

# 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 2011. First, the paper covers the key regulatory developments in the field, including proposed criteria pollutant tightening in California; and in Europe, the newly proposed PN (particle number) regulation for direct injection gasoline engines, test cycle development, and in-use testing discussions. The proposed US LD (light-duty) greenhouse gas (GHG) regulation for 2017-25 is reviewed, as well as the finalized, first-ever, US HD (heavy duty) GHG rule for 2014-17. The paper then gives a brief, high-level overview of key emissions developments in LD and HD engine technology, covering both gasoline and diesel. Emissions challenges include lean NO<sub>x</sub> remediation for diesel and lean-burn gasoline to meet both the emerging NO<sub>x</sub> and GHG regulations. NO<sub>x</sub> control technologies are then summarized, including SCR (selective catalytic reduction) with ammonia, and hydrocarbon-based approaches. Nitrous oxide (N<sub>2</sub>O) emissions are also addressed. These technologies are achieving >95% deNO<sub>x</sub> efficiency averaged over the certification test cycles. PM (particulate matter) reduction technologies are evolving around new DPF (diesel particulate filter) materials for reduced back pressure and SCR integration. Next, DOC (diesel oxidation catalyst) developments are summarized. They mainly involve NO oxidation to NO<sub>2</sub> as a function of catalyst formulation and hydrocarbon oxidation parameters. Finally, the paper discusses some key developments gasoline emission controls. Advanced three-way catalysts improve with zone coating technology, and with precious metal thrifting. Sulfur impacts are significant on the new formulations. Finally, the emerging technology of GPFs (gasoline particulate filters) is summarized.

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## INTRODUCTION

The automotive and heavy-duty vehicle industries are going through a revolution like none other in their histories. 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 improvements are being aggressively regulated to reduce CO<sub>2</sub> 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. Not only are engines significantly downsized in plug-in hybrids, like in the Chevrolet Volt, but they are replaced entirely in pure battery electric vehicles, like the Nissan Leaf. To address these forces, engine manufacturers are relying very heavily on technology developments.

It is interesting to note that the automotive industry has traditionally been quite conservative in implementing

technologies. Figure 1 shows that for five common engine technologies from 1975 to 2010, it took about 20 years from the start of production of a viable technology to reach a market penetration of 75-80% (1). Hybrid electric vehicles appear to be on the same or slower path, with the first US market introduction being in 1999 and market penetration of all HEVs being less than 2.5% twelve years later. Some notable exceptions to this trend are regulatory-driven emissions control technologies. For example, diesel particulate filters (DPFs) were introduced by Peugeot in 1999, and less than twelve years later, are on all light-duty diesel engines in the US, Europe, and Japan. One could also place heavy-duty (HD) SCR (selective catalytic reduction) catalysts systems (introduced in 2003) and HD DPFs (introduced in 2006) in the same category. Given the tightening CO<sub>2</sub> regulations, which primarily drive engine technologies, engine advancements could come much faster than in the past.

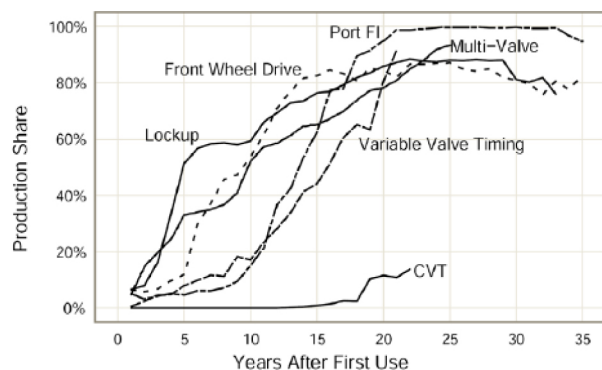


**Figure 1. Technology penetration rates for five representative engine technologies. It takes 15 to 20 years from the first major market introduction of a new technology to penetrate to 75 to 80% of the market. (1)**

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 of key developments in diesel emissions and control from 2010 (2) left off. Given the significant developments in gasoline engines and emissions control, this year an attempt is made to briefly summarize emissions developments in this field. Also, like in previous years, 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 CO<sub>2</sub>. Next, the paper then 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 NO<sub>x</sub> control, diesel PM control, diesel oxidation catalysts, and closes with representative papers on gasoline emission control.

