

Review of Diesel Emissions and Control

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Corning Inc.

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ABSTRACT

This review summarizes the latest developments in diesel emissions regarding regulations, engines, NO_x (nitrogen oxides) control, particulate matter (PM) reductions, and hydrocarbon (HC) and CO oxidation.

Regulations are advancing with proposals for PN (particle number) regulations that require diesel particulate filters (DPFs) for Euro VI in 2013-14, and SULEV (super ultra low emission vehicle) fleet average light-duty (LD) emissions likely to be proposed in California for ~2017. CO₂ regulations will also impact diesel engines and emissions, probably long into the future.

Engine technology is addressing these needs. Heavy-duty (HD) research engines show 90% lower NO_x at the same PM or fuel consumption levels as a reference 2007 production engine. Work is starting on HD gasoline engines with promising results. In light duty (LD), engine downsizing is progressing and deNO_x is emerging as a fuel savings strategy.

Much has recently been reported on optimized selective catalytic reduction (SCR) systems. The SCR catalyst can be placed before, after, or on the DPF. Work is progressing on non-urea ammonia systems, mixed zeolite catalysts, and on fundamental understanding on issues like ammonia storage, sulfur impacts, and reaction mechanisms. Developments on HC-based deNO_x, like lean NO_x traps (LNTs), result in a better understanding of durability, reduction in desulfation temperatures, and the use of LNT+SCR systems, wherein the LNT is calibrated to generate ammonia for use in a downstream SCR.

PM control is very effective. US2007 HD engines are very clean, with the DPF systems delivering PM, HC, and CO

emissions at levels lower than 10% of the regulation. DPF regeneration advances are reported in strategy, modeling PM loading, and catalyst utilization. The effect of catalyst coatings on PN emissions, and behavior of captured ash is becoming better understood. NO₂ based regeneration of soot is very critical for proper functioning of partial filters. Biodiesel effects on DPF functions are becoming clearer.

Finally, diesel oxidation catalysts (DOCs) are being developed for use with premixed combustion engine strategies that function better at low temperatures, low oxygen levels, and at high HC+CO levels. The problem of platinum (Pt) migration to SCR catalysts from DOCs exposed to high temperatures for long times (850°C, 16 hours) is alleviated somewhat by using palladium (Pd) to replace some of the platinum.

INTRODUCTION

Diesel emissions and control are still very much in the forefront. Interest in the diesel powertrain for LD applications is continuing, and may be increasing as a result of tightening vehicular CO₂ regulations. Also, California is planning a nominal 70% tightening of standards, so efforts are accelerating to continue emissions parity with gasoline vehicles. Although the HD truck market is generally depressed due to economic conditions, Japan and the US implemented the last step in tailpipe regulations in the latter half of 2009 and in 2010. The Euro VI HD regulations (2013-14) will help drive the next generation of technology. The non-road market is in durability testing in preparation for 2011-12 emissions tightening, and technologies are moving into development for the 2014 step. Large locomotive and marine engines are also coming under emissions pressure (but will not specifically be covered here).

This review will delve into the more significant developments and insights that were recently brought to the forefront in the previous year. It will begin where the previous review (1) left off, and will cover the key regulatory developments, engine technologies, and technologies for the control of NO_x, particulates, and HC/CO. Although it is now considered an emission, this review will not delve much into CO₂. Given its breadth and significance on technology trends, a separate review covers fuel consumption and CO₂ reductions (2). Also, probably due to the economic situation in the industry over the last two years, it is noted that technical paper offerings in 2009 seemed much more focused on two large conferences than in previous years, the 2009 SAE World Congress and the 2009 Directions in Engine Efficiency and Emissions Research (DEER) Conference. But nonetheless, the developments, quantity, and quality of the work were very good. Finally, as in previous reviews, this one is not intended to be all-encompassing and comprehensive. Representative papers and presentations are chosen here that provide examples of developments and direction.

REGULATORY DEVELOPMENTS

Significant diesel emissions regulations are focused on two different developments - Wrap up of the Euro VI particle number comitology, and work on the California Low Emissions Vehicle 3 (LEV3) light-duty standards.

