

Vehicular Emissions in Review

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ABSTRACT

The review paper summarizes major developments in vehicular emissions regulations and technologies in 2013. First, the paper covers the key regulatory developments in the field, including proposed light-duty (LD) criteria pollutant tightening in the US; and in Europe, the continuing developments towards real-world driving emissions (RDE) standards. Significant shifts are occurring in China and India in addressing their severe air quality problems. The paper then gives a brief, high-level overview of key developments in fuels. Projections are that we are in the early stages of oil supply stability, which could stabilize fuel prices. LD and HD (heavy-duty) engine technology continues showing marked improvements in engine efficiency. Key developments are summarized for gasoline and diesel engines to meet both the emerging NO_x and GHG regulations. HD engines are or will soon be demonstrating 50% brake thermal efficiency using common approaches. NO_x control technologies are then summarized, including SCR (selective catalytic reduction) systems and SCR filter developments. Emphasis is on low-temperature deNO_x and integration of components and control. Diesel PM (particulate matter) reduction technologies are evolving around the behavior of ash deposits and SCR integration. Filters for direct injection gasoline applications are developing very rapidly, and in some cases the back pressure, light-off characteristics, and emissions reductions are very similar to standard three way catalysts (TWCs). Oxidation catalysts mainly involve developments towards stubborn problems, like low-temperature performance with exhaust with high hydrocarbon and CO, and methane oxidation. Finally, the paper discusses some key developments in gasoline gaseous emission control, focusing on matching engine calibration with emissions system characteristics; and on lean burn gasoline emissions control.

CITATION: Johnson, T., "Vehicular Emissions in Review," *SAE Int. J. Engines* 7(3):2014, doi:10.4271/2014-01-1491.

INTRODUCTION

The vehicle industry is faced with very challenging and diverse emissions requirements. In addition to the new cutting-edge criteria pollutant regulations being phased-in starting in 2015 in California, large developing countries like China and Brazil are moving forward with their own regulations. The range of allowable emissions in major markets will be more than an order of magnitude. Adding to the challenge are the various fuel consumption or greenhouse gas regulations, fuel quality differences, and very-different market requirements. The technology to help meet these diverse emissions requirements is developing very quickly, and a review of these new developments might be useful to those with an interest.

This paper focuses on key developments in 2013 related to emissions and technologies for both diesel and gasoline engines in the automotive and heavy-duty markets. As in reviews from previous years [1], this paper begins with an overview of the major regulatory developments covering criteria pollutants and CO₂. As the fuels market is changing more now than in decades, and fuels can have major impacts on engine and emissions control, a high-level review of fuel trends is added. This sets the stage for a review of engine

technologies, starting with light-duty gasoline and diesel engines, and then heavy-duty diesel engines. In this section, only broad developments are covered with the intent of summarizing the directions and emissions challenges for exhaust technologies. Next, the paper covers lean NO_x control, oxidation catalysts, diesel and gasoline PM filters, 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

There were not many major regulatory initiatives in 2013, but mainly continuous progress on several large programs. Those covered here are:

- US EPA (Environmental Protection Agency) light-duty Tier 3 emissions.
- European light-duty Real-Driving Emissions (RDE)
- Developments in China

- Other - India Roadmap, California HD Low-NOx program, Europe Non-Road, International Maritime Organization ship NOx delay

US Light-Duty Tier 3 Proposal

The proposed US Tier 3 regulations [2] closely follow the California LEV III tailpipe regulations that were finalized in January 2012 [3]. Following are the general features of the proposal:

- Starts in model year 2017-18 for cars <6000 pound (one year later for larger cars) and is fully phased-in by 2025.
- Eventual harmonization of passenger car and light-duty truck standards to 30 mg/mile combined non-methane organic gases (NMOG) plus NOx, nominally 80% tighter than Tier 2 Bin 5 (fleet average).
- 5 certification levels: 20 to 160 mg/mile NMOG+NOx.
- 3 mg/mile FTP PM (particulate matter) standard; 10 and 20 mg/mi on the US06 drive cycle for smaller and larger cars, respectively
- 150,000 mile emissions durability by 2020; 120,000 mile durability option for smaller classes, but with a 15% tighter emission standard
- Fuel enrichment is limited to the leanest mixture that achieves the best torque (no enrichment for cooling the exhaust)
- MDV (medium duty vehicles; 8500-14,000 lbs.) must chassis certify. Fleet average 147 & 278 mg/mile NMOG+NOx (higher value for >10,000 lbs. gross vehicle weight); 7 certification levels: 200 to 400 mg/mile NMOG+NOx; 8-10 mg/mile PM on the FTP (Federal Test Procedure) cycle; 7-10 mg/mile Supplemental FTP
- E15 (15% ethanol in gasoline) certification fuel, 10 ppm maximum sulfur; 87 octane, RVP (Reed Vapor Pressure) 10 psi

Major differences between the Tier 3 proposal and LEVIII are: LEVIII PM standard drops to 1 mg/mile in 2025, subject to review in 2015; LEVIII starts with model year 2015; and LEVIII uses E10 certification fuel with 20 ppm maximum sulfur.