Finally, as in previous reviews, this review is not intended to be all-encompassing and comprehensive. Representative papers and presentations were chosen here that provide examples of new, key developments and direction.

## REGULATIONS

Although many of the initiatives described here are formal proposals, they are all developed with close cooperation with the key stakeholders. As such, the final regulations will be very similar. The major vehicular regulatory initiatives of 2011 that will be summarized here include

- Proposed LEVIII LD regulation from the California Air Resources Board (CARB)

- Proposed US LD greenhouse gas reduction regulation from the US Environmental Protection Agency (EPA)
- Proposed Euro 6 gasoline PN (particle number) limits
- Developments on the LD test cycle in Europe and in-use emissions directions.
- Finalized US HD greenhouse gas regulation.

## LIGHT DUTY REGULATIONS

### Criteria Pollutants

#### California

CARB has been working with stakeholders on the LEVIII proposal since about 2008. In December 2011 they put forth a formal Advanced Clean Vehicle Program proposal, which covers LEVIII and greenhouse gas (GHG) regulations (3), and ZEV (zero emissions vehicle) requirements (4), to be finalized late-January 2012.

The LEVIII portion covers criteria exhaust emission standards for light-duty and medium-duty vehicles starting with model year 2015. Key provisions include:

- Reduce new vehicle fleet average emissions approximately 75% to super-ultra-low-emission vehicle (SULEV) levels (30 mg/mile NMOG+NO<sub>x</sub>). Non-methane organic gas refers to hydrocarbon levels adjusted for atmospheric reactivity.
- Phase-in begins in 2015 and ends in 2025. Figure 2 shows the straight-line reductions expected for cars and light-duty trucks (LDT1<3751 lbs., LDT2<8501 lbs.).
- Add new emission certification categories, designated SULEV20, ULEV50 (ultra-low emission vehicle), and ULEV70 (the 20, 50, and 70 designations refer to the NMOG+NO<sub>x</sub> emissions (mg/mile) measured using the Federal Test Procedure, FTP, test cycle.
- Increase full useful life durability requirements from 120,000 miles to 150,000 miles.
- Tighten particulate matter (PM) standards for light-duty vehicles from 10 mg/mile on the FTP today to 3 mg/mile phasing-in 2017-21 (20% of vehicles per year), and 1 mg/mile phasing-in 2025-28.
- Tighten supplemental FTP (SFTP) standards for light-duty vehicles and establish new limits for MDVs (>8500 lbs.), including a PM standard. US06 emissions (the high-speed cycle) tighten to 50 mg/mile NMOG+NO<sub>x</sub>, a 64% reduction for cars and LDT1, and 80% for the LDT2 class. A composite value, made up of the US06, SC03 (air conditioning cycle), and FTP results in similar reductions. PM levels are 10 mg/mi for PC and LDT<6000 lbs fully loaded on the US06.
- Require all medium duty vehicles (MDVs) between 8,501-10,000 lbs. to certify on a chassis dynamometer.
- Shift to an E10 (10% ethanol) certification gasoline

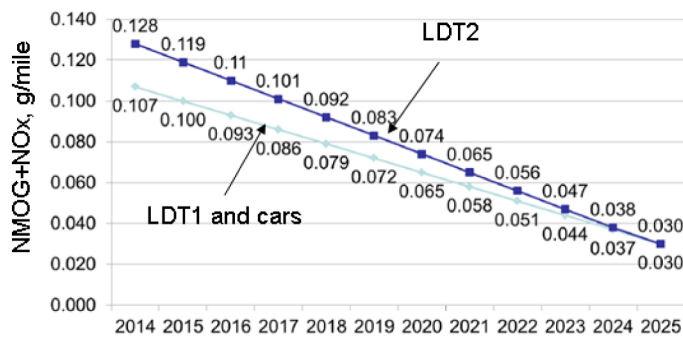


**Figure 2. Proposed California LEV III fleet average combined non-methane organic gas and NOx standards (NMOG+NOx) for cars and light-duty trucks (LDT1 up to 3750 lbs.; LDT2 3751-8500 lbs.). (3)**

