

Diesel Emission Control in Review

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ABSTRACT

This summary covers representative developments from 2008 in diesel regulations, engine technology, and NO_x, particulate matter (PM), and hydrocarbon (HC) control.

Europe is finalizing the Euro VI heavy-duty (HD) regulations for 2013 with the intent of technologically harmonizing with the US. A new particle number standard will be adopted. California is considering tightening the light-duty fleet average to US Tier 2 Bin 2 levels, and CO₂ mandates are emerging in Europe for LD, and in the US for all vehicles.

LD engine technology is focused on downsizing to deliver lower CO₂ emissions, enabled by advances in boost and EGR (exhaust gas recirculation). Emerging concepts are shown for attaining Bin 2 emission levels. HD engines will make deNO_x systems optional for even the tightest NO_x standards, but deNO_x systems enable much lower fuel consumption levels and will likely be used.

NO_x control is centered on SCR (selective catalytic reduction) for diverse applications. Focus is on cold operation, system optimization, and catalyst durability. LNT (lean NO_x trap) performance is advancing and precious metal cost content is decreasing. Desulfation is enhanced, and new compositions are emerging based on alumina and ceria. LNCs (lean NO_x catalysts or HC-SCR) developments are updated.

Diesel particulate filter (DPF) technology is in a state of optimization and cost reduction. New DPF regeneration strategies are described as well as the new learnings on the fundamentals of soot/catalyst interaction and the impact of DPF pore structure.

Finally an update on diesel oxidation catalysts (DOCs) is provided showing potential solutions for advanced combustion strategies.

INTRODUCTION

The field of diesel engines and emission control technology has been very dynamic since the mid-1990s. Much of the technology evolution is regulatory-driven, and those regulations are now in various stages of implementation. The field is ripe with incremental improvements to address new and old challenges as there are well over 1000 technical papers concerning diesel engines, fuels and emissions, comparable to earlier years.

As in the past (1), this review is not intended to be all-encompassing. Rather, the objective is to summarize representative studies that show the key directions in the industry, with an emphasis on reports from 2008. First, the regulatory issues are addressed, followed by a quick overview of engine technologies most pertinent to emissions control. The author will then review NO_x, PM (particulate matter), and hydrocarbon/CO control developments.

Regulatory Developments

Regulations are continuing to evolve. California is considering a fleet average emission level equivalent to SULEV (Super Ultra-Low Emission Vehicle), and CO₂ mandates are developing. On the heavy-duty side, Europe is proposing new Euro VI standards.

LIGHT-DUTY

Light-duty diesel (LDD) criteria emissions regulations are undergoing another round of tightening in California. For LDD, NO_x is the most demanding pollutant to address, as diesel particulate filters (DPF) are an established technology and are very efficient in eliminating PM. Hydrocarbons (HCs) are generally not an issue with LDD. Although quite preliminary, indications are that the California Air Resources Board (CARB) staff are considering fleet average Super Ultra-Low Emission Vehicle (SULEV) standards, equivalent to US EPA Tier 2 Bin 2, for all LD vehicles. Today, nominally 30% of new cars sold into California are at this level. Figure 1 shows a comparison of this proposal to the Euro 6 regulation (2014) and the US Tier 2 Bin 5 standard on the US Federal Test Procedure (FTP) cycle. While adopting a Euro 6 engine to US Bin 5 standards can be accomplished adding 65% more deNO_x control, the required 85% control to meet SULEV standards is a stretch for today's deNO_x technology when cold start emissions are considered. Thus, to meet these proposed regulatory directions, it is likely auto companies would need to develop California-specific engines.

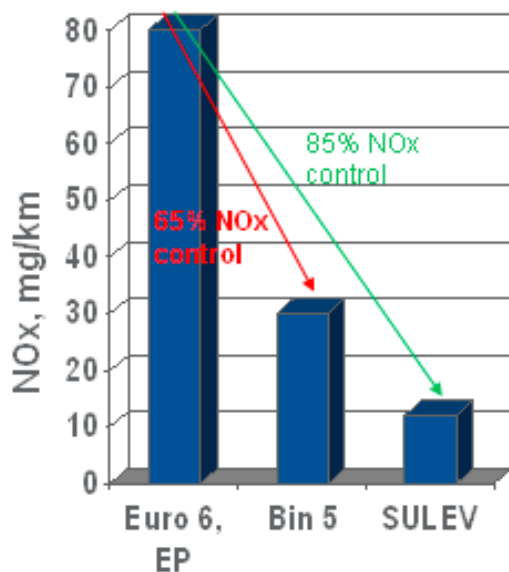


Figure 1. Euro 6 (2014) LDD NO_x regulations compared to US Tier 2 Bin 5 and California SULEV (Bin 2). Test cycle differences are not considered here.