Currently, the Office of Management and Budget (OMB in the White House) is evaluating the regulation and needs to approve the final version before it is done.

Europe RDE Regulatory Developments

In Europe, the European Commission has been moving forward with developing the Real-Driving Emissions (RDE) supplement to the automobile type approval certification procedure. The primary purposes of the regulation are to better match the NOx emissions from diesels, and PN (particle number) emissions from direct-injection gasoline cars to those measured in certification testing. These two emissions have been problematic. For example, despite European diesel NOx emissions being cut 60%, real emissions have not changed

much in 15 years [4]. Depending on driving conditions, NOx emissions can be multiples higher than measured on the test cycle - averaging about 3X in rural and urban conditions, and 2X on the motorway for six Euro 5 diesels [5]. Similarly, in one study, a Euro 6 gasoline direct injection (GDI) car had about 2X higher PN emissions on the autobahn versus on the NEDC [6]. In another study [7] two Euro 6 GDI cars had nearly 10X higher PN emissions versus the NEDC at 130 kph (km per hour).

As such, the Commission is proposing [4] to implement RDE comitology measurements using portable emissions monitoring systems (PEMS) for gaseous pollutants, without mandatory emission limits but with recording of the results in the Certificate of Conformity, by December 2014. It is similar for PN but they propose implementation as soon as possible but no later than September 2017. Mandatory not-to-exceed (NTE) emission limits for both gaseous and PN emissions would be established by mid-2015, and then be introduced from 1 September 2017/18 for all new type approvals/new vehicles.

The lead RDE approach by the Commission for the GDI PN is to use PEMS in on-road driving of cars. PEMS for PN measurements have made much recent progress. Figure 1 shows the correlation to be quite good between PN PEMS and the PMP (particle measurement protocol) over a range of PN emissions [8]. Others have shown excellent correlation between PEMS and laboratory equipment for measuring PN in a variety of exhaust streams [9]. As a back-up plan in case PN PEMS is not satisfactory, the Commission is also developing a random drive cycle methodology that can be conducted in a dynamometer laboratory.

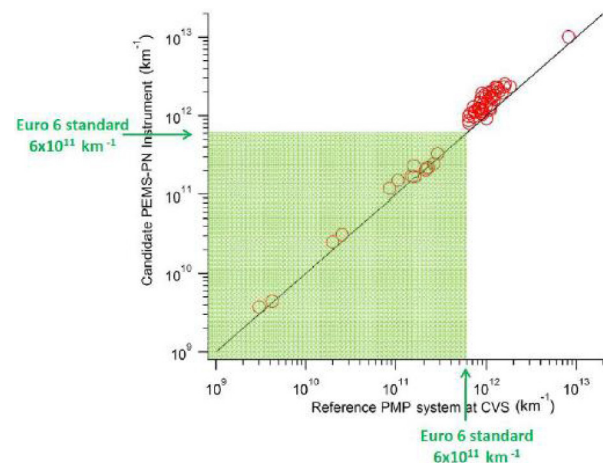


Figure 1. Correlation between PN PEMS measurements on a vehicle and dynamometer testing using laboratory instruments and the PMP protocol [8].

The RDE developments are expected to drive advanced NOx emissions controls for light-duty diesels and gasoline particulate filters (GPFs) for GDI engines. A Euro 6 car with SCR (selective catalytic reduction) had about half of the NOx emissions in urban, rural, and motorway testing than similar Euro 4 and Euro 5 cars [10]. However, the RDE NOx emissions were the second highest of all seven cars tested, and the RDE NOx

emissions were still 2 to 4X higher than on the NEDC. In other testing [7], four SCR cars had on average about 30% lower NOx emissions in high-load driving versus eight cars with a lean NOx trap (LNT). One D-segment Euro 6 car without NOx aftertreatment had NOx emissions on the WLTC (World-harmonized Light-duty Test Cycle) that were 3X those of a SCR car or an LNT car. For cars with SCR, urea consumption is expected to go up about 50% from current Euro 6 levels to meet future RDE requirements. Instead of increasing tank size to ~40 liters, the fill interval will decrease from 30,000 km to 8-10,000 km and tank size will drop from 20-30 liters down to 8-15 liters [11, 12].