The regulation will drive emission control and engine technologies in all LD classes. For example, for every ULEV50 or ULEV70 vehicle sold, two or four SULEV20 cars will be needed to meet the fleet average SULEV30 requirement. This could drive current LEV (160 mg/mile NMOG+NOx) and ULEV (125 mg/mile) vehicles to reduce emissions up to 70% (LEV to SULEV); and could reduce emissions from current ULEV and SULEV vehicles up to 85% (ULEV to SULEV20) to get enough low-emission offsets for ULEV50+ vehicles.

## Europe

Much activity is also happening in Europe on criteria pollutants. Most significantly, the European Commission proposed particle number regulations for Euro 6 direct injection gasoline engines (5). For new vehicle types made after 1 September 2014 and all vehicle models made after 1 September 2015, the PN emissions on the NEDC (New European Drive Cycle) can not exceed  $6 \times 10^{11}$  #/km, the same limit value established a few years ago as for diesel. However, for up to three years after these dates a particle number emission limit of  $60 \times 10^{11}$  #/km may be applied to Euro 6 direct injection gasoline vehicles upon request of the manufacturer. The intent is to allow manufacturers an additional three years to develop alternatives to meeting the regulations besides gasoline particulate filters (GPFs), acknowledged to perform well and be cost effective.

Also of importance, the United Nations Economic Commission for Europe - The Working Party on Pollution and Energy (UNECEGRPE) is developing the World-Harmonized Light-Duty Test Cycle (WLTC) for application at first for CO<sub>2</sub> regulations, but also for criteria pollutants (6). The developments are still dynamic, but Figure 3 illustrates the general concept (7). Urban, extra-urban, highway, and autobahn cycles are shown in series and each sub-cycle would be tested. Individual countries would arithmetically adjust the weighting of these cycles to best-match their regional driving behavior.

Europe is also looking at using these cycles or portable emissions monitoring systems (PEMS) to reduce in-use emissions relative to vehicle certification value. If the dynamometer testing is considered using these cycles, the lead proposal is to randomize them, conceivably allowing, for example four autobahn cycles to be used. Alternatively, the PEMS method would test vehicles in actual use. Depending on the details, still in development, the in-use emissions program could drive the design of emissions systems and dictate approaches.

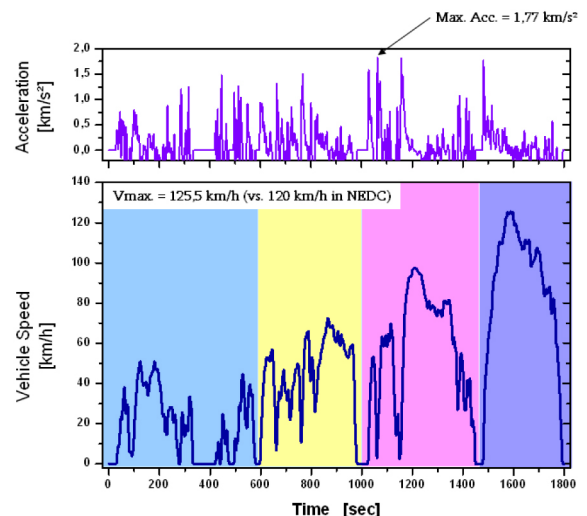


**Figure 3. One version of the proposed World-Harmonize Light-Duty Test Cycle (WLTC). Countries would weight each portion of the cycle to match the regional drive behavior.**

## On-Board Diagnostics (OBD)

In the US, OBD requirements are led by California. As part of the LEV III proposal (3), CARB is proposing minor changes to the 2013 LD OBD regulations related to DOC (diesel oxidation catalyst) NO<sub>2</sub> generation and catalyzed DPF NMHC performance. Of most significance, acknowledging that PM sensors are not yet widely available in sufficient volumes, CARB relaxed the 2013 LD PM OBD threshold value (17.5 mg/mile or 1.75X the standard) for at least one year. However, manufacturers still need to be able to detect specific DPF failure modes like partial cracks and melting. Generally the same alterations are made to the US HD OBD requirements.