HEAVY DUTY

On July 18, 2009 the European Union (EU) published the final Euro VI regulation, setting the limit values of 400 mg/kW-hr NO_x, 10 mg/kW-hr PM, and 10 ppm ammonia on the European Transient and European Steady-State Cycles (3). Still to be defined through comitology by the Commission are the particle number standards (PN), calculation method for ammonia (generally an average level calculated by an integration method), on-board diagnostic (OBD) details, and limit values on the World-Harmonized Transient and Steady State Cycles (WHTC, WHSC), among other issues. The final comitology is due April 1, 2010. So far, the Commission has proposed the NO_x limit be increased to 460 mg/kW-hr, with no increase in PM when using the world cycles. In November 2009, the US EPA (Environmental Protection Agency) agreed to allow US HD certifications on the WHTC, wherein the hot soak period between the cold and hot portions is increased from 5 minutes in Europe to 10 minutes (the US test is 20 minutes), and the cold start weighting is increased from 10% to 14.3% (same as in the US test). Both these changes increase the need for better deNO_x performance at the lower temperatures.

Figure 1 shows the collected data on PN emissions on the WHTC from 20 engines equipped with a variety of technologies as measured in the Commission program (4). Based on these tests and numerous workshops, for the

purposes of furthering the discussion, the European Commission proposed 6×10^{11} particles/kW-hr on the WHTC, and 8×10^{11} particles/kW-hr on the WHSC (5). It is perceived that all major stakeholders are satisfied with the proposed limit values, subject to the specific test protocols still to be determined. Unlike the light-duty Euro 5/6 requirements, it is proposed that these limits include weighted figures for periodic DPF regeneration. As in the light-duty PN standard, filter pre-conditioning was shown to be very important, especially on the WHSC.

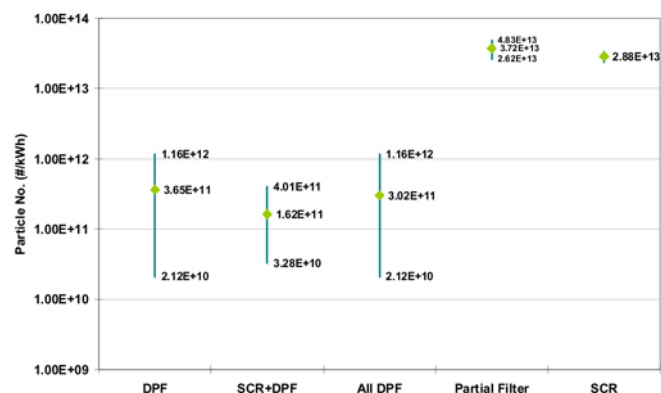


Figure 1. Particle number emissions for various Euro VI engine configurations as measured on the WHTC (4).

LIGHT DUTY

The California Air Resources Board (CARB) is planning to propose new light-duty tailpipe regulations soon. It is widely assumed that they will move to a fleet average requirement roughly equal to SULEV or US Tier 2 Bin 2 levels of 10 mg/mi non-methane organic gases (NMOG) and 20 mg/mi NO_x. This is about a 70% tightening from today's FTP cycle (Federal Test Procedure) limit value. On the table for discussion are a significant tightening of the US06 standards (up to 90%), using a NMOG+NO_x standard, significant tightening of PM (80-90%), and extending the phase-in time for the last portions of the fleet to comply.

The US EPA will work with CARB on the regulations, but is noncommittal at this time on a national regulation. They did release a new mobile emissions model (6) called MOVES 2010 (Motor Vehicle Emissions Simulator). Instead of being based on certification data on standard test cycles, the new model uses modal tests and estimates actual driving patterns. Heavy-duty and light-duty NO_x and PM_{2.5} emissions went up relative to the earlier model meaning that mobile emissions are a larger part of the pollution inventory than previously thought.

Summarized in more detail elsewhere (2), both Europe and the US introduced an effective 20-25% tightening of CO₂ emission standards for full implementation in 2015 in Europe

and 2016 in the US (proposed). The European standards are based on vehicle mass, and the US standards are based on the area between the tires. As such, each manufacturer will have different fleet-average standards. More direct injection gasoline, turbocharging, engine downsizing and stop-start systems are expected. This could be the start of a significant trend of continuous tightening, as the United Nations Intergovernmental Panel on Climate Change (UN IPCC) is recommending 80% cuts in all greenhouse gases (GHG) from 1990 levels by 2050. In that regard, diesel hybrid electric vehicles (HEVs) offer the greatest emissions reductions at the best value over the foreseeable future (2).

BLACK CARBON

Climate change impacts and criteria pollutant emissions have a juncture at black carbon or soot. With the global warming potential factor of black carbon at about 2000X versus CO₂ on a mass basis (7), about 20-25% of the carbon footprint from an unfiltered diesel vehicle is from black carbon. Remediation of diesel soot today is primarily done to minimize the adverse health effects, but the climate forcing impact could further increase interest. Figure 2 shows how worldwide on-road vehicle black carbon emissions vary over time (8). About 60% of the emissions are from diesel trucks. The base case assumes PM regulations that are currently planned. Emissions increase after about 2025 as the developing countries grow. The bars represent emissions if, by 2015, Euro VI HD and Euro 6 LD regulations are implemented in China, India, and Brazil; Euro IV HD and Euro 4 LD standards are implemented in Africa and the Middle East; and Euro 3 motorcycle regulations are implemented in Africa, the Middle East, and Latin America. By 2050, these advanced regulator initiatives remove 19 million tonnes of black carbon, or the equivalent of 38 billion tonnes of CO₂. This is ~20% of the total CO₂ reductions the UN proposes between now and 2050.

