

Diesel Emission Control in Review

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ABSTRACT

This summary covers the developments from 2007 in diesel regulations, engine technology, and NO_x and PM control.

Regulatory developments are now focused on Europe, where heavy-duty regulations have been proposed for 2013. The regulations are similar in technology needs to US2010. Also, the European Commission proposed the first CO₂ emission limits of 130 g/km, which are nearly at parity to the Japanese fuel economy standards.

Engines are making very impressive progress, with clean combustion strategies in active development mainly for US light-duty application. Heavy-duty research engines are more focused on traditional approaches, and will provide numerous engine/aftertreatment options for hitting the tight US 2010 regulations.

NO_x control is centered on SCR (selective catalytic reduction) for diverse applications. Focus is on cold operation and system optimization. LNT (lean NO_x traps) durability is quantified, and performance enhanced with a sulfur trap. LNCs 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 issues with advanced combustion strategies, important interactions on NO₂ formation, and new formulations for enhanced durability.

INTRODUCTION

The field of diesel engines and emission 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. Perhaps we are not seeing the dramatic step changes in developments as in the earlier years, but nonetheless,

the field is ripe with incremental improvements to address new and old challenges. There are still well over 1000 technical papers concerning diesel engines, fuels and emissions, comparable to earlier years. Consolidating, absorbing, and summarizing all this information is a huge task, but others have recently brought the interested reader up to date (1).

As in the past (2), 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 2007. First, the regulatory issues are addressed, followed by a quick overview of engine technologies as a means of estimating the exhaust emission control requirements. Then the author will then review NO_x, PM (particulate matter), and hydrocarbon/CO control developments.

REGULATIONS

It is important to put emission control technologies in the perspective of regulations, which are the primary driver for advancements.

Most of the development of new regulations in 2007 occurred in Europe, with the finalization of the light-duty Euro 5 and 6 emissions standards, and a proposal from the Commission for Euro VI heavy-duty standards. In addition to criteria pollutant standards, the first standards on CO₂ were proposed in Europe late in the year, and are expected shortly in the US from the EPA (Environmental Protection Agency).

The US finalized their light duty, on-road, and non-road regulations several years ago, but the final locomotive and marine rule is expected shortly. California is exploring LEV3 (Low Emission Vehicle), but no formal proposals have been put forth. Japan finalized regulations on light and heavy duty vehicles a few years ago for 2009+, and has harmonized with the US and Europe on non-road applications. Other countries have adopted either the European or US protocols with time lags reflective of the relative state of their transportation sectors.

Given this, the author will focus primarily on the more pertinent developments in Europe that will impact the field of diesel emissions.

LIGHT-DUTY DIESEL

Europe finalized their light-duty criteria pollutant regulations for at least the next ~10 years (3). On greenhouse gases, the European Commission proposed mandatory standards in December 2007 yet to be considered by the Parliament and the Council of Ministers. California finalized similar regulations in 2005, but implementation is uncertain pending appeal in the courts after the US EPA denied the necessary waiver in the last quarter of 2007.

The regulations of significance on diesel passenger cars are as follows:

	Euro 5	Euro 6
Phase-in Dates	Sept 1, 2009 to Jan 1, 2011	Sept 1, 2014 to Sept 1, 2015
NOx	180 mg/km	80 mg/km
PM	5 mg/km	4.5 mg/km

The first date of implementation is for new vehicle types, and the second date is for all vehicles. In addition to these, there is a “Euro 5.5” (informal designation) PM standard of 4.5 mg/km and a P# (particle number) standard of 6X10¹¹/km that are determined using the UN/ECE PMP (Particulate Measurement Program) protocols. These are effective January 1, 2011 through January 1, 2012 for new types and all diesel vehicles, respectively.

The Japanese 2009 NOx and PM standards are numerically identical to the Euro 5 standards but are measured on a different test cycle. The US Tier 2 Bin 5 NOx standards, effective for MY2007 (model year), are nominally 30 mg/km at 80,000 km and 42 mg/km at 190,000 km. PM standards are nominally 13 mg/km for both durability requirements. (Euro 5 and 6 durability requirements are 160,000 km.)