Similarly in Europe, the European Commission is proposing relaxing the PM OBD threshold value for gasoline and diesel vehicles to 25 mg/km for Euro 6 (September 2014 and September 2015), tightening to 12 mg/km three years later (5). The previous threshold limit was 9 mg/km (2X the limit value). Euro 6 NOx thresholds of 150 and 180 g/km for gasoline and diesel vehicles respectively, tighten to 105 and 140 g/km three years later. NMHC proposal thresholds

remain at 170 mg/km for gasoline and 290 mg/km for diesel for Euro 6 and beyond.

### Greenhouse Gas Regulations

California's GHG program is harmonized with the US EPA-NHTSA (National Highway Transportation and Safety Administration) 2017-25 proposal that was released on November 16, 2011 (8).

General provisions are summarized as follows:

- A 163 g/mile (102 g/km) CO<sub>2</sub> industry fleet average emission limit in 2025 is proposed; nominally equivalent to a 54.5 mpg (miles per gallon; 24 km/liter, 4.2 liters/100 km). Reductions would be 5%/year for passenger cars in 2017-25 (ending at 144 g/mi or 90 g/km CO<sub>2</sub>; or 62 mpg, 27 km/l, 3.7 l/100 km). For light-duty trucks, 3.5%/year reductions would come in 2017-2021 (going to 40.9 mpg, 17.7 l/km, 5.7 l/100 km), followed by 5%/year reductions in 2022-2025 (ending at 203 g/mile or 125 g/km CO<sub>2</sub>; 49.6 mpg, 21.4 l/km, 4.7 l/100 km). There will be a progress review in 2018.
- Like in Europe, all manufacturers will have different fleet average CO<sub>2</sub> requirements, dependent on the size of their cars. However, in Europe the CO<sub>2</sub> requirements are based on vehicle weight; in the US proposal it is based on vehicle footprint (area between the tires).
- Averaging, banking, and trading of credits, established in the MY 2012-2016 program, may be carried forward, or banked, for five years, or carried back three years to cover a deficit in a previous year. Credits will also be allowed for efficiency and leakage improvements in air conditioning systems, and for various "off-cycle" credits (like stop-start systems and high-efficiency lighting). With all credits, in real world driving (five-test-cycle evaluation vs. two-cycle, above), cars are estimated to achieve 40 to 45 mpg (17 to 19 km/l; 5.8 to 5.1 l/100 km).
- The 10 mg/mile (6.2 mg/km) N<sub>2</sub>O and 30 mg/mile (19 mg/km) CH<sub>4</sub> caps in the 2012-2016 rule are continued, but the proposal allows for use of CO<sub>2</sub> credits to comply.
- Quite importantly, electrical-grid-powered vehicles are offered significant incentives. For 2017-2021 all plug-in and fuel cell vehicles, grid CO<sub>2</sub> is counted as 0 g/mile. From 2022-25, the cumulative number of vehicles that a company can use here is limited to 200,000 or 600,000, depending on plug-in sales in 2019-2021. Further, a multiplier is offered for all 2017-2021 plug-ins, allowing these vehicles to count as more than one vehicle for the purposes of compliance. For battery electric vehicles/fuel cell vehicles the multiplier starts at 2.0 in 2017 and is reduced to 1.5 by 2021; plug-in hybrid multiplier starts at 1.6 in 2017 and is reduced to 1.3 by 2021.
- Other provisions include a 10-20 g/mile CO<sub>2</sub> credit for hybridizing full-size pickups in significant volumes; and using the "SAE utility factor" for accounting for CO<sub>2</sub>

emissions from CNG (compressed natural gas) or dual-fueled vehicles. This accounting does not extend to flex-fueled vehicles (i.e., E85 fuel), for which manufacturers will need to demonstrate real-world use.

