

Vehicular Emissions in Review

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ABSTRACT

This review paper summarizes major developments in vehicular emissions regulations and technologies (light-duty, heavy-duty, gasoline, diesel) in 2012. First, the paper covers the key regulatory developments in the field, including finalized criteria pollutant tightening in California; and in Europe, the development of real-world driving emissions (RDE) standards. The US finalized LD (light-duty) greenhouse gas (GHG) regulation for 2017-25. The paper then gives a brief, high-level overview of key developments in LD and HD engine technology, covering both gasoline and diesel. Marked improvements in engine efficiency are summarized for gasoline and diesel engines to meet both the emerging NOx and GHG regulations. HD engines are just starting to demonstrate 50% brake thermal efficiency. NOx control technologies are then summarized, including SCR (selective catalytic reduction) with ammonia, and hydrocarbon-based approaches. Emphasis is on low-temperature deNOx, durability, and cost reduction. PM (particulate matter) reduction technologies are evolving around SCR integration and the behavior of soot and ash deposits. Next, DOC (diesel oxidation catalyst) developments are summarized. They mainly involve better understanding of aging and substitution of base metals oxides for precious metal. The paper then discusses some key developments in gasoline emission controls, focusing on new coated GPF (gasoline particulate filter) understanding. Advanced three-way catalysts improve with layered coating technology, and with improved understanding on engine calibration.

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INTRODUCTION

The pressures on the automotive and heavy-duty vehicle industries are like none other in their histories. The pressures are coming from the public and regulatory agencies to decrease criteria pollutants in both the developed and especially in developing countries. Also, fuel efficiency is being aggressively regulated to reduce CO₂ emissions and decrease dependencies on petroleum fuels. And, although markets are growing rapidly in the developing countries, market and economic pressures are forcing vehicle manufacturers in the established markets to strive for the best competitive advantage. On top of this, traditional engines are beginning to be replaced by the grid-powered electric drive train. To address these forces, engine manufacturers are relying very heavily on technology developments.

This review focuses on key developments related to emissions and technologies for both diesel and gasoline engines in the automotive and heavy-duty markets. As in previous years this review paper begins where the previous review [1] of major developments in vehicular emissions and control from 2011 left off. The paper will not specifically address very large bore engines, such as locomotive and

ocean marine. However, many of the emission control technologies are transferable.

The review begins with an overview of the major regulatory developments covering criteria pollutants and CO₂. Next, the paper delves into technologies, first very generally covering light-duty gasoline and diesel engines, and then heavy-duty diesel engines. In this section, only high-level broad developments are covered with the intent of summarizing the directions and emissions challenges for the exhaust technologies. Next, the paper covers lean NOx control, diesel PM control, diesel oxidation catalysts, and closes with representative papers on gasoline emission control.

This review is not intended to be all-encompassing and comprehensive. Representative papers and presentations were chosen that provide examples of new, key developments and direction.

REGULATIONS

Most of the regulatory initiatives in 2012 were completions of proposals from 2011, which are detailed elsewhere [1]. The major vehicular regulatory initiatives of 2012 that will be summarized here include

- Finalized LEV III LD (light duty) regulation from the California Air Resources Board (CARB)
- Developments on real world driving emissions (RDE) in Europe.
- Finalized US LD greenhouse gas reduction regulation from the US Environmental Protection Agency (EPA) and CARB.
- HD regulatory developments - California OBD (onboard diagnostics) and future NOx.
- Non-Road Update
- Developments in China and India

LD Criteria Pollutants

In January 2012 CARB unanimously approved the staff proposals for their Advanced Clean Cars Program [2]. These proposals include future criteria exhaust and evaporative emission standards for light-duty and medium-duty vehicles (LEV III emission standards), post-2016 light-duty greenhouse gas (GHG) emission standards, revisions to ARB's Zero Emission Vehicle (ZEV) requirements, and requirements associated with their Clean Fuels Outlet Program. In addition to these vehicle emission standards, CARB also proposed changes for light-duty and medium-duty OBD II (On-Board Diagnostic) requirements.

