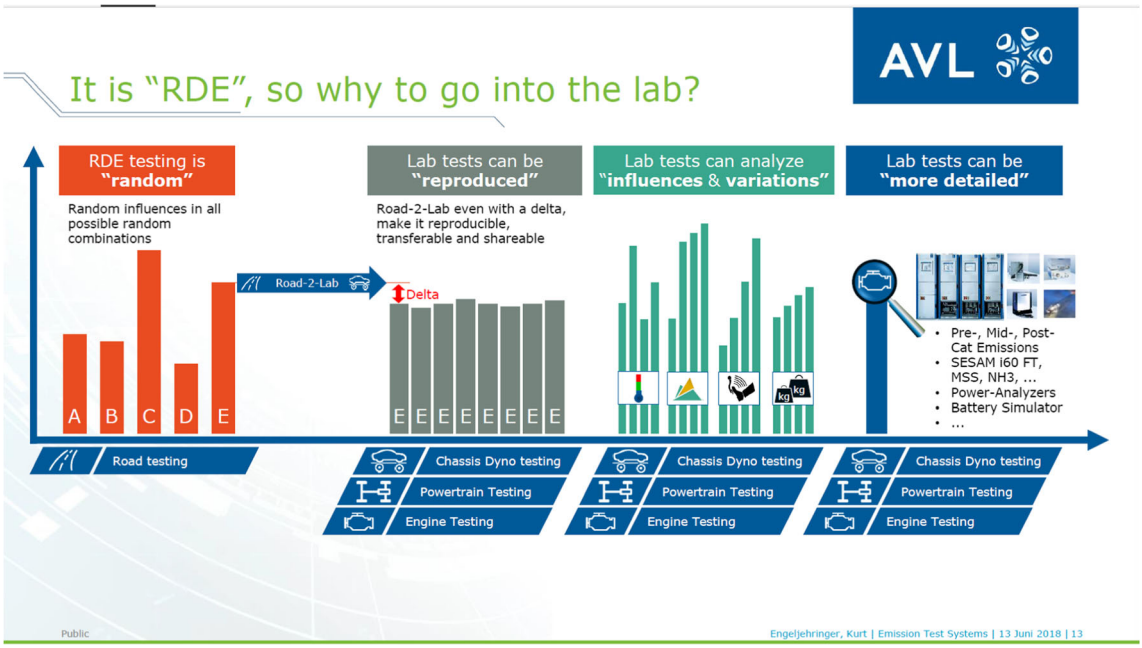

Fig. 6 The importance of the laboratory environment for RDE development

Jon Andersson (Ricardo, UK) presented the research program conducted for the CONCAWE association, concerning the possibility of reducing real road emissions by diesel-powered cars in terms of Euro 6d standards through the use of advanced SCR, SCRF and LNT catalytic systems in various configurations. The presented solutions show the possibility of fulfilling the limits of PN and NO_x emissions by a car with a CI engine in various driving cycles, including those with high energy demand (WLTC, US06, RDE).

A properly selected SCR system ensures very low NO_2 emissions from the vehicle, far below the limits and requirements for Euro 6d (Fig. 7). He emphasised that diesel engines—recently much criticised for their environmental performance—should remain an important source of propulsion due to their high efficiency and existing catalytic solutions, allowing significant reduction of NO_x emissions and the ability to meet emission limits also in RDE tests while maintaining their high efficiency and low CO_2 emissions.