It is expected that the Euro 5 NOx regulations will largely be met without NOx aftertreatment (4), but significant controls will be needed to sell these vehicles in all 50 states of the US. It is more likely that Euro 6 vehicles will be developed in 2009/10 leveraging early incentive programs. Some NOx aftertreatment will be required in that timeframe on the larger vehicles. To sell these vehicles in all 50 states in the US, either lean NOx traps (LNT) or selective catalytic reduction (SCR), will be applied to the lighter vehicles to achieve the additional 65% NOx control. Indeed, some European manufacturers have announced Bin 5 diesels for the US

in this timeframe using these two NOx control technologies.

CO₂

The European Commission made a formal proposal to the European Parliament and Council in December 2007 (5). It calls for an emissions limit averaging 130 g/km of CO₂ in 2012 as measured on the NEDC (New European Drive Cycle) test cycle. An additional 10 g/km reduction is to come from implementation of biofuels. The emissions limits vary according to vehicle weight, and manufacturers can pool vehicles with each other to meet the fleet average. This value compares with the Parliament’s October 2007 recommendation of a fleet average of 125 g/km in 2015, with limits being based on vehicle foot print. The Parliament also recommended directional targets of 95 g/km in 2020 and 70 g/km in 2025.

Figure 1 shows how the Commission’s CO₂ proposal compares with CO₂-equivalent fuel economy mandates in other countries, adjusted for the NEDC test cycle (6). This author added the point for the US showing the comparison with the recently passed CAFE standards (Corporate Average Fuel Economy) of 35 mpg (miles per gallon) in 2020. The European proposal is near parity with Japan, and the tightest in the world.

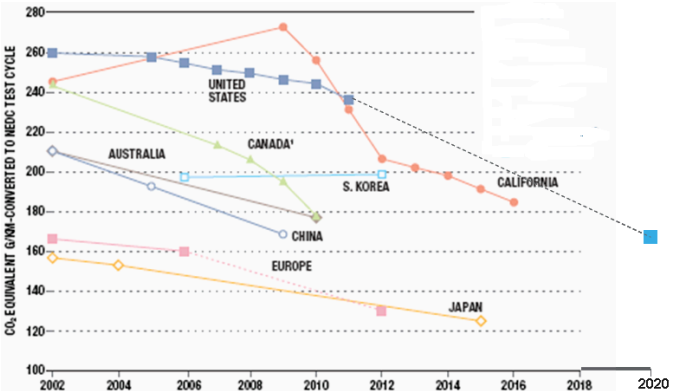


Figure 1. Cycle-adjusted equivalent CO₂ regulations derived from fuel economy standards in place throughout the world (6).

According to the Commission, the fuel economy of European cars has improved by 12.4% from 1995 to 2004. This averages 1.2% per year, and was achieved by the industry under a voluntary CO₂ reduction commitment, while still meeting market demands (increased weight, power, and performance). This was achieved largely by increasing diesel penetration from nominally 20% to about 50% in this timeframe. Moving forward, the industry will need nominally 4%/year improvements to hit the Commissions proposed target. This will be especially demanding given that significantly increased diesel penetration is not likely.

HEAVY-DUTY DIESEL

The on-road heavy-duty diesel (HDD) standards are shown in Figure 2, as are estimates of engine emissions performance. These are unchanged from the author's estimates of last year (2).

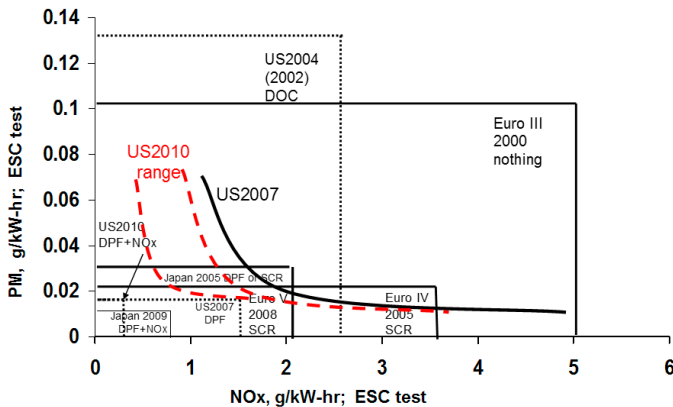


Figure 2. General comparison of on-road HDD standards in the US, Japan, and Europe. Estimated engine-out emissions for 2007 and 2010 (range) are shown. Steady-state cycle.