The most significant highlights on LD criteria tailpipe emissions include a 75% reduction in fleet average non-methane organic gases (NMOG) and NOx, phased in from 2015 to 2025, at which time NMOG+NOx will be 30 mg/mile for both cars and light-duty trucks. The PM (particulate mass) standard is tightening 90% from 10 mg/mile down to 1 mg/mile by 2025, with an interim value of 6 mg/mile in 2017, and a phase in to 3 mg/mile occurring from 2017 to 2021. CARB will hold a technology review in 2015 to determine the feasibility of measuring to 1 mg/mile, and of moving the full implementation date to 2022. CARB mentioned in oral comments they will consider a PN (particle number) standard if the proposed PM standard is not measurable.

To ensure more representative in-use emissions, the Supplemental Federal Test Procedure (SFTP) limit values are nominally reduced 75% to 50 mg/mile NMOG+NOx on the US06 high-load cycle. The SFTP options include using a test-cycle composite emission calculation, and light-duty diesel provision (60 mg/mile NMOG+NOx in exchange for a 200,000 mile warranty on the diesel particulate filter).

Medium-duty diesel vehicles, up to 14,000 pound (6360 kg) gross vehicle weight, must now certify on the chassis dynamometer and have a new set of NMOG+NOx fleet average standards. This represents about a 50-60% tightening from current certifications [3].

One of the most significant challenges of the regulation is the durability requirements are now 150,000 miles, up from 120,000 miles in LEV II.

The US EPA recently sent the LEV III-harmonized Tier 3 proposal to the Office of Management and Budget for review.

This is the first step in the formal process to expand LEV III to the full US. Details are sketchy, but the plans are to finalize the regulation by year-end 2013 to allow it to include MY2017 vehicles. As shown in Figure 1, aside from the timing difference between Tier 3 and LEV III (2015 in LEV III), other potential differences in the proposal are E15 certification fuel for gasoline (CARB is E10), 120,000 mile durability, and a 3 mg/mile PM standard [4].

ARB LEV III	vs.	EPA Tier 3
• OAL approval complete; waiver request at EPA • SULEV fleet ave. by 2025; start in 2015; multiple bins • 150K mi durability with credit • Extend "zero" evap. to all LD & MD vehicles • E10 cert. fuel (existing 20 ppm S cap for gasoline) • Full useful life SFTP • Tighter MD exhaust standards • 3 mg/mi PM standards starting in 2017, 1 mg/mi in 2025, US06 PM standard, 2015 review of 1 mg/mi standard		• Proposal in 2012 with final rule by end of 2013 (?) • SULEV fleet ave. by 2025; start in 2017 (?); multiple bins • 120K mi durability for lighter weight vehicles • Add ARB "zero" evap. + leak detection for cert. and in-use • E15 cert. fuel; 10 ppm S ave. for gasoline • Full useful life SFTP • Tighter MD exhaust standards • 3 mg/mi PM standards starting in 2017 + US06 PM standard



Figure 1. Comparison of California LEV III regulations and a possible US EPA Tier 3 harmonized proposal, as estimated by ref. 4.

In Europe, an equally significant development is occurring on RDE (real-world driving emissions). The Parliament has requested of the Commission to develop a procedure to bring in-use emissions more in line with type approval levels [5]. One example of the discrepancy was shown in a study done by the Joint Research Center (JRC) in which in-use NOx emissions from light-duty diesels in Europe are 3 to 4X more than the certification test limit values [6]. Although in-use gasoline engine NOx is well within the certification limit, gasoline PN was shown also to have issues [7]. Of the late model vehicles test, both the port-fuel injected (PFI) and gasoline direct injected (GDI) met the PM certification levels. Although the PFI vehicles were close to the certification PN level ($6 \times 10^{11}/\text{km}$), elevated particle emissions were observed under unregulated conditions (low temperature, aggressive acceleration), due to excess over-enrichment. GDIs were found to be high PN-emitters under all driving conditions. Low temperature tests resulted in large PN increases (up to 210%) over the cold start NEDC especially for stoichiometric GDIs.