The need for GPFs to meet RDE PN standards will depend on vehicle segment, timing, and RDE limit value. One study [13] measured random-cycle RDE PN emissions that were 2X higher than allowed on the NEDC in 2017 (limit of 6×10^{11} particles per km) using a C-segment vehicle that had NEDC PN emissions half the 2017 requirement. Depending on test procedures, the RDE PN emissions might be 4X the NEDC limit value.

China

World-wide news on poor air quality in Chinese cities was quite common in 2013. Citizens are watching ambient PM_{2.5} (mass concentration of particles $<2.5 \mu\text{m}$) concentrations as they watch the weather. As such, experts are seeing more movement now on air quality initiatives in China than in the past [14]. For example, senior leaders at the highest levels are concerned. Local officials now have ambitious ambient air quality goals, and much air quality data are public. Further, the public is more aware of the adverse health impacts of air pollution. Importantly, the scientific and technical experts are now much more engaged at all policy levels. And, the international community is involved in unprecedented ways. Not only are leading countries offering support, but the World Bank is increasingly active, and the United Nations Environment Program (UNEP) is giving priority to China. Climate change is also coming more to the forefront, and this is leading to awareness on the need for a more coordinated air quality policy.

These high-level movements are resulting in actions on vehicular emissions:

1. The State Council (top of the government) stepped in and laid out a clean fuels roadmap for the country. Now in place is a plan that will require gasoline and diesel fuels with a maximum of 50 ppm sulfur by the end of 2014, and 10 ppm sulfur by the end of 2017. In line with this, the government announced China 5 (similar to Euro 5) light-duty tailpipe regulations effective January 1, 2018. Major regions and cities have an even more aggressive schedule, requiring 10 ppm sulfur fuels by 2015. Beijing is already has 10 ppm sulfur fuel for both gasoline and diesel.
2. The detailed specification for China 5 gasoline has recently been issued for January 1, 2018, resolving the final

technical hurdle to mandatory implementation of this fuel. Of significant note, maximum allowable manganese octane enhancer is dropped from 8 to 2 mg/liter. Light-duty China 5 standards will be adopted with the same timing, and they are very similar to Euro 5.

3. Beijing is continuing its lead to implement emissions standards. Only China V (like Euro V) trucks and buses with DPFs can be sold in Beijing after January 1, 2015. On light-duty, Beijing is considering a move to California or US EPA standards instead of the Euro 6 requirements in 2016, because Euro 6 does not tighten gasoline gaseous emissions enough from Euro 5 levels. (Europe is much tighter on particulates.) This could place China on a potential pathway toward the significantly more stringent gaseous standards of the US.
4. China is now committed to a very aggressive scrappage program intended to remove all pre-2000 model year cars and all pre-2005 diesel vehicles from China's road by 2017 (2015 in the key regions). This will be very difficult, but the national and local governments are pursuing various tools of implementation. If China succeeds, it could be a model for other countries that have problems with older vehicles.

Other Regulatory Developments

In India, a committee of senior stakeholders is recommending a fuel and vehicular emissions plan for the next 10 years or more. Thirteen major cities currently have Bharat Standards IV (BS IV), similar to Euro IV heavy-duty and Euro 4 light-duty standards, with the rest of the country at BS III. The recommendations are due in early 2014, but in a recent interview [15], the committee's chairman said it is set to recommend BS IV+ light- and heavy-duty standards country wide by 2017 with 40 ppm sulfur fuels (50 ppm sulfur currently required in current 13 cities); and BS V standards by 2022 with 10 ppm sulfur fuel.

In other emerging regulatory developments, the European Commission is developing the Stage V Non-Road Mobile Machinery (NRMM) regulations [16]. It will likely not be implemented before 2020. The Commission appears to be favoring expanding the regulation to smaller ($<19 \text{ kW}$) and larger ($>560 \text{ kW}$) engines, dropping the PM standard by 40% to 15 mg/kW-hr, adding a PN limit, harmonizing comitology with the highway sector, and perhaps dropping NOx further. In a stakeholder survey, the adopting the PN standard and expanding the range of engines were strongly supported.

