

Review of Vehicular Emissions Trends

Timothy V. Johnson
Corning Inc.

ABSTRACT

This review paper summarizes major developments in vehicular emissions regulations and technologies from 2014. The paper starts with the key regulatory advancements in the field, including newly proposed Non-Road Mobile Machinery regulations for 2019-20 in Europe, and the continuing developments towards real driving emissions (RDE) standards. An expert panel in India proposed a roadmap through 2025 for clean fuels and tailpipe regulations. LD (light duty) 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 demonstrating more than 50% brake thermal efficiency using methods that can reasonably be commercialized. Next, NO_x control technologies are summarized, including SCR (selective catalytic reduction), lean NO_x traps, and combination systems. Emphasis is on durability and control. Diesel PM (particulate matter) reduction findings are evolving around the behavior of the soot cake and PM sensors. Gasoline particulates are further described and gasoline particulate filter regeneration is now better understood. Oxidation catalysts mainly involve developments towards stubborn problems, like sulfur tolerance, 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 meeting new regulatory requirements in the US, durability, and on lean burn gasoline emissions control.

CITATION: Johnson, T., "Review of Vehicular Emissions Trends," *SAE Int. J. Engines* 8(3):2015, doi:10.4271/2015-01-0993.

INTRODUCTION

Progress in emissions and fuel consumption reductions over the last 15 years or so have been very impressive, and it is continuing.

Since before the deliberations on LEVII (Low Emission Vehicle II) tailpipe standards in 1997 to the start of implementation of LEVIII standards in 2015, the automotive industry has faced a total tightening of emissions standards of about 97%. On-road heavy-duty (HD) trucks and non-road (NR) equipment faced similar reductions over the same time period. The challenges are continuing as the LEVIII and US Tier 3 implementation proceeds through 2025, the EU shifts to an emphasis on real-driving emissions (RDE), and the California HD and European NR sectors tighten further.

Similarly, since about 2000 light-duty (LD) greenhouse gas (GHG) emissions have dropped about 25-30%, with further reductions being required on the order of 25-30% through 2021. HD engine fuel consumption has dropped about 10% over the last 15-20 years with further reductions coming, perhaps another 10% through 2025.

These two trends have put a tremendous burden on the vehicle industry, with many experts proclaiming that these continuing challenges are among the greatest the industry has ever faced. In response, the technical community has been very active, with hundreds of papers and presentations on emissions control, and another thousand or more on engine technology.

A high-level review of these developments from the last year is presented here. As in previous years (1), this review paper covers representative regulatory, engine technology, and emission control technology developments reported in 2014 and is not intended to be comprehensive. The review covers LD, HD, and NR applications fueled by natural gas, gasoline, and diesel fuel.

REGULATIONS

Regulatory activity in 2014 that will affect vehicular emissions technologies were a mix of proposals that were developed in previous years and some finalization and development efforts. This section will touch upon the following key regulatory initiatives from 2014:

- Non-Road Mobile Machinery (NRMM) Stage V proposal. This will harmonize the EU with Switzerland, and implements a particle number (PN) regulation.
- Light-Duty Initiatives: Real-Driving Emissions (RDE), WLTP (World-Harmonized Light-Duty Test Procedure) for Euro 6c (2017), and finalization of US Tier 3.
- Indian fuels and emissions roadmap: Bharat IV nationwide by April 2017.
- China air quality initiatives.
- Other - California HD NO_x program.

Non-Road Mobile Machinery - Stage V

The proposed Stage V regulation introduces a limit on the number of particles (PN) of 1×10^{12} /kW-hr complementing a particulate mass limit of 15 mg/kW-hr for land-based engines between 19 and 560 kW. This aligns with the Swiss standard which was the first one ever to introduce a PN limit in the NRMM sector. There is however no PN limit for engines >560 kW in the main category but a PN standard applies to all inland waterway engines above 300 kW.