To address the regulatory challenge, the JRC is undertaking a study to evaluate the efficacy of using random dynamometer testing or PEMS (portable emissions monitoring systems) testing on the road to enforce RDE. Regulators tend to favor the PEMS approach, but there is a technology gap on robustly measuring PN on a vehicle, so it was decided to develop both methods, and phase-in to the PEMS method when suitable technology is available. Test

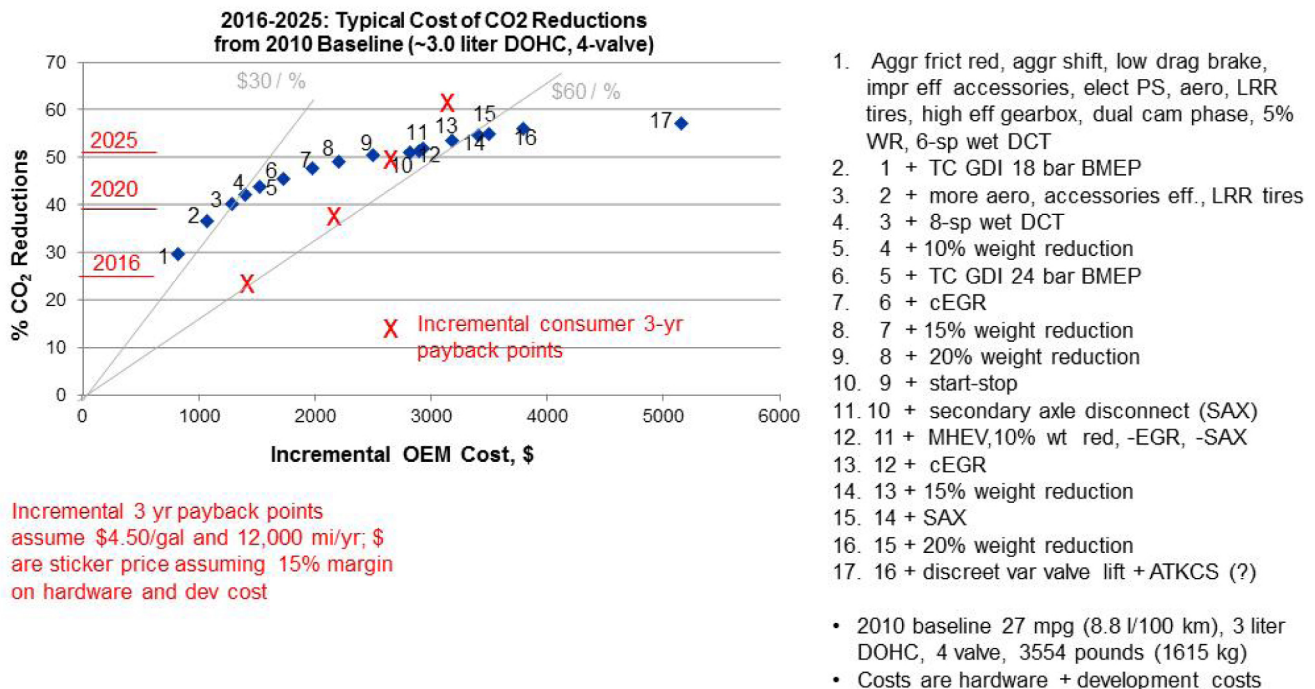


Figure 2. Cost of CO₂ reductions and payback period using US EPA data and one of four incremental technology scenarios.

procedures are expected to be recommended by late-2013 based on the study.

