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SAE 2014 Heavy-Duty Diesel Emissions Control Symposium

Improving air quality while reducing the emission of greenhouse gases

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1. Introduction

The Society of Automotive Engineers (SAE) 2014 Heavy-Duty Diesel Emission Control Symposium was, like its predecessors, hosted in Gothenburg, Sweden. This biennial two-day event attracted around 160 delegates. Most of the delegates (>95%) came from catalyst system and component suppliers as well as original equipment manufacturers (OEMs). A few delegates came from academia, government organisations, media and consultancies. Most delegates came from Europe (>80%) with the remainder from the USA, Japan, China, India and Brazil. The conference was set up to provide attendees with the latest in upcoming regulatory actions, state-of-the-art technical information and first-hand experience relating to heavy-duty diesel (HDD) emission control strategies, engine and aftertreatment systems integration and the future direction of the industry.

This review aims to capture the key messages of the presentations given and to identify common views and differences between the presentations given in each session. The keynote lectures will be looked at individually. The other presentations will be summarised under their session headlines, with special attention given to the impact on catalytic emission control.

2. Keynote Lectures

2.1 Emissions and Environment for Bus Systems

Both conference days began with keynote lectures. On day one Edward Jobson (Volvo Bus Corporation, Sweden) gave an insight into an OEM's view on 'Emissions and Environment for Bus Systems'. He explained that Volvo places its commitment to hybrid city buses in line with its commitment to seat belts in 1959 and three-way catalysts (TWCs) in 1976. Pure diesel buses are now only available for regional and line-haul routes. Volvo city buses are now hybrids, plug-in hybrids or entirely electric. Utilising braking energy offers not only environmental benefits from lower emissions but also lower operational costs. Additional benefits are the options of utilising quiet emission free electrical driving for emission free and quiet city zones.

2.2 Improving Air Quality in Gothenburg

The second keynote lecture was given by Anders Roth (Gothenburg City), titled 'Improving Air Quality in Gothenburg – From Bans of Dirty Vehicles to Behaviour Change – The Role and Possibilities of Local Authorities'. Roth gave an insight into what the City of Gothenburg has done to improve its air quality. The early introduction of an environmental zone banning the most polluting buses and trucks from the city centre reduced particulate matter (PM) levels by 30% and nitrogen oxides (NOx) levels by 10%. A legal ban of studded tyres reduced the PM levels further. Procuring low emission vehicles (LEVs) for the city's vehicle fleet and aiming for a 90% reduction of fossil fuel use from 2010 to 2020 will minimise the emissions of the city's own vehicles. Currently the city of Gothenburg expresses a clear preference for gasoline over diesel vehicles. Other measures include utilising biofuels (especially biogas) to reduce CO_2 emissions, incentivising the use of modern (low emission) construction machines, introducing congestion charging, investing in public transport and minimising truck traffic to and from the harbour by utilising a harbour railway system. Mandatory car sharing for business trips, a free bicycle service and bus cards in compensation for no free parking as well as payments per avoided tonne of CO_2 emissions have been introduced for city authority employees with the aim of changing their travelling behaviour. Improving the air quality in the City of Gothenburg makes the central area around the river a more attractive place to live and increases its value dramatically. Being a coastal city, concerns about sea level rises through global warming make the City of Gothenburg very committed to minimising its greenhouse gas (GHG) emissions.

2.3 Exhaust Emissions and Carbon Dioxide Regulations

On day two Jürgen Stein (Daimler AG, Germany) gave a keynote talk titled 'Exhaust Emissions and CO_2 Regulations for Heavy Duty and Non-road Engines – An Outlook Beyond Euro VI and Stage IV'. Stein took the audience through the issues with a focus on the triad markets (EU, USA and Japan). The emissions limits are similar to those for on-road applications allowing the introduction of a global base technology. For non-road applications harmonisation (with minor differences in the timeline) has largely been achieved since 2000 and the use of a global base technology is already established. Emission testing against the World Harmonised Test Cycles aims to enable technology harmonisation but differences in details may lead to diversification. The introduction of particulate number (PN) limits for Euro VI forced the introduction of diesel particulate filters (DPFs). The Euro VI package ensures the lowest in-use emissions of any current legislation. While limits between heavy-duty and non-road are converging, the difference in PM/PN limits is decisive for the aftertreatment technology.

In-service conformity requirements vary between the EU and the USA. In Europe there are currently no activities towards a HDD Euro VII standard. However, it seems likely that NOx emission values might become aligned with the Environmental Protection Agency (EPA) 10 value of 0.27 g (kW h)$^{-1}$. Limiting nitrogen dioxide (NO_2) emissions to 50% of the NOx seems likely as well. Further work on portable emissions measurement systems (PEMS) might also find its way into a future Euro VII regulation. In the USA there are currently no EPA activities on further emissions reductions, but the California Air Resources Board (CARB) will introduce optional low NOx limit values in 2015. However, Stein reckons that further tightening of Euro VI or EPA 2010 limit values will have no significant effect on air quality. Instead an efficient in-use scheme such as that in the EU is key to low in-use emissions.

For non-road applications the EU will introduce non-road mobile machinery (NRMM) Stage V by 2019/2020. The introduction of a PN limit value will force DPF technology for most applications. NRMM PEMS provisions derived from Euro VI are expected for Stage V (reporting only as a first step). Daimler would welcome the USA to harmonise with Stage V. Stein also reported on a recently completed test procedure for heavy-duty hybrid vehicles. In view of emerging regulations regarding CO_2 emissions in Europe and the USA Stein sees the key challenge for the next year in the reduction of CO_2 emissions and fuel consumption and demands that contrary to criteria pollutants a CO_2 regulation must be a whole-vehicle approach for heavy-duty vehicles and NRMM.

3. Legislation and Global Trends

This session contained three presentations.

Erik White (CARB, USA) presented the 'Long Term Impact on Air Quality (ARB-2020 Initiative): California's Comprehensive Program for Reducing Heavy Duty Diesel Emissions'. With an ozone map of the USA (**Figure 1**), White showed that California has a unique need for NOx reduction. CARB sees opportunities to strengthen the current standard with improved certification and durability requirements, improved durability testing and expanded warranties. Low temperature/low load NOx issues could be addressed through supplementary test cycles, expanded not-to-exceed (NTE) zones and PEMS-based compliance testing. California is interested in pushing the technical boundaries regarding NOx emissions and aims to demonstrate 0.02 g (bhp h)$^{-1}$ NOx emissions over the Federal Test Procedure (FTP) cycle without GHG or fuel efficiency penalties. California also pushes for a new national standard as one million interstate