The NOx limit for the main engine category remains unchanged compared with Stage IV at 400 mg/kW-hr but engines >560 kW have now to meet 3.5 g/kW-hr. Emissions durability periods vary by engine category. In the land-based engine category, the durability requirement is 8000 hours for engines >37 kW. In the main category, Stage V requirements will become effective on 1 January 2018 for new engines designs and 1 January 2019 for all engines. Engines in the power band 56-130 kW which benefit from a 1-year delay. Inland waterway engines between 300 and 1000 kW implement one-year later while those >1000 kW and railway engines have a 2-year delay (i.e. 1/1/2020 for TA of engines - 1/1/2021 for placing on the market of engines). The Commission will have to report by the end of 2020 on the potential for further measures, and by the end of 2025 on the monitoring of in-service conformity testing results, and on the use of exemption clauses. Further definition of implementation details and requirements will be adopted by the end of 2016.

Light-Duty Initiatives

Real-Driving Emissions (RDE)

Numerous reports have shown that in-use emissions from cars can be much higher than would be indicated by certification testing. For example more than half of the 14 Euro 6 diesel cars tested with SCR (selective catalytic reduction), LNT (lean NOx trap), or EGR (exhaust gas recirculation) systems had NOx emissions >6X higher than certified (2). Two cars, each with LNT or SCR systems, came in at ~25X higher than certified. In another study (3), of three such vehicles tested, the best (urea-SCR) was 3-4X higher, and the highest (EGR; and LNT+urea-SCR) were 5-7X the certified level in PEMS (portable emissions measurement system) testing. Even US Tier 3 light-duty diesel can show high in-use emissions (4), wherein two cars with either an LNT or SCR emitted 4-20X the Bin 5 allowable NOx, depending on route. Most SCR emissions were in the range of 10X. However, a third SCR vehicle had in-use emissions similar to the certification, demonstrating the feasibility of doing such. The investigators think engine calibrations, not additional hardware, can solve the problem of excessive NOx emissions.

Similarly, GDI (gasoline direct injection) PN (particle number) emissions are a concern. In one study, a Euro 6 gasoline direct injection (GDI) car had about 2X higher PN emissions on the autobahn versus on the NEDC [5]. In another study [6] two Euro 6 GDI cars had nearly 10X higher PN emissions at 130 kph (km/hr) versus the NEDC. Numerous studies have also shown most of the GDI PN comes from cold start. Khalek, et al., (7) showed 1.5 to 2.5 orders of magnitude higher hot-start solid PN emissions (10-15 second duration) from both GDI and MPI gasoline engines relative to LD diesels with DPFs. PN emissions from cars were measured

coming out of a parking area on a hot day (35°C). The engines were stopped, and PN emissions were measured upon start-up. Not only were the emissions high (1000X ambient) but they were small, with PFI solid particles averaging only 6-7 nm. More work is needed, but as stop-start systems propagate, this could become an exposure issue at major intersections.

The European Commission agreed to use PEMS in regulating RDE for both diesel NOx and GDI PN. As part of their certification package, auto companies are soon required to report for monitoring purposes in-use emissions measured by two techniques - the power binning approach and the moving average window approach.

Vlachos, et al., described these two approaches (8). In general, in the power bin method data on pollutant and CO₂ emissions as well as vehicle speed and power at the wheels are calculated over intervals of 3 seconds, which are categorized into power bins. The averages of pollutant emissions for each power interval are weighed by the relative power frequency distribution from the WLTP database. Finally the weighed distance-specific and CO₂ specific emissions over all power bins are summed up to calculate a single emissions value, expressed in g/km.

In the moving average window method, second-by-second emissions data (g/km) are averaged over moving averaging windows (MAWs), the duration of which is determined from a certification cycle (i.e., CO₂ on the WLTP). Averaging windows are categorized according to their average speed into bins that represent urban ($v < 45$ km/h), rural ($45 \leq v < 85$ km/h) and motorway ($v > 85$ km/h). The resulting distance specific emission averages can be calculated for each speed bin. Data screening is determined by the CO₂ emission in each speed bin relative to that obtain on the WLTP. Figure 1 shows some representative data using this approach. If data fall outside of the tolerance zones, which are to be determined but are key to the level of stringency of the regulation, they are eliminated.