LD Greenhouse Gases

The US EPA and US DOT (Department of Transportation) jointly released the final 2017-2025 light-duty vehicle (LDV) fuel economy and greenhouse gas (GHG) emissions standards in August 2012 (8). They are harmonized with the CARB rules that were finalized in January 2012. CAFE (Corporate Average Fuel Economy) standards are projected to require, on an average industry fleet-wide basis for cars and trucks combined, 40.3-41.0 miles/gallon (~5.8 l/100 km) in model year 2021 and 48.7-49.7 miles/gallon (~4.8 l/100 km) in model year 2025, after all credits are considered. Actual values in real-world driving could be 20% lower. The DOT CAFE values can only be set through 2021, and will need to be formally finalized 2025 in an interim ruling no later than April 2018. The Rule requires fleet average CO₂ emissions of 163 g/mile (~98 g/km) in model year 2025, equivalent to 54.5 miles/gallon (4.3 l/100 km) if the vehicles were to meet this CO₂ standard only through fuel economy improvements. Some of the key provisions include:

- A generous CO₂/CAFE credit averaging, banking, and trading program.
- Credits for some “off-cycle” technologies that are not captured in dynamometer testing, like high-efficiency lights, start/stop, solar roof panels for battery charging, active transmission warm-up, etc.
- An incentive multiplier for electric vehicles, plug-in hybrids, CNG, and fuel cell vehicles.

• Grid-charged vehicles and fuel cell vehicles are assigned zero GHG tailpipe emissions for model years 2017-2021, within production volume caps thereafter. Upstream accounting will be used on volumes exceeding the cap in 2022+.

• For dual-fuel CNG vehicles and plug-in hybrids, EPA will use the SAE “utility factor” method to determine the assumed percentage of operation on CNG or electricity for CO₂ emissions compliance.

As part of the rulemaking package, the EPA did vehicle cost and GHG reduction estimates [9, 10]. An analysis of the data in light of the consumer payback period is shown in Figure 2. EPA used four technology pathway scenarios to reach 2025 requirements. All scenarios are close in terms of cost and GHG reductions. Figure 2 depicts the scenario using the mainly incremental technology. The three-year consumer payback calculation is based on a customer replacing a 2010 car with a 2016 car, then replacing the 2016 car with a 2020 car, and finally replacing the 2020 car with a 2025 car (12,000 miles/yr \$4.50/gal). The points (X) represent the incremental price to the consumer that provides a three-year payback. The analysis, using the EPA data and the above assumptions on fuel cost and annual miles, shows that in 2016 and 2020 the payback period is much less than three years, and in 2025 it is about three years.

Heavy-Duty Regulations

Very few regulatory developments in HD vehicles occurred in 2012. Perhaps the most significant is that CARB is exploring 75% NO_x reductions from trucks, reducing them

to 50 mg/bhp-hr from today's 200 mg/bhp-hr level [11]. The additional reductions are needed for California to meet their ozone requirements about 10 years out.

California also revised and finalized the heavy-duty OBD requirements [12], summarized in Table 1.

Table 1. California finalized HD OBD requirements.

PM				
	13MY	14MY	15MY	16MY
Original	3x (one engine) 5x (all others)	← Same	← Same	3x all engines
Revised	Detect a fault at 5x PM standards (all engines)	Phase-in 5x w/o FME* (20% of all engines)	← Same	20%: 5x Rest: 3x
		← Same	Phase-in 3x w/o FME (50% of all engines)	All 3x

NOx				
	13MY	14MY	15MY	16MY
Original	+0.2 NOx	← same	← same	← same
Revised	+0.4 NOx	20% at +0.3 Rest at +0.4	50% at +0.3 Rest at +0.4	50% at +0.3 Rest at +0.2

- Natural Gas Trucks: OBD pulled ahead from 2020 to 2018
- HD-HEV – Same engine requirements, but HEV system OBD delayed to 2014

Zwissler [13] compared these requirements with the Euro VI OBD requirements on 16 key DPF (diesel particulate filter) and SCR (selective catalytic reduction) parameters, among a total of 23 total parameters. Of the 23 parameters, 11 had significant discrepancies in requirements. For example, California requires emission threshold monitoring of DPF regeneration and DOC (diesel oxidation catalyst), while Europe requires total system failure monitoring. California requires emission threshold monitoring of urea delivery, while Europe is more stringent and requires performance monitoring.

