

Diesel Emissions in Review

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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 70% tightening of fleet average light-duty (LD) criteria emissions likely to be proposed in California for ~2016-22. CO₂ regulations in both the heavy - and light-duty sectors will also tighten and impact diesel engines and emissions, probably long into the future.

Engine technology is addressing these needs. Light-duty diesel engines are making incremental gains with combustion enhancements that allow downsizing for CO₂ savings. Heavy-duty (HD) engine show trade-offs between hardware recipes, exhaust deNO_x control, and fuel consumption.

Much has recently been reported on optimized selective catalytic reduction (SCR) systems, with many reports on improving low temperature performance with proper reductant management and new catalyst formulations. Developments on HC-based deNO_x are focused on lean NO_x traps (LNTs) and the LNT+SCR systems, wherein the LNT is calibrated to generate ammonia for use in a downstream SCR.

PM control with DPFs (diesel particulate filters) are very effective. DPF regeneration advances are reported in strategy, catalyst utilization, and substrate design. Biodiesel effects on DPF functions are becoming clearer.

Finally, diesel oxidation catalysts (DOCs) are investigated in the context of impacting NO₂ coming from a downstream

catalyzed DPF for use in an SCR system. Hydrocarbon removal from the DOC is quite important in this regard.

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 criteria pollutant standards, so efforts are accelerating to continue emissions parity with gasoline vehicles. In the HD truck market, criteria pollutant regulations will not tighten until 2013 in Europe, but the US is proposing the first CO₂ regulations for 2014. The combination of criteria pollutant and efficiency mandates will push diesel technologies in both sectors. The non-road market is implementing technologies to meet new 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 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 CO₂, NO_x, particulates, and HC/CO. It is noted that technical paper offerings in 2010 again seemed focused on two large conferences as in previous years, the 2010 SAE World Congress and the 2010 Directions in Engine Efficiency and Emissions Research (DEER) Conference, but there were more excellent papers presented at the smaller conferences this year, probably due to the improved economic situation in the industry. The developments, quantity, and quality of the work continue to be very good. Finally, as in previous

reviews, this review is not intended to be all-encompassing and comprehensive. Representative papers and presentations are chosen here that provide examples of key developments and direction.

REGULATIONS

Diesel regulatory initiatives are focused on a new set of light-duty (LD) regulations in California referred to as LEVIII (Low Emission Vehicle III), and the first-ever proposed CO₂ regulations on heavy-duty (HD) highway vehicles by the US EPA (Environmental Protection Agency).

LIGHT DUTY

The California Air Resources Board (CARB) is planning to propose new light-duty tailpipe regulations soon that will present a new challenge for light-duty diesels. The formal proposal is expected in February and finalization is expected in April of this year. The US EPA is working with CARB on the regulations, with the aim of developing a national regulation (Tier 3).

As indicated in two workshops [2, 3], they will move to a fleet average requirement of NMOG+NO_x (non-methane organic gases + nitrogen oxides) roughly equal to SULEV (Super Ultra-Low Emission Vehicle) or US Tier 2 Bin 2 levels of 30 mg/mi. This is about a 70% tightening from today's FTP cycle (Federal Test Procedure) limit value. Up 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.

Specifically, CARB is considering adding three new certification levels to help the automakers meet the SULEV fleet average requirement - two new levels between ULEV (Ultra-Low Emission Vehicle) and SULEV, named ULEV70 and ULEV50 for 70 and 50 mg/mile NMOG+NO_x; and SULEV20 to indicate 20 mg/mile NMOG+NO_x. All applicable light-duty certification levels being discussed are shown in [Figure 1](#). The two new ULEV levels bridge the relatively large gap between current ULEV and SULEV level allowing more fine-tuning of certification levels, and the SULEV20 level allows a non-zero emission offset. (Note: One ULEV50 vehicle nominally requires two SULEV20 vehicles to offset it.) CARB is also discussing dropping the PM (particulate mass) levels from a cap of 10 mg/mile today to 6 mg/mile in 2016, 3 mg/mile in 2022, and 1 mg/mile in 2025. As an alternative, CARB would allow a PN (particle number) certification of 6×10^{12} /mile for 2016, 3×10^{12} /mile in 2022, and 1×10^{12} /mile in 2025 using the European test protocol. Also worth noting is that the durability requirements are increased from 120,000 miles to 150,000 miles and the 50,000 mile emissions requirements are eliminated.