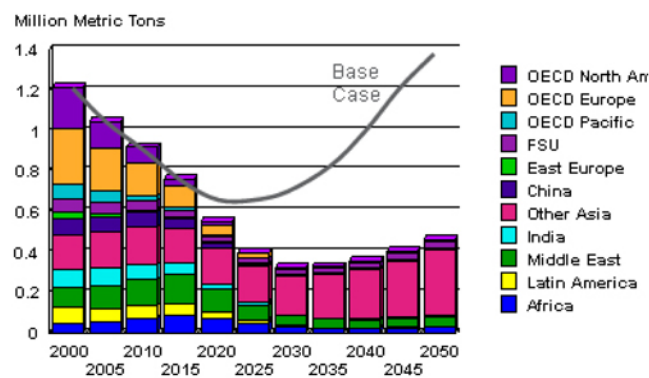


Figure 2. Black carbon reductions from current regulations (line) compared to those if developing countries adopt tighter PM standards by 2015. About 60% are for the HD sector. The difference represents about 20% of the total CO₂ reductions proposed by 2050 (8).

ENGINE DEVELOPMENTS

Engine technology is evolving very rapidly. Most of the developments in the market to date were implemented to address ever tightening criteria pollutant emission standards. However, moving into the future the emphasis will shift to meeting CO₂ or fuel consumption regulations (2). This section will cover the heavy-and light-duty engine developments from a criteria pollutant emissions perspective.

HEAVY DUTY

There is still much room for improvement in emissions from heavy-duty engines. Stanton gave an update on progress using incremental technologies applied to research engines that can result in nominally 90% reductions in engine-out NO_x at the same fuel consumption or same PM levels as a 2007 production engine (9). Figure 3 shows the results. Technologies employed included combustion optimization utilizing high pressure and multiple fuel injections, bowl design, variable swirl, variable valve actuation; advanced exhaust gas recirculation (EGR) with low pressure drop, high flow, and advanced cooling; air management with 2-stage boost, electrically assisted turbocharger; and advanced controls for mixed mode combustion, and closed-loop control. Note that deNO_x systems are optional on these engines to attain the US2010 NO_x standards (0.2 g/bhp-hr), but employing an 85 to 88% efficient deNO_x system can result in a 5 to 11% fuel savings. If exhaust emission control achieves 97% deNO_x efficiency instead of 85% to attain US2010 NO_x standards, an additional 10% fuel consumption reduction might be achieved, exclusive of additional urea consumption.

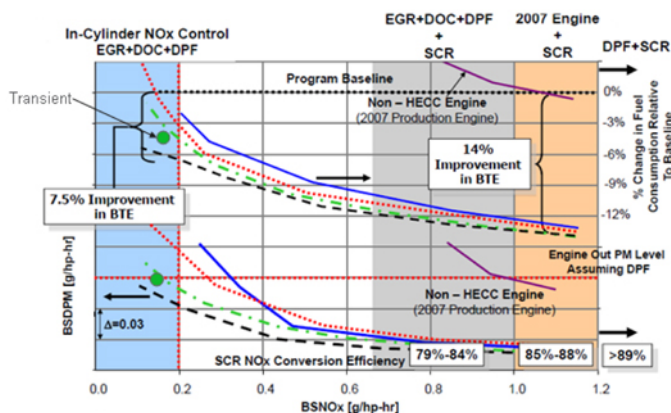


Figure 3. Fuel consumption savings (top curves) and PM reductions (bottom curves) for research engines utilizing generally incremental technologies (9).

There are two general engine pathways to meeting the emerging tailpipe regulations, low EGR and high EGR (exhaust gas recirculation) utilization resulting in significantly different exhaust deNOx strategies. Achieving high levels of EGR can be problematic due to unfavorable pressure differentials between the exhaust and intake manifolds that drive EGR. Specifically, at the later portions of the intake stroke, intake pressures can be higher than EGR loop pressures. A fast intake manifold valve that operates with crank angle resolution was developed to decrease intake pressures in this part of the cycle to drive more EGR (10). Using the system, Euro VI NOx regulations can be attained with no additional NOx emission control and at favorable operating costs compared to selective catalytic reduction (SCR) approaches when considering fuel and urea consumption.