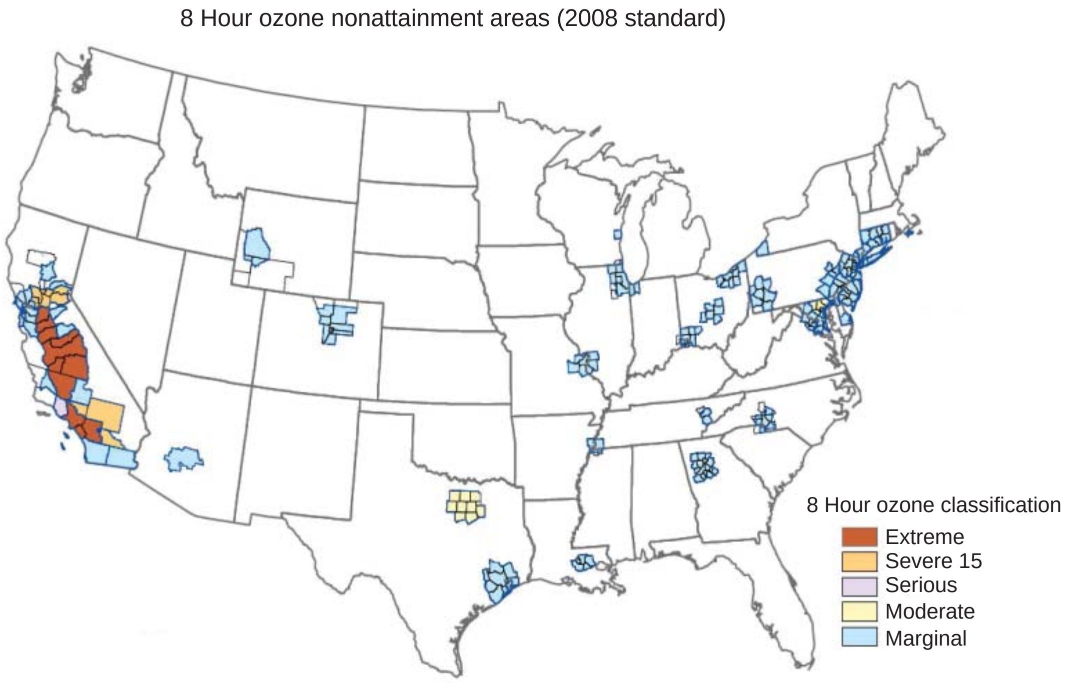

Fig. 1. California's need for NOx reduction is unique in the USA. Nonattainment areas are indicated by colour. When only a portion of a county is shown in colour, it indicates that only part of the county is within a nonattainment area boundary. Data collected on 31st July 2013 (Reproduced with kind permission from Erik White, CARB)

trucks operate there. Current and future GHG rules are harmonised with the rest of the USA. California's long term priorities are to continue to be a global leader in the pursuit of advanced emission control requirements; to pursue advanced technologies like zero-emission vehicles, near-zero emission vehicles and renewable fuels; and finally to implement strategies to develop, demonstrate and deploy these technologies.

A 'Review of HD Regulations and Technology Implications' was presented by Timothy Johnson (Corning Inc, USA). Three regulatory megatrends were highlighted:

(a) The World Health Organization (WHO) has designated air pollution as a carcinogen causing 7 million deaths worldwide (1).
(b) The PN fraction of $PM_{2.5}$ is emerging as the most harmful fraction responsible for 90% of PM toxicity (2).
(c) The United Nations (UN) Intergovernmental Panel on Climate Change (IPCC) placed a CO_2 limit for the atmosphere of 1 trillion tonnes cumulative. This would be exceeded in 2040 in a status quo scenario and would mean that only 17% of the feasible fossil fuels can be burned to prevent massive climate change.

Johnson then went on to present some emission control highlights, such as California's voluntary NOx standards reaching down to 0.02 g (bhp h)$^{-1}$ NOx, for which feasibility is going to be demonstrated in a Southwest Research Institute (SwRI) programme. He also discussed the schedules for introducing Euro V and Euro VI emission levels in China and India. **Figure 2** shows HDD vehicle timelines around the world.

Johnson then reported that various GHG emission regulations are being introduced in Japan, the USA, China, the EU, Canada and Mexico. There is also significant progress in improving HDD engine efficiencies. 50% brake thermal efficiency (BTE) has been demonstrated through the US Department of Energy (DOE) SuperTruck programme. A pathway to 55% BTE has been shown by Cummins. Through engine, truck and trailer modifications freight efficiency can be increased by 86%. Trailer modifications in particular offer large gains for a very small investment. Significant progress has been reported for NOx aftertreatment systems. DPF developments are focused on ash management and selective catalytic reduction (SCR) consolidation such as 'SCR on filter' concepts. For the success of SCR on filter systems it is important to find the optimum balance between good deNOx

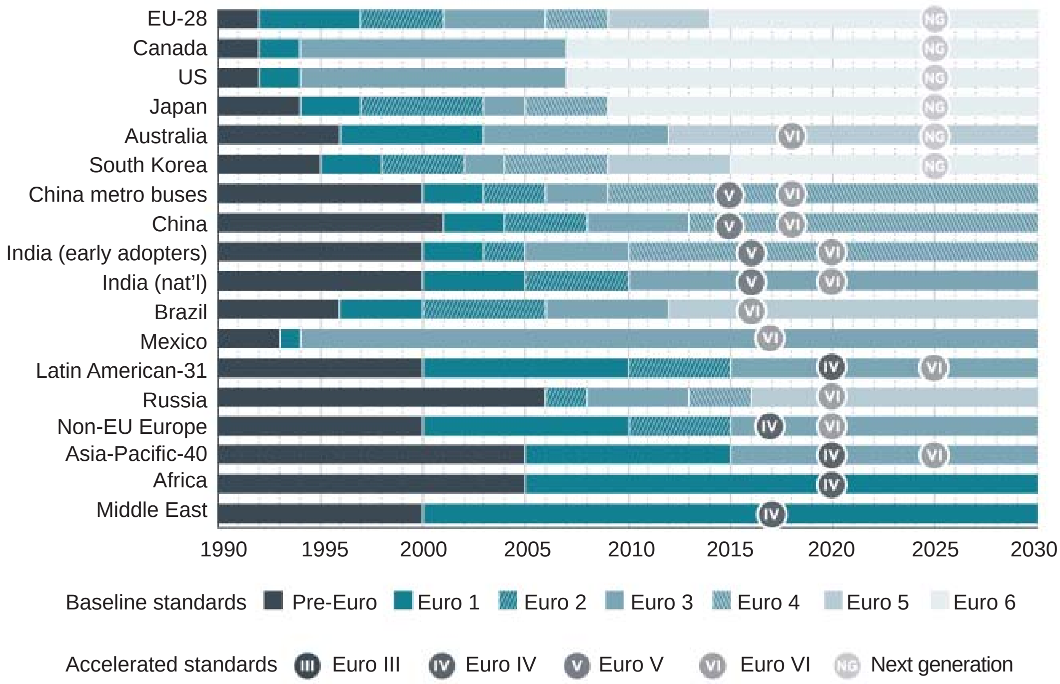

Fig. 2. HDD vehicle policy timelines (ICCT Bosmal 5/14) (Source: International Council on Clean Transportation 2013)

performance and sufficient PN filtration efficiency on one side against an increase of backpressure on the other.