Vehicle emission category	Existing NMOG standards ^a (g/mi)	Existing NO _x standards ^a (g/mi)	Combined NMOG+NO _x standards (g/mi)	Proposed NMOG+NO _x emission standards ^b (g/mi)
LEV	0.090	0.070	0.160	0.160
ULEV	0.055	0.070	0.125	0.125
ULEV70	-	-	-	0.070
ULEV50	-	-	-	0.050
SULEV	0.020	0.010	0.030	0.030
SULEV20	-	-	-	0.020

^a These emission certification levels are for a 120,000-mile durability basis

^b These proposed emission certification levels are for a 150,000-mile durability basis

Figure 1. New certification levels being discussed by CARB for the new LEVIII regulation governing light duty vehicle emissions in the 2016-22 timeframe [2]. Indicated fleet average requirements are at the SULEV level, about a 70% tightening from today.

CARB will also be proposing new light-duty CO₂ standards for 2017-2025 as part of the LEVIII package. They are evaluating tightening between 3 and 6% per year [4]. In September 2010, the US EPA published a Joint Notice of Intent (with CARB and the National Highway Traffic Safety Administration, NHTSA) to propose light-duty greenhouse gas emissions standards within the same range and timeframe by September 30, 2011 and finalize them by July 31, 2012 [5]. A 6%/yr tightening will drop CO₂ levels by 40% relative to 2016, and bring fleet average emissions to about 148 g/mile (89 g/km) in 2025 as measured on the FTP cycle (US Federal Test Procedure). This value is nominally 100 g/km when adjusted to the New European Drive Cycle using the methodology of An [6], and compares to a level of 95 g/km in 2020 in Europe.

HEAVY DUTY

Aside from the continued wrap-up of the Euro VI heavy duty regulations comitology reported last year [1], there was little change on heavy duty criteria pollutants in 2010. India started implementing Bharat Stage IV standards (similar to Euro IV) in eleven major cities in 2010. However, sales have largely gone to Bharat III vehicles, except in Delhi where laws prohibit the practice of registering vehicles outside of the city [7]. China recently delayed the implementation of Euro IV for heavy-duty diesels one year until January 1, 2012; heavy-duty gasoline must still comply to Euro IV norms on January 1, 2011. (Euro 4 light-duty diesel regulations are delayed until July 1, 2013.) Discussions are beginning in Japan to adopt a regulation in 2016 similar to Euro VI.

The most significant regulatory initiative for 2010 came from the US EPA in the form of a proposed greenhouse gas emission standard for heavy duty engines and vehicles [8]. The proposal requires by 2017 about 20% reductions from tractors used to pull trailers, 7 to 10% reductions from vocational vehicles, and 17% from large pick-up trucks and vans (by 2017 or 2018). Except for vocational vehicles, most of these reductions come from vehicle modifications (aerodynamics, idling reduction, low rolling resistance tires),

but 3 to 5% CO₂ reductions are required from the engine relative to 2010 industry average levels by 2014, and another 2 to 4% by 2017. (In special cases, a manufacturer can use their own 2010 engines as the baseline, but only in 2014.) The regulation covers all engines installed in Class 2b (large pick-ups, utility and step vans) through Class 8b vehicles. [Figure 2](#) shows the proposed CO₂ reductions for all classes of engines. [Figure 3](#) shows the CO₂ and fuel consumption standards for engines installed on tractors (for pulling trailers). These engines are tested using the steady state test (SET), and vocational engines are tested on the transient HD FTP cycle (Federal Test Procedure). In the proposal, N₂O and methane emissions are each capped at 0.050 g/bhp-h. This level of N₂O is roughly 3% of the carbon footprint of the engine and is about 2X the 2010 capability level.

The only HD fuel consumption regulation in place now is in Japan (9). It calls for nominally 12% increases in fuel economy (km/liter) from a 2002 baseline by 2015.