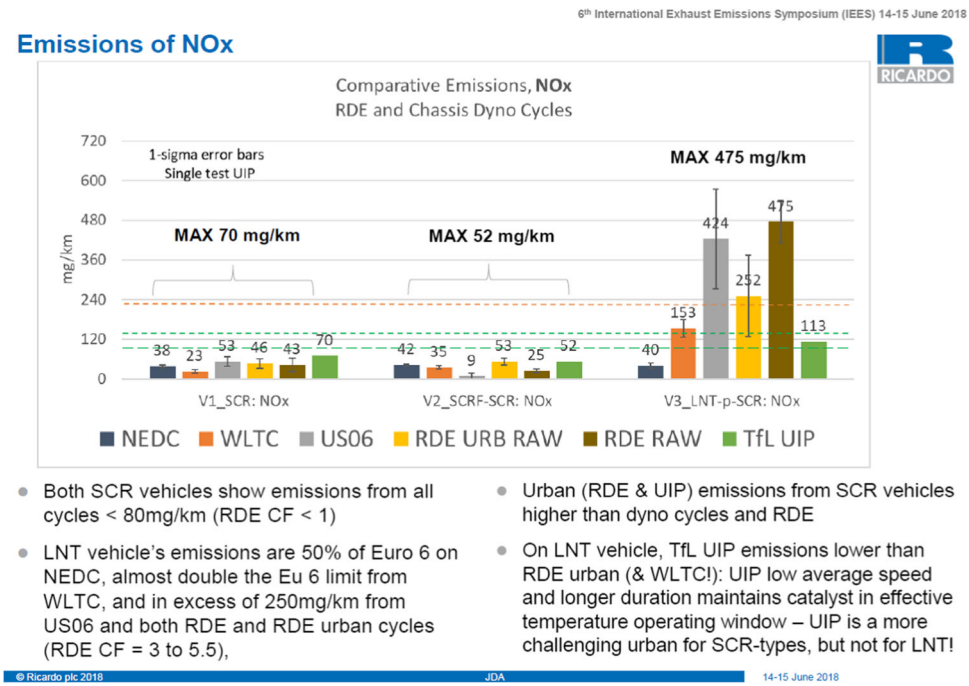

Fig. 7 The NO_x performance of various diesel ATS architectures tested using RDE and various driving cycles

Dr. Katarzyna Matusik (Argonne National Laboratory, USA) presented advanced methods of testing fuel atomisation by injectors used in SI and CI engines using X-ray and photon synchrotron diagnostics. This methodology allows for very accurate analysis of fuel atomisation through injector holes, stream shape, evaluation of cavitation problems, accurate hole geometry measurements and many quantitative other analyses of the atomisation of the fuel. Given the importance of fuel injection parameters on a range of engine operation and emissions topics—and the near-universal proliferation of direct injection in modern engines—this topic is arguably an important direction for the future which will be increasingly relied upon to provide insights in this area.

Dr. Tue Johannessen (Aminnex, Denmark) and Dr. Toni Kinnunen (Proventia, Finland) presented the possibilities of using advanced SCR catalytic systems to reduce NO_x emissions in the captive fleet (i.e. currently used LD, HD vehicles and buses). This method is referred to as retrofitting and enables older vehicles to meet new emission standards at Euro 6 (LD) and Euro VI (HD) levels (Fig. 8). This could significantly reduce the actual emissions from millions of vehicles with CI engines currently in use on Europe's roads. Examples of applications of this technique can be found in many cities in Germany and Scandinavia, as well as London buses.

Maciej Hadryś (Mahle, Poland) presented new piston design solutions for SI and CI engines that allow their overall temperatures to be lowered and for better temperature distribution on the piston surface. Such thermal management via advanced designs and use of optimal materials can even assist with emissions control, as well as make a contribution to lightweighting efforts.

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

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

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

3.1.4 Fourth Session

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

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

The first RDE package was published 2 years ago in the Commission Regulation (EU) 2016/427 and the second and third package in the Commission Regulations (EU) respectively 2016/626, 2017/1151 and 2017/1154 respectively. Further updates are expected late in 2018, as well as in future years.