Finally Magnus Lindgren (Swedish Transport Administration, Sweden) presented 'Euro VI *vs.* Transport Sector, An Environmental and Climate Success or Not?'. Large trucks (>20 tons) and truck trailers emit higher levels of CO_2 than inland water vessels, diesel trains and especially electric trains (see **Figure 3**).

A similar order is found for current PM_{10} emissions for these transport modes (**Figure 4**). However with the new Euro VI PM_{10} emission limits for heavy trucks and truck trailers set between 0 and 0.01 g PM_{10} per ton-km, and the NOx emission limits for Euro VI trucks being 10 times lower per kWh than for diesel trains and more than 20 times lower than for inland waterway vessels, trucks and truck trailers will leave diesel trains and inland water vessels behind regarding PM and NOx emissions.

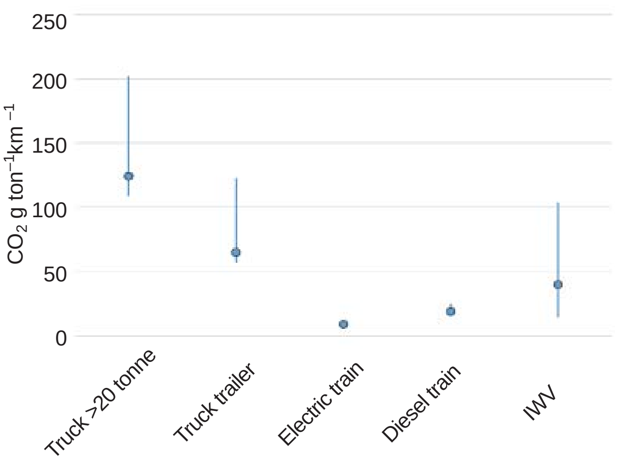

Fig. 3. Emissions of carbon dioxide. The length of the lines represents the range of emissions possible for distance, type of engine, vehicle or vessel, fuel etc. (IWV = inland water vessels) (Reproduced with kind permission from Magnus Lindgren, Swedish Transport Administration)

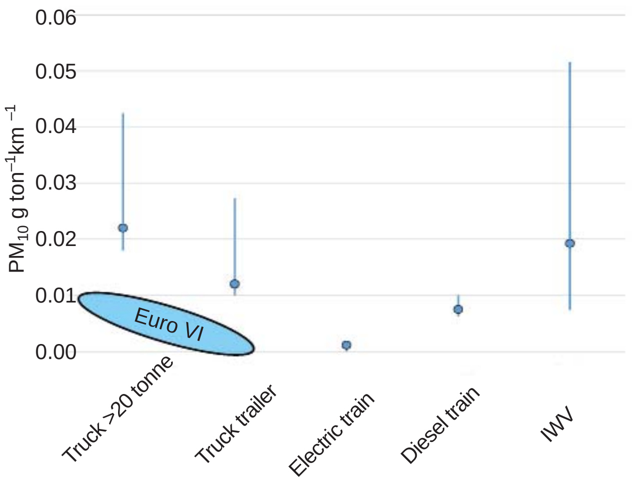

Fig. 4. PM_{10} emissions from cargo transport – long distance systems (Reproduced with kind permission from Magnus Lindgren, Swedish Transport Administration)

To get out of this CO_2 emissions *vs.* pollutant emissions dilemma, Lindgren concludes that the climate impact of heavy-duty trucks must be reduced through higher energy efficiency and alternative, sustainable fuels while inland waterway vessels, diesel locomotives (and other NRMM) must be as clean as heavy-duty trucks.

4. Non-Road Strategies and Future Developments

This session contained four presentations.

'Off-road Mobile Machinery Fuel Efficiency – A Total Systems Perspective' was presented by M. Lou Balmer-Millar (Caterpillar Inc, USA). She showed that while there are regional differences in the cost split between depreciation, labour, fuel and maintenance costs, a more efficient, less fuel consuming machine is universally desirable. Balmer-Millar showed potential CO_2 savings for the example of non-road machine applications: the choice of fuel offers the biggest CO_2 saving potential of up to 100%. (Balmer-Millar's presentation did not specify which fuels she had in mind, but the use of biofuels could count as CO_2 free). Components (these were not specified, but could be for example a transmission) offering 5%–10% and machine systems (these were also not specified but could be a hydraulic system) 10%–25% CO_2 saving potential. A greater CO_2 savings potential comes from the operator and job site of the application. Balmer-Millar showed that through a range of small measures, which improve engine efficiency each by 0.5%–4%, a combined improvement of 15% can be achieved. She then went on to show various examples of how system integration, hybridisation, innovative transmissions, high conversion efficiency SCR, machine control and Global Positioning System (GPS) based guidance technology can be used to significantly reduce fuel consumption, save on labour costs and complete work ahead of schedule.

Regis Vonarb (Liebherr Machines Bulle SA, Switzerland) presented 'The Next Liebherr Aftertreatment Solution: Towards Stage V?'. Vonarb started with an overview of Liebherr Machines Bulle's (LMB's) NRMM product range and showed that these are meeting Stage IV/Tier 4 final emission requirements through a vanadium-based SCR-only system without exhaust gas recirculation (EGR), a diesel oxidation catalyst (DOC) or a DPF, while being spark arrestor approved. For the Swiss market and LEZs closed DPFs are mandatory. For this market LMB offers an SCR on filter system. For the same NOx conversion efficiency the SCR on filter system volume is 1.2 times the SCR system volume. Substrate and coating definitions were found to be key for achieving the PN emissions limit. The NO_2:soot ratio was found to be the key parameter for passive regeneration behaviour and is impacted by the application cycle, the DOC design and the engine calibration. A 4000 h durability test showed the SCR on filter system has very stable functionality.

'Model Based SCR Control – Key to Meet Tier 4 Final with Lowest Calibration Effort' was presented by Markus Iivonen (AGCO Power, Finland) and Armin Wabnig (AVL, Austria). Iivonen explained that AGCO Power's engines, some of which have EGR, range from 50 kW to 440 kW and all have the same principle exhaust aftertreatment system containing DOC + SCR + ammonia slip catalyst (ASC). They are used in different, mainly agricultural, applications with different exhaust line layouts, therefore a model based exhaust aftertreatment strategy was chosen. Wabnig led through the model based development process and showed how the SCR control algorithms were implemented and tested. An adaptive dosing control strategy ensured the system was robust against dosing errors. AGCO was very pleased with this approach as different engine variants can be handled with reasonable calibration effort and development time can be reduced by utilising models in the software functionality and in off-line calibration.

Markus Müller (Deutz AG, Germany) concluded the non-road session by presenting 'Deutz Emission Control Solutions for a Diversity of Applications'. He gave an overview of the Deutz engine range from 30 kW to 520 kW. The focus of his presentation was the company's Tier 4 exhaust aftertreatment system, which contains DOC + DPF (or DPF with integrated DOC) + SCR + slip catalyst and emphasises DPF soot regeneration allowing their engines to operate under extreme conditions.

5. Emerging Markets

This session contained three presentations.