GVWR CLASS	FUEL	MODEL YEARS	CO ₂ REDUCTION FROM REFERENCE CASE
HHD (8a-8b)	Diesel	2014-2016	3%
		2017+	6%
MHD (6-7) and LHD 4-5	Diesel	2014-2016	5%
		2017+	9%
	Gasoline	2016+	5%
LHD 2b-3	Gasoline	2016+	5%
	Diesel	2016+	9%

Figure 2. Proposed CO₂ reductions for 2014 and 2017 for all classes of HD engines. The reference case is the 2010 industry average for the class. Except for vocational vehicles, large reductions would be required from the vehicle. [8]

Effective 2014 Model Year		
	MHD Diesel Engine	HHD Diesel Engine
CO ₂ Standard (g/bhp-hr)	502	475
Voluntary Fuel Consumption Standard (gallon/100 bhp-hr)	4.93	4.67
Effective 2017 Model Year		
	MHD Diesel Engine	HHD Diesel Engine
CO ₂ Standard (g/bhp-hr)	487	460
Fuel Consumption (gallon/100 bhp-hr)	4.78	4.52

Figure 3. Proposed CO₂ and fuel consumption standards for engines installed on tractors. Medium heavy-duty (MHD) and heavy heavy-duty (HHD) reductions are –3% for 2014, and –3% for 2017 from a 2010 industry average baseline, as measured on the US supplemental steady- state emissions test (SET). [8]

ENGINE TECHNOLOGIES

Engine technology is evolving very rapidly, but incrementally. 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.

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 gasoline hybrid electric vehicles (HEVs). However, diesel platforms are still very attractive for meeting the emerging CO₂ regulations, in which diesels have a 20% advantage over their gasoline counterparts. Furthermore, given the high incremental cost of batteries for the incremental CO₂ benefits gained from battery electric vehicles [10], it is reasonable that the diesel engine will continue to receive interest before we see a widespread shift away from the internal combustion engine. The technology pressure is being met with increasingly sophisticated combustion designs and control on diesel engines.

To illustrate the cost-effectiveness of the diesel in meeting CO₂ regulations, Koerfer, et al. (11) compare the costs of bringing a gasoline and a diesel medium-sized Euro 5 car to compliance with the 2020 European CO₂ requirements. They consider 10 different technologies judged to be the most cost effective way for each platform to comply. In the end, the gasoline car fell 13 g CO₂/km short, despite the €670 added cost, resulting in a €1270 penalty. It would need to be hybridized to eliminate the penalty. On the other hand, at an added cost of €380, the diesel vehicle had a 5 g CO₂/km surplus.

To maintain this advantage, most of the efforts in diesel engine technology are focused on downsizing without sacrificing performance, as offered by improved combustion control. A good example is described by Tatur [12], who shows a range of technology options for meeting US EPA Tier 2 Bin 5 standards depending on vehicle size and class. Main differences are in fuel injection, boost, and NO_x aftertreatment. Larger cars will need >2000 bar piezo-electric injectors, 2-stage turbocharging, and selective catalytic reduction (SCR) NO_x control. Smaller cars can get by with 1450-1800 bar injectors, variable nozzle turbochargers, and lean NO_x traps (LNTs). Medium sized cars need a mix of these technologies. On the cutting edge, Tatur [12] updates earlier work on advancing LD diesels [13] by adding higher peak cylinder pressure (200 bar), a belt drive stop-start system, advanced cooling control, better air handling (2-stage turbocharging and EGR control), improved combustion

control strategies, and a variable swirl concept using a variable valve train. The result is lower process and cooling losses, delivering the same fuel consumption but with 10% of the NO_x as the previous design calibrated to low fuel consumption, as shown [Figure 4](#).

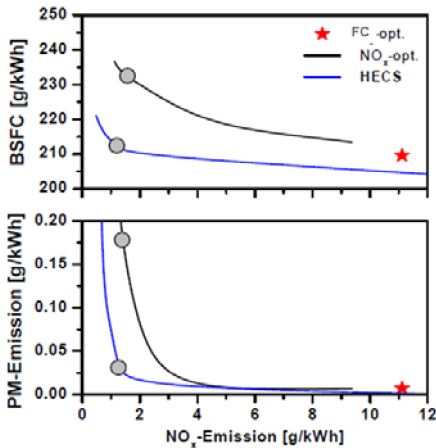


Figure 4. Advances in LD engine design result in 10% of the NO_x at roughly the same fuel consumption as an earlier advanced engine calibrated to low fuel consumption. [12]

Tomoda, et al., [14] show a decreasing trend on diesel engine compression ratio (CR) to reduce frictional losses and NO_x, but it plateaus at about 15.5:1. Lower compression ratios compromise thermodynamic efficiency but they show an optimum efficiency at 14:1. The problem is poor cold start, especially in cold ambient conditions or at high altitude. The charge does not get hot enough to burn the hydrocarbons or give smooth operation. Tomoda, et al., address these issues by redesigning the bowl, adding more holes to the injector to get more air entrainment, and increasing the number of pilot injections from three to four. With these measures, after about 100 seconds of operation at -25°C, hydrocarbon emissions from a low CR engine are half those of an engine with CR=15.7.