Non-Road Developments

US Tier 4 final and Europe Stage IV (very similar regulations) will be implemented in 2014. When the regulations were finalized about 10 years ago, it was anticipated both DPFs and deNOx controls would be needed in all but the smallest engine classes. A review of recent equipment manufacturer announcements shows that if a DPF is used to meet the current Tier 4 interim or Stage IIIB standards, they will also be used along with SCR in 2014 for the next step of tightening. If SCR-only is used to meet today's regulation, the 2014 step will use similar architectures.

The European Parliament requested the Commission to begin developing the next round of Non-Road Mobile Machinery regulations (Stage V). The objective is to harmonize with the Euro VI heavy-duty truck regulations regarding PN, in-use monitoring, and comitology. It should also consider retrofit programs. The proposal is due April 2013, the deadline for consideration before the Parliamentary elections. Submission will likely slip to 2014, making it unlikely that a new emissions standard could be implemented before 2018-19.

In late-2011, Beijing announced it is implementing Euro Stage IIIB non-road regulations by January 2014 [14]. The fuel sulfur level is to be 10 ppm.

China and India

With the growth of these two important emerging markets, air quality issues are emerging. For example, more than 50 of India's largest cities exceed the country's own air quality standards, and Beijing's PM levels on several occasions have been more than 10X higher than the World Health Organization (WHO) standards. In response to populace outcries, the governments are taking action.

In December the Chinese State Council announced significant tightening of ambient air quality standards throughout China. The plan requires key regions (including the city clusters) to reduce ambient concentration of SO₂ and PM₁₀ (particulate matter <10 µm) by 10%, NO₂ by 7%, and PM_{2.5} by 5%. The plan also requires three key regions, namely Beijing-Tianjin-Hebei, Yangtze River Delta, Pearl River Delta to reduce PM_{2.5} concentration by 6% by 2015, and makes it a binding target for local government in these regions. The focus is on reduced coal burning in populated regions, but it also calls out transportation emissions regulations and clean fuel.

In that regard, recently the government announced the following plans:

- 50 ppm sulfur gasoline will be available nationwide by December 31, 2013. It is only available in major metropolitan areas now (Beijing is supposed to be at 10 ppm). 10 ppm sulfur gasoline needs to be fully phased-in throughout the country by year end 2017.
- 350 ppm sulfur diesel will be available nationwide by July 1, 2013. 50 ppm diesel will go nationwide by year end 2014. 10 ppm will be fully implemented by year end 2017.
- Work to replace all pre-2005 commercial trucks by December 31, 2015 in the three criteria regions (Beijing, Yangtze, Pearl).
- Enhanced inspection and maintenance for emissions by the end of 2013 in priority areas, and by the end of 2014 nationwide. ~\$50B (350B RMB) network needs to be built to monitor all air pollution - stationary and vehicles.
- Build up coordinated enforcement and other government programs, and research capability on air pollution. Early focus of investigations will be on construction equipment.

The plans are significant in that they provide realistic phase-in periods with binding endpoints, and place a new emphasis on compliance and enforcement.

India is embarking on the next round vehicular emissions tightening by forming a roadmapping panel to make recommendations on approach through 2025. The panel may find a study [15] by the International Council on Clean Transportation (ICCT) useful. It estimates the cost of converting the refineries in India to make 10 ppm sulfur fuels

amortized at about Rs0.50/liter (€0.71/liter, C\$3.5/gal). If Euro 6/VI regulations are implemented now, the total benefit:cost ratio is 9:1 in 2030 as shown in Figure 3.