A key part of the Commission's NRMM initiatives is to improve in-use conformity. In this regard the framework to help screen in-use engines for further testing is described [17]. Figure 2 shows the principle. The work-based moving window approach will be used to determine emissions, similar to Euro VI for trucks. Windows with less than 20% average work are excluded. Figure 2 shows an example of a work-based window with the operating portions outlined that will be included in emissions measurements. Numbered portions are excluded or included because:

1. Exclude periods <10% power and longer than 2 min.
2. Excluded events shorter than 2 min are merged with surrounding idles >2 min.
3. Exclude first period of stability after >2 min idle until 250°C is reached.
4. Include last 2 min of a working period.

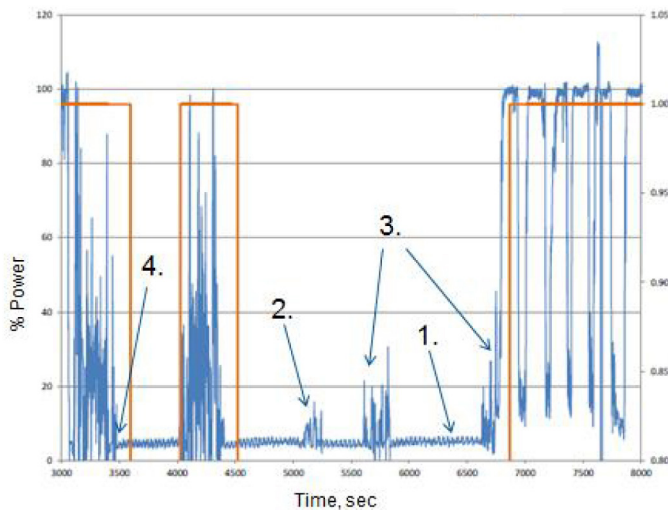


Figure 2. Examples of exclusions and inclusions for work-based window averaging of emissions from in-use non-road equipment. See the text for numbered descriptions [17].

On emerging regulations, California nominally needs another 80% NO_x reductions to meet 2023 ambient air quality ozone standards in some regions. They are looking to the HD truck sector for more reductions from the US 2010 emissions levels. In that regard, California is sponsoring a technology program to demonstrate 0.020 g/bhp-hr (0.026 g/kW-hr) NO_x on the HD FTP (Federal Test Procedure; US HD transient test). The Manufacturers of Emissions Control Association (MECA) will be contributing emissions systems. Southwest Research Institute (SwRI) will be conducting the tests on two engines - a 13 liter diesel and an 11 liter natural gas. For the diesel engine, nominally 99.3% blended cold- and hot- start NO_x reductions will be needed on aged parts. Testing is scheduled to be completed by the end of 2015.

Finally, the International Maritime Organization (IMO) is proposing to delay the implementation of Tier 3 NO_x standards from 2016 to 2022 for ships operating in the US Emissions Control Areas [18]. The regulations would have dropped the NO_x levels for ships made after January 2016 about 75% down to 2.0 to 3.4 g/kW-hr. The ruling will be reviewed for finalization in a March 2014 meeting. Options for meeting the standards are SCR (selective catalytic reduction), EGR (exhaust gas recirculation), and partial or full switching to natural gas [19]. Several hundred ships use SCR today, but only one manufacturer uses EGR.

Regulatory Summary

California finalized the LEV_{III} LD emissions standards in January 2012, and the US EPA is now finalizing their approach, calling for nominally a 75% reduction in NMOG+NO_x, down to 30 mg/mile combined. Europe is also tightening down on LD diesel NO_x and GDI PN, but using the RDE (Real Driving Emissions) model of putting vehicles on the road and measuring emissions as part of the certification procedure. China and India both have severe air quality problems in which vehicular emissions are significant part. China is implementing and appears to be very serious. India is putting together a fuel and vehicle technology roadmap through about 2025. Europe is moving to tighten non-road emissions, wherein expansion of the regulation into smaller and larger engines, and harmonization with HD truck test methods and regulations are the direction. Finally, California is investigating the feasibility of tightening HD truck NO_x regulations down to 0.020 g/bhp-hr, and a test program is in place to look at it.

FUELS

There are several recent developments that are highlighted here:

- Long term trends in oil production could affect fuel pricing for the next 15 to 20 years
- Transportation fuel demand will shift from gasoline to diesel
- Natural gas production is significantly increasing, driving interest in natural gas vehicles
- Fuel quality can significantly impact emissions

Oil Production and Transportation Fuel Trends

New oil extraction technology is impacting the oil markets in the next decade or two. Deep water exploration has opened up large reserves, particularly off Brazil; and hydraulic fracturing technology (called "fracking") is starting to produce light crudes from oil shale.