Jacob David Raj (Mahindra Trucks and Buses, India) could not be in Gothenburg to present the 'Indian Emissions Update' and asked Sougato Chatterjee (Johnson Matthey, USA) to present on his behalf. Raj's presentation gave an introduction into the Indian HDD market, which is undergoing fast changes from conventional trucks, which are often overloaded, have low power and torque, no safety norms, a single speed axle and a hard wired network, to the new generation trucks, which operate at rated load, have tubeless tyres, slightly higher power and torque, anti-lock braking system (ABS), speed limiter, twin speed axles and a controller area network (CAN). Despite new market requirements like better comfort, drivability, reliability, warranty, and reduced cost of operation, there are still challenges such as an aversion to new technology, driver shortages and the need for local truck servicing to be able to handle modern trucks. Further concerns are the skill level of mechanics and local modification of emission components. The general emission strategy in India is:

- For light commercial vehicles (LCVs): cooled EGR + oxidation catalyst + partial filter
- For medium commercial vehicles (MCVs): EGR or SCR
- For heavy commercial vehicles (HCVs): SCR is preferred (EGR option package as back-up).

Mahindra's recipe for technology to meet emissions requirements is: to keep costs low but provide reliability, to design for abuse and servicing which can be done locally, to keep trouble shooting simple and to increase the warranty of emission control components.

Qin Li (Weichai Power Co, Ltd, China) presented 'Challenge and Solution for Reduction of Emissions from Commercial Vehicle in Beijing'. Li started with an overview of the heavy-duty regulations in Beijing. These have been introduced up to seven years ahead of regulations for the rest of China. Beijing 1–3 limits were the same as those for Euro I–III. However, Beijing 4 and 5 show interesting additions to the European standards they are based on: Beijing 4 is Euro IV + World Harmonised Transient Cycle (WHTC) and Beijing 5 is Euro V + WHTC + PN limit. PEMS is used for in-use engine control and a heavy-duty vehicle cycle is under development. After introducing the company, which produces more HDD engines than any other company worldwide, Li presented its emission solutions, summarised in **Table I**.

Georg Hüthwohl (Albonair GmbH, Germany) presented 'Introduction of the Bharat Stage (BS) 4 Emission Legislation in India'. India is ranked 155th of 178 in the Environmental Performance Index and 174th out of 178 for air quality. In 2010 commercial vehicles were responsible for 90% of NOx, 80% of sulfur dioxide (SO_2), 70% of CO_2 and 55% of PM_{10} emissions in India. He then presented the schedule for introducing the BS IV in India, which has already been introduced in major cities and will come to the north of India in 2015 and to five additional provinces in 2016 before being rolled out nationwide in 2017. Fuel changes (BS III fuel has 350 ppm S, BS IV fuel has 50 ppm S) are scheduled to match this timescale. However, the AdBlue® infrastructure is a bottleneck for the introduction of BS IV. The main reason for a very slow uptake of BS IV technologies is a loophole in the legislation which allows commercial BS III vehicles registered outside of BS IV cities to enter these cities. Therefore city buses are almost the only BS IV vehicles in BS IV cities.

6. Alternative Fuels and Powertrains

This session contained two presentations.

Donald Stanton (Cummins Inc, USA) was not able to be in Gothenburg to present 'High Efficient Natural Gas Engine Technologies to Meet the New U.S. Greenhouse Gas Emissions for Commercial Vehicles' but had submitted his presentation for publication. Stanton's presentation explained that in the USA the natural gas vehicle market is driven by the lower cost of natural gas compared to oil. An additional benefit is the potential for nearly 25% reduction in CO_2 emissions. **Figure 5** shows the cost comparison of oil *vs.* natural gas. However, natural gas adoption in the transport market is facing several challenges, including

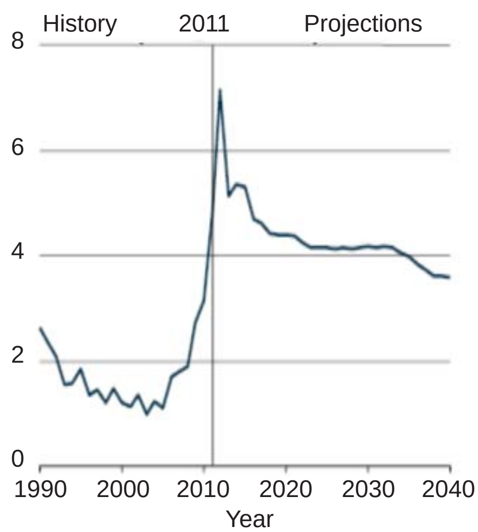

Fig. 5. Ratio of Brent crude oil price to Henry Hub spot natural gas price in energy equivalent terms 1990–2040. Energy from natural gas remains far less expensive than energy from oil through 2040 (Source: US Energy Information Administration 2013)

Table I Some Proposed Commercial Vehicle Emission Control Solutions for Beijing 4 to 6 Standards

Standard	Application	Solution
Beijing 4	HDD	Euro IV engine with SCR and optional thermal management
	Heavy-duty gas	Euro IV lean burn gas engine
Beijing 5	HDD	Euro VI engine, without EGR system and with new DPF calibration
	Heavy-duty gas	Euro V lean burn gas engine
Beijing 6	HDD	Euro VI engine
	Heavy-duty gas	Euro VI gas engine

vehicle fuel storage, delivery system costs and weight; limited fuel station infrastructure; maintenance facility upgrade costs; and an inefficient component and vehicle supply chain.

Cummins has a broad natural gas product line and offers lean burn (meeting Euro V emission limits) and stoichiometric gas engines (meeting Euro VI/EPA13 emission limits). His presentation included a natural gas technology comparison discussing the pros and cons of dedicated natural gas engines *vs.* dual fuel engines and high pressure direct injection (HPDI) engines. While the dedicated spark ignited natural gas engine is 10%–15% less efficient than diesel engines or the dual fuel and HPDI engines, it only requires TWC aftertreatment compared to a DOC + DPF + SCR aftertreatment system for the diesel or HPDI engines. If the deNOx capability of the TWC could be extended, it would be possible to improve the fuel economy of dedicated natural gas engines.

'CO_2 and Energy: Challenges of Future Heavy Duty Propulsion' was presented by Staffan H. Lundgren (Volvo (HD), Sweden). Lundgren's presentation showed strategies for reducing fuel consumption and CO_2 emissions from heavy-duty vehicles. Starting from the energy flow chart (**Figure 6**), he highlighted charge air cooling, exhaust gas energy and heat to coolant losses on the engine side and air drag and rolling resistance on the vehicle side as targets for improvements.

In order to refine diesel internal combustion engines he suggested sustainable fuel, efficient engine configuration, an optimised combustion process for the selected fuel, exhaust heat and brake energy recovery and the utilisation of the engine configuration and transmission. To increase the engine's BTE to between 55% and 60% Lundgren suggests optimisation of the thermodynamic cycle(s) through more expansion, higher peak pressure, thermal insulation and reduced friction losses and de-coupling the soot-NOx trade off. Further fuel savings can be achieved through energy recovery by either an electrical hybrid or Rankine waste heat recovery.