Figure 4 shows how the US proposal generally compares to others around the world (9). The European 2020 regulation of 95 g/km CO<sub>2</sub> is the most demanding, as it comes five years ahead of the US regulation. However, the US levels are similar, considering fleet mix. (Directionally, Europe is headed towards 75 g/km in 2025.) Other regions of the world are also tightening to similar levels, namely China and Japan.

The EPA technology assessment indicates there is a wide range of technologies available for manufacturers to consider in reducing GHG emissions and improving fuel economy:

- Advances in gasoline engines and transmissions will account for most of the reductions.
- Vehicle weight reduction, lower tire rolling resistance, improvements in vehicle aerodynamics, diesel engines, and more efficient vehicle accessories.
- Increased electrification of the fleet through stop-start, hybrid, plug-in hybrid electric, and electric vehicles. However, attainment of the proposed 2025 GHG regulations generally does not require plug-in vehicles.
- Air conditioner improvements could provide 10-20% GHG reductions.

The ZEV (zero emission vehicle) part of the California Advanced Clean Vehicle Program (4) proposes, beginning in 2017, to increase ZEV requirements (generally regarded as battery electric vehicles and hydrogen fuel cell vehicles) and plug-in hybrids to about 15.4% of new sales by 2025, for all but the smallest auto manufacturers.

## HEAVY DUTY REGULATIONS

### Criteria Pollutants

The most significant development on HD on-road regulations is the year-end announcement that China IV regulations will be delayed until July 2013 (10). The original data was January 1, 2011. The delay will better allow the introduction of 350 ppm sulfur fuel throughout the country.

Also significant is that Japan is targeting to harmonize with Euro VI regulations in 2016, but with a 400 mg/kW-hr NO<sub>x</sub> limit on the World-Harmonized Transient Cycle (WHTC), versus a 460 mg/kW-hr level for Euro VI (11). It is not known whether Japan will adopt the Euro VI PN standard.

As in the previous round of regulations, Europe is leading the way on Non-Road Mobile Machinery (NRMM) standards. The European Parliament instructed the European Commission to finalize the next round, Stage V, of NRMM by 2014 (12). Goals should be to:

- Harmonize requirements of Euro VI standards for heavy-duty vehicles

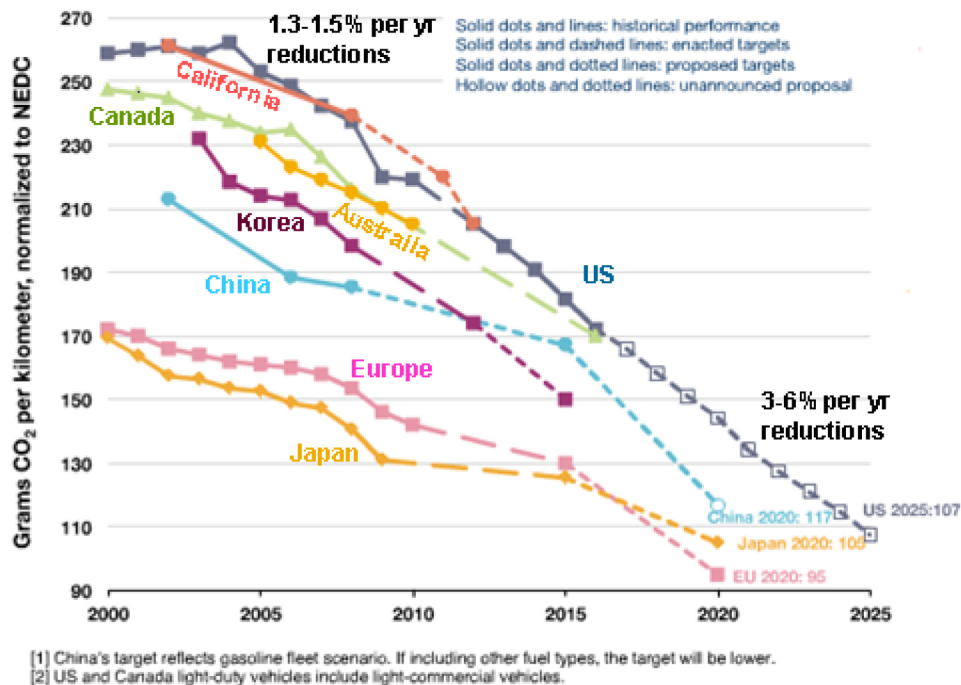


**Figure 4. Comparison of finalized and proposed fuel economy or CO<sub>2</sub> regulations around the world, normalized to CO<sub>2</sub> emissions on the New European Drive Cycle (9).**