A very different approach beside downsizing and adding technology to meet CO₂ requirements is to de-rate the diesel to take out cost, but still keeping it attractive relative to gasoline or downsizing options. Weissbaeck, et. al, [15] argue that downsized engines with high specific power add expense and perhaps require three engines to meet diverse vehicle needs (1.0, 1.5, 2.0 liter). On the other hand, starting with a standard base engine with lower specific power (reduced friction) and taking out cost and weight through optimization, like using an integrated exhaust manifold, and adding or subtracting components, like fuel injectors, can meet mass market vehicle needs with one platform. The high displacement allows low-load operation in certification cycles, eliminating the need for NO_x aftertreatment.

Performance is reduced compared to the downsized engine, but still attractive, and CO₂ levels of <100 g /km might be attained. (In the simulated vehicle comparison, the downsized diesel with SCR attained 91 g/km CO₂.)

Diesel engines are moving into hybridization, and seeing unique synergies related to emissions that may give them a relative advantage over similar steps with gasoline engines. Cisternino evaluated a second generation mild hybrid architecture on a 1.9 liter Euro 4 engine in dynamometer testing [16]. The hybrid system (15 kW motor, 0.63 kWh battery) utilized stop-start for idle reduction and assist on starts and accelerations, and enabled energy recuperation going downhill or on decelerations. Fuel consumption is dropped 10%. CO is cut 80% and hydrocarbon (HC) drops 20% due to hotter DOC (diesel oxidation catalyst) temperatures as a result of less idling. NO_x is reduced 15% due to milder transients. The emissions reductions are unique synergies to diesel, which can result in further fuel reductions upon recalibration. When tested on a vehicle, time to accelerate from 24 to 100 km/sec drops 15% and noise and vibration decrease substantially. Similarly, upon hybridizing (25 kW motor, 1.5 kWh battery) a 1.6 liter engine, Krueger, et al. [17] realized synergies unique to the diesel engine. The low-load hybrid assist meshes well with the high-load diesel efficiencies to provide near uniform fuel consumption in urban and highway driving, giving about 20% less fuel consumption than the conventional diesel on certification test cycles. Further, CO and HC are cut 75% as a result of lower engine-out emissions and faster DOC light-off.

HEAVY DUTY

The first heavy-duty systems incorporating both diesel particulate filters (DPFs) and selective catalytic reduction (SCR) were introduced into the market in Japan in late 2009 and in the US in late 2010. Generally, the US trucks have 3 to 5% lower fuel consumption than their 2009 counterparts (no SCR), but consume upwards of about 2% urea relative to the fuel. The required NO_x levels are less than 0.2 g/bhp-h (0.27 g/kWh) as measured in certification test cycles compared to their 2009 counterparts at about 1.1 g/bhp-h (1.5 g/kWh).

A nice summary of the US 2010 large HD engine features was provided by Charlton who described the Cummins 11.9 liter engine [18]. As shown in [Figure 5](#), assuming the price of urea is 70% that of the fuel, the engine is calibrated to optimum fuel and urea consumption at about 2.5 g/bhp-h (3.3 g/kWh) NO_x, or more than 2X the 2009 level. Note that the combined fuel and urea consumption is relatively flat at NO_x levels greater than about 2.3 g/bhp-h (3.1 g/kWh). As urea has a fraction of the CO₂ emission of diesel fuel, under a tight CO₂ regulation it seems plausible to operate at higher NO_x levels without adversely affecting operating cost, yet achieve lower CO₂ emissions. This requires an SCR system that can

remove 95% of the NOx to meet current regulations. Charlton shows an average of 94.2% deNOx efficiency over a field run of 24 hours for a line haul truck using the engine.