Perhaps the more far-reaching regulatory development on LD relates to CO₂ emissions mandates. California was the first to require CO₂ (equivalent) mandates, but the US EPA declined a waiver needed for implementation. (This decision is being re-evaluated by the new EPA Administrator.) Similarly, in December 2008 the European Parliament approved CO₂ mandates for 2016 of 130 g/km on the New European Drive Cycle (NEDC), and 95 g/km in 2020. The Council of Ministers, although in agreement, still needs to formally approve these standards. Similarly, the US EPA closed a formal comment period on an Advanced Notice of Proposed

Rulemaking (ANPRM) that signaled CO₂ mandates may be forthcoming at the US national level.

Figure 2 shows a comparison of how these mandates compare with fuel economy or consumption requirements across the world, normalized to CO₂ emissions on the New European Drive Cycle (NEDC) (2). For the purposes here, the rate of change of reductions is most interesting. In both the US and Europe if all technology improvements went into fuel consumption improvement, vehicle CO₂ reductions progressed nominally 1.0 to 1.5% per year. Decisions to use technologies were based on the value proposition on returning fuel savings to the end customer. Going into the future, regulators are requiring 3 to 11% per year improvements, meaning a much faster pace of reductions than the market demanded in the past will be required. Technology additions will be treated similar to criteria emission (NO_x, PM, etc.) reduction technologies, that is, best performance relative to one another rather than being based on a customer value proposition. This is a major paradigm shift.

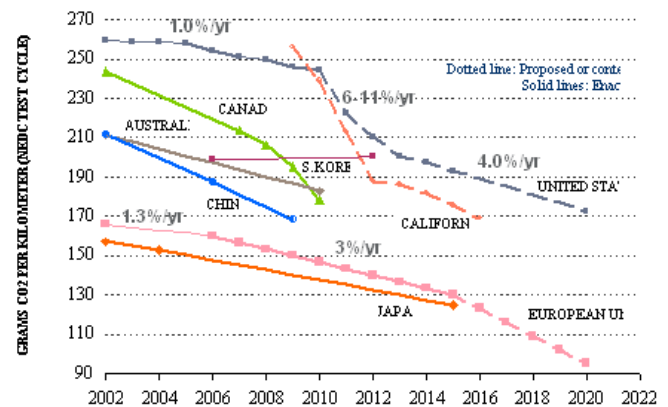


Figure 2. Comparison of worldwide fuel economy, fuel consumption, or proposed CO₂ standards, all normalized to the NEDC and adjusted for fuel mix (2).

HEAVY-DUTY

On the emerging heavy-duty regulatory front, Europe is finalizing its Euro VI regulations for the 2013 timeframe. In December 2008 the European Parliament passed onto the Council of Ministers a final proposal that should technologically harmonize the European regulations with those of the US and Japan. Key provisions are:

- European Transient Cycle (ETC) NO_x emissions of 400 mg/kW-hr vs. 260 mg/kW-hr in the US2010 regulation.
- PM emissions of 10 mg/kW-hr vs. 13 mg/kW-hr in the US2010 regulation.
- A Particle Number (PN) regulation that is based on DPF capability.
- Ammonia slip limits of 10 ppm.

A PN regulation was developed for the Euro 5b LDD regulation (2011), and its principles are now expanding into heavy duty. The European Union regulators' stated desire is to have DPFs on all these engines. The limit value is still to be determined by the European Commission, and is to be based on DPF capability. Figure 3 shows how the PN values vary with test cycle and technology using the European test protocols (3). A limit value of $\sim 10^{11}$ #/kW-hr seems reasonable, given DPF blended (10% cold and 90% hot) World Harmonized Test Cycle (WHTC) performance of $\sim 3.5 \times 10^{10}$ #/kW-hr (99.95% efficiency). Further, it seems reasonable that future engines could have engine-out emissions approaching 10^{13} #/kW-hr levels. As open filters show potential for 90% PN removal (4), tailpipe levels with such devices can approach 10^{12} #/kW-hr levels. To ensure DPFs as desired by the regulators, limit values less than 10^{12} #/kW-hr levels are thus needed, in this author's opinion.

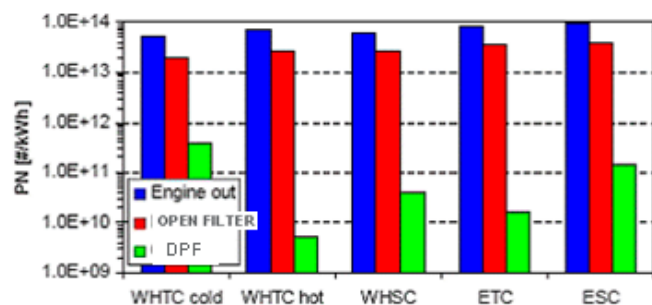


Figure 3. HDD PN emissions using different test cycles and technologies (3).