- Adopt a particulate number limit that applies for all compression ignition engine categories
- Retrofit of after-treatment systems on the existing fleet of non- road mobile machinery for a comprehensive approach to AQ
- Periodic in-use testing of non-road mobile machinery and vehicles

Also noteworthy, Beijing will be introducing Stage IIIB equivalent NRMM standards in 2014.

### Greenhouse Gases

On August 9, 2011, the US EPA and NHTSA jointly issued their final regulations for establishing fuel efficiency and greenhouse gas emission standards for medium- and heavy-duty trucks (13). The regulation, which begins in 2015 and is fully phased-in by 2018, is the first of its kind in the world, and has some new features that are different from other HD truck regulations (14):

- Breaks diverse truck sector into 3 distinct categories - Line haul tractors, heavy-duty pickups and vans, and vocational trucks.
- Sets separate standards for engines and vehicles to ensure improvements for both
- Sets separate standards for fuel consumption, CO<sub>2</sub>, N<sub>2</sub>O (0.10 g/bhp-hr), CH<sub>4</sub> (0.10 g/bhp-hr), and hydrofluorocarbons (HFCs).
- Provides incentives for advanced technologies (e.g. EVs, Hybrids, waste heat recovery) - can be counted as 1.5 vehicles

- Manufacturer flexibilities, including averaging, banking and trading
- New compliance methods for heavy-duty hybrids and innovative technologies not contemplated in existing engine and vehicle test procedures

The CO<sub>2</sub> standards for compression ignition engines tested using the US HD engine-dynamometer test procedures are shown in Table 1 (14). In the table, tractor engines (long-haul freight) are measured on the SET cycle (steady-state engine test), and the other vocational engine classes are measured on the US HD FTP cycle (Federal Test Procedure; transient cycle). Not shown are the large pick-ups and vans, which are measured on the highway fuel economy test cycle (chassis test). Relative to the 2010 industry baseline, by 2017 the regulation results in CO<sub>2</sub> reductions from the engine of: 6% for class 7 and 8 tractors, 5% (gasoline) and 8% (diesel) for class 4-8 vocational engines, and 5% (gasoline) to 9% (diesel) for light-heavy duty trucks. Manufacturers can choose an alternative phase-in schedule more aligned to the OBD implementation schedule for 2013 and 2016. Instead of phasing in yearly, in this option the CO<sub>2</sub> standards start about 3% tighter, but are held constant and end somewhat higher than under the main plan in both phase-in periods.

**Table 1. CO<sub>2</sub> standards (g/bhp-hr) for various HD compression ignition engine classes that are certified on the engine dynamometer. (14)**

| Model Years | Light HD | Medium HD, Vocational | Heavy HD, Vocational | Medium HD, Tractor | Heavy HD, Tractor |
|-------------|----------|-----------------------|----------------------|--------------------|-------------------|
| 2014-2016   | 600      | 600                   | 567                  | 502                | 475               |
| 2017+       | 576      | 576                   | 555                  | 487                | 460               |

In addition to the engine standards, the total vehicle also needs to incorporate CO<sub>2</sub> reduction technologies, like reduced aerodynamic drag and rolling resistance. These reductions are on the order of 17% for tractors, 1% for vocational trucks, and 8% for the light heavy-duty trucks.