The International Energy Agency (IEA), which advises governments around the world on energy policy, predicts [20] that of the new net growth in oil supply of about 8 million barrels per day through 2025 (8-9% growth), 80% will equally come from Brazil, shale oil, and bitumen (Canada oil sands). This growth generally comes from the Americas [21], and conventional oil production is predicted to decline [22]. The Americas will surpass the Middle East in oil production in a few years [21].

Not only will this new supply of oil result in better matching of supply and demand, but it will help to stabilize the oil markets. Figure 3 shows the IEA's projections [23] of oil production and oil price through 2035 in three different scenarios. In the

Current Policies Scenario, which is a snapshot of today's policies, oil price increases about 20% through 2035. In the New Policies Scenario, which is based on new policies that are coming but not yet implemented, the price stabilizes and increases little from today. In the most aggressive 450 Scenario, wherein policies are enacted to maintain atmospheric CO₂ concentrations at 450ppm, prices decline 20%.

The stabilizing of oil supply and therefore prices could have a big impact on future direction of engine efficiency and GHG (greenhouse gas) reductions, as this could take out a strong market driver for reducing fuel consumption in the absence changes in fuel tax policy.

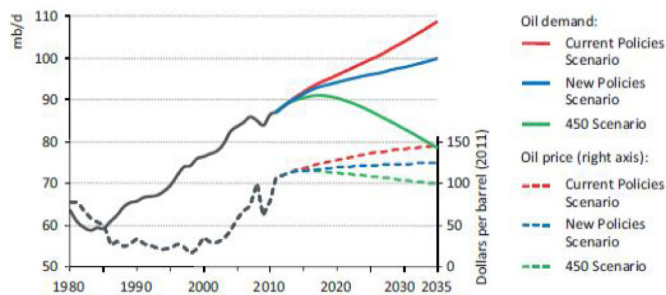


Figure 3. IEA projection of oil production and prices for three different scenarios (see text). Oil prices could stabilize in the next two decade [23].

Shifts in Transportation Fuel Type

In general, the light-duty transportation fuel is gasoline and the heavy-duty fuel is distillate (like diesel). Although the number of automotive VMT (vehicle miles travelled) in the world will increase, OECD (Organization of Economic Cooperation and Development; generally North America, Europe, and developed Asian countries) gasoline demand is now dropping and total worldwide light-duty fuel demand is projected to drop or flatten after about 2020 [22]. This is mainly due to fuel consumption improvements in cars and to a lesser degree, ethanol substitution for gasoline. At the same time, distillate demand is increasing because it is used to move freight, and this is strongly tied to economic growth. The net result is a change in the distillate to gasoline demand ratio from about 1.5 today to 2.0 in the 2025 to 2030 timeframe, after which it accelerates rapidly to 3.8 in 2050 [24]. This could stress refineries, along with an over-capacity build expected in the developing countries [20]. The net impact is a trend towards diesel fuel prices increasing relative to gasoline prices. This could shift freight and other high-distillate-consuming applications (like mining) away from diesel into natural gas and biodiesel, [Figure 4](#) [22]. Indeed, much development work is going into shifting ships, locomotive, and mining applications to liquid natural gas [25, 26, 27].

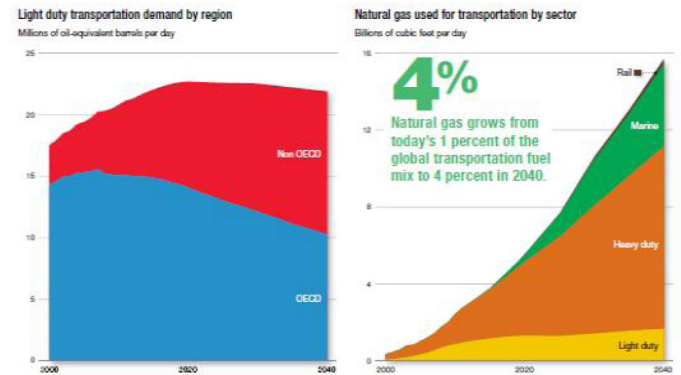


Figure 4. Light-duty fuel demand in the OECD is decreasing but increasing in the non-OECD countries. The net demand could decrease after 2020. Natural gas usage in transportation could quadruple by 2040. [22]