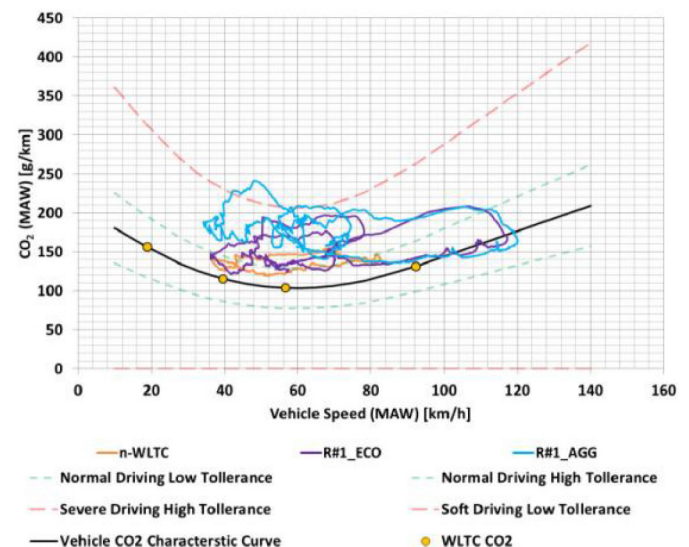


Figure 1. Representation of the Moving Average Window (MAW) approach to determining applicability of PEMS data from in-use emissions. Solid lines represent test data. Dashed lines represent two levels of stringency of acceptability of the data. (8)

An RDE regulatory proposal was recently signed by European Commission Vice President Frans Timmermans for approval by member state commissioners (9). The proposal content is uncertain at this time, but it likely calls for GDI PN and diesel NOx not-to-exceed (NTE) RDE limits by September 2017 (new engine types) and September 2018 (all engines). Further tightening is likely proposed for a few years later. The details of the test procedures and limit values will come by mid-2015.

Introduction of WLTP in Euro 6

Development of the EU-WLTP has been on-going for years. The intent is to use it to harmonize test procedures around the world using one basic test cycle that can be split into four segments (types of driving) that can be weighted to meet regional needs. There is still much discussion on the role out of the test. Indications are that it will be introduced by 1 September 2017 for new engines and September 2019 for all engines (10, 11). Correlation of CO₂ emissions relative to those on the NEDC (New European Drive Cycle), and the appropriate regulatory values is in process with the objective of adoption by mid-2015. No change in Euro 6 limits for criteria pollutants are expected.

US Tier 3

The US EPA (Environmental Protection Agency) finalized the Light-Duty Tier 3 regulations in April 2014 (12). Although it is closely harmonized with the California LEVIII regulation, which begins phasing in this year, there are differences as shown in Table 1 (13).

Table 1. Although LEVIII and US Tier 3 were developed together, there are differences. (13)

Similarities	Differences
NMOG+NOx fleet average identical for 2017-2025	California Zero Emission Vehicle (ZEV) Program
Emission categories/bins essentially identical*	LEV III starts in MY 2015, Tier 3 starts in MY 2017
Certification fuel specifications very similar (E10) and have reciprocity	Full useful life standards:
Evaporative emission standards essentially identical*	- LEV III - 150k miles; Tier 3 - 120k miles w/ optional 150k - LEV III FTP limits also apply at 50°F (Tier 3 applies only after 4K miles)
Similar US06 PM standard phase-in: 10 mg/mi reducing to 6 mg/mi (ARB has anti-backsliding provision)	LEV III 3 mg/mi PM standard phase-in ends in 2021; Tier 3 ends in 2022
*Some minor differences may exist relative to early phase-in/first years of implementation	LEV III 1 mg/mi PM standard starting in MY 2025 (Tier 3 remains at 3 mg/mi from MY 2017+)
	LEV III fleet average based on CA+S177 state sales (Tier 3 fleet average based on 50-state sales)
	LEV III credit life capped at 5 years (8 years for Tier 3: 2017-2022)

Both regulations are nominally a 70-80% tightening of NMOG (non-methane organic gases) and NOx from Tier 2 or LEVII levels, and these are roughly 40% tighter than Euro 6. A key difference between LEVIII and Tier 3 are that in 2025 the LEVIII PM (particle mass) standard tightens to 1 mg/mile (subject to review this year) while Tier 3 remains at 3 mg/mile. Given today's level of GDI engine technology, the 1 mg/mile standard would likely require a GPF (gasoline particulate filter).