## REGULATORY SUMMARY

The California LEVIII regulations will drive another round of emissions control technologies on the engines and in the tailpipe. The fleet average emissions structure, as well as the sum of NMOG+NO<sub>x</sub> provides flexibility without sacrificing air quality. Europe is headed towards assuring that real-driving emissions are reduced as much as the certification testing predicts. The US LD GHG proposal also provides flexibility but likewise calls for significant reductions. The combination of criteria pollutant tightening and mandated CO<sub>2</sub> reductions present surmountable but challenging requirements on the auto industry. Long term mandates are defined to provide the industry time to meet the challenge. On the heavy-duty side, GHG emissions reductions are just beginning, and cover both engine and vehicle reductions. For NRMM (non-road mobile machinery) applications, as with the previous round of tightening, Europe is setting up for the next round of criteria pollutant tightening, generally harmonizing with Euro VI.

## ENGINE TECHNOLOGIES

Historically, engine technologies were largely influenced by and developed for meeting criteria emissions regulations. However, this is now shifting due to the tighter greenhouse gas regulations in both the light- and heavy-duty sectors. The challenge is significant, and converse to the past wherein exhaust emission control technologies could reduce much of the burden, engine technologies will need to take up most of the challenge of CO<sub>2</sub> reductions.

## LIGHT DUTY

### Gasoline

Gasoline engines are developing very rapidly to meet the tight European 2020 CO<sub>2</sub> regulations. Various roadmaps are showing 20 to 30% reductions in CO<sub>2</sub> for stoichiometric gasoline engine engines in this timeframe (e.g. 15, 16, 17). Figure 5 shows one such approach, providing 23%

reductions, more than half of which comes from significant downsizing enabled by advanced turbocharging, variable valve technology, and cooled exhaust manifolds (16). The balance comes from continuously variable valve lift and variable compression ratio (8% reductions), and optimized thermal management and friction reduction (3%). These technologies are generally additive, but may have small synergies. These are common technologies in most advanced gasoline engine roadmaps.

Engine downsizing calls for higher peak brake mean effective cylinder pressures (BMEPs) to deliver the same power as engines with larger cylinders. For reference, traditional gasoline engines have BMEPs in the 9 to 15 bar range. Fraidl and Kapus (18) show that downsized production engines today are available up to 25 bar BMEP, with prototype engines approaching 30 bar. They estimate ideal maximum BMEP of 30 to 35 bar, with the peak occurring at the lower speed range to enable long gearing. High BMEP engines require high octane fuel to minimize auto-ignition, and even then, a significant issue called low-speed pre-ignition is emerging. It is the subject of several technical symposia. High BMEP engines may require a different trend in fuel. The key could be a larger difference between the RON and MON (research octane number, motor octane number) with an emphasis on reduced MON, rather than the average of the two, as is currently used to qualify fuel octane (19).

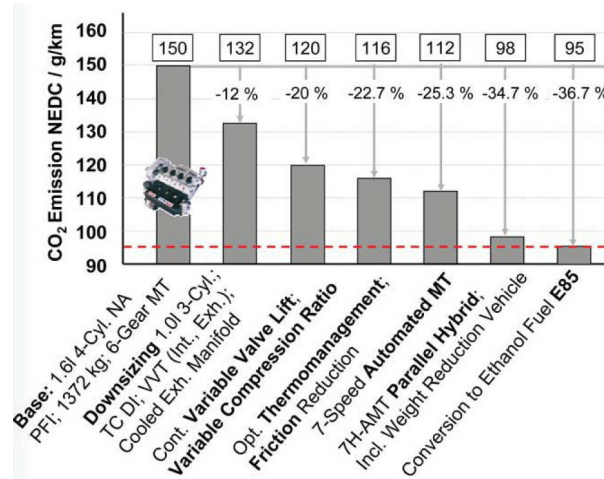


**Figure 5. Gasoline engine technologies to achieve European 2020 CO<sub>2</sub> regulations of 95 g/km. (16).**

Regarding unique emissions control requirements, direct injection gasoline engines also have high PN emissions and need specific technologies to meet the emerging Euro 6 PN regulations. PN emissions generally come from cold start and from accelerations, but can be emitted throughout the test cycle (18). Remediation approaches generally revolve around keeping the flame out of the rich, high-temperature PM-formation zone using improved air-fuel mixing, reduced wall impingement of the fuel, increased fuel injection pressures