There is much discussion now on natural gas trucks in North America due to an abundance of natural gas afforded by new extraction methods. A large proportion of new refuse haulers are now fueled on compressed natural gas (CNG) due to quieter operation and the possibility of relatively cheap methane from landfills; and some publicly-financed transit buses have been using CNG for a number of years. A spark ignition (SI) CNG class-8 vocational trucks can cost about \$60,000 more (\$50,000 for the truck, plus tax) than a comparable diesel truck, but might save \$1300 per month in fuel at recent fuel price differentials (\$1.35/gallon of diesel equivalent, \$0.36/liter) on 100,000 miles (160,000 km) per year [28]. Tailpipe greenhouse gas emissions (GHG) for such an engine can be nominally 15% lower than diesel, considering 28% less CO₂ per unit of energy than diesel [29], but operating at 10-15% lower energy efficiency [30]. When considering a 0.5% methane leakage rate during production [31], the well-to-wheel GHG emissions are similar to diesel. For lean-burn compression ignition LNG trucks, the leading approach for line-haul trucks, energy efficiency is similar to diesel [30], and well-to-wheel GHG emissions can be 17-25% lower [32]. However, in both CNG and LNG cases, the GHG advantages can be reduced (or become a liability) depending on drive cycle and LNG tank venting [33], or on LNG sources [32].

Fuel Quality and Emissions

Fuel quality can have a huge impact on emissions, so it is important for policymakers to match the fuel to the emissions regulations. In that regard, the vehicle and engine trade associations of the US, Europe, and Japan published their latest recommendations on gasoline and diesel fuel quality for different tailpipe emission regulatory limits [34]. A new category was added for markets with highly advanced requirements for emission control and fuel efficiency. For gasoline the minimum research octane number (RON) is raised to 95 to enable some engine technologies that can increase fuel efficiency. For diesel fuel, this category establishes a high quality hydrocarbon-only specification that takes advantage of the characteristics of certain advanced biofuels, including hydrotreated vegetable oil

(HVO) and Biomass-to-Liquid (BTL), provided all other specifications are respected and the resulting blend meets defined legislated limits.

Similarly, Walsh summarized the impact of various gasoline and diesel properties on emissions [35]. Table 1 shows the impact of gasoline properties on emissions. The main diesel fuel parameters that affect emissions are sulfur, cetane, poly-aromatic hydrocarbons, density, and volatility.

Despite specific fuel quality requirements in developing countries, the actual fuel quality in the market can be much worse. For example, in one developing country the sulfur specification was tightened to 150 ppm, but five years after the requirement was implemented, six fuel samples contained 400 to 800 ppm sulfur [13]. Given such a frequency, engine manufacturers need to design for this worst case to provide customer satisfaction.

Fuels Summary

Incremental oil production over the next 10 to 15 years will shift from the Middle East to the Americas. Soon, the Americas will surpass the Middle East in oil production. Further, natural gas production is ramping up quickly, relieving oil demand. All this portends stable fuel prices. However, there are trends towards shifts in fuel type, namely more diesel demand than gasoline demand. Also, with increased demands on efficiency and emissions, fuel quality becomes even more important, and harmonization and enforcement of fuel standards will increase in importance.

Table 1. Impact of various gasoline fuel properties and emissions at different levels of vehicle technology. [35]

Gasoline	No Catalyst	Euro 1	Euro 2	Euro 3	Euro 4	Euro 5/6*	Comments
Lead ↑	Pb, HC↑	CO, HC, NO _x all increase dramatically as catalyst destroyed					Lead is banned in China gasoline since 2000
Sulfur ↑ (50 to 450 ppm)	SO ₂ ↑	CO, HC, NO _x all increase ~15-20% SO ₂ and SO ₃ increase					Onboard Diagnostic light may come on incorrectly
Olefins ↑	Increased 1,3 butadiene, increased HC reactivity, NO _x , small increases in HC for Euro 3 and cleaner						Potential deposit buildup
Aromatics ↑	Increased benzene in exhaust						Deposits on intake valves and combustion chamber tend to increase
	Potential increases in HC, NO _x	HC↑, NO _x ↓, CO↑	HC, NO _x , CO ↑				
Benzene ↑	Increased benzene exhaust and evaporative emissions						
Ethanol ↑ up to 3.5% O ₂	Lower CO, HC, slight NO _x increase(when above 2% oxygen content), Higher aldehydes	Minimal effect with new vehicles equipped with oxygen sensors, adaptive learning systems					Increased evaporative emissions unless RVP adjusted, potential effects on fuel system components, potential deposit issues, small fuel economy penalty
MTBE ↑ up to 2.7% O ₂	Lower CO, HC, higher aldehydes	Minimal effect with new vehicles equipped with oxygen sensors, adaptive learning systems					Concerns over water contamination
Distillation Characteristics T50, T90↑	Probably HC↑	HC↑					
MMT ↑	Increased Manganese Emissions			Possible Catalyst Plugging	Likely Catalyst Plugging		O ₂ sensor and OBD may be damaged, MIL light may come on incorrectly
RVP ↑	Increased evaporative HC Emissions						Most critical parameter for Asian countries because of high ambient Temperatures
Deposit control additives ↑	Potential HC, NO _x emissions benefits						Help to reduce deposits on fuel injectors, carburetors, intake valves, combustion chamber