Japan and the US have finalized their regulations for the next five to ten years, but Europe is just beginning the process. In that regard, based on industry stakeholder surveys, the European Commission recently proposed (7) NOx standards of 400 mg/kW-hr and PM standards of 10 mg/kW-hr as measured on the current European steady state (ESC) and transient (ETC) cycles. Major stakeholders representing the truck manufacturing industry (The European Automobile Manufacturers Association, ACEA), the emissions controls industry (The Association for Emissions Control by Catalyst, AECC), and the environmental community (The International Council for Clean Transportation, ICCT) supported these levels prior to the Commission's proposal.

As in the final Euro 6 light-duty regulations, the Commission also proposed that particle numbers be limited, with the limit value to be determined later via the UN/ECE PMP process.

In 2006 the European Commission adopted the new World Harmonized Transient Cycle (WHTC) as well as the steady state counterpart. The WHTC is cooler than the European Transient Cycle, with common engines not achieving 200°C until after 500 seconds starting with a cold engine (8). The cold start weighting factor is still to be finalized. In going from the ETC to the WHTC with a 10% cold start weighting factor, ACEA is recommending a +0.3 g/kW-hr NOx adjustment factor (9), as the four engines in their test program using EGR+SCR+DPF (Exhaust Gas Recirculation, Selective Catalytic Reduction, and Diesel Particulate Filters) had WHTC-ETC differences ranging from 0.20 to 0.45 g/kW-hr NOx. The difference in NOx on one engine in an AECC test

program (10) using similar technology was about 0.1 g/kW-hr.

ENGINE TECHNOLOGIES

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, better EGR (exhaust gas recirculation) control, advanced and two-stage turbocharging, variable valve actuation, closed loop combustion control, and advanced model-based control.

Figure 3 depicts the PM/NOx trade-off curve for a light-duty diesel technology package to meet the US Tier 2 Bin 5 standards (11). A similar package was shown for Euro 6, but with a different engine calibration: 165 mg NOx /km (0.26 g/mi) vs. ~ 70 mg/km (0.12 g/mi) in the US. In both systems the deNOx efficiency is nominally 75%, but more NOx has to be removed in Europe (~85 mg/km) than in the US (40 mg/km) presumably resulting in a higher urea consumption for SCR, or a higher fuel penalty for an LNT (lean NOx trap) in Europe which is likely more than offset by the fuel consumption advantage of running at the higher NOx level.

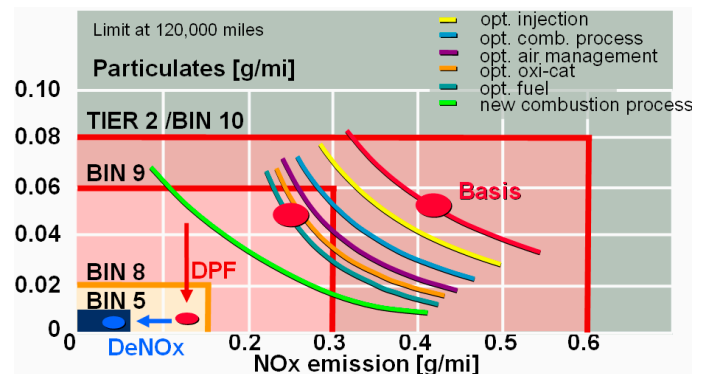


Figure 3. Emissions results for a US Tier 2 Bin 5 technology package. The same generally technologies are also applied to meet Euro 6 standards, but with a different NOx/PM calibration (11).