India

To address some of the most polluted air in the world, the Indian government assembled a group of experts to assess vehicle-based solutions. After a couple years of gathering data and discussing approaches, a report of findings and recommendations was published (14):

- Three of four major cities investigated exceed India's own PM10 (particles <10µm) ambient standards by 2-4X.
- Vehicles account for nominally 20-50% PM2.5, and 10-95% of NO₂.
- Adopt nationwide BS IV (essentially Euro IV standards) diesel and gasoline fuel (50 ppm sulfur) and emissions standards by April 2017. Adopt BS V fuel (10 ppm) and emission standards by April 2019 (new engines)-April 2020 (all). Adopt BS VI four years after BS V (1 April 2024)

China

China is by far the largest market for cars and trucks. If the rate of growth of auto sales continues at 9% per year, annual sales in 2020 could reach 40 million cars, roughly on par with that of the US, EU, and Japan combined. However, this large and continuing influx of cars will put further stress on the notorious air quality in major Chinese cities.

Although air quality is a major problem, 2014 saw very little regulatory activity in China. In late-2013, China implemented the Clean Air Action Plan, which set out city and regional air quality goals, among other top-level initiatives. Although the China IV HD regulations (similar to Euro IV) were officially in force in July 2013, very few China IV trucks have been sold, as it was preferred to buy new China III trucks (and China II trucks in some regions). In support of the MEP (Ministry of Environmental Protection), the MIIT (Ministry of Industry and Information Technology) ruled that new China III trucks are no longer allowed to be sold as of January 1, 2015. Low sulfur fuel (50 ppm) is available nationwide, and 10 ppm fuel is available in major cities. Compliance rates are still uncertain.

Also in 2013, Beijing also put forth an Air Pollution Action Plan with aggressive reductions in major pollutants. They started implementing China V requiring wall-flow DPFs (diesel particulate filters) on all new HD vehicles registered in the city. Beijing is aiming to implement China VI standards in 2016.

Perhaps the most far-reaching development of 2014 is the Special Policy Study by China Council for International Cooperation on Environment and Development (CCICED; ref. [15](#)). It is a far-reaching document that recommends fundamental changes in how China regulates air quality. For example, recommendations are to move to a more regional approach on air quality, like setting goals and managing air quality on a regional basis. They would legally bind regions to achieve air quality standards, and group regions by air basin characteristics rather than political boundaries. Goals and assessments would be developed based on technology and scientific principles. The national government would strive to coordinate regional goals and move China into a modern infrastructure.

These recommendations, as well as much of China's air quality initiatives are on hold until a new minister of the MEP is named in the March Party Congress.

Also pertinent, China set new LD fuel consumption standards, tightening 17 to 36% depending on vehicle weight from 2015 standards (Phase III) with an average reduction of 27%, from 6.9 l/km to 5.0 l/km on the NEDC. This is about 120 g CO₂/km compared to 95 g/km in the EU for 2020-21. Further tightening of 15-30% is estimated for 2025 ([16](#)).

Other

Other on-going regulatory initiatives that will affect the vehicle emissions directions include the California HD low NOx program, and the US EPA's Phase 2 HD greenhouse (GHG) rule.