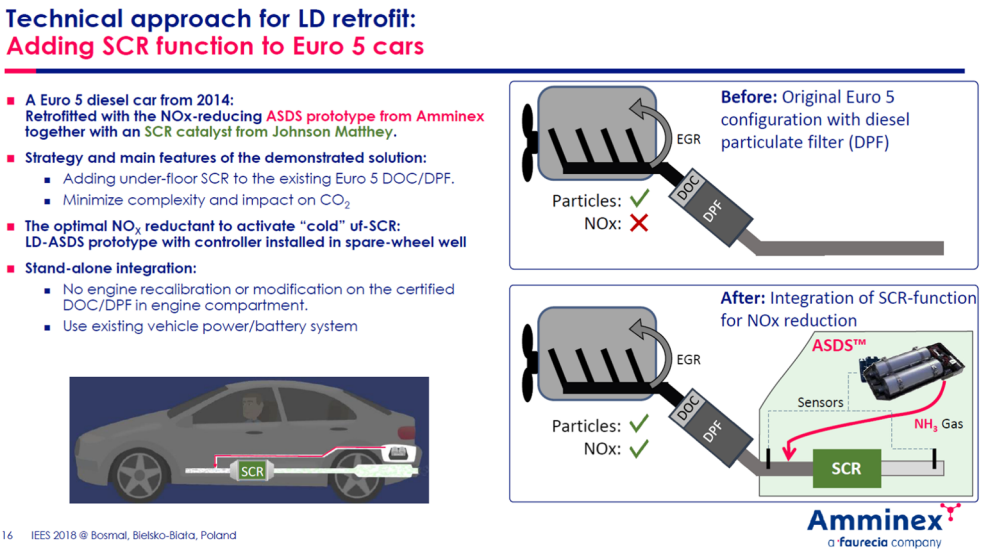

Fig. 8 Retrofit SCR as a means to upgrade Euro 5 passenger cars to guarantee lower NOx emissions

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

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

Sam van Goethem (TNO, the Netherlands) presented a new exhaust gas analyser for mobile measurements, referred to as SEMS (Smart Emissions Measurement System), based on sensors (as opposed to full chemical analysers), thermocouples and CAN bus connection via OBD II and J1939 interfaces. Such a system can measure fuel consumption, CO_2, NO_x and NH_3 emissions and may also be useful in the continuous monitoring of these parameters in a vehicle. Given incoming requirements for market surveillance and even constant monitoring of HD vehicle fleets, such simplified low-cost alternatives to full PEMS are of considerable interest.

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

Professor Gordon Andrews (University of Leeds, UK) emphasised the fact that the largest local air pollution levels are caused by traffic jams and sub-optimal or inadequate road layout, which is related to the low-mean driving speed, the high frequency of stop events and the frequency and intensity of acceleration events, which often occur from idling. This is the main cause of high levels of air pollution in urban areas. While both the WLTP and RDE procedures require the engine to be started from cold, traffic conditions with very high emission intensity and very low-mean speed (below 15 km/h) are not included in either test type (Fig. 9). RDE tests of cars and heavy goods vehicles with an SCR catalytic system on congested roads in Leeds, UK as well as in China have shown that the highest emissions occurred when pulling away from a standstill, and that the final emissions are correlated with the mean driving speed, a revelation which should be taken into account in further modifications to RDE regulations.

3.1.5 Fifth Session

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

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

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

Dr. Piotr Bielaczyc (co-author Dr. Marek Rylko—an expert on hybrids and electric vehicles) presented a general report on the history, characteristics and the advantages and disadvantages of electric vehicle drives.