Lundgren suggests methane and its derivatives as energy carriers that can improve the efficiency of diesel

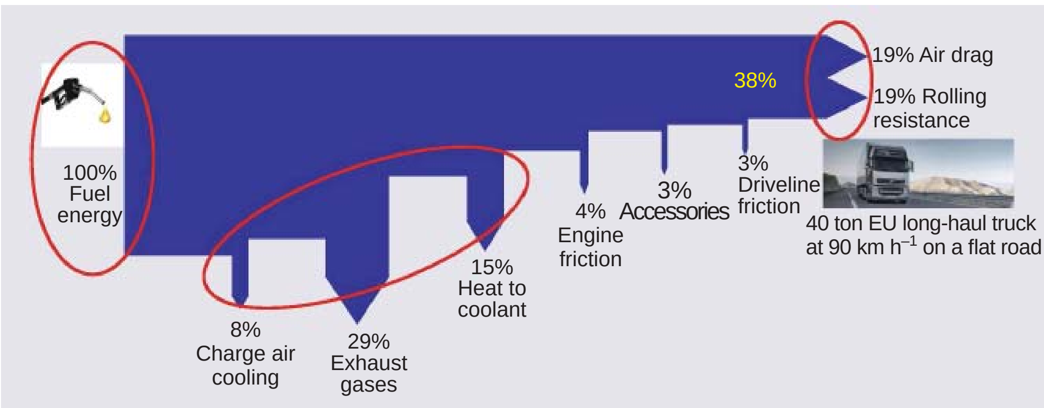

Fig. 6. Current energy flow from fuel to wheels for a Swedish heavy-duty truck (Reproduced with kind permission from Staffan Lundgren, Volvo (HD))

internal combustion independently of whether they are derived from fossil or renewable sources.

He then compared the CO_2 emissions of comparable energy carriers from fossil sources *vs*. renewable sources. While fossil fuel based diesel, natural gas and dimethyl ether (DME) cause between 85 kg and 95 kg CO_2 emissions per 100 km, biodiesel causes less than 60 kg CO_2 emissions per 100 km, biogas around 25 kg CO_2 emissions per 100 km and DME from wood less than 10 kg CO_2 emissions per 100 km. Vehicle based measures are to use the correct engine size (operate near peak efficiency), improve vehicle aerodynamics and reduce rolling resistance. Lundgren reckons that product improvements could provide *ca*. 25%–30% fuel savings with reasonable added costs and complexity.

7. Engine Developments

This session contained four presentations.

Chris Such (Ricardo UK, Ltd) presented 'Developments to Reduce CO_2 Emissions from Heavy Duty Engines'. The first part of the presentation was a report about the European CO_2 Reduction (CO_2RE) Project, which addresses the reduction of CO_2 emissions from HDD engines for long distance transport through conventional methods. The four-year CO_2RE project, which is run by 16 partners and coordinated by Volvo, started in 2012. So far, design analysis and rig testing has been carried out. Multi-cylinder testing is on its way. Waste heat recovery is covered by another project. The project aim is a 15% fuel consumption reduction compared to Euro V while being Euro VI compliant. These improvements will be achieved by addressing the engine platform, hybridisation, friction reduction and exhaust aftertreatment. The technologies investigated for the engine platform are down speeding, variable valve actuation, increased peak and cylinder pressures and high efficiency turbocharging. For friction reduction revised pistons and rings and lower viscosity lubricants were investigated. For exhaust aftertreatment optimisation low flow resistance DPFs and higher SCR efficiency at low exhaust temperatures were studied.

The second part of Such's presentation started with the question: "Is there an alternative to evolutionary development of current technologies?" He introduced the concept of a split cycle engine in which the compression and combustion/expansion processes are separated in different cylinders (**Figure 7**). A split cycle isothermal compression engine has already demonstrated >55% thermal efficiency in diesel generator set applications in 2002. Concept simulation work at Ricardo indicates that >60% thermal efficiency could be achieved. This work will be taken forward in the Innovate UK project 'CryoPower'. Such suggested investigating this engine concept within the EU project framework Horizon 2020.

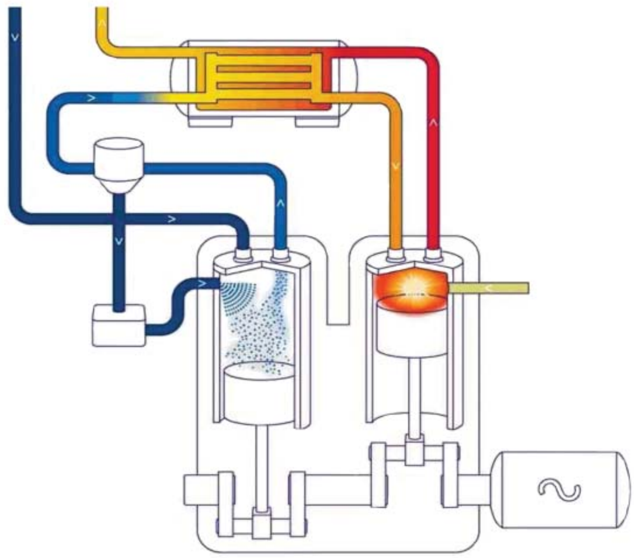

Fig. 7. Split cycle engine (Copyright 2014 Chris Such, Ricardo UK, Ltd)

Martin Tunér (Lund University, Sweden) presented 'The Journey from direct injection (DI)-diesel *via* HCCI to Partially Pre-mixed Combustion with Very High Thermal Efficiency'. The advantages of the homogenous charge compression ignition (HCCI) combustion process are high efficiency, fuel flexibility and ultra-low NOx and soot emissions, but the disadvantages are high hydrocarbon emissions, limited load and difficulties in control with the risk of engine destruction through misfire. Tunér then developed the concept of combining HCCI with DI diesel combustion to come to a partially premixed combustion (PPC). The advantages of PPC are that it is simple and rugged, fuel flexible, highly efficient and capable of high load operation, it has low emissions and is suitable for waste heat recovery. The challenges are idle to low load operation, transient emissions and combustion noise.

Vadim Strots (IAV GmbH, Germany) presented 'Modelling and Simulation for the Development of the Next Generation of Aftertreatment Systems'. Strots showed that exhaust aftertreatment system modelling is an integral part of the modern system development process. The kinetic models of exhaust aftertreatment components support the early evaluation of system solutions and optimisation of the component parameters at the concept development stage. Modelling and simulation is further applied to check the system performance in virtual certification work as well as in-use compliance simulations. Model based calibration aids the control concept selection as well as the engine control unit (ECU) calibration itself. It allows improved system robustness and diagnostics. However, high quality models are crucial and should be validated on gas benches and engines.