California HD Low NOx Program

Much of California is in a severe ozone non-attainment region, with parts of South Coast and San Joaquin Valleys at 85 or even 95 ppb annual ozone levels compared to a 75 ppb national requirement. CARB (California Air Resources Board) showed that NOx rather than volatile organic compound (VOC) reductions are key in these regions, and 75% reductions in the inventory are not enough ([17](#)). About a third of the NOx inventory comes from HD vehicles, so CARB is sponsoring a technology demonstration program for completion in mid- to late-2016 aimed at reducing HD NOx by 90%, to 0.020 g/bhp-hr NOx (0.026 g/kW-hr) on the combined cold and hot certification cycles. CARB showed NOx emissions at 8-15 mph (miles per hour; 13-24 km/hr) were up to 7X the 2010 certification level on some trucks ([18](#)), so it is looking at expanding the NTE (not to exceed) zone on the operating map to lower loads. Further, about a quarter of the NOx inventory comes from the non-road sector, so CARB is evaluating these for further NOx reductions. As many trucks operating in California are from out-of-state, CARB is also calling on the US EPA to set a tighter national standard. In that regard, in December 2014 the EPA proposed tightening the ozone National Ambient Air Quality Standards (NAAQS) from 75 ppb

annual average to 65-70 ppb ([19](#)). Depending on how low the final standard is set, further national HD NOx reductions may be implemented to help states reach attainment.

HD Greenhouse Gases

In March 2015 the US EPA will be proposing the second phase of HD GHG reductions beginning in ~2021. The first phase started in 2014 and will be complete in 2017, with 6-23% CO₂ reductions from the overall vehicle and 6-9% reductions coming from the engine alone, relative to a 2010 baseline. In Phase 2, the EPA will propose regulating trailers in addition to more reductions from the engines and/or total vehicle.

The European Commission is anticipated to submit a HD CO₂ proposal soon, for implementation in the 2018-20 timeframe. It will be vehicle based using simulations to take into account configurations ([20](#)).

ENGINE TECHNOLOGIES

Driven mainly by greenhouse gas regulations in major markets throughout the world, both LD and HD engine technologies are making impressive gains in the market. But the challenges are not letting up. Looking to 2020 and beyond, LD CO₂ reductions of 16 to 30% from 2014 levels are indicated by the regulations, and further HD reductions up to 10% or more are possible.

This section will summarize the leading LD gasoline and LD and HD diesel engine technologies that will help engine and vehicle manufacturers meet these goals.

Light Duty

Gasoline direct injection (GDI) engines were introduced into the market in the 1990's, but it wasn't until 2008-09 that they started to grow in market share. By 2020 they could comprise 50-60% ([21](#)) of the gasoline engines, as they provide excellent performance and save about 10-15% on fuel consumption versus the multi-port injection counterparts. Most of the GDIs being built today are in the intermediate specific power ranges (60-80 kW/liter) and designed for efficiency ([20](#)), however some are primarily designed for performance. This is not enough to meet the emerging greenhouse gas regulations, and many LD engine technologies are being evaluated to build upon this. [Table 2](#) provides an overview of many of these technologies.

Another dimension to the scenario is cost. Shown in [Figure 2](#), Kirwan ([22](#)) provided a perspective on costs for some of the technologies in [Table 2](#). The solid lines were added to illustrate the incremental costs in \$ per % CO₂ reduction for three incremental steps.

Some of the technologies in [Table 2](#) will be highlighted in the next sections.

Table 2. General overview of various engine technologies showing CO₂ reductions relative to the GDI engine, some key emissions issues, and rough estimate of the development status.

Engine Technology	CO ₂ Reduction	Emissions Issues	Status
GDI base, turbo, stoich; baseline	0	PN	Implemented
Stratified GDI	5-8%	PN	Implementing
Cylinder de-activation	5-8%	-	Implemented
Spark assist CI gasoline	5-10%	-	Research
Homogeneous Lean SI	5-10%	Lean NOx	Development
Reaction Controlled Compression Ignition	15%	LT HC+CO	Research
HEV (additive to others)	7-15%	-	Implemented
Downsize GDI, 18 → 24 bar BMEP high CR, Miller stoic	10-15%	PN	Implementing
d- and c-EGR	10-15%	Cold start, controls	Implementing
Lean-burn GDI	10-20%	Lean NOx, PN	Implementing
Light-duty diesel	15-20%	Lean NOx	Implemented
Gasoline direct-injection compression ignition	15-25%	Lean NOx, LT HC	Advanced Engineering
Diesel 2-stroke opposed piston	25-35%	Lean NOx	Development

Gasoline Engine Technology

Homogeneous lean spark ignition engines can provide both low engine-out NO_x, and lower pumping and thermal losses. Kondo, et al. (23) demonstrated a nominal 40% BTE (brake thermal efficiency) on a single-cylinder engine at the load point of 1500 RPM and 5 bar BMEP (brake mean effective pressure). The engine has a compression ratio of 13.2 and runs at an air/fuel=30. NO_x emissions are 50 ppm, but still requiring lean NO_x aftertreatment. The investigators contend the engine is well-suited for mass production.