On the HD CO₂ regulatory front, it appears imminent that CO₂ regulations will also apply to HD. CARB held a HD CO₂ workshop in December 2008 exploring the possibility of using low rolling resistant tires and aerodynamic cowling beginning in 2010 for large fleets. Also, the EPA ANPRM referenced above solicited comments on HD and non-road vehicle CO₂ reductions.

Finally, US EPA and CARB On-Board Diagnostic (OBD) requirements were finalized. In place now is the rudimentary monitoring just to make sure the DPF is present and other systems are functioning. In 2010, the OEMs have to implement more demanding OBD on one engine family in each year from 2010-12, and across the board in 2013. NOx OBD is needed on all engine platforms beginning in 2010, as there are adequate sensors available today. In 2010, the DOC, deNOx, and DPF will have emission threshold warnings which tighten in 2013, shown Table 1. In other words, if emissions exceed these values, the malfunction indicator light (MIL) goes on. The pertinent NOx standard is with credits. Additionally, DPF regenerations and partial regenerations need to be monitored (no MIL warning). CARB DPF frequent regeneration monitoring is to 2X the NMHC (non-methane hydrocarbon) standard or the NOx standard + 0.2g/bhp-hr starting in MY 2013. EPA light-

duty OBD limits are 1.5X the standard for NMHC and NOx, and to alert of a catastrophic DPF failure.

CARB LD OBD limits are 3X for NMHC, 2.5X for NOx, and 4X for PM in 2010, and 1.75X for all emissions in 2013.

	2010		2013	
	EPA	CARB	EPA	CARB
NOx	Std+0.6	Std + 0.3	Std+0.3	Std + 0.2
PM	0.05	0.07	0.05	0.03 (2016)
NMHC	2.5X	2.5X	2.0X	2.0X

Table 1. Recently finalized HDD OBD standards. The values are relative to the tailpipe standards, except if a number is given. Units are g/bhp-hr.

In 2013 it is estimated that in addition to NOx sensors, PM sensors will also be needed.

Finally, the emissions of NO₂ from diesel vehicles are of increasing interest. Although no tailpipe regulations on NO₂ have been implemented or even proposed, several regions in Europe will have difficulty meeting their 2010 NO₂ immission (ambient air levels) requirements. In the US, California now requires that NO₂ comprises no more than 20% of the NOx in the tailpipe for retrofit systems.

Engine Developments

LIGHT DUTY

Regulatory, market, and fuel economy requirements are making great demands on the diesel engine. Further, advanced gasoline concepts and hybrid electric vehicles are exerting competitive technology pressures. Diesel engine developers are responding by using advanced fuel injection technologies, EGR (exhaust gas recirculation) control, advanced and two-stage turbocharging, variable valve actuation, closed loop combustion control, and advanced model-based control. Downsized prototype diesel engines (5) are now approaching 110 kW/liter specific power and 31 bar Indicated Mean Effective Pressure (IMEP). However, as shown in Figure 4, NOx emissions can increase 50% for such engines over advanced engines (80 kW/liter), but CO₂ emissions will be reduced nominally 15% in premium vehicle applications (6). Other opportunities for CO₂ savings are shown in Figure 5 (6).

Regarding advances in EGR and boost, Czarnowski, et al. (7) show that low pressure loop EGR and series turbocharging are valuable tools for achieving low engine-out NOx while still returning up to a 3% fuel savings. BMW is using variable twin series turbochargers on their US Bin 5 diesels (8), and stated that low pressure loop EGR can drop NOx 30% more and save fuel. Dual loop EGR with a single turbocharger is on the 2 liter engine of the award-winning (California Green Vehicle of the Year) Bin 5 Volkswagen Jetta (9), and can deliver 30% EGR at full load. By adding a second set of series turbochargers a

3 liter sport utility vehicle is close to attaining Euro 6 NOx standards, engine-out (10).

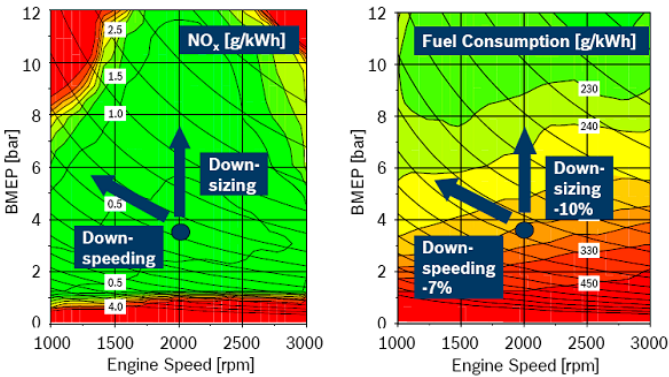


Figure 4. Downsizing and down-speeding engines can result in nominally 10 and 7% decreases in fuel consumption (right), but with ~50% increases in NOx (left). Reference 6.