In that regard, Akmadza (12) presented the graph shown in Figure 4, illustrating the fuel consumption NOx trade-off curve for two advanced engine technologies. Going from a Euro 5 calibration (0.18 g/km NOx) to a Euro 6 calibration (0.080 g/km NOx) results in a nominal 7% fuel penalty. However, in another slide the author shows a "Step 3" engine technology using premixed combustion and long-loop EGR with an optional deNOx solution for "extreme" cases. The choice between additional engine technologies and NOx aftertreatment will need to balance costs and fuel economy benefits.

Sasaki and Sono, et al., (13) describe an advanced combustion engine with three modes of operation, generally characterized by injection timing and EGR levels, Figure 5. To balance between unstable combustion and soot formation regimes, very careful control of injection timing and EGR is needed. At low loads, high EGR and early injection timing is used (upper left of diagram) for low NOx and PM, but higher CO and HC (hydrocarbon). In intermediate loads, "mixture formation phasing" is used, wherein some fuel is injected into the squish zone (outside the bowl) and the rest is injected into the bowl as the piston rises. The result is that the mixture is locally leaner than if all the fuel was injected into the bowl. At higher loads, later injection and lower EGR are used for traditional diesel combustion.

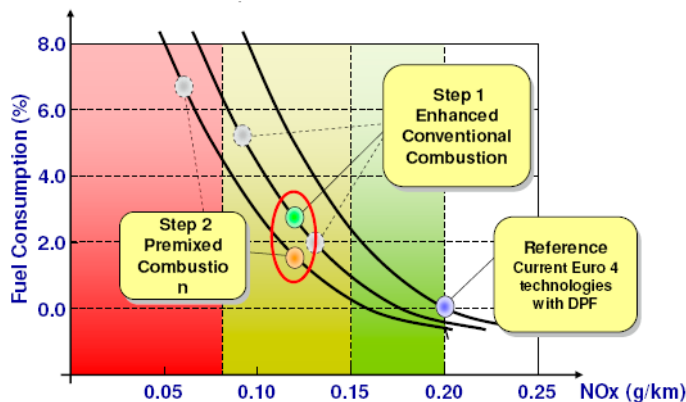


Figure 4. Fuel consumption vs. NOx trade-off curves for three different engine technologies. Approximately 7% fuel penalty is implied when going from a Euro 5 (0.180 g/km) to a Euro 6 (0.080 g/km NOx) level (12).

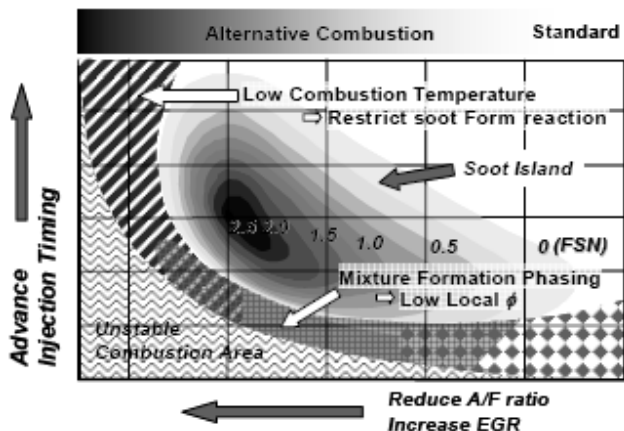


Figure 5. A three-mode advanced combustion engine is depicted on the fuel injection vs. EGR map. The strategy is to balance between high soot formation and unstable combustion at all loads (13).

Kuhn (14) gave a pathway to hitting SULEV (Super Ultra Low Emission Vehicle California certification or Tier 2 Bin 2 US Federal level). The fully pre-mixed combustion regime was extended to about 8 bar BMEP (brake mean effective pressure) or about 45% peak load. Advanced EGR handling was described to drop the specific NOx in

this regime to <0.3 g/kW-hr. Regarding fuel consumption, simulation shows that when going from a Euro 4 to a Tier 2 Bin 5 engine configuration, net fuel consumption decreases ~3.5% to accompany the 87% engine-out NOx reduction. Kuhn estimates that a modest LNT would be needed to hit SULEV, but the simulation results show a stiff 15% fuel penalty from the Bin configuration.