Frank Peter Zimmermann (Daimler AG) presented the 'Global Emission Strategy of the New Mercedes Benz Medium Duty Engines'. Zimmermann's historical retrospect about Daimler's medium duty engines since 1949 was followed by an overview on today's Euro VI engine and a comparison of emission concepts based on EGR and non-EGR, which require a different amount of NOx reduction through an SCR system. He argued that achieving the NOx limit through a combination of EGR and SCR enables 50% lower AdBlue® consumption, a smaller SCR volume and low tailpipe NOx emissions even under low load conditions. After covering engine thermodynamics he then focused on the Euro VI exhaust aftertreatment system. He started with the effect of thermal ageing on DOC performance and how Daimler addresses this issue. He then explained why silicon carbide (SiC) has been chosen over cordierite as the filter substrate material and that Daimler applies passive and active filter regeneration. The company had considered various SCR options (**Figure 8**) and concluded that there is no 'universal' catalyst.

Daimler selected iron-based SCR catalysts. It excluded V-based SCR catalysts due to the need for active regeneration at temperatures exceeding 550ºC, and Cu-based SCR catalysts because of concerns about nitrous oxide (N_2O) emissions. Using an Fe-based SCR catalyst allows Daimler to meet EPA10, JP05, JP09 and Euro VI emission limits. For non-road applications Daimler can fulfil the PM certification limits without a DPF. This opens the way to use a V-based SCR catalyst.

Finally Zimmermann compared Daimler's Euro VI and Tier 4 concepts with its previous generations Euro V and Tier 4 Interim and showed a reduction in operating costs of about 3% for the new systems.

8. Catalyst and Substrate Developments

This session contained three presentations.

Adolf Schafer-Sindlinger (NGK Europe GmbH, Germany) presented 'Cordierite and SiC Filters for On-road and Off-road Heavy Duty Applications'. He focused on two areas: catalysed soot filters and SCR on filter concepts.

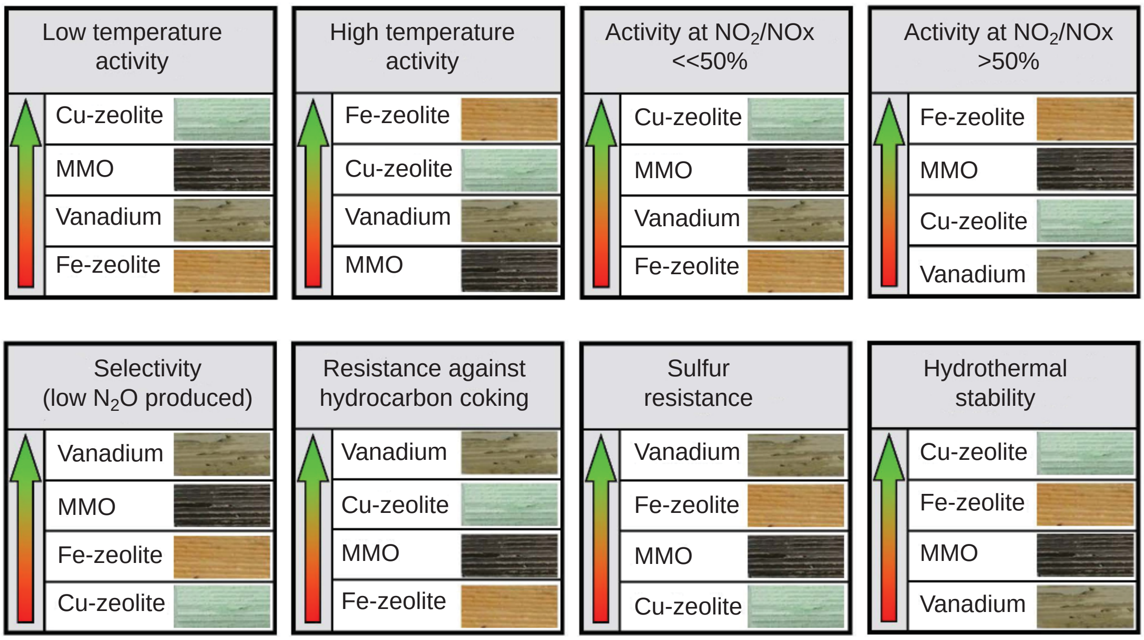

Fig. 8. A generalised view of current known SCR technologies – characterisation criteria series (MMO = mixed metal oxides) (Reprinted with permission from F. Zimmermann, U. Gärtner, P. Benz, M. Ernst and J. Lehmann, 'Global Emission Strategy of the New Mercedes Benz Medium Duty Engines', SAE 2014 Heavy-Duty Emissions Control Symposium, Gothenburg, Sweden, 17th–18th September, 2014)

For catalysed soot filter applications, requirements for robustness have to be balanced against the pressure of soot loaded filters. For minimum pressure drop performance thin wall technologies offer advantages over standard types. The higher sensitivity to thermal stress of thin wall filters can be compensated by new reinforced designs. Pore size and pore volume of the filter material shows a clear influence on PN emissions. With pre-conditioning, all thin wall filters in the study achieve the Euro VI PN limits. For SCR on filter applications the pore size distribution must be optimised to satisfy low pressure drop and high PN filtration efficiency requirements.

Andrew P. Walker (Johnson Matthey Plc, UK) presented 'Future Challenges and Incoming Solutions in the Global Catalyst-based Emission Control Area'. Starting with a global regulations overview and a description of typical exhaust aftertreatment systems for on-road and non-road applications he explained the general challenges for future applications. Further fuel economy improvements will increase engine out NOx, reduce exhaust temperatures and require reductions in backpressure. Further regulatory reductions in NOx emissions will increase the system NOx conversion requirements. DPFs are expected to be used for PN compliance, for example for non-road Stage V in Europe. There will also be an increased focus on other emissions like N_2O, NO_2, CH_4 and carbon black and a drive for further reductions in system volume.

Walker then moved on to show how extruded and high porosity substrates with increased cell density can improve SCR conversion efficiency (**Figure 9**) allowing potentially up to 50% volume reduction.

He gave an insight into the capabilities and challenges of the SCRF® component (which is the Johnson Matthey term for SCR on filter systems). Applying an SCR coating to the filter enables the SCR component to get hotter earlier and increases the SCR volume in the system, both of which enable increased NOx conversion. It also increases the PN filtration efficiency. However, increased competition for NO_2 between PM combustion and NOx conversion require attention and good system design.

Another important incoming technology is the diesel Cold Start Concept (dCSC™) component, which traps NOx from cold start and releases it when the downstream SCRF® component is hot enough to convert the NOx. A highly efficient SCR system can also be enabled by low temperature ammonia availability, which can be realised through converting urea to ammonia in a side stream, bypassing the DOC component and injecting ammonia directly onto the SCRF®. As increasing NOx conversion requirements lead to more aggressive urea dosing strategies, highly efficient and highly selective ASCs are required and significant improvements in selectivity have already been made.