Looking at the longer term, there was a marked shift in HD engine technology regarding pre-mixed combustion. Previous efforts on HCCI-type (homogeneous charge compression ignition) combustion hit an obstacle on controlling heat release at mid-load conditions and higher. The problem relates to a large charge igniting within a short timeframe under compression ignition. New approaches take advantage of premixed gasoline charges to produce low emissions and delay ignition; high levels of EGR to slow and further delay combustion; but may use some stratification to ignite the mix under compression (11, 12, for example), hence the name, partially-premixed combustion (PPC).

Three representative approaches are summarized here. Dec, et al., attained stable and low-emission combustion using a fully premixed regular gasoline charge, 60% EGR and 3.2 bar boost (13) at stoichiometry. Indicated thermal efficiency (gross ITE, no friction or pumping losses taken into account) was high for gasoline, 47% at 16.5 bar IMEP (indicated mean effective pressure) and NOx emissions were below US2010 levels. High levels of boost enabled high levels of EGR,

which resulted in a better-controlled release of heat for the fully premixed charge, despite a high and efficient compression ration (CR=14). Reitz, et al., also tested a premixed gasoline charge with high levels of EGR, but ignited the charge with 20% diesel fuel (14). Their 2-liter single-cylinder engine achieved 53% ITE at 11 bar IMEP, with emissions at 20 mg/kW-hr NOx and 8 mg/kW-hr PM. Like Dec, Johansson used only gasoline, but split the injection to give a significant early premixed charge, and a second late injection to stratify some charge for ignition (15). With this strategy, a 12 liter 6-cylinder HD engine achieved a brake thermal efficiency (BTE; all engine losses) of 48% at 18 bar IMEP and 1300 RPM, Figure 4. This represents a 10-15% fuel consumption savings and a greater than 20% CO₂ reduction versus today's diesel engines. However, NOx and PM emissions were much higher than reported by Dec or Reitz.

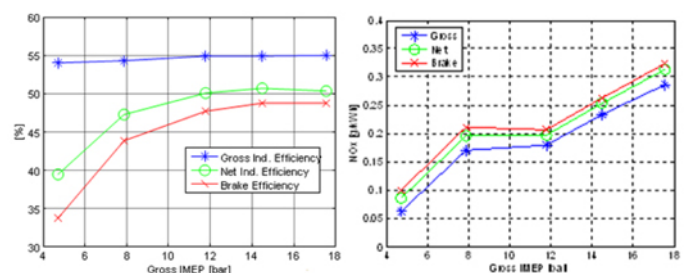


Figure 4. Gasoline PPC using a 6-cylinder, 12-liter engine. High BTE (48%, left panel) at relatively high loads (18 bar IMEP) with moderate NOx emissions (right) were achieved using commercial gasoline (15).

Strategies are beginning to emerge for attaining the final non-road Tier 4 tailpipe regulations. Two strategies were described by Kraljevic and Vlaskos (16). The high-EGR approach (25-35%) requires 2400 bar common rail fuel injection, and 80-85% deNOx efficiency in the exhaust, plus a diesel particulate filter. Engine specific power can range from 26 to 30 kW/liter, depending on turbocharging hardware. The low-EGR approach (15 to 20%) requires a 2000 bar fuel injection system, 90+% deNOx, and 50% PM removal. Engine specific power range is higher, from 30 to 32 kW/liter. Going one step further, the possibility of attaining the final Tier 4 regulation without EGR has also been proposed (17), utilizing SCR to accomplish all required NOx reductions.

LIGHT DUTY

Technology pressure on the light-duty diesel manufacturers is coming from emerging SULEV regulations in California, advances in gasoline engines, and increased offerings of hybrid electric vehicles (HEVs). On the other side, diesel platforms are very attractive for meeting the emerging CO₂ regulations, in which diesels have a 20% advantage over their

gasoline counterparts. The technology pressure is being met with increasingly sophisticated combustion designs and control on diesel engines.

To maintain this advantage, most of the efforts in diesel engine technology are focused on reducing fuel consumption rather than criteria pollutant reductions (2). Rueger gave examples of gasoline and diesel engine trends to reduce CO₂ emissions (18). Most of the reductions in both types of engines came from downsizing, enabled by advances in turbocharging and fuel injection. On the diesel side, deNO_x additions and calibrations gave diesel a net 4% added edge, resulting in a widening of the margin.