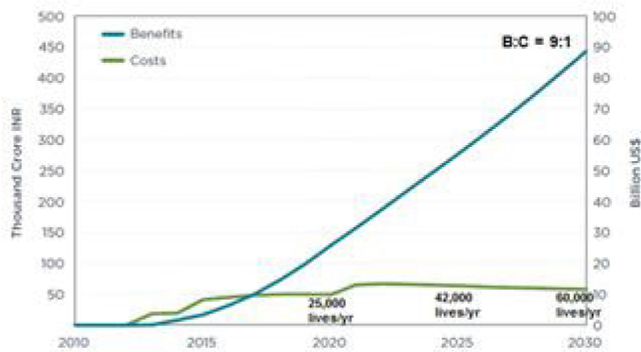


Figure 3. Societal costs and benefits of implementing Euro 6/VI LD and HD standards in India [15].

ENGINE DEVELOPMENTS

Light-Duty Engines

Light-duty engines developments have been focused for a few years on decreasing CO₂ emissions. The progress is quite impressive and costs are coming down.

Table 2. Estimated costs and CO₂ reductions for a collection of engine technologies as determined in teardown analyses. [16, 17]

Technology	Hardware Cost	% CO ₂ Reduction	\$ per %CO ₂
5-speed transmission → 6-speed	(\$108)	0.7%	----
6-speed trans → 6 speed dual clutch	(\$154)	3.7%	----
V6 N.A., MPI, 31 → I4 21, TC, GDI, 18 bar BMEP	\$113	12%	\$9.40
Dual VVT (I4) → hydraulic VVT/L (Fiat)	\$149	7%	\$21
Cylinder deactivation	\$176	6.5%	\$27
10% weight reduction	\$198	7%	\$28
I4, N.A., MPI, 2.4l → I4 1.6l TC GDI 24 bar	\$562	20%	\$28
Level 1 friction reduction	\$80	2.7%	\$30
V8, 5.4l SOHC → V6, 3.5l, 2xTC, DOHC, 24 bar	\$825	20%	\$41
Level 1 friction → Level 2 friction	\$97	2.1%	\$46
DS, TC, GDI, 24 bar → DS, TC, GDI w/ cEGR	\$210	3.6%	\$58
MPI, I4, N.A. → LDD, T2B2	\$1857	22%	\$84
10% wt red pkg → 20% wt red pkg	\$688	7%	\$98
MPI, N.A., I4 → BEV100 (w/10% wt red)	\$15, 459	100%	\$155
MPI, N.A. → PHEV40 (w/o charger, 20% wt red)	\$12,883	63%	\$204
MPI, N.A., 31 → 2.5 l, power split HEV, NiMH	\$3589	15.4%	\$233
MPI, N.A. → PHEV20 (w/o charger, 20% wt red)	\$9724	40%	\$243
Mid-SUV I4 → BAS mild HEV, I4	\$1726	6.8%	\$254

To support the LD GHG rulemaking, the US EPA did a very comprehensive tear-down analysis of late fuel efficiency technologies [16], and projected costs in a volume production mode. The CO₂ reductions were reported separately [17], and the results are combined and summarized in Table 2. Referring to Figure 2, a rough metric of consumer attractiveness might be on the order of \$60/percent CO₂

reduction. Many technologies are cheaper, but several are more than 2.5X times this amount. The focus here will be on those engine technologies that seem most attractive and, as a result, mostly incremental.

Gasoline

Gasoline engine technology is advancing surprisingly fast. Three years ago, a review in 2010 showed gasoline engine technologies delivering 15 to 20% CO₂ reductions at an incremental cost of about \$500-\$750 relative to a 6-cylinder, multiport-fuel injected engine [18]. A year ago, published gasoline engine pathways to the EU 2020 CO₂ goal of 95 g/km required mild hybridization [1], and engine-only reductions were approaching 20-25% at a cost of ~\$800 [19]. Common themes are direct injection with turbo-charging, cooled EGR (exhaust gas recirculation), variable valve timing, thermal management, stop-start systems, and significant downsizing.