ENGINE DEVELOPMENTS

Engines are going through a remarkable renaissance that is primarily being driven by market pressures and GHG emissions regulations. Very attractive concepts are being described that will drop fuel consumption as much as 40% in LD gasoline applications (versus multiport-injected engines) and upwards of 20% in HD truck applications. In many cases the criteria emissions also drop, but they can increase (e.g., NO_x in HD), or be reduced in a couple categories (NO_x, PM) and increased in others (HC, CO).

Following are some examples of the progress being made in both light-duty and heavy-duty applications.

Light-Duty Engines

Most market projections show the internal combustion engine (ICE) will dominate the LD vehicle market (>90%) through at least 2025. Both the US EPA 2025 greenhouse gas rule and the European Union counterpart for 2020 can be met without electric vehicles. Indeed, given that engine-based CO₂ reductions are less than half the cost (\$/percent) of plug-ins [1], it is logical that, absent significant government incentives or mandates, the ICE will be developed to its maximum (reasonable) efficiency before a significant penetration of plug-ins are used to meet the regulatory or market efficiency requirements.

Gasoline Engines

Gasoline engine developments have lagged behind their diesel counterparts mainly because significant engine modifications were not needed to meet criteria emissions regulations. This was accomplished very efficiently with the three-way catalytic converter (TWC). The European CO₂ regulations have changed this historic trend.

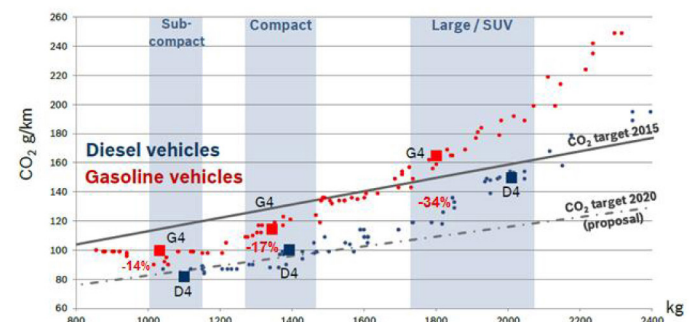


Figure 5. Best-in-class CO₂ emissions of 2012 European gasoline (G4) and diesel (D4) cars relative to the European 2020 CO₂ regulations. The percentages refer to the approximate reductions needed for gasoline cars. [36]

Figure 5 shows the best-in-class European CO₂ emissions for 2012 gasoline and diesel cars relative to the 2020 regulation [36]. Subcompact cars (60 kW engines) will likely adapt efficiency measures already on the larger vehicles, like friction reduction, variable valve timing, direct injection, high

compression ratio, automatic transmissions, downsizing, turbocharging, variable valve lift, and/or cooled EGR (exhaust gas recirculation). Compact cars (90 kW) will be similar, but with more downsizing and perhaps lean-burn. Larger cars will need much more effort, and are likely candidates for mild- or full-hybridization.

Although lean-burn direct injection engines were commercialized by Mitsubishi more than 15 year ago, and more recently both BMW and Mercedes had lean-burn engines on the market, now only Mercedes has a commercial lean-burn engine. They reported that at low speeds the fuel consumption is reduced up to 20% in urban driving and 10% in extra-urban driving relative to homogeneous combustion [37]. In highway driving the fuel consumption is similar to a diesel engine but the CO₂ emission is 13% less. The emission control system utilizes a close-coupled three-way catalyst (TWC), and underbody NOx storage catalyst (NSC), and a combination of the two in between. Relative to advanced and downsized stoichiometric direct injection engines, Bosch estimates lean-burn engine CO₂ emissions can be reduced in NEDC testing by 5 to 8% [36]. Even at these levels, lean-burn engines can deliver relatively cost-effective CO₂ reductions compared to alternatives like full hybridization, so it seems likely interest will grow.