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

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

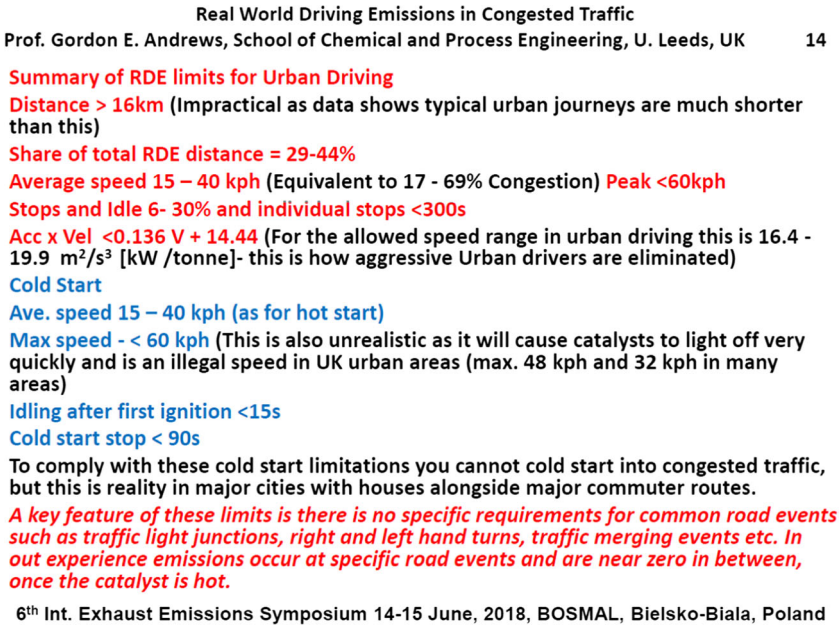

Fig. 9 RDE urban driving requirements and the resulting impact on cold start/warm-up emissions measured during an RDE-PEMS test

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

4 Conclusions

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

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

Conclusions regarding the reduction of fuel consumption and emission of carbon dioxide (CO_2), methods of reducing these emissions, development of test methodology for exhaust emissions from internal combustion engines used in motor vehicles and other means of transport as well as off-road vehicles and working machines were also discussed.

Reducing emissions of harmful compounds and toxic fumes and now the especially important reduction of particulate matter (PM) in terms of their mass and number (PN) of emitted nanoparticles, reduction of real NOx emissions and new tests and WLTP and RDE emission testing methodology are the main challenges for the automotive and motor industries caused by political, economic and technical factors.

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

New challenges currently faced by manufacturers of drive systems of motor vehicles, but also off-road vehicles and working machines, related to the decarbonisation of the economy, the need to reduce fuel consumption, which is equivalent to reducing greenhouse gas (GHG) emissions, especially CO_2, caused the necessity of further development of various types of powertrains, both internal combustion engines, adapted to be fuelled with improved fuels of mineral origin, as well as new types of ecological and alternative fuels, hybrid systems,

built from an internal combustion engine and an electric motor, especially in the Plug-in Hybrid system, as well as fully electric powertrains.

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

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

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

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

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

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

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

5 Final Overall Technical Message

The paragraphs that follow offer some summaries and tentative conclusions on various main points from the symposium which were mentioned in multiple presentations and which featured prominently in discussions.

The WLTP is now the standard test cycle for the EU market and is undergoing implementation in large and important markets such as India, China and Japan. While implemented to make up for shortcomings in the determination of official CO_2/FC figures, the new test procedure also has an influence on regulated emissions. However, the stringency of RDE requirements means that in terms of regulated emissions the WLTP is not the main challenge. That laboratory cycle will be the focus of CO_2/FC optimization, but regulated emissions will be largely examined by the RDE test. The development of a type VI test (cold start at − 7 °C) using the WLTP may alter this situation somewhat, but this test requirement has not yet been finalised or implemented. However, notwithstanding the new test procedure, the current limits have been in force since 2014 (and were decided and published back in 2007). The term "Euro 7" is starting to be used and informed sources confirm that Euro 6d will not be the end of the story in the EU. In addition to potentially reducing numerical emissions limits, a greater size range of particulates will be measured for comparison with the PN limit (from 10 nm, as opposed to 23 nm). A further possible development is the introduction of limits for NO_2, and even N_2O, NH_3 and aldehydes. Such changes may increase the difficulty of meeting laboratory test requirements in comparison with RDE requirements, as new emissions limits are likely to be introduced in the laboratory first (and perhaps later duplicated in RDE legislative requirements).

There has been considerable convergence in the design and emissions control requirements of spark—and compression—ignition engines, to the point where traditional categories are blurring. The prospect of gasoline compression ignition could alter this situation further still in the future. Current production DISI engines are parallel with diesel engines in terms of particulate emissions and their control. Legislative limits for PN are now identical for DISI and CI engines, reflecting the slow but ongoing trend towards numerically identical emission limits for all engine types.