In 2012, a demonstration vehicle with a downsized GDI engine and mild-hybrid system (using an ultra-capacitor) delivered 45% CO₂ reductions at an estimated cost (mine) of \$750 [20], relative to a similar baseline as the earlier studies. Figure 4 shows the concept. Energy from an electric turbo-compounder (and braking) is stored in an ultra-capacitor. The stored energy is used by a supercharger and starter generator. (Mild hybridization is used, but the costs are much lower than others, see Table 2 last line, and the energy is mainly used for combustion optimization.) About 10% of the improvements came from reduced friction, improved transmission, and improved control.

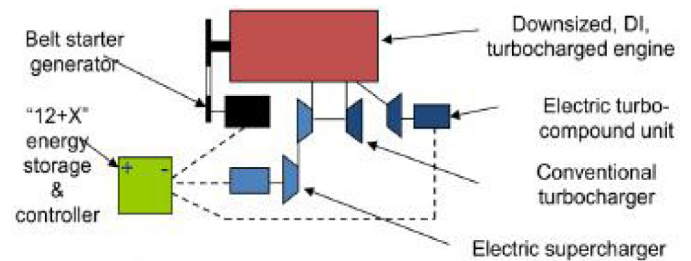


Figure 4. Schematic of a highly efficient gasoline engine concept that delivers 45% CO₂ reductions for the MPI naturally aspirated engine baseline. [18]

Perhaps the most common approach to gasoline CO₂ reductions is the use of direct fuel injection (GDI). The most significant emission trade-off is a tendency to form fine particles. Engines can be designed to meet the 2017 Euro 6c PN emissions regulations of 6×10¹¹/km in certification testing, and even in real-world driving conditions. Winkler [21] described the use of split injections and timing, injection pressure, and internal EGR for dropping cold start and warm emissions by 80 to 90% and hot emissions by 60%. However, fuel penalties ranged from 0 to 5%. Similarly, Walther [22]

dropped PN emissions 97%, mostly with advanced injector design, but with a 1-2% fuel penalty.

Fraidl [23] showed that minor perturbations can cause the PN emissions to increase, perhaps 10X. Engine deposits are especially troublesome and suspect. Figure 5 illustrates the issue, wherein a fuel injector with a deposit had more than 2.5X more PN emission than an injector after cleaning. Examples were made of allowable pump fuels in Europe (1.7X increase), slightly misaligned injectors (1.8 to 5X), and 30 minute idling time (10X).

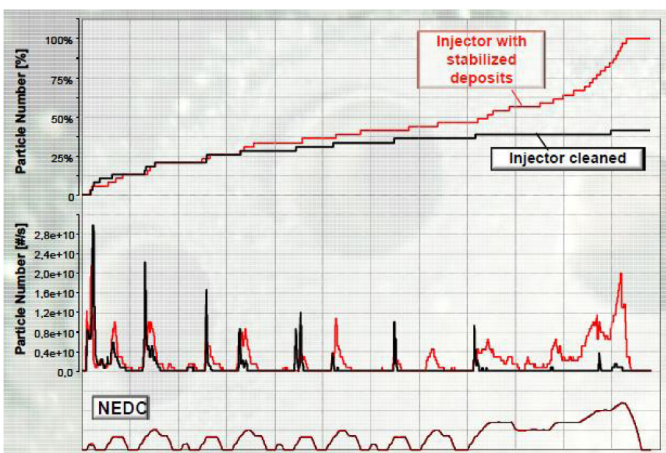


Figure 5. PN emissions are strongly affected by deposits inside the cylinder. Other effects are injector misalignment, pump fuel variations, and idling time. [23]

Cooled EGR is a technology that has been discussed for several years as a CO₂ reduction technology. Alger reported [24] on an extension of this to a technology called “dedicated EGR”, wherein all the exhaust from one cylinder goes back into the engine with the air (25% constant EGR with a 4-cylinder engine). This allows that cylinder to run rich, with the remaining cylinders adjusting to maintain stoichiometry for the catalytic converter. This, in turn, generates hydrogen which helps combustion, minimizes knock tendency, and reduces emissions. Fuel consumption dropped 12 to 15%, and the brake thermal efficiency (BTE) is about 42%, similar to today's LD diesel engines. The technology is going commercial in 2018 [25].