NO_x emissions can go up 20% to 100% with engine downsizing if appropriate measures are not taken. Koerfer, et al. (19), described an integrated engine design approach utilizing advanced swirl concepts, EGR control, high-pressure and flexible injection, and sophisticated combustion chamber design. As a result, CO₂ emissions can drop 17%, NO_x emissions 50%, and PM emissions by 10% when downsizing a 2.0 liter Euro 4 baseline engine to 1.6 liters. Leonhard, taking a different approach, described (20) the interplay between and impact of boost, fuel injector design, and injection strategy on fuel consumption and emissions. Fuel consumption is positively affected by the combination of 2-stage turbocharging and a close pilot injection; by the combination of low-flow nozzles and higher injection pressure; and by injection strategy (like a close coupled pilot) with better results coming using a direct needle versus a piezo injector. NO_x emissions are not very dependent on the close pilot, but are very strongly impacted by high boost, nozzle flow rate, and injection pressure.

Given California directions towards a SULEV fleet average emission requirement, diesel engineers are moving in that direction on research engines. Cooper (21) extended previous work on a Tier 2 Bin 5 diesel, towards one that can efficiently attain SULEV (Tier 2 Bin 2) levels. They chose an LNT as their exhaust deNO_x technology. At these low emission levels, cold-start hydrocarbons become a problem as well as the slip from LNT regeneration. Cold start is aided with pre-turbo oxidation catalysts, but the LNT strategy needs to be developed.

NO_x CONTROL

As Figure 3 illustrates, within a given diesel engine hardware package fuel consumption goes down as NO_x emissions are allowed to increase. In other words, as illustrated with a couple of examples above, deNO_x efficiency can translate into fuel consumption savings for both heavy-duty and light-duty applications. Figure 5 illustrates the principle in a light-duty application (20). In this case, increasing levels of engine technology added to a Euro 5 base engine can drop fuel consumption nominally 6% at the same level of NO_x (0.15 g/

km, for example). However, an advanced engine package can bring the Euro 5 engine to Euro 6 NO_x levels at the same fuel consumption, but added to this, 45 to 50% NO_x control can deliver a 6% fuel consumption advantage. Severin showed a similar impact, but the fuel saving is reduced for smaller cars because the flat part of the fuel consumption curve is shifted to the left levels versus for a larger car (22).

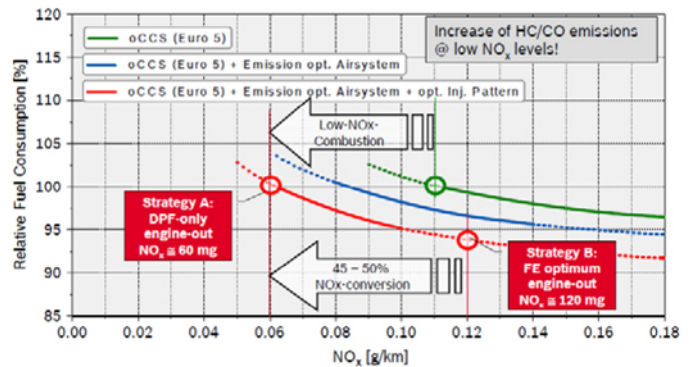


Figure 5. Modest tailpipe NO_x control can drop fuel consumption 6% (20).

SELECTIVE CATALYTIC REDUCTION

Selective catalytic reduction (SCR) still remains the leading deNO_x approach for diesel engines. DeNO_x efficiencies can be 90% or higher with proper control and design.

System level work is continuing on delivering ammonia to the SCR without using liquid urea. Spurred by a truck and engine manufacturer investment (23), a leading non-urea technology is advancing that uses metal amines to store gaseous ammonia, thus resulting in a large increase in specific ammonia storage capacity (~2.5X that of urea on a volumetric basis). The ammonia is released with heat, wherein power consumption is significantly reduced using cooling water (24). A 250 watt power draw during cold start allows low-temperature delivery of ammonia at SCR catalyst temperatures down to 100°C. With similar objectives of replacing liquid urea, Tatur, et al. (25) described a truck test using ammonium carbamate [(NH₂-CO₂)-(NH₄)], which has a specific ammonia storage capacity 3-4X more than urea. The solid is converted to ammonia by heating with a heat transfer fluid (such as oil). Once heated, the system delivers ammonia as needed for high efficiency.

Looking at another key part of the SCR system, Holderbaum, et al.(26) evaluated the placement of the SCR relative to the DPF. Considering the added fuel needed to heat the SCR system for cold start, and to regenerate the DPF with different frequencies due to changes in passive NO₂ regeneration, the authors conclude that for an 1800 kg car with a 2-liter engine, if cold starts occur more frequently than once every 60 km it is better to place the SCR in front of the DPF. Figure 6 shows