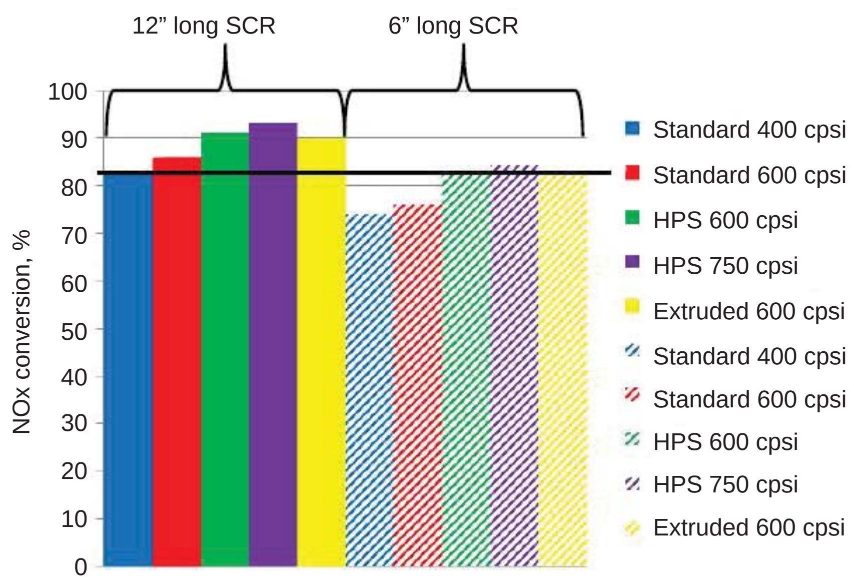

Fig. 9. Comparison of Cu-SCR on various substrates (HPS = high porosity substrate) (Copyright Johnson Matthey)

Andreas Geisselmann (Umicore AG & Co KG, Germany) presented 'Future Aftertreatment Concepts for Heavy Duty Application'. Geisselmann's presentation confirmed the general view of Walker's presentation but focused on SCR on filter systems, which are called SDPF by Umicore. He listed possible reasons why the HDD on-road sector appears to be reluctant to implement SDPF systems, while the non-road sector appears to be more open to them. In his very detailed analysis Geisselmann showed various SCR coating choices and concluded that Cu-SCR appears to be most attractive for SDPF applications. He also presented details on active and passive SDPF regenerations. He emphasised the passive regeneration challenges caused by back diffusion and missing NO_2 recycling. Geisselmann anticipates that there are still challenges in this technology.

9. On-Road Strategies and Future Developments

This final session contained three presentations.

Richard Dorenkamp (Volkswagen AG, Germany) presented 'How the European LDD Industry Cope with Incoming RDE Regulations?' He briefly introduced some key challenges, such as the LEV III regulations in the USA with very low NOx emission limits, real world driving emissions (RDE) requirements in Europe and the requirement to meet emission standards in China under poor fuel quality conditions. Global CO_2 emission reduction requirements add another challenge to the light-duty diesel (LDD) industry. Key enabling technologies are engine modifications, the ECU which links the fuel with the exhaust aftertreatment system, sensors and actuators. He gave an overview of the measures applied inside the engine starting from high level areas like weight, friction, combustion, recuperation, exhaust gas aftertreatment, temperature management, air management, energy, control and consumables before zooming in into the component level of the engine itself, the air/gas system and the exhaust aftertreatment system. A key message for the exhaust aftertreatment system was that measures to bring down CO_2 emissions cause a decrease in exhaust gas temperatures. Therefore the exhaust aftertreatment system needs to be close coupled in order to reach a high enough temperature for effective operation. VW's current LDD emission control concept combines a close coupled NOx storage component, a urea injection point and mixer, and a Cu-zeolite SCR coated DPF.

Dorenkamp summarised the requirements and concluded that the exhaust gas aftertreatment system needs to be effective in a wider temperature range, have a higher deposition rate of pollutant removal and no negative impact on the fuel consumption. Finally he highlighted the differences between LDD and HDD exhaust aftertreatment especially regarding system volume to engine size ratio.

Magnus Mackaldener (Scania AB, Sweden) presented 'A Bumpy Road Towards Euro 6: How Scania Did it and the Experience After 2 Years in the Field'. After a brief introduction to the Euro VI challenge and the history of Scania aftertreatment development, he gave a detailed description of the modular Scania Euro VI exhaust aftertreatment system, which comprises a replaceable DOC followed by a serviceable DPF, an AdBlue® injection and twin parallel SCR/ASC units. After showing a few performance results he presented relative cost benchmarks for engine and aftertreatment systems between Euro III, Euro IV, Euro V and Euro VI technologies showing that the costs for engine plus aftertreatment have more than doubled from Euro III to Euro VI. Mackaldener then went on to show a cost analysis of engine and aftertreatment systems for Scania, Volvo, MAN, Mercedes Benz, Iveco and DAF HDD Euro VI engines concluding that Scania engines have lower relative costs and lower exhaust treatment costs per g $(kW\ h)^{-1}$ NOx reduced. The next part of his presentation showed how the amount of fuel consumed by food distribution, taking into account both trucks and cars, could be reduced: each 25 tons of food distributed through supermarkets today requires 860 l of fuel; if this food were distributed *via* local stores it would require 312 l and if it were sold over the internet it would require 300 l. Finally he showed the trade-off between engine efficiency and NOx emissions, for example in Scania's D13 engine a 1% fuel economy improvement would increase NOx raw emissions from 10 g $(kW\ h)^{-1}$ to 14 g $(kW\ h)^{-1}$.

Heimo Schreier (AVL) presented 'Potentials and Challenges for Next Generation HD Diesel Engines'. After briefly describing the commercial vehicle market situation he used a Euro VI fuel efficiency roadmap for HDD engines to show that the engine efficiency BTE can be increased from 45% to 50% between 2014 and 2020, causing the brake specific fuel consumption to decrease by about 10%. This could be done through advanced turbocharging concepts, increased compression ratio, thermal insulation, friction reduction, variable valve timing and waste heat recovery. This would require significant base engine design modifications (for example peak firing pressure (PFP) >220 bar). Further improvement could be achieved through powertrain system optimisation including smart auxiliaries, down speeding, advanced shifting strategies and predictive powertrain control.

Schreier then focused on technologies to improve the engine efficiency. He explained that turbocharging efficiency is key to further fuel consumption improvements. High turbocharging efficiency resulting in higher exhaust mass flows and lower exhaust temperatures will require alternative EGR concepts, like turbo compound and low pressure EGR. This will be an increasing challenge for exhaust aftertreatment systems. He showed the influence of compression ratio (CR) and advanced timing on fuel consumption and PFP. With higher CR improving fuel economy PFP demand will increase beyond 220 bar, requiring base engine modifications. Through model based adaptive emission control, engine settings can be optimised according to the exhaust aftertreatment status or performance level. Advanced aftertreatment systems (**Figure 10**) include one close coupled component (DOC or DPF) and may incorporate SCR on filter technology. The warmer location makes volume reductions of 15%–35% seem possible without loss of performance. The larger volume of SCR coated components and higher temperatures of the SCR on filter leads to higher deNOx capability for these variants.