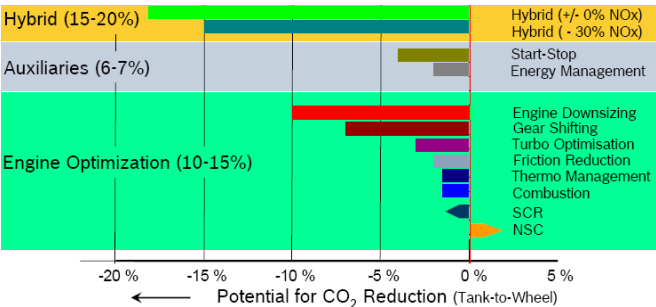


Figure 5. Relative to a Euro 4 diesel with DPF, 20 to 40% CO₂ reductions are possible with light-duty diesels. The engine can contribute 10 to 15% more reductions (6).

On the cutting edge for attaining SULEV, Cooper (11) updated a previous Tier 2 Bin 5 (engine-out) demonstration vehicle with further controls and NOx aftertreatment. Figure 6 shows the outline. The lower part of the chart shows a red region of operation, which is bordered on the top by a maximum deNOx aftertreatment efficiencies of ~80% and to the left by the best engine-out NOx levels. Notice the best fuel economies are derived by applying the cleanest engine technologies.

Heavy-Duty Engine Developments

Heavy-duty diesel engine advancements are primarily aimed at improved fuel economy, reliability, cost, and durability. As such, advancements tend to be conservative and incremental. The US 2004 regulations were generally addressed using advanced EGR and turbocharging concepts. US 2007 and Japan 2005 technologies added diesel particulate filters, while Euro IV (2005) and now Euro V (2008) regulations are largely addressed using more conventional engine technologies and SCR.

Moving on to Japan 2009 and US 2010, we will also see incremental advancements from the earlier regulatory technologies. However, as with light-duty engines, we could see some advanced combustion strategies emerge to handle low-load NOx emissions issues. Because most of the fuel in heavy-duty applications is spent under higher load regimes, engine researchers are focusing more on traditional diesel combustion hardware and strategies, and they are making significant progress.

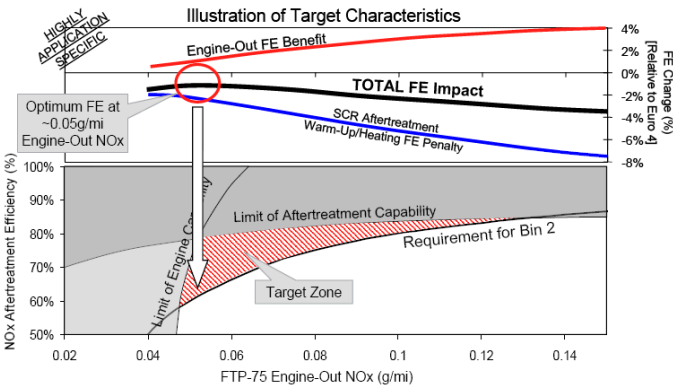


Figure 6. Summary of the challenge of SULEV for LDD (11). The red zone represents the engine and aftertreatment options and is bordered by the engine-out emissions (Bin 5) of a demonstration vehicle and the estimated limit of deNOx aftertreatment of ~80%. The best fuel economy is derived when using the cleanest engines.

Table 2 shows a summary from the literature of >300 kW HD engine technologies that might be used to attain the next wave of tailpipe regulations. These advanced engines might have 2-stage turbocharging, and will have significant EGR, >200 bar peak cylinder pressures and >2000 bar common rail fuel injection pressures.

	US2007	US2010	Euro VI	Tier 4A Non-Road w/ DPF
Turbocharging	1- and 2-stage; up to 4.5 bar	2-stage;	2-stage	1- and 2-stage
Full load EGR	25%	up to 35%	25%	~15%
Peak cylinder pressure	190-210 bar	220-250 bar	220 bar	180-210 bar
Fuel injection	2200 bar UI	2500 bar CR	>2200 bar CR	2000 bar CR

Table 2. Summary of expected HD engine technologies for the >300 kW class of engines to attain future tailpipe regulations.

Moving into the future, Stanton provides a roadmap for improving brake thermal efficiency from about 43% today to 52% by 2015 (12). Figure 7 shows some of the results. The top part of the figure shows how brake specific fuel consumption (BSFC) depends on engine