Emerging RDE and more realistic test cycle development for CO₂ reductions will push more emphasis on higher power levels. Fraidl (21) showed that by adding the Miller cycle (extended expansion stroke), cooled EGR (driven by a small supercharger), and higher compression ratio to a 1.6 liter turbo-charged GDI engine, high-load fuel consumption (2000 RPM 14 bar BMEP) is cut by 15%, down to ~200 g/kW-hr. Even at 4 bar BMEP the fuel savings is 10%. The low-fuel consumption “sweet spot” on the engine map is quite large, and the region of minimum fuel

consumption is lower than 220 g/kW-hr. A 1250 kg demonstration vehicle was built using the engine technology along with a cooled exhaust manifold, reduced friction, and enhanced warm-up strategy. It achieved 3.8 l/km fuel consumption on the NEDC and the 2020 EU CO₂ values without hybridization.

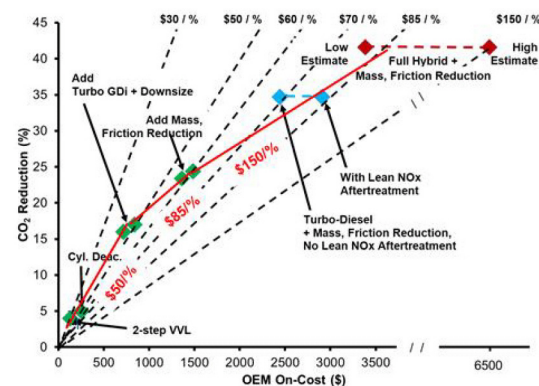


Figure 2. CO₂ reductions and cost for a variety of LD engine technologies, relative to a 4-cylinder dual overhead cam multi-port injection engine with dual independent cam phasing. (22)

A dedicated-EGR engine, wherein one cylinder's exhaust is fully fed into the intake manifold for constant 25% EGR for a four cylinder engine, was demonstrated on a vehicle (24). Besides the configuration change, other additions include pistons for CR=11.7, an additional port fuel injector to allow separate fuel control on the dedicated cylinder, and a low temperature coolant loop for the additional supercharger and aftercooler. The fuel consumption was cut 10% relative to the base GDI vehicle, and torque and peak power increased 25%, and was higher for the 2.0 liter engine than for a comparable 2.4 liter baseline GDI engine. Because the engine runs at stoichiometry, a three-way catalyst achieved emissions just shy of LEVIII. The boosting system was not well matched, more sophisticated controls are needed for a production version, this base engine is not as dilution-tolerant as others, so further optimization is possible.

An interesting detail on cooled EGR was presented by Tsuchida (25). The knock suppression of cooled EGR is improved about 4 crank angle degrees if the EGR is taken after the catalyst, with much-reduced NO_x levels. The explanation is related to the oxidation effect of NO_x.

The gasoline-based engine technology with the lowest potential CO₂ emission is the GDCI (gasoline direct-injection compression ignition) engine, mainly due to dilution and use of the diesel cycle. Sellnau (26) reported the first results on a multi-cylinder engine, and has one installed on a vehicle, although it is too early to have results on it. In an interesting comparison to eight advanced gasoline and diesel engines in the same size and power class, fuel consumption of the GDCI engine at the eight load points was compared to the “composite” engine with the best fuel consumption at any load point. Averaged over all points, the GDCI had 2% lower fuel consumption than the composite engine. The best fuel consumption of the GDCI engine was only 2% higher than the best diesel engine fuel consumption. Cost is expected to be competitive. In a schematic