Friction reduction will provide limited fuel consumption savings. However, some measures might require significant base engine modifications. Organic Rankine cycle based waste heat recovery (**Figure 11**), which provides a 3%–5% fuel saving in the European long haul cycle, can be expected to be in series production by model years 2018 or 2020. The integration of waste heat recovery with calibration requires system simulation. The current focus is on product cost and weight reduction.

10. Summary

The SAE 2014 Heavy-Duty Diesel Emission Control Symposium was very well attended and well organised.

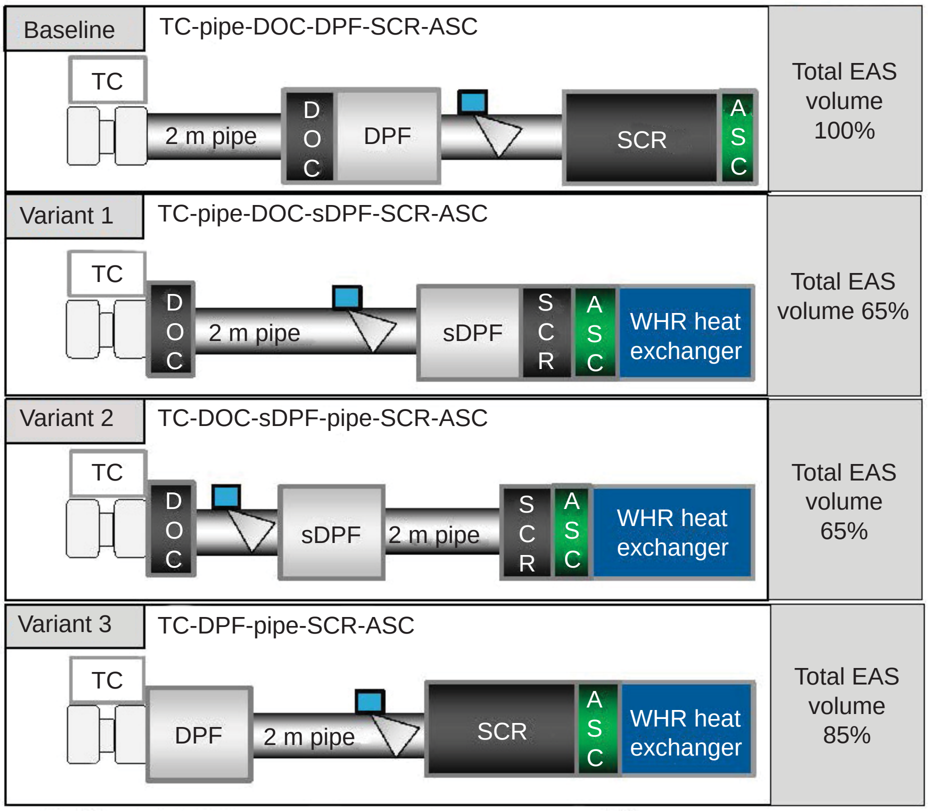

Fig. 10. Advanced exhaust aftertreatment systems (TC = turbocharging, WHR = waste heat recovery, EAS = exhaust aftertreatment system) (Reproduced with kind permission from Heimo Schreier, AVL)

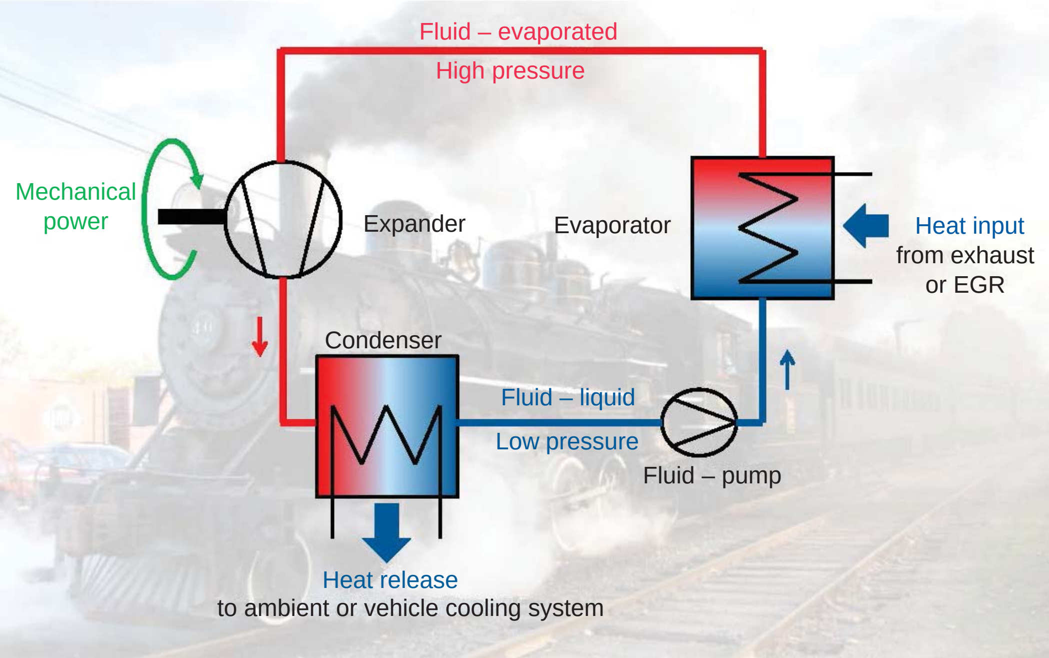

Fig. 11. Waste heat recovery Rankine cycle process (Reproduced with kind permission from Heimo Schreier, AVL)

The sessions covered a wide range of relevant topics. Emission control and GHG regulations in many parts of the world present current and future challenges for both on-road and non-road applications, and technical solutions to many of these challenges were presented. Emerging markets largely follow the European emission legislation with a few years' delay. Legislative advances in emission control legislation mainly focus on closing the gaps between real world driving or operation and durability legislative requirements. The introduction of particulate number regulation will clean up NRMM in Europe. California continues to push the technical boundaries in emission control by working towards highly efficient NOx control. GHG regulations are emerging in a wide range of countries and attract an increasing amount of resources to meet the challenge. HDD engines are becoming more and more efficient and these efficiency improvements, together with integrated machine- or vehicle-based approaches, show tremendous potential to limit GHG emissions even further. Despite higher demands on emission control the required system volumes are only increasing moderately due to increased integration of functionalities, for example SCR on filter systems. The industry is learning lessons from each other's successes as well as from related industries like the light duty vehicle manufacturers. Overall the symposium drew an optimistic picture of exciting challenges ahead.

References

1 '7 Million Premature Deaths Annually Linked to Air Pollution', World Health Organization, Geneva, Switzerland, 25th March, 2014

2 A. C. R. Mayer, 'PM Versus PN: Which Parameter Describes the Toxic Air Contaminant Emitted by CI and SI Engines Better and Should thus be Used for Emissions Limits and AQ-Limits', 18th ETH Conference on Combustion Generated Nanoparticles, Zürich, Switzerland, 22nd–25th June, 2014

The Reviewer

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