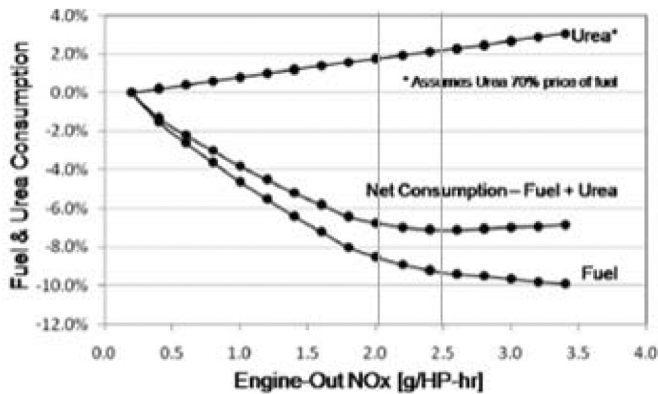


Figure 5. Fuel and urea consumption depends on engine-out NOx levels. These values are for the 2010 11.9 liter Cummins engine. The minimum “fluid consumption” level is at about 2.5 g/bhp-h NOx. [18].

In that regard, high-efficiency SCR will require less engine technology. Parche, et al., [19] and Sassen [20] make estimates of required engine hardware and operating parameters needed to meet a range of NOx levels. A summary is shown in Table 1. Regarding fuel consumption, Parche, et al., show the higher NOx calibrations using 1800 bar injection pressure have 1% lower fuel consumption than the lowest NOx calibration using 3000 bar pressure. Fuel consumption at the higher NOx calibrations is much less dependent on fuel injection pressure than at the lower NOx calibrations. Not discussed is the impact of other advanced engine designs on fuel consumption when calibrated for high NOx emissions. Stanton [21] shows continuously decreasing fuel consumption with increasing NOx emissions (up to 11 g/kWh) as more advanced engine hardware and calibration is employed. Given this, it is reasonable that tight CO₂ regulations will require both advanced engine technologies as well as highly efficient deNOx exhaust emission control.

Table 1. Estimated hardware and operating parameters to achieve designated engine-out NOx levels, according to Parche, et al. [19] and Sassen[20].

Engine-out NOx levels	Euro VI 0.4 g/kW-hr	~US2007 1.6 g/kW-hr	Euro VI - 90% deNOx ~US2010 - 94% deNOx 3.2 g/kW-hr
Fuel injection pressure, bar	3000 bar	2200 bar	1800 bar
Peak cylinder pressure	230 bar	180 bar	150 bar
EGR at full load	45%	27%	15%
Charge cooling relative to rated engine power	90%	50%	30%

An emerging issue for HD trucks with SCR is their capability to reduce NOx emissions under low-load driving when urea injection is not feasible. Ligterink, et al., [22] report that Euro V with SCR have NOx emissions 2 to 4X higher (per kg of CO₂) than trucks that primarily use engine methods, like EGR, for NOx control when driven at speeds less than about 60 km per hour (kph). At 80 kph both truck type have similar NOx emissions. Engine thermal management is one approach to managing this problem. Dollmeyer and Grana [23] use control of fuel inject and air handling parameters to increase exhaust gas temperatures more than 100C° during the idle and low-load portions of the cold FTP certification test, and reach urea injection temperatures of 200°C about 200 seconds faster than without the strategies. If air flow is reduced at any given load, exhaust temperatures will increase with little or no fuel penalty [24].

Much of the HD engine work recently reported pertains to non-road engines. Conicella [25] was one of the first to report the capability of meeting Euro 2012 Stage IIIB (or US Tier 4 interim) non-road regulations in the 56 to 130 kW engine class without aftertreatment. The engine family uses 15% cooled EGR at rated power 2000 bar common rail fuel injection with a specific spray configuration, unique piston bowl design, variable geometry turbocharging, and closed-loop combustion control with accurate control of the air:fuel ratio. The engine will need an additional ~90% deNOx control to attain 2014 standards.

Unger [26] describes non-road engine strategies for 2014 Euro Stage IV (US Tier 4 final) for multiple applications in the 56-500 kW class using a modular engine and aftertreatment approach. Figure 6 shows a summary. It is suggested that high-load applications, like agricultural tractors, use mid-level engine technologies to achieve NOx levels of about 3 to 4 g/kWh (requiring 90% deNOx and PM control) on the Non-Road Transient Cycle (NRTC), depicted as curve B in the figure. This will result in lower fuel consumption and less heat rejection. Light load applications