Ryan (15) also briefly described results from steady-state engine testing and transient testing simulation showing a pathway to SULEV with a modest LNT and Bin 5 engine-out NOx.

To wrap-up, Euro 5 regulations will require diesel particulate filters (DPFs) but no NOx aftertreatment. To meet Euro 6 early tax incentives in 2009 and beyond, NOx aftertreatment will be needed on the heavier vehicles, although deNOx aftertreatment can deliver fuel consumption benefits. US Tier 2 Bin 5 standards will be met with advanced deNOx technologies. Advanced combustion strategies, in which engine-out NOx levels over large parts of the certification cycle are very low, would require some NOx aftertreatment in the higher load regimes.

HEAVY-DUTY

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 Euro V (2008) regulations are largely addressed using more conventional engine technologies and SCR. (Some Japan 2005 applications also use SCR.)

For reference, the reader is pointed to Charlton (16) for an excellent comprehensive overview of US2007 technologies. He describes how EGR flow doubled while EGR cooler effectiveness improved from US2004 levels. Injection pressure increased 40% approaching 2000 bar at higher speeds. NOx dropped 50% and fuel consumption is down 2%, with modest PM reduction on top of it.

Moving on to Japan 2009, US2010, and Euro VI, we will also see incremental advancements from the earlier regulatory technology requirements. For Japan 2009 (0.7 g/kW-hr NOx), Shimoda (17) lists 2000 to 2400 bar injection pressures, up to 30% cooled EGR using both short and long loops, pre-mixed combustion up to 3 bar BMEP, new combustion chamber design, and nominally 50% deNOx from aftertreatment. Requirements for US2010 are similar, but 2-stage boost is added and 85% deNOx is needed (18). Peak cylinder pressures range from 220 to 250 bar. Technologies for Euro VI are similar (19), but pre-mixed combustion regimes are not described, deNOx levels of 80% are required, and cooled EGR levels of 20% are proposed.

On the cutting edge of emissions results, Emmerling (20) showed the NO_x/PM trade-off curve reproduced in Figure 6. Technologies were not described. The relatively sharp corner at low NO_x and PM levels, shown here at nominally 0.5 g/kW-hr NO_x, in combination with rapid increases in PM at lower NO_x levels and the flat character at higher NO_x levels is an interesting characteristic. If the shape duplicates itself on the BSFC/NO_x (brake specific fuel consumption) trade-off curve, as is common with most technology packages, little is gained by running at higher NO_x levels. More moderate levels of deNO_x would be needed.

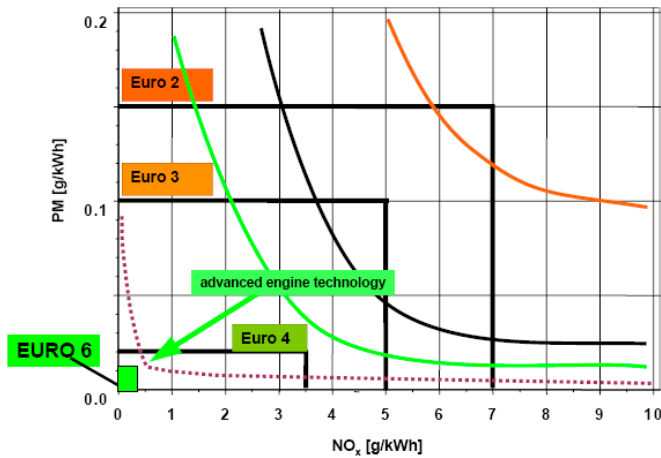


Figure 6. Cutting edge NO_x/PM trade-off curve for a HD engine with advanced technologies (20).

Regarding improving the fuel efficiency of HD engines, Schmidt (21) summarized the theoretical opportunities for gains. Improving combustion efficiency from 57 to 60% and reducing wall heat loss emerge for the greatest improvements.