Moving to prototype engines, the “dedicated EGR” approach is making progress [38, 39]. In this concept the exhaust from one cylinder is completely fed back into the intake, thus allowing that cylinder to operate rich to generate hydrogen. This enhances the combustion of the remaining cylinders to tolerate a high EGR rate, enhancing efficiency. Peugeot intends to commercialize the technology in 2018 for a 10% fuel savings [40]. Retrofit onto a multi-port injection (MPI) 2.4 liter baseline engine, fuel savings 12-15% are reported [39]. Torque is increased 20%, and knock is reduced, allowing 17 bar BMEP (brake mean effective pressure) and/or lower octane fuel than might be required for such loads. The effect comes from improved thermodynamics resulting from increased high levels of EGR (25% for a 4-cylinder engine), high CO and hydrogen content (6% and 2% respectively at an equivalency ratio of 1.2 for the dedicated cylinder), and higher compression ratio [40]. Future work is targeting 20% fuel savings on a direct-injection gasoline engine.

Diesel Engines

Diesel engines are still improving, with perhaps another 10% fuel consumption reduction from today's best engines [41]. The challenge will be to deliver both lower fuel consumption and meet tighter US emissions regulations.

To achieve this, the engine needs to be optimized to minimize emissions. Ruth, et al., [42] optimized combustion with high swirl, dual-loop EGR, and an optimized turbocharger to achieve the target 40 mg/mi PM (24 mg/km) and 400 mg/mi NOx (240 mg/km) on the LA4 cycle and 200 mg/mile NOx (120 g/km) on the HWFET (US Highway Federal Emissions Test)

cycle [43] for a 2300 kg pick-up truck. The fuel consumption is 25 miles/gallon (9.2 liters/100 km) or 417 g CO₂/mile (250 g/km). To meet the LEVIII emissions standards an estimated 90-93% NOx + NMOG (non-methane organic gas) reduction will be needed from the exhaust aftertreatment system.

Diesel hybrid electric vehicles show promise for delivering very low CO₂ values at lower cost than plug-ins. Freitag [44] showed two different operating principles for a full-hybrid diesel architecture. About 18% CO₂ reductions relative to the standard diesel engine were measured on the NEDC when the battery was managed incrementally during the test and kept close to the full state of charge. An improved 20% CO₂ reduction was measured when the battery was more-completely drained during urban driving, and then fully charged in the higher-speed driving at the end of the test.

The 2-stroke opposed piston design concept shows potential for even more reductions in fuel consumption and emissions [45]. In simulations of a multi-cylinder engine using data from a single-cylinder engine, 44% BTE (brake thermal efficiency) is estimated over the speed range of 1600-2100 RPM. In a simulated comparison to Ruth, et al. [42], the concept engine is estimated to achieve 20% lower fuel consumption, but with similar HC+NOx emissions. Interestingly, due to the opposed-piston design, vibration calculations show residual moments that are four orders of magnitude lower than for a similarly powered 60° 3.5 liter V6.

Advanced LD Concept Engines

Years of effort went into understanding HCCI (homogeneous charged compression ignition) engines. The main problem is that the charge ignites too rapidly at higher loads. This is now being addressed with strategies like Reactivity Controlled Compression Ignition (RCCI), wherein stratification is introduced into the charge by using two fuels of differing reactivity. The combustion is spread out over more crank angle degrees, yet the advantages of low NOx and low PM from low-temperature combustion are largely maintained.

Some of the challenges with RCCI are reported in a 1.9 liter engine using port-fuel injected gasoline to deliver power and direct-injected diesel fuel to react it [46]. In steady-state testing the engine delivers 5-7% higher BTE than diesel combustion (nominally 15% lower fuel consumption) in the operating range of typical LD test cycles, but HCs and CO are 10X higher and exhaust temperatures 80-120C° lower, presenting a challenge to oxidation catalysts. NOx emissions are up to 20% lower, but typically 5-10% lower, and PM is 30-70% lower. Solid particulate numbers are reduced two orders of magnitude from diesel.

A direct-injection compression ignition gasoline concept engine is moving from single-cylinder to multi-cylinder testing [47]. Indicated fuel steady-state fuel consumption is 184 g/kW-hr at 1500 RPM and 6 bar BMEP, and 175 g/kW-hr at 1100 RPM and 11 bar BMEP using 88 octane (RON: 10% ethanol).