After decades of catalytically facilitated emissions control, progress continues to be made in altering the chemical composition of exhaust gas to reduce its harmful effects. Even a seemingly "simple" device such as a three-way catalyst for stoichiometric applications is a complex system which requires considerable optimization to meet all the requirements demanded of it. Now that GPFs are essential for approximately half of all gasoline-fuelled engines sold in the EU, the question of integration of the GPF and TWC into a four-way catalyst has become an urgent practical question. For diesels, the success of DPFs over the past decade is an inspiration to achieve the same successes with DeNO$_x$ systems. Here, despite the complexity of the overall challenge in the era of RDE, the fundamental fact remains that ammonia is the chemical antidote to NO_x, capable of completely eliminating NO_x from the tailpipe gas stream—it is a matter of creating the right thermochemical conditions which favour the appropriate reactions, while keeping side reactions to a minimum and avoiding excessively high urea consumption. Despite the bad press that NO_x storage catalysts have received recently, they can play a part in combination with SCR systems, as they have advantages, especially at cold start and for urban operation. Alternatively (or even additionally), gaseous (non-urea) ammonia delivery systems allow for dosing at lower

temperatures to take care of NO_x emissions as soon as possible after cold start, thereby avoiding the fuel consumption penalties associated with catalyst heating modes.

The introduction of electrical and electromechanical powertrains is hardly a new topic, but the issue is of paramount importance in the current political and technical climate. Hybrid powertrains are not simply a combustion engine with an electrical motor/generator/battery system added "on top"; the altered working regimes and added degree of freedom radically change the way the engine is used during a test cycle or during normal driving. Of particular concern regarding emissions control is the reduced availability of waste heat during episodes of engine shutoff, which has the potential to create perpetual cold start conditions. Particularly when considering RDE emission requirements (i.e. the need to respect emission limits under virtually all conditions of operation), the number of parameters which have to be optimised is very high in comparison with more traditional powertrain concepts and the calibration effort therefore increases massively.

Fuel and lubricant are of vital importance to all the aforementioned efforts to combat harmful emissions and minimise CO_2/FC. As is increasingly often pointed out, they should be considered powertrain components—and are as important as research on engine hardware, etc. Longstanding technical conventions are beginning to break down somewhat—some of the differences between "gasoline engines" and "diesel engines" are slowly disappearing; some SI engines will soon be able to run at the high efficiency levels which were once only thought to be achievable for CI engines running on diesel. A limiting factor—a glass ceiling—for gasoline efficiency is the octane number of the fuel. Pressure is building to alter specifications to boost the fuel's octane rating and thereby increase the realisable thermodynamic efficiency. On the subject of lubricants, it might be though that little scope for further improvement remains; however, that is not the case, as improved formulations can have measurable impacts on a range of parameters, from fuel consumption to engine wear to particulate emissions and their toxicity. As improvements are made to fuels and fuel delivery systems to reduce the quantity of fuel-derived particulate, oil-derived particulate will necessarily increase in importance and relevance as a result.

6 Documentation and Archiving of the Event and Its Materials

The presentations, abstracts and posters submitted to the 6th IEES are included in conference materials entitled "Symposium Proceedings - Trends in Automotive emissions legislation: Impact on LD engine development, fuels lubricants and test methods - a global view with focus on the WLTP and RDE regulations", ISBN 978-83-946334-1-7, issued by BOSMAL on CD [6]; a printed Book of Abstracts is also available, ISBN 978- 83-946334-2-4 [7]. The Symposium Proceedings are available for download at https://www.bosmal.eu/605-organised_events___symposia. Parties wishing to receive copies of the Book of Abstracts are asked to contact the authors of this paper.

A film documenting and reporting on the symposium is archived on a DVD attached to the Combustion Engines number 3/2018. A special edition of the journal Combustion Engines (3/2018) has also been released with articles and presentations from the symposium. DieselNet.com (Canada) has prepared a report on the symposium, which is freely available online https://dieselnet.com/news/2018/06bosmal.php. Information and reports from previous iterations of the IEES (2010–2016) are available in previous issues of Combustion Engines, as well as in various volumes issued by BOSMAL and on the internet [8–22]. https://www.dieselnet.com/news/2014/05bosmal.php, https://www.dieselnet.com/news/2016/05bosmal.php.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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