Stanton (22) took the analyses one step further and summarized engine results and gave insights into the technologies. Using increased injection pressure (unspecified), multiple injections, improved EGR, improved combustion controls, pre-mixed combustion, and electric turbocharging, Stanton shows BTE (brake thermal efficiency) improving from 42.5% for US2007 engines to 45% in the lab today, to 47% projected for 2008. Along with the efficiency improvements, NO_x levels from nominally 0.22 to 0.46 g/kW-hr were shown (presumably cycle averaged), while still achieving 6 and 8% relative thermal efficiency gains.

NON-ROAD

Dreisbach (23) very nicely summarizes the technologies needed for non-road engines to attain the interim Tier 4 (2011) and final Tier 4 (2014) emission levels. The results are summarized in Figure 8. In the reference he describes the technology packages for 56-130 kW and >130 kW engines to hit the interim Tier 4 (2011) and final Tier 4 (2014) standards. The details are beyond the scope of this review. In short, EGR and filters are capable of hitting

the interim levels for all engines, but need higher injection pressures (200 bar more), 2-stage turbocharging (for the higher specific power engines) and better cooling systems than SCR-only options. He chooses SCR because high deNO_x capability (>80%) is desired and the high exhaust temperatures (>250°C) in the Non-Road Transient Cycle (NRTC) fit SCR nicely. Moving into the final Tier 4 engines, EGR, advanced cooling, and SCR are needed in all cases, except the 56 to 75 kW class where-in SCR is not needed. In almost all cases, PM regulations can be reached with partial filters, but DPFs are recommended to meet certain market or political needs. Others (24, 25) are showing only DPFs as the non-road PM-reduction technology solution. In that regard, this author notes that Switzerland is proposing a particle number emission cap for new construction equipment with engines >18 kW of 1X10¹² particles per kW-hr measured on the NRTC.

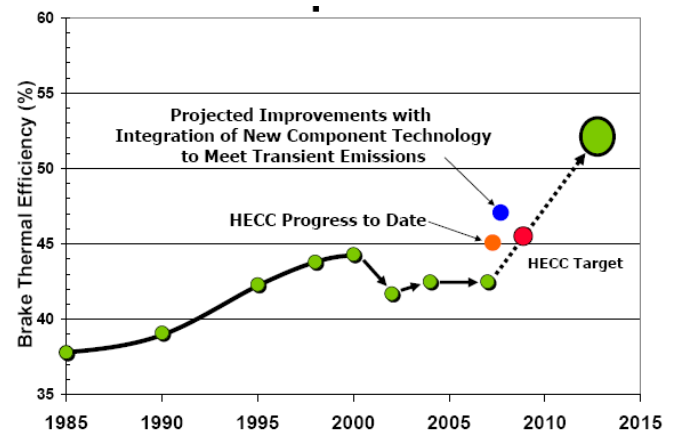


Figure 7. Progress to date on achieving high BTE engines (22).

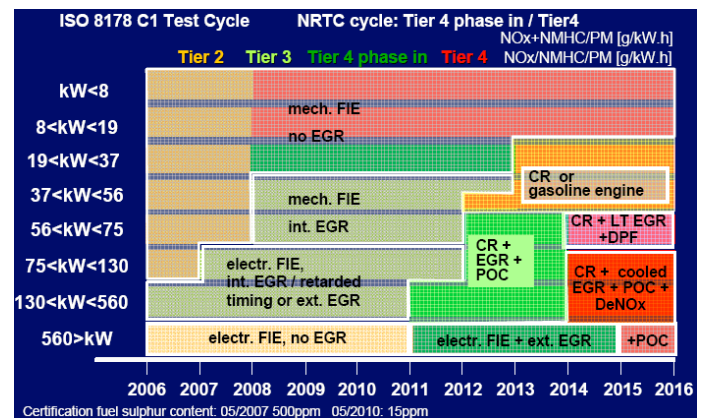


Figure 8. Non-Road technology roadmap for addressing future emissions regulations (23).

NO_x CONTROL

Given the tight NO_x emission regulations in the US and Japan, and the fuel economy impacts NO_x aftertreatment can have, NO_x control technologies will play a key role going into the future. Following is an assessment of the state-of-the-art on selective catalytic reduction (SCR), lean NO_x traps (LNT), and lean NO_x catalysts.