Diesel

Diesel engines are also improving, albeit, perhaps not at the same pace as gasoline engines. Tomazic and Nanjundaswamy provided an overview of diesel engine directions [26]. Relative to Euro 4 engines, current leading engines are delivering 17% lower fuel consumption with 67% lower NO_x (Euro 6 engine-out, 1700 kg car), with better performance. Emerging engines will have higher specific power (105 kW/liter vs. 80-90 kW/liter), using higher peak cylinder pressure (220 bar vs. 180 bar), higher injection pressure (2500 bar vs. 2000 bar), lower friction, and better

auxiliary systems design. The vehicles will have -95% NO_x emissions vs. Euro 6 with advanced emission control design.

Similarly, McCartney, et al. [27] describe developments on downsizing a Euro 5 vehicle in the E-category 3 liter V6 engine with a 2.2 liter engine. They report ~17% reductions with combustion upgrades and a stop-start system, but also use oil and water thermal management to achieve an additional 8% measured fuel consumption reduction. They are expecting another 10-12% reduction from better air management, calibration, parasitic reduction, and fuel injection, bringing total expected reductions to 30% vs. the Euro 5 baseline.

Ruth [28] took a somewhat different approach to diesel engine improvements as part of a US Department of Energy program to replace a 5.6 liter V8 gasoline engine with a 2.8 liter diesel engine in a pick-up truck demonstration. They spent more than 15,000 hours analyzing and optimizing the structural design of the engine. This, plus calibration and combustion design [29], led to an engine that is 63 kg lighter than the gasoline engine (same mass specific power), delivers the same torque, and has 25% less fuel consumption. The team is also achieving LEVIII emissions.

Another LEVIII approach was reported by Balland, et al, [30]. The most significant challenge for SCR and other deNO_x systems is in reducing high-load NO_x. They show that a standard diesel oxidation catalyst (DOC) can efficiently remove NO_x if run rich or at stoichiometry. Given this, they use tight control of EGR, the turbocharger, and other engine parameters to run the engine accordingly during accelerations. This “air-based control” approach, similar to that of gasoline engines, puts much of the high-flux deNO_x burden on the DOC. The strategy is part of cold-start thermal management, as exhaust temperatures increase in this mode of operation.

Finally, Mazda is signaling a 2014 introduction of a full size car with a 2.2 liter advanced diesel engine that achieves US EPA Tier 2 Bin 5 NO_x levels (7 mg/mile, 4.2 mg/km) without NO_x aftertreatment [31, 32]. Such a design would nominally need 75% NO_x and hydrocarbon reductions to achieve the LEVIII fleet average emissions requirements. The technology [33] delivers 20% lower fuel consumption versus their current diesel version, and is based on a 14:1 compression ratio. The cold start is managed with strong glow plugs, variable valves to enhance exhaust scavenging, two-stage turbocharging, and an egg-shaped combustion chamber design and calibration to minimize diffusion flame combustion.

Contrary to HD applications, wherein deNO_x improvements are now being pushed further to their limits to reduce fuel consumption, modern light-duty diesel engines do not have as strong a relationship between NO_x and fuel consumption in their typical low load operation range. In the US, most of the available deNO_x efficiency will be needed to meet the LEVIII LD NO_x regulations. In Europe, engine technologies could meet the NO_x regulations without aftertreatment in all but the heaviest vehicles, but emission